VTR02-01 Bilaga 1 GÄLLANDE STANDARDER OCH FÖRESKRIFTER med tillämpningar och förtydliganden (för kontrollutrustning)

SS-EN 50272-2

Laddningsbara batterier och batterianläggningar – Säkerhet- Del 2: Stationära batterier

SS-EN 50522

Starkströmsanläggningar med nominell spänning överstigande 1 kV AC – Jordning

SS-EN 60073

Gränssnitt människa-maskin - Regler för kodning av indikatorer och manöverdon

SS-EN 60146-1-1

Halvledarströmriktare - Allmänna fordringar och nätkommuterade strömriktare - Del 1-1: Grundläggande fordringar

SS-EN 60146-2

Halvledarströmriktare - Del 2: Självkommuterande strömriktare inklusive likströmsomriktare utan växelströmsmellanled

SS-EN 60255-1

Mätande reläer och skyddsutrustningar
(Measuring relays and protection equipment)
Standarden rekommenderar att tillåten avvikelse i hjälpliksspänning ska vara 80-110% av nominellt värde.

SS-EN 60255-21-1

Vibrationsprovning (sinusformad)
(Section One – Vibration tests (sinusoidal))
Utrustningen ska klara störmiljöklass klass 1 enligt denna standard med där specificerad provutrustning och metoder.

SS-EN 60255-21-2

Stöt och skakprovning.
(Section Two – Shock and bump tests)
Utrustningen ska klara störmiljöklass klass 1 enligt denna standard med där specificerad provutrustning och metoder.

SS-EN 60255-22-1

1 MHz-störningsprovning
(Section 1 – 1 MHz burst disturbance tests)
Utrustningen ska klara störmiljöklass klass III enligt denna standard med där specificerad provutrustning och metoder.

SS-EN 60255-22-5

Insulation tests for electrical relays, part 6.1.4.2 table 6

Krav på isolation, kretsar i kontrollutrustning

Kretsar direkt galvaniskt anslutna till strömtransformatorer i ställverk	2,0 kV
Kretsar direkt galvaniskt anslutna till spänningstransformatorer i ställverk	2,0 kV
Kretsar med 110-220 V systemspänning	2,0 kV
Kretsar med 24-48 V systemspänning	0,5 kV

SS-EN 60255-22-6

Reläer: Störningsprovning av mätande reläer och skyddsutrustningar - Provning av tålighet mot ledningsbundna störningar orsakade av radiofrekventa fält

IEC 60255-24

Electrical relays: Common format for transient data exchange (COMTRADE) for power systems

SS-EN 60255-26

Mätande reläer och skyddsutrustningar - Del 26: EMC-fordringar
Utrustningen ska klara störmiljöklass klass III enligt denna standard med där specificerad provutrustning och metoder.

SS-EN 60297-3-100

Elektronikutrustningar - Mekaniska byggmått i 482,6 mm (19-tum)-serien

SS-EN 60445

Gränssnitt människa-maskin (MMI) – Grundläggande regler för märkning av uttag och ledare

SS-EN 60529

Kapslingsklasser för elektrisk material (IP-beteckningar)

SS-EN 60664-1

Isolationsnivå för elektriska anläggningsdelar och utrustningar i lågspänningssystem - Del 1: Principer, fordringar och provning

SS-EN 60834-1

Sträckskyddsutrustningar för kraftsystem – Prestanda och provning – Del 1: Smalbandiga system för fjärrmanövrering

SS-EN 60870-2-1

Utrustning för fjärrstyrning - Del 2: Driftförhållanden - Elförsörjning och elektromagnetisk kompatibilitet (EMC)

SS-EN 60870-5-101

Utrustning för fjärrstyrning - Del 5-101: Överföringsprotokoll - Tillämpningsstandard för grundläggande fjärrstyrningsfunktioner

SS-EN 60870-5-104

Utrustning för fjärrstyrning - Del 5-104: Nätåtkomst för IEC 60870-5-101 med standardiserade transportprofiler

SS-EN 60896-11

Blybatterier för stationär användning - Del 11: Öppna typer - Allmänna fordringar och provningsmetoder

SS-EN 60896-21

Blybatterier för stationär användning - Del 21: Ventilreglerade typer – Provningsmetoder

SS-EN 60947-7-1

Kopplingsapparater för högst 1000 V, kopplingsplintar för kopparledare

SS-EN 61000-4-1

Elektromagnetisk kompatibilitet (EMC) - Del 4:1 Mät- och provningsmetoder - Översikt av immunitetsprovningar

SS-EN 61000-4-2

Elektromagnetisk kompatibilitet (EMC) - Del 4:2 Mät- och provningsmetoder - Provning av immunitet mot elektrostatiska urladdningar
Utrustningen skall klara störmiljöklass nivå 3 enligt denna standard med där specificerad provutrustning och metoder.

SS-EN 61000-4-3

Elektromagnetisk kompatibilitet (EMC) - Del 4-3: Mät- och provningsmetoder - Provning av immunitet mot utstrålade radiofrekventa elektromagnetiska fält
Utrustningen ska klara störmiljöklass nivå 3 enligt denna standard med där specificerad provutrustning och metoder.

SS-EN 61000-4-4

Elektromagnetisk kompatibilitet (EMC) - Del 4-4: Mät- och provningsmetoder - Provning av immunitet mot snabba transienter och pulsskurar
Utrustningen ska klara störmiljöklass nivå 3 eller 4 enligt denna standard med där specificerad provutrustning och metoder.

SS-EN 61000-4-6

Elektromagnetisk kompatibilitet (EMC) - Del 4-6: Elektromagnetisk kompatibilitet (EMC) - Del 4-6: Mät- och provningsmetoder - Immunitet mot ledningsbundna störningar orsakade av radiofrekventa fält
Utrustningen ska klara störmiljöklass nivå 3 enligt denna standard med där specificerad provutrustning och metoder.

SS-EN 61000-4-12

Electromagnetic compatibility (EMC) - Part 4-12: Testing and measurement techniques - Oscillatory waves immunity test

SS-EN 61000-6-2

Elektromagnetisk kompatibilitet (EMC) - Del 6-2: Generella fordringar - Immunitet hos utrustning i industrimiljö

SS-EN 61000-6-4

Elektromagnetisk kompatibilitet (EMC) - Del 6-4: Generella fordringar - Emission från utrustning i industrimiljö

SS-EN 61000-6-5

Elektromagnetisk kompatibilitet (EMC) - Del 6-5: Generella fordringar - Immunitetsfordringar på utrustning för kraft- och transformatorstationer och liknande miljöer

Avbrott och pulsation i hjälpliksspänning för matning av mätande reläer.
I anläggningar med sub-uppdelad hjälpkraft gäller standarden. För övriga anläggningar skall förstärkt skydd mot avbrott finnas så att utrustningen klara avbrott på 200 ms utan att funktionen påverkas.
Dessutom ska utrustningen klara rippel (pulsationer) i matningsspänningen på upp till 12 %.

SS-EN 61131

Programmerbara styrsystem

SS-EN 61439-1

Kopplingsutrustningar för högst 1000 V växelspänning eller 1500 V likspänning – Del 1: Allmänt

IEC 61588

Precision clock synchronization protocol for networked measurement and control systems

SS-EN 61810-1

Elektromekaniska elementarreläer - Del 1: Allmänna fordringar och säkerhetsfordringar

SS-EN 61810-2

Elektromekaniska elementarreläer - Del 2: Funktionssäkerhet
Fordringar på reläkontakter.
(Contact performance of electrical relay)
Reläkontakter ska uppfylla följande kontaktdata:

Strömbelastningsförmåga

Last	Utlösningsgång	Signalutgång
Kontinuerligt	4 A	0,4 A
1 s	12 A	0,4 A

Slutförmåga likström L/R>10ms

Last	Utlösningsgång	Signalutgång
0,2 s	20 A	0,4 A
1 s	8 A	0,4 A

Brytförmåga likström L/R<40ms

Hjälpspänning	Utlösningsgång	Signalutgång
24 V	Ej aktuell	0,2 A
48 V	1,0 A	0,1 A
110 V	0,4 A	0,04 A
220 V	0,2 A	0,02 A

Skydd som normalt ska driva flera objekt ska kunna förses med kraftigare kontakter än i ovanstående tabeller. Kraven för dessa kontakter specificeras i förekommande fall för dessa skydd.
För typprovade, fabriksmonterade, kapslade ställverk accepteras att reläkontakternas brytförmåga är anpassad till den ställverksutrustning som den är avsedd att bryta, brytförmågan skall anges.

SS-EN 61811-1
Elektromekaniska tele-elementarreläer med fastställd kvalitet - Del 1: Artspecifikation

SS-EN 61850-3
Kommunikationsnät och system för kraftföretagsautomation - Del 3: Allmänna fordringar

SS-EN 61850-6
System och nät för kommunikation i stationer och ställverk - Del 6: Konfigurationsbeskrivande språk för kommunikation i ställverk med IED

SS-EN 61850-7-1
System och nät för kommunikation i stationer och ställverk - Del 7-1: Grundläggande kommunikationsstruktur för utrustning för stationer och fack - Principer och modeller

SS-EN 61850-7-2
System och nät för kommunikation i stationer och ställverk - Del 7-2: Grundläggande kommunikationsstruktur för utrustning för stationer och fack - Abstrakt gränssnitt för kommunikationstjänster (ACSI)

SS-EN 61850-7-3
System och nät för kommunikation i stationer och ställverk - Del 7-3: Grundläggande kommunikationsstruktur - Gemensamma dataklasser

SS-EN 61850-7-4
System och nät för kommunikation i stationer och ställverk - Del 7-4: Grundläggande kommunikationsstruktur för utrustning för stationer och fack - Kompatibla logiknod- och dataklasser

SS-EN 61850-8-1
System och nät för kommunikation i stationer och ställverk - Del 8-1: Specifik mappning av kommunikationstjänster (SCSM) - Mappning till MMS (ISO 9506-1 och ISO 9506-2) och till ISO/IEC 8802-3

SS-EN 61850-10
System och nät för kommunikation i stationer och ställverk - Del 10: Provning av konformitet

SS-EN 61936-1
Starkströmsanläggningar med nominell spänning överstigande 1 kV AC –
Del 1: Allmänna fodringar

SS-EN 62439

Industriell processtyrning nät med hög driftsäkerhet

IEC 62531

Property Specification Language (PSL)

SS 401 03 82

Kablar – Ordlista

SS 424 14 05

Ledningsnät för max 1000 V - Dimensionering med hänsyn till utlösningsvillkoret - Direkt jordade nät och icke direkt jordade nät skyddade av säkringar

SS 424 14 24

Kraftkablar - Dimensionering av kablar med märkspänning högst 0,6/1 kV med hänsyn till belastningsförmåga, skydd mot överlast och skydd vid kortslutning

SS 424 14 37

Kabelförläggning i mark

SS 424 14 38

Kabelförläggning i byggnader

SS 424 14 75

Kablar - Provning av egenskaper vid brand

SS 424 17 20

Kraftkablar och installationskablar - Partmärkning och mantelmärkning

SS 428 19 02

Reläskyddssystem - Hjälplikspänning för matning

SS 428 19 50

Reläer – Ordlista

SS 436 40 00

Elinstallationer i byggnader – Utförande av elinstallationer för lågspänning

SS 437 01 02

Elinstallationer för lågspänning - Vägledning för anslutning, mätning, placering och montage av el- och teleinstallationer

ELSÄK-FS

Elsäkerhetsverkets föreskrifter

SvkFS

Svenska Kraftnäts föreskrifter

EIFS 2019:7

Energimarknadsinspektionens föreskrifter om fastställande av krav på datautbyte mellan elnätsföretag och betydande nätanvändare

EU-förordning

EU-förordningen 2017/2196 av den 24 november 2017 om fastställande av nätföreskrifter för nödsituationer och återuppbyggnad avseende elektricitet

Cigre' rapport

Cigré WG36.04 april 1997, Guide on EMC in Power Plants and Substations

VTR02-02 Bilaga 1 - Generell felsignallista för IEC 61850 stationsbuss - rev. 7

Rev	Nr	Objekttyp	Apparattyp *alt.* Delsystem	Signalnamn / Larmtext *1: Littera *alt.* Spänningsnivå	SUB * 2	Funktion	Delfunktion	Signal	Larmtext (exempel) OBS! Endast VERSALER ska användas.	Signal-fördröjn. [s] *3	HMI: Händelselista	HMI: Larmlista	Fjärr (driftcentral): Fjärrindikering	Larmkl	Reservlarm	Reserv-indikerings-plats	Anmärkning
6	1	Transformator	Vakt	Objektslittera		Gasvakt		Signal	T1 GASVAKT SIGNAL	0	X	X	X	A	Stort larm	Vaktenhet	Gasvakt av Buchholz-typ
6	2	Transformator	Vakt	Objektslittera		Gasvakt		Utlöst	T1 GASVAKT UTLÖST	0	X	X	X	H	Utlöst brytare	Vaktenhet	Gasvakt av Buchholz-typ
6	3	Transformator	Vakt	Objektslittera		Temperaturvakt	Olja	Signal	T1 TEMPERATURVAKT OLJA SIGNAL	30	X	X	X	A	Stort larm	Vaktenhet	
6	4	Transformator	Vakt	Objektslittera		Temperaturvakt	Olja	Utlöst	T1 TEMPERATURVAKT OLJA UTLÖST	0	X	X	X	H	Utlöst brytare	Vaktenhet	
6	5	Transformator	Vakt	Objektslittera		Temperaturvakt	Lindning	Signal	T1 TEMPERATURVAKT LINDNING SIGNAL	30	X	X	X	A	Stort larm	Vaktenhet	
6	6	Transformator	Vakt	Objektslittera		Temperaturvakt	Lindning	Utlöst	T1 TEMPERATURVAKT LINDNING UTLÖST	0	X	X	X	H	Utlöst brytare	Vaktenhet	
6	7	Transformator	Vakt	Objektslittera		Tryckvakt		Utlöst	T1 TRYCKVAKT UTLÖST	0	X	X	X	H	Utlöst brytare	Vaktenhet	
6	8	Transformator	Vakt	Objektslittera-LK		Tryckvakt		Utlöst	T1-LK TRYCKVAKT UTLÖST	0	X	X	X	H	Utlöst brytare	Vaktenhet	Förekommer t.ex. på lindningskopplare av fabrikat ABB
6	9	Transformator	Vakt	Objektslittera-LK		Flödesvakt		Utlöst	T1-LK FLÖDESVAKT UTLÖST	0	X	X	X	H	Utlöst brytare	Vaktenhet	Förekommer t.ex. på lindningskopplare av fabrikat MR (Reinhausen)
6	10	Transformator	Vakt	Objektslittera		Oljenivå		Signal	T1 OLJENIVÅ SIGNAL	30	X	X	X	B	Litet larm	Reläskydd	Omfattar oljenivå hög/låg i expansionskärl samt oljenivå hög i lindningskopplare.
6	11	Transformator	Vakt	Objektslittera		Oljenivå		Kritiskt låg	T1 OLJENIVÅ KRITISKT LÅG	30	X	X	X	A	Stort larm	Reläskydd	Omfattar oljenivå kritiskt låg i expansionskärl samt oljenivå låg i lindningskopplare.
6	12	Transformator	Transformator	Objektslittera		Oljegrop	Nivå	Hög	T1 OLJEGROP NIVÅ HÖG	30	X	X	X	B/A	Litet larm / Stort larm	Reläskydd	Normalt klassat som B-larm. Klassas som A-larm vid vattentäkt.
6	13	Transformator	Transformator	Objektslittera		Kylutrustning		Fel	T1 KYLUTRUSTNING FEL	30	X	X	X	B	Litet larm	Reläskydd	Flödesvakter vatten/olja. Tryckvakter vatten/olja. Utlösta säkringar för fläktar/pumpar. Skall klassas som A-larm/Stort larm om det är en ODAF eller OFAF transformator.
6	14	Transformator	Transformator	Objektslittera		Torkapparat		Fel	T1 TORKAPPARAT FEL	30	X	X	X	B	Litet larm	Reläskydd	
6	15	Transformator	Transformator	Objektslittera		Skåptemperatur		Fel	T1 SKÅPTEMPERATUR FEL	30	X	X	X	B	Litet larm	Reläskydd	Övervakning grundvärme i trafolåda och övriga lådor (-IT, AUX). Övervakning VS-säkring för värme. Larm för låg temperatur i trafolåda, LK-låda och övriga lådor.
6	16	Transformator	Transformator	Objektslittera		Övriga Fel		Larm	T1 ÖVRIGA FEL LARM	30	X	X	X	B	Litet larm	Reläskydd	Signal och antal lokala signaler beroende på transformatortyp. Exempel: LS matning utlöst, Fasövervakning fel, Utlösta säkringar för annat än kylutrustning, Oljegasanalysutrustning.
6	17	Transformator	Reläskydd	Objektslittera	SUBx	DS		Start	T1 SUB1 DS START	0	X					Reläskydd	Differentialskydd
6	18	Transformator	Reläskydd	Objektslittera	SUBx	DS		Utlöst	T1 SUB1 DS UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Differentialskydd
6	19	Transformator	Reläskydd	Objektslittera	SUBx	JDS		Start	T1 SUB1 JDS START	0	X					Reläskydd	Jordströmsdifferentialskydd
6	20	Transformator	Reläskydd	Objektslittera	SUBx	JDS		Utlöst	T1 SUB1 JDS UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Jordströmsdifferentialskydd
6	21	Transformator	Reläskydd	Facklittera	SUBx	I>		Start	T1-130 SUB1 I> START	0	X					Reläskydd	
6	22	Transformator	Reläskydd	Facklittera	SUBx	I>		Utlöst	T1-130 SUB1 I> UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	
6	23	Transformator	Reläskydd	Facklittera	SUBx	I>>		Start	T1-130 SUB1 I>> START	0	X					Reläskydd	
6	24	Transformator	Reläskydd	Facklittera	SUBx	I>>		Utlöst	T1-130 SUB1 I>> UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	
6	25	Transformator	Reläskydd	Facklittera	SUBx	I>>		Blockerat	T1-130 SUB1 I>> BLOCKERAT	0	X					Reläskydd	
6	26	Transformator	Reläskydd	Facklittera	SUBx	ZS1	Framriktning	Start	T1-130 SUB1 ZS1 FRAMRIKTNING START	0	X					Reläskydd	Underimpedansskydd, framåtriktning = in mot transformatorn
6	27	Transformator	Reläskydd	Facklittera	SUBx	ZS1	Framriktning	Utlöst	T1-130 SUB1 ZS1 FRAMRIKTNING UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Underimpedansskydd, framåtriktning = in mot transformatorn
6	28	Transformator	Reläskydd	Facklittera	SUBx	ZS2	Framriktning	Start	T1-130 SUB1 ZS2 FRAMRIKTNING START	0	X					Reläskydd	Underimpedansskydd, framåtriktning = in mot transformatorn
6	29	Transformator	Reläskydd	Facklittera	SUBx	ZS2	Framriktning	Utlöst	T1-130 SUB1 ZS2 FRAMRIKTNING UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Underimpedansskydd, framåtriktning = in mot transformatorn
6	30	Transformator	Reläskydd	Facklittera	SUBx	ZS3	Backriktning	Start	T1-130 SUB1 ZS3 BACKRIKTNING START	0	X					Reläskydd	Underimpedansskydd, bakåtriktning = mot samlingsskena/ledningar
6	31	Transformator	Reläskydd	Facklittera	SUBx	ZS3	Backriktning	Utlöst	T1-130 SUB1 ZS3 BACKRIKTNING UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Underimpedansskydd, bakåtriktning = mot samlingsskena/ledningar
6	32	Transformator	Reläskydd	Facklittera	SUBx	ZS4	Backriktning	Start	T1-130 SUB1 ZS4 BACKRIKTNING START	0	X					Reläskydd	Underimpedansskydd, bakåtriktning = mot samlingsskena/ledningar
6	33	Transformator	Reläskydd	Facklittera	SUBx	ZS4	Backriktning	Utlöst	T1-130 SUB1 ZS4 BACKRIKTNING UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Underimpedansskydd, bakåtriktning = mot samlingsskena/ledningar
6	34	Transformator	Reläskydd	Facklittera	SUBx	NIS1		Start	T1-N130 SUB1 NIS1 START	0	X					Reläskydd	Gäller för NIS i direktjordat nät. För sparkopplad transformator används Objektslittera.
6	35	Transformator	Reläskydd	Facklittera	SUBx	NIS1		Utlöst	T1-N130 SUB1 NIS1 UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Gäller för NIS i direktjordat nät. För sparkopplad transformator används Objektslittera.
6	36	Transformator	Reläskydd	Facklittera	SUBx	NIS2		Start	T1-N130 SUB1 NIS2 START	0	X					Reläskydd	Gäller för NIS i direktjordat nät. För sparkopplad transformator används Objektslittera.
6	37	Transformator	Reläskydd	Facklittera	SUBx	NIS2		Utlöst	T1-N130 SUB1 NIS2 UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Gäller för NIS i direktjordat nät. För sparkopplad transformator används Objektslittera.
6	38	Transformator	Reläskydd	Facklittera	SUBx	NIS2	Undertid	Utlöst	T1-N130 SUB1 NIS2 UNDERTID UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Gäller för NIS i direktjordat nät. För sparkopplad transformator används Objektslittera.
6	39	Transformator	Reläskydd	Facklittera	SUBx	JS1		Start	T1-130 SUB1 JS1 START	0	X					Reläskydd	Gäller för JS i direktjordat nät (summaströmmätande jordfelsskydd).
6	40	Transformator	Reläskydd	Facklittera	SUBx	JS1		Utlöst	T1-130 SUB1 JS1 UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Gäller för JS i direktjordat nät (summaströmmätande jordfelsskydd).
6	41	Transformator	Reläskydd	Facklittera	SUBx	JS2		Start	T1-130 SUB1 JS2 START	0	X					Reläskydd	Gäller för JS i direktjordat nät (summaströmmätande jordfelsskydd).
6	42	Transformator	Reläskydd	Facklittera	SUBx	JS2		Utlöst	T1-130 SUB1 JS2 UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Gäller för JS i direktjordat nät (summaströmmätande jordfelsskydd).
6	43	Transformator	Reläskydd	Facklittera	SUBx	JS2	Undertid	Utlöst	T1-130 SUB1 JS2 UNDERTID UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Gäller för JS i direktjordat nät (summaströmmätande jordfelsskydd).
6	44	Transformator	Reläskydd	Facklittera	SUBx	JS/JSR		Start	T1-70 SUB1 JSR START	0	X					Reläskydd	Gäller för JS i impedansjordat nät. "JS" vid oriktat skydd, "JSR" vid riktat skydd.
6	45	Transformator	Reläskydd	Facklittera	SUBx	JS/JSR		Utlöst	T1-70 SUB1 JSR UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Gäller för JS i impedansjordat nät. "JS" vid oriktat skydd, "JSR" vid riktat skydd.
6	46	Transformator	Reläskydd (vid produktion)	Facklittera		NUS1		Start	T1-70 NUS1 START	0	X					Reläskydd	Gäller för uppsida av transformator vid spänningssättning från underliggande nät.
6	47	Transformator	Reläskydd (vid produktion)	Facklittera		NUS1		Utlöst	T1-70 NUS1 UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Gäller för uppsida av transformator vid spänningssättning från underliggande nät.
6	48	Transformator	Reläskydd (vid produktion)	Facklittera		NUS2		Start	T1-70 NUS2 START	0	X					Reläskydd	Gäller för uppsida av transformator vid spänningssättning från underliggande nät.
6	49	Transformator	Reläskydd (vid produktion)	Facklittera		NUS2		Utlöst	T1-70 NUS2 UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Gäller för uppsida av transformator vid spänningssättning från underliggande nät.
6	50	Transformator	Reläskydd	Facklittera		NUS2		Start	T1-20 NUS2 START	0	X					Reläskydd	Nedsida transformator.
6	51	Transformator	Reläskydd	Facklittera		NUS2		Utlöst	T1-20 NUS2 UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Nedsida transformator.
6	52	Transformator	Reläskydd	Facklittera		NUS3		Start	T1-20 NUS3 START	0	X					Reläskydd	Nedsida transformator.
6	53	Transformator	Reläskydd	Facklittera		NUS3		Utlöst	T1-20 NUS3 UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Nedsida transformator.
6	54	Transformator	Reläskydd	Facklittera		Högohmigt jordfel		Signal	T1-20 HÖGOHMIGT JORDFEL SIGNAL	300	X	X	X	B	Litet larm	Reläskydd	Detektering av högohmiga jordfel. Vid mätning på nedsida transformator.
6	55	Transformator	Reläskydd	Objektslittera		Nollspänningsautomatik		Utlöst	T1 NOLLSPÄNNINGSAUTOMATIK UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	
6	56	Transformator	Reläskydd	Objektslittera		TM-block		Inkopplingsförbud	T1 TM-BLOCK INKOPPLINGSFÖRBUD	0	X	X	X	A	Stort larm	Lamptryckknapp	Signal från vipprelä för tillslagsblockering.
7	57	Transformator	Reläskydd	Objektslittera-LK		I> LK		Blockerad	T1-LK I> LK BLOCKERAD	0	X					Spänningsreglering	Äldre benämning: "ISm-LK"
6	58	Transformator	Lindningskopplare	Objektslittera-LK		Temperatur låg		Blockerad	T1-LK TEMPERATUR LÅG BLOCKERAD	30	X	X	X	B	Litet larm	Spänningsreglering	Temperaturövervakning olja i LK kopplardelen. Manöverdon blockerat.
6	59	Transformator	Lindningskopplare	Objektslittera-LK		Säkring		Utlöst	T1-LK SÄKRING UTLÖST	0	X	X	X	B	Litet larm	Spänningsreglering	
6	60	Transformator	Lindningskopplare	Objektslittera-LK		Lindningskopplare		Mellanläge	T1-LK LINDNINGSKOPPLARE MELLANLÄGE	30	X	X	X	B	Litet larm	Spänningsreglering	Mellanläge är om lindningskopplaren hamnar mellan två lägen. Signalen kan även inkludera eventuellt larm från funktionsblock i spänningsregulatorn.
6	61	Transformator	Spänningsreglering	Objektslittera-LK		Samreglering		Fel	T1-LK SAMREGLERING FEL	30	X	X	X	B	Litet larm	Spänningsreglering	Används för avvikande läge vid samreglering mellan två transformatorer.
6	62																

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Denna lista beskriver den namngivning som ska användas för felsignaler och händelser inom Vattenfall Eldistribution AB.

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Rev	Nr	Objekttyp	Apparattyp *alt.* Delsystem	Signalnamn / Larmtext **1*					Larmtext (exempel)	Signal-fördröjn. [s] **3*	HMI		Fjärr (driftcentral)			Reserv-indikerings-plats	Anmärkning
				Littera *alt.* Spänningsnivå	SUB ** 2*	Funktion	Delfunktion	Signal	OBS! Endast VERSALER ska användas.		Händelselista	Larmlista	Fjärrindikering	Larm-kl	Reservlarm		
6	63	Nollpunktsbildare	Vakt	Objektslittera		Gasvakt		Signal	NT2 GASVAKT SIGNAL	0	X	X	X	A	Stort larm	Vaktenhet	
6	64	Nollpunktsbildare	Vakt	Objektslittera		Gasvakt		Utlöst	NT2 GASVAKT UTLÖST	0	X	X	X	H	Utlöst brytare	Vaktenhet	
6	65	Nollpunktsbildare	Vakt	Objektslittera		Temperaturvakt	Olja	Signal	NT2 TEMPERATURVAKT OLJA SIGNAL	30	X	X	X	A	Stort larm	Vaktenhet	
6	66	Nollpunktsbildare	Vakt	Objektslittera		Oljenivå		Signal	NT2 OLJENIVÅ SIGNAL	30	X	X	X	B	Litet larm	Vaktenhet	
6	67	Nollpunktsbildare	Reläskydd	Objektslittera		TM-block		Inkopplingsförbud	NT2 TM-BLOCK INKOPPLINGSFÖRBUD	0	X	X	X	A	Stort larm	Lamptryckknapp	Signal från vipprelä för tillslagsblockering.
6	68	Nollpunktsbildare	Reläskydd	Objektslittera		I>		Start	NT2 I> START	0	X					Reläskydd	
6	69	Nollpunktsbildare	Reläskydd	Objektslittera		I>		Utlöst	NT2 I> UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	
6	70	Nollpunktsbildare	Reläskydd	Objektslittera		I>>		Start	NT2 I>> START	0	X					Reläskydd	
6	71	Nollpunktsbildare	Reläskydd	Objektslittera		I>>		Utlöst	NT2 I>> UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	
6	72	Nollpunktsbildare	Reläskydd	Objektslittera		JDS		Start	NT70 JDS START	0	X					Reläskydd	Endast 70 kV
6	73	Nollpunktsbildare	Reläskydd	Objektslittera		JDS		Utlöst	NT70 JDS UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Endast 70 kV
6	74	Nollpunktsmotstånd	Automatik	Objektslittera		Nollpunktsautomatik		Fel	T1-N70-NM NOLLPUNKTSAUTOMATIK FEL	30	X	X	X	B	Litet larm	Signalcentral	Endast 70 kV
6	75	Nollpunktsmotstånd	Vakt	Objektslittera		Övertemperatur		Utlöst	NT2-N20-NM ÖVERTEMPERATUR UTLÖST	0	X	X	X	A	Stort larm	Signalcentral	
6	76	Nollpunktsreaktor	Vakt	Objektslittera		Gasvakt		Signal	NT2-N20-NX GASVAKT SIGNAL	0	X	X	X	A	Stort larm	Vaktenhet	
6	77	Nollpunktsreaktor	Vakt	Objektslittera		Gasvakt		Utlöst	NT2-N20-NX GASVAKT UTLÖST	0	X	X	X	H	Utlöst brytare	Vaktenhet	
6	78	Nollpunktsreaktor	Vakt	Objektslittera		Temperaturvakt	Olja	Signal	NT2-N20-NX TEMPERATURVAKT OLJA SIGNAL	30	X	X	X	A	Stort larm	Vaktenhet	
6	79	Nollpunktsreaktor	Vakt	Objektslittera		Oljenivå		Signal	NT2-N20-NX OLJENIVÅ SIGNAL	30	X	X	X	B	Litet larm	Vaktenhet	
6	80	Nollpunktsreaktor	Nollpunktsreaktor	Objektslittera		Säkring		Utlöst	NT2-N20-NX SÄKRING UTLÖST	0	X	X	X	A	Stort larm	Signalcentral	
6	81	Nollpunktsreaktor	Automatik	Objektslittera		Avstämning		Misslyckad	NT2-N20-NX AVSTÄMNING MISSLYCKAD	0	X	X	X	A	Stort larm	Avstämningsaut.	
6	82	Nollpunktsreaktor	Automatik	Objektslittera		Avstämningsautomatik		Fel	NT2-N20-NX AVSTÄMNINGSAUTOMATIK FEL	30	X	X	X	A	Stort larm	Signalcentral	
6	83																
6	84	Kondensatorbatteri	Reläskydd	Objektslittera	SUBx	Underström		Start	EK1 SUB1 UNDERSTRÖM START	0	X					Reläskydd	
6	85	Kondensatorbatteri	Reläskydd	Objektslittera	SUBx	Underström		Utlöst	EK1 SUB1 UNDERSTRÖM UTLÖST	0	X					Reläskydd	Funktion för blockering av tillslag under pågående urladdningstid.
6	86	Kondensatorbatteri	Reläskydd	Objektslittera	SUBx	Överlast		Start	EK1 SUB1 ÖVERLAST START	0	X					Reläskydd	
6	87	Kondensatorbatteri	Reläskydd	Objektslittera	SUBx	Överlast		Utlöst	EK1 SUB1 ÖVERLAST UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	
6	88	Kondensatorbatteri	Reläskydd	Objektslittera	SUBx	I>		Start	EK1 SUB1 I> START	0	X					Reläskydd	
6	89	Kondensatorbatteri	Reläskydd	Objektslittera	SUBx	I>		Utlöst	EK1 SUB1 I> UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	
6	90	Kondensatorbatteri	Reläskydd	Objektslittera	SUBx	I>>		Start	EK1 SUB1 I>> START	0	X					Reläskydd	
6	91	Kondensatorbatteri	Reläskydd	Objektslittera	SUBx	I>>		Utlöst	EK1 SUB1 I>> UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	
6	92	Kondensatorbatteri	Reläskydd	Objektslittera	SUBx	JS/JSR		Start	EK1 SUB1 JSR START	0	X					Reläskydd	"JS" används för oriktat skydd, "JSR" används för riktat skydd.
6	93	Kondensatorbatteri	Reläskydd	Objektslittera	SUBx	JS/JSR		Utlöst	EK1 SUB1 JSR UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	"JS" används för oriktat skydd, "JSR" används för riktat skydd.
6	94	Kondensatorbatteri	Reläskydd	Objektslittera	SUBx	NUS1		Start	EK1 SUB1 NUS1 START	0	X					Reläskydd	
6	95	Kondensatorbatteri	Reläskydd	Objektslittera	SUBx	NUS1		Utlöst	EK1 SUB1 NUS1 UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	
6	96	Kondensatorbatteri	Reläskydd	Objektslittera	SUBx	NUS-UTT	Tillslag mot fel	Utlöst	EK1 SUB1 NUS-UTT TILLSLAG MOT FEL UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	
6	97	Kondensatorbatteri	Reläskydd	Objektslittera	SUBx	Obalansskydd		Signal	EK1 SUB1 OBALANSSKYDD SIGNAL	0	X	X	X	B	Litet larm	Reläskydd	
6	98	Kondensatorbatteri	Reläskydd	Objektslittera	SUBx	Obalansskydd		Utlöst	EK1 SUB1 OBALANSSKYDD UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	
6	99	Kondensatorbatteri	Reläskydd	Objektslittera	SUBx	Nollspänningsautomatik		Utlöst	EK1 SUB1 NOLLSPÄNNINGSAUTOMATIK UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	
6	100																
6	101	Sektioneringsfack (U ≥ 220 kV)	Reläskydd	Objektslittera	SUBx	JS3		Start	A220 S1S2 SUB1 JS3 START	0	X					Reläskydd	
6	102	Sektioneringsfack (U ≥ 220 kV)	Reläskydd	Objektslittera	SUBx	JS3		Utlöst	A220 S1S2 SUB1 JS3 UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	
6	103	Sektioneringsfack (U ≥ 220 kV)	Reläskydd	Objektslittera	SUBx	JS	Tillslag mot fel	Utlöst	A220 S1S2 SUB1 JS TILLSLAG MOT FEL UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Signal för undertidsfunktion (JS3)
6	104	Sektioneringsfack (U ≥ 220 kV)	Reläskydd	Objektslittera	SUBx	Osymmetriström		Signal	A220 S1S2 SUB1 OSYMMETRISTRÖM SIGNAL	0	X	X	X	B	Litet larm	Reläskydd	Poldiskrepans
6	105	Sektioneringsfack (U ≥ 220 kV)	Reläskydd	Objektslittera	SUBx	Nollspänningsautomatik		Utlöst	A220 S1S2 SUB1 NOLLSPÄNNINGSAUTOMATIK UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	
6	106																
6	107	Samlingsskena (U ≥ 70 kV)	Reläskydd	Objektslittera	SUBx	SS-skydd		Utlöst	A130 SUB1 SS-SKYDD UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Gäller differentialmätande samlingsskeneskydd.
6	108	Samlingsskena (U ≥ 70 kV)	Reläskydd	Objektslittera	SUBx	SS-skydd		Blockerat	A130 SUB1 SS-SKYDD BLOCKERAT	0	X	X	X	B	Litet larm	Reläskydd	Gäller differentialmätande samlingsskeneskydd.
6	109																
6	110	Samlingsskena (U < 50 kV)	Reläskydd	Objektslittera		Högohmigt jordfel		Signal	A20 HÖGOHMIGT JORDFEL SIGNAL	300	X	X	X	B	Litet larm	Reläskydd	Detektering av högohmiga jordfel. Vid mätning på samlingsskena.
6	111	Samlingsskena (U < 50 kV)	Reläskydd	Objektslittera		Ljusbågsvakt		Utlöst	A20 LJUSBÅGSVAKT UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	
6	112	Samlingsskena (U < 50 kV)	Reläskydd	Objektslittera		Ljusbågsvakt	TM-block	Inkopplingsförbud	A20 LJUSBÅGSVAKT TM-BLOCK INKOPPLINGSFÖRBUD	0	X	X	X	A	Stort larm	Lamptryckknapp	Signal från vipprelä för tillslagsblockering.
6	113	Samlingsskena (U < 50 kV)	Reläskydd	Objektslittera		Ljusbågsvakt		Fel	A20 LJUSBÅGSVAKT FEL	5	X	X	X	A	Stort larm	Reläskydd	
6	114	Samlingsskena (U < 50 kV)	Reläskydd	Objektslittera		Ljusbågsvakt		Avställd	A20 LJUSBÅGSVAKT AVSTÄLLD	5	X	X	X	A	Stort larm	Reläskydd	
6	115																
6	116	MSP-ställverk (U ≤ 46 kV)	Ställverksfack	Fackbeteckning		Säkring		Utlöst	HA101 SÄKRING UTLÖST	30	X	X	X	A	Stort larm	Reläskydd	Används endast för ev. summalarm för säkringar/dvärgbrytare i metallkapslade MSP-stv.
6	117																
6	118	GIS-ställverk (U ≤ 220 kV)	Spänningstransformator	Apparatlittera				Ej ansluten	BL7 S1-UT EJ ANSLUTEN	30	X	X	X	A	Stort larm	Reläskydd	Vid frånskiljbar -UT i gasisolerade ställverk.
6	119	GIS-ställverk (U ≤ 220 kV)	Ställverksfack	Objektslittera			Densitet	A-Larm	BL7 S1 DENSITET A-LARM	30	X	X	X	A	Stort larm	Reläskydd	Nivå 2 larmer för samtliga gassektioner inom ett fack summeras till en larmpunkt. Gassektion med brytare signalbehandlas likt övriga brytare. Se signalpunkt 250.
6	120	GIS-ställverk (U ≤ 220 kV)	Ställverksfack	Objektslittera		Gassektion *XX*	Densitet	B-Larm	BL7 S1 GASSEKTION GS01 DENSITET B-LARM	30	X	X	X	B	Litet larm	Reläskydd	Nivå 1 larm för gassektion inom ett fack. Varje gassektion ska ha individuellt larm. Gassektion med brytare signalbehandlas likt övriga brytare. Se signalpunkt 251.
6	121	GIS-ställverk (U ≤ 220 kV)	Samlingsskena	Objektslittera			Densitet	A-Larm	A130 DENSITET A-LARM	30	X	X	X	A	Stort larm	Reläskydd	Nivå 2 larmer för samtliga gassektioner för samlingsskena summeras till en larmpunkt.
6	122	GIS-ställverk (U ≤ 220 kV)	Samlingsskena	Objektslittera		Gassektion *XX*	Densitet	B-Larm	A130 GASSEKTION GS01 DENSITET B-LARM	30	X	X	X	B	Litet larm	Reläskydd	Nivå 1 larm för gassektion inom en samlingsskena. Varje gassektion ska ha individuellt larm.
6	123	GIS-ställverk (U ≤ 220 kV)	Gasevakueringsfläkt	Spänningsnivå		GIS-Hall	Gasdetektering	Larm	130 KV GIS-HALL GASDETEKTERING LARM	30	X	X	X	A	Stort larm	Reläskydd	I SF6 anläggningar kan det finnas utrustning (sniffers) som vid detektering av SF6 larmar.
6	124	GIS-ställverk (U ≤ 220 kV)	Gasevakueringsfläkt	Spänningsnivå		GIS-Hall	Gasevakuering	Fel	130 KV GIS-HALL GASEVAKUERING FEL	30	X	X	X	B	Litet larm	Reläskydd	I SF6 anläggningar kan det finnas utrustning (sniffers) som vid detektering av startar gasevakuering.
6	125																

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Rev	Nr	Objekttyp	Apparattyp *alt.* Delsystem	Signalnamn / Larmtext *1					Larmtext (exempel)	Signal-fördröjn. [s] *3	HMI		Fjärr (driftcentral)			Reserv-indikerings-plats	Anmärkning
				Littera *alt.* Spänningsnivå	SUB *2	Funktion	Delfunktion	Signal	OBS! Endast VERSALER ska användas.		Händelselista	Larmlista	Fjärrindikering	Larm-kl	Reservlarm		
6	126	Ledning (U ≥ 70 kV)	Reläskydd	Objektslittera	SUBx	LDS		Utlöst	BL7 S8 SUB1 LDS UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	LDS = Längsdiffskydd
6	127	Ledning (U ≥ 70 kV)	Reläskydd	Objektslittera	SUBx	LDS		Blockerat	BL7 S8 SUB1 LDS BLOCKERAT	30	X	X	X	B	Litet larm	Reläskydd	
6	128	Ledning (U ≥ 70 kV)	Reläskydd	Objektslittera	SUBx	LDS	Kommunikation	Fel - Kontakta NOC	BL7 S8 SUB1 LDS KOMMUNIKATON FEL - KONTAKTA NOC	30	X	X	X	B	Litet larm	Reläskydd	Längsdiffskydd kommunikationsfel. NOC = Network Operations Center, Luleå
6	129	Ledning (U ≥ 70 kV)	Reläskydd	Objektslittera	SUBx	LDS	Redundant kanal	Fel - Kontakta NOC	BL7 S8 SUB1 LDS REDUNDANT KANAL FEL - KONTAKTA NOC	30	X	X	X	B	Litet larm	Reläskydd	Längsdiffskydd kommunikationsfel, vid dubbla kommunikationskanaler
6	130	Ledning (U ≥ 70 kV)	Reläskydd	Objektslittera	SUBx	LDS	Diffström	Onormal - Kontakta NOC	BL7 S8 SUB1 LDS DIFFSTRÖM ONORMAL - KONTAKTA NOC	30	X	X	X	B	Litet larm	Reläskydd	Obefogad diffström pga. tidsavvikelse. Gäller vid LDS över IP/UCN (ej vid direktfiber).
6	131	Ledning (U ≥ 70 kV)	Reläskydd	Objektslittera	SUBx	ZS1		Start	BL7 S8 SUB1 ZS1 START	0	X					Reläskydd	
6	132	Ledning (U ≥ 70 kV)	Reläskydd	Objektslittera	SUBx	ZS1		Utlöst	BL7 S8 SUB1 ZS1 UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Distansskydd, framåtriktad zon
6	133	Ledning (U ≥ 70 kV)	Reläskydd	Objektslittera	SUBx	ZS2		Start	BL7 S8 SUB1 ZS2 START	0	X					Reläskydd	
6	134	Ledning (U ≥ 70 kV)	Reläskydd	Objektslittera	SUBx	ZS2		Utlöst	BL7 S8 SUB1 ZS2 UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Distansskydd, framåtriktad zon
6	135	Ledning (U ≥ 70 kV)	Reläskydd	Objektslittera	SUBx	ZS3		Start	BL7 S8 SUB1 ZS3 START	0	X					Reläskydd	
6	136	Ledning (U ≥ 70 kV)	Reläskydd	Objektslittera	SUBx	ZS3		Utlöst	BL7 S8 SUB1 ZS3 UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Distansskydd, framåtriktad zon
6	137	Ledning (U ≥ 70 kV)	Reläskydd	Objektslittera	SUBx	ZS4		Start	BL7 S8 SUB1 ZS4 START	0	X					Reläskydd	
6	138	Ledning (U ≥ 70 kV)	Reläskydd	Objektslittera	SUBx	ZS4		Utlöst	BL7 S8 SUB1 ZS4 UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Distansskydd, kan användas som oriktad eller bakåtriktad zon.
6	139	Ledning (U ≥ 70 kV)	Reläskydd	Objektslittera	SUBx	ZS5		Start	BL7 S8 SUB1 ZS5 START	0	X					Reläskydd	
6	140	Ledning (U ≥ 70 kV)	Reläskydd	Objektslittera	SUBx	ZS5		Utlöst	BL7 S8 SUB1 ZS5 UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Distansskydd, kan användas som oriktad eller bakåtriktad zon.
6	141	Ledning (U ≥ 70 kV)	Reläskydd	Objektslittera	SUBx	ZS	Tillslag mot fel	Utlöst	BL7 S8 SUB1 ZS TILLSLAG MOT FEL UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	ZS-SOTF = SwitchOnToFault
6	142	Ledning (U ≥ 70 kV)	Reläskydd	Objektslittera	SUBx	ZS	RSK-accelererad	Utlöst	BL7 S8 SUB1 ZS RSK-ACCELERERAD UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Utlösning vid reläsamverkan mellan ledningsändar. RSK = Reläskyddskommunikation
6	143	Ledning (U ≥ 70 kV)	Reläskydd	Objektslittera	SUBx	JS1		Start	BL7 S8 SUB1 JS1 START	0	X					Reläskydd	Används för JS i direktjordat nät
6	144	Ledning (U ≥ 70 kV)	Reläskydd	Objektslittera	SUBx	JS1		Utlöst	BL7 S8 SUB1 JS1 UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Används för JS i direktjordat nät
6	145	Ledning (U ≥ 70 kV)	Reläskydd	Objektslittera	SUBx	JS2		Start	BL7 S8 SUB1 JS2 START	0	X					Reläskydd	Används för JS i direktjordat nät
6	146	Ledning (U ≥ 70 kV)	Reläskydd	Objektslittera	SUBx	JS2		Utlöst	BL7 S8 SUB1 JS2 UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Används för JS i direktjordat nät
6	147	Ledning (U ≥ 70 kV)	Reläskydd	Objektslittera	SUBx	JS23		Start	BL7 S8 SUB1 JS23 START	0	X					Reläskydd	Används för JS i direktjordat nät
6	148	Ledning (U ≥ 70 kV)	Reläskydd	Objektslittera	SUBx	JS23		Utlöst	BL7 S8 SUB1 JS23 UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Används för JS i direktjordat nät
6	149	Ledning (U ≥ 70 kV)	Reläskydd	Objektslittera	SUBx	JS3		Start	BL7 S8 SUB1 JS3 START	0	X					Reläskydd	Används för JS i direktjordat nät
6	150	Ledning (U ≥ 70 kV)	Reläskydd	Objektslittera	SUBx	JS3		Utlöst	BL7 S8 SUB1 JS3 UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Används för JS i direktjordat nät
6	151	Ledning (U ≥ 70 kV)	Reläskydd	Objektslittera	SUBx	JS	Tillslag mot fel	Utlöst	BL7 S8 SUB1 JS TILLSLAG MOT FEL UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Gemensam signal för JS2-SOTF, JS23-SOTF och JS3-Rt3u (undertidsfunktion)
6	152	Ledning (U ≥ 70 kV)	Reläskydd	Objektslittera	SUBx	JS	RSK-accelererad	Utlöst	BL7 S8 SUB1 JS RSK-ACCELERERAD UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Utlösning vid reläsamverkan mellan ledningsändar. RSK = Reläskyddskommunikation
6	153	Ledning (U ≥ 70 kV)	Reläskydd	Objektslittera	SUBx	I>		Start	BL7 S8 SUB1 I> START	0	X					Reläskydd	Normalt backup för ZS vid utlöst -UT-säkring.
6	154	Ledning (U ≥ 70 kV)	Reläskydd	Objektslittera	SUBx	I>		Utlöst	BL7 S8 SUB1 I> UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Normalt backup för ZS vid utlöst -UT-säkring.
6	155	Ledning (U ≥ 70 kV)	Reläskydd	Objektslittera	SUBx	JSR		Start	BL7 S8 SUB1 JSR START	0	X					Reläskydd	Endast 70 kV
6	156	Ledning (U ≥ 70 kV)	Reläskydd	Objektslittera	SUBx	JSR		Utlöst	BL7 S8 SUB1 JSR UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Endast 70 kV
6	157	Ledning (U ≥ 70 kV)	Reläskydd	Objektslittera	SUBx	JSR	Transient	Start	BL7 S8 SUB1 JSR TRANSIENT START	0	X					Reläskydd	Endast 70 kV
6	158	Ledning (U ≥ 70 kV)	Reläskydd	Objektslittera	SUBx	JSR	Transient	Utlöst	BL7 S8 SUB1 JSR TRANSIENT UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Endast 70 kV
6	159	Ledning (U ≥ 70 kV)	Reläskydd	Objektslittera	SUBx	NUS		Start	BL7 S8 SUB1 NUS START	0	X					Reläskydd	Endast 70 kV, s.k. "NUS-klipp"
6	160	Ledning (U ≥ 70 kV)	Reläskydd	Objektslittera	SUBx	NUS		Utlöst	BL7 S8 SUB1 NUS UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Endast 70 kV, s.k. "NUS-klipp"
6	161	Ledning (U ≥ 70 kV)	Reläskydd	Objektslittera	SUBx	NUS-UTT	Tillslag mot fel	Utlöst	BL7 S8 SUB1 NUS-UTT TILLSLAG MOT FEL UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Endast 70 kV
6	162	Ledning (U ≥ 70 kV)	Reläskydd	Objektslittera	SUBx	Nollspänningsautomatik		Utlöst	BL7 S8 SUB1 NOLLSPÄNNINGSAUTOMATIK UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	
6	163	Ledning (U ≥ 70 kV)	Reläskydd	Objektslittera	SUBx	Fasavbrott		Signal	BL7 S8 SUB1 FASAVBROTT SIGNAL	0	X	X	X	A	Stort larm	Reläskydd	
6	164	Ledning (U ≥ 70 kV)	Reläskydd	Objektslittera	SUBx	RSK		Mottagen	BL7 S8 SUB1 RSK MOTTAGEN	0	X					Reläskydd	RSK-SM = Reläskyddskommunikation Signal Mottagen
6	165	Ledning (U ≥ 70 kV)	Reläskydd	Objektslittera	SUBx	RSK		Sänd	BL7 S8 SUB1 RSK SÄND	0	X					Reläskydd	RSK-SS = Reläskyddskommunikation Signal Sänd
6	166	Ledning (U ≥ 70 kV)	Reläskydd	Objektslittera	SUBx	RSK		Fel/Ur drift	BL7 S8 SUB1 RSK FEL/UR DRIFT	30	X	X	X	B	Litet larm	Reläskydd	Övervakning av RSK-kanal *(ersätter äldre benämning "Teletillsats ur drift")* Från kontakt i TPE-utrustning, alt. övervakning av direkt kommunikation mellan skydd.
6	167	Ledning (U ≥ 70 kV)	Reläskydd	Objektslittera	SUBx	FUT		Utlöst	BL7 S8 SUB1 FUT UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	FUT UTLÖST = Fjärrutlösning Mottagen
6	168	Ledning (U ≥ 70 kV)	Reläskydd	Objektslittera	SUBx	FUT		Fel	BL7 S8 SUB1 FUT FEL	30	X	X	X	A	Stort larm	Reläskydd	Övervakning av fjärrutlösningskanal Från kontakt i TPE-utrustning, alt. övervakning av direkt kommunikation mellan skydd.
6	169	Ledning (U ≥ 70 kV)	Reläskydd (vid produktion)	Objektslittera	SUBx	F<		Start	BL7 S8 SUB1 F< START	0	X					Reläskydd	
6	170	Ledning (U ≥ 70 kV)	Reläskydd (vid produktion)	Objektslittera	SUBx	F<		Utlöst	BL7 S8 SUB1 F< UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Underfrekvensskydd
6	171	Ledning (U ≥ 70 kV)	Reläskydd (vid produktion)	Objektslittera	SUBx	F<<		Start	BL7 S8 SUB1 F<< START	0	X					Reläskydd	
6	172	Ledning (U ≥ 70 kV)	Reläskydd (vid produktion)	Objektslittera	SUBx	F<<		Utlöst	BL7 S8 SUB1 F<< UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Underfrekvensskydd
6	173	Ledning (U ≥ 70 kV)	Reläskydd (vid produktion)	Objektslittera	SUBx	F>		Start	BL7 S8 SUB1 F> START	0	X					Reläskydd	
6	174	Ledning (U ≥ 70 kV)	Reläskydd (vid produktion)	Objektslittera	SUBx	F>		Utlöst	BL7 S8 SUB1 F> UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Överfrekvensskydd
6	175	Ledning (U ≥ 70 kV)	Reläskydd (vid produktion)	Objektslittera	SUBx	F>>		Start	BL7 S8 SUB1 F>> START	0	X					Reläskydd	
6	176	Ledning (U ≥ 70 kV)	Reläskydd (vid produktion)	Objektslittera	SUBx	F>>		Utlöst	BL7 S8 SUB1 F>> UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Överfrekvensskydd
6	177	Ledning (U ≥ 70 kV)	Reläskydd (vid produktion)	Objektslittera	SUBx	U<		Start	BL7 S8 SUB1 U< START	0	X					Reläskydd	
6	178	Ledning (U ≥ 70 kV)	Reläskydd (vid produktion)	Objektslittera	SUBx	U<		Utlöst	BL7 S8 SUB1 U< UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Underspänningsskydd
6	179	Ledning (U ≥ 70 kV)	Reläskydd (vid produktion)	Objektslittera	SUBx	U<<		Start	BL7 S8 SUB1 U<< START	0	X					Reläskydd	
6	180	Ledning (U ≥ 70 kV)	Reläskydd (vid produktion)	Objektslittera	SUBx	U<<		Utlöst	BL7 S8 SUB1 U<< UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Underspänningsskydd
6	181	Ledning (U ≥ 70 kV)	Reläskydd (vid produktion)	Objektslittera	SUBx	U>		Start	BL7 S8 SUB1 U> START	0	X					Reläskydd	
6	182	Ledning (U ≥ 70 kV)	Reläskydd (vid produktion)	Objektslittera	SUBx	U>		Utlöst	BL7 S8 SUB1 U> UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Överspänningsskydd
6	183	Ledning (U ≥ 70 kV)	Reläskydd (vid produktion)	Objektslittera	SUBx	U>>		Start	BL7 S8 SUB1 U>> START	0	X					Reläskydd	
6	184	Ledning (U ≥ 70 kV)	Reläskydd (vid produktion)	Objektslittera	SUBx	U>>		Utlöst	BL7 S8 SUB1 U>> UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Överspänningsskydd
6	185																

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Rev	Nr	Objekttyp	Apparattyp *alt.* Delsystem	Signalnamn / Larmtext **1*: Littera *alt.* Spänningsnivå	SUB ** 2*	Funktion	Delfunktion	Signal	Larmtext (exempel) OBS! Endast VERSALER ska användas.	Signal-fördröjn. [s] **3*	HMI: Händelselista	HMI: Larmlista	Fjärr (driftcentral): Fjärrindikering	Larm-kl	Reservlarm	Reserv-indikerings-plats	Anmärkning
6	186	Ledning (U < 50 kV)	Reläskydd	Objektslittera		LDS		Utlöst	BL333 LDS UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	LDS = Längsdiffskydd
6	187	Ledning (U < 50 kV)	Reläskydd	Objektslittera		LDS		Blockerat	BL333 LDS BLOCKERAT	30	X	X	X	B	Litet larm	Reläskydd	
6	188	Ledning (U < 50 kV)	Reläskydd	Objektslittera		LDS	Kommunikation	Fel - Kontakta NOC	BL333 LDS KOMMUNIKATON FEL - KONTAKTA NOC	30	X	X	X	B	Litet larm	Reläskydd	Längsdiffskydd kommunikationsfel. NOC = Network Operations Center, Luleå
6	189	Ledning (U < 50 kV)	Reläskydd	Objektslittera		LDS	Diffström	Onormal - Kontakta NOC	BL333 LDS DIFFSTRÖM ONORMAL - KONTAKTA NOC	30	X	X	X	B	Litet larm	Reläskydd	Obefogad diffström pga. tidsavvikelse. Gäller vid LDS över IP/UCN (ej vid direktfiber).
6	190	Ledning (U < 50 kV)	Reläskydd	Objektslittera		ZS1		Start	BL333 ZS1 START	0	X					Reläskydd	
6	191	Ledning (U < 50 kV)	Reläskydd	Objektslittera		ZS1		Utlöst	BL333 ZS1 UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Distansskydd, framåtriktad zon
6	192	Ledning (U < 50 kV)	Reläskydd	Objektslittera		ZS2		Start	BL333 ZS2 START	0	X					Reläskydd	
6	193	Ledning (U < 50 kV)	Reläskydd	Objektslittera		ZS2		Utlöst	BL333 ZS2 UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Distansskydd, framåtriktad zon
6	194	Ledning (U < 50 kV)	Reläskydd	Objektslittera		ZS3		Start	BL333 ZS3 START	0	X					Reläskydd	
6	195	Ledning (U < 50 kV)	Reläskydd	Objektslittera		ZS3		Utlöst	BL333 ZS3 UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Distansskydd, framåtriktad zon
6	196	Ledning (U < 50 kV)	Reläskydd	Objektslittera		ZS4		Start	BL333 ZS4 START	0	X					Reläskydd	
6	197	Ledning (U < 50 kV)	Reläskydd	Objektslittera		ZS4		Utlöst	BL333 ZS4 UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Distansskydd, kan användas som oriktad eller bakåtriktad zon.
6	198	Ledning (U < 50 kV)	Reläskydd	Objektslittera		ZS5		Start	BL333 ZS5 START	0	X					Reläskydd	
6	199	Ledning (U < 50 kV)	Reläskydd	Objektslittera		ZS5		Utlöst	BL333 ZS5 UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Distansskydd, kan användas som oriktad eller bakåtriktad zon.
6	200	Ledning (U < 50 kV)	Reläskydd	Objektslittera		ZS	Tillslag mot fel	Utlöst	BL333 ZS TILLSLAG MOT FEL UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	ZS-SOTF = SwitchOnToFault
6	201	Ledning (U < 50 kV)	Reläskydd	Objektslittera		ZS	RSK-accelererad	Utlöst	BL333 ZS RSK-ACCELERERAD UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Utlösning vid reläsamverkan mellan ledningsändar. RSK = Reläskyddskommunikation
6	202	Ledning (U < 50 kV)	Reläskydd	Objektslittera		I>		Start	BL333 I> START	0	X					Reläskydd	
6	203	Ledning (U < 50 kV)	Reläskydd	Objektslittera		I>		Utlöst	BL333 I> UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	
6	204	Ledning (U < 50 kV)	Reläskydd	Objektslittera		I>>		Start	BL333 I>> START	0	X					Reläskydd	
6	205	Ledning (U < 50 kV)	Reläskydd	Objektslittera		I>>		Utlöst	BL333 I>> UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	
6	206	Ledning (U < 50 kV)	Reläskydd	Objektslittera		I>>>		Start	BL333 I>>> START	0	X					Reläskydd	
6	207	Ledning (U < 50 kV)	Reläskydd	Objektslittera		I>>>		Utlöst	BL333 I>>> UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	
6	208	Ledning (U < 50 kV)	Reläskydd	Objektslittera	Reservskydd	I>		Start	BL333 RESERVSKYDD I> START	0	X					Reläskydd	För parallellarbetande skydd utan SUB-uppdelning.
6	209	Ledning (U < 50 kV)	Reläskydd	Objektslittera	Reservskydd	I>		Utlöst	BL333 RESERVSKYDD I> UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	För parallellarbetande skydd utan SUB-uppdelning.
6	210	Ledning (U < 50 kV)	Reläskydd	Objektslittera	Reservskydd	I>>		Start	BL333 RESERVSKYDD I>> START	0	X					Reläskydd	För parallellarbetande skydd utan SUB-uppdelning.
6	211	Ledning (U < 50 kV)	Reläskydd	Objektslittera	Reservskydd	I>>		Utlöst	BL333 RESERVSKYDD I>> UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	För parallellarbetande skydd utan SUB-uppdelning.
6	212	Ledning (U < 50 kV)	Reläskydd	Objektslittera		JS1		Start	BL333 JS1 START	0	X					Reläskydd	Dubbelt jordfel (Cross Country fel)
6	213	Ledning (U < 50 kV)	Reläskydd	Objektslittera		JS1		Utlöst	BL333 JS1 UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Dubbelt jordfel (Cross Country fel)
6	214	Ledning (U < 50 kV)	Reläskydd	Objektslittera		JS2		Start	BL333 JS2 START	0	X					Reläskydd	Dubbelt jordfel (Cross Country fel)
6	215	Ledning (U < 50 kV)	Reläskydd	Objektslittera		JS2		Utlöst	BL333 JS2 UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Dubbelt jordfel (Cross Country fel)
6	216	Ledning (U < 50 kV)	Reläskydd	Objektslittera		JSR		Start	BL333 JSR START	0	X					Reläskydd	
6	217	Ledning (U < 50 kV)	Reläskydd	Objektslittera		JSR		Utlöst	BL333 JSR UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	
6	218	Ledning (U < 50 kV)	Reläskydd	Objektslittera		JSR	Transient	Start	BL333 JSR TRANSIENT START	0	X					Reläskydd	
6	219	Ledning (U < 50 kV)	Reläskydd	Objektslittera		JSR	Transient	Utlöst	BL333 JSR TRANSIENT UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	
6	220	Ledning (U < 50 kV)	Reläskydd	Objektslittera		NUS1		Start	BL333 NUS1 START	0	X					Reläskydd	
6	221	Ledning (U < 50 kV)	Reläskydd	Objektslittera		NUS1		Utlöst	BL333 NUS1 UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	
6	222	Ledning (U < 50 kV)	Reläskydd	Objektslittera		NUS-UTT	Tillslag mot fel	Utlöst	BL333 NUS-UTT TILLSLAG MOT FEL UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	
6	223	Ledning (U < 50 kV)	Reläskydd	Objektslittera		Högohmigt jordfel		Signal	BL333 HÖGOHMIGT JORDFEL SIGNAL	300	X	X	X	B	Litet larm	Reläskydd	Detektering av högohmiga jordfel.
6	224	Ledning (U < 50 kV)	Reläskydd	Objektslittera		Fasavbrott		Signal	BL333 FASAVBROTT SIGNAL	0	X	X	X	A	Stort larm	Reläskydd	
6	225	Ledning (U < 50 kV)	Reläskydd	Objektslittera		RSK		Mottagen	BL333 RSK MOTTAGEN	0	X					Reläskydd	RSK-SM = Reläskyddskommunikation Signal Mottagen
6	226	Ledning (U < 50 kV)	Reläskydd	Objektslittera		RSK		Sänd	BL333 RSK SÄND	0	X					Reläskydd	RSK-SS = Reläskyddskommunikation Signal Sänd
6	227	Ledning (U < 50 kV)	Reläskydd	Objektslittera		RSK		Fel/Ur drift	BL333 RSK FEL/UR DRIFT	30	X	X	X	B	Litet larm	Reläskydd	Övervakning av RSK-kanal *(ersätter äldre benämning "Teletillsats ur drift")* Från kontakt i TPE-utrustning, alt. övervakning av direkt kommunikation mellan skydd.
6	228	Ledning (U < 50 kV)	Reläskydd	Objektslittera		FUT		Utlöst	BL333 FUT UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	FUT UTLÖST = Fjärrutlösning Mottagen
6	229	Ledning (U < 50 kV)	Reläskydd	Objektslittera		FUT		Fel	BL333 FUT FEL	30	X	X	X	A	Stort larm	Reläskydd	Övervakning av fjärrutlösningskanal Från kontakt i TPE-utrustning, alt. övervakning av direkt kommunikation mellan skydd.
6	230	Ledning (U < 50 kV)	Reläskydd	Objektslittera		F<		Start	BL333 F< START	0	X					Reläskydd	
6	231	Ledning (U < 50 kV)	Reläskydd	Objektslittera		F<		Utlöst	BL333 F< UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Underfrekvensskydd
6	232	Ledning (U < 50 kV)	Reläskydd	Objektslittera		F<<		Start	BL333 F<< START	0	X					Reläskydd	
6	233	Ledning (U < 50 kV)	Reläskydd	Objektslittera		F<<		Utlöst	BL333 F<< UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Underfrekvensskydd
6	234	Ledning (U < 50 kV)	Reläskydd	Objektslittera		F>		Start	BL333 F> START	0	X					Reläskydd	
6	235	Ledning (U < 50 kV)	Reläskydd	Objektslittera		F>		Utlöst	BL333 F> UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Överfrekvensskydd
6	236	Ledning (U < 50 kV)	Reläskydd	Objektslittera		F>>		Start	BL333 F>> START	0	X					Reläskydd	
6	237	Ledning (U < 50 kV)	Reläskydd	Objektslittera		F>>		Utlöst	BL333 F>> UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Överfrekvensskydd
6	238	Ledning (U < 50 kV)	Reläskydd	Objektslittera		U<		Start	BL333 U< START	0	X					Reläskydd	
6	239	Ledning (U < 50 kV)	Reläskydd	Objektslittera		U<		Utlöst	BL333 U< UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Underspänningsskydd
6	240	Ledning (U < 50 kV)	Reläskydd	Objektslittera		U<<		Start	BL333 U<< START	0	X					Reläskydd	
6	241	Ledning (U < 50 kV)	Reläskydd	Objektslittera		U<<		Utlöst	BL333 U<< UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Underspänningsskydd
6	242	Ledning (U < 50 kV)	Reläskydd	Objektslittera		U>		Start	BL333 U> START	0	X					Reläskydd	
6	243	Ledning (U < 50 kV)	Reläskydd	Objektslittera		U>		Utlöst	BL333 U> UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Överspänningsskydd
6	244	Ledning (U < 50 kV)	Reläskydd	Objektslittera		U>>		Start	BL333 U>> START	0	X					Reläskydd	
6	245	Ledning (U < 50 kV)	Reläskydd	Objektslittera		U>>		Utlöst	BL333 U>> UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Överspänningsskydd
6	246																

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Rev	Nr	Objekttyp	Apparattyp *alt.* Delsystem	Signalnamn / Larmtext **1*					Larmtext (exempel)	Signal-fördröjn. [s] **3*	HMI		Fjärr (driftcentral)			Reserv-indikerings-plats	Anmärkning
				Littera *alt.* Spänningsnivå	SUB ** 2*	Funktion	Delfunktion	Signal	OBS! Endast VERSALER ska användas.		Händelselista	Larmlista	Fjärrindikering	Larm-kl	Reservlarm		
6	247	Primärapparat (-S) **4*	Reläskydd	Apparatlittera	SUBx	BFS		Start	BL7 S8-F-S SUB1 BFS START	0	X					Reläskydd	Brytarfelsskydd
6	248	Primärapparat (-S) **4*	Reläskydd	Apparatlittera	SUBx	BFS		Utlöst	BL7 S8-F-S SUB1 BFS UTLÖST	0	X	X	X	H	Utlöst brytare	Reläskydd	Brytarfelsskydd, steg 2 "Backup trip" - utlösning av kringliggande brytare
6	249	Primärapparat (-S) **4*	Reläskydd	Apparatlittera	SUBx	BFS	Retrip	Utlöst	BL7 S8-F-S SUB1 BFS RETRIP UTLÖST	0	X					Reläskydd	Brytarfelsskydd, steg 1 "Re-trip" - utlösning av egen brytare
6	250	Primärapparat (-S) **4*	Brytare	Apparatlittera		Brytarmanöverdon		A-Larm	BL7 S8-F-S BRYTARMANÖVERDON A-LARM	30	X	X	X	A	Stort larm	Reläskydd	Ospänd fjäder, manöverdon avställt, densitet nivå 2 och nivå 3. (Samt övriga larmer som bryter upp krets för tillslagsmagnet i manöverdonet)
6	251	Primärapparat (-S) **4*	Brytare	Apparatlittera		Brytarmanöverdon		B-Larm	BL7 S8-F-S BRYTARMANÖVERDON B-LARM	30	X	X	X	B	Litet larm	Reläskydd	Utlöst motorskydd, övervakning motorspänning, låg temp i kopplingslåda, VS värmefel. (Samt övriga larmer som inte bryter upp krets för tillslagsmagnet i manöverdonet)
6	252	Primärapparat (-S) **4*	Brytare	Apparatlittera		Brytare	Densitet	Larm	BL7 S8-F-S BRYTARE DENSITET LARM	30	X	X	X	B	Litet larm	Reläskydd	Densitet nivå 1
6	253	Primärapparat (-S) **4*	Brytare	Apparatlittera		Utlösningskrets	Spole 1	Fel	BL7 S8-F-S UTLÖSNINGSKRETS SPOLE 1 FEL	5	X	X	X	A	Stort larm	Reläskydd	TCS (Trip Circuit Supervision) för UM1
6	254	Primärapparat (-S) **4*	Brytare	Apparatlittera		Utlösningskrets	Spole 2	Fel	BL7 S8-F-S UTLÖSNINGSKRETS SPOLE 2 FEL	5	X	X	X	A	Stort larm	Reläskydd	TCS (Trip Circuit Supervision) för UM2
6	255	Primärapparat (-S) **4*	Brytare	Apparatlittera	SUBx	Brytare	Läge	Avvikande	BL7 S8-F-S SUB1 BRYTARE LÄGE AVVIKANDE	30	X	X			Stort larm	Reläskydd	Övervakning av binära ingångar för lägesindikering. Övervakas även i SUB2-skydd.
6	256	Primärapparat (-S) **4*	Brytare	Apparatlittera		Blockeringsdon	Läge	Avvikande	BL7 S8-F-S BLOCKERINGSDON LÄGE AVVIKANDE	30	X	X			Stort larm	Reläskydd	Övervakning av binära ingångar för lägesindikering.
6	257	Primärapparat (-S) **4*	Brytare	Apparatlittera		Blockeringsdon		Fel	BL7 S8-F-S BLOCKERINGSDON FEL	30	X	X	X	B	Litet larm	Reläskydd	Motorskydd utlöst, DC/DC-omvandlare fel, etc.
6	258	Primärapparat (-S) **4*	Brytare	Apparatlittera		Brytarsynkroniseringsdon		Fel	BL7 S8-F-S BRYTARSYNKRONISERINGSDON FEL	30	X	X	X	B	Litet larm	Kontrollterminal (IED)	Felsignaler från synkroniseringsdon för styrd manöver per brytarpol.
6	259	Primärapparat (-F) **4*	Frånskiljare	Apparatlittera		Frånskiljare	Motorskydd	Utlöst	T1-A130-F FRÅNSKILJARE MOTORSKYDD UTLÖST	30	X	X	X	B	Litet larm	Reläskydd	
6	260	Primärapparat (-F) **4*	Frånskiljare	Apparatlittera		Frånskiljare	Läge	Avvikande	T1-A130-F FRÅNSKILJARE LÄGE AVVIKANDE	30	X	X			Stort larm	Reläskydd	Övervakning av binära ingångar för lägesindikering.
6	261	Primärapparat (-JF) **4*	Jordningskopplare	Apparatlittera		Jordningskopplare	Motorskydd	Utlöst	BL7 S8-J2F JORDNINGSKOPPLARE MOTORSKYDD UTLÖST	30	X	X	X	B	Litet larm	Reläskydd	
6	262	Primärapparat (-JF) **4*	Jordningskopplare	Apparatlittera		Jordningskopplare	Läge	Avvikande	BL7 S8-J2F JORDNINGSKOPPLARE LÄGE AVVIKANDE	30	X	X			Stort larm	Reläskydd	Övervakning av binära ingångar för lägesindikering.
6	263	Primärapparat (-UT) **4*	Spänningstransformator	Apparatlittera		Säkring	*Grupp X*	Utlöst	A130-UT SÄKRING GRUPP 1 UTLÖST	30	X	X	X	A	Stort larm	Reläskydd	"GRUPP X" används vid behov (när olika säkringsgrupper övervakas i olika IED:er).
6	264	Primärapparat (-UT) **4*	Spänningstransformator	Apparatlittera		Spänning		Onormal	A130-UT SPÄNNING ONORMAL	300	X	X			Stort larm	Reläskydd	Gäller samlingsskena. Larmhantering i driftcentralen sker normalt via mätvärdesövervakning.
6	265																
6	266	Lokalkraft	LS-system	110V LS	SUBx	Batterikrets		Fel	110V LS SUB1 BATTERIKRETS FEL	5	X	X	X	A	Stort larm	LS-skåp	Reservind. även i signalcentral (summa-LED 110V LS FEL).
6	267	Lokalkraft	LS-system	110V LS	SUBx	Spänning		Onormal	110V LS SUB1 SPÄNNING ONORMAL	30	X	X	X	A	Stort larm	LS-skåp	Reservind. även i signalcentral (summa-LED 110V LS FEL). Gäller för betydelseklass B1 - B4
6	268	Lokalkraft	LS-system	110V LS	SUBx	Batterispänning		Kritiskt låg	110V LS SUB1 BATTERISPÄNNING KRITISKT LÅG	30	X	X	X	A	Stort larm	LS-skåp	Reservind. även i signalcentral (summa-LED 110V LS FEL). Gäller för betydelseklass B3 resp. B4.
6	269	Lokalkraft	LS-system	110V LS	SUBx	Likriktare		Fel	110V LS SUB1 LIKRIKTARE FEL	30	X	X	X	A	Stort larm	LS-skåp	Reservind. även i signalcentral (summa-LED 110V LS FEL).
6	270	Lokalkraft	LS-system	110V LS	SUBx	Jordfel		Larm	110V LS SUB1 JORDFEL LARM	30	X	X	X	B	Litet larm	LS-skåp	Reservind. även i signalcentral (summa-LED 110V LS FEL).
6	271	Lokalkraft	LS-system	110V LS	SUBx	Säkring		Utlöst	110V LS SUB1 SÄKRING UTLÖST	30	X	X	X	A	Stort larm	LS-skåp	Reservind. även i signalcentral (summa-LED 110V LS FEL).
6	272	Lokalkraft	LS-system	Spänningsnivå LS		DC/DC-omvandlare		Fel	24V LS DC/DC-OMVANDLARE FEL	30	X	X	X	A	Stort larm	Signalcentral	Larm per spänningsnivå. Signalnamnet väljs utifrån DC/DC-omvandlarens utspänning.
6	273	Lokalkraft	LS-system	Spänningsnivå LS		Spänning		Onormal	24V LS SPÄNNING ONORMAL	30	X	X	X	A	Stort larm	Signalcentral	Larm per spänningsnivå.
6	274	Lokalkraft	LS-system	Spänningsnivå LS		Jordfel		Larm	24V LS JORDFEL LARM	30	X	X	X	B	Litet larm	Signalcentral	Larm per spänningsnivå.
6	275	Lokalkraft	LS-system	Spänningsnivå LS		Säkring		Utlöst	24V LS SÄKRING UTLÖST	30	X	X	X	A	Stort larm	Signalcentral	Larm per spänningsnivå.
6	276	Lokalkraft	VS-system			Växelriktare		Fel	VÄXELRIKTARE FEL	30	X	X	X	A	Stort larm	Signalcentral	Växelriktare för avbrottsfri kraft 230 VAC
6	277	Lokalkraft	VS-system			Växelriktare	Säkring	Utlöst	VÄXELRIKTARE SÄKRING UTLÖST	30	X	X	X	A	Stort larm	Signalcentral	Larm från säkringsfördelning för avbrottsfri kraft.
6	278	Lokalkraft	VS-system			Lokalkraft VS	Säkring/JFB/åskskydd	Utlöst	LOKALKRAFT VS SÄKRING/JFB/ÅSKSKYDD UTLÖST	0	X	X	X	A	Stort larm	Signalcentral	Inkluderar även signal för jordfelsbrytare och utlöst åskskydd.
6	279	Lokalkraft	VS-system			Lokalkraft VS	Nollspänning VHC	Larm	LOKALKRAFT VS NOLLSPÄNNING VHC LARM	30	X	X	X	B	Litet larm	Signalcentral	Signal från spänningsövervakningsrelä, mätande på skena i VHC.
6	280	Lokalkraft	VS-system			Reservkraft		A-Larm	RESERVKRAFT A-LARM	30	X	X	X	A	Stort larm	Signalcentral	Dieselgenerator
6	281	Lokalkraft	VS-system			Reservkraft		B-Larm	RESERVKRAFT B-LARM	30	X	X	X	B	Litet larm	Signalcentral	Dieselgenerator
6	282	Lokalkraft	VS-system			Reservkraft	Bränslenivå	Låg	RESERVKRAFT BRÄNSLENIVÅ LÅG	30	X	X	X	A	Stort larm	Signalcentral	Dieselgenerator
6	283	Lokalkraft	VS-system			Reservkraft	Brandlarm	Utlöst	RESERVKRAFT BRANDLARM UTLÖST	5	X	X	X	A	Brand	Signalcentral	Dieselgenerator
6	284																

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Rev	Nr	Objekttyp	Apparattyp *alt.* Delsystem	Signalnamn / Larmtext *1: Littera *alt.* Spänningsnivå	SUB *2	Funktion	Delfunktion	Signal	Larmtext (exempel) OBS! Endast VERSALER ska användas.	Signal-fördröjn. [s] *3	HMI: Händelselista	HMI: Larmlista	Fjärr (driftcentral): Fjärrindikering	Larm-kl	Reservlarm	Reserv-indikerings-plats	Anmärkning
6	285	Kontrollutrustning	Driftformsomkopplare			DFO	Reservmanöver förreglingar	Avställda	DFO RESERVMANÖVER FÖRREGLINGAR AVSTÄLLDA	5	X	X	X	A		Signalcentral	
6	286	Kontrollutrustning	Felsignalsystem			Signalcentral *IEDname*	Reservsignal	Reserv *X*	SIGNALCENTRAL SG SIGN A1 RESERVSIGNAL RESERV 5								Varje IED ska ha minst 5 st. reservsignaler i DataSet och SCD-fil.
6	287	Kontrollutrustning	Felsignalsystem			Signalcentral *IEDname*	Tidssynkronisering	Fel	SIGNALCENTRAL SG_SIGN_A1 TIDSSYNKRONISERING FEL	3600	X	X	X	B	Litet larm	Signalcentral	
6	288	Kontrollutrustning	Felsignalsystem			Signalcentral *IEDname*	Kommunikationsport A	Fel	SIGNALCENTRAL SG SIGN A1 KOMMUNIKATIONSPORT A FEL	30	X	X	X	B	Litet larm	Signalcentral	Övervakning av Ethernet-kommunikation, IED komm.port A.
6	289	Kontrollutrustning	Felsignalsystem			Signalcentral *IEDname*	Kommunikationsport B	Fel	SIGNALCENTRAL SG SIGN A1 KOMMUNIKATIONSPORT B FEL	30	X	X	X	B	Litet larm	Signalcentral	Övervakning av Ethernet-kommunikation, IED komm.port B.
6	290	Kontrollutrustning	Felsignalsystem			Signalcentral *IEDname*		Fel	SIGNALCENTRAL SG_SIGN_A1 FEL	30	X	X	X	A	Stort larm	Signalcentral	Övervakning av PhyHealth i numeriska terminaler, signalen övervakas/skapas i RTU. *LPHD.PhyHealth.stVal* skall finnas med i IED:ns 61850-DataSet. Signalfördröjning avser reservlarm som skapas med logik i IED. Reservlarmet skapas lokalt i IED vid fel på både komm.port A och komm.port B. Signalcentralens IRF-kontakt ska även den aktivera "Stort larm" till reservlarmsändaren.
6	291	Kontrollutrustning *4	Reläskydd / IED			IED *IEDname*	Reservsignal	Reserv *X*	IED T1 130 A11 RESERVSIGNAL RESERV 5								Varje reläskydd / IED ska ha minst 5 st. reservsignaler i DataSet och SCD-fil.
6	292	Kontrollutrustning *4	Reläskydd / IED			IED *IEDname*		Testläge	IED T1 130 A11 TESTLÄGE	30	X	X	X	A	Stort larm	Reläskydd	Provhandske ansluten till provdon, alt. manuellt aktiverat TestMode.
6	293	Kontrollutrustning *4	Reläskydd / IED			IED *IEDname*	IED Tidssynkronisering	Fel	IED T1_130_A11 TIDSSYNKRONISERING FEL	3600	X	X	X	B	Litet larm	Reläskydd	
6	294	Kontrollutrustning *4	Reläskydd / IED			IED *IEDname*	GOOSE Kommunikation	Fel	IED T1 130 A11 GOOSE KOMMUNIKATION FEL	30	X	X	X	A	Stort larm	Reläskydd	
6	295	Kontrollutrustning *4	Reläskydd / IED			IED *IEDname*	Kommunikationsport A	Fel	IED T1 130 A11 KOMMUNIKATIONSPORT A FEL	30	X	X	X	B	Litet larm	Reläskydd	Övervakning av Ethernet-kommunikation, IED komm.port A.
6	296	Kontrollutrustning *4	Reläskydd / IED			IED *IEDname*	Kommunikationsport B	Fel	IED T1 130 A11 KOMMUNIKATIONSPORT B FEL	30	X	X	X	B	Litet larm	Reläskydd	Övervakning av Ethernet-kommunikation, IED komm.port B.
6	297	Kontrollutrustning *4	Reläskydd / IED			IED *IEDname*		Fel	IED T1_130_A11 FEL	30	X	X	X	A	Stort larm	Reläskydd	Övervakning av PhyHealth i numeriska terminaler, signalen övervakas/skapas i RTU. *LPHD.PhyHealth.stVal* skall finnas med i IED:ns 61850-DataSet. Signalfördröjning avser reservlarm som skapas med logik i IED. Reservlarmet skapas lokalt i IED vid fel på både komm.port A och komm.port B. IRF-kontakt skall hårdtrådas till signalcentral, se separat larmpunkt nedan.
6	298	Kontrollutrustning	Reläskydd / IED	Spänningsnivå		Reläskydd/IED		Fel	130 KV RELÄSKYDD/IED FEL	5	X	X	X	A	Stort larm	Signalcentral	IRF-kontakt på samtliga reläskydd och kontrollterminaler tillhörande samma spänningsnivå hårdtrådas till gemensam binär ingång på signalcentral.
6	299	Kontrollutrustning *4	Reläskydd / IED	Facklittera	SUBx	Reläskydd		Avställt	T1-130 SUB1 RELÄSKYDD AVSTÄLLT	5	X	X	X	A	Stort larm	Reläskydd	Signal från vred i avställningsenhet.
6	300	Kontrollutrustning *4	TPE	*Objektslittera*		TPE-utrustning		Fel	BL7 S8 TPE-UTRUSTNING FEL	0	X	X	X	A	Stort larm	Reläskydd (alt. Signalcentral)	IRF-kontakt på TPE-utrustning, alt. gemensam kanalövervakning för flera funktioner. Vid gemensam TPE-utrustning för flera objekt utgår Objektslittera från signalnamnet. TPE = Tele Protection Equipment (t.ex. NSD570, SWT3000, DIMAT, etc.)
6	301	Kontrollutrustning	Fjärrutrustning (RTU)			Fjärrutrustning		Fel	FJÄRRUTRUSTNING FEL	Se anm.	X	X			Fjärrutrustning fel		Watchdogfunktion i RTU. OBS! Får ej samtidigt ge något annat larm till reservlarmsändaren.
6	302	Kontrollutrustning	Fjärrutrustning (RTU)			Fjärrutrustning	Redundant matningsdon	Fel	FJÄRRUTRUSTNING REDUNDANT MATNINGSDON FEL	30	X	X	X	B		Signalcentral	Watchdogfunktion i RTU. OBS! Får ej ge något larm till reservlarmsändaren.
6	303	Kontrollutrustning	Stations-HMI			Stations-HMI		Fel	STATIONS-HMI FEL	30			X	A			RTU övervakar stations-HMI med logikapplikation.
6	304	Kontrollutrustning	Switch (Stationsbuss)			Stationsswitch		Fel	STATIONSSWITCH FEL	30	X	X	X	A	Stort larm	Signalcentral	
6	305	Kontrollutrustning	Switch (UCN-nod)			---			---	Se anm.							Övervakas av NOC (Network Operations Center) i Luleå.
6	306	Kontrollutrustning	FPS-utrustning (fasning)			FPS-utrustning		Fel	FPS-UTRUSTNING FEL	30	X	X	X	B	Litet larm	Signalcentral	Används för stationsgemensam FPS-utrustning.
6	307	Kontrollutrustning	GPS-utrustning			GPS-utrustning		Fel	GPS-UTRUSTNING FEL	30	X	X	X	B	Litet larm	Signalcentral	GPS används normalt inte.
6	308	Kontrollutrustning	Spegelreläer	Spänningsnivå		Spegelrelä		Fel	130 KV SPEGELRELÄ FEL	30	X	X	X	A	Stort larm	Signalcentral	Används för övervakning av brytarvalsutrustning, blinkdon etc. För primärapparater används "Apparatlittera LÄGE AVVIKANDE".
6	309	Kontrollutrustning	ÖK-automatik	Spänningsnivå		ÖK-automatik		Fel	20 KV ÖK-AUTOMATIK FEL	30	X	X	X	B	Litet larm	Signalcentral	ÖK = Överkopplingsautomatik
6	310	Kontrollutrustning	ÖK-automatik	Spänningsnivå		ÖK-automatik		Avställd	20 KV ÖK-AUTOMATIK AVSTÄLLD	30	X	X	X	B	Litet larm	Kontrollterminal (IED)	
6	311	Kontrollutrustning	ÖK-automatik	Spänningsnivå		ÖK-automatik	Överkoppling	Utförd	20 KV ÖK-AUTOMATIK ÖVERKOPPLING UTFÖRD	0	X	X	X	H		Kontrollterminal (IED)	
6	312	Kontrollutrustning	AFK			AFK		Utlöst	AFK UTLÖST	0	X	X	X	H	Utlöst brytare	Kontrollterminal (IED)	AFK = Automatisk belastningsFrånKoppling
6	313	Kontrollutrustning	AFK			AFK		Fel	AFK FEL	0	X	X	X	A	Stort larm	Signalcentral	
6	314	Kontrollutrustning	AFK			AFK		Avställd	AFK AVSTÄLLD	0	X	X	X	A	Stort larm	Kontrollterminal (IED)	
6	315	Kontrollutrustning	PFK			PFK		Utlöst	PFK UTLÖST	0	X	X	X	H	Utlöst brytare	Kontrollterminal (IED)	PFK = ProduktionsFrånKoppling
6	316	Kontrollutrustning	PFK			PFK		Fel	PFK FEL	0	X	X	X	A	Stort larm	Signalcentral	
6	317	Kontrollutrustning	PFK			PFK		Avställd	PFK AVSTÄLLD	0	X	X	X	A	Stort larm	Kontrollterminal (IED)	
6	318	Kontrollutrustning	Debiteringsmätning			Debiteringsmätning		Fel	DEBITERINGSMÄTNING FEL	30	X	X	X	B	Litet larm	Signalcentral	
7	319	Kontrollutrustning	Kontrollmätning			Kontrollmätning		Fel	KONTROLLMÄTNING FEL	30	X	X	X	B	Litet larm	Signalcentral	Används normalt vid >10MW
6	320	Kontrollutrustning	Störningsskrivare			Störningsskrivare		Fel	STÖRNINGSSKRIVARE FEL	30	X	X	X	B	Litet larm	Signalcentral	Gäller endast för fristående störningsskrivare
6	321	Kontrollutrustning	Reservlarmsändare			Reservlarmsändare		Fel	RESERVLARMSÄNDARE FEL	30	X	X	X	B		Signalcentral	
6	322	Kontrollutrustning	Reservlarmsändare			Reservlarmsändare		Inkopplad	RESERVLARMSÄNDARE INKOPPLAD	5	X	X			Larmsändare inkopplad		Till fjärr (driftcentral) används dubbelindikering "Reservlarmsändare Ur drift/I drift".
6	323																
6	324	Övrig utrustning	Flyghinderbelysning			Flyghinderbelysning		Fel	FLYGHINDERBELYSNING FEL	30	X	X	X	B	Litet larm	Signalcentral	
6	325	Övrig utrustning	Flyghinderbelysning			Flyghinderbelysning		Släckt	FLYGHINDERBELYSNING SLÄCKT	30	X	X	X	A	Stort larm	Signalcentral	
6	326	Övrig utrustning	Nödlarm			Nödlarm	*XX*	Aktiverad	NÖDLARM TRANSFORMATORBÅS T1 AKTIVERAD	0	X	X	X	A	Nödlarm	Signalcentral	XX = t.ex. "TRANSFORMATORBÅS T1" (en signal per larmområde)
7	327	Övrig utrustning	Kontrollbyggnad			Inbrottslarm		Utlöst	INBROTTSLARM UTLÖST	0	X		X	H	Inbrott	Signalcentral	Inbrott övervakas av Bevakningscentralen, finns med här för att den är kopplad till reservlarm
6	328	Övrig utrustning	Kontrollbyggnad			Brandlarm		Utlöst	BRANDLARM UTLÖST	0	X	X	X	A	Brand	Signalcentral	
6	329	Övrig utrustning	Kontrollbyggnad			Septiktank	Nivå	Hög	SEPTIKTANK NIVÅ HÖG	30	X	X	X	B	Litet larm	Signalcentral	
6	330	Övrig utrustning	Kontrollbyggnad			Ventilationsutrustning		Fel	VENTILATIONSUTRUSTNING FEL	30	X	X	X	B	Litet larm	Signalcentral	Brandspjäll fel skall också ingå i detta larm.
6	331	Övrig utrustning	Kontrollbyggnad			Kontrollbyggnad	Temperatur	Onormal	KONTROLLBYGGNAD TEMPERATUR ONORMAL	3600	X	X	X	B	Litet larm	Signalcentral	Avser kontrollrum, samt ställverksrum med kontrollutrustning. Larmgränser (hög resp. låg) parametreras i signalcentral. Normalt klassat som B-larm. Klassas som A-larm vid temperaturkänslig utrustning.
6	332	Övrig utrustning	Kontrollbyggnad			Batterirum	Temperatur	Onormal	BATTERIRUM TEMPERATUR ONORMAL	3600	X	X	X	B	Litet larm	Signalcentral	Larmgränser (hög resp. låg) parametreras i signalcentral.
6	333																

Exempel på olika typer av littera:	
Ledningsobjekt - objektlittera:	**BL7 S8**
Ledningsobjekt - apparatlittera:	**BL7 S8-F-S**
Transformatorobjekt - objektlittera:	**T1**
Transformatorobjekt - facklittera:	**T1-130**
Transformatorobjekt - apparatlittera:	**T1-130-S**

Anmärkningar:

*1) Larmtext måste vara unik för varje signal för att kunna laddas in i SCADA-system. Larmtext ska alltid skrivas med VERSALER och byggs i tillämpliga delar ihop enligt: LITTERA + SUB + FUNKTION + DELFUNKTION + SIGNAL
Samma larmtext ska användas för lokal stations-HMI och Fjärr.
Gruppering av signaler ska i första hand ske med logik i IED (reläskydd/automatik/signalcentral/etc.). I andra hand kan gruppering utföras hårdtrådat före IED, olika larm måste då kunna särskiljas genom urbleckning av frånskiljbara plintar.
Normalt ska inga grupperingar utföras i RTU. Eventuella avsteg från detta ska göras i samråd med Vattenfall.

*2) SUB-uppdelade objekt ska signaleras individuellt. Vid ej SUB-uppdelade objekt utgår texten "SUBx".

*3) Signalfördröjning ska göras så nära signalkällan som möjligt.

*4) Primärapparater och fackbunden kontrollutrustning sorteras in under resp. objekt i stationens signallista.

VATTENFALL

VTR02-02 Bilaga 2 - Objektlista rev. 6

Spänning	Objekt (exempel)		Funktion	Anm.	Manöverplats			Indikeringsplats		
					Reserv-plats *1	När *2	Fjärr	Reserv-plats *1	När *2	Fjärr
≥ 70 kV	Brytare	-F-S	Från / Till		X	X	X	X	X	X
≥ 70 kV	Blockeringsdon	-F-S	Blockerad / Deblockerad		X	X	-	X	X	X
≥ 70 kV	Jordningskopplare	-JF	Öppen / Sluten		X	X	-	X	X	X
≥ 70 kV	Frånskiljare	-F	Öppen / Sluten		(X)	(X)	(X)	X	X	X
≤ 40 kV (fristående)	Brytare	-F-S	Från / Till		X	X	X	X	X	X
≤ 40 kV (fristående)	Blockeringsdon	-F-S	Blockerad / Deblockerad		X	X	-	X	X	X
≤ 40 kV (fristående)	Jordningskopplare	-JF	Öppen / Sluten		X	X	-	X	X	X
≤ 40 kV (fristående)	Frånskiljare	-F	Öppen / Sluten		(X)	(X)	(X)	X	X	X
≤ 40 kV (kapslat)	Brytare	-S	Från / Till		X	X	X	X	X	X
≤ 40 kV (kapslat)	Truck	-F12	Öppen / Sluten		-	-	-	X	X	X
≤ 40 kV (kapslat)	Jordningskopplare	-JF	Öppen / Sluten		-	-	-	X	X	X
0,4 kV (lokalkraft)	Brytare / kontaktor	-0,4-S	Från / Till		X	-	-	X	X	X
0,4 kV (lokalkraft)	Frånskiljare (sektionering)	-0,4-EF	Öppen / Sluten		-	-	-	X	X	X
0,4 kV (lokalkraft)	Omkopplingsautomatik		Hand/Auto		X	-	-	X	X	X
	Transf. spänningsreglering	-LK	Hand / Auto		X	X	X	X	X	X
	Transf. lindningskopplare	-LK	Minska / Öka		X	X	X	X	Mätvärde	Mätvärde
	Transf. lindningskopplare börvärde	-LK	visn. % (ex. 99 - 103 %)	*3	(X)	(X)	(X)	(X)	(X)	(X)
	Nollpunktsmotstånd Brytare	-NM-S	Från / Till		X	X	X	X	X	X
	Nollpunktsfrånskiljare	-NF	Öppen / Sluten		(X)	(X)	(X)	X	X	X
	Avstämningsautomatik	-NX	Hand / Auto		X	X	X	X	X	X
	Nollpunktsreaktor	-NX	Minska / Öka		X	X	X	X	Mätvärde	Mätvärde
Övriga automatiker och övrig kontrollutrustning:										
	Ål-automatik		Ur drift / I drift	*4	X	X	X	X	X	X
	Ål-automatik		Ål pågår	*5	-	-	-	-	X	X
	Övriga automatiker		Ur drift / I drift		X	X	X	X	X	X
	Nätvärn (t.ex. AFK, PFK, EXA)		Ur drift / I drift		X	X	X	X	X	X
	Reläskydd		Settinggrupp 1 - 2	*6	-	-	(X)	-	-	(X)
	Reläskydd NUS-UTT		Ur drift / I drift	*7	-	-	X	-	-	X
	PS Rak manöver		PS i drift / Rak manöver	*8	-	X	X	-	X	X
	FPS Rak manöver		FPS i drift / Rak manöver	*8	-	(X)	(X)	-	(X)	(X)
	FPS		Fasning pågår		-	-	-	-	(X)	(X)
	Frånskiljarblockering		Upphävd / I drift		(X)	(X)	-	(X)	(X)	(X)
	Reservlarmsändare		Ur drift / I drift		-	X	X	-	X	X
	Driftformsomkopplare (DFO)	Vattenfall			X	-	-	X	X	X
Externa anläggningar och produktionsanläggningar:										
	Brytare Ledning	-S / -F-S	Från / Till	*9	-	-	(Från)	-	X	X
	Brytare Transf. uppsida	-S / -F-S	Från / Till	*9	-	-	(Från)	-	X	X
	Brytare Transf. nedsida	-S / -F-S	Från / Till	*9	-	-	(Från)	-	X	X
	Brytare Kondensatorbatteri	-S / -F-S	Från / Till	*9	-	-	(Från)	-	X	X
	Brytare Shuntreaktor	-S / -F-S	Från / Till	*9	-	-	(Från)	-	X	X
	Brytare Sektionering	-S / -F-S	Från / Till	*9	-	-	(Från)	-	X	X
	Brytare Generator	-S / -F-S	Från / Till		-	-	-	-	X	X
	Blockeringsdon	-F-S	Blockerad / Deblockerad		-	-	-	-	X	X
	Jordningskopplare	-JF	Öppen / Sluten		-	-	-	-	X	X
	Frånskiljare	-F	Öppen / Sluten		-	-	-	-	X	X
	Truck	-F12	Öppen / Sluten		-	-	-	-	X	X
	Transf. spänningsreglering	-LK	Hand / Auto		-	-	-	-	X	X
	Nätvärn Extremspänningsaut.	EXA	Ur drift / I drift		-	-	-	-	X	X
	Driftformsomkopplare (DFO)	Extern			-	-	-	-	X	X

"**(X)**" = i förekommande fall.

*1) Reservmanöverplats = Objektsskåp eller lågspänningsutrymme i MSP-ställverk

*2) Närmanöverplats = Stations-HMI

*3) LK Börvärde (ex 104%, 102%, 100%, 98%, 96%) utförs som enkelindikering. Gäller för vissa specifika transformatorer för 400/220 kV.

*4) ÅI Driftläge utförs som dubbelindikering

*5) ÅI Pågår utförs som enkelindikering

*6) Reläskydd Settinggrupp utförs som enkelindikering

*7) Reläskydd NUS-UTT utförs som dubbelmanöver och dubbelindikering

*8) Rak manöver ska automatiskt återgå till (F)PS efter inställd tid.

*9) Frånslag av externt ägda brytare ska kunna utföras om det anges i anläggningsspecifik teknisk beskrivning.

VTR02-02 Bilaga 3 - Instrumentlista rev. 6

Objekt	Anm.	Storhet	Enhet	Skala *3	Indikeringsplats		
					Reserv-plats *1	När *2	Fjärr
Samlingsskena	*4	U	kV	$0 - UT_{prim} \times 1,25$	X	X	X
Ledning	*5	U	kV	$0 - UT_{prim} \times 1,25$	X	X	X
Ledning		I	A	$0 - IT_{prim} \times 1,2$	X	X	X
Ledning	*6	P	MW	$\pm \sqrt{3} \times UT_{prim} \times IT_{prim}$	X	X	X
Ledning	*6	Q	MVAr	$\pm \sqrt{3} \times UT_{prim} \times IT_{prim}$	X	X	X
Transformator uppsida		I	A	$0 - IT_{prim} \times 1,2$	X	X	X
Transformator uppsida	*6	P	MW	$\pm \sqrt{3} \times UT_{prim} \times IT_{prim}$	X	X	X
Transformator uppsida	*6	Q	MVAr	$\pm \sqrt{3} \times UT_{prim} \times IT_{prim}$	X	X	X
Transformator nedsida	*7	U	kV	$0 - UT_{prim} \times 1,25$	X	X	X
Transformator nedsida	*7	I	A	$0 - IT_{prim} \times 1,2$	X	X	X
Transformator nedsida	*6, 7	P	MW	$\pm \sqrt{3} \times UT_{prim} \times IT_{prim}$	X	X	X
Transformator nedsida	*6, 7	Q	MVAr	$\pm \sqrt{3} \times UT_{prim} \times IT_{prim}$	X	X	X
Transformator lindningskopplare läge				Läge 1 - X	X	X	X
Transformator temperatur toppolja	*8	T	°C	*Enligt transformatorns utformning, se anmärkning.*	X	X	X
Transformator temperatur lindning	*8	T	°C	*Enligt transformatorns utformning, se anmärkning.*	X	X	X
Nollpunktsspänning	*9	U_0	kV/V	0 – 10% – 100% *Voltlupp, se exempel nedan:*	X	X	X
Tx-70-UT ($3U_0$) alt. Tx-N70-NUT (U_0)			*kV*	*0 - 4,45 - 44,5 kV (motsv. 0 - 11 - 110 V sek.)*			
Tx-40-UT ($3U_0$) alt. Tx-N40-NUT (U_0)			*kV*	*0 - 2,54 - 25,4 kV (motsv. 0 - 11 - 110 V sek.)*			
Tx-20-UT ($3U_0$)			*V*	*0 - 1270 - 12702 V (motsv. 0 - 11 - 110 V sek.)*			
Tx-10-UT ($3U_0$)			*V*	*0 - 635 - 6351 V (motsv. 0 - 11 - 110 V sek.)*			
Nollpunktsreaktor (NX inställning)		I	A	Läge min – max	X	X	X
Utledningar högohmigt jordfel		R	Ohm	0 – 500 kΩ, ± 180°	-	X	X
Kondensatorbatteri		I	A	$0 - IT_{prim} * 1,2$	X	X	X
Kondensatorbatteri	*6	Q	MVAr	$\sqrt{3} \times UT_{prim} \times IT_{prim}$	X	X	X
Shuntreaktor		I	A	$0 - IT_{prim} * 1,2$	X	X	X
Shuntreaktor	*6	Q	MVAr	$\sqrt{3} \times UT_{prim} \times IT_{prim}$	X	X	X
Temperatur batterirum		T	°C	-50 °C till +50 °C	X	X	X
Temperatur kontrollrum		T	°C	-50 °C till +50 °C	X	X	-
Temperatur ställverksrum		T	°C	-50 °C till +50 °C	X	X	-
Externa anläggningar och produktionsanläggningar:							
Samlingsskena		U	kV	$0 - UT_{prim} \times 1,25$	-	X	X
Ledning	*5	U	kV	$0 - UT_{prim} \times 1,25$	-	X	X
Ledning		I	A	$0 - IT_{prim} \times 1,2$	-	X	X
Ledning	*6	P	MW	$\pm \sqrt{3} \times UT_{prim} \times IT_{prim}$	-	X	X
Ledning	*6	Q	MVAr	$\pm \sqrt{3} \times UT_{prim} \times IT_{prim}$	-	X	X
Transformator uppsida		I	A	$0 - IT_{prim} \times 1,2$	-	X	X
Transformator uppsida	*6	P	MW	$\pm \sqrt{3} \times UT_{prim} \times IT_{prim}$	-	X	X
Transformator uppsida	*6	Q	MVAr	$\pm \sqrt{3} \times UT_{prim} \times IT_{prim}$	-	X	X
Transformator nedsida	*7	U	kV	$0 - UT_{prim} \times 1,25$	-	X	X
Transformator nedsida	*7	I	A	$0 - IT_{prim} \times 1,2$	-	X	X
Transformator nedsida	*6, 7	P	MW	$\pm \sqrt{3} \times UT_{prim} \times IT_{prim}$	-	X	X
Transformator nedsida	*6, 7	Q	MVAr	$\pm \sqrt{3} \times UT_{prim} \times IT_{prim}$	-	X	X
Transformator lindningskopplare läge				Läge 1 - X	-	X	X
Kondensatorbatteri		I	A	$0 - IT_{prim} * 1,2$	-	X	X
Kondensatorbatteri	*6	Q	MVAr	$\sqrt{3} \times UT_{prim} \times IT_{prim}$	-	X	X
Shuntreaktor		I	A	$0 - IT_{prim} * 1,2$	-	X	X
Shuntreaktor	*6	Q	MVAr	$\sqrt{3} \times UT_{prim} \times IT_{prim}$	-	X	X
Generator/aggregat		I	A	$0 - IT_{prim} \times 1,2$	-	X	X
Generator/aggregat	*6	P	MW	$\sqrt{3} \times UT_{prim} \times IT_{prim}$	-	X	X
Generator/aggregat	*6	Q	MVAr	$\pm \sqrt{3} \times UT_{prim} \times IT_{prim}$	-	X	X

*1) Reservmanöverplats = Objektsskåp eller lågspänningsutrymme i MSP-ställverk.

*2) Närmanöverplats = Stations-HMI.

*3) Skala avser mätvärdesomvandlare (dvs. ej flyttal som skickas via stationsbuss). Analog utsignal: 4 - 20 mA, alt. 4 - 12 - 20 mA.
Ovanstående skalor är preliminära och ska stämmas av med beställaren före konstruktion/tillverkning.

*4) Spänning för samlingsskenor (samt VHC) ska även visas med analogt visarinstrument, se VTR02-02.

*5) Spänning ska alltid visas för ledningar $\geq$ 70 kV. Spänning ska även visas för ledningar < 70kV om det anges i anläggningsspecifik teknisk beskrivning.

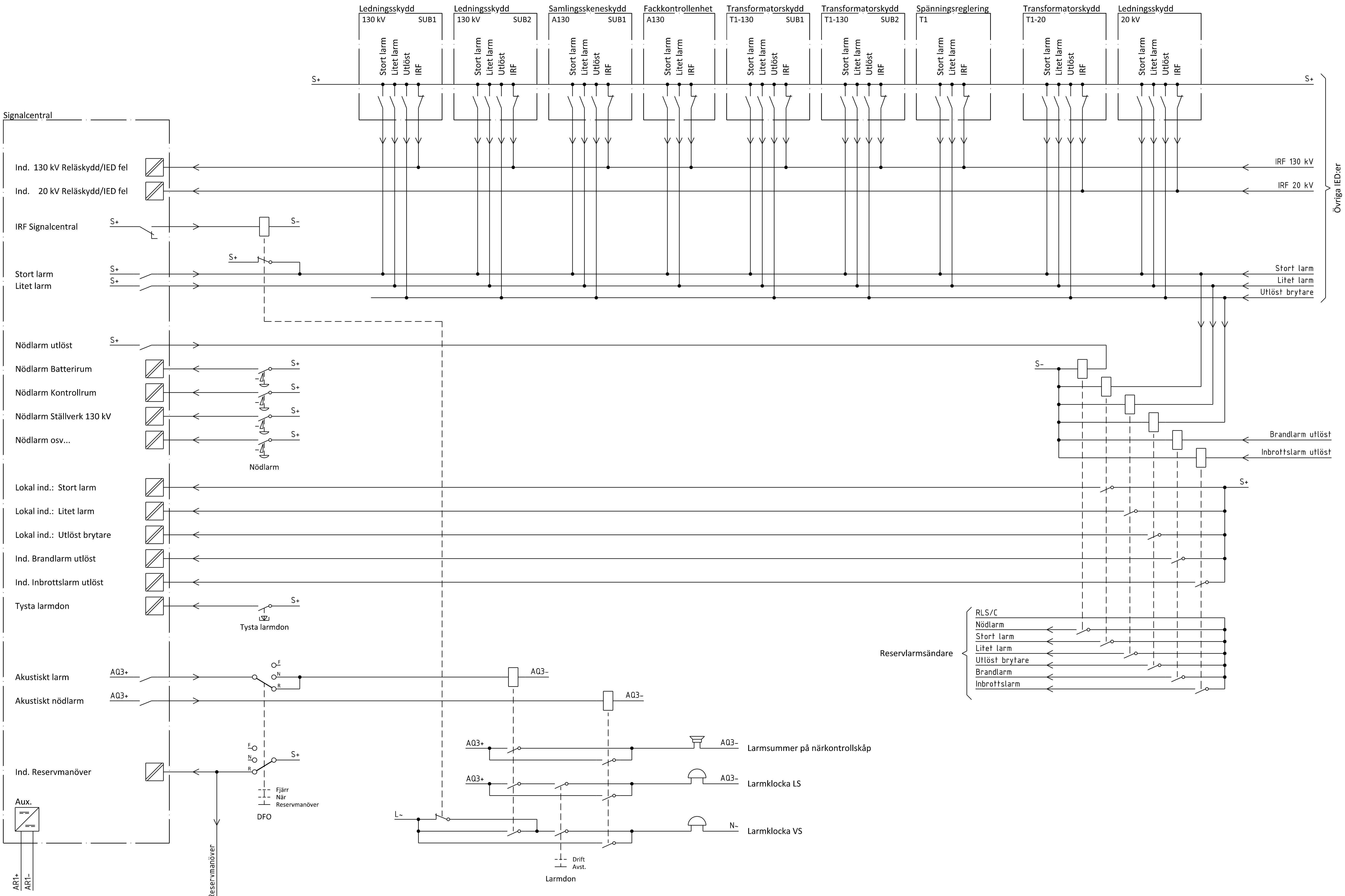
*6) För definition av effektriktning, se VTR02-02.

*7) Gäller även mellanspänningssida för trelindningstransformatorer.

*8) Omfattning av temperaturmätning kan variera beroende på transformatortyp och storlek. Om ej annat anges i anläggningsspecifik teknisk beskrivning gäller följande omfattning:
- Temperatur toppolja ska visas för samtliga transformatorer, oavsett storlek.
- Temperatur lindning uppspänningssida ska visas för transformatorer ≥ 16 MVA.
- Temperatur lindning nedspänningssida ska visas för samtliga transformatorer, oavsett storlek.
- Temperatur lindning mellanspänningssida ska visas för samtliga trelindningstransformatorer, oavsett storlek.

Skala (temperaturspann) för mA-signal kan variera beroende på transformatortyp.
För mätning med Pt100-givare och mätvärdesomvandlare kan skala -50 °C till +150 °C användas om ej annat anges i anläggningsspecifik teknisk beskrivning.

*9) Mätpunkt för nollpunktspänning ska väljas enligt VTR02-02.
Värdet vid 100% baseras på spänningstransformatorns omsättning fas - jord primärt. I exemplen används: 77 000/√3, 44 000/√3, 22 000/√3, 11 000/√3



Not	Ändring	Dat.	Inf.	Godk.	Tillhörande ritningar etc.

VATTENFALL

Avd.	Datum		Dokumenttyp	Plats-Grupp
DS-PI	2020-06-01	Signalöversikt	Principschema	
Ritad		Utformning av signalsystem, reservlarm, akustiskt larm, mm.	Ritn.nr. VTR02-02 Bilaga 5	Blad 1
				Forts.bl. –

Anm. | Skala | Granskad | Godkänd | Proj.nr

VTR02-02 bilaga 6 - Service-PC – Instruktion till projektentreprenörer

Syfte

Detta dokument beskriver rutiner angående entreprenörers mottagande, installation, användning och dokumentation av Service-PC i anläggningsprojekt.

INNEHÅLLSFÖRTECKNING

1 Beskrivning av Service-PC

Service-PC är Vattenfall Eldistributions tekniska lösning med tillhörande arbetsprocesser för att leverera, övervaka och förvalta en arbetsplats för underhåll, felsökning och dokumentation av utrustning ansluten till stationsbuss.
Service-PC ska användas vid idrifttagning, underhåll och ombyggnad av kontrollanläggningen och aktuella konfigurationsfiler skall sparas i anvisad mapp.
All konfiguration skall av IT-säkerhetsskäl ske från Service-PC. Inga andra verktyg för konfiguration får anslutas till stationsbussen.

I den tekniska lösningen ingår dator av typ industri PC för montage i apparatskåp. Skärm, skärmkablage och standard tangentbord och mus, på skrivbord samt paketering av nödvändiga verktyg för konfigurering av nätverksbaserad utrustning i kontrollanläggning.

1.1.1 Hårdvara Service-PC

Service-PC är bestyckad med:

- Minst 4 stycken Ethernet portar av typ RJ45.
- Minst 1 USB-port
- HDMI-kontakt
- VGA-kontakt

1.1.2 Hårdvara bordsmonterad bildskärm

Bildskärmen är bestyckad med:

- HDMI-kontakt
- VGA-kontakt

2 Projektgenomförande

2.1 Anskaffning och mottagande

Vattenfall Eldistribution tillhandahåller Service-PC och kringutrustning, samt ger användarstöd för Service-PC(ej för installerade verktyg).

Entreprenören skall tillhandahålla komplett lista på verktyg och programvara (med versions-nummer) för utveckling och testning för den enskilda stationen.

Service-PC avropas från Vattenfall Eldistribution.

Industri-PC, skärm, tangentbord, mus och tillhörande kablage levereras till den leveransadress som anges i beställningen.

Förkonfigurerad industri-PC med administratörsrättigheter levereras inom 6 veckor efter det att komplett beställning inkommit till Service-PC förvaltningen.

2.2 Montage

2.2.1 Allmänt

Vid utformning av kontrollrummet bör avståndet mellan skrivbordet för bildskärm och apparatskåpet där Service-PC ska monteras beaktas. Kablaget mellan industri-PC och bildskärm skall ej överstiga 15 meter.

Bildskärmen skall stå uppställd på ett skrivbord.

Vid installation i ny anläggning/transformatorstation skall Service-PC placeras i apparatskåp för kommunikation enligt ”VTR04-04 Bilaga 8.1”.
Service-PC skall monteras enligt Vattenfall Eldistributions framtagna montageanvisningar som bifogas leveransen av Service-PC.

Service-PC skall anslutas mot UCN-nod och till stationsbussens switchar enligt VTR04-05 Bilaga 8.1 -8.4.

2.2.2 Strömförsörjning

Industri-PC och bild skärm skall spänningsmatas med 24VDC avbrottsfri kraft från anläggningens batterisystem..

2.3 Installation

Service-PC levereras med beställda applikationer installerade, men inga drivers för skydden är installerade. Installationsfilerna för dessa drivers finns sparade lokalt på Service-PC och installeras av entreprenör. Eventuella programvaror som inte levererats av Vattenfall Eldistribution men behövs för att konfigurera utrustning i anläggning skall installeras av entreprenören.

Avvikelser från ursprunglig lista på verktyg och specifika versioner skall stämmas av med Vattenfall Eldistributions kontrollanläggningsingenjör.

Vid leverans är mappstrukturen på Service-PC förinstallerad och får inte förändras under projektets gång

2.4 Konfigurering av kontrollanläggning

Entreprenören kan använda Service-PC under utvecklingsarbetet och förberedande fabrikstest.

Entreprenören skall använda Service-PC från och med FAT.
Entreprenören har möjlighet att ansluta usb-enheter till Service-PC under förutsättning att nödvändiga IT-säkerhetsrutiner följs och innan Service-PC ansluts till UCN.

Förutom mappar för gällande filer och verktyg finns en arbetsmapp där entreprenör kan jobba under utveckling av stationen. Efter att ändringar är verkställda, d.v.s. testats och tagits i drift, skall projektet i denna mapp flyttas till ”Gällande” mappen.

2.5 Provning i fabrik

Testverktygen i Service-PC skall användas vid FAT, tillsammans med nödvändig extern testutrustning.

Aktuell konfiguration för samtliga skydd- och kontrollterminaler, RTU och system-konfiguration skall sparas i Service-PC.

2.6 Provning i Anläggning/station

Testverktygen i Service-PC skall användas vid anläggningsprov tillsammans med nödvändig extern testutrustning.

Aktuell konfiguration för samtliga skydd- och kontrollterminaler, RTU och system-konfiguration skall sparas i Service-PC.

2.7 Anslutning och idrifttagning till UCN

Innan Service-PC får anslutas till UCN så måste en tid bokas för driftsättning enligt instruktion som bifogas leveransen av Service-PC

3 Dokument- och filhantering

3.1 Filhantering under projektets gång

Följande filer behöver utväxlas mellan Vattenfall Eldistribution och entreprenör under genomförande av projektaktiviteter samt lagras med revisionshantering på Service-PC:

- SCD-fil
- Leverantörsspecifika konfigurations- och projektfiler för IED:er mm
- Signallista
- Konfigurationsfiler för bildbyggnation i stations HMI (lokal HMI)
- Konfigurationsfiler för RTU

IEC 61850-relaterade filer kräver varsam hantering. För varje ny SCD revision skall en tillhörande signallista revision tas fram. Dessa två dokument/filer skall ha samma revisions-nummer. När slutligt förslag på innehåll har gjorts i dessa två dokument/filer skall de skickas till Vattenfall Eldistribution för granskning innan FAT respektive SAT.
Vid FAT och SAT skall samtliga funktionerna provas och verifieras samt dokument/filer enligt ovan uppdateras. Därefter skall samtliga dokumenten/filer flyttas in i Gällande mappen enligt beskrivning ovan.

Master för digitala dokument som kräver versionshantering ska alltid vara tillgänglig i stationens Service-PC. Detta för att olika roller som behöver utföra ett arbete inte ska vara beroende av åtkomst till dokument på en central server ifall kommunikation skulle förloras.

3.2 Filöverföring efter inkoppling mot UCN

Upp och nedladdning av filer till/från driftsatt Service-PC skall utföras av resurs på Vattenfall Eldistribution.

Inga anslutningar via USB eller dylikt är tillåtna.

3.3 Typer av dokument i Service-PC

- Leverantörsspecifika konfigurationsfiler för IEDer och RTU. Kompletta projektfiler skall finnas.
- Konfigurationsfiler för RTU och lokal HMI.
- Manualer för IEDer och RTU (beskrivningar på logiker i RTUn) m.m.
- Manualer för drift, underhåll och utbyggnad av kontrollanläggning.
- System Configuration Description (SCD) fil.
- IEC 61850 signallista i Excel format.
- Driftinstruktioner för den specifika kontrollanläggningen (IEC 61850) vilket inkluderar:

    Provningsrutiner

    Felsökningsrutiner

    Underhållsrutiner

    Uppdateringar av verktyg och dokument

    Hantering av utrustning och funktioner för personal ute i station

    IP-planer

    Hantering av Service-PC

    Hantering av Stations-HMI

    Beskrivningar av hur stationshierarkin ser ut (Systemlayout)

Drifttagningsinstruktioner

Testprotokoll från:

- FAT
- SAT
- Drifttagning

3.4 Namngivningsnomenklatur för dokument i Service-PC

Dokumentnamngivning skall vara enligt nedanstående struktur. Varje ny projektfil, konfigurationsfil samt SCD-fil med tillhörande signallista skall få nytt datum och nytt revisionsnummer. Dessa två är oberoende av varandra, d.v.s. två olika datum kan inte ha samma revisionsnummer utan både datum och revisionsnummer är unika och skall uppdateras. Datumet i filnamnen anger det datum då filen har verifierats. Revisionsnumret skall vara ett löpande heltal, oberoende av datum.

Loggbok-Kontrollanläggning: Loggbok-Kontrollanläggning_Stationslittera_Stationsnamn.xlsx

Exempel: Loggbok-Kontrollanläggning _BT79_Norrtorp.xlsx

SCD filnamn: Stationslittera_Stationsnamn_Datum_Revisionnummer.scd

Exempel: BT79_Norrtorp_20160219_rev1.scd

Signallista till Fjärr och Stations HMI: Stationslittera_Stationsnamn_Datum_Revisionsnummer.xlsx

Exempel: BT79_Norrtorp_20160219_rev1.xlsx

Konfigurationsfiler: Stationslittera_Stationsnamn_Datum_Revisionnummer.filformat

Exempel: BT79_Norrtorp_20160219_rev1.pcmp

4 Slutdokumentation

Filer för de aktuella konfigurationerna av samtliga IEDer (skyddsterminaler, RTU, stations-HMI) ska ingå i slutdokumentationen.

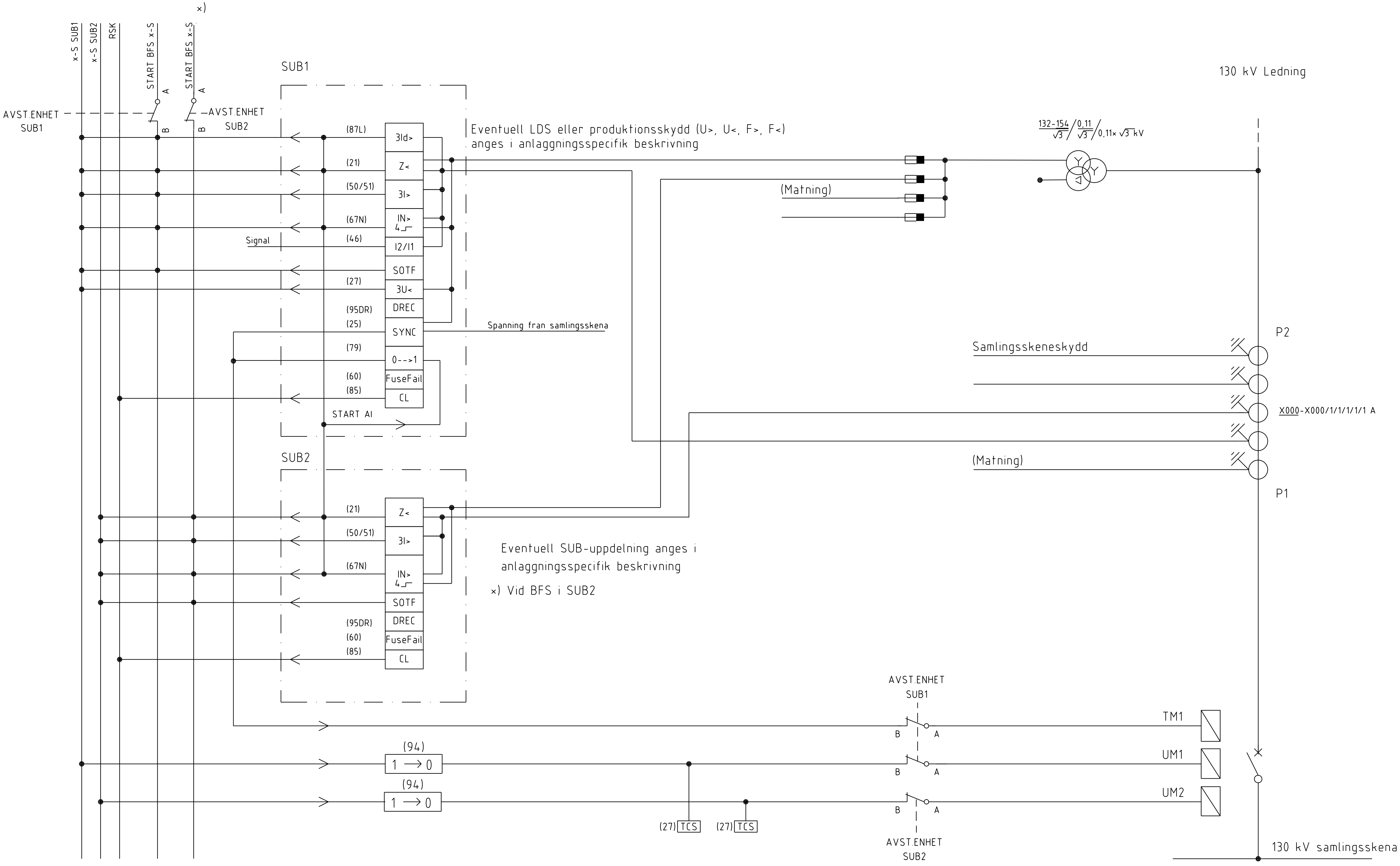
Dokumentation för anläggningen som helhet utförs enligt VTR8-01, VTR8-02 samt VTR8-03.

5 Verktyg

För att en programvara ska få installeras i Service-PC måste den ha blivit testad och godkänd av systemförvaltaren. I Service-PC skall följande verktyg finnas:

- testverktyg för IEC61850 funktioner (GOOSE, MMS)
- leverantörsspecifika konfigurationsverktyg (IEDer, RTU, switchar)
- leverantörsspecifika installationsverktyg för att uppdatera mjukvara (t.ex. connetivity package, firmware)
- till operativsystemet tillhörande standard kontorsprogram (excel och word)

Verktyg för att injicera strömmar och spänningar i syfte att testa reläskyddfunktioner skall inte finnas i Service-PC.



Proj.nr --
Godkänd --
Granskad --
Skola --
Anm. --

Not	Ändring	Dat.	Inf.	Godk.	Tillhörande ritningar etc.
1	Justerad map manöver	2019-11-27	--	--	--
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VATTENFALL

Avd. | Datum 2017-02-02
Ritad DBM

STN.LITTERA STN.NAMN

Ledningsskydd 130 KV

Enpoligt Reläschema

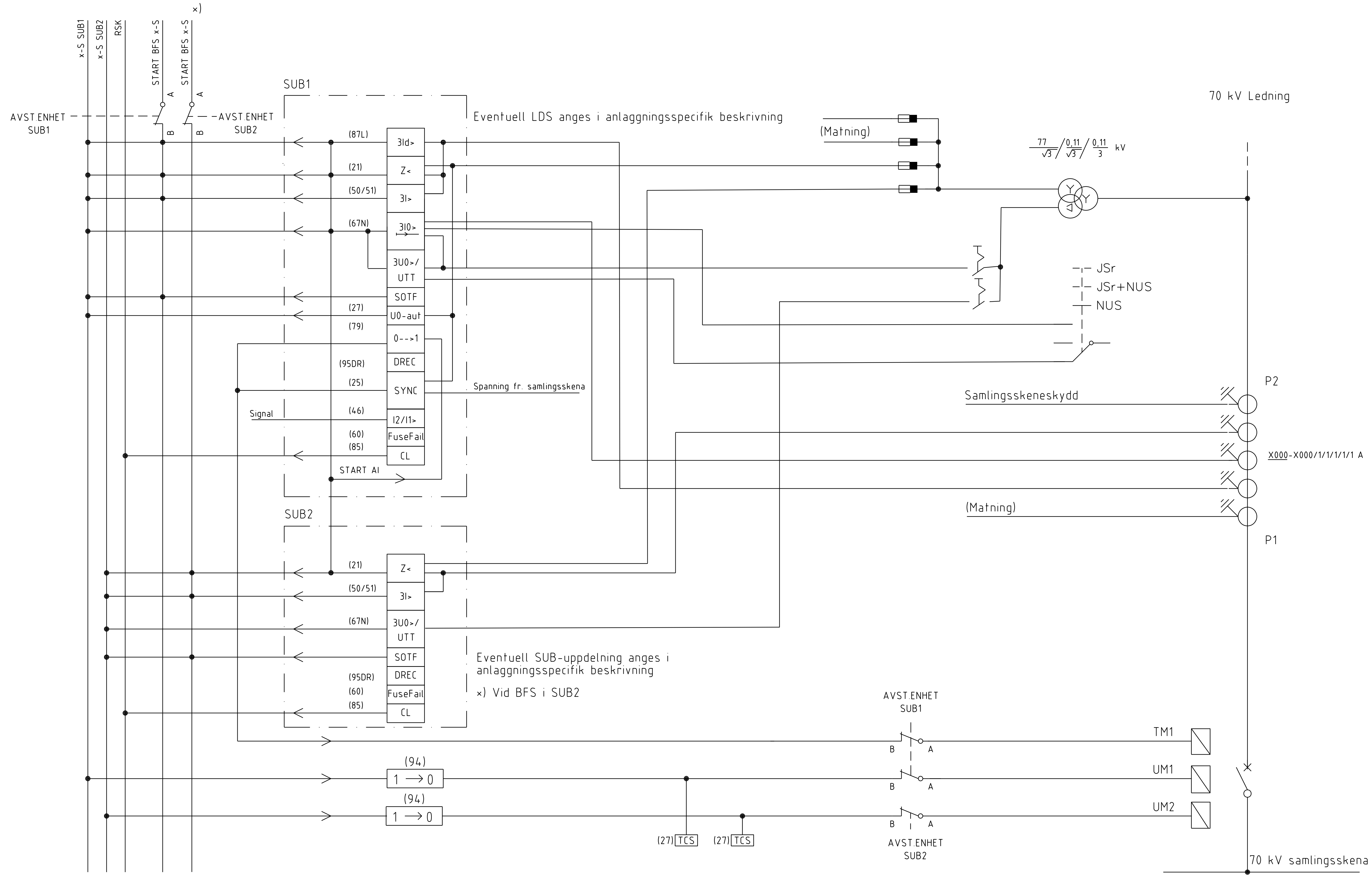
Dokumenttyp: Oversiktsschema

Plats-Grupp

Ritn.nr. VTR02-03 BILAGA 1

Blad

Forts.bl.



Not	Ändring	Dat.	Inf.	Godk.	Tillhörande ritningar etc.
1	Justerad map manöver	2019-11-27			

VATTENFALL

STN.LITTERA STN.NAMN

Avd.

Datum: 2017-02-02

Ritad: DBM

Ledningsskydd 70 KV

Enpoligt Reläschema

Dokumenttyp: Oversiktsschema

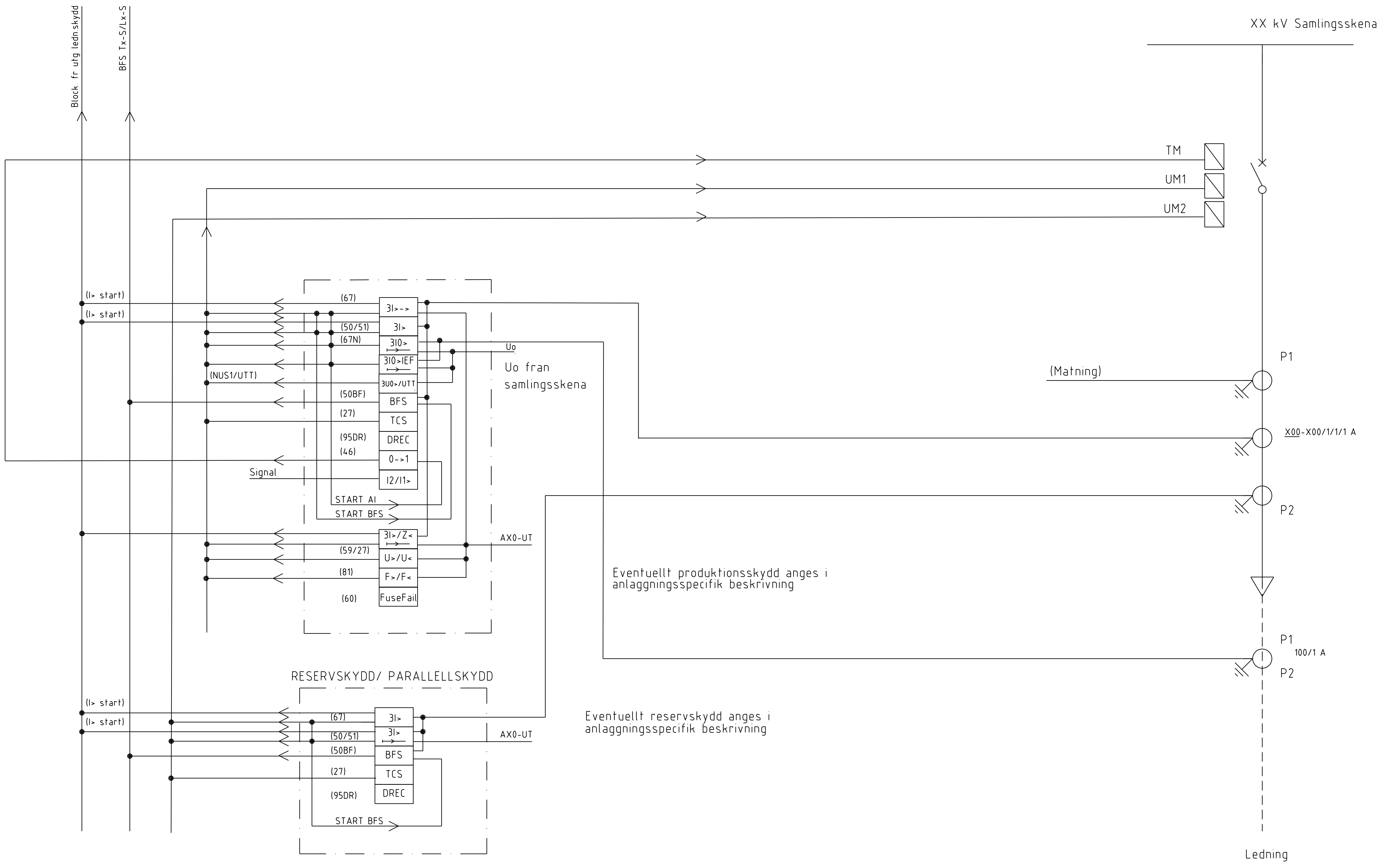
Plats-Grupp

Ritn.nr.: VTR02-03 BILAGA 2

Blad

Forts.bl.

Proj.nr
Godkänd
Granskad
Skolo
Anm.



Proj.nr --
Godkänd --
Granskad --
Skala --
Anm. --

Not	Ändring	Dat.	Inf.	Godk.	Tillhörande ritningar etc.
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VATTENFALL

STN.LITTERA STN.NAMN

Avd. | Datum 2017-02-02

Ritad DBM

Ledningsskydd 50-6 kV

Enpoligt reläschema

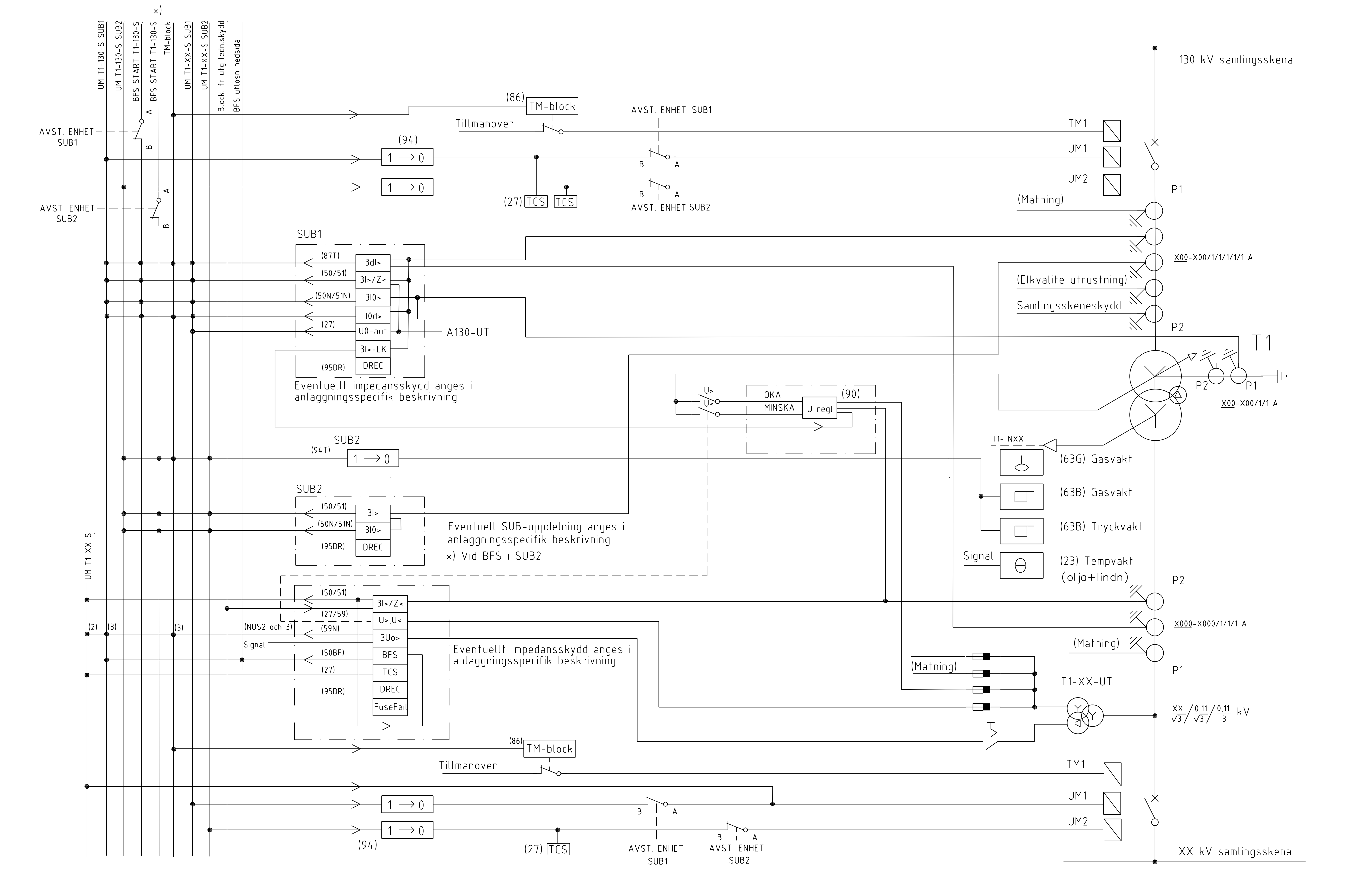
Dokumenttyp: Oversiktsschema

Plats-Grupp

Ritn.nr. VTR02-03 Bilaga 3

Blad

Forts.bl.



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1	Justerad VTR02-03 version 3	2019-11-29	--	--	--
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VATTENFALL

STN.LITTERA STN.NAMN

Avd.

Datum 2017-02-02

Ritad DBM

Trafoskydd 130 KV

Enpoligt Reläschema

Dokumenttyp: Oversiktsschema

Plats–Grupp

Ritn.nr. VTR02-03 Bilaga 4

Blad

Forts.bl.

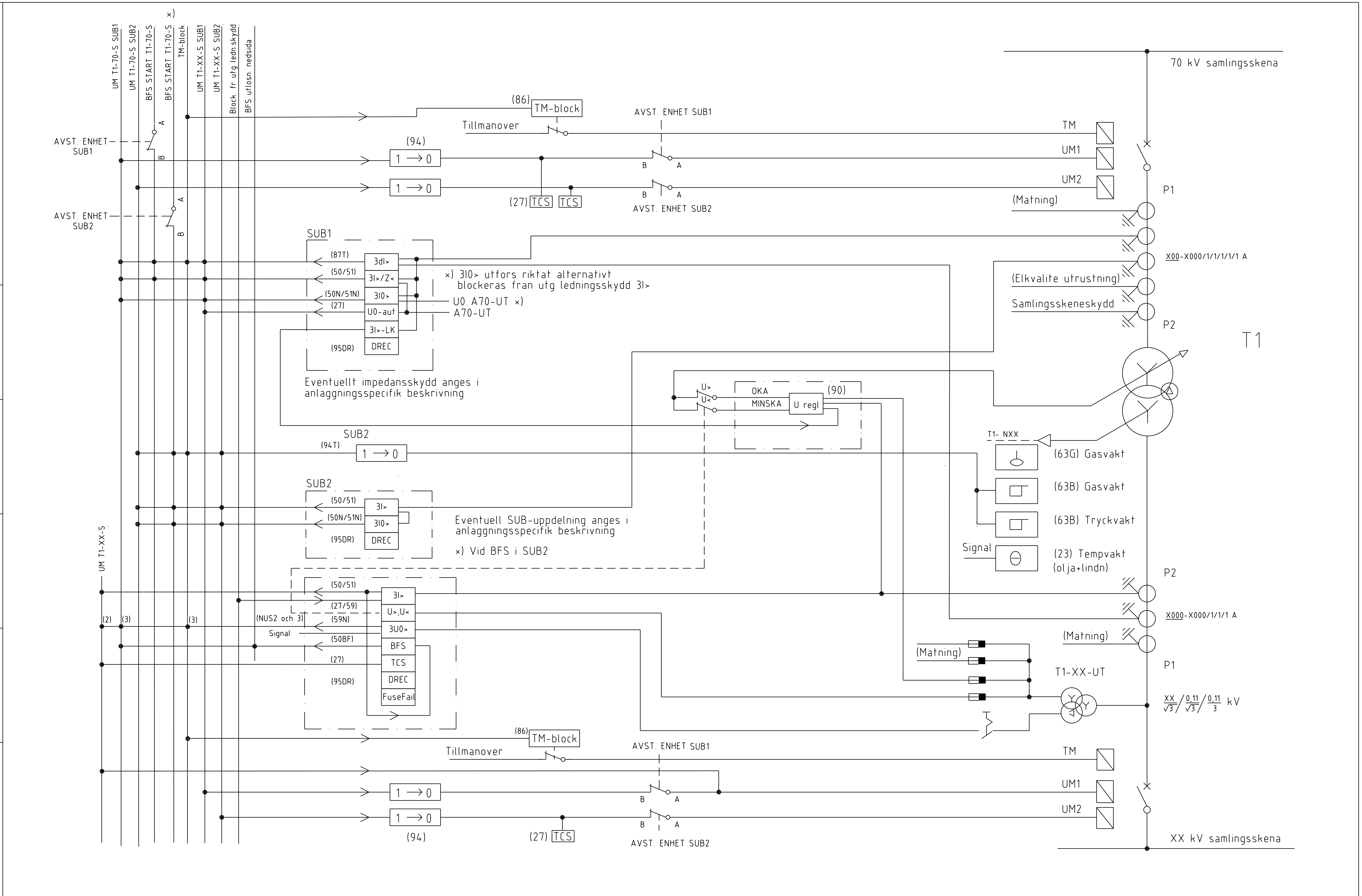
Proj.nr --

Godkänd --

Granskad --

Skolo --

Anm. --



1	Justerad VTR02-03 version 3	2019-11-29	--	--	--	VATTENFALL	STN.LITTERA STN.NAMN	Dokumenttyp: Oversiktsschema	Plats–Grupp
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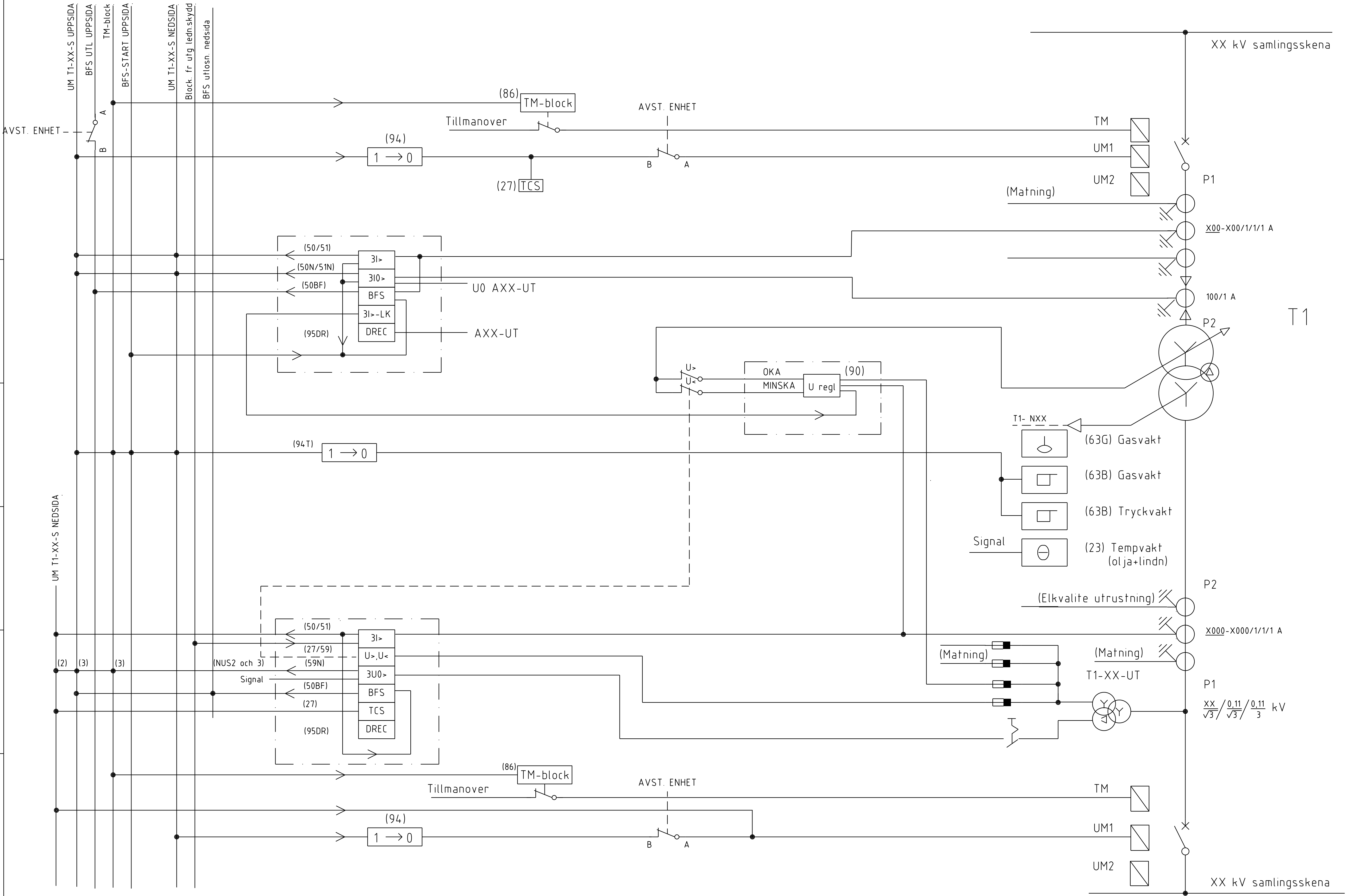
Not	Ändring	Dat.	Inf.	Godk.	Tillhörande ritningar etc.				

Anm. -- | Skola -- | Granskad -- | Godkänd -- | Proj.nr --



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Not	Ändring	Dat.	Inf.	Godk.	Tillhörande ritningar etc.	

VATTENFALL

Avd.

Datum 2017-02-02

Ritad DBM

STN.LITTERA STN.NAMN

Trafoskydd 50-20 KV

Enpoligt Reläschema

Dokumenttyp Oversiktsschema

Plats–Grupp

Ritn.nr. VTR02-03 Bilaga 6

Blad

Forts.bl.

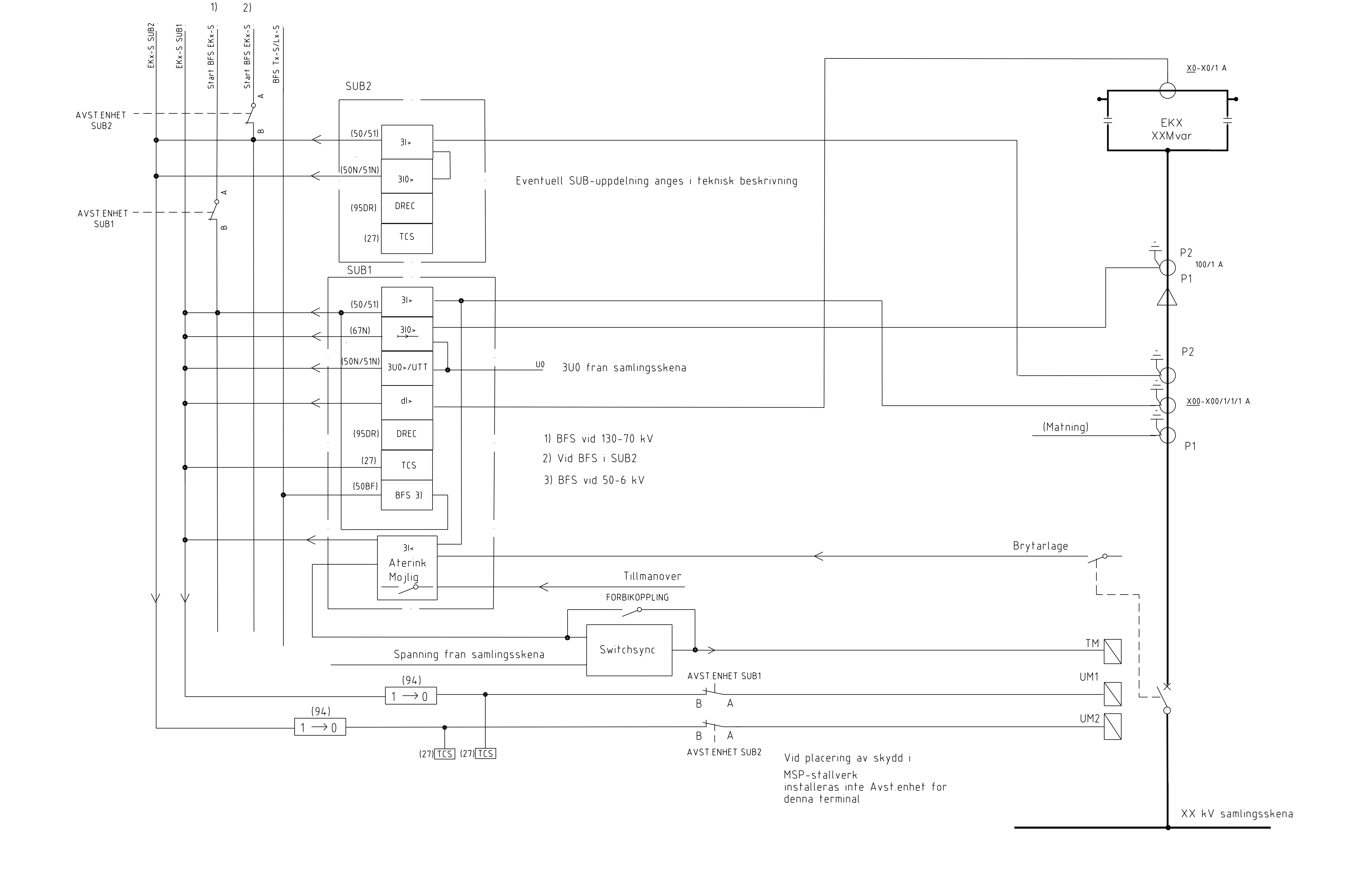
Proj.nr --

Godkänd --

Granskad --

Skolo --

Anm. --



1	Justerad VTR02-03 version 3	2019-11-29	--	--	--	
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Not	Ändring	Dat.	Inf.	Godk.	Tillhörande ritningar etc.	

VATTENFALL

Avd. | Datum 2012-11-16

Ritad

STN.LITTERA STN.NAMN

Kondensatorskydd

Enpoligt Reläschema

Dokumenttyp: Oversiktsschema

Plats–Grupp

Ritn.nr. VTR02-03 Bilaga 7

Blad

Forts.bl.

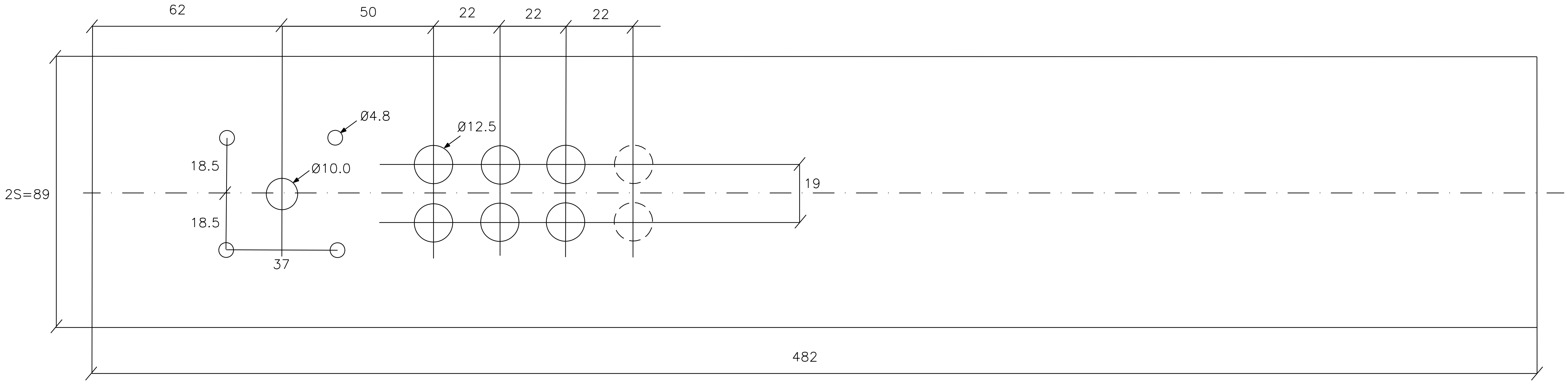
Proj.nr --

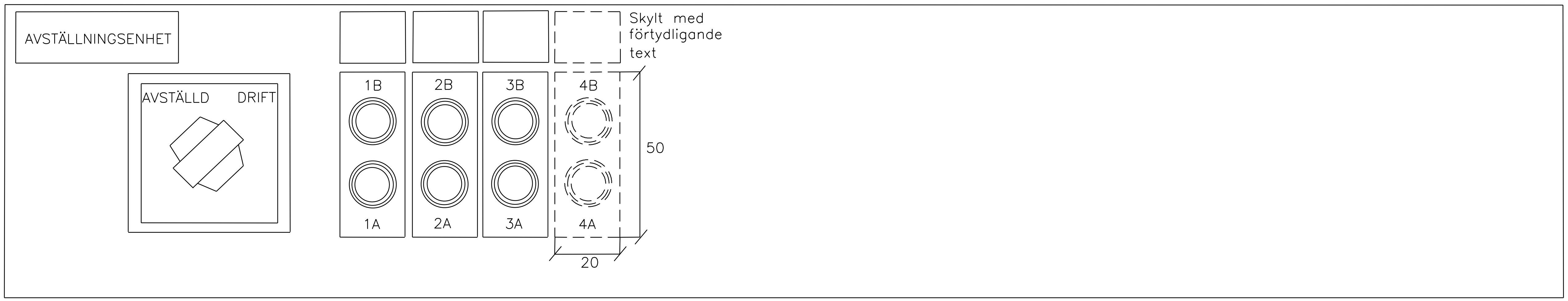
Godkänd --

Granskad --

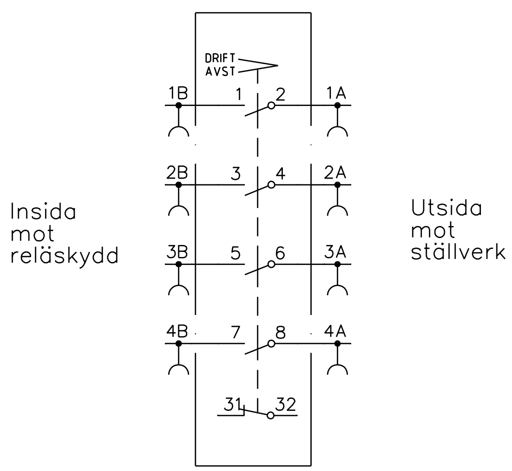
Skola --

Anm. --





Schemasymbol



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Not	Ändring	Dat.	Inf.	Godk.	Tillhörande ritningar etc.

Proj.nr --
Godkänd --
Granskad --
Skala --
Anm. --

VATTENFALL

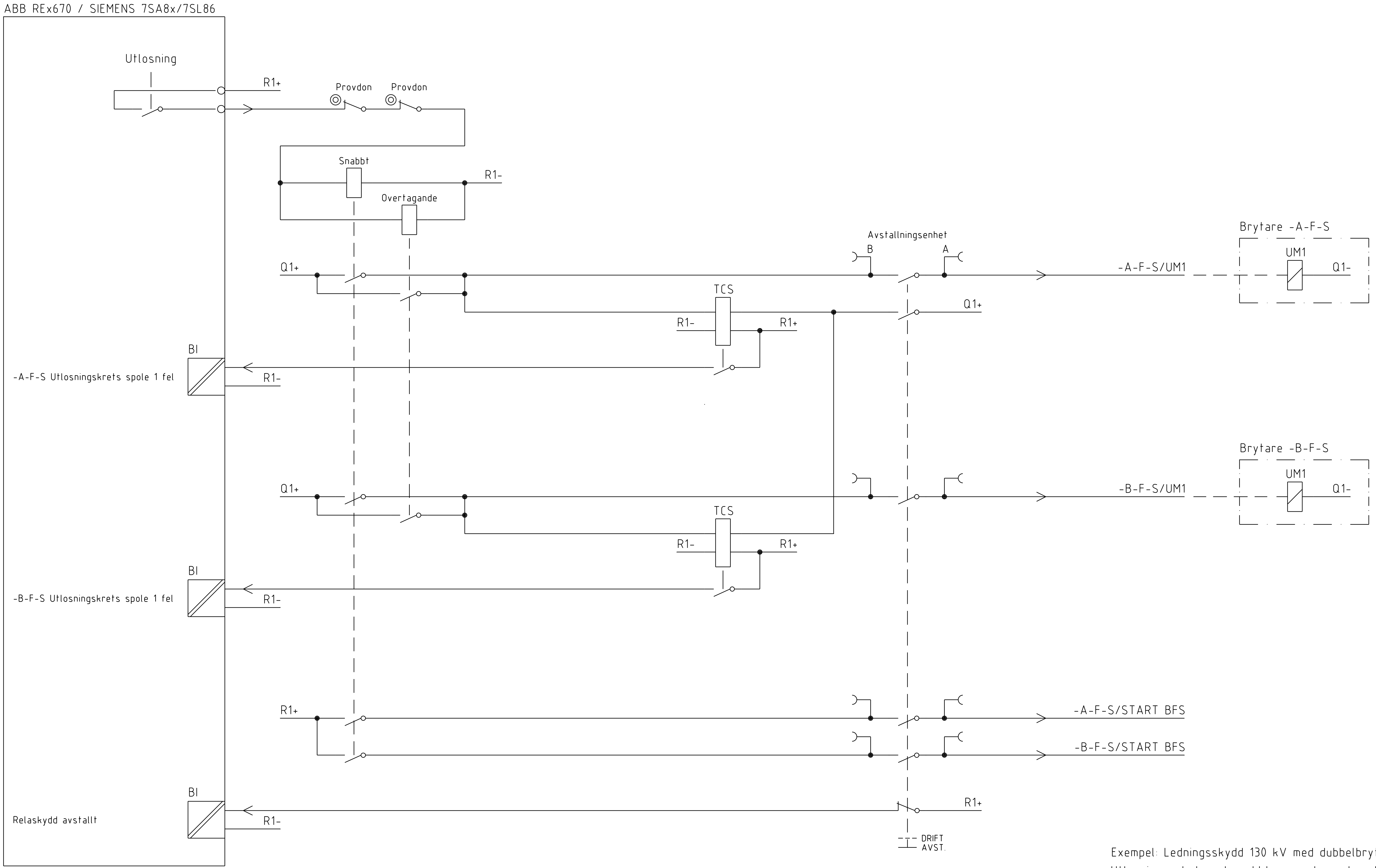
LITTERA STATIONSNAMN

Principschema Avställningsenhet

Avd.
Datum 2020-04-04
Ritad --

Dokumenttyp: Principritning
Plats–Grupp
Ritn.nr. VTR02-03 Bilaga 8
Blad
Forts.bl.

Denna ritning får inte utan Vattenfalls medgivande förevisas för eller utlämnas till obehörig

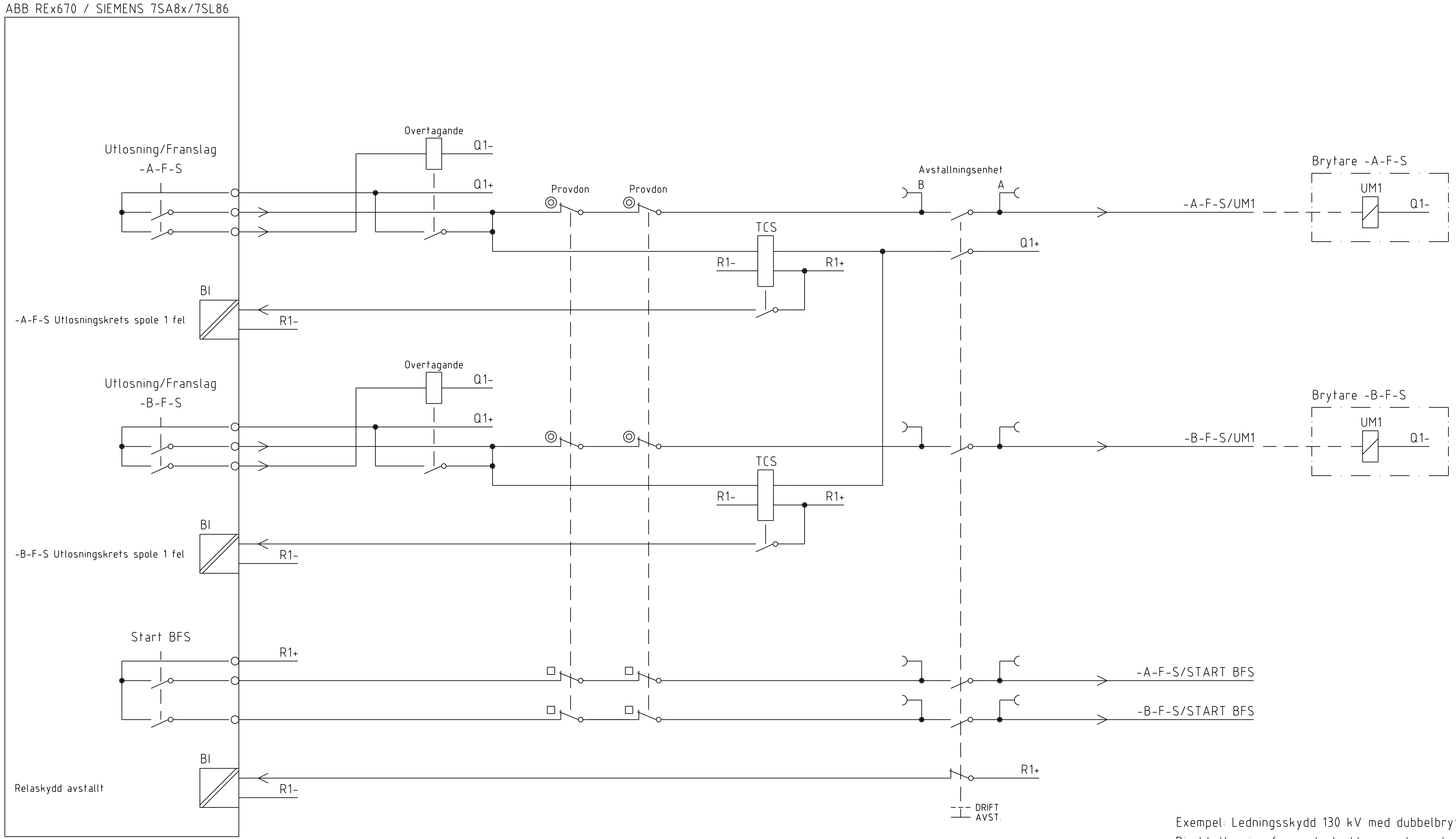


Exempel: Ledningsskydd 130 kV med dubbelbrytare
Utlosningsenhet med snabbt + overtagande rela

Proj.nr	Godkänd	Granskad	Skola	Anm.

Not	Ändring	Dat.	Inf.	Godk.	Tillhörande ritningar etc.

VATTENFALL			Dokumenttyp: Principritning	Plats–Grupp
Avd.: DS-PI	Datum: 2020-05-29	Exempel övervakning utlösningskretsar	Ritn.nr.: VTR02-03 Bilaga 9	Blad: 1
Ritad		Extern TCS, Exempel: ABB SPER/RXEM, DOLD UG5124		Forts.bl.: 2



Exempel: Ledningsskydd 130 kV med dubbelbrytare
Direktutlosning fran relaskydd + overtagande rela

Proj.nr | Godkänd | Granskad | Skala | Anm.

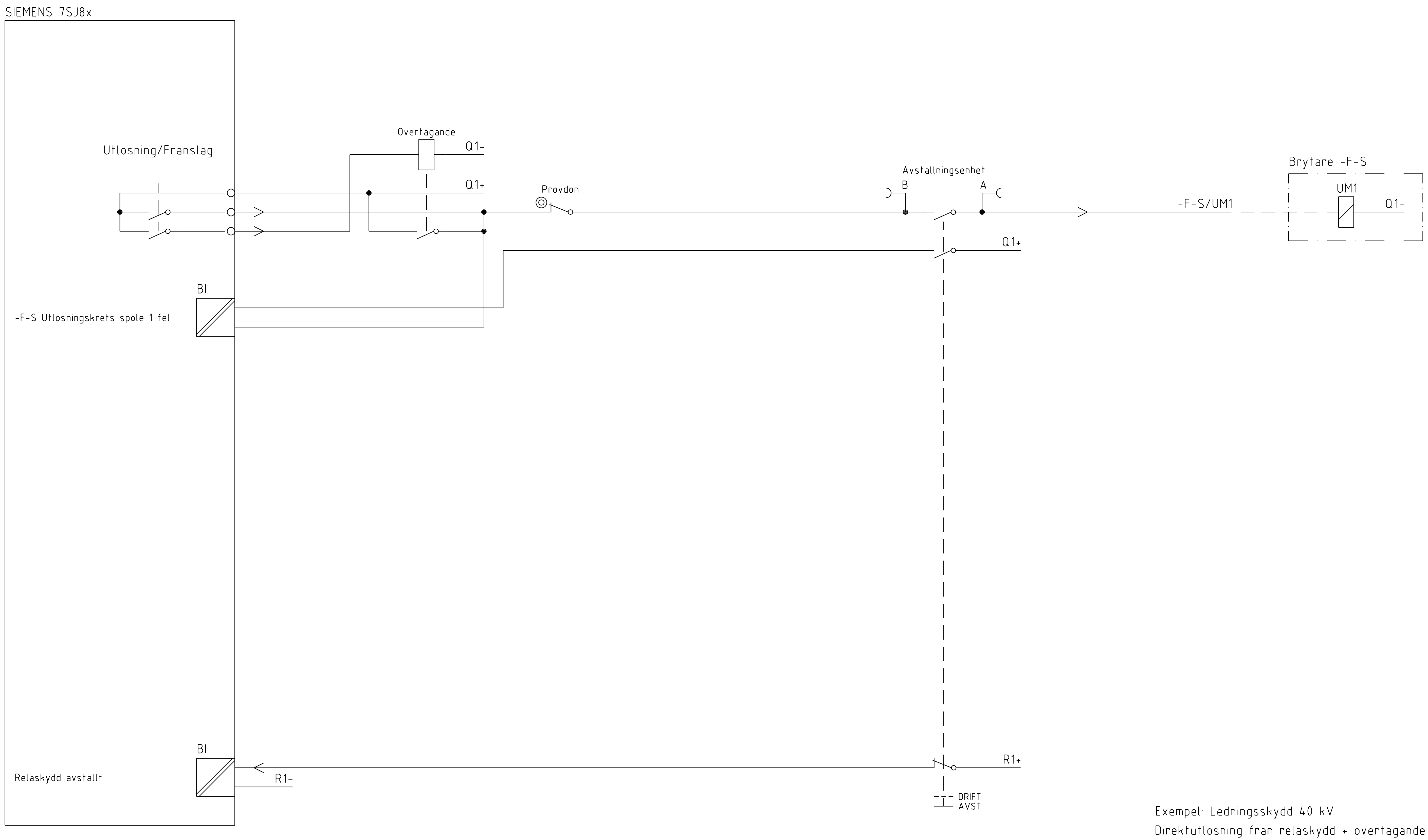
Not	Ändring	Dat.	Inf.	Godk.	Tillhörande ritningar etc.

VATTENFALL

Avd.	Datum
DS-PI	2020-05-29
Ritad	

Exempel övervakning utlösningskretsar
Extern TCS, Exempel: ABB SPER/RXEM, DOLD UG5124

Dokumenttyp	Plats–Grupp
Principritning	
Ritn.nr.	Blad 2
VTR02-03 Bilaga 9	Forts.bl. 3



Exempel: Ledningsskydd 40 kV

Direktutlosning fran relaskydd + overtagande rela

Proj.nr

Godkänd

Granskad

Skala

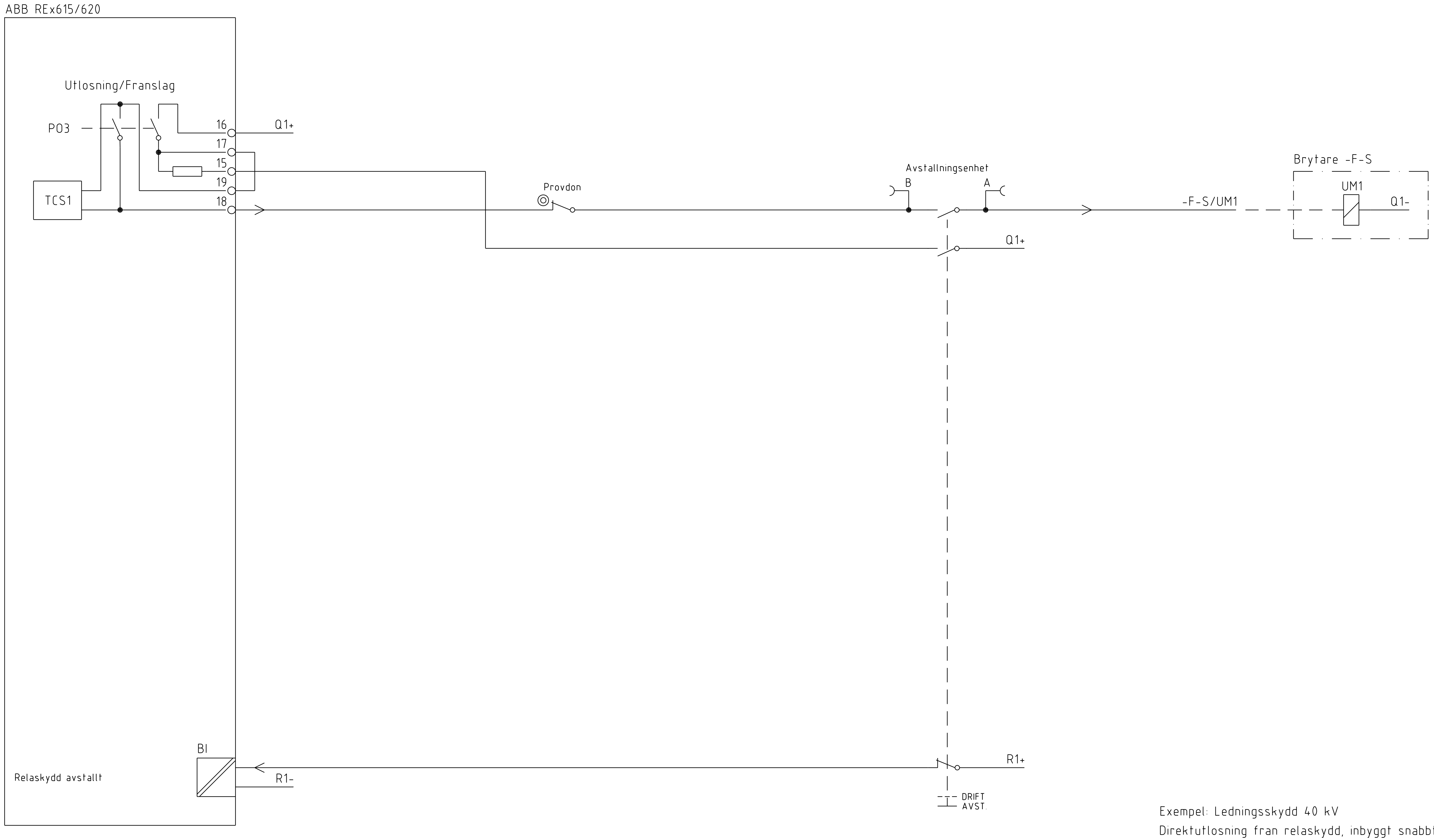
Anm.

Not	Ändring	Dat.	Inf.	Godk.	Tillhörande ritningar etc.

VATTENFALL

Avd. DS-PI	Datum 2020-05-29	Exempel övervakning utlösningskretsar
Ritad		Intern TCS, Exempel: SIEMENS 7SJ8x

Dokumenttyp Principritning	Plats–Grupp
Ritn.nr. VTR02-09	Blad 3
	Forts.bl. 4



Exempel: Ledningsskydd 40 kV

Direktutlosning fran relaskydd, inbyggt snabbt kraftrela

Not	Ändring	Dat.	Inf.	Godk.	Tillhörande ritningar etc.

VATTENFALL

Avd.: DS-PI | Datum: 2020-05-29 | Ritad

Exempel övervakning utlösningskretsar

Exempel: ABB REx615/620

Dokumenttyp: Principritning

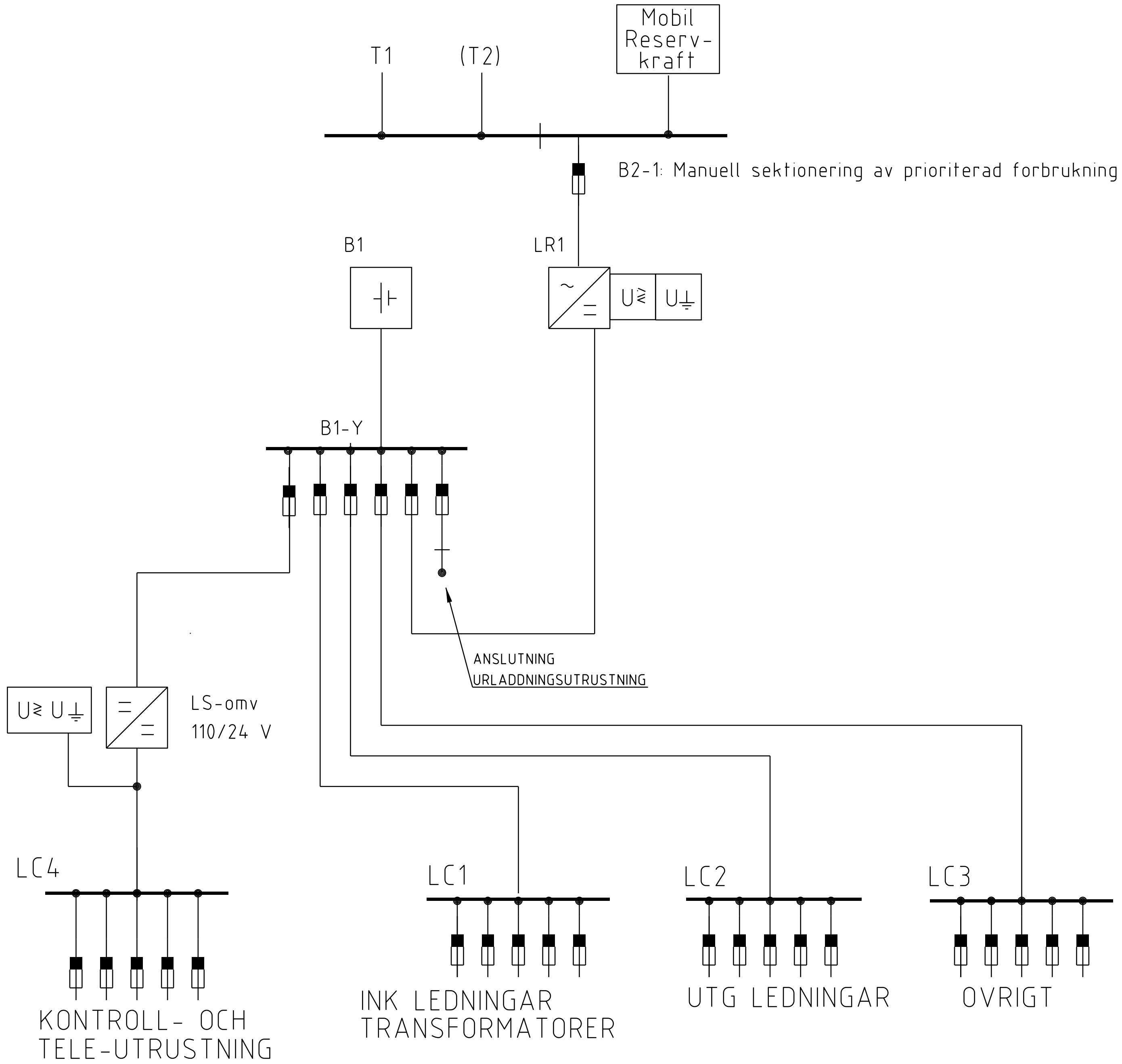
Plats–Grupp

Ritn.nr.: VTR02-03 Bilaga 9

Blad: 4

Forts.bl.: –

Proj.nr | Godkänd | Granskad | Skala | Anm.



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Not	Ändring	Dat.	Inf.	Godk.	Tillhörande ritningar etc.

Proj.nr --
Godkänd --
Granskad --
Skala --
Anm. --

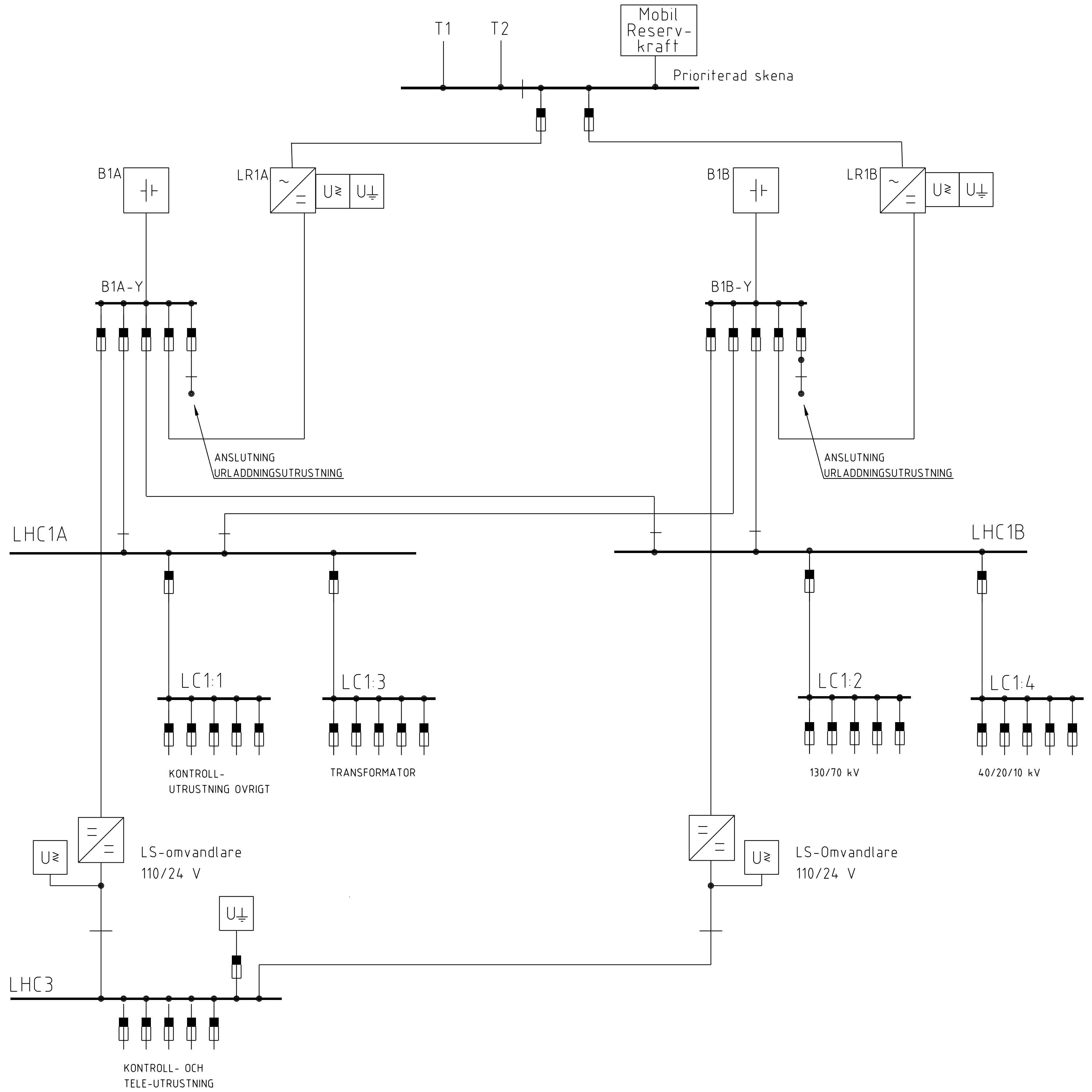
VATTENFALL

STN.LITTERA STN.NAMN

Principschema LS-System B1 och B2-1

Avd.
Datum 2012-11-16
Ritad --

Dokumenttyp Principschema
Plats–Grupp
Ritn.nr. VTR02-05 Bilaga 1
Blad
Forts.bl.



Not	Ändring	Dat.	Inf.	Godk.	Tillhörande ritningar etc.
1	Anslutning övervakning mm justerad	2020-01-10	--	--	--
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VATTENFALL

STN.LITTERA STN.NAMN

Avd.

Datum 2012-11-16

Ritad --

Principschema LS-System B2-2

Utan SUB-uppdelning

Dokumenttyp Principschema

Plats-Grupp

Ritn.nr. VTR02-05 Bilaga 2

Blad

Forts.bl.

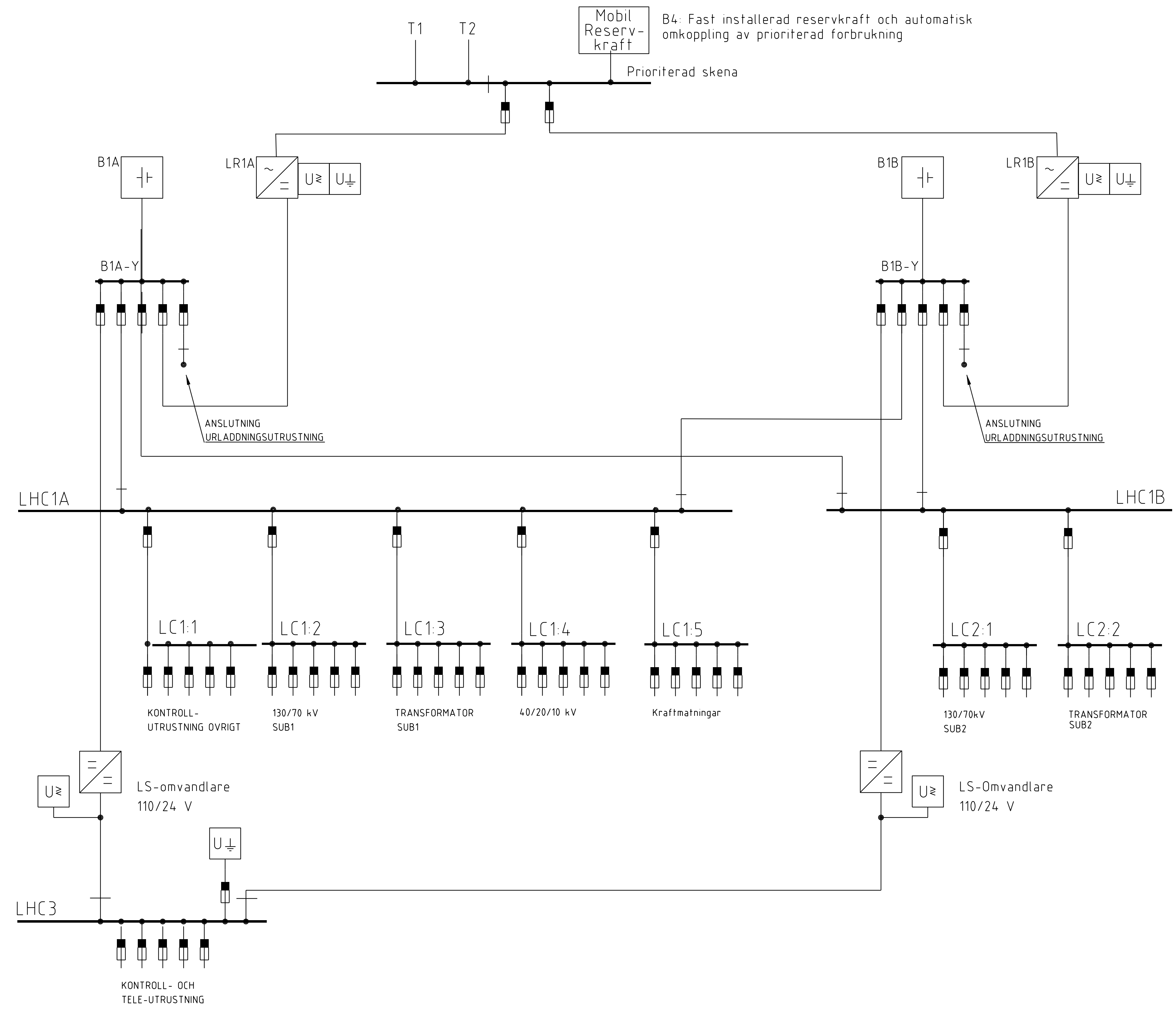
Anm. --

Proj.nr --

Godkänd --

Granskad --

Skala --



Denna ritning får inte utan Vattenfalls medgivande förevisas för eller utlämnas till obehörig

Proj.nr --
Godkänd --
Granskad --
Skala --
Anm. --

Not	Ändring	Dat.	Inf.	Godk.	Tillhörande ritningar etc.
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VATTENFALL

STN.LITTERA STN.NAMN

Avd. | Datum 2012-11-16

Ritad --

Principschema LS-System B2-2, B3 och B4
Med SUB-uppdelning

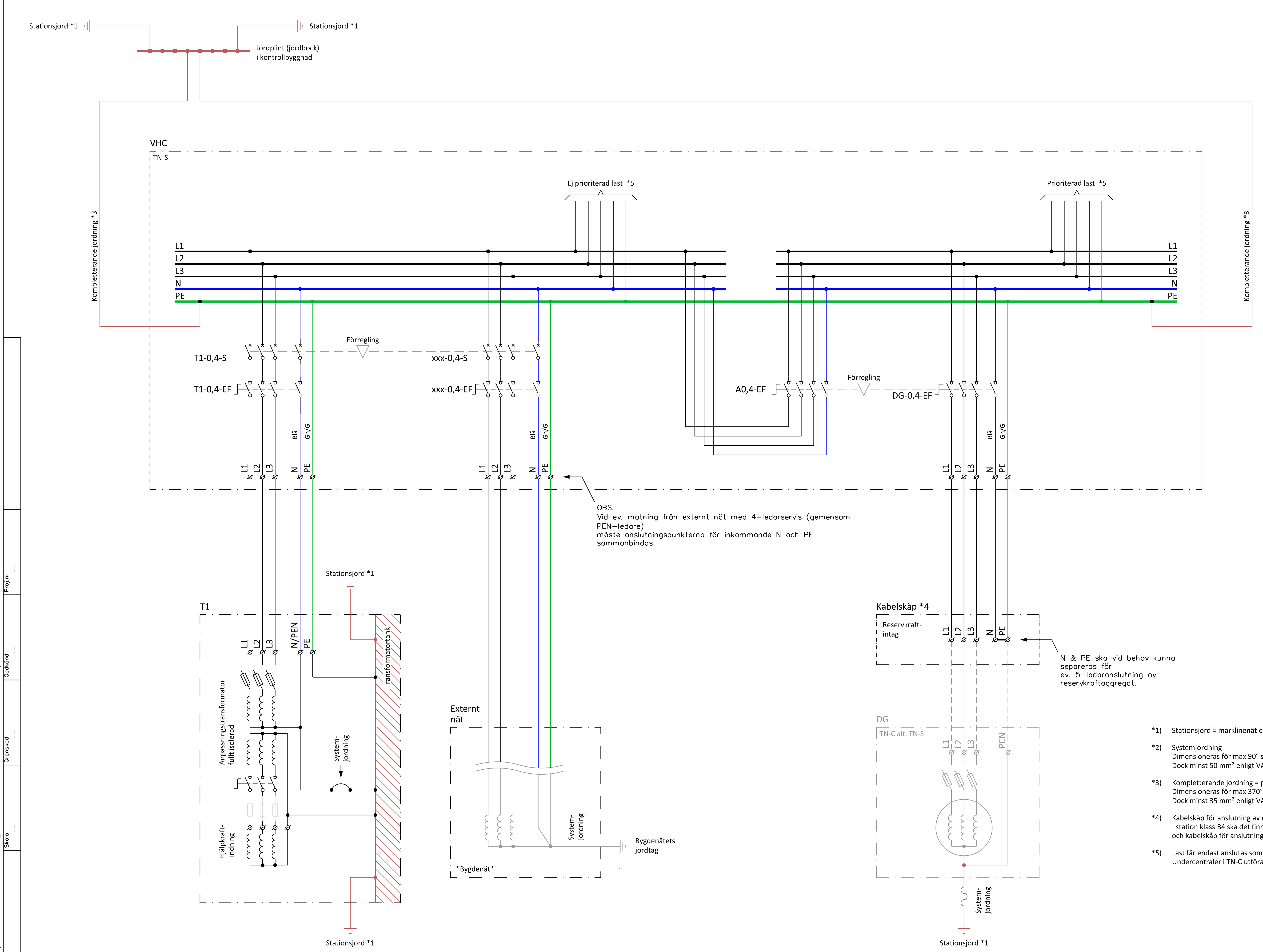
Dokumenttyp: Principschema

Plats–Grupp

Ritn.nr.: VTR02-05 Bilaga 3

Blad

Forts.bl.



*1) Stationsjord = marklinenät el. motsv.

*2) Systemjordning
Dimensioneras för max 90° sluttemperatur enligt VAST (kapitel 2.2, tabell 1).
Dock minst 50 mm² enligt VAST (kapitel 2.2, tabell 2).

*3) Kompletterande jordning = potentialstyrning
Dimensioneras för max 370° sluttemperatur enligt VAST (kapitel 2.2, tabell 1).
Dock minst 35 mm² enligt VAST (kapitel 2.2, tabell 2).

*4) Kabelskåp för anslutning av mobilt reservkraftaggregat med isolerade kopplingsplintar.
I station klass B4 ska det finnas både anslutning av fast installerad reservkraft
och kabelskåp för anslutning av mobilt reservkraftsaggregat.

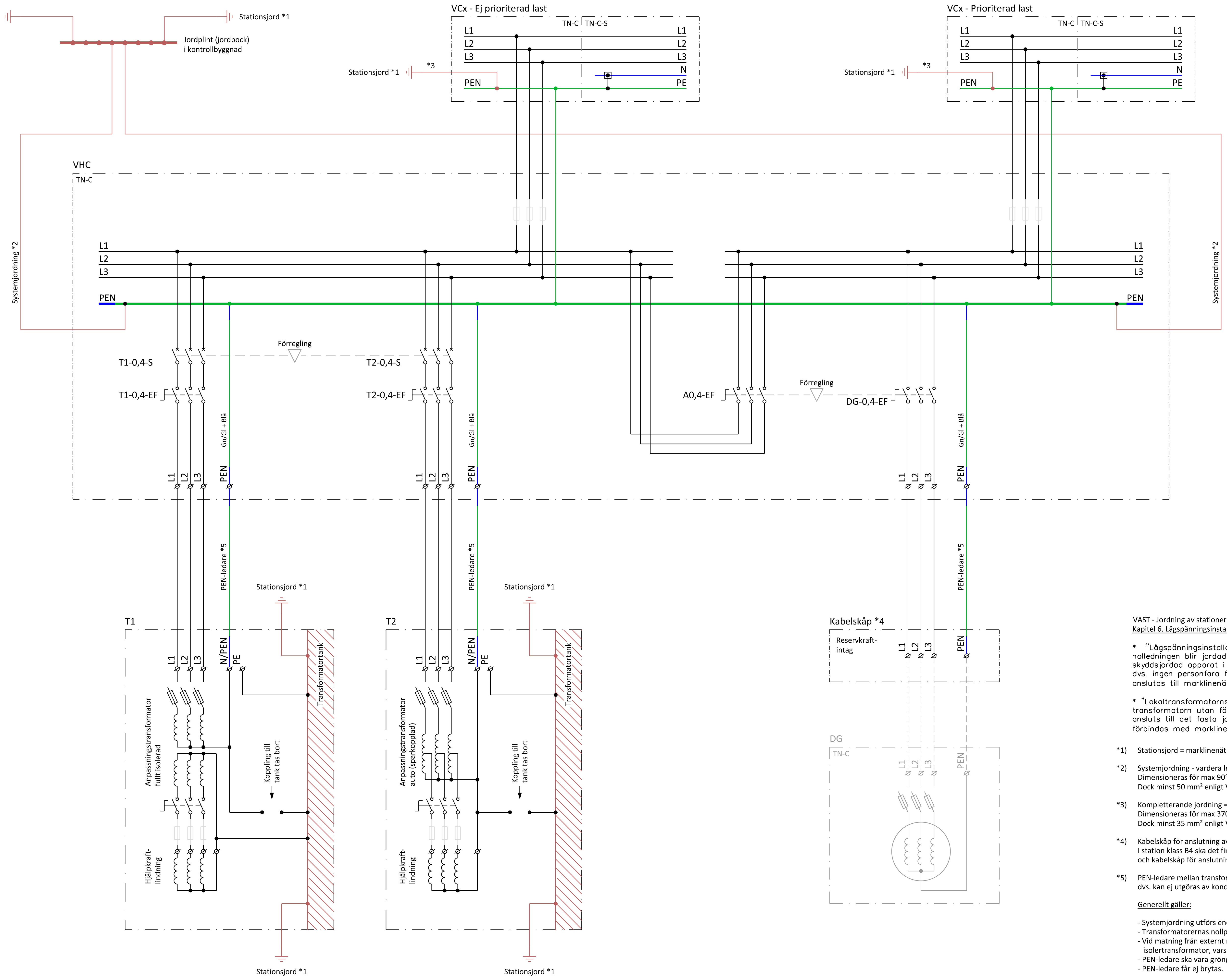
*5) Last får endast anslutas som TN-S med separata ledare för N och PE.
Undercentraler i TN-C utförande ("4-ledarsystem") får ej anslutas. Se VTR02-05.

Anm. -- | Skala -- | Granskad -- | Godkänd -- | Proj.nr --

Not	Ändring	Dat.	Inf.	Godk.	Tillhörande ritningar etc.
		--			
		--			
1	Omritad för VTR02-03 version 3	2020-05-27			

VATTENFALL

Avd.	Datum		Dokumenttyp	Plats-Grupp
DS-PI	2017-03-23	Lokalkraft med matning från flera strömkällor	Principschema	
Ritad		VHC i utförande TN-S	Ritn.nr. VTR02-05 Bilaga 4	Blad 1
				Forts.bl. --



VAST - Jordning av stationer och ställverk, Juni 1987

<u>Kapitel 6. Lågspänningsinstallationer inom stationsområdet:</u>

* "Lågspänningsinstallationen bör utföras enligt figur 6.1 så att nolledningen blir jordad till marklinenätet i varje central. Då får en skyddsjordad apparat i stort sett samma potential som sin omgivningg, dvs. ingen personfara föreligger vid beröring. Huvudcentralen skall anslutas till marklinenätet med två skilda anslutningar".

* "Lokaltransformatorns lågspänningsnolla jordas icke direkt på transformatorn utan först i huvudcentralen, där transformatornollan ansluts till det fasta jordlinesystemet i stationen. Därjämte skall nollan förbindas med marklinenätet i varje undercentral."

*1) Stationsjord = marklinenät el. motsv.

*2) Systemjordning - vardera ledaren dimensioneras för den maximala felströmmen.
Dimensioneras för max 90° sluttemperatur enligt VAST (kapitel 2.2, tabell 1).
Dock minst 50 mm^2 enligt VAST (kapitel 2.2, tabell 2).

*3) Kompletterande jordning = potentialstyrning
Dimensioneras för max 370° sluttemperatur enligt VAST (kapitel 2.2, tabell 1).
Dock minst 35 mm^2 enligt VAST (kapitel 2.2, tabell 2).

*4) Kabelskåp för anslutning av mobilt reservkraftaggregat med isolerade kopplingsplintar.
I station klass B4 ska det finnas både anslutning av fast installerad reservkraft och kabelskåp för anslutning av mobilt reservkraftsaggregat.

*5) PEN-ledare mellan transformator och VHC ska ha full area och full isolation, dvs. kan ej utgöras av koncentrisk ledare. Kabeltyp SE-N1XV el. motsv. ska användas.

<u>Generellt gäller:</u>

- Systemjordning utförs endast på ett ställe = PEN-skenan i VHC.
- Transformatorernas nollpunkter får <u>ej</u> anslutas direkt till jord.
- Vid matning från externt nät (bygdenät) med egen systemjordning måste detta ske via isolertransformator, vars nollpunkt <u>ej</u> får vara direkt ansluten till jord.
- PEN-ledare ska vara gröngul med blå tilläggsmärkning.
- PEN-ledare får ej brytas.

Not	Ändring	Dat.	Inf.	Godk.	Tillhörande ritningar etc.
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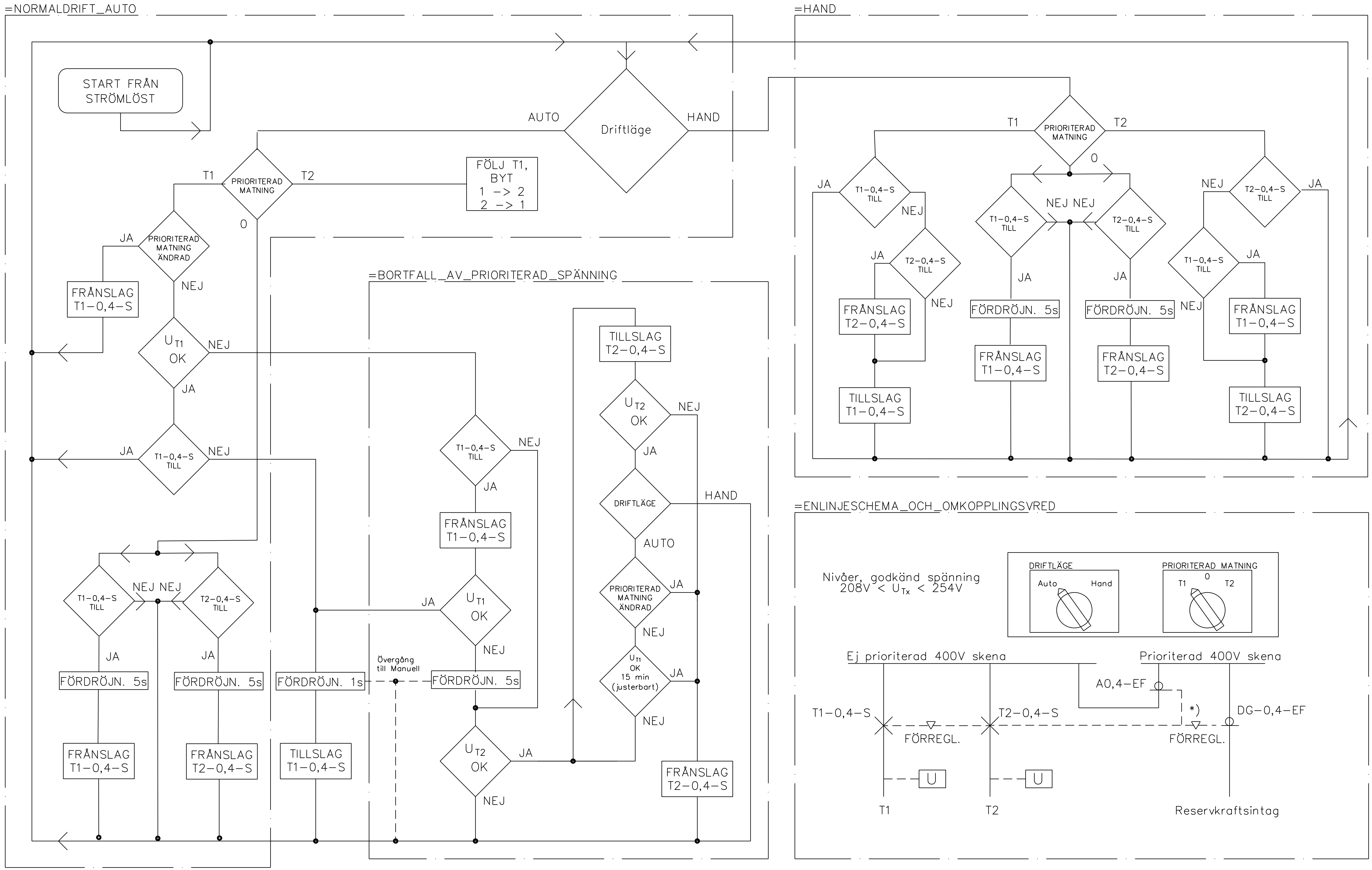
1	Omritad för VTR02-03 version 3	2020-05-27			

VATTENFALL

Avd.	Datum		Dokumenttyp	Plats–Grupp
DS-PI	2020-05-14	Lokalkraft med matning från flera strömkällor	Principschema	
Ritad		VHC i utförande TN-C (äldre stationer, utförande enl. VAST)	Ritn.nr. VTR02-05 Bilaga 5	Blad 1
				Forts.bl. --

Anm. --
Skala
Granskad --
Godkänd --
Proj.nr --



*) Förregling kan utföras mellan DG-0,4-EF och A0,4-EF alternativt mellan DG-0,4-EF och T1/T2-0,4-S

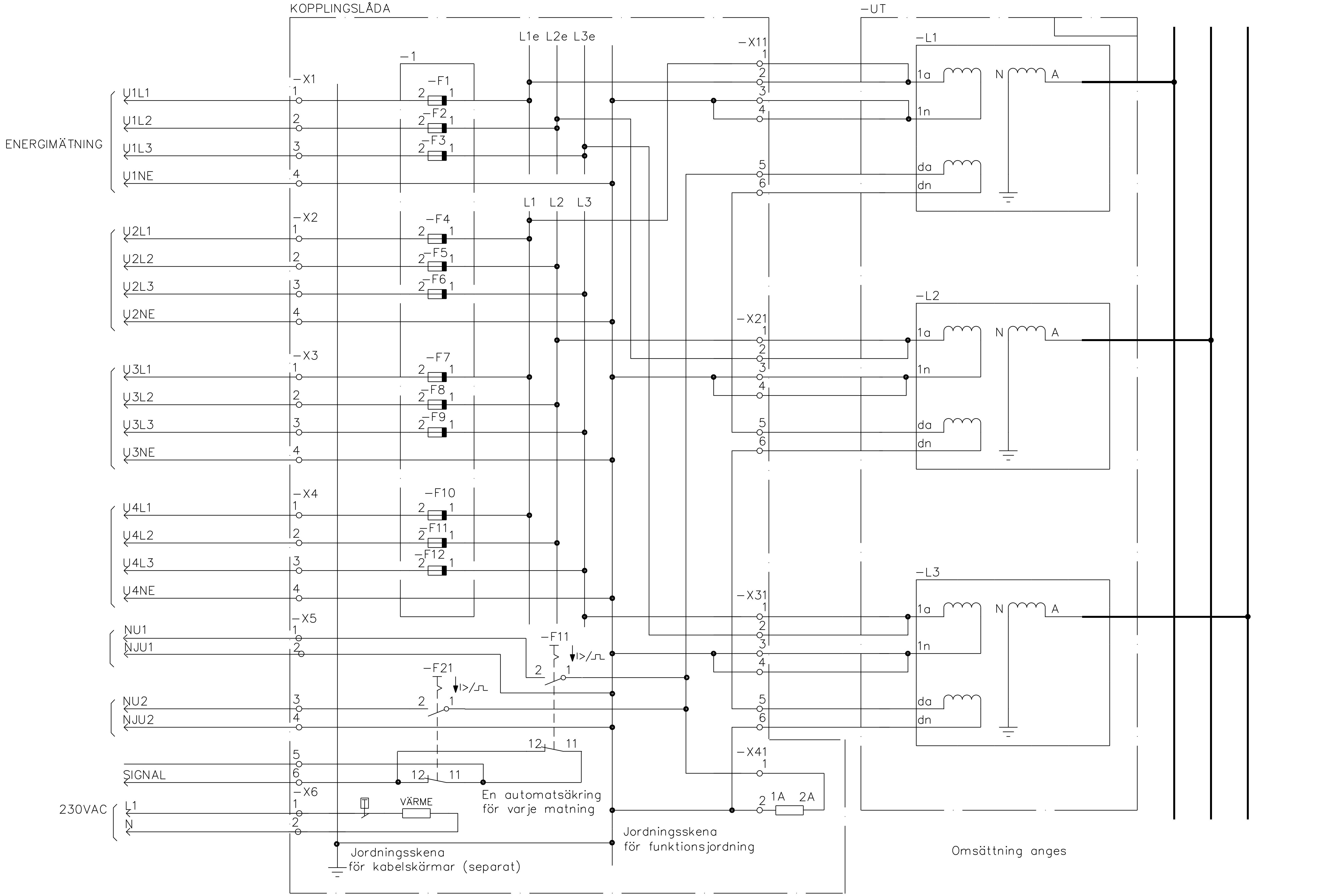
					--	**VATTENFALL**	STN.LITTERA STN.NAMN
					--	Avd. - / Datum 2020-04-16	Växelströmshuvudcentral VHC
					--	Ritad DS-PI	Omkopplingsautomatik (logik schema)
Not	Ändring	Dat.	Inf.	Godk.	Tillhörande ritningar etc.		

Dokumenttyp	Plats-Grupp
Principritning	--
Ritn.nr. VTR02-05 Bilaga 6	Blad 1
	Forts.bl. -

Anm.

Blankett ED31-10Denna ritning får inte utan Vattenfalls medgivande förevisas för eller utlämnas till obehörig

Proj.nr | Godkänd - | Granskad | Skolo



Proj.nr --
Godkänd --
Granskad --
Skala --
Anm. --

Not	Ändring	Dat.	Inf.	Godk.	Tillhörande ritningar etc.
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VATTENFALL

Avd. | Datum 2012-10-05

Ritad --

STN.LITTERA STN.NAMN

Spänningstransformator Imp.Jordat System

Med Energimätning

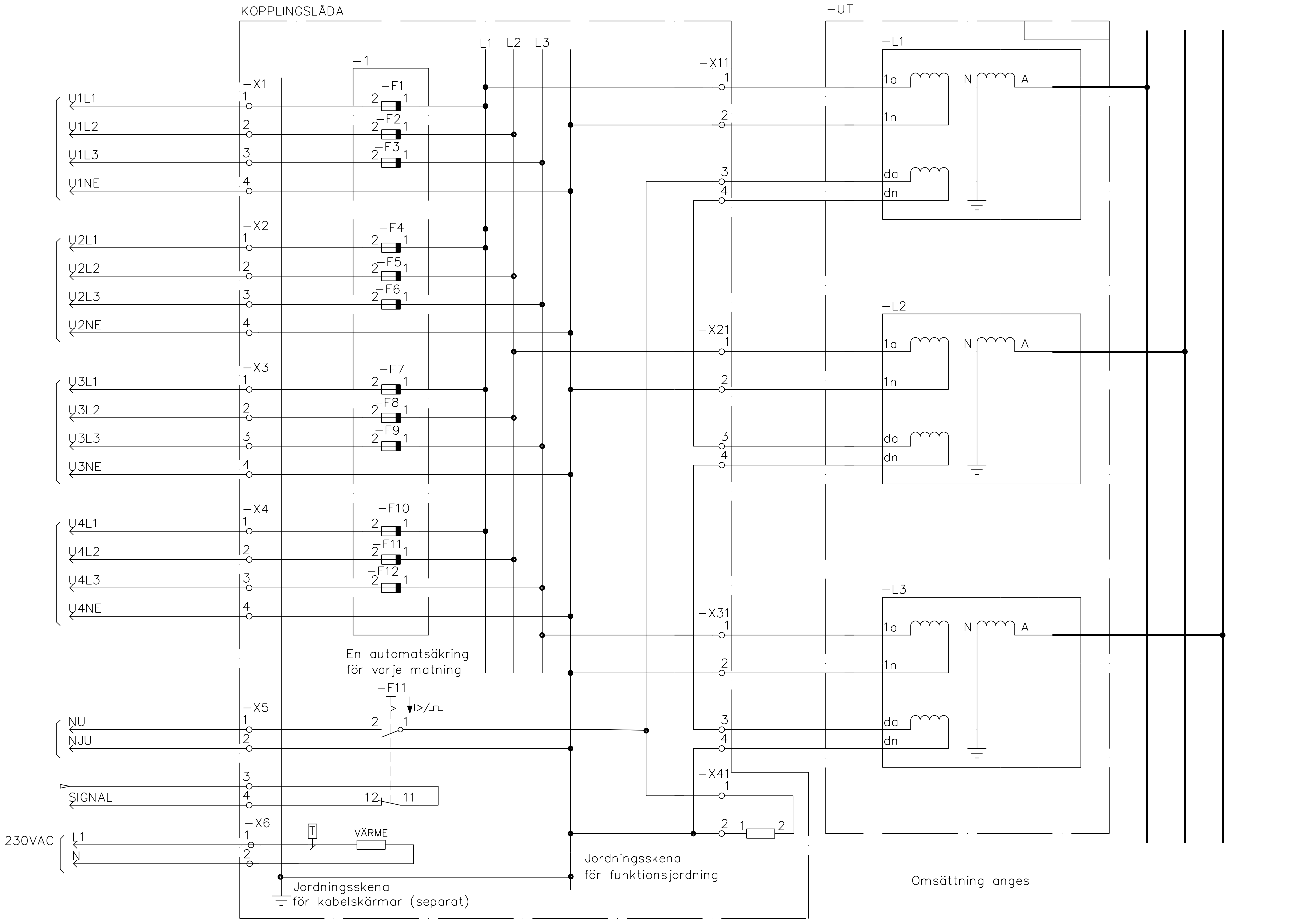
Dokumenttyp: Kretsschema

Plats-Grupp

Ritn.nr. VTR02-06 Bilaga 1

Blad

Forts.bl.



Not	Ändring	Dat.	Inf.	Godk.	Tillhörande ritningar etc.
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VATTENFALL

STN.LITTERA STN.NAMN

Avd.

Datum 2012-10-05

Ritad --

Spänningstransformator Imp-Jordat System

Ej Energimätning

Dokumenttyp Kretsschema

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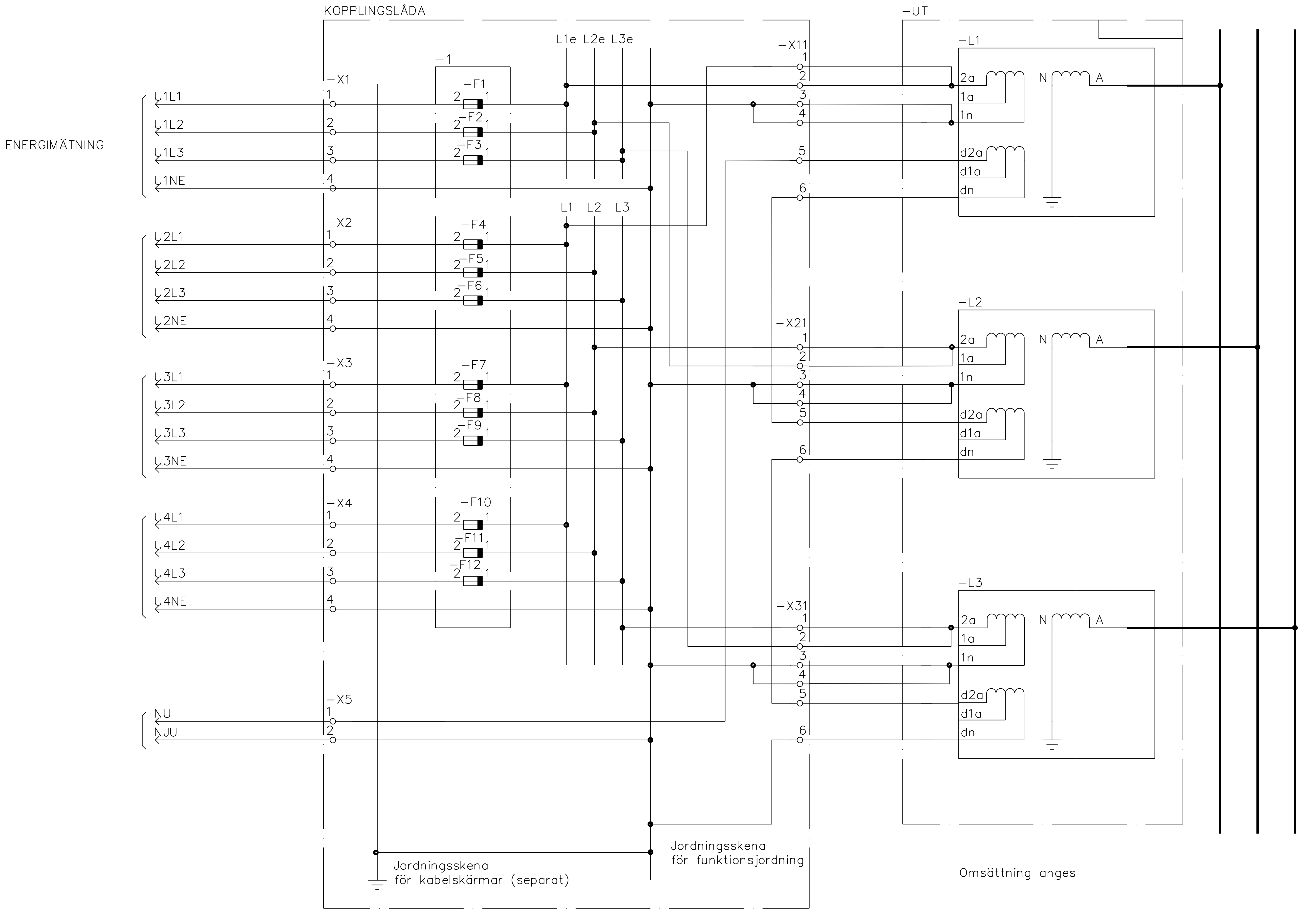

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VATTENFALL

STN.LITTERA STN.NAMN

Avd.

Datum 2012-10-05

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Spänningstransformator Direktjordat System
Med Energimätning

Dokumenttyp Kretsschema

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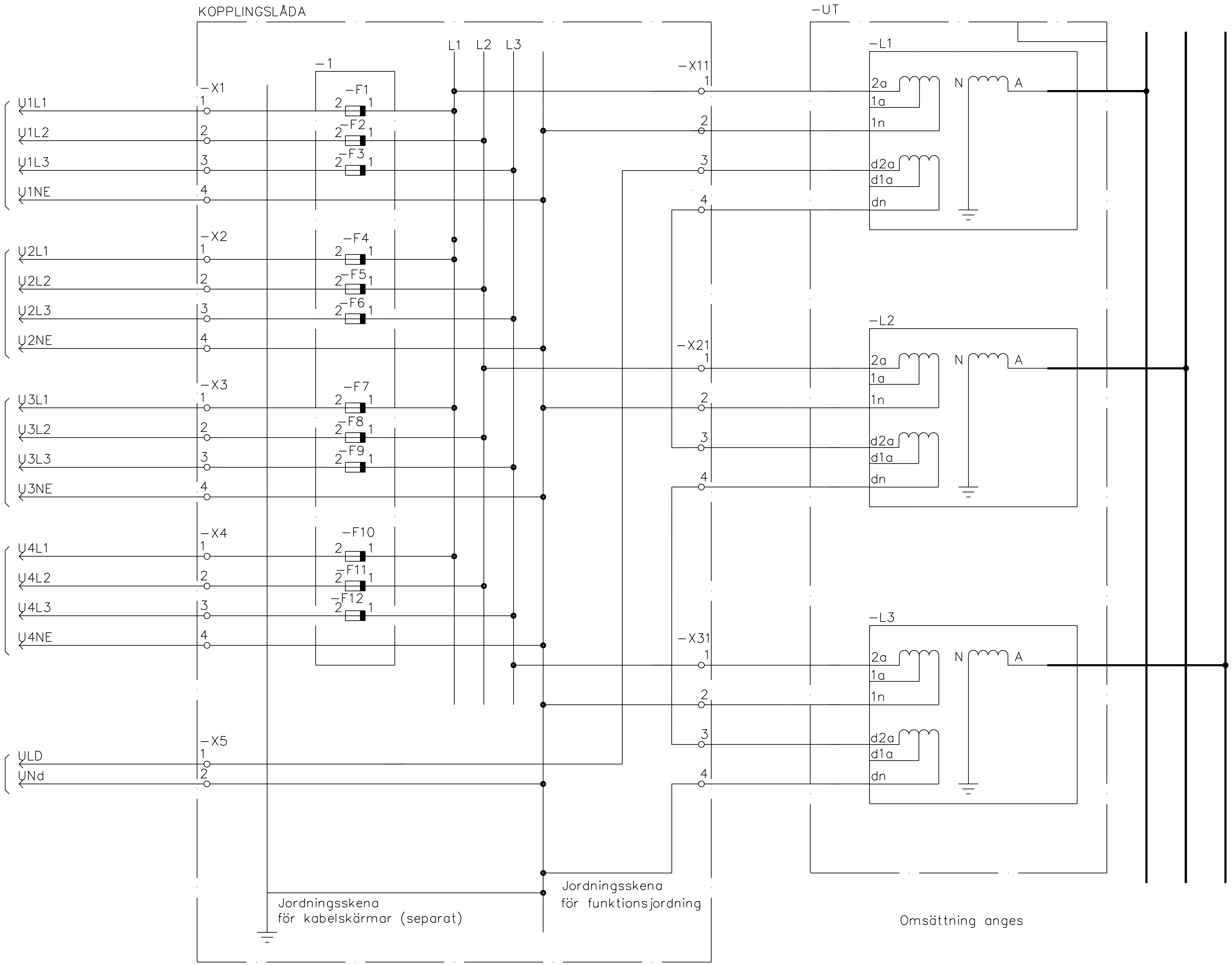

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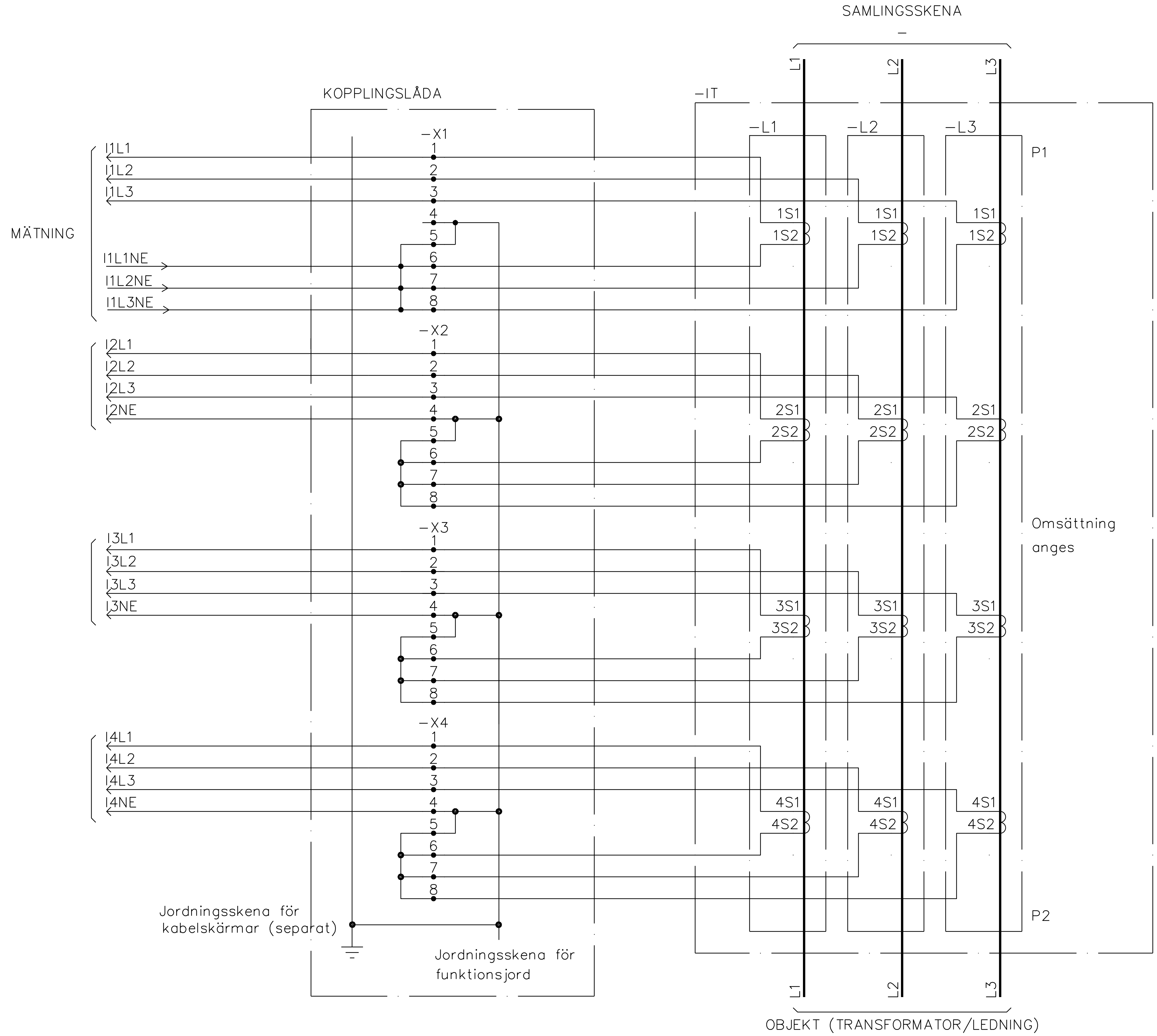

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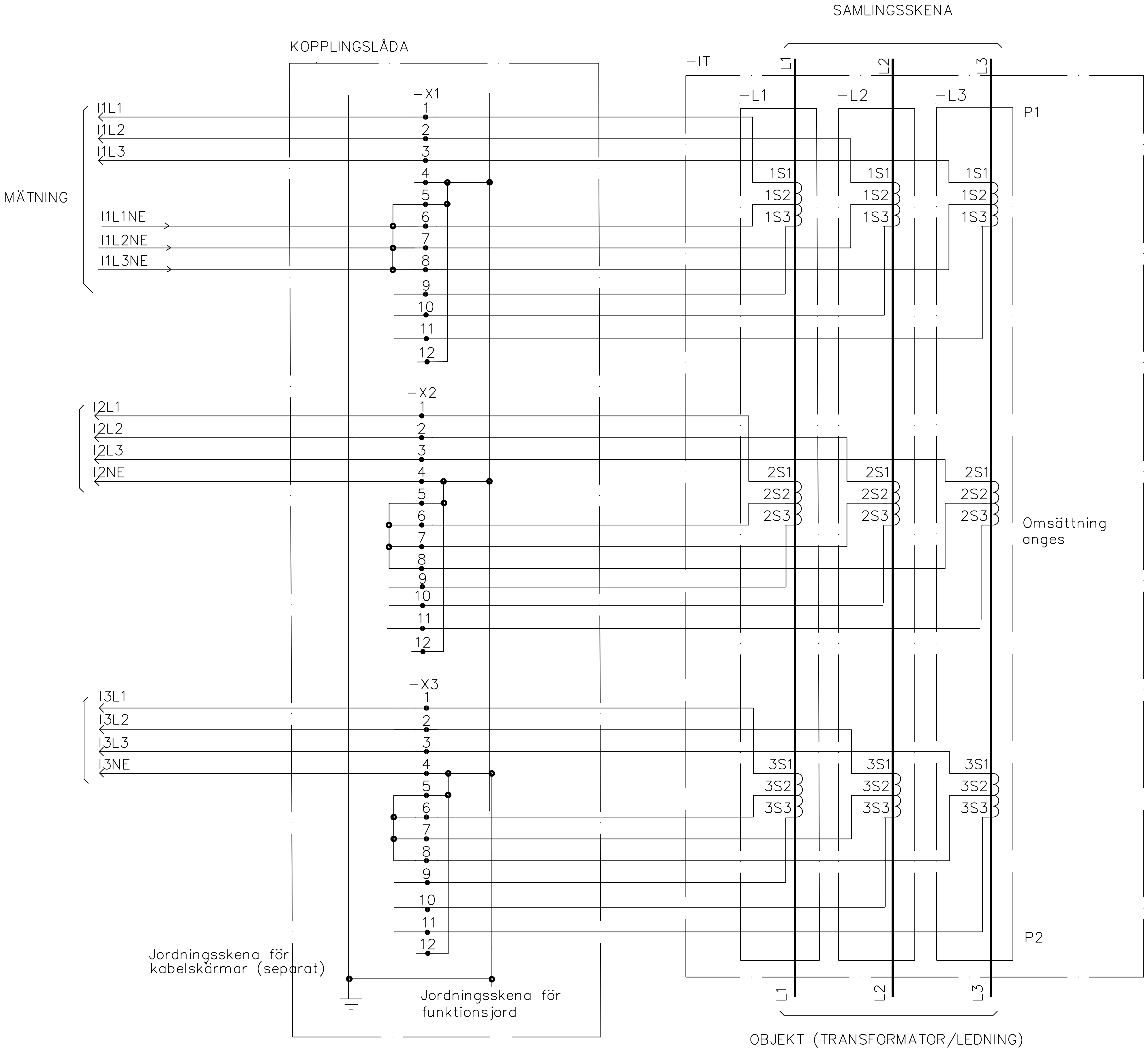

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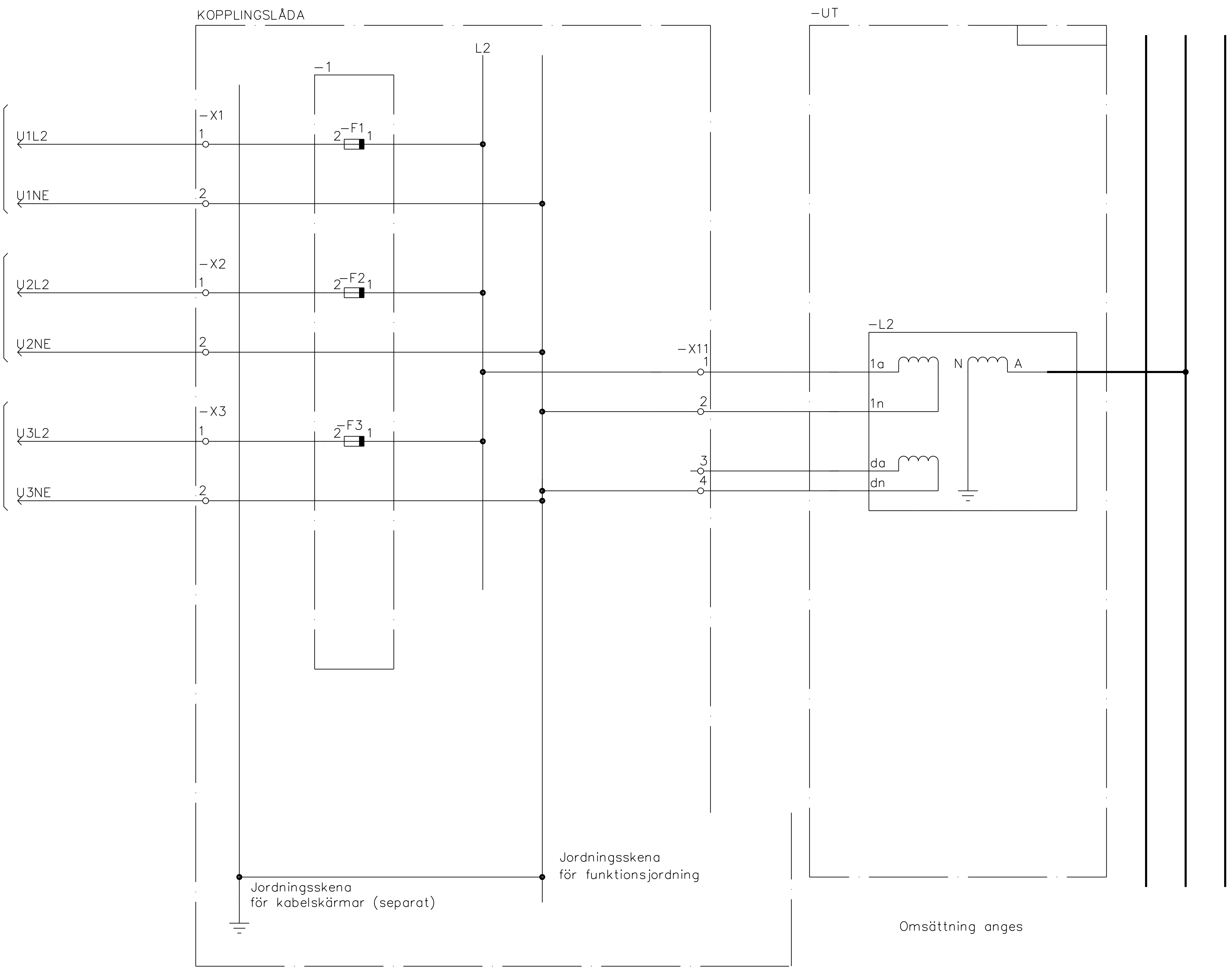

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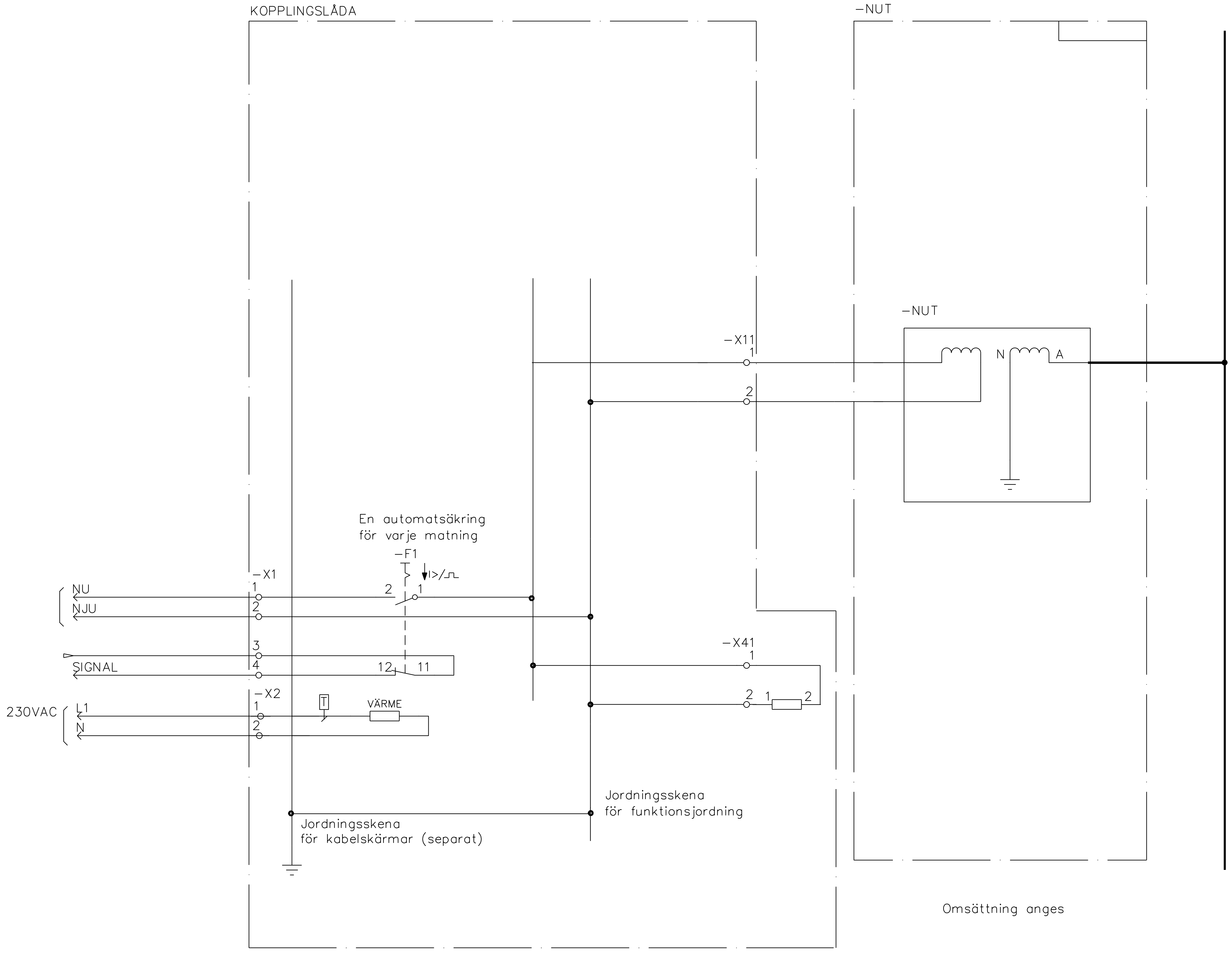

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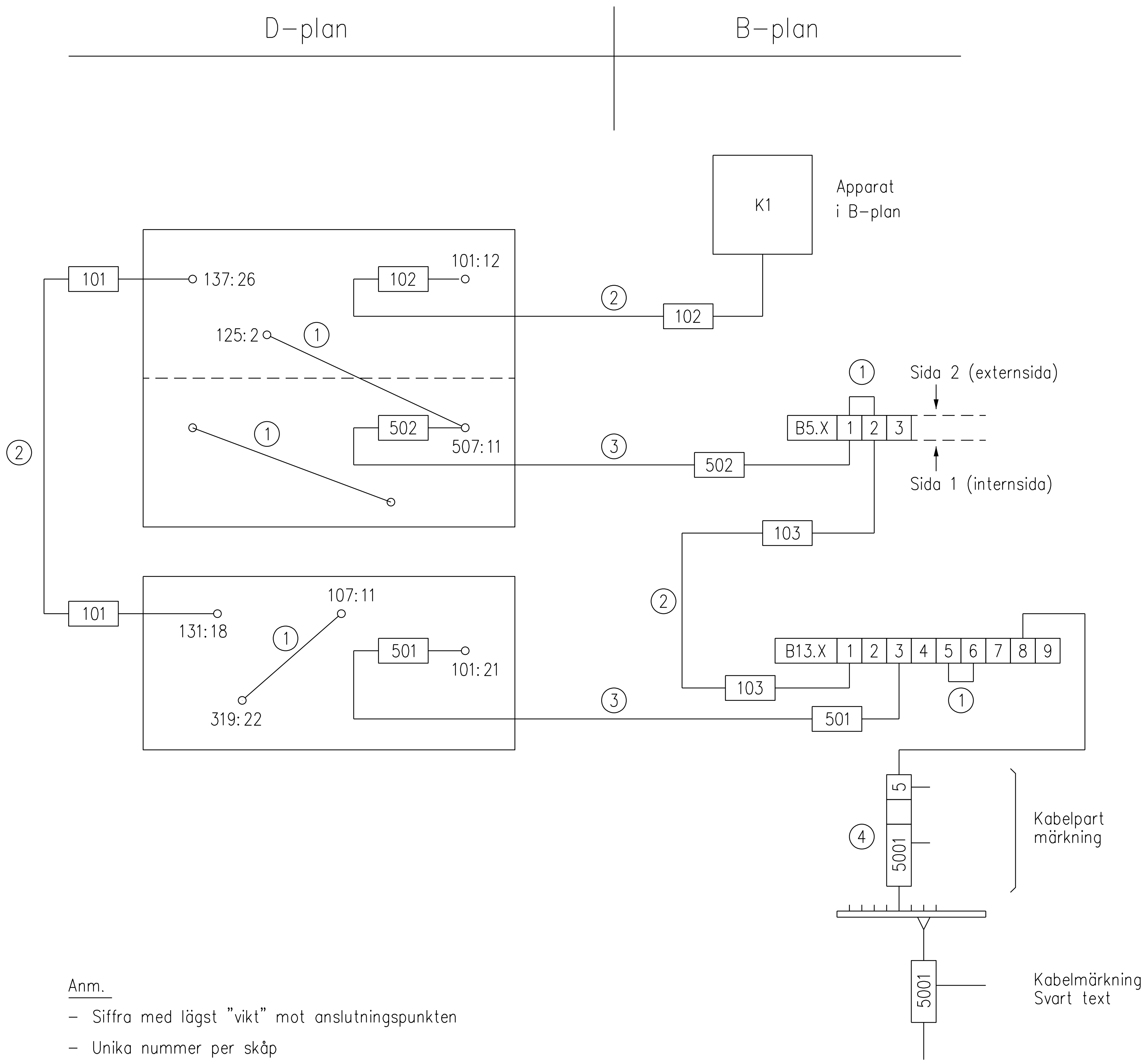

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GUIDE ON
EMC IN POWER PLANTS
AND SUBSTATIONS

Working Group

36.04

December 1997

cigré

GUIDE ON
EMC IN POWER PLANTS
AND SUBSTATIONS

Working Group 36.04
" EMC within power plants and substations "

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1 Introduction

As electrical generating stations, substations, control centres and networks have become more complex, their required standards of reliability have become more demanding.

These needs have been met by the widespread use of electronic systems, based on increasingly high-speed and low-power semiconductor technology. These systems provide the major computing power and the readily accessible information that make on-line automation possible.

However, advances in the technology have progressively reduced the levels of energy required to switch between logic states, increased the efficiency with which these levels of energy can be transferred by unintended coupling paths, and lowered the levels of energy which the components can survive.
These trends have increased their inherent susceptibility to Electromagnetic Interference (EMI).

EMI problems can manifest themselves as errors or failures after the equipment has entered service. Other hardware or software problems may be suspected initially, but the problems will recur until they are properly diagnosed and solved.

Every incident of interference involves a source of disturbance, a coupling mechanism and a susceptible piece of equipment.

Problems can arise if any immunity margin is inadequate. This happens if the product of a disturbance and its coupling factor exceeds the susceptibility threshold of the piece of equipment. Electromagnetic Compatibility (EMC) means attaining and maintaining adequate margins at all times.

In practice the enormous number of combinations of potential sources, coupling mechanisms and paths, and susceptible pieces of equipment, rules out the approach of checking each combination at the design stage. Furthermore, the detailed configuration and electromagnetic environment of each installation are unique and liable to vary with time, so it is unsafe to make detailed assumptions about any installation based on measurements at another.

The only practical approach is to use the experience of designers, builders and users of different types of installation to classify the various kinds of electromagnetic environment that are encountered and need to be managed, and then to:

- characterize worst-case disturbances, and choose reasonable levels against which immunity has to be provided in each environment;
- ensure that no level of disturbance above the threshold provided for in each environment can arise;
- specify the acceptance criteria for each function of each automation and control system;
- specify the equipment and installation practices that will provide the levels of immunity required;
- specify the tests to verify that these have been achieved.

CIGRE Study Committee 36 identified the need for this Guide as a convenient and timely introduction to the subject. It is written primarily for those engineers who are responsible for measurement, control, protection, communications and supervision circuits. It provides an overview of problems encountered, solutions adopted to solve them, practices followed in implementing the solutions, and tests recommended to ensure that such problems will not recur.

After this introduction (Chapter 1), Chapter 2 sets out the definitions, symbols and acronyms used throughout the Guide. They conform, where applicable, to the International Electrotechnical Commission (IEC) Standards.

Chapter 3 covers potential sources of disturbance, including high voltage and low voltage equipment, communication systems and natural atmospheric phenomena; it also characterises disturbances in terms of amplitude, frequency and duration.

Chapter 4 covers the coupling mechanisms, including conductive, capacitive, inductive and radiated, whereby disturbances can propagate through cables and other components and reach susceptible pieces of equipment. It also introduces general criteria for mitigation techniques.

Chapter 5 defines practical installation and mitigation techniques, and then classifies electromagnetic environments, taking into account all the practical measures adopted.

Chapter 6 defines acceptable degrees of interference, taking into account both the nature of the disturbances and the affected functions of the equipment, such as control, protection, metering, recording, communication and supervision.

Chapter 7 gives some general information for the design and manufacturing aspects of equipment and systems that contributes to their immunity and emission.

Chapter 8 lists the most important laboratory tests for various types of equipment, and the most relevant tests for complete installations.

Chapter 9 shows the strategic importance of adopting a co-ordinated EMC plan throughout each phase of a project, from conceptual design through specification, construction, installation, commissioning and testing.

2 Definitions, symbols and acronyms

The following definitions are taken from IEC Publication 50 - Chapter 161: Electromagnetic Compatibility. The labels refer to this IEC Publication. The list includes some of the terms which are most frequently used in this Guide and are pending as future entries in IEC 50(161).

2.1 Basic concepts

APPARATUS (161/A)
A finished combination of devices (or equipment) with an intrinsic function intended for final user and intended to be placed on the market as a single commercial unit.

DEGRADATION (OF PERFORMANCE) (01-19)
An undesired departure in the operational performance of any device, equipment or system from its intended performance (the term "degradation" can apply to temporary or permanent failure).

ELECTROMAGNETIC COMPATIBILITY; EMC (abbreviation) (01-07)
The ability of an equipment or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment.

ELECTROMAGNETIC DISTURBANCE (01-05)
Any electromagnetic phenomenon which may degrade the performance of a device, equipment or system, or adversely affect living or inert matter.

(ELECTROMAGNETIC) EMISSION (01-08)
The phenomenon by which electromagnetic energy emanates from a source.

ELECTROMAGNETIC ENVIRONMENT (01-01)
The totality of the electromagnetic phenomena existing at a given location.

ELECTROMAGNETIC INTERFERENCE; EMI (abbreviation) (01-06)
Degradation of the performance of an equipment, transmission channel or system caused by an electromagnetic disturbance.

ELECTROMAGNETIC NOISE (01-02)
A time-varying electromagnetic phenomenon apparently not conveying information and which may be superimposed on or combined with a wanted signal.

(ELECTROMAGNETIC) SUSCEPTIBILITY (01-21)
The inability of a device, equipment or system to perform without degradation in the presence of an electromagnetic disturbance. Susceptibility is a lack of immunity.

IMMUNITY (TO A DISTURBANCE) (01-20)
The ability of a device, equipment or system to perform without degradation in the presence of an electromagnetic disturbance.

INSTALLATION (161/A)
Several combined items of apparatus or systems put together at a given place to fulfil a specific objective but not intended to be placed on the market or put into service as a single functional unit.

PORT
Particular interface of the specified apparatus with the external electromagnetic environment.

SYSTEM (161/A)
Several items of apparatus combined to fulfil a specific objective and intended to be placed on the market or put into service as a single functional unit.

2.2 Interference control

(ELECTROMAGNETIC) COMPATIBILITY LEVEL (03-10)
The specified maximum electromagnetic disturbance level expected to be impressed on a device, equipment or system operated in particular conditions.

(ELECTROMAGNETIC) COMPATIBILITY MARGIN (03-17)
The difference between the immunity level of a device, equipment or system and the emission limit from the disturbance source.

ELECTROMAGNETIC SCREEN (03-26)
A screen of conductive material intended to reduce the penetration of a varying electromagnetic field into an assigned region.

EMISSION LIMIT (from a disturbing source) (03-12)
The specified maximum emission level of a source of electromagnetic disturbance.

IMMUNITY LEVEL (03-14)
The maximum level of a given electromagnetic disturbance incident on a particular device, equipment or system for which it remains capable of operating at a required degree of performance.

SCREEN (03-25)
A device used to reduce the penetration of a field into an assigned region.

2.3 Disturbance waveforms

BURST (of pulses or oscillations) (02-07)
A sequence of a limited number of distinct pulses or an oscillation of limited duration.

PULSE (02-02)
An abrupt variation of short duration of a physical quantity followed by a rapid return to the initial value.

RISE TIME (of a pulse) (02-05)
The interval of time between the instants at which the instantaneous value of a pulse first reaches a specified lower value and then a specified upper value. (Unless otherwise specified, the lower and upper values are fixed at 10% and 90% of the pulse magnitude).

TRANSIENT (adjective and noun) (02-01)
Pertaining to or designating a phenomenon or a quantity which varies between two consecutive steady states during a time interval short compared with the time-scale of interest.

2.4 Disturbances

COMMON MODE VOLTAGE (asymmetrical voltage) (04-09)
The mean of the phasor voltages appearing between each conductor and a specified reference, usually earth or frame.

DIFFERENTIAL MODE VOLTAGE (symmetrical voltage) (04-08)
The voltage between any two of a specified set of active conductors.

DISTURBANCE FIELD STRENGTH (04-02)
The field strength produced at a given location by an electromagnetic disturbance, measured under specific conditions.

DISTURBANCE VOLTAGE (04-01)
Voltage produced between two points on two separate conductors by an electromagnetic disturbance, measured under specified conditions.

ELECTROSTATIC DISCHARGE; ESD (01-22)
A transfer of electric charge between bodies of different electrostatic potential in proximity or through direct contact.

2.5 Bonding and earthing

BONDING
The act of connecting together exposed conductive parts of apparatus, systems or installations. (For safety purposes, bonding generally involves - but not necessarily - a connection to the immediately adjacent earthing arrangement).

EARTH ELECTRODE
A conductive part or a group of conductive parts in intimate contact with and providing an electrical connection with earth.

EARTH, GROUND
The conductive mass of the earth, whose electric potential at any point is conventionally taken as equal to zero.

EARTH NETWORK
Conductors of the earthing system, not in contact with the soil, connected at one end to the earth electrode and at the other end to the apparatus, systems, or installations.

EARTHING
The act of connecting exposed conductive parts or other selected conductors of apparatus, systems or installations to the earth arrangement.

2.6 Units of measurements and related symbols

The symbols used in the Guide are listed together with the proper units of measurements, according to the International System of Units.

Conductance (admittance, susceptance)	siemens (S)	G (Y)
Conductivity	siemens per meter (S/m)	σ
Current density	ampere per square meter (A/m^2)	J
Electric capacitance	farad (F)	C
Electric current	ampere (A)	I
Electric field strength	volt per meter (V/m)	E
Electric resistance (impedance, reactance)	ohm (Ω)	R (Z, X)
Frequency	hertz (Hz)	f, υ, ω (rad/s)
Inductance Self, Mutual	henry (H)	L, M
Length	meter (m)	d, D, R, x (distance) r (radius) ℓ (length) h (height) δ (depth) λ (wavelength)
Magnetic field strength	ampere per meter (A/m)	H
Magnetic flux	weber (Wb)	Φ (B)
Magnetic flux density	tesla (T)	B
Permeability	henry per meter (H/m)	μ
Permittivity	farad per meter (F/m)	ε

Potential difference, voltage, electric potential	volt (V)	V, U
Power	watt (W)	W
Resistivity	ohm meter (Ω·m)	ρ
Time, pulse rise time, pulse width	second (s)	t, τ
Velocity	meter per second (m/s)	v

Decibel (dB)

decibel is a dimensionless number expressing the ratio of two power levels, W_1 to W_2:

dB = 10 log (W_1 / W_2)

Further expressions of dB if both the voltages (U_1, U_2) or currents (I_1, I_2) are measured on the same impedance:

dB = 20 log (U_1 / U_2); dB = 20 log (I_1 / I_2)

2.7 Acronyms

The following list includes the acronyms frequently used in this Guide.

AGBN: Above Ground Bonding Network
AIS: Open-Air (Air Insulated) Substation
CISPR: International Special Committee on Radio Interference
CM: Common Mode
CMRR: Common Mode Rejection Ratio
CT: Current Transformer
DM: Differential Mode
EMC: ElectroMagnetic Compatibility
EMF: ElectroMagnetic Force (E)
EMI: ElectroMagnetic Interference
ECP: Parallel Earth Conductor
ERP: Effective Radiated Power
ESD: ElectroStatic Discharge
HEMP: High Altitude ElectroMagnetic Pulse
HF: High Frequency
GIC: Geomagnetic Induced Currents
GIS: Gas-Insulated Substation
IBN: Isolated Bonding Network
IEC: International Electrotechnical Commission
IGP: Integrated Ground Plane
LF: Low Frequency
LPS: Lightning Protection System
MHD-EMP: MagnetoHydrodynamic Nuclear ElectroMagnetic Pulse
NEMP: Nuclear ElectroMagnetic Pulse
PE: Protective Earth
RF: Radio-Frequency

SGEMP:	System Generated ElectroMagnetic Pulse
SPD:	Surge Protective Device
SREMP:	Source Region ElectroMagnetic Pulse
TE:	Transverse Electric
TEM:	Transverse ElectroMagnetic
TL:	Transmission Line
TM:	Transverse Magnetic
(T)GPR:	(Transient) Ground Potential Rise
UNIPEDE:	International Union of Producers and Distributors of Electrical Energy
VHF:	Very High Frequency
VLF:	Very Low Frequency
VT:	Voltage Transformer

3 Sources of disturbance

3.1 General

The most typical sources of disturbance that may affect the auxiliary systems of electrical installations, that is power stations, substations, control centres and so on, are the following:

1. electrical transient phenomena due to switching operations of circuit breakers or disconnectors in HV electrical circuits;
2. electrical transient phenomena due to insulation breakdown in HV electrical circuits or to surge-diverter and spark-gap sparkovers in the same circuits;
3. power frequency electric and magnetic fields produced by HV installations;
4. voltage rises due to short-circuit currents in earthing systems;
5. electrical transient phenomena due to lightning; these phenomena, even if present also in other installations, are particularly important for electrical installations due to the presence of tall earthed structures and power lines.

Other sources of disturbance, which are not specific for electrical installations but are also generally present in these installations, are the following:

6. electrical fast transients due to switching operations in low voltage equipment;
7. electrostatic discharges;
8. high frequency fields produced by radio transmitters, external or internal to the installation;
9. high frequency conducted and radiated disturbance from other pieces of electric or electronic equipment present in the installation;
10. low frequency conducted disturbances from power supply.

Finally, the following two other types of electromagnetic disturbance are to be considered for particular situations:

11. nuclear electromagnetic pulse (NEMP);
12. geomagnetic interference.

Figure 1 gives a picture of some disturbances included in the above list with reference to a power station with the relevant substation.

This chapter intends to summarise the main characteristics (wave-shapes, amplitudes, frequencies of occurrence, etc.) of the above-mentioned sources of disturbance on the basis of the analysis of the most recent literature in the field.

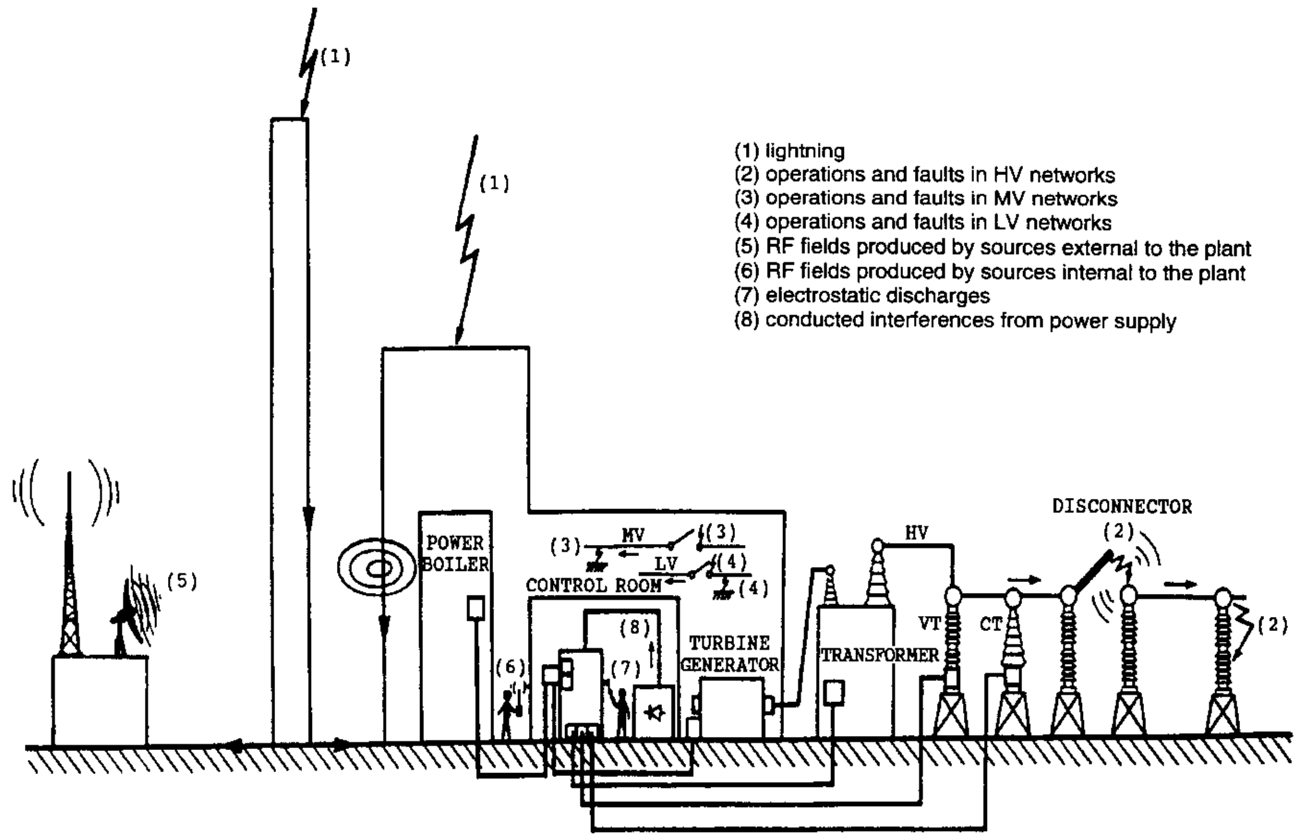


Figure 1 - Schematic diagram of sources of disturbance that may affect the auxiliary systems of a power station with the relevant substation

3.2 Transient phenomena due to switching operations in HV circuits

Switching operations of circuit breakers and disconnectors in power stations and substations give rise to electromagnetic interference because they generate abrupt voltage collapses ΔU across the contacts of the equipment. [1]

For the same ΔU the collapse time Δt is essentially dependent on the distance between the contacts: it can range from a few nanoseconds for gas-insulated substation (GIS) to several tens or some hundreds of nanoseconds for open-air substations (AIS).

The voltage collapse ΔU is generally equal to 1 p.u. of the phase-to-earth power frequency peak voltage in the case of closing operations of circuit breakers. It may reach 1,2 - 1,3 p.u. in the case of three-phase reclosing after a single-phase line fault clearing.

Switching operations of disconnectors, generally characterised by multiple (up to 5000 or more) voltage collapses (restrikes) during the switching time (from a few tens of milliseconds to a few seconds), may produce voltage collapse ΔU up to 2 p.u..

The voltage collapse ΔU applied to the circuit gives rise to a voltage and current damped oscillating wave (a burst of oscillating waves in the case of restrikes).

The initial value of the current (peak value) is proportional to the ratio between ΔU and the surge impedance of the circuit, which is more or less independent of the system voltage, at least for the range 115 kV to 500 kV; the peak current can, therefore, be expected to be proportional to the system voltage.

With regards to the waveshape of the oscillating wave, the steepness of the initial ramp is related to the collapse time and the oscillation frequencies are dependent on the characteristics of the circuit. Typical frequencies are in the range from several tens of kHz to some MHz for open-air substations and up to some tens of MHz for GIS.

The voltage and current oscillating waves propagate on the bus-bars and produce electric and magnetic fields.

Figure 2 shows the result of measurements performed by opening a 500 kV disconnector: the magnetic and electric fields were measured on the ground directly below the busbar.

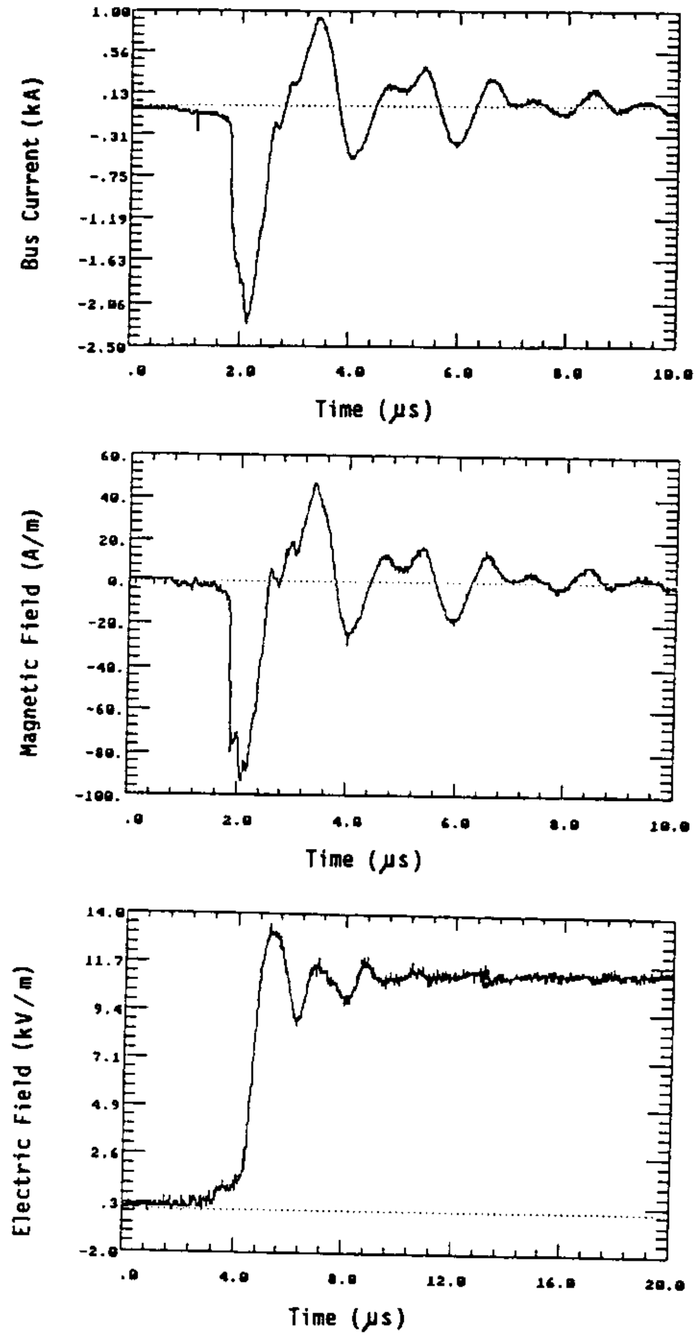


Figure 2 - Bus current and field measurements from opening a disconnector in a 500 kV AIS [2]

The magnetic field is practically proportional to the current, while the electric field, depending on the charge rather than the current, has a different behaviour. The magnetic field, as the current, approaches zero in some µs, while the electric field, as the voltage and the charge, approaches a constant value different from zero, due to trapped charges caused by the current interruption in the switch.

The rise times of the initial ramps and the oscillation frequencies are in the range already indicated for the open-air substations.

Typical values of transient electric and magnetic fields produced by switching operations in open-air substations of different voltage levels, just under the bus-bars, are given in the following table 1.

System voltage (kV)	Magnetic field (A/m)	Electric field (kV/m)
115	35	5
230	70	7
500	150	13

Table 1 - Typical values of transient electric and magnetic fields produced by switching operations of disconnectors in open-air substations (reduced values compared to disconnectors are produced by circuit breakers operations)

Figure 3 shows the transient magnetic and electric fields due to the opening of a disconnector for a 500 kV GIS substation, measured on ground under the gas enclosure; near the gas/air bushing much higher values (up to 10 - 20 kV/m for the electric field) can be detected.

Comparing the results of this figure with those of the previous figure, which is related to open-air substations, the following main differences are confirmed:

- the dominating frequencies are substantially higher (usually 10 to 100 times);
- the peak amplitudes are lower;
- the damping of the transients is higher;
- the electric field approaches to zero after a short time.

The metallic enclosure, including its grounding, is probably the main reason for the reduction of fields, especially the electric field.

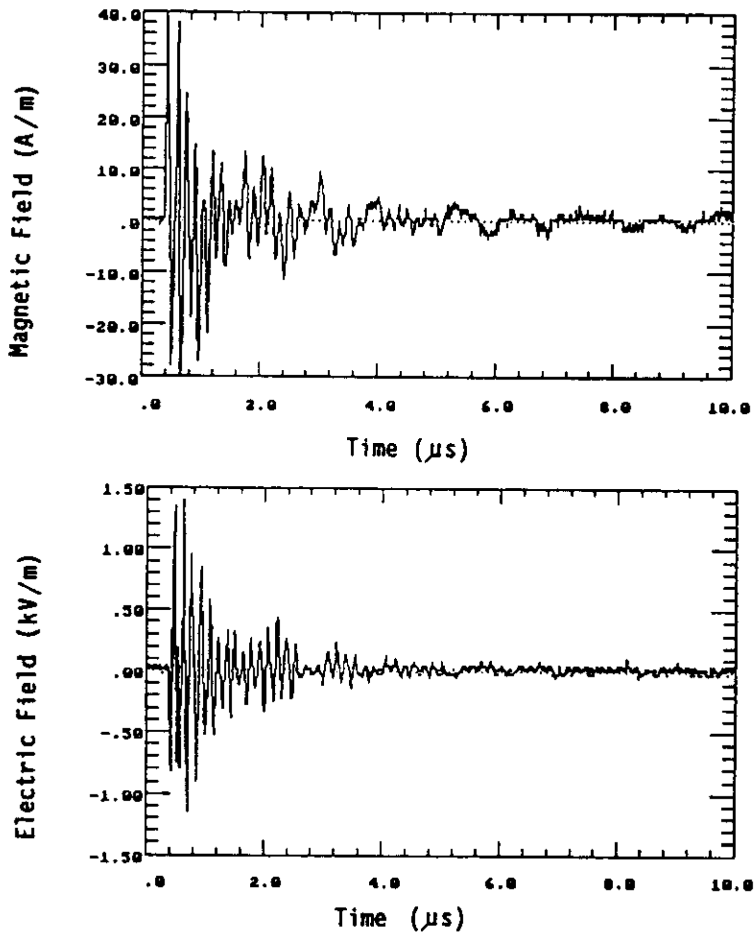


Figure 3 - Magnetic and electric field measurements from opening a disconnector in a 500 kV GIS [2]

Experience shows that higher levels of fields may be encountered in proximity of discontinuities, for instance at bushings or earthing connections. Therefore, particular care has to be taken for these discontinuities. [23]

3.3 Transient phenomena due to insulation breakdown, surge-diverter and spark-gap sparkovers in HV circuits

Insulation breakdown and spark-gap sparkover cause a rapid voltage collapse, which generates transients in a similar way to a reignition during a switching operation. The subsequent short circuit current in the earth grid of the electrical installation produces power frequency voltage rises.

The amplitude of the transients is roughly proportional to the breakdown voltage which may be much higher than the reignition voltage in a switch. The insulation breakdown voltage may be in the range 3 to 6 p.u. of the phase-to-ground peak voltage. Such situations are rare, but may cause very severe electromagnetic disturbances, especially when they occur relatively close to the receptor.

A spark-gap sparkover is generally less severe than an insulation breakdown because of a lower sparkover voltage and a less random location. The amplitude of the transients is, however, normally much higher than during a reignition in a switch.

The ignition of a surge arrester with spark-gap gives high frequency transients similar to an ordinary spark-gap. The amplitude of the transients is lower due to voltage across the arrester. The arrester prevents the development of a short-circuit current.

A gapless arrester does not generate high frequency transients because it exhibits a smooth transition from the non-conductive mode to the conductive one.

3.4 Power frequency electric and magnetic fields produced by HV installations

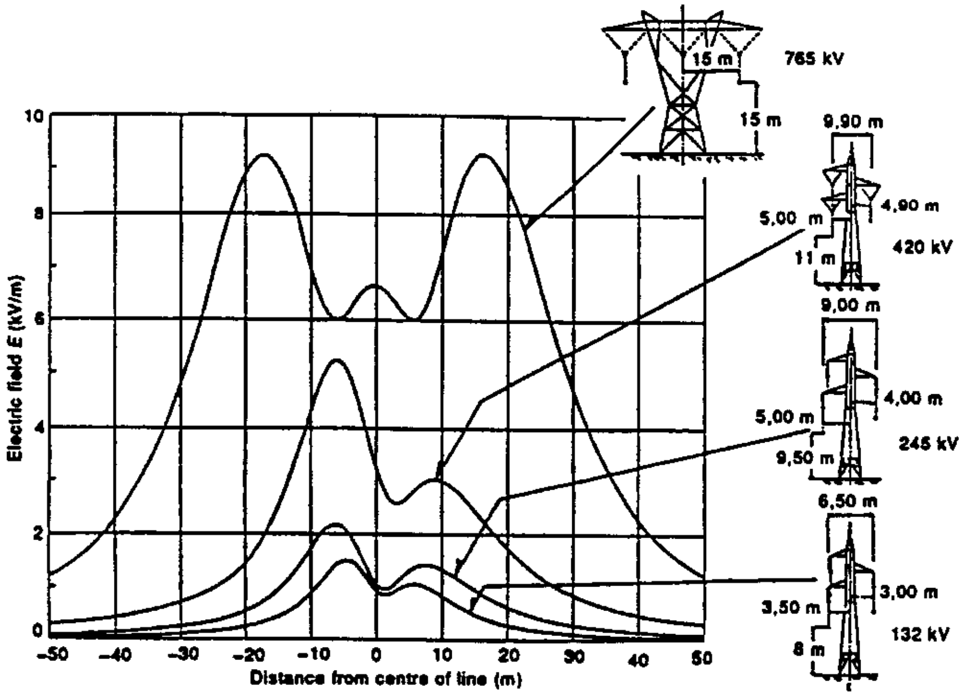
Power installations generate electric and magnetic fields in their surroundings at power and harmonic frequencies.

The level of these fields at a given point depends on the line voltage and the line current respectively, as well as on the line configuration (in particular the height of the conductors above the ground, the distances between phase conductors, the phase arrangement and the number of circuits).

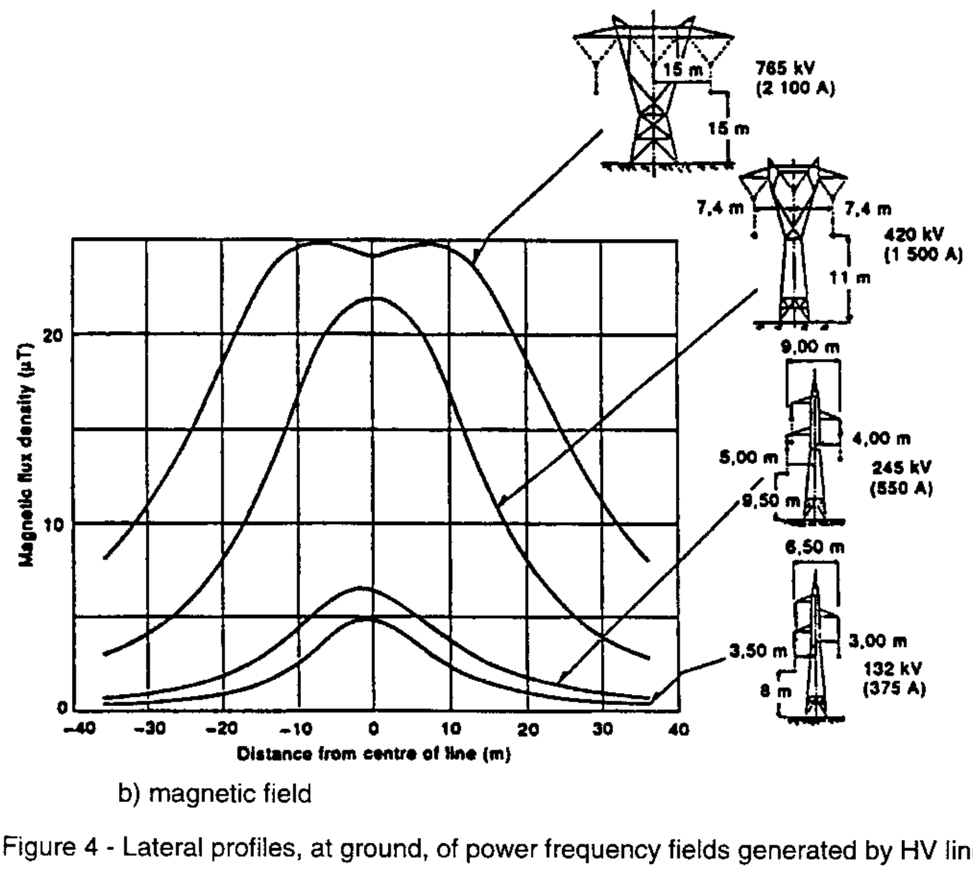
General criteria for calculation and measurement of the above fields are presented in the CIGRE GUIDE: "Electric and magnetic fields produced by transmission systems" prepared by Working Group 36.01, [3].

Figure 4 shows, as an example, the results of calculations [3] of the lateral profiles, at a mid-span cross-section, of the electric and magnetic fields generated by HV lines of average characteristics in normal loading conditions. Due to the conductor sag, considerably lower values are generated in other cross-sections of the line.

Measurements of power frequency electric and magnetic fields under power lines are generally in good agreement with calculations, as a results of the relatively simple configuration of power lines.



a) vertical components of the electric field



b) magnetic field

Figure 4 - Lateral profiles, at ground, of power frequency fields generated by HV lines

The magnetic fields are calculated with reference to the current indicated in brackets. For different values of currents, the values of fields are obtained proportionally.

On the other hand the calculation of electric and magnetic fields in power stations and substations requires sophisticated methods due to the great complexity of the layout of these installations. An example of such methods is given in [4], from which figure 5, related to the mapping of the 50 Hz magnetic field, is taken.

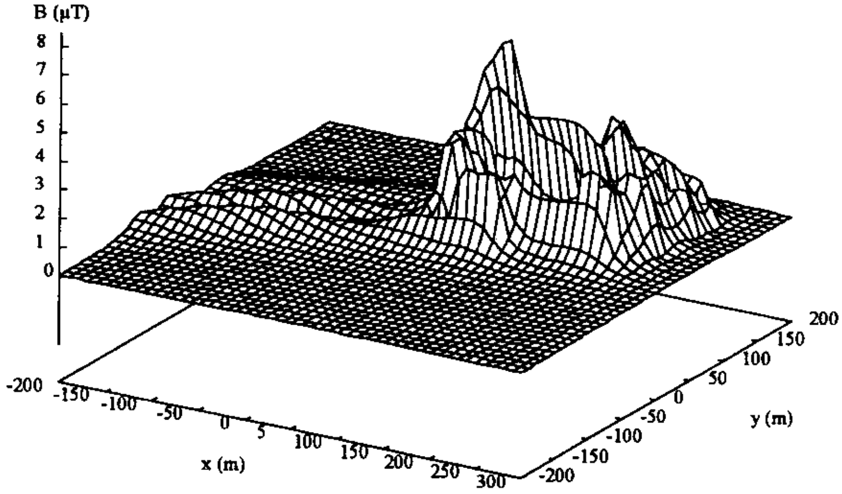


Figure 5 - Mapping of the of 50 Hz magnetic field calculated for a substation

Practical results are obtained from measurements. Figure 6 shows, as an example, the results related to a 130/380 kV substation. [5]

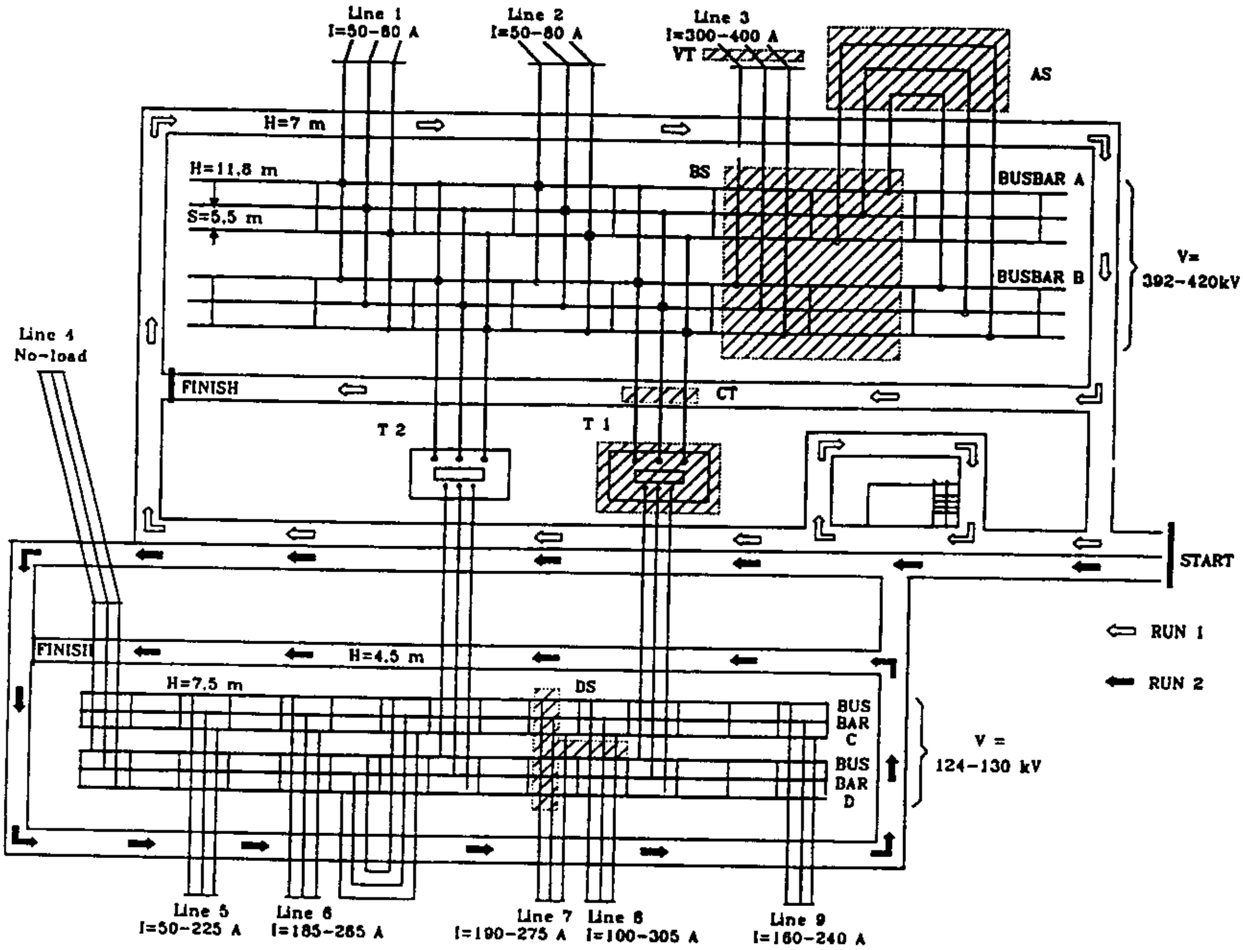


Figure 6a - Measurements of power frequency electric and magnetic fields in a 130/380 kV substation: layout of the substation

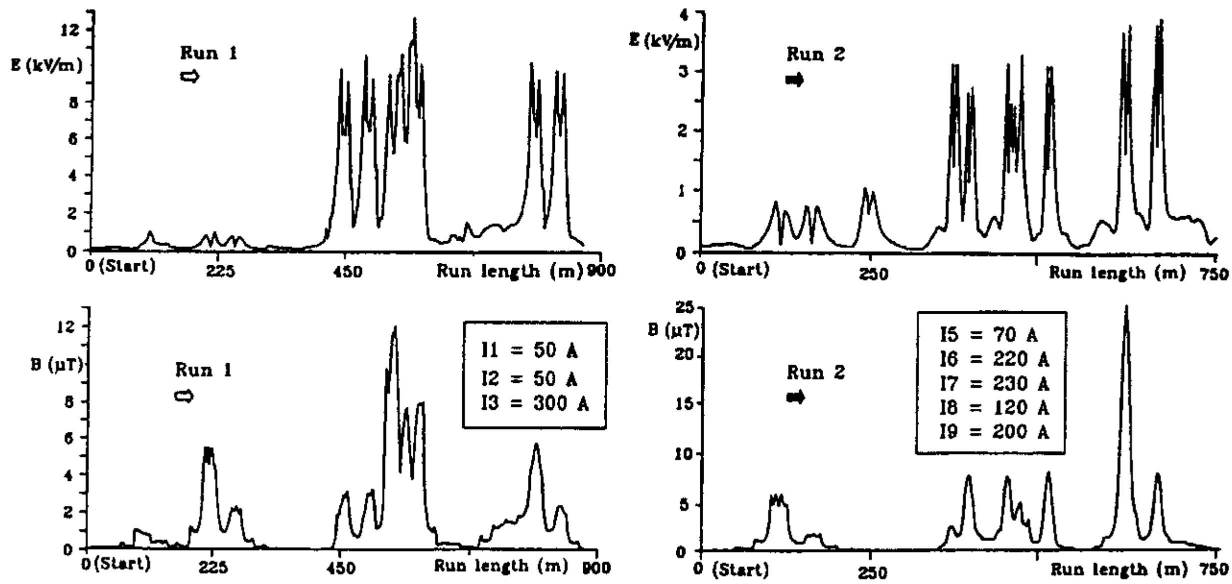


Figure 6b - Measurements of power frequency electric and magnetic fields in a 130/380 kV substation: profiles of the fields along RUN 1 and RUN 2 of figure 6a

3.5 Voltage rises due to lightning and short-circuit currents in earthing systems

Lightning and short-circuit currents flowing in the earthing system conductors may give rise to voltages that can be dangerous for automation and control systems. In particular, transient potential differences between different points of the earthing system may represent a relevant source of disturbances in case of distributed electronic equipment (see subclause 5.5.4.2).

Two different periods may be considered during the phenomena: a transient period at the beginning, which is characterised by fast transients and is usually of very short duration (in the range of microseconds), and a subsequent stationary period, characterised by nearly d.c. or power frequency excitation.

3.5.1 Transient voltages in earthing systems

As an example, figure 7 shows a 3D view of the computed voltage rise distribution on the grounding grid conductors subjected to a typical 1,2/50 µs lightning surge having an amplitude of 1 kA. [19]

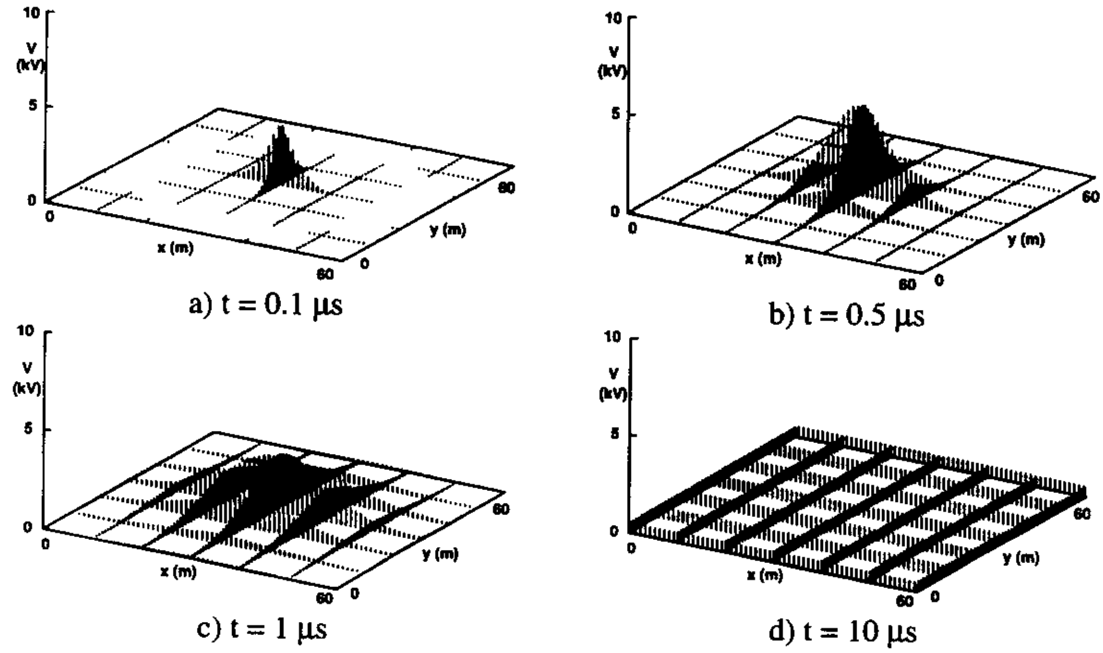


Figure 7 - Transient voltage rise on the conductors of a 60 x 60 m^2 earthing grid when a 1,2/50 μs current impulse with amplitude 1 kA is injected in the middle point

Figure 7 shows that the voltage distribution during the transient is highly irregular. After the transient period (about 10 μs) a uniform voltage distribution is reached that is typical for a d.c. excitation.

Transient voltages at different points of the earthing conductors are impulses with largest peak values near the feed point. Such peak values are several times higher than during the stationary period.

Transient voltage peak values are generally higher for less conductive soil, steeper current impulses and feed point near the edge of the grid.

3.5.2 Voltage rises due to power frequency short-circuit currents in earthing systems

Power frequency short circuit currents subsequent to fast transients due to different types of faults in power lines and substations (see clause 3.2) can circulate for a few tenths of a second in the earthing systems of power installations.

These short circuit currents can reach values up to 50 kA. They depend on the power network structure (degree of interconnections of branches), on the distance between the fault and the earthing system, and on the fault level.

The circulation of current in the earthing system produces potential differences between two different points of the earthing system. The value of the potential gradient is essentially dependent on the earth resistivity and on the configuration of the earthing system.

Power or signal cables connecting electronic devices can therefore be subjected to severe voltage and current stresses.

In the past, the evaluation of potential differences arising in an earthing system was essentially based on scaled analogue models like electrolytic tank.

Subsequently, sophisticated numerical codes, which take into account possible non-uniformities of the soil and possible non-linearity effects, have been developed by different researchers.

Figure 8 shows, as an example, a map of voltage rises on an earthing system and its vicinity.

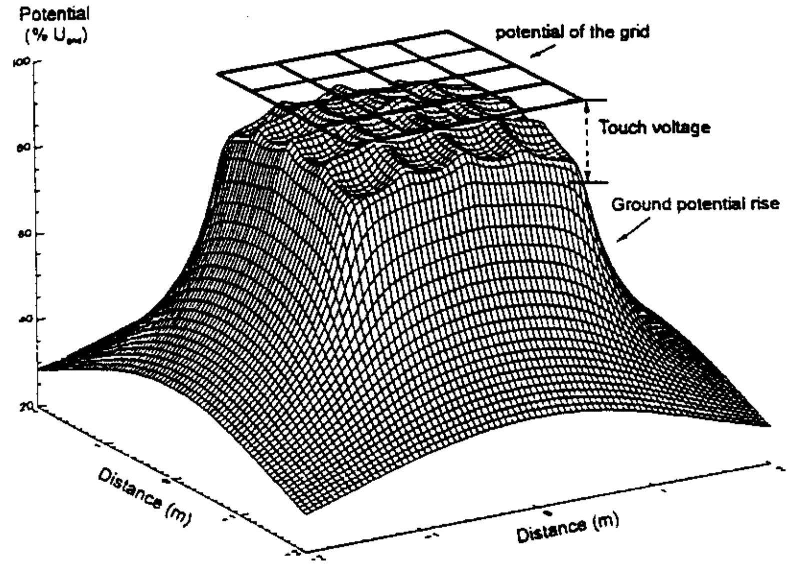


Figure 8 - Map of voltage rises on an earthing system and its vicinity

The typical values of the maximum voltage rises that can be expected in the earthing systems within the power installations can vary from one to ten V per kA of fault current.

The maximum potential rises measured far from the power plants can reach values up to a few tens of kV.

3.6 Electrical transient phenomena due to lightning

The characteristic parameters of the lightning current have been studied in depth by electrical engineers for many years due to their importance in insulation coordination.

At present, data related to fairly reliable measurements of the fundamental parameters of the lightning currents (amplitude, steepness, frequency of occurrence, etc.) are available for positive and negative strokes, and for each possible mechanism of lightning generation. [6], [7]

Referring to EMC in power installations, lightning may act mainly through the following three mechanisms:

1. direct effect to the equipment of the electromagnetic fields produced by the lightning current in proximity to, but not striking any structure of the installation;
2. direct lightning stroke to a structure of the electrical installations (e.g. power lines, earthing conductors, buildings and towers) and subsequent coupling between the currents in the structures and the equipment;
3. coupling of the electromagnetic field produced by lightning to a power line or a structure, and subsequent coupling between the current in the structure and the equipment.

For power lines, mechanisms 2 and 3 simply differ with regards to the wave shape and amplitude of the resulting transient on the structure. The wave propagation along the structure and the subsequent coupling between structure and equipment are similar.

3.6.1 Direct effect of radiation from lightning

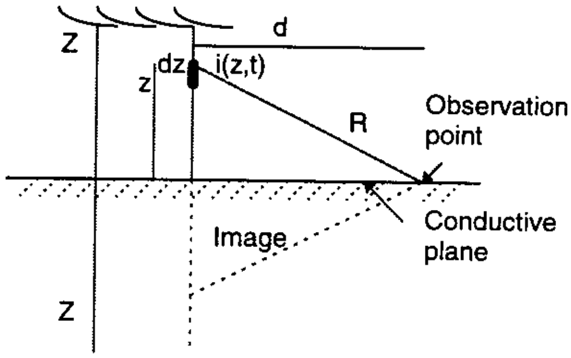
This phenomenon, related to mechanism 1, has been mainly investigated with respect to the return stroke current to ground which is characterised by the highest energy content.

Models have been implemented [7] with different assumptions of the channel current distribution.

The formulae for the calculation of electric and magnetic fields observed at ground level at different distances produced by lightning currents, according to [7], are given in figure 9.

Using the Maxwell equations applied to the vertical lightning channel, electric and magnetic fields are calculated at ground level at a distance d from the vertical channel, assuming as starting conditions that the lightning channel is a straight vertical antenna of height Z, the ground plane is perfectly conductive, and the radius of the lightning channel cross section is very small compared to the minimum typical wavelength of the phenomenon.

The formula includes the value of i(z,t), which is the lightning current, of ε_0 and μ_0, which are the permittivity and the permeability of the free space, and c, which is the speed of the light in free space. Different models have been developed to calculate i(z,t) starting from measured values of the lightning current at the channel-base [7]. Therefore today it is possible to determine the electromagnetic field components with adequate precision for engineering applications.



$$E_z(d,t)=\frac{1}{2\pi\varepsilon_0}\left[\int_0^Z\frac{(2z^2-d^2)}{R^5}\int_0^t i(z,\tau-R/c)d\tau dz+\int_0^Z\frac{(2z^2-d^2)}{cR^4}i(z,t-R/c)dz-\int_0^Z\frac{d^2}{c^2R^3}\left[\frac{\partial i(z,t-R/c)}{\partial t}\right]dz\right]$$

$$B\phi(d,t)=\frac{\mu_0}{4\pi}\left[\int_0^Z\frac{d}{R^3}i(z,t-R/c)dz+\int_0^Z\frac{d}{cR^2}\left[\frac{\partial i(z,t-R/c)}{\partial t}\right]dz\right]$$

Figure 9 - Geometrical factors and formulae for the evaluation of the vertical electric and horizontal magnetic fields from the lightning stroke current [7]

Figure 10, extracted from [8], shows typical measurements, taken simultaneously, of electric and magnetic fields at distances 5 and 50 km from first and subsequent return strokes.

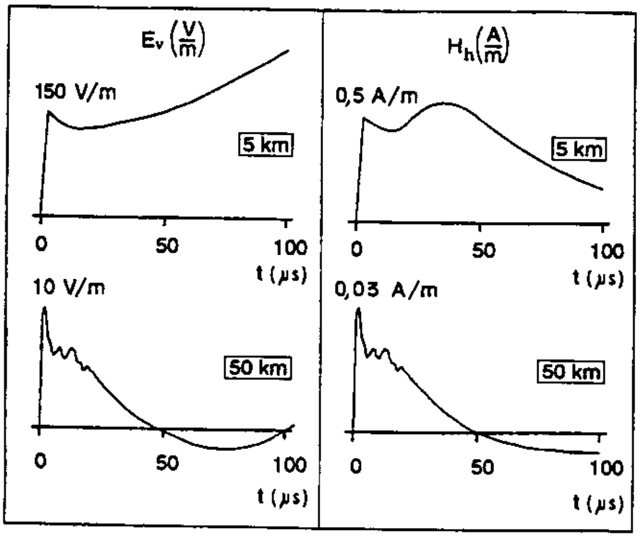


Figure 10 - Typical vertical electric field component E_v and horizontal component of the magnetic field H_h measured 5 km and 50 km from the return stroke current

On the basis of the above mentioned investigations, electric and magnetic fields due to a lightning stroke have the following main characteristics:

- the vertical electric field component E_v and the horizontal magnetic field component H_h prevail with respect to the horizontal component E_h and the vertical component H_v respectively by about a decade or more.
- both vertical electric field component E_v and horizontal magnetic field component H_h present a very steep initial ramp followed by far less steep ramps or bumps (see figure 10).
  The initial ramp of these components has the same steepness and corresponds to the "radiated component" of the field and attenuates with the inverse of the distance (1/d).
  The following ramps or bumps correspond to the "capacitive or inductive component" of the field and attenuate much more quickly ($1/d^3$, $1/d^2$ respectively). As a consequence, at sufficient distances, of the order of some tens of km, the radiated component prevails and the vertical electric field component E_v and the horizontal magnetic field component H_h become interdependent through the surge impedance of free space, 377 Ω (E/H = 120 π Ω).
- the maximum steepness of the initial ramp of the electric field, S_{Em}, is a very important parameter from the EMC point of view. It is proportional to the maximum steepness of the return stroke current S_{Im} = (dI/dt)max:

  $$S_{Em} = [v/(2\pi \varepsilon_0 c^2)]\, S_{Im}/d \qquad [V, A, m, s]$$

  where c is the speed of the light, v is the speed of the return stroke current (0,2c to 0,6c), ε_0 is the permittivity of the air and d is the distance from the lightning channel.
  Values of S_{Im} up to about 300 kA/µs have recently been measured for triggered strokes [10]. The values reported in older widely known CIGRE documents [11] were most probably truncated to 100 kA/µs, due to the frequency response of the measuring instruments.
  Values of steepness near to the maximum one, S_{Em}, may last for few hundreds of ns.

An exhaustive survey of the state of the art of the electromagnetic effects of the lightning is in [24].

Fields not related to the return stroke current, e.g. inter-cloud discharges, generally generate EM fields much lower than those due to ground return strokes. The fields encountered in the proximity of the inter-cloud discharges are comparable to those at about 10 km distance from the return stroke to ground [6]. For these reasons they are of a certain importance only for aeronautical navigation.

Other than the return stroke current or intercloud discharges, recombination of charges or dart leaders seem to be able to generate EM fields in the VHF-UHF range of frequency.

Figure 11 illustrates the curve of Pierce [9], which gives a summary, in the frequency domain, of the measured electric fields due to all the above mentioned lightning activity components.
The curve shows the electric fields in the frequency range 1 kHz to 1 MHz, which are related to return stroke currents, and the fields in the VHF-UHF range (from some tens of MHz to GHz), which are probably due to recombination of charges or dart leaders.

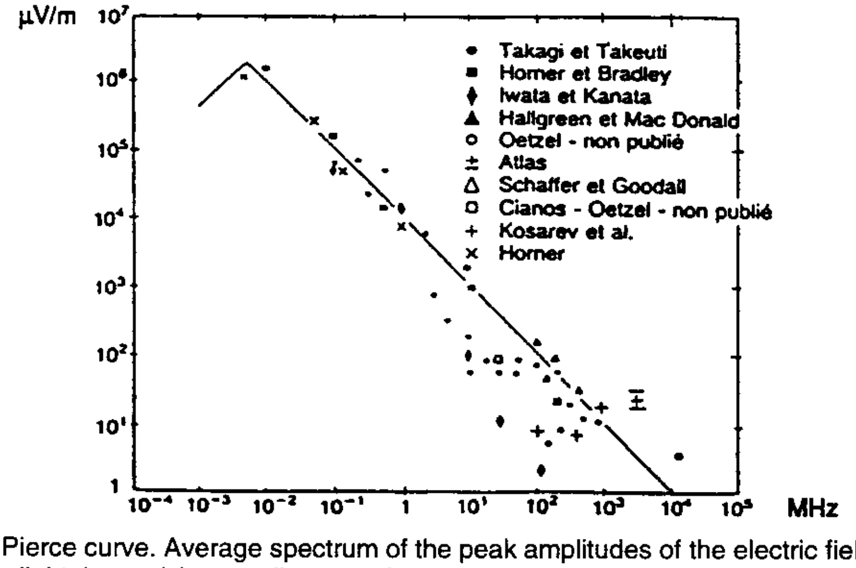


Figure 11 - Pierce curve. Average spectrum of the peak amplitudes of the electric field radiated by a lightning activity at a distance of 10 km and measured with a 1 kHz bandpass filter

3.6.2 Direct stroke to power lines or other structures in electrical installations

3.6.2.1 Direct stroke to a power line

The effect of such an event is a travelling wave that propagates along the line. The direct radiation from the return current channel has some influence only on the withstand behaviour of the insulation at the point where the line is struck, but not on the propagation of the wave along the line.

In the case of a lightning stroke direct to the phase conductors, the voltage wave has a front and a tail interdependent through the shape of the lightning stroke current.

The rise time of the shape may be very short, with a time to crest down to a fraction of µs, and may have a maximum slope up to about 50 MV/µs because:

$$V_{max\ slope} = S_{Im}\ Z_c/2$$

where Z_c is the line surge impedance. The tail has a time to half value of the order of some tens of µs.

In the case of back flashovers, with lightning strokes to the tower or to the earth wire and subsequent insulation breakdown towards the phase conductor, the front of the voltage wave is of the order of several tens of ns (up to few hundreds of ns for large gaps) and the tail has a duration lower than for direct strokes to the phase conductor, around 5 µs to 15 µs.

In both cases, the slope S of the part of the front above the impulse corona inception voltage U_0 is quickly damped by corona, resulting in a lower slope S_d after a certain distance d. For practical purposes, S_d may be calculated from S by means of the following formula:

$$S_d = \frac{S}{1 + A \cdot d \cdot S} \qquad \text{[S in kV/µs, d in m]}$$

where A, the distortion parameter, is about 10^{-6} µs/kV/m and depends on the inception voltage U_0 and on the geometrical lay-out of the line conductors.

The effect of corona distortion is very important. At a distance of about 1 km or a little more, regard less of the shape of the wave at the struck point, the slope of the front will be less than 1 MV/µs.

Much more critical, from the EMC point of view, is a breakdown of the line insulation. It introduces a sharp truncation, generally on the tail of the wave, of the order of several tens to a few hundreds of ns.

The slope of the truncation is not affected by corona distortion and only the dissipative effects due to the line resistance and conductance will contribute to its damping, so that it remains almost unchanged for a long distance.

As a consequence, the tail truncations, due to insulation breakdown, produce higher stresses to the equipment connected to line terminals (as, for instance, the secondary windings of current transformers), than the fronts of the waves.

3.6.2.2 Direct stroke to a structure

The calculation of the effects of lightning directly striking a structure (a building, the wires of the lightning protection system or the earth wires of an open air substation) is generally made disregarding the HF radiation of the return stroke current.

In this situation, the impulse current distribution along various paths of the structure play the dominant role, from the EMC point of view, with respect to equipment inside or in the proximity of the structure.

The following two main interference mechanisms can be distinguished:

a) low frequency mechanism, strictly related to the voltage potential rises of the grounding system and directly related to the lightning current amplitude;

b) high frequency mechanism, mainly related to the spatial disposition of the structure (and of secondary importance to its grounding) and directly related to the slope of the lightning current.

Some recent publications [6] suggest the idea that the mechanism b) could be of great effect immediately after the final jump, that is the time when a very abrupt neutralisation current wave occurs. However, the present knowledge around the fundamental parameters of such a phenomenon, for instance the collapse time, is quite limited.

In addition, in the practical cases of interest, the direct stroke to a structure can be considered a quasi-stationary phenomenon. For these reasons, a circuit approach seems to be appropriate to simulate practical cases, especially when the structure can be reasonably approximated by a set of interconnected conductive branches. Therefore, the classical circuit approach offers an easy tool to evaluate the impulse current distribution.

A model based on the circuit approach was set up and laboratory tests on reduced scale structures were carried out to validate the method. [12]

To simplify the analysis of the circuits, the circuit parameters related to "partial" inductances have been adopted as indicated in Appendix 3.14.

The analysis is carried out in the frequency domain, then the effects due to each frequency are added.

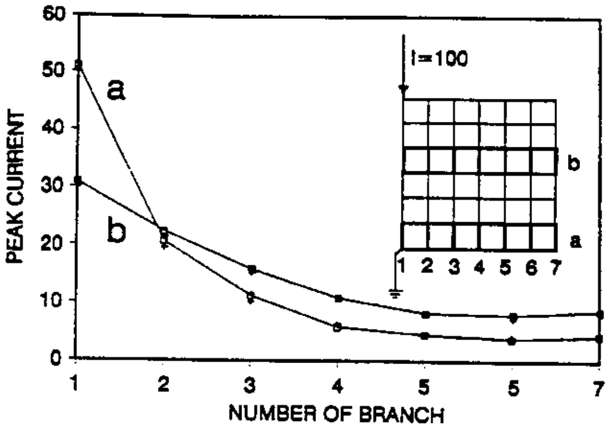
The main features of the model are reported herein after.

- The interference to victim circuits or equipment are evaluated by considering them directly as part of the network, obtaining in this way the voltages and currents induced on such elements. With such an approach the problems of wave propagation along the structure can also be handled, if the structure is sufficiently well discretized and if stray capacitances are suitably included in the model.
- The computer model calculates and represents simultaneously all the mutual interactions of the currents flowing in the various branches of the structure. The branch resistances are calculated taking into account the skin effect. Lumped resistances, inductances and capacitances (RLC branches) can be introduced between any consecutive nodes. If the distances between branches are large enough with respect to the lengths of the branches, the mutual inductance may be neglected.
- The presence of the ground is taken into account by introducing the images of the conductors at a certain depth in the ground as a function of the frequency and of the earth resistivity.

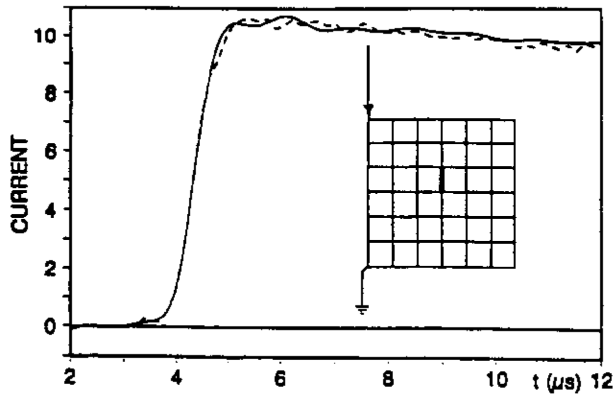
The results of the laboratory tests [12], which are in good agreement with the calculated data, are reported in the figure 12.

For the cases where the propagation phenomena are of great importance, more sophisticated approaches based on line theory are being developed by various researchers, taking into account:

- distributed self and mutual inductances and capacitances of the various sections of the structure;
- high frequency simulation of the ground according to the Carson approach or other more recent theories (D'Amore and Sarto).



Amplitudes of the current along the branches **a** and **b**.
+ measured values
□ calculated values



Waveshape of the current in a branch.
---- measured values
— calculated values

Figure 12 - Results of laboratory measurements and calculation of the lightning current (1,2/50 µs waveshape) in the branches of a structure made of a net of thin copper wires (1 mm diameter, 500 mm spacing)

3.6.3 Radiation to power lines or structures and subsequent coupling to the equipment

This mechanism is of great importance for MV and LV distribution lines (conducted disturbances affecting LV networks, like voltage dips and short interruptions, are originated by MV line faults due to induced lightning overvoltages) and far less important for high voltage lines.

The result of this coupling is a voltage-current wave that travels along the line in a similar manner to those generated by direct lightning strokes on high voltage lines.

The wave amplitude strongly depends on the distance between the lightning stroke and the line. It increases with the height of the line while a significant screening is offered by earth wires, if present.

In MV and LV lines, the overvoltage amplitude very often exceeds the insulation withstand level, thus producing breakdown and consequent wave truncation.

In the section of the line close to the struck point, the front of the voltage wave is similar to that generated by direct strokes, while the tail duration is essentially shorter, around 5 µs to 10 µs. The comments on corona distortion and insulation breakdown discussed for the case of direct stroke to the line conductors or back flashovers are then applicable in the same way.

In case of structure of relatively short dimensions, the electromagnetic energy collected by the structure is lower than that by the power lines; the consequent disturbance transferred by the structure to connected or nearby equipment results in lower stresses than those by direct radiation from the lightning if the equipment is properly connected to the ground. In this case the structure acts as a screen against the radiated field.

3.7 Electrical fast transients due to switching operations in low voltage equipment

When switches are used to interrupt inductive loads such as solenoids or motors, an undesired phenomenon called showering arc can develop between the contacts of the switch. This phenomenon produces electrical fast transients which are characterised by a short rise time, a short duration, a low energy and a high frequency rate. [20]

Figure 13 shows the model used to explain the mechanism of generation of a showering arc. In the circuit, which includes a switch and an inductive load, the parasitic capacitance is placed in parallel with the inductive load.

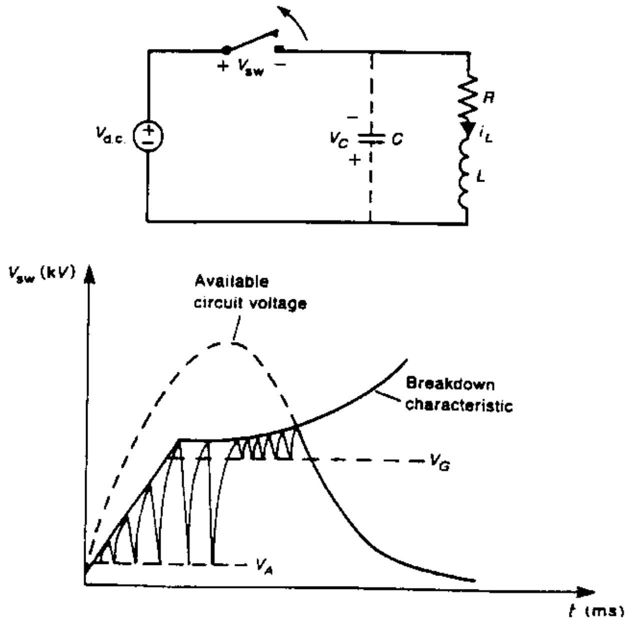


Figure 13 - Model of generation and waveshape of a showering arc for an inductive load

When the switch is closed, a steady-state current $I = V_{dc}/R$ is established in the inductor. When the switch opens, the inductor attempts to maintain this current. This current is therefore diverted through the capacitance, charging the latter and increasing the switch voltage.

As the switch voltage increases it may exceed the switch breakdown voltage. In this case a short arc is generated and the switch drops to V_A. The capacitor begins to recharge again.
This leads to a sequence consisting of rising (as the capacitor charges) and rapidly falling (as the switch breaks down) voltages across the contacts, which has been referred to as a showering arc:

- after charging the capacitor, it discharges through the switch, with the current being primarily limited by the local resistance and inductance of the switch wiring;
- if the switch current continues to exceed the minimum arc-sustaining current I_A (from 0,1 A to 1 A), the arc is sustained. If not, the arc extinguishes and the capacitor begins to recharge;
- the switch once again exceeds the switch breakdown voltage, and the switch voltage drops to V_A (whose value is about 12 V for air contacts). If arc is not sustainable, the capacitor begins to recharge once again;
- eventually, the energy stored initially is dissipated and the capacitor voltage decays to zero.

In addition figure 13 shows that, as the contact separation increases, a glow discharge may also develop and may or may not be sustainable (for contacts in air V_G = 280 V; I_G varies from 1 mA to 100 mA) resulting in miniature showering arcs.

Showering arcs have significant spectral content and may therefore create EMC problems. To reduce their formation it is necessary to prevent the switch voltage from exceeding the breakdown voltage or to insure that the arc current is below the minimum arc-sustaining current. As shown in figure 14, a sufficiently large capacitor placed in parallel to the inductor reduces the switch voltage and also the initial rise of the voltage.

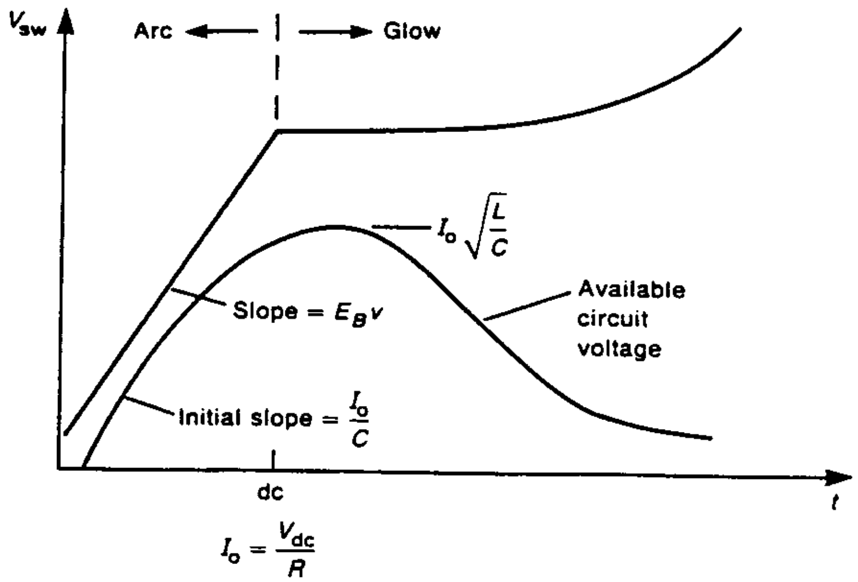


Figure 14 - Contact protection by reducing the circuit available voltage

Referring to the mechanism of generation of the switching transients, the typical parameters are:

- burst duration, mainly determined by the energy stored in the inductance prior to switching;
- repetition rate of singular transients;
- varying amplitude of the transients composing a burst.

Both the repetition rate and the amplitude are mainly determined by the mechanical and electrical characteristics of the switching contacts (speed of the contacts in opening operation, voltage withstanding of the contacts in their open condition).

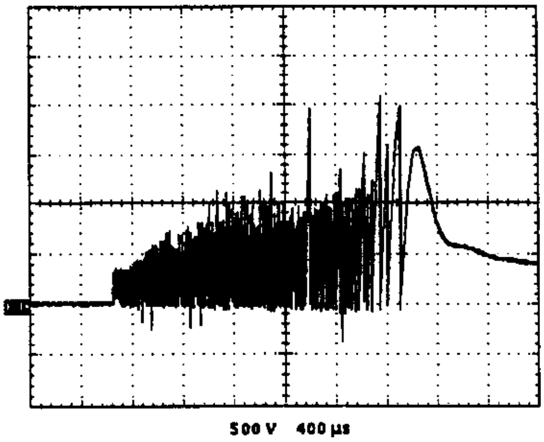
Measurements have been carried out in different laboratories to characterise the typical parameters of the electrical fast transients/burst impulse.
One example is the investigation involving a switched load represented by a relay coil with inductance 160 H, resistance 6 kΩ, about 26 ms time constant, controlled by a switching relay.

Table 2 shows the results of the measurements made directly on the switching contacts. Different bursts were obtained by changing the relay used for switching the inductive load. The switching relays were chosen with different rated currents (1 A, 5 A, 7 A or 10 A) but at the same voltage (250 V); two of them were mercury relays. The range specified for some parameters is related to measurements made around the first part of the burst, which contains high frequency and short duration spikes, and repeated also around the end of the burst, where the lowest frequency and spike duration are recorded. The rise time of the spikes was generally in the order of a few ns.

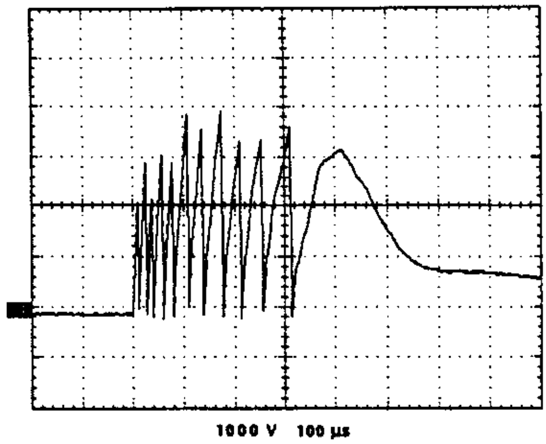
	SWITCHING RELAYS					
PARAMETERS	Mercury A 1 A	Mercury B 1 A	1 A	5 A	7 A	10 A
Spike repetition frequency range (kHz)	70 17	46 12	1700 11	470 12	700 12	1000 9
Range of spike duration (μs)	9 35	10 39	0,35 50	0,28 50	0,7 46	0,3 70
Burst duration (ms)	0,3	0,2	2,5	2	2,4	2,4
Range of spike amplitude (kV)	1,9 4,2	1,8 5,2	0,3 2,4	0,1 2,0	0,2 2,5	0,1 2,2

Table 2 - Parameters of electrical fast transients generated by different switching relays

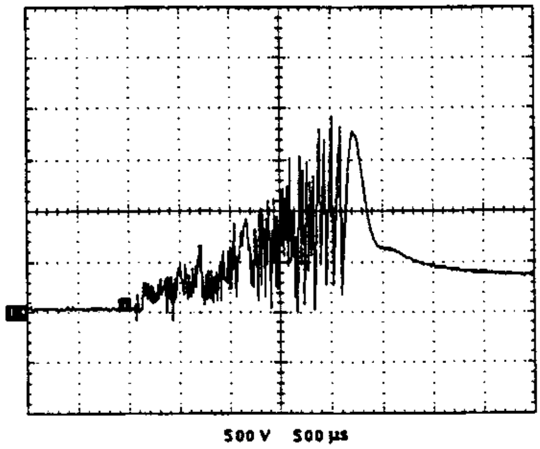
Some examples of bursts are reported in figure 15.



10 A switching relay



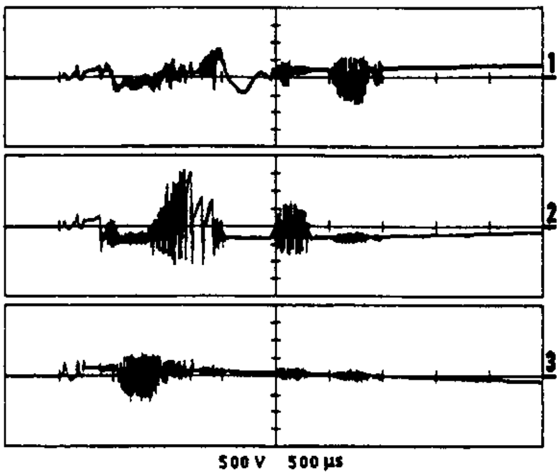
1 A (mercury) relay



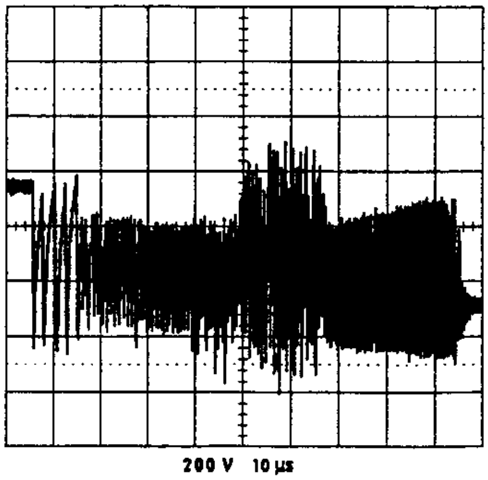
5 A switching relay

Figure 15 - Examples of bursts produced by different relays

Electrical fast transients are also generated by contactors. In particular, in the case of three-phase devices, the whole transient consists of a sequence of bursts generated by multiple switching phenomena, as shown in figure 16. The transient reported is an example (the phenomenon is very non-repeatable) generated by a contactor switching a 380 V a.c. motor of several kW.



Profile of the whole switching phenomena



Detail of the fast transient on a phase

Figure 16 - Example of burst produced by a contactor switching a motor of some kW

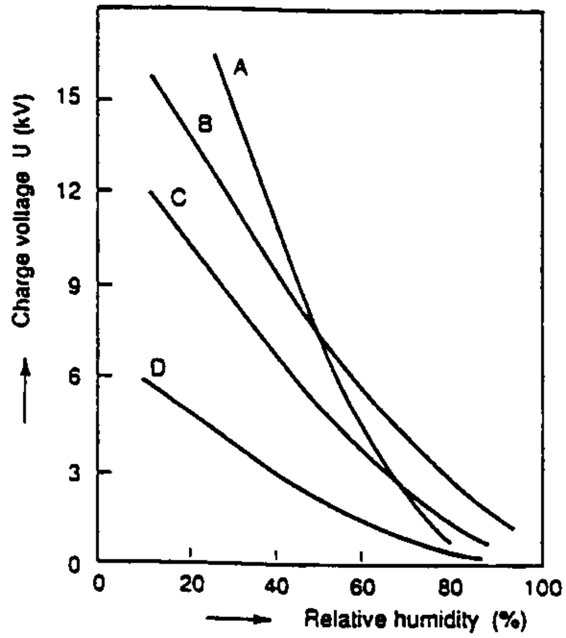
3.8 Electrostatic discharges

The charging phenomenon of a person is usually of the triboelectric type, in which the charge originates by friction between two materials, one of which is non-conducting (plastic, synthetic materials). [21]

The charge is affected by the following factors:

- the relative humidity of the air because the charge is conducted away more quickly when the relative humidity is higher;
- the insulation resistance of the dielectric such as soles of shoes, carpets, clothing, wheels and so on;
- the dielectric constant of the insulating material;
- the capacitance of a person or piece of furniture relative to the reference earth;
- rhythmic movement while walking;
- skin resistance (perspiration by the person concerned);
- surface pressure between two materials.

Depending on the environment, such charging can build up substantial potentials (10-25 kV) with stored energies of a few mJ. Figure 17 gives examples of the charging voltage of a person as a function of the relative humidity.



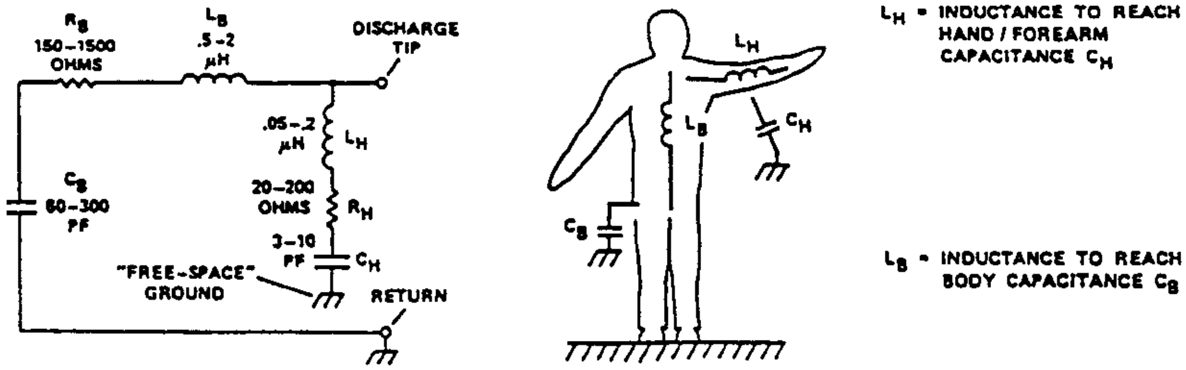
A: walking across a rubber mat for a distance of 6 m;
B: lifting a plastic bag off a workbench;
C: walking across a vinyl floor for a distance of 6 m;
D: standing up from a sitting position.

Figure 17 - Examples of charging voltage as a function of the relative humidity [22]

The discharging of this energy can produce fast rising current pulses (rise time from hundreds of ps to a few ns) that can reach amplitude values of several tens of A and have a duration of a hundred ns, depending on the voltage level and the circuit parameters.

In the charging process the human body behaves as a capacitor of capacitance C_B of about 100 pF to 200 pF. If the charged person alters posture, this will change the capacitance to the surroundings and hence also the charge voltage U. For example, when the person gets up out of a chair, C is reduced, and therefore U is increased. From the values of U reported in figure 17, it follows that the stored energy may quite exceed 1 mJ. For the discharge it is usually assumed that the human body has an internal resistance of between 150 Ω and 1500 Ω.

A model of the discharge circuit is possible, based on the simplified circuit lay-out reported in the following. The model is based on the separation of the contributions due to the human body (R_B, L_B, C_B) and the hand/forearm (R_H, L_H, C_H) as shown in figure 18. As a consequence, hand/forearm R-L-C path generates the typical sharp initial spike.



THE DUAL-RLC™ MODEL FOR ESD PROPERLY SIMULATES THE INITIAL SPIKE

REAL-WORLD HUMAN-BODY ESD MODEL WITH RESISTANCES OMITTED FOR SIMPLICITY

Figure 18 - Computer simulation based on the human-body ESD model [21]

ESD is an extremely fast phenomenon. In addition, it sometimes consists of a very fast "pre-pulse" on the leading edge of a "slow" pulse.

This is particularly clear in the figure 19, related to measurements of the discharge currents obtained from a tool held by an operator charged at 8 kV; the bandwidth of the measuring system was 1 GHz.

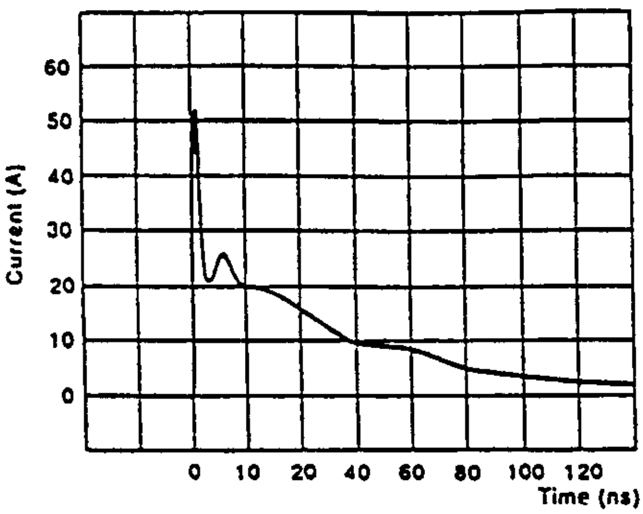


Figure 19 - Typical current discharge from an operator holding a metallic object (a key) in the hand

Fast pre-pulse occurs mainly with low charge voltages.

The presence or absence of the pre-pulse makes a large difference to the effect of the phenomenon when interference is involved.
Figure 20 shows the spectral density of the complete ESD pulse (pre-pulse and slow pulse). The steep initial spike clearly increases the spectral density at the high frequency end. The initial spike is important because most coupling mechanisms are of the high-pass type.

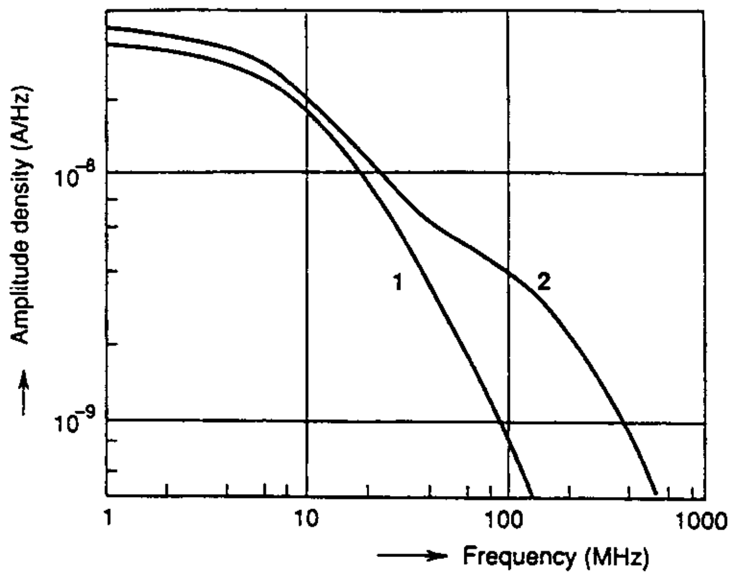


Figure 20 - Spectrum of a complete ESD discharge: "slow" pulse (1) and total pulse (2) [22]

With charge voltages at which corona effect is involved, the steepness of the discharge pulse is to a great extent determined by the speed with which the charged object approaches the discharge point. With a quick approach, the ejected ions do not have enough time to make the discharge path weakly conductive, so that the pulse is once again exceedingly steep.

3.9 High frequency fields produced by radio transmitters

Radio transmitters are classified as intentional emitters because they produce intentional signals in the electromagnetic environment. Examples of intentional radiated emission are broadcast radio transmitters, navigational aids and remote control devices.
Table 3 shows some information on authorised broadcast services with values of radiated power, typical transmitter/receiver distances in populated areas and calculated electric field strength.

The field strengths at typical distances are calculated for various applications. With the exception of the VLF range (0,014 - 0,5 MHz), the calculations have been performed according to the criteria applicable to far-field conditions.

Source	Frequency range (MHz)	Typical maximum ERP (W)	Typical minimum distances (m)	Related electric field * (V/m)
LF broadcast and maritime	0,014 - 0,5	$2,5\times10^6$	2×10^3	5,5
AM broadcast	0,2 - 1,6	800×10^3	500	12,5
HF amateur	1,8 - 30	1×10^3	10	22
HF communications including broadcasting	1,6 - 30	10×10^3	1×10^3	0,1
Citizens Band	27 - 28	12	10	2,5
Amateur VHF/UHF	50 - 52 144 - 146 432 - 438 1290 - 1300	8×10^3 8×10^3 8×10^3 8×10^3	10	65
Fixed and mobile communications	29 - 40 68 - 87 146 - 174 422 - 432 438 - 470 860 - 990	130 130 130 130 130 130	2	40
Portable telephones including cordless and cellular phones	900 - 1990	5	0,5	30
VHF TV	48 - 68 174 - 230	320×10^3 320×10^3	500	8
FM broadcast	88-108	100×10^3	250	9
UHF TV	470 - 853	500×10^3	500	10
Radar	1000 - 30000	10×10^6	200	110
walkie-talkies	27 - 1000	5	0,5	30

* Calculated electric field at typical minimum distances

Table 3 - Examples of Field Strengths from Authorised Transmitters

The values of the electric field included in table 3 (adapted from IEC 1000-2-3, 1992) are obtained as the maximum value of the expression:

$$E = k(ERP)^{0,5}\ r^{-1} \qquad (1)$$

where r is the minimum distance value (expressed in meters), ERP is the "Effective Radiated Power" (expressed in W) and k is a constant; for the sources in table 3 the adopted value of k is 7, except walkie-talkies where k = 3 (see IEC 1000-4-3).

In the model applied here, it was assumed that the transmitting antenna behaves as a half-wave dipole, is in the far field (the distance between the source and the point of observation of the field is greater than $\lambda/2\pi$, where λ is the wavelength of the field, and larger than the dimension of the source), and is in free space (E/H = 377 Ω).

In addition, values about radar for military applications are reported in table 3. The electric fields are calculated here for a minimum distance of 200 m because power plants or substations can be located near places where radar can be used (for example, near the sea).

Radiation can also occur from devices other than the transmitters listed in table 3, for example remote control devices, like garage-door openers and intrusion alarms. These devices operate in restricted frequency bands and have relatively low power output.

3.10 Radio frequency from electric or electronic equipment

In addition to the sources considered in the previous sections, other sources of HF disturbances (like motors, generators, power converters, lighting devices and electronic systems, etc.) are present in power installations.

The characterisation of these additional sources of radio frequency conducted and radiated disturbances can be made on the basis of the emission limits defined by proper product standards and CISPR publications. [15] [16] [17] [18]

3.11 Low frequency disturbances from the power network

Automation and control systems are generally supplied by dedicated power networks. In this case the assessment of the disturbances typical of the power supply can be made by considering the characteristics of the power supply systems. In addition, the effect of disturbing loads connected to the power network has to be taken into consideration.

In the case where electronic devices or systems are connected to the public network, the disturbances from the power supply can be established on the basis of standards related to the voltage quality (for example the series of IEC publications 1000-2).

3.12 Nuclear electromagnetic pulse

The term Nuclear ElectroMagnetic Pulse covers many categories of nuclear EMP, including those produced by surface bursts (SREMP - Source Region EMP) or created on space systems (SGEMP - System Generated EMP). A high altitude (above 30 km) nuclear burst (HEMP) produces three types of electromagnetic pulses which are observed on the earth's surface:

1. the early-time HEMP (fast pulse);
2. the intermediate-time HEMP (medium pulse);
3. the late-time magnetohydrodynamic HEMP (slow pulse).

The early time HEMP is related to the deflections of Compton electrons produced by X-rays, Γ-rays and neutrons interacting with the molecules of the air, as a result of a nuclear weapon detonating at high altitude as shown in figure 21. These electrons are deflected in a coherent manner by the earth's magnetic field, so that the transverse electron currents produce transverse electric fields which propagate down to the earth's surface.

The early-time HEMP is characterised by a large peak electric field (tens kV/m), a fast rise time (ns) a short pulse duration (up to about one hundred nanoseconds), and a wave impedance of 377 Ω.

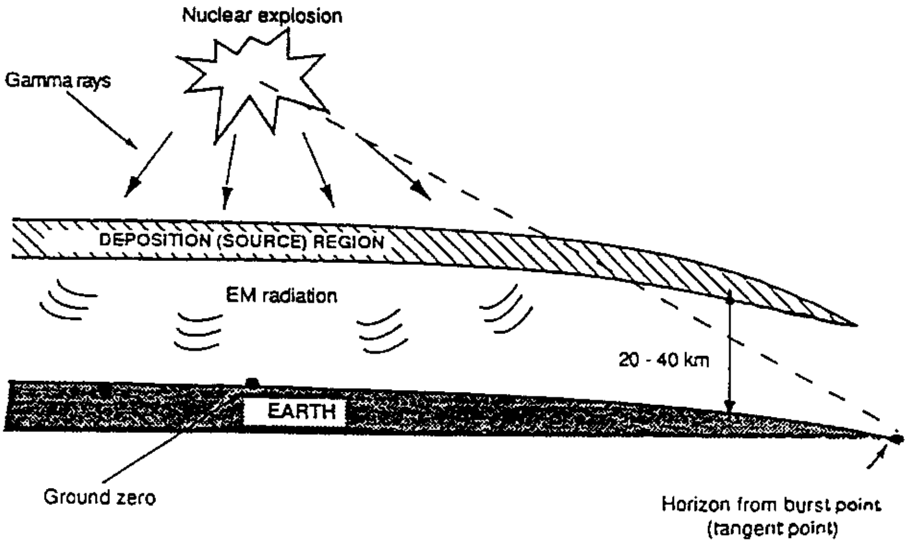


Figure 21 - Early-time HEMP from a high-altitude burst

Immediately following the initial fast HEMP transient, scattered gamma rays and gamma rays resulting from inelastic collisions from weapon neutrons create additional ionisation resulting in the second part (intermediate time) of the HEMP signal.

This second signal is of the order of 10 V/m to 100 V/m and can occur in a time interval from one to tens of ms.

The last type of HEMP, designated as magnetohydrodynamic HEMP (MHD-EMP), is generated from the same nuclear burst and is characterised by a low amplitude electric field of tens of mV/m, a slow rise time (s) and a long pulse duration (hundreds of s).

Figure 22, taken from IEC 1000-2-9 (1996), shows the time behaviour of all the three contributions to the HEMP, and the total electric field which is defined as:

$$E(t) = E_1(t) + E_2(t) + E_3(t)$$

where E_1 is the electric field of the early-time HEMP, E_2 is the electric field of the intermediate-time HEMP and E_3 is the MHD-HEMP.

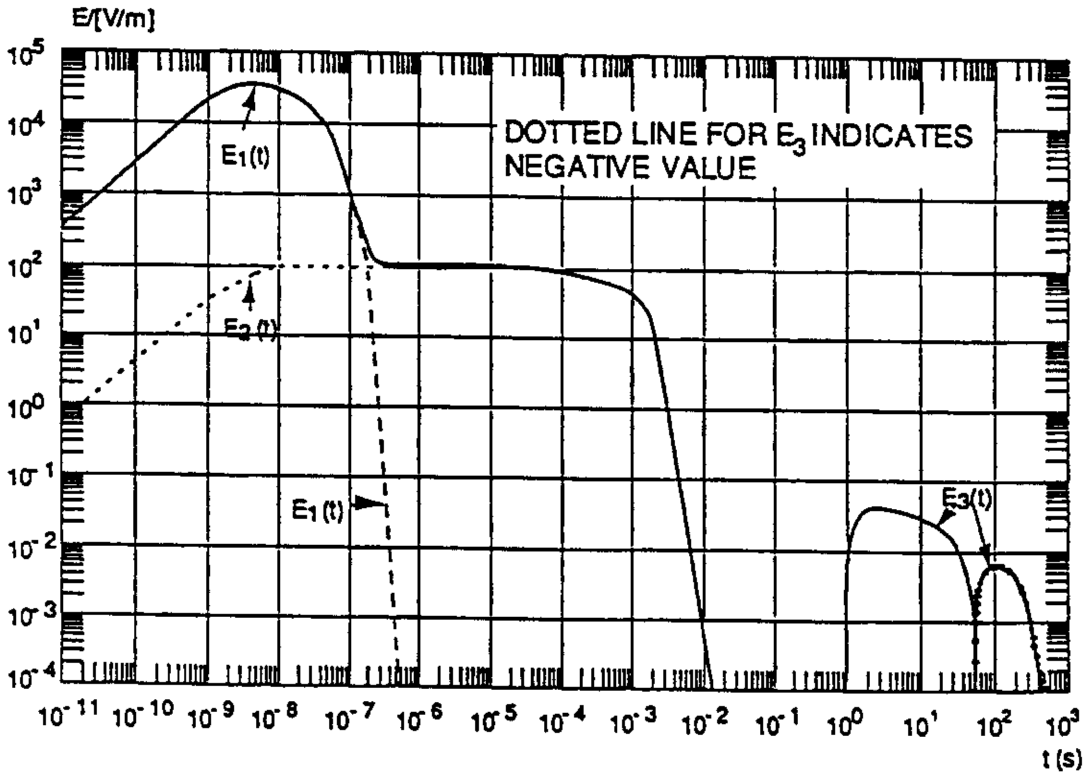


Figure 22 - Waveform of the complete HEMP

Two conditions must be present for HEMP to become a threat to power system component. They both relate to the coupling of the hemp pulses with power installations:

- transmissions lines must be sufficiently long to allow for large potential differences to develop between endpoints;
- a low d.c. ground impedance must exist at both ends of the transmission line to allow dc currents to flow (several hundred amperes, for example, can have saturation effects in a transformer core).

In particular, the MHD-HEMP has the right characteristics to interact with very long transmission lines to induce currents that result in harmonics and phase imbalances which can potentially damage major power system components (e.g. transformers). Fields caused by MHD-EMP cause similar induction effects as those associated with magnetic storms which are well-known in Nordic Countries and in telephone networks (telluric currents).

3.13 Geomagnetic interference

Geomagnetic induced currents (GICs) flow in power systems due to the variations in the earth's magnetic field ([13], [14]). The primary source of GIC is the sun.

Major disturbances in the sun emit enormous amounts of charged particles which are superimposed on the constant stream of charged particles from the sun (solar wind). Solar ejections are correlated, but not fully, with sunspot cycles. Occasionally, magnetic storms arise also due to "corona holes", which are leaking "punctures" at the sun's surface. In general, however, more ejections are taking place when sunspot activity is high and the peak ejections tend to come during the declining portion of the sunspot cycle.

As the charged particles emitted by the sun approach the earth (after a travel of about three days) they are deflected by the magnetic field of the earth. The interaction between the charged particles and the earth's magnetic field causes a circular particle motion in the ionosphere and magnetosphere around the magnetic poles. Currents flowing in the ionosphere and magnetosphere may therefore cause magnetic disturbances and storms with time scales of hours or less.

Statistically, the induced geoelectric field has its maximum in the geomagnetic west-east direction. The North pole of the earth-dipole is situated in Greenland and its location favours eastern parts of Asia and discriminates against north-east parts of North America.

In addition, the intensity of geomagnetic disturbances is highest at the auroral zones and usually during the night. The phenomenon, however, is highly stochastic and major exceptions in the regional and diurnal occurrence of the magnetic storms are possible.

GICs, which are basically quasi d.c. phenomena, (frequency range of some mHz), may have great amplitudes when the system is situated at auroral zones and when the earth resistivity is high.

In order for a high degree of coupling of GICs with power installations to occur, one of two conditions must be present:

- the earth resistivity is high;
- the system is connected to the earth with low resistances at two points at least. This is usually the case with solid or effectively earthed power systems where the long transmission lines are subjected to relatively high GICs (some tens of amperes per phase).

The main effects of GICs are:

- problems caused by power transformers which are deeply saturated when GICs flow to the transformers. As a consequence, the transformers can be thermally damaged, the voltages and the line currents are distorted and the reactive power flowing in the power transmission network is disturbed;
- due to the harmonics, even the control devices and protective relays may operate in an unwanted way. Also equipment with isolated neutrals may suffer due to harmonics.

In North America these kinds of problems have caused failures of transformers and once even a vast black out [13]. As an example, figure 23 shows an eastward electric field of 2 mV/m produced at 07.45 UT. This was responsible for the power outage on the Hydro-Quebec system. It is interesting to note that a larger magnitude magnetic variation three hours later produced a smaller electric field because of the slower variation of magnetic field. The later magnetic disturbances, and their associated electric fields, were also responsible for power system problems at a number of sites throughout North America.

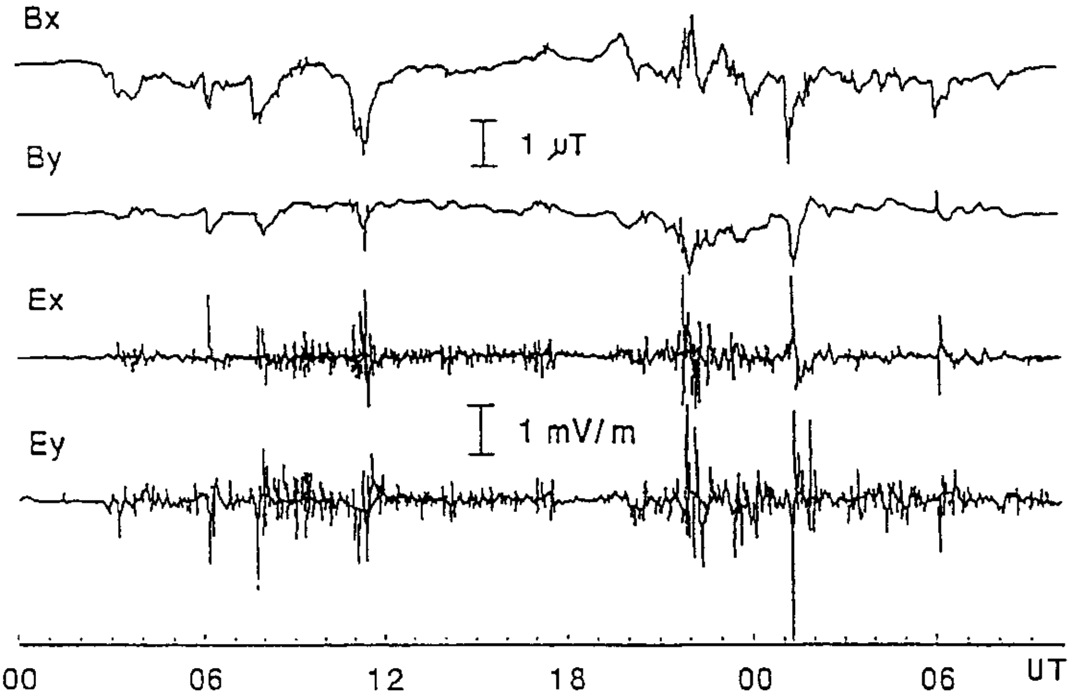
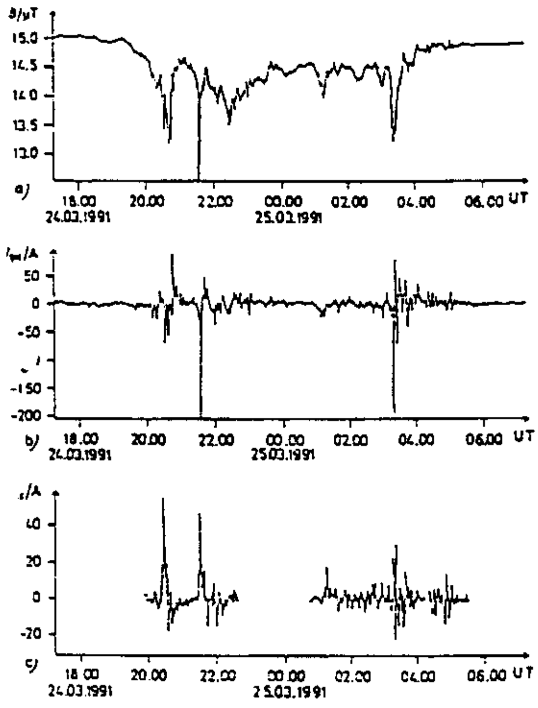


Figure 23 - Magnetic field recorded (Ottawa) and E fields calculated for Quebec [13]

Several unwanted line and transformer trip-outs have resulted in the Nordic power system.

An example of recorded GICs observed in Finland [14] is shown in figure 24. The total distortion of a.c. line currents caused by these GICs is presented in figure 25.

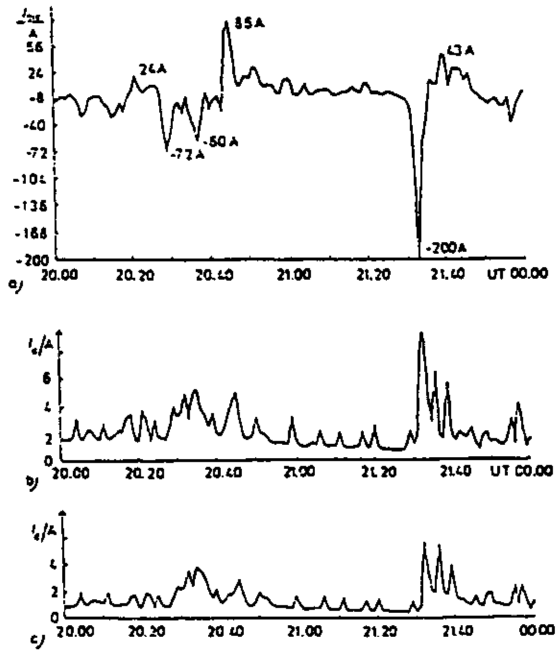


(a) variation of the north component of the geomagnetic field at Nurmijärvi;

(b) corresponding GICs (one minute means) in the earthing leads of the 400 kV transformers at Rauma;

(c) at Pirttikoski on March 24 and 25, 1991 [14].

Figure 24 - GIC in the earthing lead of a 400 kV transformer



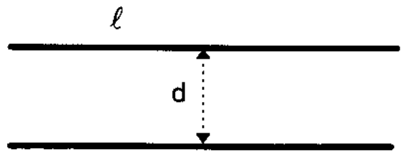
(a) total distortions of the currents of the 400 kV a.c. lines entering Rauma from north;
(b) and south;
(c) Transformer at Rauma, event registered on March 24, 1991. [14]

Figure 25 - Total distortion due to GIC in the earthing lead of a 400 kV transformer

3.14 Appendix

3.14.1 Formulae for the calculation of electrical parameters of sections of conductors (HF)

a) Parallel and faced conductors of length ℓ, radius r and distance d



$$R = \frac{\ell}{2r}\sqrt{\frac{\rho\mu_0 f}{\pi}}$$ resistance

$$L_i = \frac{\ell}{4\pi r}\sqrt{\frac{\mu_0\rho}{\pi f}}$$ internal inductance

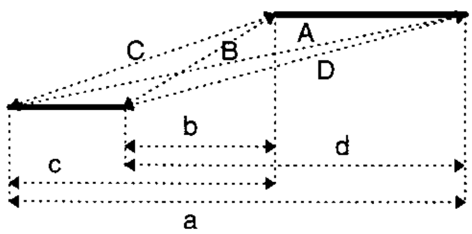
$$L_{ii} = \frac{\ell\mu_0}{2\pi}\left[\ln\left[\frac{\ell}{r}+\sqrt{\left(\frac{\ell}{r}\right)^2+1}\right]-\frac{r}{\ell}-\sqrt{\left(\frac{r}{\ell}\right)^2+1}\right]$$ self inductance

$$L_{ij} = \frac{\ell\mu_0}{2\pi}\left[\ln\left[\frac{\ell}{d}+\sqrt{\left(\frac{\ell}{d}\right)^2+1}\right]-\frac{d}{\ell}-\sqrt{\left(\frac{d}{\ell}\right)^2+1}\right]$$ mutual inductance

where:

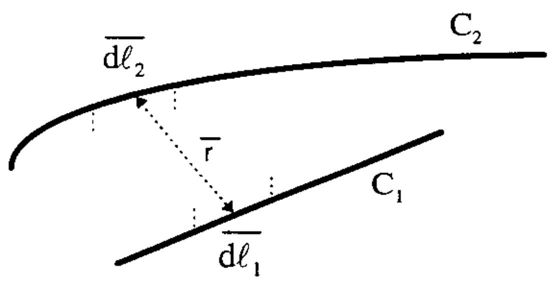
ρ = resistivity of the conductor
f = frequency
$\mu_0 = 4\pi\ 10^{-7}$

b) Mutual inductance for parallel non-faced conductors



$$L_{ij} = \frac{\mu_0}{4\pi}\left[\ln\left[\frac{(A+a)^a(B+b)^b}{(C+c)^c(D+d)^d}\right]+(C+D)-(A+B)\right]$$

c) Other configurations



$$L_{ij} = \frac{\mu_0}{4\pi}\oint_{C_1}\oint_{C_2}\frac{\overline{d\ell_1}\,\overline{d\ell_2}}{\overline{r}}$$

3.15 References

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4 Coupling mechanisms and mitigation methods

4.1 General considerations

The most frequently encountered sources of disturbances have been described in Chapter 3. Although they sometimes consist of a current (or potential) directly affecting a "victim" circuit, they appear in the most general cases in the form of an electromagnetic (EM) field.

It will be assumed here that a model exists to calculate this EM field or, if not, that it is possible to quantify it by making some measurements (characterising the environment).

The problem is then to find a model for calculating the field-to-victim coupling.

It will be the objective of the present chapter to describe the different fundamental mechanisms involved in this coupling, and to derive, from the knowledge of these mechanisms, the basis of the main mitigation methods.

4.1.1 Coupling models

All the models describing the coupling of an EM field to any structure can be built starting from the well known Maxwell equations, of which the most usual implementation leading to numerical models, is the ***Antenna theory*** or ***Scattering theory***.
This is based on the fundamental principle that each current is the source of a field (emission problem) and that each field can be the source of a current (reception problem), which in turn is the source of a *scattered* field.
This leads to integral equations describing the behaviour of a conductive body illuminated by an impinging electromagnetic wave.
These equations normally have no analytic solution and need to be solved by numerical methods.
The Antenna theory is one of the most general and rigorous theories used to solve coupling problems and, as such, requires only one important restricting assumption: that the electrical body is a perfect conductor.

This theory, however, needs considerable computing time and memory.

Another widely used theory is the ***Transmission Line theory (TL)***

This is based on the following assumptions:

- the electrical body has small transverse dimensions compared with the wavelength, i.e.: the diameter of the conductors and the distance between them (or above ground) is small compared with the wavelength (quasi-TEM assumption, see subclause 4.2.4);
- there is no mutual influence between different elements of current flowing along the line, the induced currents do not interfere by radiation with each other (this implies that the line is more or less rectilinear).

The TL theory provides quick, accurate results and is therefore widely used for solving problems of coupling to cables and lines.

Apart from these two "general" theories there is a third one which is much simpler, the ***Quasi-Static theory*** or ***Circuit theory***, sometimes also called the ***Kirchhoff theory*** or ***Lenz theory*** because the well known laws of Kirchhoff and Lenz are pillars of this theory.
The additional restrictions necessary to apply this theory are:

- the circuit length is much shorter than the wavelength, i.e. no propagation effects are involved;
- the current remains constant in each circuit element.

These conditions allow circuits to be represented by lumped elements (without any spatial dimension) connected in series or in parallel to form a network comprising nodes and branches to which Kirchhoff's equations apply.

The effect of a magnetic flux crossing a circuit is represented by a lumped element known as inductance. Since magnetic flux linkage can only be defined for a region with a finite boundary, inductance can only be defined for a closed loop.

We will come back to this important point later.

All the above restrictions prevent us, at least quantitatively, from extending the conclusions of the circuit theory to large circuits (compared with the wavelength), for which it will be necessary either to have recourse to the more general theories or to use some statistical or empirical law. It is worth stressing, however, that the circuit theory approach is usually conservative and that it is not in conflict with the other theories, each theory starting from the antenna theory, being derivable from the preceding one by adding more assumptions. [8]
One of the main advantages of the circuit theory approach is that it leads to very simple calculations and does not require the use of extensive computing methods. As a result it allows the physical mechanisms involved in the coupling to be understood when the dimensions of the circuits remain small. Furthermore, it avoids the necessity of determining the EM field and the need to build up a corresponding model, the source always being represented by a current or a voltage. So the same model can be used for describing the direct contact with a source of disturbance (current or potential injected directly into the victim circuit) and the indirect interaction by means of an electric or magnetic field.
For these reasons most of the coupling mechanisms presented in the following paragraphs will be based on this theory.

It is well known, on the other hand, that simplified theories lead to the creation of tools that are sometimes misused or abused. This is particularly so when dealing with the concepts of *potential difference, potential rise* or *inductance*. In the following clauses we will try to highlight this issue each time it could lead to a misunderstanding.

4.1.2 Earthing, grounding and bonding

The very important role played by the ground in most coupling mechanisms warrants a review of some basic concepts and definitions.

Grounding (earthing) in its classical usage covers in fact two separate concepts:

1. a physical connection to the earth;
2. an equipotential bonding to, or between, metallic structures.

We will see that this latter concept, as far as EMC is concerned, is the more important one.
In order to avoid any confusion in the following paragraphs, we will use the terms ***Earth network*** or ***Earth electrode*** to designate all groups of interconnected conductive parts in intimate contact and providing electrical connection with the earth, and we will use the term ***Bonding network*** to designate all sets of conductive structures interconnected in order to make a substantially equipotential network (at least at low frequencies), to short-circuit the electric field and to provide an electromagnetic shield (from d.c. to low RF). The bonding network is normally itself connected to the earth network.
We will also use the term ***earthing*** and the term ***bonding*** to describe making a connection to an earth network or to a bonding network respectively.
However when the distinction between both concepts is not important we will preferably use the term ***grounding***.

Earthing and bonding networks are required for different reasons, and their implementation in practice reflects these differences.

These networks provide two main functions: a *protective* function (against overvoltages) and a *mitigation* function (in the EMC context).

a) Protection (of people and equipment)

The protective earth is intended to reduce the risk due to accidental potential differences.
The cause of these potential differences can be either of internal origin (e.g. earth fault within the substation) or of external origin (e.g. lightning).

When the origin is internal, it is not the value of the earth impedance which is important, but only the potential difference between simultaneously accessible structures.

This is also true, to some extent, when the source of fault current is external but the ground of the faulty installation and that of the source are interconnected (e.g. TN power distribution systems).

When the current (fault, lightning) is of external origin, apart from the voltage drops in the ground conductors, there will also be a potential rise of the earth network with respect to a "distant earth" and thus also to all conductors coming from outside the protected area.

Unless special care is taken to protect the equipment connected to these conductors, lightning and severe fault currents will always have destructive effects.

b) Electromagnetic compatibility

The second part played by the grounding (bonding) network is the reduction of all kinds of disturbances regardless of their coupling mode.
This function will be described in more detail in the following clauses.

4.2 Simplified coupling models based on circuit theory and related mitigation methods

When trying to understand the way disturbances are transmitted from source to victim it appears that a distinction has to be made between all the coupling modes.

The coupling either involves a direct electrical contact between source and victim, or occurs through the medium of the EM field (E field, H field or both).

In the first case it is often referred to as ***conductive coupling*** or ***galvanic coupling***.
This occurs, for example, when the disturbance is conducted via the cabling system.
So, a first distinction could be made between those two modes of coupling: conducted or radiated.
However, once a conducted disturbance has reached the victim, its influence on the sensitive circuits can again imply different mechanisms depending on the type of impedance (resistive or reactive, self or mutual) through which the disturbance current flows.

For that reason, and although it sometimes combines different physical mechanisms of influence, we will prefer in the following the concept of ***common impedance coupling*** to describe coupling involving direct electrical contact with the source of disturbance, appreciating that at very low frequencies or when this impedance is purely resistive - and only then - this coupling mode can be called ***resistive coupling***.

On the other hand, coupling without electrical contact will be split into three different categories depending on whether the electric and magnetic components of the EM field can be considered as independent from each other or not.

Consequently it will be possible to distinguish four modes of coupling:

- ***coupling by common impedance*** (the resistive coupling being a special case);
- ***inductive*** or ***magnetic coupling*** (near H-field);
- ***capacitive*** or ***electric coupling*** (near E-field);
- ***radiative coupling*** or ***electromagnetic coupling*** (far field).

Only the first three modes can be treated by circuit theory. The fourth one obviously requires one of the general theories mentioned previously.

In fact none of these modes appears separately, but usually, at least in the low or medium frequency range, one will prevail over the others.

For all the coupling modes it is possible to determine a ***transfer function*** [3], between the energy ***source*** or ***emitter*** and the susceptible equipment or ***susceptor*** or ***victim***.

The transfer function can be an impedance, an admittance or a dimensionless quantity, depending on the nature of the impressed quantity and of the "result" of the coupling, i.e. voltage or current.
In all cases the electromagnetic interaction between emitter (E_e, Z_e) and susceptor (U_s, Z_s) can be modelled by a two-port network, represented in figure 26 in the simplest situation, by a T network consisting of impedances Z_A, Z_B and Z_C [1].

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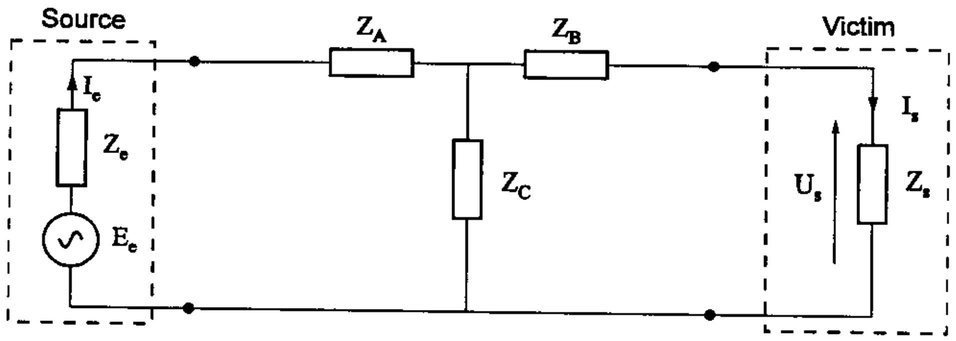
[1] *In this figure and in the following ones, when there is no risk of confusion with the electric field, the symbol E is used to represent a voltage source and the symbol U to represent a voltage drop or an induced EMF.*



$$(U_s, I_s)/(E_e, I_e) = F_t(Z_A, Z_B, Z_C, Z_e, Z_s)$$

Figure 26 - Transfer function between source of disturbance (emitter) and victim (susceptor)

This circuit model, in which the return conductor is usually the ground, suggests the two main strategies for reducing the EM coupling between susceptor and emitter: the ***"short-circuit"*** and the ***"open-circuit"*** strategies.

It is clear that if Z_C is zero, no energy from the emitter can reach the susceptor.
Similarly, if Z_A and Z_B are either or both infinite in magnitude (i.e. open-circuit) no emitter energy will reach the susceptor.
It is worth noting that, in general, perfect short or open circuits are not possible to achieve, since even the best implementation possesses stray inductance and capacitance.
The short-circuit strategy is aimed at reducing the impedance of all grounding conductors and in particular their inductance which usually dominates above 1 kHz.
The open-circuit strategy is aimed at isolating the susceptor from the emitter either by increasing the distance or by inserting physical barriers (reduction of the coupling factor), or by making an isolated bonding network with "single point" connections to earth. We will see in subclauses 4.2.1 and 4.5 that this latter grounding strategy has serious drawbacks.

On the other hand, as the characterisation of a disturbance is most often given in terms of ***voltages*** appearing at the inputs of the equipment, and as these voltages are often the result of the currents flowing in the grounding and shielding components, the ***Transfer Impedance*** concept will play a very important role in the following clauses and more particularly in the determination of the shielding effectiveness of structures like cables and enclosures (subclauses 4.2.2.2, 4.2.2.3, 4.2.2.4).

4.2.1 Common impedance coupling (shared path coupling)

4.2.1.1 Basic principles

This coupling appears each time different circuits share one or several impedances.

The simplest and most typical case is that of circuits having a "common return", which is the earthing network itself and which is assumed to be not ideal; for example it presents a non-zero impedance. [5]

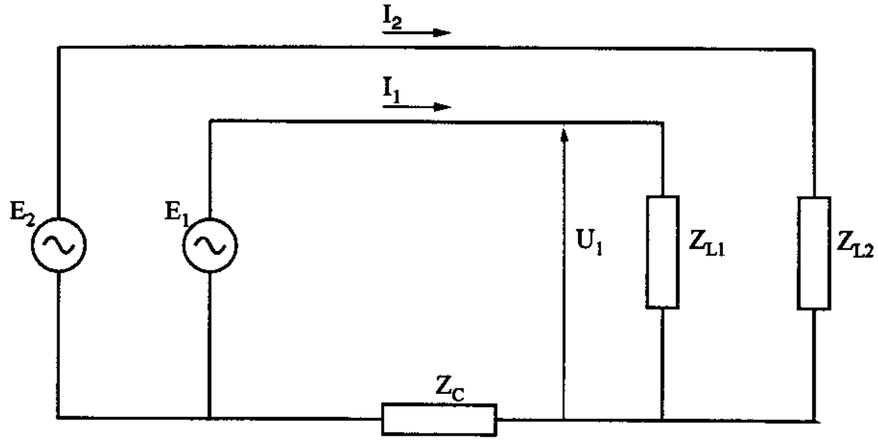
A simplified example comprising two circuits is given in figure 27.

Because of the common impedance Z_C, the voltage drop across the load impedance of circuit 1 is the algebraic sum of the signal voltage E_1 and an interference voltage due to the flow of the current in circuit 2.

As the load impedance Z_{L1} is usually much higher than the common impedance Z_C, the disturbance voltage reduces to - $Z_C I_2$ where Z_C corresponds with the transfer function of figure 26, and as such, can be called a "transfer impedance"(see subclause 4.4.3). We will see however that the ***transfer impedance*** concept has very often a more restrictive meaning.

Without acting on the disturbance sources, there are only two ways of reducing the common impedance coupling:

- eliminating the common return (open-circuit strategy);
- reducing the impedance of the common return (short-circuit strategy).



$$U_1 = (E_1 - I_2 Z_C)\frac{Z_{L1}}{Z_{L1}+Z_C} \qquad \text{with } Z_{L2} >> Z_C$$

Figure 27 - Common impedance coupling

Curiously, when dealing with earthing networks, the two methods lead sometimes to radically different solutions:

- eliminating common returns is equivalent to mandating that no bonding circuit has more than one connection to earth; it is the hunt for ground loops leading to the star earthing philosophy;
- reducing the impedance of the common return means, on the contrary, increasing the number of conductors (increasing their section only has little influence on their inductance), multiplying the earthing points and leading to a cross meshed network.

The apparent contradiction between these philosophies can easily been removed when the distinction is made between the grounding of active circuits carrying signals or energy and the grounding of metallic enclosures and shielding circuits.

The open-circuit strategy applies to the active circuits: ***common returns to active circuits should (when possible) be avoided.***
Active circuits should (when possible) be grounded at only one point (see subclause 4.3.4).

The short circuit strategy, on the other hand, applies to most other grounding circuits and more particularly, as will be seen in the next clauses, to the shielding circuits.

This distinction between open- and short-circuit strategy refers also respectively to the concepts of ***differential mode*** (DM), which concerns mainly the signals, and ***common mode*** (CM), which concerns mainly the disturbances (see subclause 4.2.2.2).
We will also discuss in more detail in clause 4.5 the application of both philosophies to earthing networks.

Two important exceptions where common impedance couplings in active circuits cannot be avoided are *power supply circuits* and *coaxial links* (see subclause 4.3.3).
Fortunately, concerning coaxial circuits, and more generally for all a.c. circuits, a natural decoupling is achieved by reducing the loop area of each circuit as shown in figure 28 where the spatial layout of two circuits with three different return paths is shown [2].
Here, the three return conductors with impedances Z_1, Z_C and Z_2, even if their sections and lengths are practically equal, will carry currents of very different magnitudes: a.c. current I_1 will flow back mainly via conductor Z_1, a.c. current I_2 via conductor Z_2 and practically no current will flow back via conductor Z_C.
This property, which is in fact a particular case of inductive coupling, is significant even at 50 Hz. For example, when a short circuit to earth appears on a high voltage line, the current will generally

[2] *In this figure and in most subsequent ones the circuit is represented by its two- or tridimensional aspect, on which the lumped elements of the circuit theory have been superimposed in order to highlight their mutual correspondence. Care must be taken, however, not to confuse both concepts (spatial and symbolic), particularly in regard to self and mutual inductances.*

return to the source following the HV line instead of in a straight line between the fault and the source (figure 29).

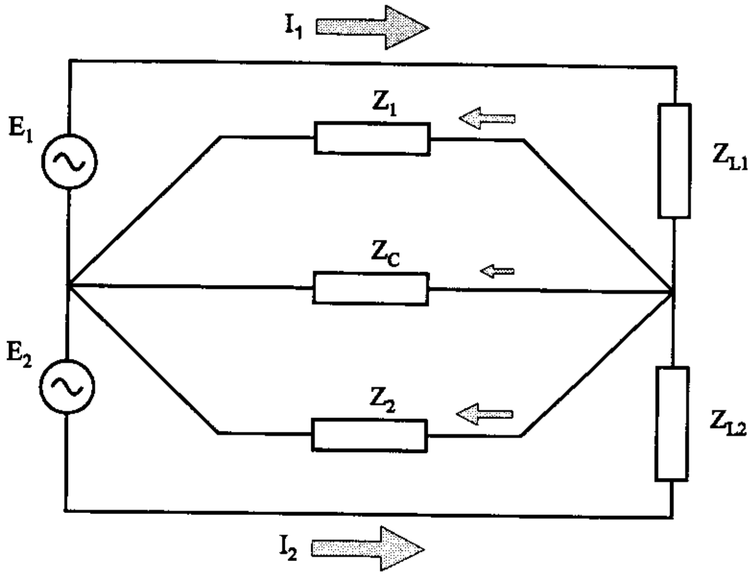


Figure 28 - a.c. natural decoupling of circuits sharing common impedances

The mechanism is known as ***proximity effect*** and leads, at high frequencies to the ***skin effect***. Thanks to this important effect it is possible to realise *multigrounded* HF circuits without having problems due to external disturbance currents.

This principle of ***magnetic decoupling*** will be further examined in the following subclause 4.2.2.

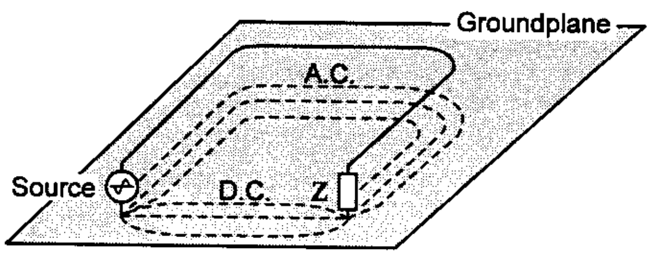


Figure 29 - Differences in the current patterns for a.c. and d.c. ground returns [1]

4.2.1.2 Examples of disturbances coupled by common impedance

- 50 / 60 Hz short-circuit currents in an earthing system used as a potential reference plane;
- direct lightning stroke to earthing systems, circuits or equipment (e.g. antenna circuit);
- electrostatic discharge directly applied to equipment;
- cross-talk between circuits sharing a common return;
- harmonics, flicker, voltage dips on power supplies.

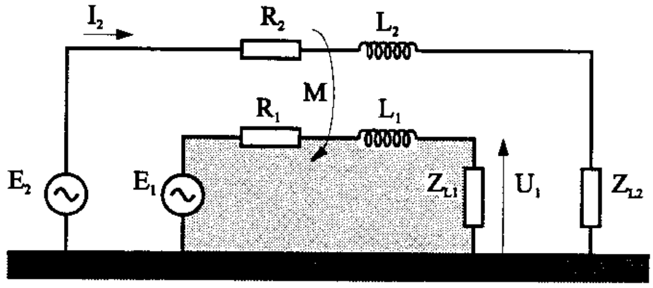
4.2.2 Inductive (magnetic) coupling

4.2.2.1 Basic principles

Inductive coupling is certainly (with common impedance coupling) the most frequently encountered penetration mode of disturbances.

It happens whenever two circuits share a common induction flux; this is always the case when the ground is part of both circuits, and when current is flowing in at least one of the conductors.

The simplest case, shown on figure 30, involves two parallel conductors above a ground plane that serves as a return path for both circuits.



$$Z_1 = R_1 + j\omega L_1$$
$$Z_2 = R_2 + j\omega L_2$$

$$U_1 = (E_1 + I_2\, j\omega M)\,\frac{Z_{L1}}{Z_{L1} + Z_1}$$

Figure 30 - Inductive coupling

Suppose again that circuit 2 is the source of disturbances and circuit 1 the victim. Suppose also that the signal current in this latter circuit is much smaller than the disturbance current in circuit 2, so that its influence on circuit 2 can be neglected. The shaded zone represents the area crossed by the common flux and determines the value of the mutual inductance M between the two circuits.

The resolution of the equations of these circuits shows that U_1 is the sum of:

- a signal voltage $E_1\, Z_{L1}/(Z_{L1} + Z_1)$;
- an induced interference voltage $j\omega\, M\, I_2\, Z_{L1}/(Z_{L1} + Z_1)$.

When the two circuits are close together the value of M approaches that of L_1, so comparing this expression with that of figure 27 leads to the statement that the factor $j\omega M$ plays the same role as Z_C. This shows that common impedance coupling and inductive coupling are sometimes difficult to distinguish from each other.

The distinction indeed is somewhat artificial and bound in fact to the circuit theory approach.

At this point it is worth making an important digression and returning to one of the fundamental laws derived from the Maxwell equations. The second Maxwell equation (also known as Faraday's law), expressed in its integral form, can be written as follows:

$$U = \oint \bar{E}\, d\bar{s} = -\partial\Phi(B)\,/\,\partial t$$

It tells us that *the contour integral of the electric field **E** along any closed path is equal to the magnetic flux variation across any surface bounded by this contour* (figure 31).

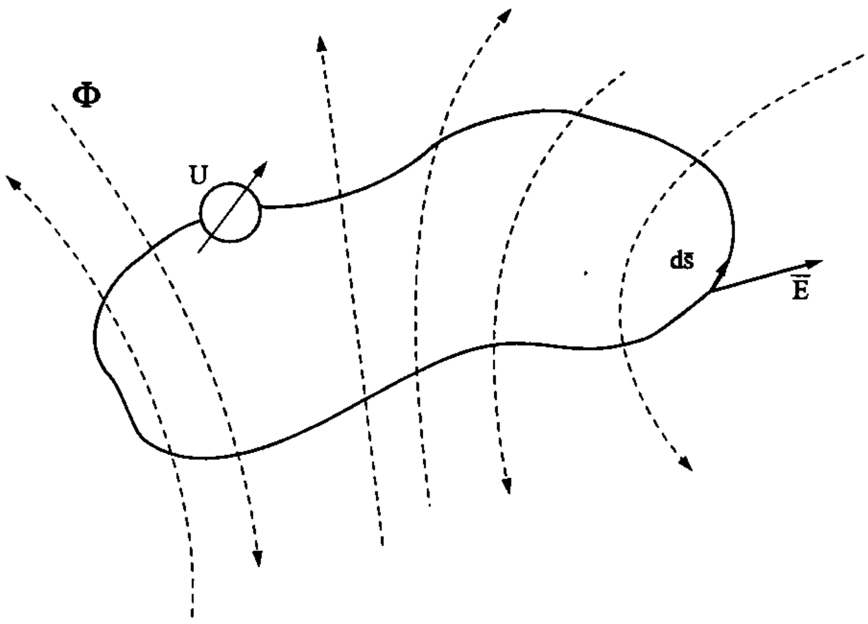


Figure 31 - Contour integral of the electrical field along a closed path (Faraday's law)

This means in practice that, if the path follows an electrical circuit, then the integral (or the sum in the Kirchhoff theory) of all voltage drops along this circuit is equal to the derivative of the flux intercepted by this circuit whatever the origin of this flux is. It can be caused by an EM field (radiation), by a current flowing in another circuit (mutual induction) or by the current flowing in the circuit itself (self induction).

It is precisely this latter situation which constitutes the link between "common impedance coupling" (the disturbance current flows in the victim circuit) and "inductive coupling" (the disturbance current flows in a separate circuit).

The problem when using circuit theory is that the application of Kirchhoff's law:

$$\sum_{mesh} Un = 0 \text{ equivalent to: } \oint \bar{E} d\bar{s} + \partial\Phi / \partial t = 0$$

implies that the term $\partial\Phi / \partial t$ be converted into a $L\ \partial i / \partial t$ (or $M\ \partial i / \partial t$) term.

This requires that the inductance L be determined for the complete closed contour (i.e. circuit) encompassing the flux Φ.

This statement leads to the following important conclusions:

- voltage drops between remote points are not univocally defined as they depend on the path used to measure them (figure 32).
  For the same reason the widely used concept of ***Transient Ground Potential Rise*** (TGPR) has to be considered with great care (see subclause 5.5.4.2);
- induced voltages cannot be localised in some part of the wiring (the voltage drop between the terminals of a coil is a practical exception due to the fact that the flux contained in the core is much larger than the flux in the external circuit);
- inductance is the property of a closed loop. However, it is possible to uniquely ascribe an inductance to portions of this loop using the concept of partial inductance. [24]

In fact the main concept that one has to keep in mind when dealing with self or mutual inductances of circuits is the magnetic flux created or intercepted by the circuits. This flux concept is universal and not related to any simplified theory. It applies regardless of the frequency and the dimensions of the circuits.

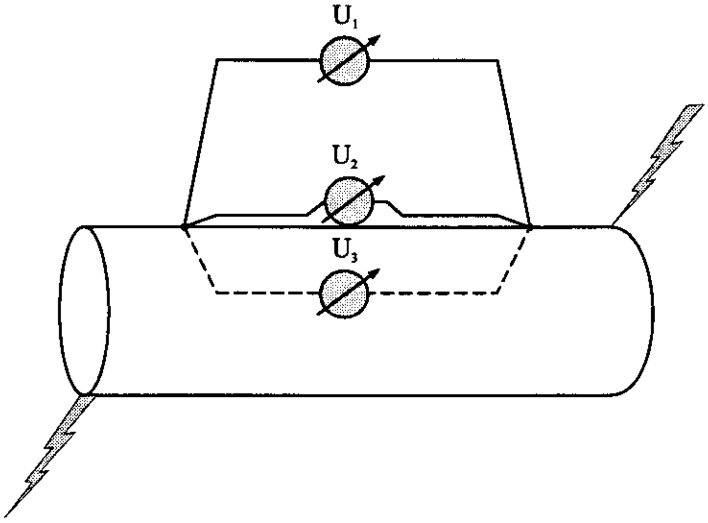
Being aware of those conclusions, the question however can be raised: are we allowed to speak about the inductance of a single wire?

The "voltage drop" between remote points in a circuit depends on the way it is measured:

Voltmeter 1 measures the sum of a resistive voltage drop along the tube and an electromagnetic force (EMF) induced in the external loop;

Voltmeter 2 measures only the resistive voltage drop (on the outer surface of the tube) which increases at high frequencies due to the skin effect;

Voltmeter 3 measures the voltage drop along the inside of the tube. Owing to the decrease of the skin depth with frequency it decreases also, and, as no magnetic field penetrates inside the tube, no additional EMF is added (see transfer impedance of cables: subclause 4.2.2.4).



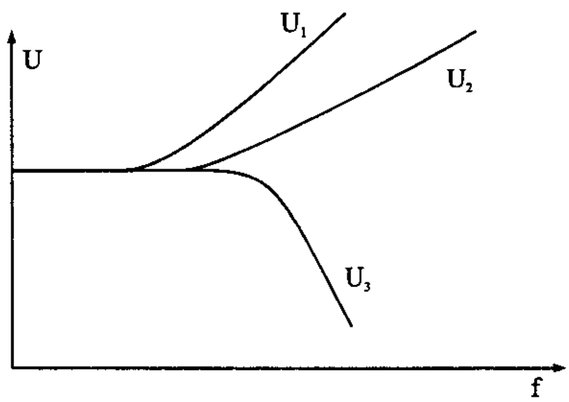


Figure 32 - Voltage drop between remote points in a circuit

Values of 1 or 2 μH/m are widely encountered in the literature for characterising single wire inductances. What is their meaning?

To understand this it is necessary to recall Neumann's formulas giving the per unit length inductance of long parallel wires (see subclause 4.6.1).

The value of the inductance of a long wire of radius r situated at a height h above a perfectly conductive ground plane is:

$$L = \frac{\mu}{2\pi} \ln \frac{2h}{r}$$

Assuming a wire radius of 5 mm and a height above ground ranging from 25 cm to 25 m (or what is equivalent - a return path, i.e. an image conductor, situated at a distance between 0,5 m and 50 m), we find, in air where $\mu = \mu_0$, a value of the loop inductance ranging from 0,9 to 1,8 μH/m.

This means in practice that, as far as EMC is concerned, and whenever the return path is at a distance which is large compared to the radius of the wire (or equivalent radius when dealing with a cable), it is meaningful to speak about an inductance (actually self inductance) of about ***1 µH/m***.

Returning to our original inductive coupling problem, we now examine possible ways for reducing the inductive coupling between circuits.

4.2.2.2 Reduction by use of balanced circuits and loop area reduction (open-circuit strategy)

Removal of a common return path and reducing the common loop area can be achieved by symmetrising circuit 1 with respect to ground (figure 33), i.e. by creating a ***balanced*** circuit.

The voltages appearing between conductors of a symmetrical circuit are referred to as being in ***differential mode (or normal mode)*** in contrast to those appearing between conductors and ground which are referred to as being in ***common mode (or longitudinal mode)***.

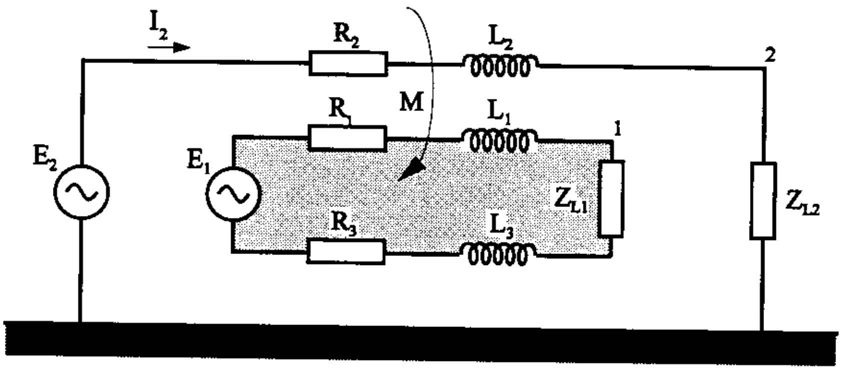


Figure 33 - Balanced circuits reduce the inductive coupling

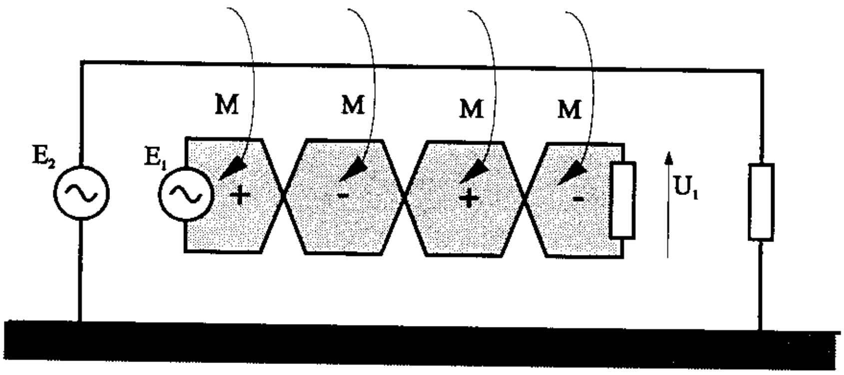


Figure 34 - Twisted pairs allow a further reduction of the inductive coupling

The ratio (expressed in dB) of the disturbing voltage appearing in differential mode at the extremities of a circuit to the voltage induced in common mode is often referred to in the telecommunication literature as the ***Longitudinal Conversion Loss*** and in circuit theory as ***Common Mode Rejection Ratio (CMRR)***. It depends largely on the unbalance of the circuit (line + terminal equipment) to ground.

The best method to achieve balanced circuits is to use twisted pairs. In this case many loops are generated with oppositely induced voltages cancelling each other (figure 34).

The reduction provided by a twisted pair (with respect to an untwisted pair) increases with the number of twists per unit length and by the length of the cable, but decreases with the value of the load impedances.

At low frequencies it is possible to achieve a factor greater than 100 (40 dB) with a pitch (distance between two successive loop inversions) of 5 cm but it becomes difficult to go much further because of small dissymmetries within the cable and at the ends.

Moreover, at frequencies higher than 100 kHz, the benefit of using twisted pairs decreases and disappears almost completely above a few MHz. [14]

With regards to the Longitudinal Conversion Loss, typical values can range from 90 dB at low frequencies (twisted pair alone) to 30 dB at 1 MHz.

4.2.2.3 Reduction by shielding

Another way to reduce the common mode inductive coupling between conductors 1 and 2 is to put near conductor 1 (or conductor 2 as we will see below) a short circuited conductor 3 that encompasses as far as possible the same flux as conductor 1 (or 2, as appropriate) (figure 35).

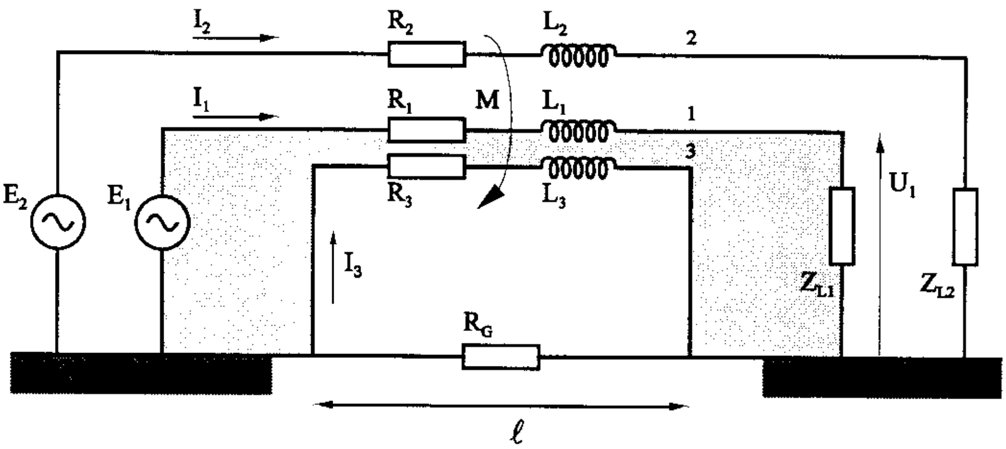


Figure 35 - Magnetic shielding action of grounded conductors

Conductor 3 reacts with the induction flux as if it were a short-circuited secondary winding of a transformer. Following Lenz's law a current I_3 flows in conductor 3 giving rise to an induction flux of approximately the same magnitude but of opposite sign to the disturbance flux, and which thereby cancels it.
The only way to be sure that circuits 1 and 3 (or 2 and 3) encompass the same flux is to use for conductor 3 a tube surrounding conductor 1 (or 2). This means a **shield grounded at both ends** (figure 36).

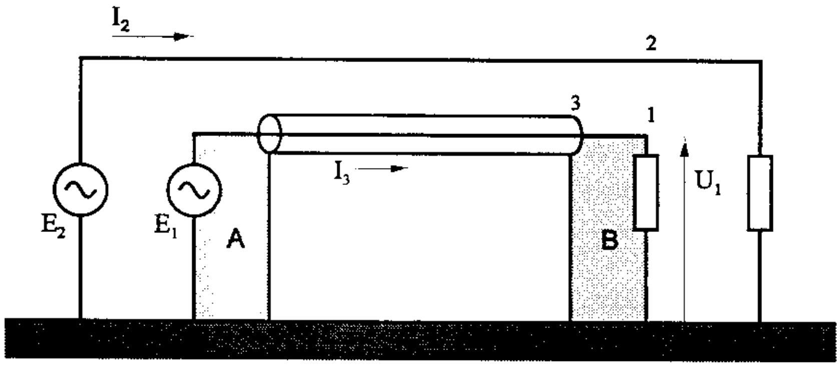


Figure 36 - Shielding action of a tubular conductor surrounding the victim

1) Shielding of the victim

Let us see in more detail the efficiency of such a shield by solving the equations for the circuit of figure 35 in the layout of figure 36.

(For simplicity, we will assume that $E_1 = 0$ and that $Z_{L1} = \infty$, or that I_1 can be neglected with respect to I_3 and I_2):

$$\begin{cases} Z_{12} I_2 + Z_{13} I_3 = U_1 \\ Z_{32} I_2 + Z_{33} I_3 = 0 \end{cases} \qquad (1)$$

$$U_1 = \left(Z_{12} - \frac{Z_{13} Z_{32}}{Z_{33}} \right) I_2 \qquad (2)$$

with: $Z_{ij} = R_G + j\omega M_{ij}$ $(i \neq j)$

$Z_{32} = R_G + j\omega M_{32}$

$Z_{33} = R_G + R_3 + j\omega L_3$

If, as is the case here, conductor 3 is very close to conductor 1, the fluxes induced in both circuits by I_2 are almost identical. Hence: $M_{12} = M_{32}$ and $Z_{12} = Z_{32}$

So (2) becomes:

$$U_1 = Z_{12} I_2 (Z_{33} - Z_{13}) / Z_{33} \qquad (3)$$

or:

$$U_1 = Z_{12} I_2 [R_3 + j\omega (L_3 - M_{13})] / Z_{33} \qquad (4)$$

Let Φ_3 and Φ_{13} be respectively the fluxes intercepted by the shield and by conductor 1 when a current I_3 is flowing in the shield. Then we have:

$\Phi_3 = L_3 I_3$

$\Phi_{13} = M_{13} I_3$

If the shield is a perfect tube no flux is induced inside it: $\Phi_3 = \Phi_{13}$ and $L_3 = M_{13}$

In the more likely case (braids, foils, etc.) the current in the shield develops some longitudinal or radial flux component which is not intercepted by circuit 1. The difference $L_t = L_3 - M_{13}$ is not equal to zero and is called ***transfer inductance*** (in fact the transfer inductance is normally defined per unit length, so it has to be multiplied by the length ℓ of the circuit, which is assumed here to be much smaller than the wavelength).

Likewise the per unit length impedance $Z_t = (R_3 + j\omega L_t) / \ell$ is called the ***transfer impedance*** of the shield (we will see in subclause 4.2.2.4 that this corresponds to the concept introduced previously and that it is an intrinsic property of the cable); so the expression giving the induced voltage in circuit 1 becomes:

$$U_1 = (R_G + j\omega M_{12}) I_2 k = U'_1 k \qquad (5)$$

with:

$$k = \frac{Z_t \ell}{R_G + R_3 + j\omega L_3} \qquad (6)$$

In this expression:

- $U'_1 = Z_{12} I_2 = (R_G + j\omega M_{12}) I_2$ is the interference voltage (induced longitudinal EMF) appearing at the end of circuit 1 in the absence of shielding;
- $k = Z_t \ell / (R_G + R_3 + j\omega L_3)$ is the ***reduction factor*** due to the shielding, or ***shielding factor***.

  It is the ratio of the interference voltage U_1 measured in the presence of a grounded shield to the same voltage U'_1 measured in the absence of shield.

  This factor is called the ***shielding effectiveness*** (S) when expressed in dB:

  $S = - 20 \log k$;

- R_G is the *ground return* resistance of the shield, i.e. twice its grounding resistance (assuming a splitting of R_G between both ends).

It is thus necessary, in order to get a large reduction effect, that the ***transfer impedance be low compared to the impedance of the shielding circuit with ground return.***

General comments about the factors influencing the shielding effectiveness

The reason why L_3 has to be kept high is due to the need of having circuit 1 and 3 tightly coupled in order to get $\Phi_{32} \cong \Phi_{12}$.

The actual limitation factor in the reduction of the interference voltage is due to the resistance R_3 of the shielding (at high frequency Z_t).

Note that R_G, appearing simultaneously in the numerator and in the denominator of the expression for U_1, is not a dominant parameter.
It is quite evident that increasing R_G will increase the voltage drop in the earthing network between the extremities of the circuit and hence the longitudinal interference voltage (common impedance coupling).
It is less evident to understand why increasing R_G leads also to a reduction (i.e. an improvement) of the shielding factor.

In fact two cases have to be considered:

a) The coupling is purely inductive

$Z_{12} = j\omega M_{12} \cong j\omega M_{32} = Z_{32}$

The induced EMF: $U'_1 = j\omega M_{12} I_2$ is split between R_3 and R_G

Hence, the higher the value of R_G is, the lower the voltage drop on R_3 i.e. the interference voltage U_1 will be.

b) The coupling is partly inductive and partly by common impedance
(as in figures 35 and 36)

$Z_{12} = R_G + j\omega M_{12} \cong R_G + j\omega M_{32} = Z_{32}$

$$I_3 = -I_2 \frac{Z_{32}}{Z_{33}} = -I_2 \frac{R_G + j\omega M_{32}}{R_G + R_3 + j\omega L_3}$$

If R_G increases too much, I_3 tends to be equal to I_2 and can exceed the current carrying capability of the shield.

So in most situations R_G is kept as low as possible.

Anyway, what is important is not that the shield be earthed but that it be *bonded to the grounded frame* of the equipment (figure 37) in order to greatly reduce the shaded areas (A and B in figure 36).
These shaded areas correspond to the part of the flux produced by circuit 2 (source) and intercepted by circuit 1 (victim) but not by circuit 3 (shielding). The ratio of this flux to the current I_3 is nothing other than the so called self inductance L_g of the shield grounding leads (about 1 µH/m).
As it appears in the difference $L_3 - M_{13}$, it should be added to $Z_t \ell$, leading to the following extended expression for k:

$$k = \frac{Z_t \ell + j\omega L_g}{R_G + R_3 + j\omega L_3} \qquad (7)$$

Ideally a cable shield should be the continuation towards the external circuits of the metal enclosure of the equipment to which it is connected.

A practical example will make it easier to understand how a low-quality shield connection to ground can degrade the shielding effectiveness.

A "good" shield can have at 1 MHz a typical transfer impedance of less than 10 mΩ·m. This means, for a 20 m cable, a value for $Z_t \ell$ of less than 0,2 Ω.
Assume the cable shield is bonded at both ends by 20 cm conductors. This translates, at both ends and at 1 MHz, a reactance of a little more than 1 Ω (based on 1 µH/m); thus roughly a 2 Ω impedance must be added to the 0,2 Ω transfer impedance of the cable.

Knowing that the reactance $j\omega L_3$ of such a cable is approximately equal to 100 Ω at 1 MHz (also based on 1 μH/m), we get a reduction factor falling from 0,2/100 to 2,2/100, or a loss of effectiveness of one order of magnitude!

The best ground connection is one involving electrical contact over the full circumference of the cable screen. This should always be recommended whenever a cable enters a metallic equipment cabinet.

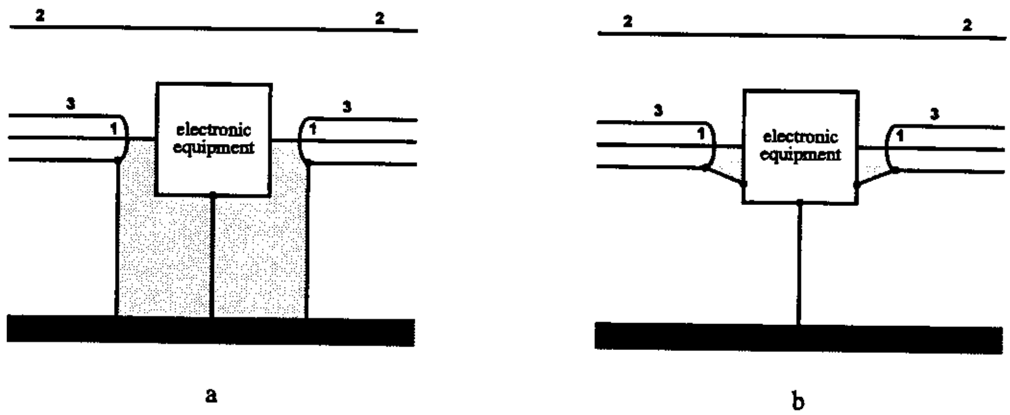


Figure 37 - Difference between "earthed" and "bonded" shield

Shielding as a mitigation method against common impedance coupling

It is interesting to note that the reduction factor of a cable shield applies irrespective of the origin of the interference voltage U'_1.
In other words U'_1 can be a purely inductively coupled EMF: $U'_1 = j\omega M_{12} I_2$, but it can also be the consequence of a conductively coupled GPR (ground potential rise): $U'_1 = R_G I_2$ or more generally $U'_1 = Z_G I_2$.

It makes no difference whether U'_1 is due to the resistive part R_G of a ground conductor or to its inductive part.
However, we will see in the following that the shielding effectiveness is usually very poor at low frequency, and is almost ineffective in reducing LF common impedance coupling.

Shielding effectiveness at low frequency

Looking at expression (6) and, knowing that L_3 is always much greater than L_t , it is clear that the shielding effectiveness decreases with the frequency and can be approximated at 50/60 Hz by the expression:

$$k = \frac{R_3}{R_G + R_3 + j\omega L_3} \qquad (8)$$

In order to reduce the value of k it is necessary either to reduce R_3 (e.g. increase of the cross sectional area of the screen, use of copper or aluminium instead of lead, grounding of the unused conductors) or to increase the inductance of the circuit with ground return (L_3) by using magnetic materials (steel armour, mumetal, ferrite, etc.).
In this way the impedance $j\omega L_3$ of an armoured cable can be easily increased by a factor 7 (≈ 5 Ω/km instead of 0,7 Ω/km).
Care must be taken, however, when dealing with ferromagnetic material, not to saturate it.
This happens for magnetic fields approaching 10 A/cm (1000 A/m).

Assuming a longitudinal EMF "E", giving rise to a current "I" and a magnetic field "H" in the shield, we get:

$H = I/2\pi r$ (with r being the radius of the shield)

$I = E/Z$ (with $Z \approx j\omega L_3$ being the cable impedance with ground return)

and thus $E = 2\pi r\, H\, Z$

Hence, with $H \approx 10$ A/cm, $r \approx 1$ cm and $Z \approx 5$ Ω/km, we obtain the typical maximum allowable voltage which can be induced at 50/60 Hz in an armoured cable without saturating it:

$E \approx 300$ to 400 V/km

Such a low value is very often exceeded in the case of short circuits in HV substations or power plants.

Shielding effectiveness at high frequency or for long cables

When the frequency increases, the assumptions $Z_{L1} = \infty$ (and also $Z_{S1} = 0$, with Z_{S1} being the source impedance of E_1) are no longer valid.
The conductor impedance ωL_1 becomes higher than the load impedance and of the same order of magnitude as the shield impedance ωL_3.
In this case an approximate expression for the reduction factor is given by [6]:

$$k \cong \frac{Z_t \ell}{Z_{S1} + Z_{L1}} \frac{L_1}{L_3} \approx \frac{Z_t \ell}{Z_{S1} + Z_{L1}} \qquad (9)$$

For a matched circuit, $Z_{S1} = Z_{L1} = Z_{c1}$,
with Z_{c1} the common mode characteristic (surge) impedance of the cable.

Hence:

$$k \approx \frac{Z_t \ell}{2 Z_{c1}} \qquad (10)$$

This latter expression, though very simple and dependent only on the characteristics of the cable, has to be used with care because it does not take into account any propagation effect, and assumes the absence of resonances and the uniformity of I_3.

A more general - though still approximate expression - is sometimes given with reference to both the characteristic impedances Z_{c1} of the wire/shield line and Z_{c3} of the shield/ground line [13]:

$$k \approx \frac{Z_t \ell}{2\sqrt{Z_{c1} Z_{c3}}}$$

This leads, when the characteristic impedances are taken as being equal to 50 Ω, to the classical expression for the shielding effectiveness:

$$S \approx 40 - 20 \log Z_t \ell$$

If the length of the cable cannot be neglected compared to half the wavelength, the propagation effects have to be taken into account, requiring, usually, computer solutions.

However, making the further assumptions that both the conductor and the shield are matched at their ends and that attenuation can be neglected, it can been shown (subclause 4.6.3) that expression (10) becomes:

$$k \approx \frac{Z_t \ell}{2 Z_{c1}} F(\omega \ell) \qquad (11)$$

The factor $F(\omega\ell)$ is equal to unity at low frequency and its envelope decreases as $1/f$ for frequencies higher than $v_1 v_3 / (v_1 + v_3) \ell$ or $v_1 v_3 / (v_3 - v_1) \ell$, ($v_1$ and v_3 being the propagation velocities along circuits 1 and 3), depending on whether the disturbance current is flowing from the load (paradiaphony) or towards the load (telediaphony).

When conductor and shield are not matched at their ends resonances occur modifying the maximum value of $F(\omega\ell)$.
Generally, however, the above expression gives a good indication of the behaviour of long shielded cables at high frequency, as the resonances are very often damped by the attenuation of the cable.

2) Shielding of the source

As suggested previously, it is also possible to put a shield around the source instead of around the victim (figure 38).

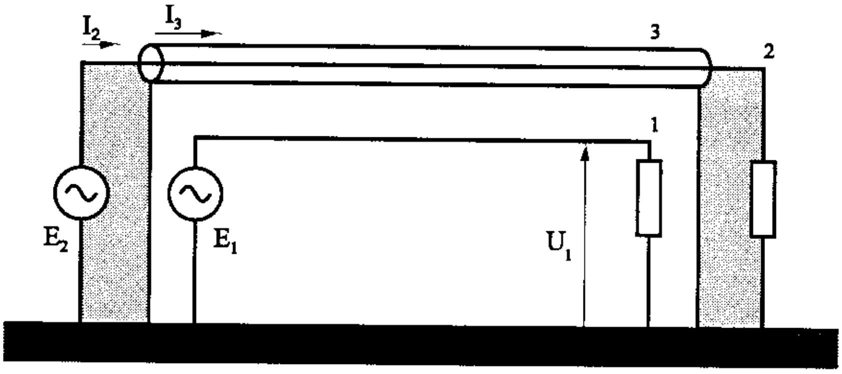


Figure 38 - Shielding action of a tubular conductor surrounding the source of disturbance

The principle here is to reduce directly the flux at the source. Moreover it offers, in the case of an earth fault in a power circuit, a return path of lower impedance than the earth or the earth network (see figure 28) and prevents the circulation of dangerous currents into the shields of the cables to be protected. More generally it reduces problems due to common impedance coupling (principle of *magnetic decoupling*).

The expression for the reduction factor can again be derived from the general equation (2), taking into account now that $Z_{12} \approx Z_{13}$. Hence:

$$U_1 = Z_{12}\, I_2\, (Z_{33} - Z_{32}) / Z_{33} \qquad (12)$$

For the same reason as before we have $L_3 \approx M_{23}$ and $L_t = L_3 - M_{23}$, leading to exactly the same expression of k as for the shielding of the victim.

The shielding factor of power cable is sometimes expressed by an equivalent expression, i.e: ***the ratio of the earth current $I_2 + I_3$ to the disturbance current I_2.***
Indeed, it is easy to show from (1) that $(Z_{33} - Z_{32}) / Z_{33}$ is identical to $(I_2 + I_3) / I_2$.

The 50 / 60 Hz value of k can go down to 0,1 when the shield has a very low resistance and contains magnetic materials (steel sheet) which is not saturated by the magnetic flux (saturation occurs typically for currents exceeding 2000 A).

The shielding factor K resulting from the shielding of both source and victim is, of course, better than either individual reduction factor but its value remains, in general, higher (i.e. worse) than the product of both factors:

$$K = \frac{Z_{t1}\, Z_{t2}\, \ell^2}{Z_1 Z_2 - Z_M^2} \qquad (13)$$

In this expression Z_{t1} and Z_{t2} are respectively the transfer impedances of the source shielding and of the victim shielding, $Z_1 \approx Z_{11}$ and $Z_2 \approx Z_{22}$ are their impedances with ground return, and Z_M is their mutual impedance also with ground return.

Note that in many cases an important reduction effect can be achieved without cable shielding by installing the cables in very close proximity to metallic structures with multiple interconnections to ground such as cable supports, trays, racks, raceways, ground conductors, and shielding of other cables.
Depending on the material characteristics (ρ, μ, thickness, shape, etc.) a wide range of reduction factors can be achieved. This will be developed in more detail in subclause 5.4.1.2.

3) Combined action of balancing and shielding

Shielding is mainly effective at high frequencies (> 10 kHz) and acts directly on the voltages appearing between all the conductors and the ground (common mode), whereas balancing is more effective at low frequencies (< 100 kHz) and acts directly on the disturbing voltages appearing between conductors (differential mode). So it is clear that combining both techniques offers the best results. However, also here, there is no multiplication of the individual effects. The common mode voltages are partly converted into differential mode by the unbalances of the cable and of the load impedances, making it very difficult to predict the residual differential voltages. In particular, studies [9] have shown that the transfer impedance measured in differential mode does not always correlate with the same impedance measured in common mode and thus to the quality of the shielding.

4.2.2.4 Transfer impedance (and admittance) of cable shields

In the previous subclause the concept of transfer impedance of a shield was introduced.
Due to its very important role in EMC, it will now be presented and discussed in more detail.

Figure 39 represents a coaxial cable (i.e. a conductor with a shield) above a conductive reference plane.

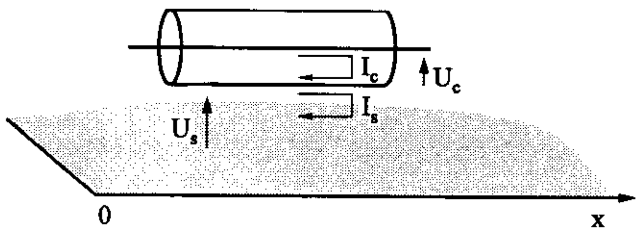


Figure 39 - Shielded conductor above a conductive plane

As far as EMC is concerned this cable can be seen as a set of two coupled transmission lines.
The first is composed of the inner conductor (**core**) and the outer conductor (**shield**) of the cable, the second being composed of the outer conductor (shield) and the ground plane (environment).
If I_C and I_S are respectively the currents flowing in the core / shield circuit and in the shield / ground circuit, and if U_C and U_S are the voltages between core and shield and between shield and reference plane, it is possible to describe the system by a set of linear differential equations [6]:

$$\begin{cases} -\dfrac{d\,U_C}{dx} = Z_c\, I_C - Z_t\, I_s \\ -\dfrac{d\,U_S}{dx} = -Z_t\, I_c + Z_s\, I_s \end{cases}$$

$$\begin{cases} -\dfrac{d\,I_C}{dx} = Y_c\, U_c + Y_t\, U_s \\ -\dfrac{d\,I_S}{dx} = Y_t\, U_c + Y_s\, U_s \end{cases}$$

with Z_C, Z_S, Y_C and Y_S being the per unit impedances and admittances of both lines, and Z_t and Y_t being the coupling impedance and admittance due to the common conductor, i.e. the shield.
Note here that Z_S is different from Z_t because it includes the ground impedance. Moreover, due to skin effect some natural decoupling occurs between both circuits modifying completely both impedances at high frequencies (see subclause 4.6.2).

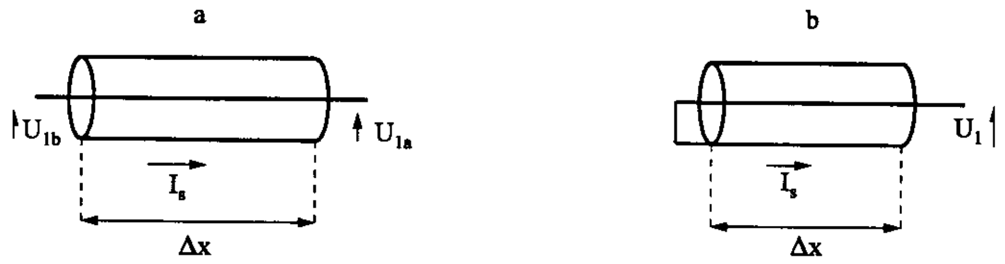
The coupling elements can now be derived from the previous equations:

$$\begin{cases} Z_t = \dfrac{1}{I_s}\left(\dfrac{d\,U_C}{dx}\right)_{I_C = 0} \\ Y_t = -\dfrac{1}{U_S}\left(\dfrac{d\,I_C}{dx}\right)_{U_C = 0} \end{cases}$$

The first parameter Z_t dx is the ratio of the voltage difference, measured between core and shield, at the two ends of a short section dx of the coaxial cable, to the current flowing in the shield when no current is flowing in the core (open-circuit measurement) (figure 40 a).

An equivalent arrangement with finite elements (Δx instead of dx), commonly used for making practical measurements, is given in figure 40 b.

Usually, up to a few tens of MHz, Δx can be chosen equal to 1 m.



$Z_t=(U_{1a}-U_{1b})/I_s\Delta x$ $\qquad$ $Z_t=U_1/I_s\Delta x$

Figure 40 - Transfer impedance of a shield

This ratio is the sum of a resistive and a reactive term. The resistive term is nothing other - at least at low frequency - than the resistance of the shield. The reactive term is due to the flux variation induced between the inner and outer conductors by I_s.
This flux is zero for a perfect homogeneous tube but will differ from zero whenever the shield has holes or discontinuities, or the current paths are not all parallel to the axis of the cable (e.g. for helically wound tapes or wires) as illustrated in figure 60.

When we compare these components with the expression for Z_t introduced in subclause 4.2.2.3, we see that they are equivalent (with $I_s = I_3$, $R_t = R_3$), the present approach being however more rigorous.

The expression $Z_t = R_t + j\omega L_t$ is thus nothing other than a simplified expression for the transfer impedance of the shield.
It characterises directly, at least for short cables (with respect to the wavelength), the level of common mode interference voltage induced into the cable (between wires and shield) when a disturbance current is flowing in the shield.

Appendix 4.6.2 gives an overview of the behaviour of Z_t as a function of frequency for different cable layouts.

By analogy with Z_t, Y_t is the ***transfer admittance*** resulting from the voltage U_s existing between the shield and reference plane. Contrary to Z_t which results from common impedance coupling and inductive coupling, Y_t reflects the importance of the capacitive current penetrating into the cable, through the openings in the shield, under the influence of the voltage applied to it (or the electric field). It is of lesser practical importance than the transfer impedance and will be discussed in subclause 4.2.3.

Importance of the transfer impedance

It has been shown in subclause 4.2 that the transfer function is a basic concept for solving any kind of coupling problem. Among all types of transfer functions that can be described, the transfer impedance of cable shields is one of the most important for several reasons:

1. it is an intrinsic parameter of each cable, is well known and can be measured and specified;
2. the cabling system of an installation plays one of the main roles in the coupling mechanism of disturbances;
3. knowledge of the transfer impedance of a cable allows - to a certain extent - the splitting of the general coupling problem into two steps which are usually easier to solve individually.
   The first step, sometimes called the *external problem*, consists of determining the current I flowing along the cable shield when the EM field illuminates it (or the current in the source in the case of the circuit theory approach).
   The second step, the *internal problem*, involves the determination of the common mode voltage U appearing at the extremities of the shielded cable.

This latter step is quite simple when the circuit length ℓ is small compared to the shortest wavelength, as then we have: $U = Z_t \ell I$.
It becomes more complex when this condition is not fullfilled. In this case it becomes necessary to find an expression such as: $U = f(Z_t, \ell, I)$, or to resort to computer solutions.

4.2.2.5 Examples of inductively coupled disturbances

- Switching operations in open air substations;
- Magnetic field produced by HV / LV installations at power frequency;
- Close indirect lightning stroke; i.e. a lightning stroke terminating near a circuit but not directly on it, as is usually the case when it is intercepted by an external lightning protection system;
- Electrostatic discharge in the vicinity of equipment.

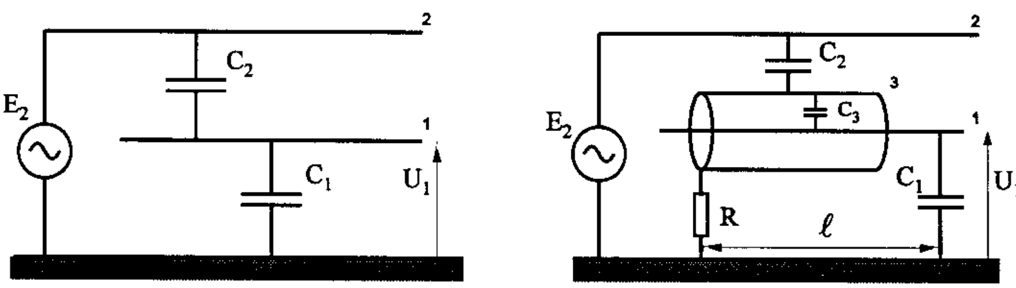
4.2.3 Capacitive coupling

4.2.3.1 Basic principles

Contrary to inductive coupling, capacitive coupling is due to the voltage of the source of the disturbance and not to the current flowing in it.
The coupling capacitances being quite low when the distance between source and victim is significant, capacitive coupling mainly occurs when the impedance of the victim circuit (or the common mode load impedances when the victim is a cable) is high and/or when source and victim are close together.
It is worth recalling indeed that the logarithm of the distance between conductors appears in the expression of the capacitance. As an example, two conductors in the same cable have a capacitance of approximately 100 pF/m. Increasing the distance between them by only 5 cm reduces the capacitance by a factor of 70 whereas a further increase up to 50 cm reduces the last value by less than a factor of 2.
This explains the importance of capacitive coupling in the problems of proximity between circuits (i.e. cross-talk).

The only way to reduce capacitive coupling, when an increase in the separation or a decrease in the impedance level is not possible (open-circuit strategy), is to put a screen around the circuit to be protected, with at least one point connected to ground (short-circuit strategy) (figure 41).

a b



$$U_1 = E_2 \frac{C_2}{C_2 + C_1}$$

$$U_1 \simeq j \omega R C_2 E_2$$

$$\text{if} \begin{cases} C_3 >> C_1 \\ \omega << 1/R(C_1+C_2) \\ \omega << 3\ 10^8/\ell \end{cases}$$

Figure 41 - Capacitive coupling and capacitive shielding

The quality of this screen is not as critical as that required for reducing magnetic coupling
Indeed it is no longer the transfer impedance which is applicable but the transfer admittance Y_t.

This latter depends on the structure of the holes in the shield and on the per unit length capacitances of the two coupled lines (source and victim) defined in the previous paragraph.
Braided cables with high covering ratios and cables covered by metallic foils or tapes (even helically wound) usually have a very low transfer admittance which can usually be neglected when the shield is connected to ground.
This is particularly true at 50 (60) Hz and explains why, for example, even non perfect conductors such as the walls of a house are sufficiently effective to cancel the E field, due to an external power line, inside the house.

However, the effectiveness of a screen in reducing disturbances due to electric fields only exists at low frequencies when the longitudinal impedances can be neglected with respect to the capacitances.
At higher frequencies it remains necessary to ground the screen at more than one point, and in particular at both ends of a cable.

4.2.3.2 Examples of capacitively coupled disturbances

- Low frequency electric field produced by HV installations, this kind of disturbance can sometimes be at the origin of security problems. Details about coupling calculations can be found in [20] and [21].
- Fast transients due to switching operations in LV equipment.
- Cross-talk in signal cables.
- Common mode coupling between primary and secondary windings of isolation transformers, optocouplers or voltage / current transformers in substations.

4.2.4 Radiative coupling

4.2.4.1 Near field / far field boundary

It has been assumed in the previous clauses that the circuit dimensions (including source and victim) were much shorter than the wavelength $\lambda = c/f$ corresponding to the highest significant frequency component f of the disturbance [3].
This is usually known as the *near field* or *induction* condition.
In the zone where this condition applies the ratio $Z_W = E/H$ of the electric field to the magnetic field, that is the ***wave impedance***, may assume any value.
When $Z_W < 377\ \Omega$ ($120\ \pi\ \Omega$), the magnetic field is dominant, the source is called a low impedance source involving large currents (and low voltages), and the inductive coupling model can be used.
Conversely, when $Z_W > 377\ \Omega$, the electric field prevails, the source has large voltages but low currents associated with it (high impedance source) and the capacitive coupling model is used.
As the distance from the source increases, the ratio E/H tends progressively to 377 Ω, the value of the ***free space impedance***. It becomes impossible to tell which field component prevails and the field is described as being a *radiated electromagnetic field.*

The distance at which this occurs determines the limit between the *near field* and the *far* or *radiated field* and depends on the dimensions of the source.
When the source is much smaller than the wavelength, the limit between the far field and the near field is at a distance $R = \lambda / 2\pi$ from it (about a sixth of the wavelength).
However, when the maximum dimension D of the source is greater than $\lambda/2$, the boundary distance becomes: $R \approx D^2 / 2\lambda$.
The variation of Z_W with the normalised distance x from the source, together with the rate of decrease of the transverse field components are described in figure 42 (the radial field components have been neglected).

---

[3] *When the disturbance is of an impulsive nature, the highest significant component of its spectrum, its cut off frequency, is usually given by the expression:*

$f = 1 / \pi \tau_r$ *where* τ_r *is the rise time of the impulse.*

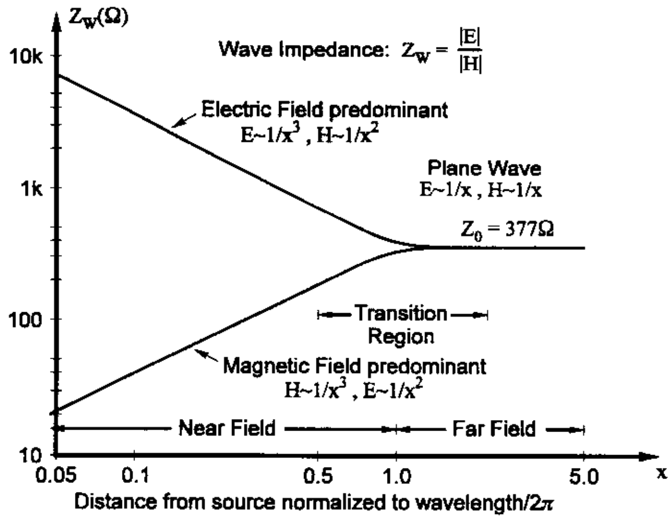


Figure 42 - Wave impedance as a function of distance and type of source, showing near-field and far-field regions

The main sources of radiated fields are lightning, switching of GIS, radio transmitters and walkie-talkies. The first two sources produce an impulse field, the other two a fixed frequency field.

For instance, a radio transmitter working in the medium wave band (f = 1 MHz) has a wavelength $\lambda = c/f = 3\ 10^8/10^6 = 300$ m, which means that radiation coupling takes place at distances larger than 300 / 2π ≈ 50 m.
Distances of the same order of magnitude will be obtained for lightning fields, as $\tau_r \approx 0{,}5\ \mu s$ and f ≈ 0,6 MHz.
On the other hand, the typical rise time of the field produced by switching operations in GIS is $\tau_r \approx 5$ ns. This corresponds to $\lambda \approx 4.5$ m; so radiative coupling can be considered to take place at less than 1 m!

Whenever the far field conditions apply, the study of the phenomena becomes very complex (particularly if the circuit itself is large compared to the wavelength) and it can no longer be approached by Kirchhoff theory. It is necessary to make resort to the general models based on Maxwell theory.

4.2.4.2 Mathematical models

As explained in the introduction (subclause 4.1.1), the coupling of electromagnetic fields to wire structures can be represented using two main mathematical models: the ***Scattering*** or ***Antenna*** theory and the ***Transmission Line*** approximation (TL).

Both modelling techniques require knowledge of the electromagnetic field, i.e. of the electric and/or magnetic field components in the vicinity of the structure illuminated by the field.

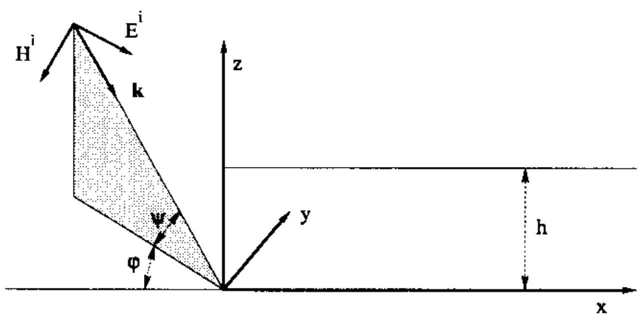


Figure 43 - Coupling of an electromagnetic plane wave with a conductor over a ground plane

Figure 43 shows the classical layout of an electromagnetic plane wave illuminating a conductor parallel to and at a height h above the ground plane.

The magnetic (H^i) and electric (E^i) components of the incident field are perpendicular to each other and to their vectorial product **k** (Poynting vector) which indicates the propagation direction of the field.

The plane containing **k** and perpendicular to the ground plane is called the *incident plane*.
When the E field component is contained within the incident plane and the H field component is parallel to the ground plane, the EM field is said to be *vertically polarised* or ***transverse magnetic* (TM).**
When it is the H component which is in the incident plane and the E component is parallel to the ground plane, the field is said to be *horizontally polarised* or ***transverse electric* (TE).**

It is always possible to split any EM field into the sum of a TE field and a TM field.

The general model using the scattering theory results in an integro-differential equation which can be solved only by numerical methods. This numerical solution involves the division of the structure to which the field is coupled into a number of segments for which the following condition has to be fulfilled:

$\ell_{segm} \leq \lambda / 10$ (with ℓ_{segm} the length of one segment).

This means that long structures have to be divided into a large number of segments, which results in significant memory and computing time demands.

For this kind of problem the Transmission Line approximation provides a powerful tool for solving the field-to-line coupling.
It was introduced in 1965 by Taylor, Satterwhite and Harrison for two conductors in free space, but since then a lot of work has been done to improve the possibilities of the method (see [6], [17], [18], for the main references).

As already mentioned in the introduction, the basic assumptions in the TL model are that the structure be a good conductor and that its transverse dimensions be small compared to the minimum wavelength, in order to allow only one mode of propagation i.e. the TEM mode (see below).
It should be recalled that in a wave guide - and a line is a particular case of wave guide - there are three possible modes of propagation:

1. *Transverse Electric* (TE), for which the electric field component along the guide (line) axis is equal to 0, i.e. $E_x = 0$;
2. *Transverse Magnetic* (TM), for which the magnetic field component along the guide axis is equal to 0, i.e. $H_x = 0$;
3. ***Transverse ElectroMagnetic* (TEM)**, for which both the electric and magnetic field components along the guide axis are equal to 0, i.e. $E_x = 0$, $H_x = 0$.

This means that the electromagnetic field is orthogonal to the guide axis or, alternatively, that the Poynting vector is parallel to it.

Strictly speaking, the propagation along a transmission line of the response to an external excitation is transverse magnetic (TM). However, owing to the small resistivity of the line, the axial electric field component is much smaller than the transverse components, which allows propagation to be considered as being ***quasi*-TEM**.

The model is described by the telegrapher's equations to which forcing functions are added. For a conductor over a soil of finite conductivity one more term appears in the forcing functions, namely the horizontal electric field component tangential to the ground surface. So the TL equations read:

$$\begin{cases} \dfrac{\partial U(x)}{\partial x} + Z' I(x) = j\omega \displaystyle\int_o^h B_y^e(x,o,z)dz + E_x^e(x,o,o) \\ \dfrac{\partial I(x)}{\partial x} + Y' U(x) = -Y' \displaystyle\int_o^h E_z^e(x,o,z)dz \end{cases} \tag{14}$$

where:

$E_z^e(x,o,z)$, $E_x^e(x,o,o)$, and $B_y^e(x,o,z)$ are respectively the vertical and the longitudinal electric field components and the transverse induction field component. The superscript e indicates that the ***excitation*** field is involved; this field, also sometimes called the ***applied*** field, is the sum of the

incident field [4] radiated by the disturbance source and the ground ***reflected*** field, both considered in the absence of the victim , i.e:

$E^e = E^i + E^r$ and $B^e = B^i + B^r$

(Note that the total field, which is not referred to, is in fact the sum of the excitation field and the field ***scattered*** by the illuminated structure, i.e.; the field radiated by the currents and charges induced in the structure: $E = E^e + E^s$ and $B = B^e + B^s$).

Z' is the distributed longitudinal impedance and Y' the distributed transversal admittance (the prime indicates per unit length):

$$Z' = Z'_i + Z'_g + j\omega L'_e \qquad (15)$$

$$Y' = \frac{j\omega C' Y'_g}{Y'_g + j\omega C'} \qquad (16)$$

$$\text{with } Y'_g Z'_g = -\omega^2 \varepsilon_g \mu_o \qquad (17)$$

$(\varepsilon_g = \varepsilon_{rg} \cdot \varepsilon_o \approx 10\,\varepsilon_o)$

In these expressions Z'_i represents the internal wire impedance (i.e. its frequency dependent resistance), Z'_g the ground impedance and L'_e the self inductance of the circuit formed by the conductor and the ground return.
It is worth noting that, for most practical HF problems involving power lines, aerial communication cables, etc., the internal impedance Z'_i of the cable can be neglected compared to the ground impedance Z'_g.
The calculation of the ground impedance represents one of the main problems for the coupling modelling. This is due to skin effect which cannot be described easily in the time domain and also, for both frequency and time domain calculations, to the non uniformity of the ground conductivity.

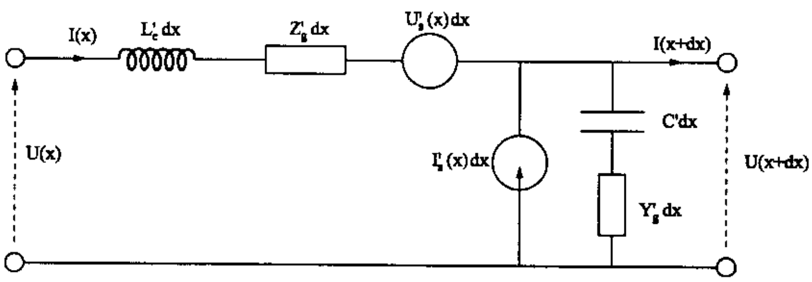


Figure 44 - Differential equivalent lumped circuit of a lossy wire-ground transmission line excited by an electromagnetic field

Figure 44 represents the equivalent lumped circuit of a line section excited by an electromagnetic field. The expressions for the lumped excitation voltage and current sources U'_s and I'_s (referred to as the source terms) are given by the terms in the second members of equations (14).

$$\begin{cases} U'_s(x) = j\omega \int_o^h B_y^e(x,o,z)dz + E_x^e(x,o,o) \\ I'_s(x) = -Y' \int_o^h E_z^e(x,o,z)dz \end{cases} \qquad (18)$$

The boundary conditions are expressed by the relationships:

$U(O) = -Z_A\, I(O)$ and $U(L) = Z_B\, I(L)$

where Z_A and Z_B are the load impedances at the origin O and the extremity L of the line.

Time and frequency-domain methods can be used to solve equations (14): at present, many computer codes are available (see appendix 4.6.4), in different universities and research centres of

[4] *Some authors use the word "incident" to qualify the excitation field and "primary incident" for the actual incident field, with the corresponding superscripts.*

electrical utilities, which can perform such coupling calculations. A validation of these theoretical approaches has been carried out ([25], [26], [27]) by means of EMP test facilities.

The advantage of using the time domain approach is that non-linear behaviour like that of surge protective devices can be modelled. On the other hand the frequency domain computation allows frequency dependent phenomena, like skin effect, to be taken into account in a more straightforward way.
Inverse Fourier techniques can be used to transform the frequency domain into the time domain.

The TL method can also be used without difficulty for multiconductor lines, in particular when the assumption is made that the modal speeds of voltages and current induced by the external electromagnetic field are not very different from one conductor to the other. The validity of this assumption has been verified by measurements.

The TL theory has also been extended to multiconductor lines with non-parallel conductors (figure 45) and even to structures for which the transverse dimensions are not negligible compared to the wavelength. [16]

A recent survey of different field-to-transmission line coupling models and also the description of some of the codes introduced in subclause 4.6.4 can be found in ref. [28].

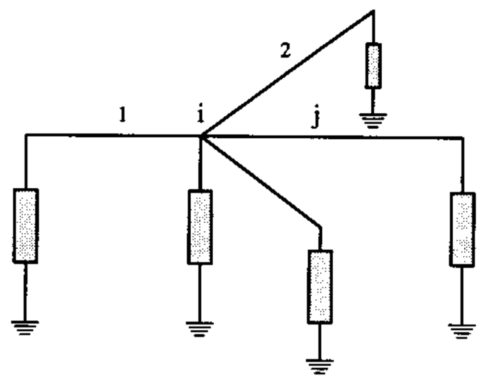


Figure 45 - Network with non-parallel multiconductor lines

4.2.4.3 Practical results

Computer simulation is required to determine which are the most important parameters which have to be taken into account when designing important cabling systems. Therefore more details about available codes can be found in appendix 4.6.4.

It is clear, however, that all the basic principles described in the preceding paragraphs and more particularly all the mitigation methods which derive from them are effective also for the reduction of HF disturbances resulting from radiative coupling.
Moreover the introduction of propagation phenomena means also the existence of attenuation. Therefore, at least in the context of substations and power plants, radiated disturbances are generally of lesser magnitude than those resulting from direct induction.

In order to illustrate this assertion we will briefly discuss one of the few analytical expressions derived from the TL theory.

It can be shown [6] that the mean value of the common mode voltage measured on a matched load at the end of a long shielded cable, grounded at both ends, and illuminated by an electromagnetic field, is given by the very simple expression:

$$U_L = \frac{2E_x^i h}{Z_{c3}} L_t \frac{c}{\sqrt{\varepsilon_r}} \qquad (19)$$

where Z_{c3} is the surge impedance of the shield/ground line, L_t is its transfer inductance (assumed to be much larger than its resistance), c is the speed of light, ε_r is the relative permittivity of the medium between conductor(s) and shield and h is the height of the cable above ground.

This expression shows that the mean interference level is in fact independent of the length of the line, whereas the expressions of subclause 4.2.2.3, which do not take into account any propagation effect are proportional to it, and lead to overestimation of interference levels.

On the other hand it should be pointed out that expression (19) is not valid when resonances occur, i.e. when the cable length is a multiple of $\lambda/2$.

It is well known that resonances, unless they are correctly damped, can considerably reduce the effectiveness of shielded cables. The paradox is that the better a shielding is, i.e. the higher its conductivity is, the higher the risk that resonances are not sufficiently damped. This is the main reason why cables with a double shielding, in contact only at the ends, have a shielding effectiveness much lower than would be expected from the measurement of the transfer impedance.

Another limitation of expression (19) comes from the assumption that the shielded cable is matched at its ends.
This is normally true for coaxial cables but not for balanced circuits where the common mode input impedance of the terminal equipment is usually higher than the characteristic impedance of the cables.
However, due to the significant decrease of the CM impedances with frequency, it can be assumed that this expression gives a good estimation of the interference levels that are met in practice.

4.2.4.4 Examples of radiated disturbances

- Electrical transient phenomena due to switching operations in GIS;
- Remote lightning stroke (a few hundred meters or more from the victim);
- High frequency field produced by radio transmitters.

4.3 Grounding of cable shields

We have seen in subclause 4.2 that the reduction of HF common mode disturbances requires the cable shield to be grounded at both ends, or more exactly, to be bonded to the shielding (enclosure) of the equipment.
It has also been shown that, at low frequencies (50/60 Hz, audio frequencies), it was sufficient - for reducing capacitive coupling only - to ground the shield at one end.

We will see now that, depending on the ratio of the load impedances, the degree of symmetry of the circuits and the grounding philosophy the common mode interference voltage will be differently shared between the extremities and possibly converted to differential mode. [5]

4.3.1 Low frequency common mode disturbance voltages

In the previous clauses, for simplicity reasons, the load and the CM interference voltage were presumed to exist at one end only.
Consider now the circuit of figure 46 in which a *longitudinal*[5] LF voltage E is applied to a shielded conductor with terminal impedances Z_S and Z_L, as can result from common impedance coupling or from inductive coupling.

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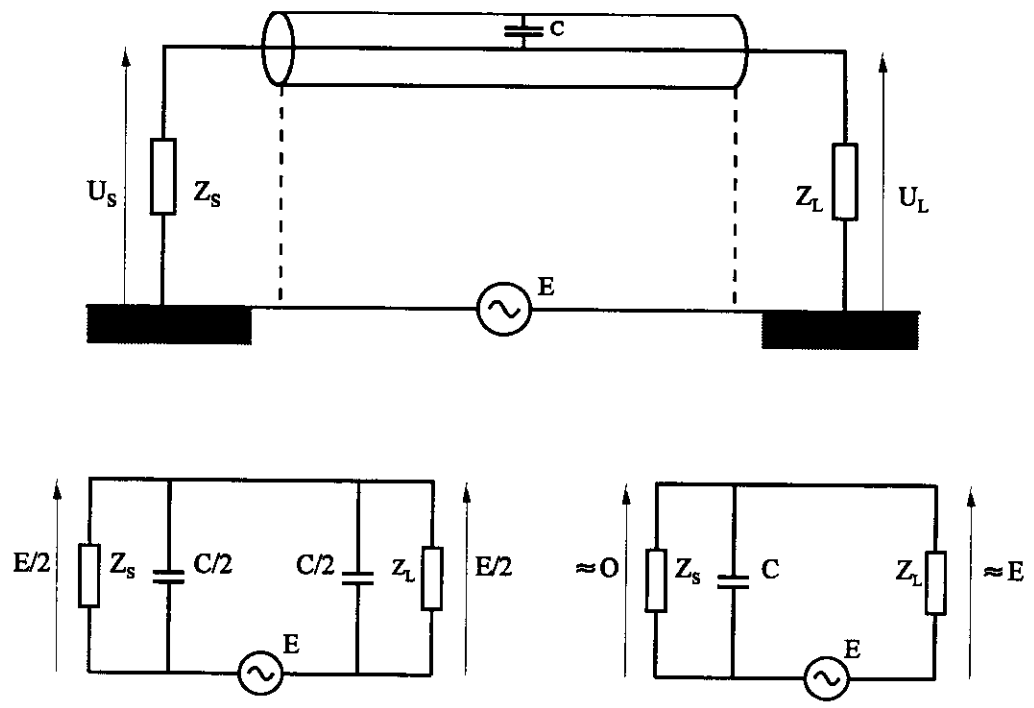
[5] *Longitudinal means normally between the extremities of a circuit or of a transmission line (or part of it). Remember that this concept is only valid at low frequency or when the measuring path is well defined. In this case, the measuring path is along the conductor inside the shield. It is thus nothing other than the voltage drop on the shield, as would result from a transfer impedance measurement. In other words,* ***it includes the shielding factor brought by the shield*** *as defined in subclause 4.2.2.3.*
However if the shield is grounded at only one end, no shielding factor can exist and the longitudinal voltage represents the actual voltage induced in the circuit formed by the conductor and the ground, or resulting from the resistive voltage drop in the ground (GPR).



shield grounded at both ends **shield grounded at one end**

Figure 46 - Voltage transfer from longitudinal to common mode

Suppose that the admittance jωC of the shield is large with respect to $1/Z_S$ and $1/Z_L$.

Suppose also that the longitudinal impedance $Z = R + j\omega L$ of the conductor (with ground return) is much smaller than the load impedances Z_S and Z_L. Then:

- if the circuit itself is grounded at one end, as in the layout a and b of figure 47 (i.e. Z_S or $Z_L = 0$), or if it is protected at one end by surge protective devices (SPDs) in working condition, or if the shield is grounded at only one end, its capacitance short-circuits the corresponding terminal impedance and the whole longitudinal voltage is transferred in common mode to the other end of the circuit;
- if the shield is grounded at both ends and the circuit is floating, as in the layout c of figure 47, where ungrounded transformers are reported, its capacitance becomes equally shared between both ends and the common mode voltages U_L and U_S are approximately equal to E/2;
- if the circuit is protected at both ends by SPDs, as in the layout d of figure 47, Z is no longer negligible compared to Z_S and Z_L, leading to values of U_L and U_S equal to the residual voltage of the SPDs.

The transfer of the longitudinal voltage in common mode to the extremities, as a function of the impedance ratio, is of great importance in many situations, especially in those involving isolating transformers with *grounded* or *ungrounded (floating)* mid point at the line side.

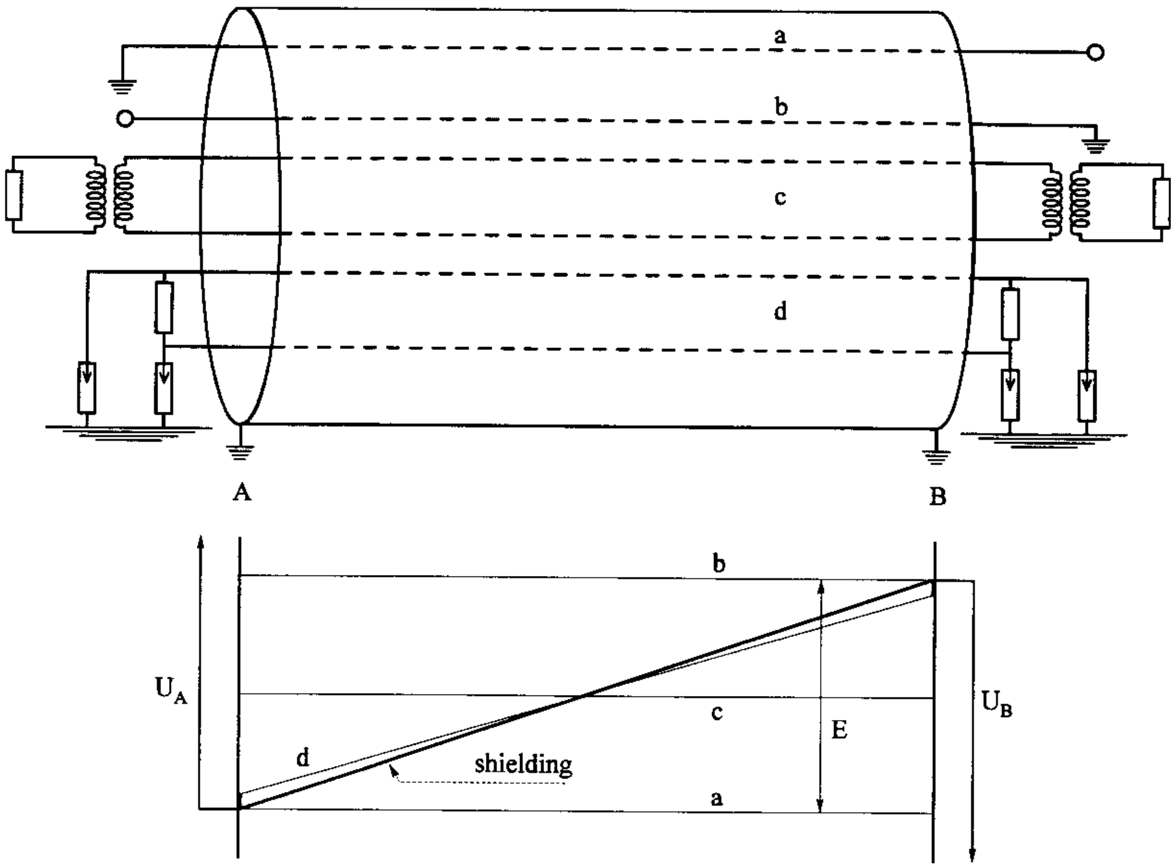


Figure 47 - Voltage profile for different types of circuits depending of the grounding practices

4.3.2 Low frequency differential disturbance voltages

The grounding of cable shields also plays an important role, at low frequencies, in the reduction of differential disturbance voltages (or ***transverse voltages***, or ***normal voltages***) due to imperfectly balanced symmetrical circuits.
An illustration of this mechanism is given in figure 48.

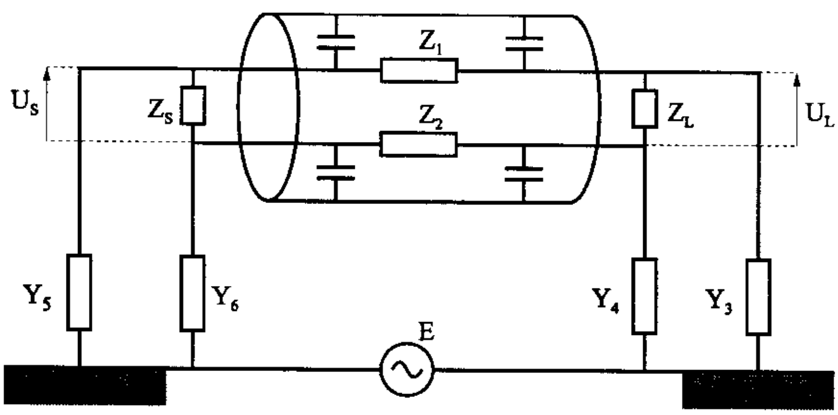


Figure 48 - Conversion from CM to DM voltages in low frequency unbalanced circuits

Depending on the value of the terminal impedances and their unbalance with respect to ground, and also the unbalance of the conductors themselves, differential disturbance voltages U_S, U_L will appear at each end.
It is not possible to study here and discuss in detail the complex expressions relating U to E.

We will consider only two important conclusions:

- in case of unbalance of the impedances (admittances) at one end (Y_3 - Y_4 or Y_5 - Y_6), the differential voltages will be minimum for the shield grounded at that end, maximum for the shield grounded at the other end and medium for the shield grounded at both ends.
  This results from the fact that grounding the shield at one end is equivalent to localising the capacitances between shield and conductors at that end. The connection in parallel of balanced capacitances with unbalanced admittances reduces the relative unbalance.
- the lower the input impedances (Z_S, Z_L) of the terminal equipment, the lower the differential disturbance voltages will be.

4.3.3 Practical rules for grounding signal cables

The following rules result from the above considerations:

Base rule

The shields of signal and power cables have to be grounded at both ends.

This is the best way to reduce common mode disturbances, particularly at medium and high frequencies.
The reducing factor remains significant (i.e. << 1) at low frequencies when the shield contains magnetic materials (steel, permalloy, ferrite).

Exception rule

The shield of signal cables has to be grounded at only one end when:

- A large current flow along the cable shield is feared.

  This can result from a fault in an unshielded power circuit or, simply, from the absence of a good earthing network (common impedance coupling).
  It is worth recalling, however, that it is *thanks to the current flow* in the shield that a reduction effect exists.
  This is the reason why it is always preferable to keep the shield grounded at both ends and to design its characteristics in such a way that it can sustain large current flows. If this is impossible install a ground wire in parallel or reinforce the earthing network;
- The circuit is used for transmitting low frequency, low level signals and presents major unbalances with respect to the shield or to the ground (e.g. thermocouples, thermoresistances, etc.).
  In this case ***the shield must be earthed at the end with the highest unbalance*** or where the circuit itself is earthed. All the circuits included in the shielded cable have to be grounded at the same end.
  If this is not possible then it is necessary to use galvanic or interference barriers (transformer, filter, etc.).
  For a long circuit it can be better to ground the shield at the end where the highest reduction of the differential voltage is desired (i.e. at the electronic equipment).

Particular rules

Double shielding, grounding through a capacitor or a SPD

It is sometimes possible, to a certain extent, to combine the advantages of the preceding rules by using:

- a double shielded cable of which only the external shield is grounded at both ends;
- a single shield of which one end is directly grounded and the other end is grounded through a capacitor (to prevent circulation of LF current) or through a surge protective device (SPD) to allow only lightning or fault current to flow in the shield.

Coaxial circuits

Coaxial cables are shielded cables where the shielding is used as the return path for the signal.

As such, the general rule appropriate for the active circuit should apply and the shield should be grounded at only one end.

However, coaxial cables are usually used for transmitting HF or VHF signals where, due to skin effect, a natural decoupling occurs between the currents flowing on the inner surface of the shield (signals), and those flowing on the outer surface of the shield (disturbances). Due to this phenomenon which has been described in subclause 4.2.2.4 dealing with transfer impedance, the shield of coaxial cables can in most cases be grounded at both ends.
This assumes, of course, that the disturbances are at high frequency or, if they are not, that the signals are high-pass filtered.

For long distance connections and in particular for connections involving different earth networks it remains advisable not to ground the shield at both ends or to put an ***Earthed Conductor in Parallel*** (ECP).

It is worth recalling that the earthing of a cable shield, in itself, is meaningless; it is only the consequence of the earthing of the equipment to which it is bonded (see figure 37).

Circuits with active elements at one end only

Even if a cable shield is grounded at one end only, high frequency disturbance currents are able to flow in it and to return to the ground by capacitive coupling.
Hence, for circuits involving sensitive circuits at one end only, it would be possible to reduce HF CM disturbances by grounding the shielding at that end only.
However this practice, if generalised, would introduce a lot of exceptions and would be in opposition with the trend to achieve, by multiple grounded conductors, a good equipotential bonding network (see clause 4.5).
For that reason, this practice has to be considered as an exception rule.

4.3.4 Summary of the main grounding practices for cable shields and circuits

Figure 49 illustrates the possible arrangements resulting from the above recommendations [6]. Each arrangement corresponds to a well defined category of situations in which reference is made to the different types of signals usually encountered in substations and power plants as described in subclause 5.1.2.
Although some arrangements are not symmetric with respect to the grounding, no indication is given about the respective location of the source and the load. This is because the circuit can be bi-directional and also because the choice of the grounding point is not always free. When the choice is free, the most sensitive equipment should be located at the grounded end.

Arrangement a

This is the most commonly recommended layout where the <u>signal circuit is grounded at one end</u> in order to avoid power frequency interference and the <u>shielding circuit is grounded at both ends</u> for optimum reduction of high frequency interference.
It is widely used for the connection of equipment in substation switchyards (signal type 4), and for process control signals or medium level digital signals in power plants (signal type 3).
It is not suitable for sensitive low frequency signals (type 2b) flowing in asymmetric (unbalanced) circuits, and can also cause problems in high speed digital circuits which have no ground reference (signal type 1a).

Arrangement b

In this arrangement, <u>not only the shield but also the signal circuit is grounded at both ends.</u>
This constitutes the best solution for high frequency circuits (signal type 1) but requires a very good equipotential bonding network which, in practice, can only be found in small area networks confined to the same premises.
Indeed, any longitudinal ground potential E, whatever its origin, even if reduced by the effectiveness k of the shield will be spread in common mode at both ends (with a ratio depending on the ratio of the load impedances).
However, as the common mode in this configuration is identical to the differential mode, no further reduction will occur. So, knowing that at low frequency k cannot be much smaller than 1, it is

[6] *This figure presents schematic configurations and not physical layouts. It is clear that each balanced circuit should be implemented following the rules defined in the previous paragraphs. In particular, balanced circuits should be made with twisted conductors, and grounding conductors should be as short as possible (or even coaxial).*

evident that this configuration has to be avoided whenever LF circuits are involved or large LF ground potentials are feared [7].

In order to avoid this problem, preference is usually given to a balanced layout (arrangement **c**) or to an arrangement in which LF and HF currents are separated (arrangement **e**).

Arrangement c

This utilises the _balanced circuit_ principle where the terminal equipment and the associated connections to the signal circuit are equally disposed (electrically) with respect to ground. Such a circuit can either float or employ a mid-point ground connection.
It is mainly used in remote control circuits where long transmitting distances are involved.
The cable shield is grounded at both ends and provides screening from longitudinal disturbances.
This arrangement is sometimes expensive but it solves problems of interference from the lowest (balanced circuit) to the highest frequencies (screening) and should therefore be used for all types of signals.

Arrangements d and d'

These are the _normal arrangements for low level signals_ (type 2a) when low frequency disturbances are present, in order to retain a low level of differential mode interference (unbalanced circuits). They can also be used for circuits where the ungrounded end (not protected against longitudinal interference) contains only passive or insensitive components.
When the comparison is made between the layouts of the two arrangements, it appears that arrangement **d'** with an ungrounded cabinet offers better protection (shielding continuity) but can sometimes lead to safety problems (touch voltage). Therefore it will usually be restricted to small pieces of equipment in the vicinity of the grounded equipment.

Arrangement e

In this arrangement _decoupling is introduced between the HF and LF currents by means of capacitors_, allowing benefit to be taken of the HF reducing factor provided by the double grounding, without fearing any LF differential interference resulting from the unbalance of the signal circuit.
The HF grounding of the signal circuit can result from stray capacitances or from the existence of decoupling capacitors.

Arrangement f

This _double shielded circuit combines the advantages of arrangements **a** and **d**_ giving good protection against all types of interference over the whole frequency range. It is therefore suitable for use with low level low frequency signals (type 2) in severe environments.

Arrangement g

A _multigrounded coaxial layout_ is generally used for carrying very high frequency signals to equipment which is reasonably insensitive to LF or HF interference. This is particularly so with microwave radio equipment of which the working frequencies are much higher than the usual interference frequency spectrum.
It is also widely used for high speed digital signals (type 1a) when distances are short (a few tens of meters) and when the existence of a good earthing network is guaranteed (see arrangement **b**).
It remains suitable for longer distances when the transfer impedance is low enough and the interference currents are limited by a good earthing network or by an Earthed Conductor Parallel (ECP) to the cable to protect.

Arrangement h

A _singly grounded coaxial layout_ is adopted whenever the circulation of (low frequency) disturbances in the outer conductor can interfere with the signal.
This can be the case for circuits linking different earth networks.

It can also be used for connecting floating equipment like video cameras or monitors.

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[7] *In fact, the only method to reduce the LF interference voltage in this configuration is to ensure that the load impedances be low compared to the longitudinal impedance of the conductors (i.e. their impedance with ground return). As the resistive part of this impedance is normally very small, only its inductive part can be increased, for instance by putting magnetic material around the conductors. This is the well known method used to achieve reasonable LF shielding.*

If necessary the floating equipment can be grounded via a capacitor (dotted line).

It is clear that, like in arrangement **f**, the use of a triaxial layout can sometimes solve all the possible interference problems and, as such, can be recommended for very sensitive circuits carrying, fo example, type **1** signals.

Arrangement i

As in arrangement ***e****, this layout makes use of capacitor for grounding the shield* and ensures good HF shielding effectiveness without the risks posed by the circulation of LF currents.

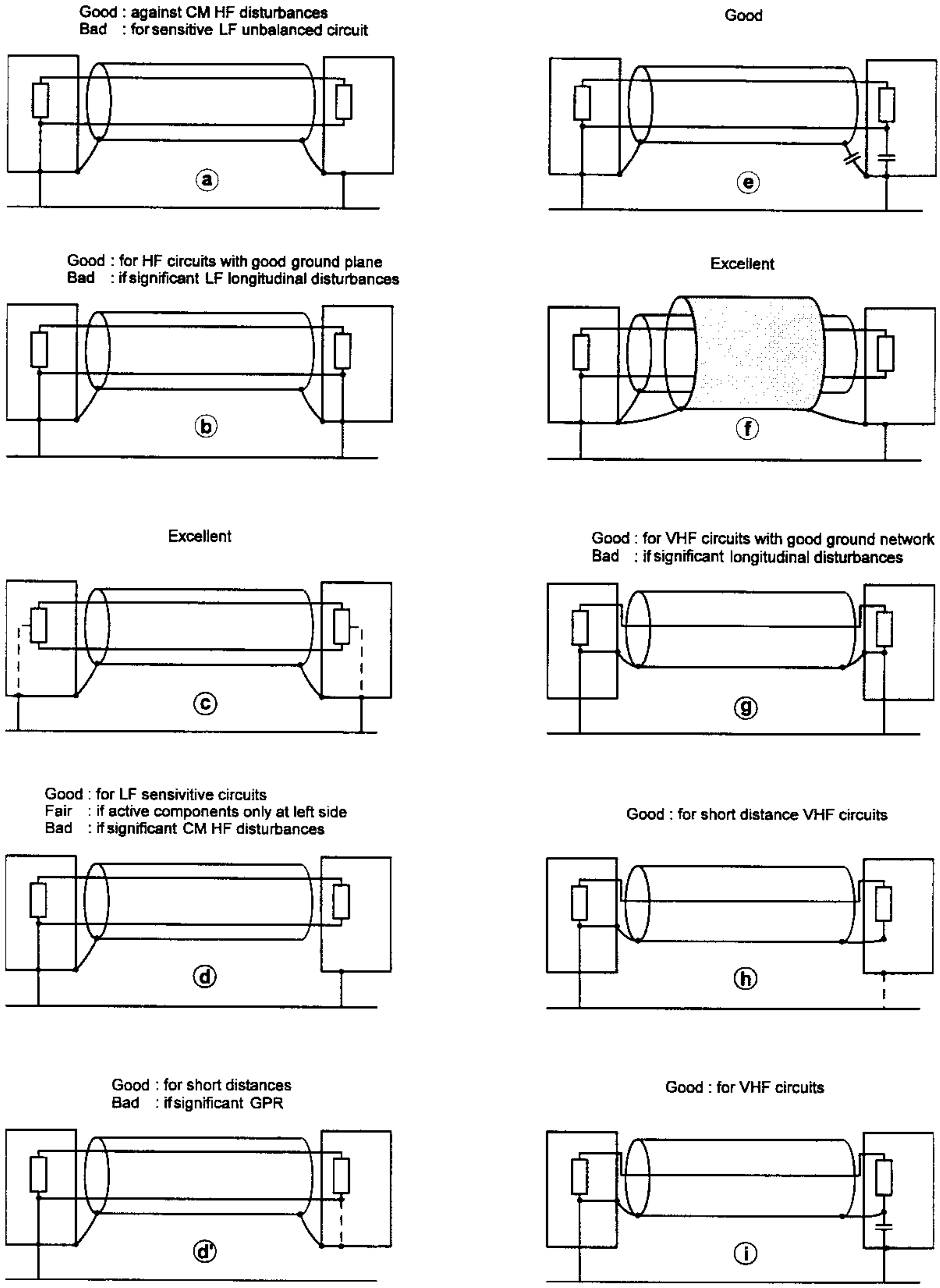


Figure 49 - Bonding practices for cable shields and circuits

4.4 Shielding by enclosures

4.4.1 Basic mechanisms

It has been shown in the previous clauses how a cable screen is able to reduce the interference level in a cable.

Depending on the type of coupling (capacitive, inductive) different mechanisms are involved.

The capacitively coupled disturbances, due to the electric field, are mainly reduced by the screen acting as a short-circuit ($Z_C \approx 0$ in the transfer function described in figure 26). It needs therefore to be grounded at least at one point.

The inductively coupled disturbances, due to the magnetic field, are reduced by the circulation of a current in the shield. This current acts as a secondary source counterbalancing the impinging field in the form of a buckler (a serial high impedance in the transfer function of figure 26). Of course, as already explained, the circulation of this current needs the screen to be grounded at least at two points.

These two shielding mechanisms, together with a third one, are also the basic mechanisms involved in the shielding of volumes by metallic sheets.

In the *electric shielding mechanism* better known as ***electrostatic shielding***, the electric field lines (lines of constant field) are bent toward the surface of the shield (figure 50a) as if they were attracted and short-circuited by the shield, with the result that the electric field is practically zero inside the shielded volume.

In the *magnetic shielding mechanism* better known as ***shielding by eddy current***, currents are induced within the shield - in the same way as they are induced into a cable shield - creating a new magnetic field which repels the external magnetic field lines (figure 50c).

The third mechanism (figure 50b), called ***magnetostatic shielding***, acts only on low frequency magnetic fields, exactly as the electrostatic shielding acts on the electric field. The shield offers to the magnetic field lines a low reluctance path (and not only a low resistance path, giving rise, in addition to the electrical short-circuit, to a magnetic short-circuit), with the result that they are bent towards the shield and that the field inside the shielded volume is reduced.
In order to be efficient, the shield needs to be thick with respect to the dimensions of the protected volume, it needs also, as far as possible, to completely enclose the protected volume (no gap or significant discontinuities), and it needs to be made of ferromagnetic material with high permeability (e.g. permalloy, ferrite or, in a lesser degree, steel, iron).

Among these three mechanisms, the shielding by eddy current is the more important and dominates largely at medium and high frequencies.

Eddy currents attenuate the magnetic field within the shield and prevent it from penetrating deeply. Therefore the concept of ***skin depth*** has been introduced. It is the depth at which the magnetic field is reduced by 3 dB, and it is given by the formula:

$$\delta = \sqrt{\frac{2}{\sigma\mu\omega}}$$

where σ is the conductivity of the material, μ its permeability and ω the angular frequency.

On this base it is possible to calculate the shielding effectiveness S_H of a shielded enclosure (supposed to be here, for the sake of simplicity, a sphere of radius r_o much smaller than the wavelength) [19], [23]:

$S_H = 20 \log H_e / H_i$

$H_e / H_i = ch\,(kt) + 1/3\,(K + 2/K)\,sh\,(kt)$

$k = (1 + j)\,\delta$

$K = k\,r_o / \mu_r$

where H_e is the external field, H_i the internal field, μ_r the relative permeability and t the thickness of the shield.

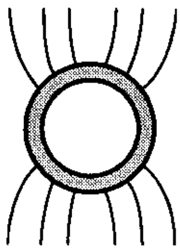
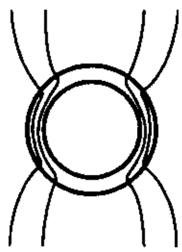
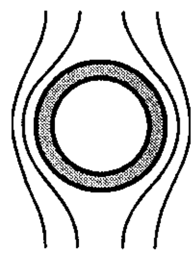
Usual name	Electrostatic	Magnetostatic	Eddy currents
Acts upon	E-field	H-field	H-field
Basic mecha-nism	Field lines end on charges in the shield	Field lines are absorbed by the shield	Induction currents in the shield repel the field lines
Required property of the wall material	Conductivity (at low frequencies a weak conductivity is sufficient)	High permeability	High conductivity (at low frequencies)
Efficiency at low frequency	Excellent	Good, when the wall is thick enough	Poor (non-existent for d.c.)
Efficiency at high frequency	Excellent (holes in the wall lead to increasing leakage)	Problematic: Eddy currents take over and $\mu_r \rightarrow 1$	Excellent (holes in the wall lead to increasing leakage)
	 a	 b	 c

Figure 50 - Shielding mechanisms [19]

When the shield thickness remains much smaller than the skin depth, it becomes possible to derive simplified expressions like (for a sphere of radius r_o):

$S_H = 10 \log \{ 1 + (\omega \mu_o r_o t \sigma / 3)^2 \}$

or for a cylinder of radius r_c:

$S_H = 10 \log \{ 1 + (\omega \mu_o r_c t \sigma / 2)^2 \}$

For higher frequencies when δ becomes comparable to t, but in the absence of any resonance phenomenon, the above expressions give conservative values (i.e. too low).

4.4.2 Travelling-wave concept

Another approach developed by Schelkunoff [22] is very often found in the literature to describe the two main shielding mechanisms.

It is based on an analogy between the transmission line theory with its characteristic impedance (mis)matching concept, and the way an incident electromagnetic wave is affected by the presence of a shield, i.e. of a medium with other propagation characteristics than free space (figure 51).

As already mentioned in subclause 4.2.4.1, the incident wave has its own characteristic (or wave) impedance $Z_w = E / H$ which is lower than 377 Ω for a predominantly magnetic field (transformer, coils, loop antenna, etc.), and higher than 377 Ω for a predominantly electric field (rod antenna, high voltage transmission line, etc.).

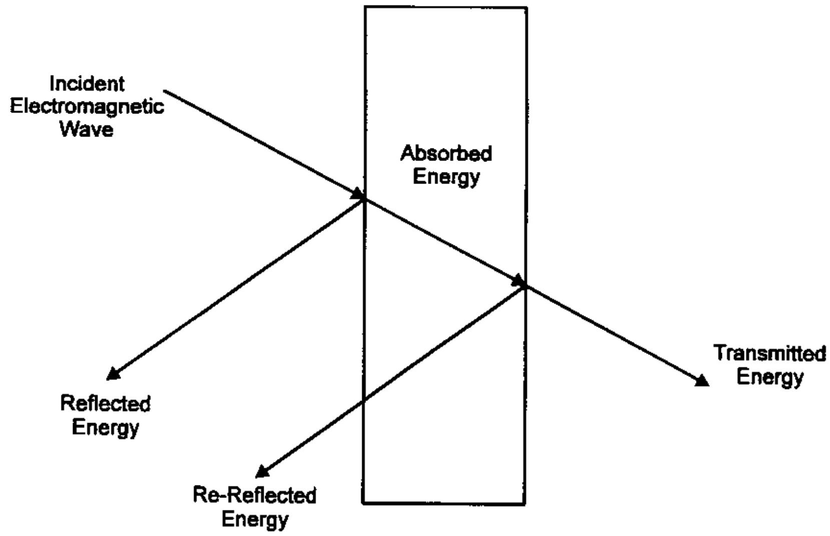


Figure 51 - Travelling-wave mechanism of a shielding

4.4.2.1 Reflection loss

When an EM wave impinges on a shield, it is partly reflected depending on the ratio of the wave impedance to the ***intrinsic impedance*** of the shield.

This latter is given by the formula:

$$Z_S = \sqrt{\frac{j\omega\mu}{\sigma + j\omega\varepsilon}}$$

or for a metal:

$$Z_S = \sqrt{\frac{j\omega\mu}{\sigma}} = 3.7\ 10^{-7}\sqrt{\frac{j\mu_r f}{\sigma_r}}$$

where the conductivity σ_r and the permeability μ_r are expressed relative to copper.

The higher the mismatch between Z_S and Z_W, the better the shield will be, as far as reflection is concerned.

The contribution to the shielding effectiveness due to this reflection mechanism (i.e. the *reflection loss*) is given by the expression:

$$S_R = -20\log\frac{(Z_S + Z_W)^2}{4 Z_S Z_W}$$

or, as Z_S is usually smaller than Z_W:

$$S_R = -20\log\frac{Z_w}{4 Z_s} = -20\log\frac{Z_w}{4}\sqrt{\frac{\sigma}{\mu\omega}} \quad \text{(dB)}$$

Although the theory of travelling waves does not apply to low frequency phenomena, it is sometimes mentioned in the literature that the easy shielding of LF electric fields is due to the fact that Z_W is always much smaller than Z_S.

This is nothing else than the *electrostatic shielding* effect presented previously.

As the value of Z_W (in air), for distances R between source and shield that are much smaller than $\lambda / 2\pi$, is given by: $Z_W = 1 / \omega\, \varepsilon_0\, R$, the reflection loss can be expressed in the following way:

$$S_{RE} = 322 + 10\log\frac{\sigma_r}{f^3 R^2 \mu_r} \quad \text{(dB)}$$

For the magnetic field, taking into account the lower value of Z_w, the reflection loss remains always quite poor.

Here the asymptotic value Z_w (in air) is given by: $Z_w = \omega \mu_o R$ for $R << \lambda / 2\pi$

Hence the corresponding reflection loss becomes:

$$S_{RH} = 14.6 + 10 \log \frac{f R^2 \sigma_r}{\mu_r} \quad \text{(dB)}$$

In the case of a plane wave, i.e. when $R >> \lambda / 2\pi$, $Z_w = \sqrt{\mu_o / \varepsilon_o} = 377\ \Omega$ and:

$$S_R = 168 + 10 \log \frac{\sigma_r}{\mu_r f} \quad \text{(dB)}$$

4.4.2.2 Absorption loss

The part of the EM field which is not reflected by the shield propagates through the metal where it is attenuated by skin effect.
This second important contribution to the shielding effectiveness is called *absorption loss*. It is independent of the nature of the incident wave and is given by the expression:

$$S_A = 8{,}7 \frac{t}{\delta} \quad \text{(dB)}$$

or

$$S_A = 132\, t \sqrt{f \mu_r \sigma_r} \quad \text{(dB)}$$

where: δ = skin depth; t = thickness.

This is the main mechanism involved in the reduction of magnetic fields.

Since maximum absorption implies minimum skin depth, the only parameter available to decrease δ, once high conductivity material is used, is the permeability μ of the material.
Obviously this implies that ferromagnetic materials must be used with the caveat, though, that saturation of the material must be avoided.

4.4.2.3 Total loss

Figure 51 illustrates the way an incident wave is partly reflected and partly absorbed by a metallic shield.
The total shielding effectiveness is the sum of the reflection and the absorption losses (to which, for absorption losses smaller than about 10 dB, an internal re-reflection term at the second metal-air interface should be added).

It should be stressed however that all the expressions given in subclause 4.4.2 are set for an infinite plane metallic wall and are seldom suitable for calculating actual shielding effectiveness of metallic enclosures the shape of which are much more complicated.
Moreover resonance phenomena inside a shielded enclosure can sometimes alter the calculation results.

Better results are usually obtained by the expressions based on the eddy current concept (subclause 4.4.1).

4.4.3 Transfer impedance of metallic enclosures

It has been shown in subclauses 4.4.1 and 4.4.2 how metallic shielding could attenuate an EM field, i.e. reduce the coupling between a source and a victim which are not in electrical contact with each other.

In most of the situations there exists some cabling between the shielded enclosure and the "outside world".
If this cabling is shielded and if this shield is correctly bonded to the enclosure, the current I flowing in the cable shield will flow across the enclosure and return either to ground, or to another cable shield.

Depending on the way the cable shields are bonded to the enclosure, on the way the enclosure is built (material, continuity, existence of openings, etc.), and on the coupling existing between the internal circuits and the enclosure, some interference voltage U will appear across the sensitive elements of these circuits.

The ratio U / I is by definition the transfer impedance Z_t of the enclosure (with respect to a particular circuit and to a particular port).

For a very well designed enclosure, the variation of Z_t with the frequency will exhibit a decrease at high frequency, thanks to skin effect. However in most practical situations, like for cable shields, some inductive effect will take over, reducing the overall shielding effectiveness of the system (enclosure plus cable).

The transfer impedance of metallic enclosures is a very important factor which is often ignored or neglected.
In can be shown in particular that for HF conducted disturbances like the well known fast transients or the electrostatic discharges this parameter plays one of the most important roles in the coupling mechanisms.

4.5 Earth networks and bonding networks for EMC

As referred to in subclause 4.2.1, two philosophies exist for the realisation of a bonding network.

- The star network
- The meshed network

4.5.1 Star network or isolated bonding network

The principle of the star network is to connect each piece of equipment to the earth network at one point only by single and direct links which may be shared only by equipment belonging to the same circuit or system (figure 52). [11]

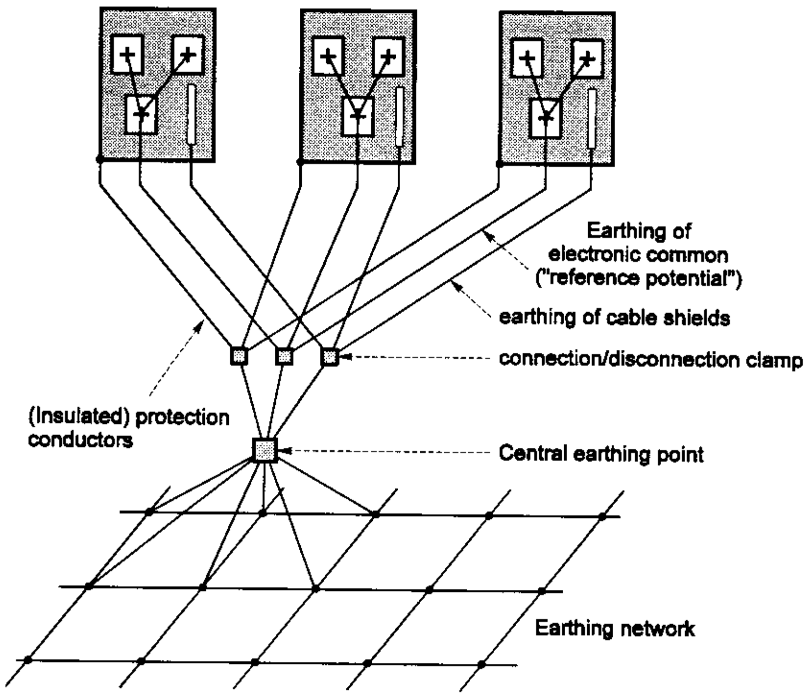


Figure 52 - Star grounding network

The idea is to prevent, as far as possible, common impedance coupling due to current flowing in the earth network.
This practice is no longer advisable today - at least in its strict application.

Indeed:

- it is worth recalling, at first, that a grounding system never resembles a sewage system where more and more drainage pipes converge into one main pipe with "unknown" destination (figure 53a). Instead, a grounding system is a group of interlinked current loops (figure 53b);
- the connection to earth in figure 53b is not unique but is only part of a current loop, as Kirchhoff's law - or the more general Gauss' law: div $(J + \partial D/\partial t) = 0$ - prescribes that each current injected into the ground comes back to its source by at least one other conductor.

So two situations can arise: either the equipment is connected to earth by a single link and no current will ever flow through it; or the disturbances do indeed flow through this link but come back to the equipment by other unwanted and uncontrolled routes.

Furthermore, notwithstanding this basic principle, the earthing conductors are necessarily long and thus very inductive and inefficient at high frequencies. Considering that modern electronics is especially sensitive to high frequency disturbances like fast transients and electrostatic discharges, it is easy to understand why this grounding method is obsolete.

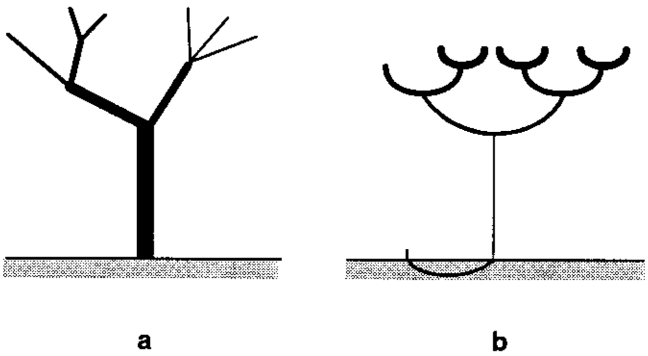


Figure 53 - Incorrect (a) and correct (b) picture of what a grounding system is supposed to do. The thickness of the lines corresponds to the magnitude of the currents

4.5.2 Meshed network

Contrary to the star network, the meshed network (figure 54) is composed of a great number of highly interconnected conductors. No effort is made to avoid ground loops, but only to try keeping their area small in order to reduce the impedances.

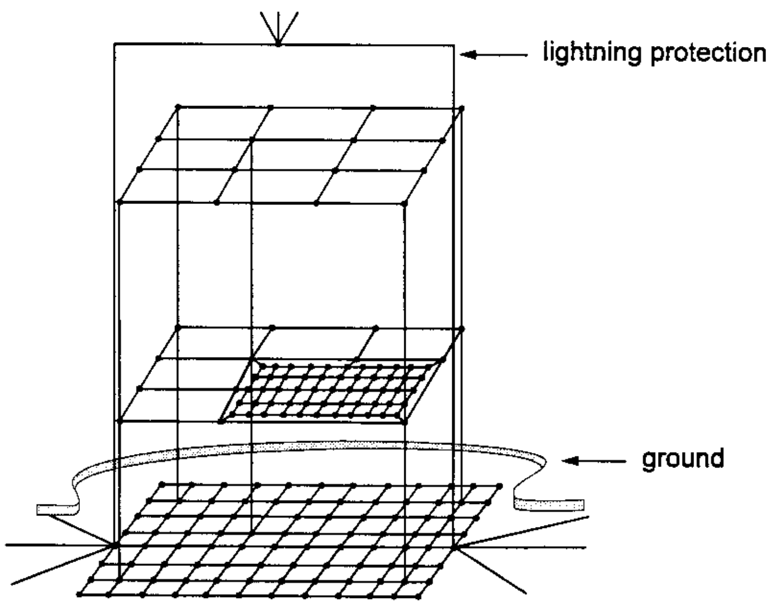


Figure 54 - Meshed grounding network

In fact there is a trend to carry out ***equipotential bonding*** which constitutes not only a low impedance return path but also a shield against electromagnetic fields (see subclause 4.4.1).
With this technique becoming more widespread in the electrical and telecommunication world [2], [3], all existing metallic structural parts, both horizontal and vertical, are used (frames, rails, I-beams, concrete reinforcing, cable supports, a.c. power conduit, etc.).
In this way a tridimensional ground plane is implemented which can be, in turn, connected to the earth network (protective ground) at several points.
The more sensitive the installed equipment is (e.g. computers), the tighter the ground mesh should be.
One of the major advantages of the bonding network - in addition to its high effectiveness - is that it is very easy to build up, does not require any controls or checks, and is self-developing. Indeed all new equipment, all new bonding elements and all new shields automatically reinforce the overall effectiveness of the network.
With a good meshed network, the isolated earthing conductors can be eliminated (with the exception, of course, of the PE safety conductor) along with the incredible "screened earth" which, as the Loch Ness monster, reappears regularly in some publications.

4.5.3 Hybrid network

Some organisations are supporters of mixed structures offering the advantages of the meshed network at local level - for instance each floor or each room of a building - but keeping a single connection to earth for the circulation of external currents i.e. lightning.

This concept, justified in some installations, has certain drawbacks:

- first the problem exists of the interconnection between the safety bonding network (PE conductors) and the EMC bonding network. This leads to the necessity to use isolating transformers or class II equipment;
- furthermore, all the Isolated Bonding Networks (IBN) have to be very well and completely thought through during conception. There is no question afterwards of adding a new link (telecommunication cable, LAN, etc.) between equipment belonging to different IBNs without the use of galvanic isolation.

The system is really complex and difficult to maintain. The slightest accidental loop closing occurs necessarily through long inductive paths and produces large voltage drops with all the drawbacks they bring (figure 55).

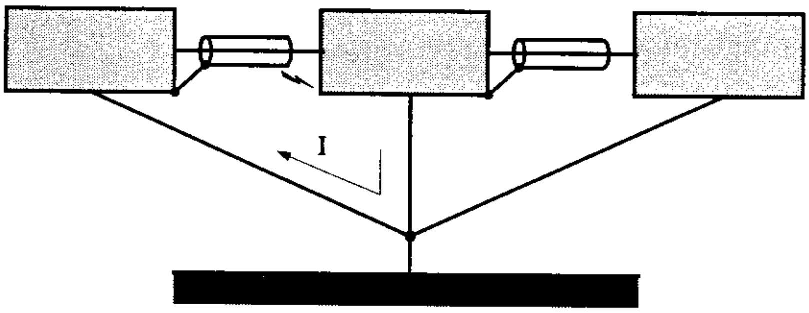


Figure 55 - Flash-over and current return path in a star network

Finally the method of grounding all cable shields at both ends - which, it should be remembered, is best for the majority of the cases - is practically impossible to carry out.

The only principle that we would retain from hybrid networks is that it is always worth keeping away from each other those circuits which can strongly interfere, i.e. circuits with large differences in voltage or current.
For example, one should avoid installing sensitive electronic equipment near a lightning down conductor (or any conductor liable to play that role, like a ventilation shaft, or a lift). The conductors for lightning protection are, in that respect, the only ones which we recommend to be interconnected with the meshed network at ground level only.
However, this is not always easy to implement (and sometimes impossible like in some telecommunication buildings); also here an installation with multiple interconnections (figure 56a) will behave better than an installation with single connection to ground, presenting a high risk of flashing over (figure 56b).

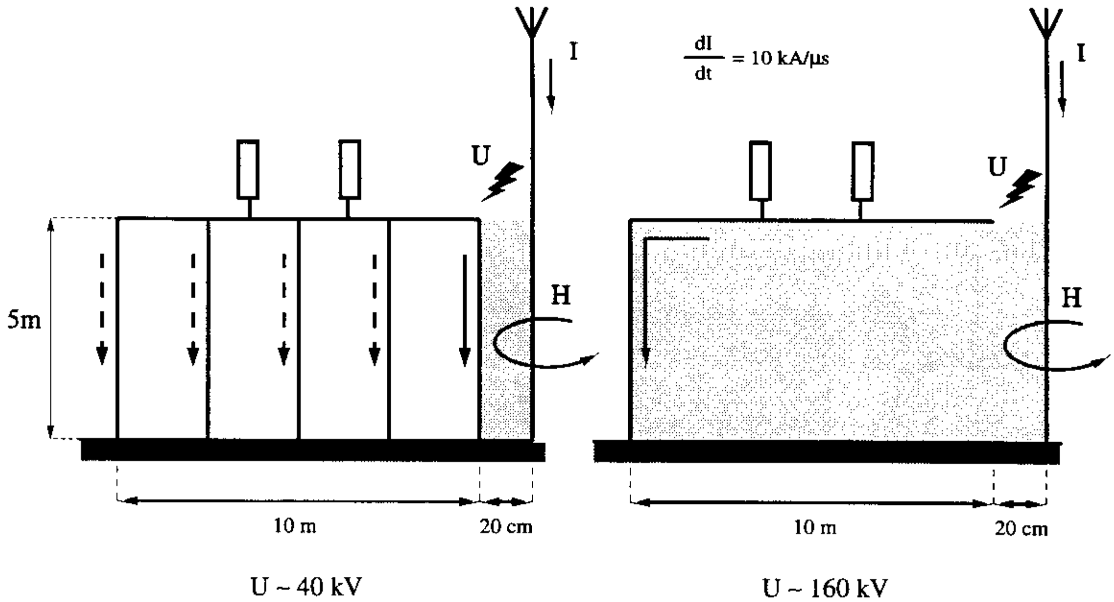


Figure 56 - Voltage induced by lightning in two different grounding structures involving multiple or single grounding conductors

4.6 Appendix

4.6.1 Self and mutual inductance of parallel conductors

Consider two closed circuits which are long compared to their height (figure 57a).

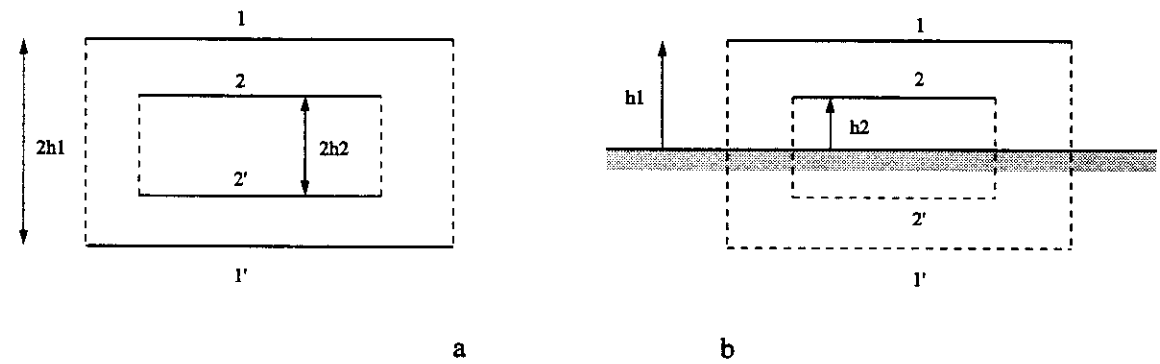


Figure 57 - Equivalence between a symmetrical circuit and an asymmetrical circuit involving its electric image

The per unit length value of the flux induced in circuit 1 by a current I flowing in conductor 2 and a return conductor at infinity is:

$$\Phi_{11',2\infty} = I\frac{\mu}{2\pi}\ln\frac{D_{21'}}{D_{21}}$$

with D_{ij} being the distance between conductors i and j

For the same reason:

$$\Phi_{11',2'\infty} = I\frac{\mu}{2\pi}\ln\frac{D_{2'1'}}{D_{2'1}}$$

So the flux induced in circuit 1 by circuit 2 is:

$$\Phi_{11',22'} = I\frac{\mu}{2\pi}(\ln\frac{D_{21'}}{D_{21}} - \ln\frac{D_{2'1'}}{D_{2'1}}) = I\frac{\mu}{2\pi}\ln\frac{D_{21'}.D_{2'1}}{D_{21}.D_{2'1'}}$$

which leads to a mutual inductance of:

$$M_{12} = M_{11',22'} = \frac{\mu}{2\pi}\ln\frac{D_{21'}.D_{2'1}}{D_{21}.D_{2'1'}} \quad \text{or:}$$

$$M_{12} = \frac{\mu}{2\pi}\ln\left(\frac{h_1+h_2}{h_1-h_2}\right)^2 = \frac{\mu}{\pi}\ln\frac{h_1+h_2}{h_1-h_2}$$

Making circuit 2 equal to circuit 1 leads to:

$$M_{11',11'} = L_{11'} = L_1 = \frac{\mu}{2\pi}\ln\frac{D_{11'}.D_{1'1}}{D_{11}.D_{1'1'}} = \frac{\mu}{\pi}\ln\frac{D_{11'}}{D_{11}} = \frac{\mu}{\pi}\ln\frac{2h_1}{r}$$

with $r = D_{11} = D_{1'1}$ the mean geometric radius of conductor 1 (1').

Suppose now that conductors 1 and 2 have the ground as return path and that the ground is a perfect conductor (resistivity $\rho = 0$). It can be shown, with the electric image theory, that this layout is equivalent to that of conductors having their return paths at a depth equal to their height above ground (figure 57b).

So the per unit length self and mutual inductances of conductors 1 and 2 should be identical to those calculated for figure 57a. However, if the electrical image theory can be applied to calculate the flux above ground, this flux must be equal to zero in the ground (supposed to be perfectly conductive in this theory), and the values of the corresponding inductances have to be divided by a factor two compared to those of figure 57a:

$$M'_{12} = \frac{\mu}{2\pi}\ln\frac{h_1+h_2}{h_1-h_2}$$

(or more generally if the conductors are not in the same vertical plane: $M'_{12} = \frac{\mu}{2\pi}\ln\frac{D_{21'}}{D_{21}}$)

$$L'_1 = \frac{\mu}{2\pi}\ln\frac{2h_1}{r}$$

These expressions are also valid at high frequency when the soil is not a perfect conductor.

At low frequency the surface of the soil can not be considered as a mirror plane.
The image theory may however be applied thanks to the introduction of a complex image plane ([20] Volume II, subclause 4.1.2) which is placed below the ground surface at a complex distance depending of the soil resistivity ρ and of the frequency f.

For power frequency, including harmonics, the simplified Carson - Clem formula [20], can be applied for calculating the mutual and self inductance with ground return.

In this calculation the equivalent distance D_e of the hypothetical return path is given by:

$$D_e = 659\sqrt{\frac{\rho}{f}}$$

Hence, assuming $h << D_e$, the above expressions become at 50 Hz:

$$M'_{12} = \frac{\mu}{2\pi}\ln\frac{93\sqrt{\rho}}{h_1-h_2}$$

$$L'_1 = \frac{\mu}{2\pi}\ln\frac{93\sqrt{\rho}}{r}$$

In air, for a ground resistivity of 100 Ω·m and a conductor radius of 1 cm we get:

$L'_1 = 2\ \mu H/m$

This value can be compared with the traditional value of 1 µH/m given for a single conductor at high frequency.

4.6.2 Variation of Z_t with frequency

It has been shown in subclauses 4.2.2.3 and 4.2.2.4 that the transfer impedance Z_t of a cable shield relates to a resistive voltage drop IR_t along the shield and an induced voltage $j\omega IL_t$ between core and shield.

In fact the relationship between Z_t and ω is not so simple, R_t and L_t being themselves complex and frequency-dependent.
So the decomposition of Z_t into a resistive and an inductive component is only a simplified approach intended to apply circuit theory concepts to the phenomena.

A more rigorous description of the physical behaviour of Z_t with the frequency will be given now.

"Resistive part": (component that decreases when the frequency increases)

For a homogeneous shield the variation of R_t with frequency is quite easy to understand:
When the frequency increases the current I_s due to skin effect tends to flow on the outer part of the shield. So, paradoxically, although the resistance of the shield, as measured in the external circuit (U_s, I_s in figure 39) increases with frequency, the voltage drop on the inner part of the shield, measured in the inner circuit as in figure 40, decreases.
The decrease of R_t with frequency depends on the shield thickness t, its conductivity σ and its permeability µ.
An approximate expression of R_t is given by:

$$R_t = \frac{R_{to}(1+j)\ t/\delta}{sh[(1+j)t/\delta]} \approx \frac{R_{to}}{1-e^{-\delta/t}} \quad \text{for } \delta < t$$

with $\delta = \sqrt{\frac{2}{\omega\mu\sigma}}$ the skin depth, and R_{to} the d.c. value of R_t

The cut-off frequency at which R_t starts to decrease is:

$f_c = 1 / \pi\, t^2\, \mu\, \sigma$

The higher the frequency, the lower the coupling between the two transmission lines will be. This refers to the well known high frequency behaviour of coaxial cables (already referred to in subclause 4.2.1) under the influence of ***diffusion***.

This behaviour remains valid - to some extent - for other kinds of cables where the shield arrangement approaches that of a continuous tube. This is the case, in a certain frequency range, for braided shields with braid angles α close to 45° (figure 58).When this angle is very different, other physical mechanisms, such as described below, dominate.

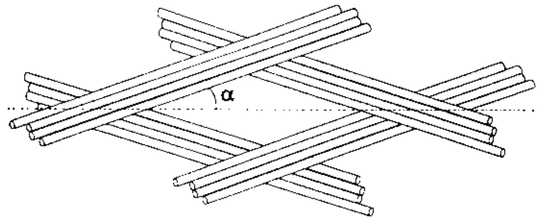


Figure 58 - Braid angle of a shield

"Reactive part" *(component that increases with the frequency)*

The reactive part of Z_t, when it is present, seems to be partly due to the **diffraction** (leakage) of the electromagnetic field through the openings in the shield and partly to the **induction** of eddy currents in the inner layers (stranded conductors) of the shield by the currents flowing in the outer layers.

The first contribution is mainly encountered in braided shields and is responsible for a quasi-linear increase of Z_t with frequency.
It depends on the braid angle and on the ***Filling factor*** F.
This latter factor is a measure of the braid density and is expressed in % (it is worth pointing out here that the filling factor F differs from the classical factor K called ***Optical coverage factor (or ratio)***.They are however related to each other by the expression: $K = 2F - F^2$).

The second contribution to L_t is based on the same diffusion phenomenon described for the homogeneous shield and is usually responsible for an increase of Z_t proportional to $\sqrt{\omega}$.

It is also important to note that shields based on helically wound tapes or wires always exhibit a linear increase of Z_t with frequency.

Figure 59 gives some examples of transfer impedance measurements made on a set of four-conductor shielded cables used in power plants. It highlights very clearly the important differences that exists at high frequency between the different shielding arrangements.

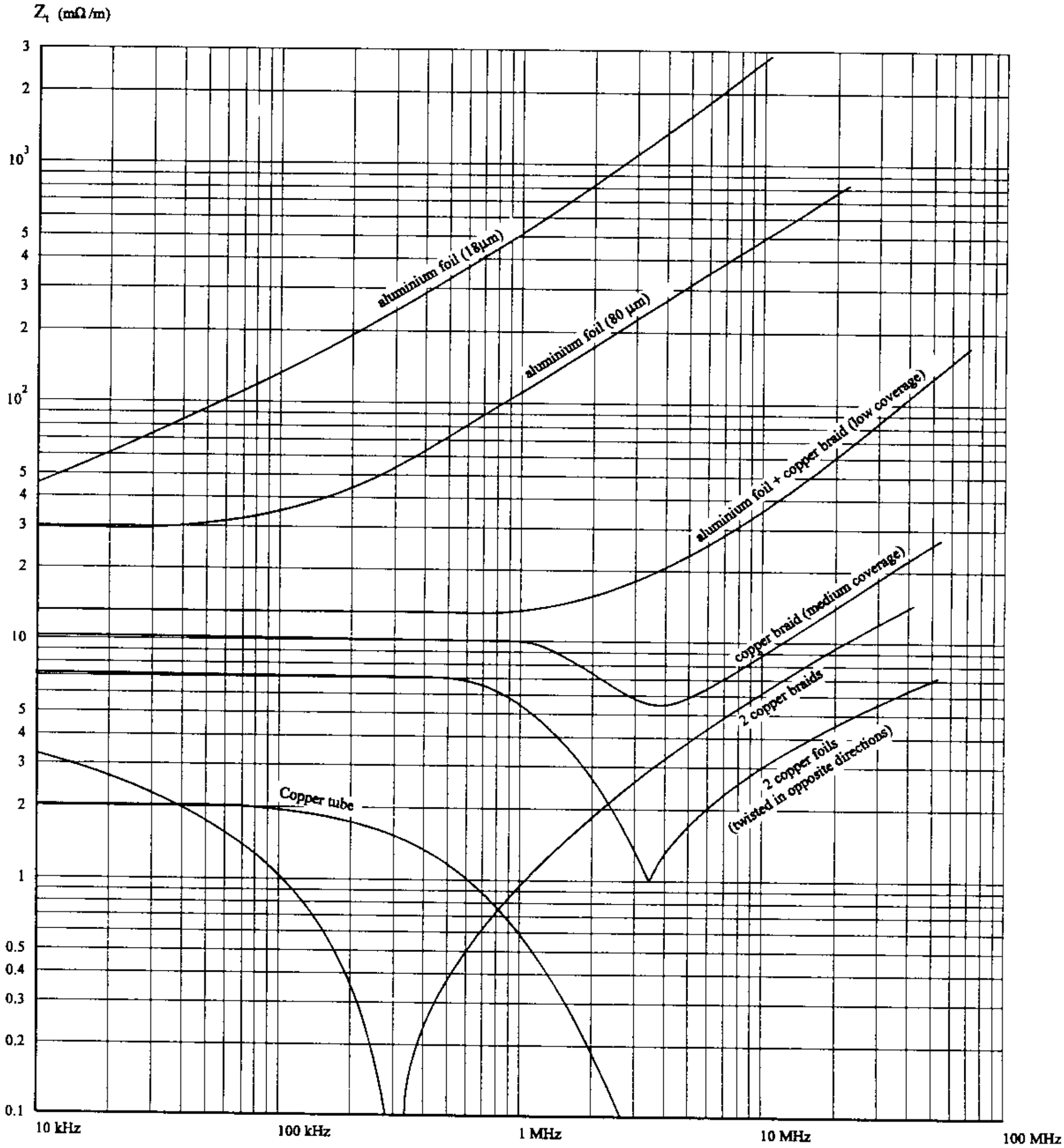


Figure 59 - Typical transfer impedances of shielded cables used in power plants

4.6.3 Shielding effectiveness of long cables

It can been shown [6] that when a progressive current wave $I_3 = I_{3o}\, e^{-\gamma x}$ flows on the shield (see figure 36).of a matched coaxial cable (whose transfer admittance can be neglected), the voltages U_{1S} and U_{1L} appearing between core and shield respectively at the origin and at the extremity (referred here as Source end and Load end) of the cable are given by the expressions:

$$U_{1S} = \frac{I_{3o}}{2} Z_t\, \ell \frac{1-\exp\left(-(\gamma_1+\gamma_3)\ell\right)}{(\gamma_1+\gamma_3)\ell}$$

$$U_{1L} = \frac{I_{3o}}{2} Z_t\, \ell \frac{1-\exp\left(-(\gamma_1-\gamma_3)\ell\right)}{(\gamma_1-\gamma_3)\ell}\exp(-\gamma_3\ell)$$

where Z_t is the transfer impedance of the shield,
ℓ is the length of the cable,
γ_1 and γ_3 are respectively the propagation constants of the waves flowing between shield and ground and between core and shield.

Assuming low loss circuits, $\gamma \cong j\omega / v$, with v the propagation velocity, these expressions become:

$$|U_{1S}| = I_{3o}\, Z_t\, \ell\, F_S(\omega\ell)$$

$$|U_{1L}| = I_{3o}\, Z_t\, \ell\, F_L(\omega\ell)$$

where $F_S(\omega\ell) = \dfrac{\sin\frac{\omega\ell}{2}\left(\frac{1}{v_1}+\frac{1}{v_3}\right)}{\frac{\omega\ell}{2}\left(\frac{1}{v_1}+\frac{1}{v_3}\right)}$, and $F_L(\omega\ell) = \dfrac{\sin\frac{\omega\ell}{2}\left(\frac{1}{v_1}-\frac{1}{v_3}\right)}{\frac{\omega\ell}{2}\left(\frac{1}{v_1}-\frac{1}{v_3}\right)}$

Knowing that $F(x) = \dfrac{\sin x}{x}$ is equal to 1 when x tends to 0 and presents different zeros, the first of which appears at $x = \pi$, the variation of F_S and F_L with frequency will look as in figure 60, with:

$$f_S = \frac{1}{\left(\frac{1}{v_1}+\frac{1}{v_3}\right)\ell} \quad \text{and} \quad f_L = \frac{1}{\left(\frac{1}{v_1}-\frac{1}{v_3}\right)\ell}$$

These expressions show that the cut-off frequencies depend on the length of the cable and on the speeds of the waves inside the cable and between cable and ground.

If the current I_3 in the shield, instead of having the shape of a simple progressive wave, has any other shape, it is still possible to calculate the interference U_1 by means of a Fourier expansion. [12]

On the other hand, let I_1 be the current flowing in the inner conductor in the absence of any shielding; in this case, the interference voltage appearing across a matched load Z_{c1} at the end will be:

$U'_1 = Z_{c1}\, I_1$

Suppose, in order to be able to apply the above equations, that the circuit formed by the shield and the ground is also matched, then:

$I_1 \approx I_3$

With these assumptions, the *reduction factor* can be expressed as:

$$k = \left|\frac{U_1}{U'_1}\right| = \frac{Z_t\, \ell}{2 Z_{c1}} F(\omega\ell)$$

and the *shielding effectiveness* : S = - 20 log k with $F(\omega\ell) = F_S(\omega\ell)$ or $F_L(\omega\ell)$, depending on whether the disturbance is flowing from or towards that end.

As shown in figure 61, the magnetic field H_{ext} due to the CM current in the wall of a coaxial system penetrate to some part through the openings in the wall. This leakage flux induces a DM voltage which can be measured at the end of the cable and is responsible for the increase of Z_t with frequency.

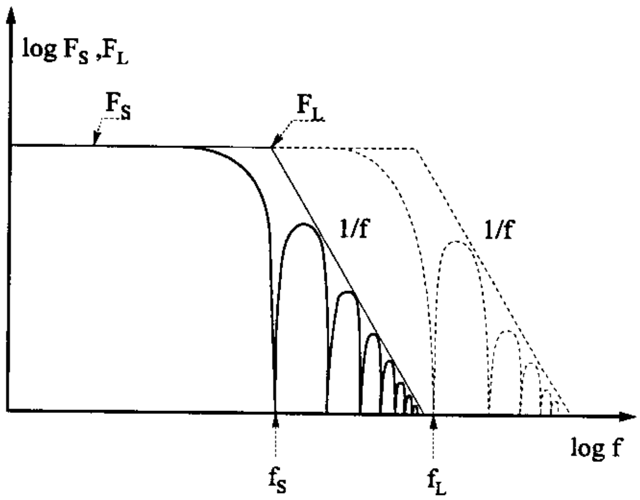


Figure 60 - Envelope of the voltages measured across matched loads at the extremities of a long cable when a progressive current wave flows along its shield

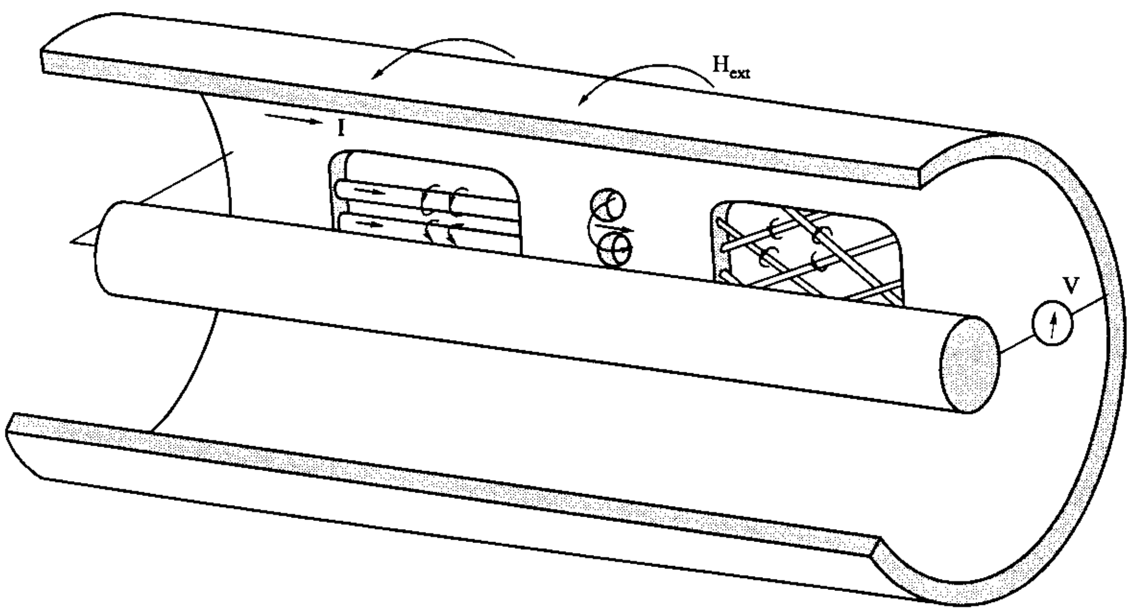


Figure 61 - Penetration of external magnetic field in the wall of a coaxial system

4.6.4 Electromagnetic field and coupling codes

A large variety of codes which calculate electromagnetic fields from various sources and field coupling to lines and cables have been reported in the EMC literature.

The codes which are listed in this Guide are known by the authors of the Guide to be codes which have been validated by comparison with measurements.

Any suggestion from authors of codes validated by experiments are very welcome and will be integrated in further editions of this Guide.

Electromagnetic Field Codes

These codes permit the calculation of the disturbing electromagnetic field due to different sources.

The sources which will be considered are :

1. transient phenomena due to switching operations of circuit breakers or disconnectors;
2. lightning;
3. HEMP.

Note - For the HEMP, the exciting electromagnetic field is given as a standard double exponential function defined by IEC 1000-2-9.

Coupling Codes

The coupling codes have been developed mainly for aerial lines (power and telecommunication lines) and are not always suited for data transmission lines in substations and control cables.

Coupling and circuit codes

This case applies to installations connected to lines and protected by non-linear protection circuits. In this case, coupling codes linked to time-domain circuit codes have been developed.

Grounding codes

The grounding codes concern mainly the calculation of the behaviour of grounding structures under transient phenomena.

4.6.4.1 Electromagnetic field due to switching operations

ANAPOST

Author: Laboratoire de Génie Electrique, Institut National Polytechnique de Grenoble and EDF.

Inquiries and purchasing address:

EDF, Direction des Etudes et Recherches, Service Matériel Electrique, Laboratoire de Génie Electrique, Les Renardières, BPNo. 1, F-77250 Moret sur Loing, France,
Tel.: (+331) 60736652, Fax: (+331) 60736956.

4.6.4.2 Direct lightning effects

EMTP **(ElectroMagnetic Transients Program)**

Author: H. Dommel.

Input: an average channel-base lightning current introduced as a localised current source which is injecting a current in the network.

Output: The currents and voltages in any node of the network.

Two main versions available today:

1) ATP (Alternative Transients Program).

Advantage: Permits the introduction of personal models of circuits.

Disadvantage: less user friendly input/output.

Inquiries and purchasing address:

W. Scott Meyer, BPA, Floor 4, Post S-14, 905 N.E. 11th Avenue, Portland, Oregon 97232, USA, Tel.: (+1503) 230-4404, Fax: (+1503) 230-3212.

or for distribution within Europe:

Prof. Dr. M. Kizilcay, EEUG e.V, FH Osnabrueck, FB E, Albrechtstr. 30, D-49076 Osnabrueck, Germany,
Tel.: (+49541) 969 3065, Fax: (+49541) 969 3070/2936.
E-Mail: kizilcay@hermes.iz.fh-osnabrueck.de

2) MicroTran.

Advantage: More user friendly input/output. Possible numerical instabilities have been cancelled.

Disadvantage: no possibility to introduce personal models.

Inquiries and purchasing address:

Mr. L. Marti, Microtran Power System Analysis Corporation, 4689 West 12th Avenue, Vancouver, BC V6R 2R7, Canada,
Tel.: (+1604) 275-4726, Fax: (+1905) 275-5639.

4.6.4.3 Indirect lightning effects

4.6.4.3.1 Electromagnetic field codes

The existing codes are written using lightning return stroke models based on measured values of the channel-base current from natural or triggered lightning. [29], [30]

LEMPFIELD

Authors: Ecole Polytechnique Fédérale de Lausanne and Università di Bologna.

Information and purchasing address:

Prof. C.A. Nucci, Università di Bologna, viale Risorgimento 2, I-40136, Italy,
Tel.: (+3951) 644 3475, Fax: (+3951) 644 3470.
E-Mail: nucci@eleib1.ing.unibo.it

Prof. M. Ianoz, LRE/DE, EPFL, CH-1015 Lausanne, Switzerland,
Tel.: (+4121) 693 2664, Fax: (+4121) 693 4662.
E-Mail: michel.ianoz@lre. de.epfl.ch

Input: Lightning discharge parameters.

Output: Electromagnetic field as a function of time in a number of points.

Advantages:

- user friendly input and output (graphical) will be available;
- simplified validated expression for the calculation of the horizontal electric field component, taking into account the finite soil conductivity.

Improvements of the code are in progress in order to obtain a user friendly input/output and to write a user manual.

4.6.4.3.2 Coupling codes

These computer programs analyse the behaviour of an overhead electrical cable excited by the return-stroke portion of a near-by lightning strike. Analysis models for treating the line excited by an incident plane-wave field, such as that produced by a nuclear electromagnetic pulse (HEMP), have been used successfully for a number of years and several computer codes have been developed for conducting rapid numerical studies. These codes extend the frequency- or time-domain analysis techniques to the case on non-plane-wave incident fields. These fields are produced by a cylindrical travelling-wave current source which represents the lightning discharge channel. Because of the more complex spatial behaviour of the incident fields, the required integrals of the fields for the coupling to the lines cannot be performed analytically. The resulting numerical integration increases the computation time but reasonable results can be obtained in a few minutes on a personal computer.

In the following list, except the codes linked to EMTP and NEC, the others can take into consideration only simple geometries of transmission lines : straight multiconductor lines terminated on a load at each end. The NEC code has the disadvantage to be not very user friendly and needs more computer time.

For tree-shaped lines parallel to a ground plane, the development of more user friendly codes is in progress.

Two types of solutions are used:

- in the Frequency-Domain;
- in the Time-Domain.

A) Frequency-Domain Codes

The resolution of the coupling equations is performed in complex values. The result is converted in the time-domain using inverse Fourier Transform techniques.

LTLINE

Author: Dr. F.M. Tesche, Electromagnetic Consultant, Dallas, TX, USA.

Information and purchasing address:

www site: http://www.tesche.com
or
Dr. F.M. Tesche, 9308 Stradford Way, Dallas 75220 TX, USA,
Tel.: (+1214) 956 9378, Fax: (+1214) 956 9379.
E-Mail: 72461.3170@compuserve.com

Calculation method: Transmission Line theory, analytical solution in the frequency-domain, conversion by inverse FFT in the time-domain.

Input: lightning electromagnetic field.

Output: currents and voltages induced on transmission lines.

Advantages:

- in the Frequency-Domain;
- site on internet;
- user friendly data input;
- available user manual;
- soil with finite conductivity.

Disadvantages: can be used only for one straight overhead line.

B) Time-Domain Codes

Solutions are found by numerical methods.

LIOV

The code is equivalent in Bologna and Lausanne and presents only small differences mainly in the mathematical routines used for integration.

Authors: Università di Bologna and Ecole Polytechnique Fédérale de Lausanne.

Information and purchasing address:

Prof. C.A. Nucci, Università di Bologna, viale Risorgimento 2, I-40136, Italy,
Tel.: (+3951) 644 3475, Fax: (+3951) 644 3470.
E-Mail: nucci@eleib1.ing.unibo.it

Prof. M. Ianoz, LRE/DE, EPFL, CH-1015 Lausanne, Switzerland,
Tel.: (+4121) 693 2664, Fax: (+4121) 693 4662.
E-Mail: michel.ianoz@lre. de.epfl.ch

Calculation method: Transmission Line theory.

Input: Electromagnetic field components in a number of points along the line(s), line parameters and line configuration.

Output: Currents and voltages induced at any point of the line.

Advantages:

- user friendly input and output (graphical) will be available;
- soil with finite conductivity;
- can take into account discontinuities along the line (e.g. ground wires periodically grounded).

Disadvantages:

- only straight multiconductor lines;
- not very rapid for finite conducting ground.

Improvements of the code are in progress in order to obtain a user friendly input/output and to write a user manual.

4.6.4.3.3 Coupling linked to circuit

A) Time-Domain Codes

LIOVTRANS

In this code the LIOV coupling code of University of Bologna (and EPFL) has been linked to EMTP.

LIOV-EMTP interface authors: CESI and University of Bologna.

Technical information:

Prof. C.A. Nucci, Università di Bologna, viale Risorgimento 2, I-40136, Italy,
Tel.: (+3951) 644 3475, Fax: (+3951) 644 3470.
E-Mail: nucci@eleib1.ing.unibo.it

Mr. R. Iorio, CESI, via Rubattino 54, I - 20134 Milano, Italy,
Tel.: (+392) 21 25 236, Fax: (+392) 21 25 492.
E-Mail: iorio@cesi.it

Purchasing address: Mr. R. Iorio, CESI, via Rubattino 54, I - 20134 Milano, Italy
Tel.: (+392) 21 25 236, Fax: (+392) 21 25 492.

Input: Electromagnetic field components in a number of points along the line(s), line parameters and line configuration.

Output: lightning induced-voltages on the line and at the equipment.

Advantage: use of the environment of a well-known code like EMTP with a large spectrum of possibilities for modelling complex circuits (transformers, non-linear protection devices).

Disadvantage: at present relatively complicated input.

EIFFEL

This code is an optimised version of LIOV.

EIFFEL - EMTP interface authors: EDF and EPFL.

Technical information:

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Dr. Ph. Baraton, EDF, Dir. E&R, LGE, Les Renardières, B.P. 1, Ecuelles, F-77250 Moret sur Loing, France,
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E-Mail: nucci@eleib1.ing.unibo.it

Purchasing address:

Mr. A. Xémard, EDF, Direction des Etudes et Recherches, 1 Av. du Gén. de Gaulle, BP 408, F-92141 Clamart Cedex,
Tel.: (+33)147 653463, Fax: (+33) 147 654157.
E-Mail: alain.xemard@edfgdf.fr

Input: Electromagnetic field components in a number of points along the line(s), line parameters and line configuration.

Output: lightning induced-voltages on the line and at the equipment.

Advantage: use of the environment of a well-known code like EMTP with a large spectrum of possibilities for modelling complex circuits (transformers, non-linear protection devices).

Disadvantage: at present relatively complicated input.

B) Frequency-Time-Domain Codes

ANASTASIA

Author: CNET + EDF.

Anastasia is a combined frequency and time-domain code in which a coupling code has been linked to EMTP. The coupling code calculates lightning-induced voltages in any point of the line. These voltages represent distributed sources along the line and are used as excitation sources for EMTP.

Advantage: same as for EIFFEL and LIOVTRANS.

Disadvantage: the use of a large number of input sources needed to simulate the distributed sources can be cumbersome and time consuming.

Inquiries and purchasing address:

Mr. A. Xémard, EDF, Direction des Etudes et Recherches, 1 Av. du Gén. de Gaulle, BP 408, F-92141 Clamart Cedex,
Tel.: (+33)147 653463, Fax: (+33) 147 654157.
E-Mail: alain.xemard@edfgdf.fr

4.6.4.4. HEMP

4.6.4.4.1 Electromagnetic field codes

TOTALFLD

The TOTALFLD code is designed to compute the total (i.e. incident plus ground-reflected) electromagnetic fields at a particular height h over a lossy earth. It will also calculate the EM fields transmitted inside the earth at a depth h.

Author: Dr. F.M. Tesche, Electromagnetic Consultant, Dallas, TX, USA.

Information and purchasing address:

www site: http://www.tesche.com
or
Dr. F.M. Tesche, 9308 Stradford Way, Dallas 75220 TX, USA,
Tel.: (+1214) 956 9378, Fax: (+1214) 956 9379.
E-Mail: 72461.3170@compuserve.com

Calculation method:

This code assumes that the incident field is a plane wave having a simple user-specified time domain behaviour. The reflected field from the ground or the field transmitted into the ground is determined by the electrical conductivity of the soil and the relative permittivity, as well as by the angles of incidence and polarisation.

Input: an incident EMP field.

Output: For this code, the following quantities are calculated:

- the time dependent E and H field vector components (six waveforms) at the specified observation point for the user-specified excitation waveform,
  and
- the frequency domain spectrum for the six E and H-field vector components at the observation location, resulting from the spectrum of the incident E-field.

Advantages:

- site on internet;
- user friendly data input;
- available user manual;
- soil with finite conductivity.

4.6.4.4.2 Coupling codes

A) Frequency-domain codes

NULINE

Author: Dr. F.M. Tesche, Electromagnetic Consultant, Dallas, TX, USA.

Information and purchasing address:

www site: http://www.tesche.com
or
Dr. F.M. Tesche, 9308 Stradford Way, Dallas 75220 TX, USA,
Tel.: (+1214) 956 9378, Fax: (+1214) 956 9379.
E-Mail: 72461.3170@compuserve.com

Calculation method: TL theory, analytical solution in the frequency-domain, conversion by inverse FFT in the time-domain.

Input: an EMP field.

Output: currents and voltages induced on transmission lines.

Advantages:

- site on internet;
- user friendly data input;
- available user manual;
- soil with finite conductivity.

Disadvantages: can be used only for straight multiconductor lines.

RISER

Author: Dr. F.M. Tesche, Electromagnetic Consultant, Dallas, TX, USA.

Information and purchasing address:

www site : http://www.tesche.com
or
Dr. F.M. Tesche, 9308 Stradford Way, Dallas 75220 TX, USA,
Tel.: (+1214) 956 9378, Fax: (+1214) 956 9379.
E-Mail: 72461.3170@compuserve.com

Calculation method:

similar to NULINE. NULINE has a very simple treatment of the vertical ends of a long transmission line connected to the earth, and consequently, its accuracy for early-time responses was not adequate. As a result, the RISER code was developed which treated each end of the transmission line as separate transmission line sections, each having a length equivalent to the height of the line over the ground. This, combined with the overall transmission line model for the horizontal line provided a more accurate calculation model for a real line.

Input: an EMP field.

Output: currents and voltages induced on transmission lines.

Advantages:

- site on internet;
- user friendly data input;
- available user manual;
- soil with finite conductivity.

Disadvantages: can be used only for straight multiconductor lines.

LTLINE and TOTALFLD as well as NULINE and RISER can be free downloaded at the following Internet address: ftp://ftp.wiley.com. Wiley's tech support line is +1 212 850 6194.

B) Time-domain codes

HEMPLINE

Author: Ecole Polytechnique Fédérale de Lausanne.

Information and purchasing address:

Prof. M. Ianoz, LRE/DE, EPFL, CH-1015 Lausanne, Switzerland,
Tel.: (+4121) 693 2664, Fax: (+4121) 693 4662.
E-Mail: michel.ianoz@lre.de.epfl.ch

Calculation method: TL theory, numerical solution using finite differences.

Input: an EMP field.

Output: currents and voltages induced on transmission lines.

Advantages:

- user friendly data input;
- soil with finite conductivity;
- can take into account discontinuities along the line (e.g. ground wires periodically grounded).

Disadvantages: can be used only for straight multiconductor lines.

4.6.4.5 EMfield coupling to metallic structures or EM field radiated by a metallic structure

NEC **(Numerical Electromagnetic Code)**

Author: Lawrence Livermore Laboratory (USA).

Inquiries and purchasing address:

G.L. (Jerry) Burke, L-156, Lawrence Livermore National Laboratory, PO Box 808, Livermore, CA 94550, USA,
Tel.: (+1510) 422-8418.
E-Mail: BURKE@icdc.llnl.gov

Calculation method: scattering theory, solution by moment's method.

Input:

1. a dipole antenna which represents an electromagnetic field source, or a plane wave, or
2. an array of wires excited by a known current.

Output:

1. the currents induced in an array of wires representing a complicated structure of transmission lines excited by a source of type 1, or
2. the field radiated by an array of wires representing circuits of complicated structures.

Advantages: Complicated structures can be calculated.

Disadvantages:

- no user friendly input of data;
- the calculation must be repeated for a significative number of frequencies (256 or 512) in order to obtain correct solutions in the time-domain using the inverse FFT technique.

4.6.4.6 Grounding

CDEGS **(Current Distribution Electromagnetic Fields, Grounding and Soil Structur Analysis)**

The CDEGS Package contains several subpackages and codes to analyse problems involving electromagnetic fields, electromagnetic interference, grounding and other capabilities. No validations of the codes of this package with experimental measurements have been published.

Author: SES (Safe Engineering Services & Technologies Ltd).

Information and purchasing address:

SES, 1544 Viel, Montréal, Quebec, Canada, H3M 1G4,
Tel: (+1-514) 336-2511, Fax: (+1-514) 336-6144.

TRAGSYS **(Transient Analysis of Grounding Systems)**

Author: Prof. Dr. Leonid Grcev, Electrotechnical Faculty, University "St. Cyril and Methodius", Skopje, Macedonia.

Calculation method:

TRAGSYS is aimed for computing the low and high frequency, and the transient behaviour of grounding structures. It uses an antenna theory model based on a rigorous integral formulation derived from the complete set of Maxwell's equations. The solution is obtained in frequency-domain and the transient response by inverse Fourier transform techniques. Results are extensively validated by comparison with field measurements by the Electricité de France and by comparison with other authors' models. The link between TRAGSYS and EMTP is under development.

Input: Geometrical data of a network of connected or separated buried conductors with arbitrary orientation, conductivity of the conductors and characteristics of soil, and location and waveshape of injected current impulses.

Output: Impedance to ground, 3D perspectives or 2D plots of scalar potentials and electromagnetic fields, voltages along paths; all in frequency- and/or time-domain.

Advantage: User-friendly input of data in graphical mode that enables easy definition and modification of the geometry after viewing the results.

Disadvantage: Only buried conductors are included in the model. Soil is modelled as homogeneous and non-linear effects are not taken into account.

Information and purchasing address:

Prof. Dr. Leonid Grcev, Electrotechnical Faculty, University "St. Cyril and Methodius", Karpos II bb, P. O. Box 574, 91000 Skopje, Rep. Macedonia,
Tel.: (+389) 91-362-224, Fax: (+389) 91-364-262.

4.6.4.7 Transmission line modelling

TLM3D

Authors: Numerical Modelling Laboratory, University of Nottingham, UK.

Information:

Prof. C. Christopoulos, Electrical Engineering, Numerical Modelling Laboratory, University of Nottingham, Nottingham, NG7 2RD - UK,
Tel: (+44) 115 951 5557, Fax: (+44) 115 951 5616.
E-Mail: eezcc@vax.nott.ac.uk; www site: http://www.nml.eee.nott.ac.uk

Simulation method: Transmission-Line Modelling (TLM) as described in the text: "The Transmission line Modelling (TLM) Method", C. Christopoulos, IEEE Press 1995.

Input: text file defining, with the help of macros, geometrical and material properties of problem space. A wide range of excitations may be defined. A more friendly graphics based input is under development.

Output: time-domain output for voltages, currents and field components at any point in problems space. Output may be coupled to lumped-circuit models for more elaborate coupling studies.

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5 Practical implementation details and characterisation of disturbance levels

5.1 General

This chapter aims:

1. to propose guidelines for the general cabling of equipment and systems on the basis of the coupling mechanisms and mitigation methods discussed in chapter 4;
2. to give an overview of the disturbance levels that, taking into account these guidelines and the phenomena described in chapter 3, can be encountered in HV substations, power plants and related locations like radio stations and control centres;
3. to derive from the previous points the resulting disturbance levels likely to be applied to equipment.

5.1.1 Layouts

The more common layouts that can be encountered are presented here based on the location of the different apparatus with respect to the source of disturbance and the possible existence of reducing factors such as the presence of earth networks, shielding materials, etc..

Also the disturbance level to which a specific apparatus will be submitted will depend on its own location and on the location of all the other equipment to which its ports are connected.

For that reason the proposed division will be closely related to the different classes of environment introduced in clause 5.7.

5.1.1.1 High voltage substation

Figure 62 gives the typical layout of a HV substation.

Three to four main entities can be distinguished.

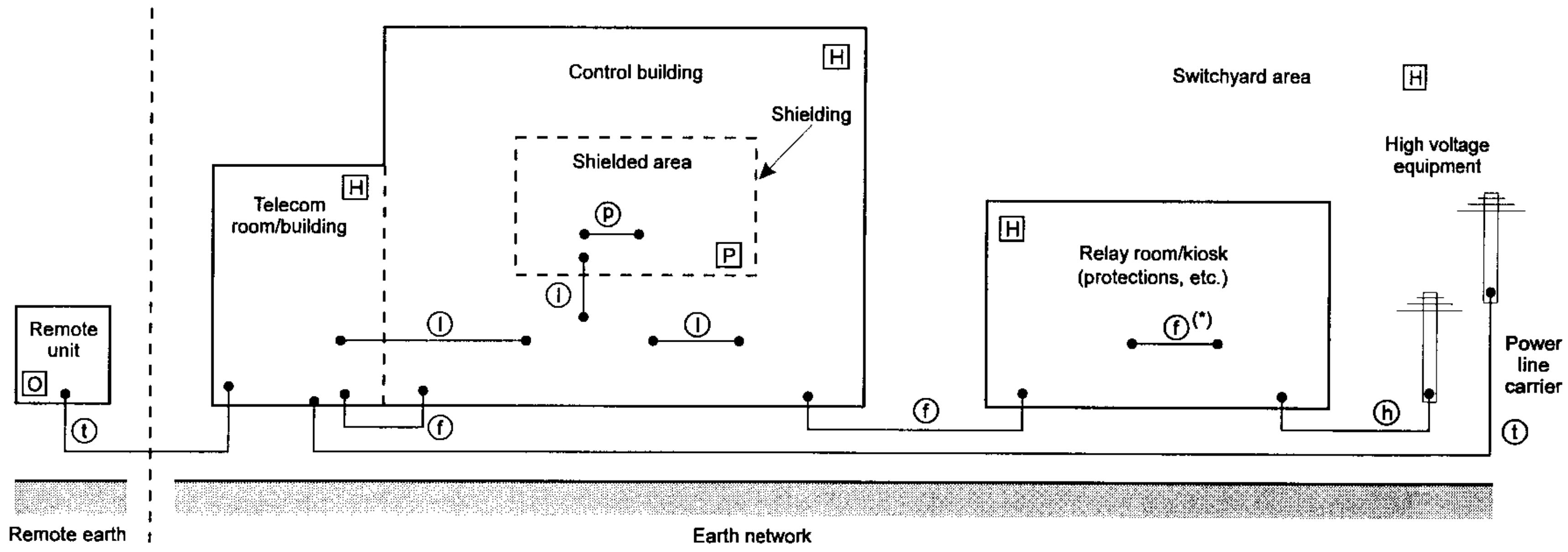
The high voltage equipment, the relay rooms, the control room and sometimes the telecommunication room, these entities being interconnected by the so called auxiliary cabling.
It has to be pointed out that, in some situations, the relay rooms don't exist. In this case all the functions they include are regrouped in the control room.
The same is valid for the telecommunication room which can be included in or separated from the control room.
All the entities described here are normally located on a single earth network or on several interconnected networks (if different voltage levels are present).

5.1.1.2 Generating plant

The typical layout for classical generating plant is given on figure 63.

With respect to their location three entities can be distinguished:

1. the main building containing rooms for:
   - the turbine / generator sets;
   - the switchgear (motor control);
   - the control functions;
   - the computers.
2. the switchyard which can be a complete HV substation.
3. auxiliaries such as:
   - fuels tanks;
   - cooling towers;
   - atmospheric measurements;
   - ash silos.



* Where special mitigation measures are adopted (e.g. shielding), (l) applies.

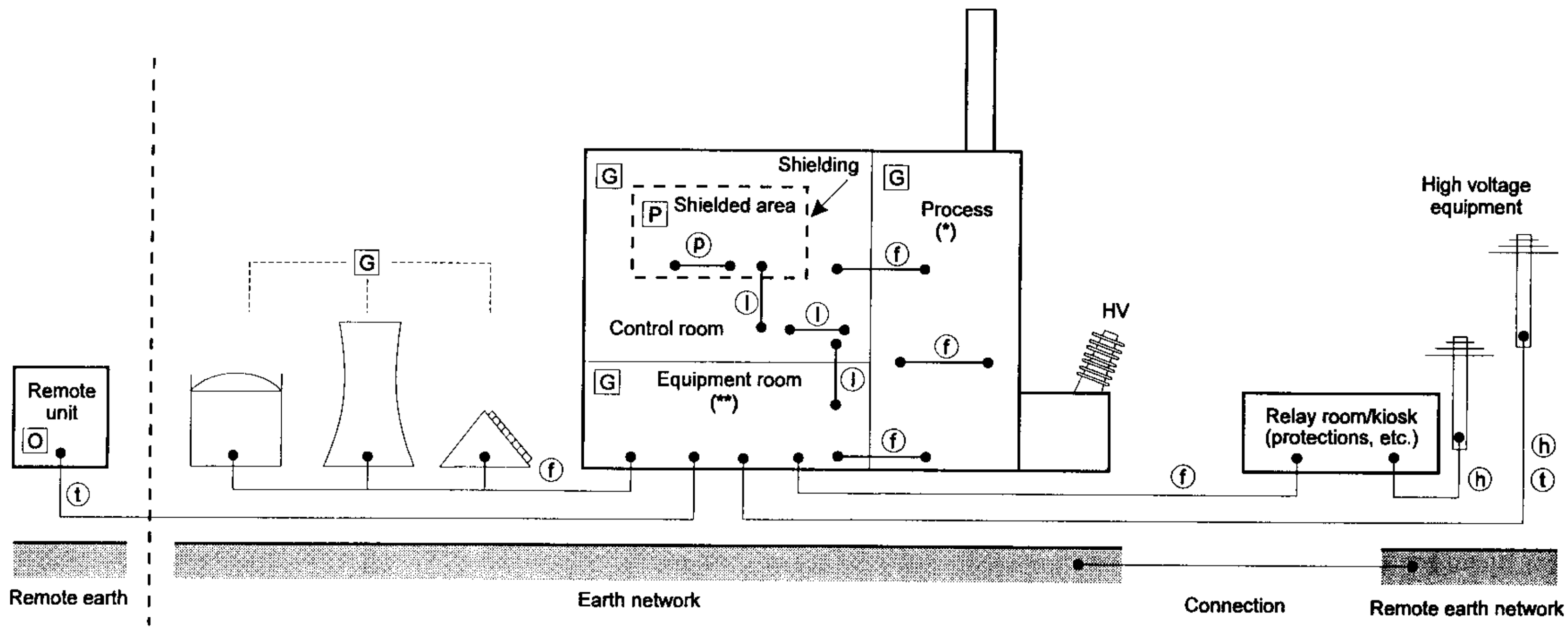
Type of location for enclosure, power supply and earth ports

- [H] **Normal** - examples are control building, relay house and switchyard area.
- [P] **Protected, if any** - examples are shielded room of the control building.
- [O] **Location remote to HV substation or MV substation or generating substation.**

Type of signal port connections

- (l) **Local** - examples are connections within the control building.
- (f) **Field** - examples are connections in the switchyard area and in a relay house/kiosk.
- (h) **HV equipment** - examples are connections to circuit breakers, voltage/current transformers, etc.
- (t) **Telecommunication** - examples are connections to power line carrier and remote terminal units.
- (p) **Protected, if any** - examples are connections inside a shielded room.

Figure 62 - Layout of a typical high voltage substation and related types of EMC environment



* Boiler, generator, turbine, switchgear, MV substations, etc.
** Control apparatus, electric relays, transducers, etc.

Type of location for enclosure, power supply and earth ports

- [G] **Normal** - examples are control room, equipment room and process area.
- [P] **Protected, if any** - examples are shielded area of the control room.
- [O] **Location remote to HV substation or MV substation or generating station.**

Type of signal port connections

- (l) **Local** - examples are connections within a control room or equipment room.
- (f) **Field (process)** - examples are field connections within generating station or MV station areas.
- (h) **HV equipment** - examples are connections to circuit breakers, voltage/current transformers, etc.
- (t) **Telecommunication** - examples are connections to power line carrier and remote terminal units.
- (p) **Protected, if any** - examples are connections inside a shielded room.

Figure 63 - Layout of a typical generating station and related types of EMC environment

Normally the main building and the switchyard are installed on the same earth network or on two interconnected networks.
The earthing of the auxiliaries can be simple protection against lightning or an extension of the main earth network or even may not exist.

With respect to the general layout there are no significant differences between a classical plant and a nuclear plant, except that this latter is more complex, requires special security measures and the use of some very low signal level circuits (i.e. neutronic flux). Moreover, as the boiler is located in a separated building, many of electrical and electronic circuits are much longer.

5.1.1.3 Radio stations

Radio stations for power utilities are often installed within substations or generating plants. In these cases, they take advantage of the good earth network and can be compared, as far as EMC is concerned, with a relay kiosk with however a higher risk of being directly struck by lightning.
When they are not close to HV electrical installations, they are usually located on raised ground that often suggests a high soil resistivity, an isolated earth network of mediocre quality and a still higher risk of direct lightning strikes.
For all these reasons special attention has to be paid to the connections (power supply, telecommunication links) with the outside world (see subclause 5.3.5.6).

5.1.1.4 Control centres

Like radio stations, control centres are not necessarily located close to HV equipment and, as such, are not always installed on a very good earth network. This can be a drawback with respect to lightning, but can be an advantage when other sources of disturbance are taken into account, such as HV faults or switching operations.
The EMC concepts which are relevant for a given control centre will thus depend on its electrical environment:

- if it is installed within a substation, it can be compared to a control building;
- if it involves a telecommunication tower, it has to be partly handled as a radio station;
- whereas if it is a stand alone building in a town, no special EMC measures will have to be taken.

5.1.2 Signal type and levels

As explained in chapter 4, the disturbances will affect the equipment either directly or, more often, through the cabling.

In this latter case, the level of disturbance and the immunity threshold will depend mainly on two factors:

- the type of cable and the way it is installed;
- the type of signals exchanged.

The first factor takes into account the shielding effectiveness defined in chapter 4.

Practical implementation of good cabling strategies is described in the following paragraphs.

The second factor can roughly be characterised by the amplitude (in V or A) and the bandwidth (or speed) of the signals.
Whether they are analogue or digital is, at first glance, less relevant as far as EMC is concerned.
It would also be possible to classify the different signals according to the equipment they interconnect or according to the classes of environment to which they are submitted.
Although there exists some correlation between the three possible classifications (signal, equipment, or environment) the first one will be adopted here because:

1. the other classifications suffer from too many exceptions i.e. low level-high bandwidth signals flowing in very disturbed environment and vice-versa;
2. signal types are more changeable than their environment.

Taking these remarks into account, the classification shown in the following table can be proposed; it contains four classes of signals listed in decreasing order of sensitivity to EM disturbances.

Signal type	Definition	Typical level	Typical bandwidth
1a	low level, high speed digital signals e.g. RS422/V11, G703, Ethernet	0,1- 5 V	> 20 kHz
1b	broad band analogue signals e.g. neutron flow meters	10 μV-1V	< 10 MHz
2a	low level, low speed digital signals e.g. pulse generators for speed or position measurement RS232/V28	< 20 V	< 20 kHz
2b	low level, low frequency analogue signals e.g. temperature measurement, vibration sensors	< 1 V	< 1 kHz
3a	medium level logic signals e.g. control and indication	> 10 V	< 100 Hz
3b	medium level analogue signals e.g. process control transducers	1-10 V 4-20 mA	< 100 Hz
4a	high level logic signals e.g. relay signals to disconnectors and breakers	> 50 V	< 100 Hz
4b	high level analogue signals current and voltage transformers	> 10 V, > 20 mA	< 1 kHz

Table 4 - Classification of typical signals in decreasing order of sensitivity to EM disturbances

It should be mentioned however that, though digital and analogue signals are treated here in the same way (with respectively an "a" or a "b" suffix), there is some limitation in the comparison as digital and analogue systems exhibit completely different behaviour.

5.2 General grounding and cabling philosophies

In all the following paragraphs concerning grounding and cabling the general philosophies discussed in chapter 4 will apply. It is worth reporting here the most important rules. [1], [2]

I. Grounding circuits must be meshed as much as possible. Except for a few special situations, don't hesitate to increase the number of grounding connections and to increase the number of them rather than their cross section.

II. Reduce the area of the loops in electrical (electronic) circuits. When possible, use the same path for circuits connected to the same equipment. Use always the same cable for the active conductor and ground return of a circuit.

   Except for some HF coaxial links or for small circuits built on a good equipotential ground plane, avoid connecting more than one point of a signal circuit to ground.

III. Keep all parts of (grounded) signal circuits close to ground conductors in order to benefit from their reducing factor and to reduce the transfer impedances.

IV. Don't install close together (grounding or signal) circuits carrying (or liable to carry) currents or voltages of very different magnitude.

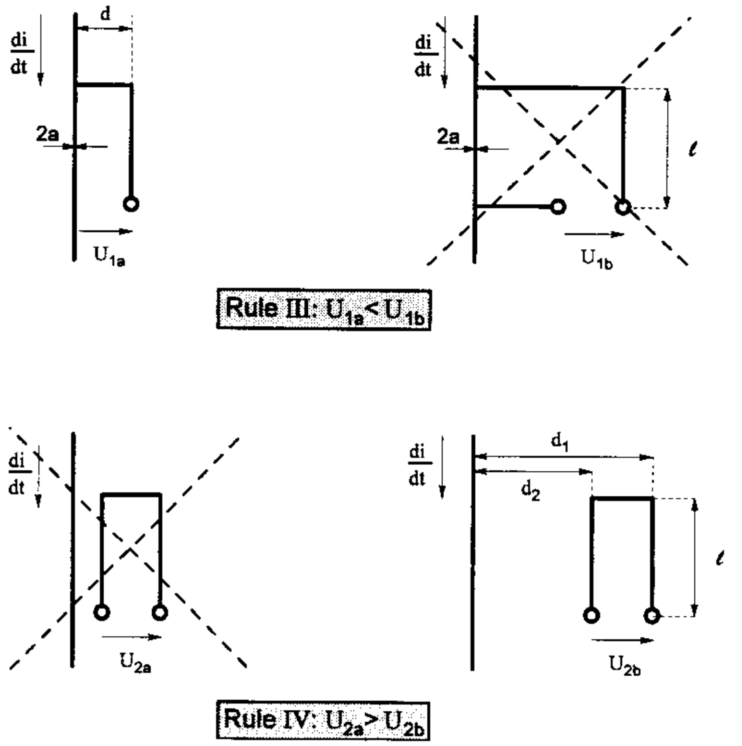
5.2.1 Comments on apparently contradictory rules

The last two rules may sometimes appear to be contradictory when dealing with grounding circuits carrying very large currents such as lightning currents.

According to rule IV, electrical circuits should be kept at distance from grounding conductors in which large disturbance currents can flow (see also subclause 5.4.2.2).

On the other hand, rule III highlights the necessity of installing electrical circuits very close to grounding circuits.

Both rules result in fact from the general principle of keeping the common magnetic flux shared by two circuits as small as possible (figure 64).



$$U_1 = \frac{di}{dt}\frac{\mu_o}{2\pi}\ell \ln\frac{d}{a} \qquad U_2 = \frac{di}{dt}\frac{\mu_o}{2\pi}\ell \ln\frac{d_1}{d_2}$$

Figure 64 - Coupling between a grounding conductor in which a disturbance current flows and a sensitive circuit

Rule IV is just a straightforward application of the "open-circuit" strategy (see chapter 4): "Keep disturbances at distances"; whereas rule III refers to the shielding properties of interconnected grounding elements (see subclause 5.2.2), taking into account that very few circuits can be considered as having no reference point grounded, and thus suitable for being kept at a distance from any ground conductor.

The trade-off between both rules can be achieved by providing multiple grounding conductors in order to reduce the mean current flowing in each individual conductor and to ensure a low-impedance path for the highest currents.

The application of rule IV results also from the wish to reduce common (ground) impedance coupling and capacitive coupling (cross-talk).

A more detailed illustration of these basic rules is given in figures 65 and 66 where a schematic comparison is made between six different ways of interconnecting a lightning conductor (which can also be an antenna feeder) to the grounding installation of an electrical circuit.

In figure 65, the circuit consists of a vertical square loop with a relatively large area:

- in layout A, part of the loop is installed in the vicinity of a grounding conductor;
- in layout B, part of the lightning current is directly diverted to earth;
- in layout C, the disturbing current is kept at distance from the circuit.

It is clear, when comparing these three layouts, that the disturbance level will decrease from A to C. This is confirmed in figure 67 a) where the shape and amplitudes of the current and of the induced voltages are shown [8].

However when the whole circuit is installed close to grounded conductors, the benefits of rules I and III become more evident:

- in layout D, though all the lightning current flows into the grounding installation of the circuit, it does not induce any disturbance in it!

This is due to the fact that the current is divided into two components generating through the square (or through any rectangular) loop fluxes of the same amplitude but opposed polarity.

With the layout of the figure, the current flowing on the right side of the grounding circuit is twice as large as that flowing on the left side but its path is half as long.

It is worth noting here (see also chapter 3.2) that for the present layout, but also for most practical situations, the current division between the different possible paths is practically inversely proportional to their length (assuming conductors with approximately the same cross section).

Paradoxically, layout E and F are less favourable for this particular configuration, because the part of the current flowing directly to earth produces in the loop a flux which cannot be counterbalanced.

So, the arrows on figure 65 point to the different layouts with decreasing induced voltages. It is clear that the circuit configuration drawn in this figure is not very representative of reality, as a circuit seldom leaves equipment and returns to the same equipment, although this can be encountered, for instance, in a telecommunication building where circuits start from one hierarchical level of a multiplexer, go to a distributing frame, and come back to another hierarchical level of the same equipment.

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[8] *The curves shown here are the results of measurements*

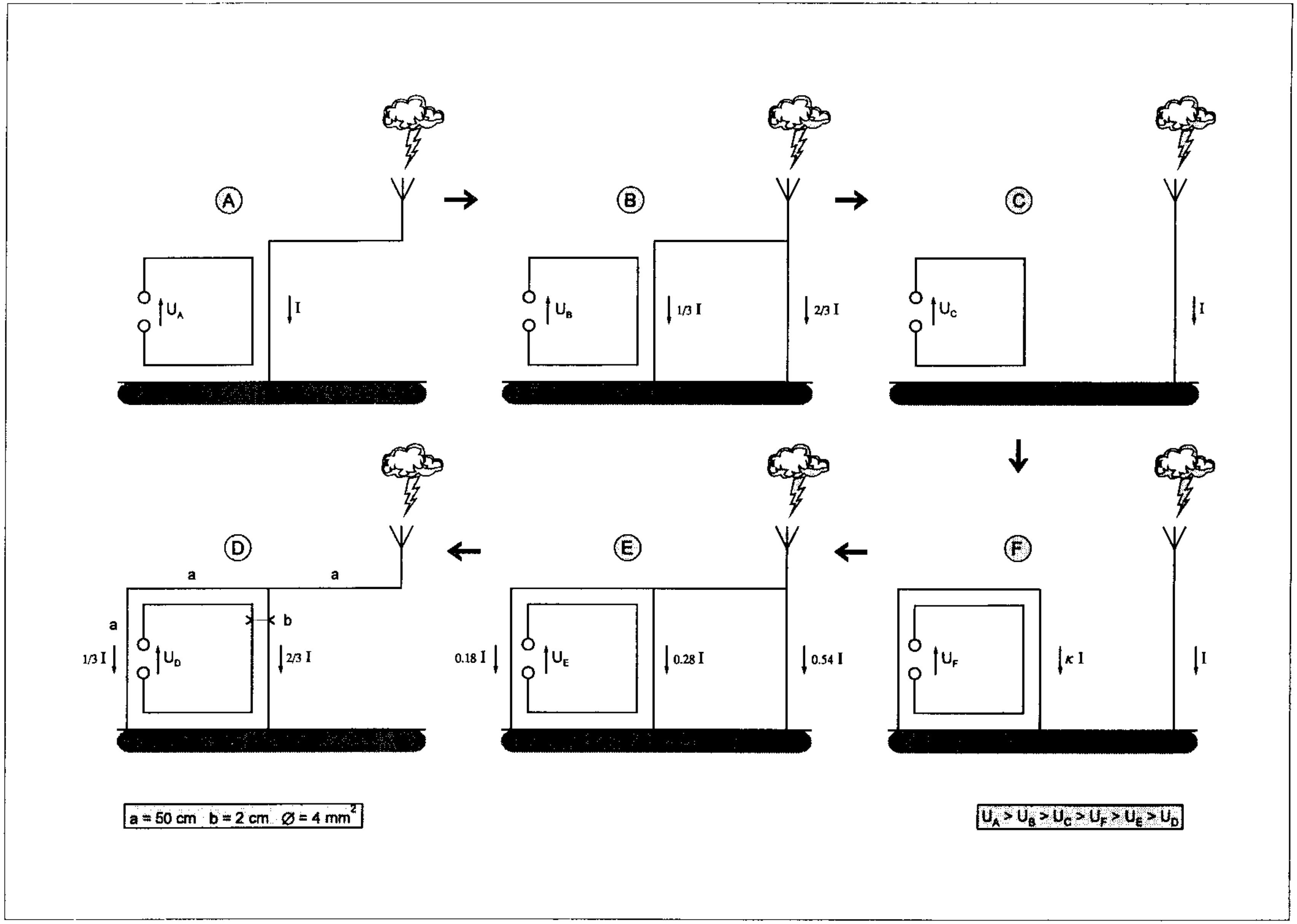


Figure 65 - Inductive coupling between a closed loop and a lightning protection structure

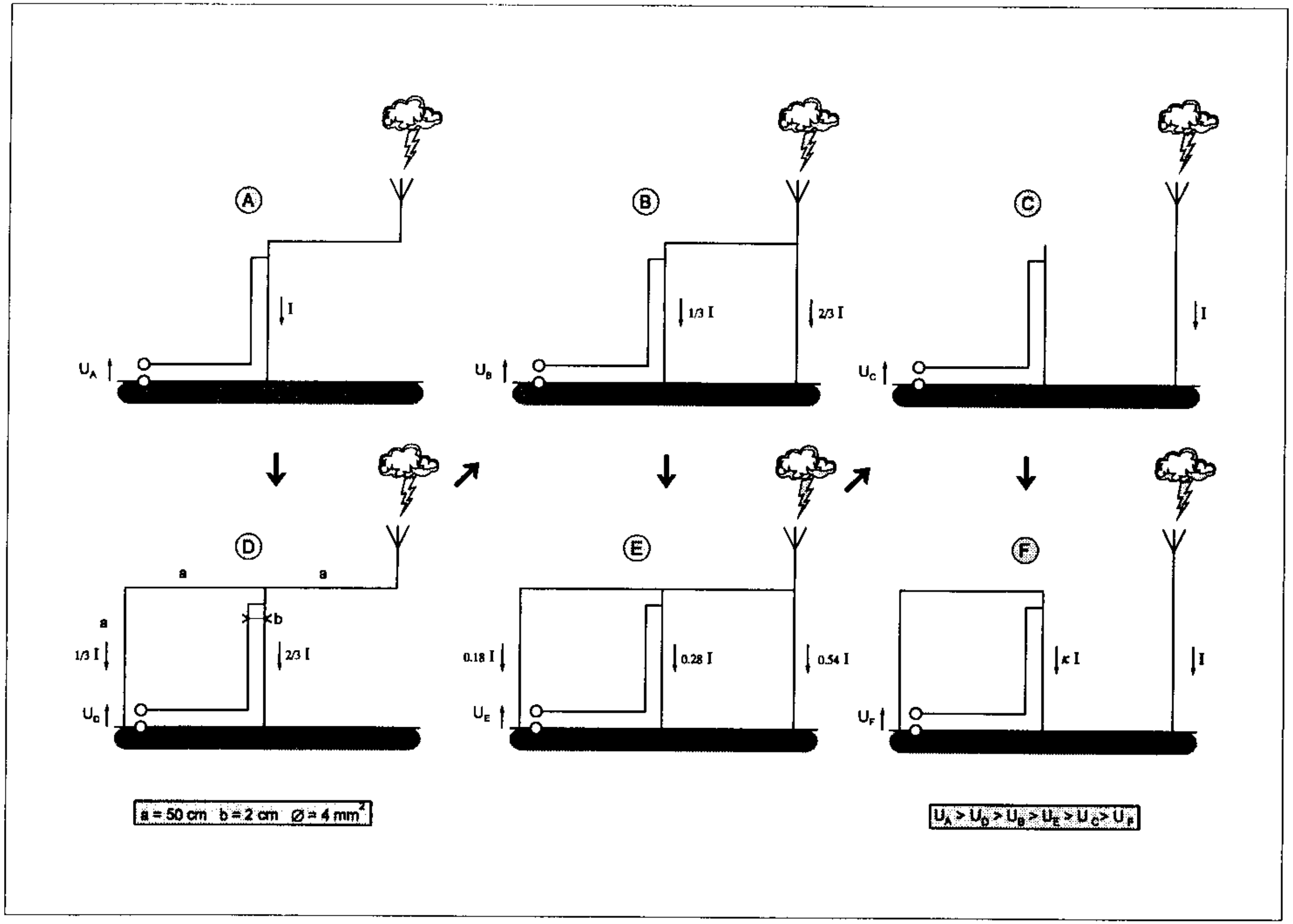
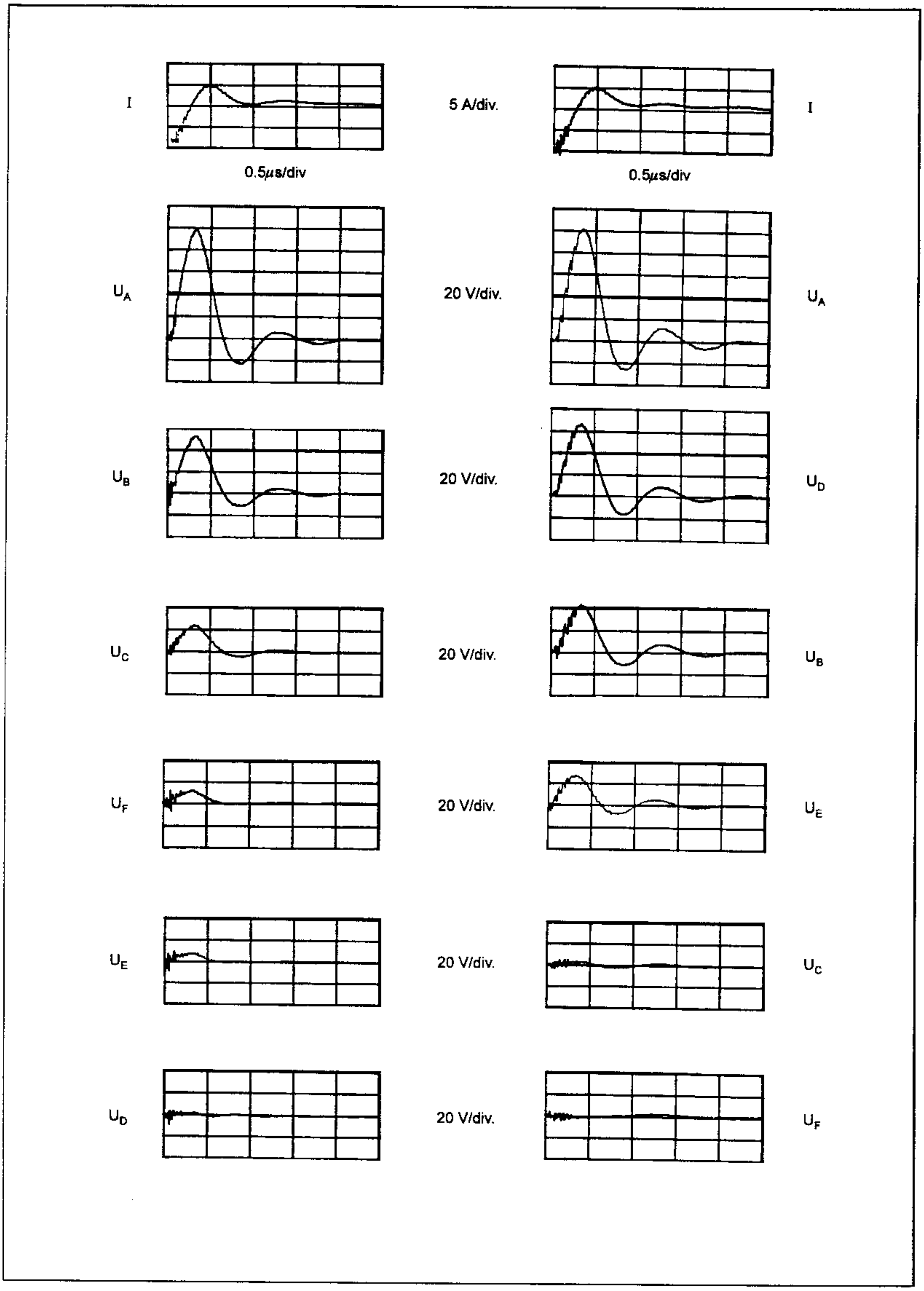


Figure 66 - Common impedance coupling and inductive coupling between a grounded circuit and a lightning protection structure



a) (see figure 65) **b)** (see figure 66)

Figure 67 - Currents and voltages in the circuits of figures 65 and 66

A more common layout is that of figure 66 which illustrates the common mode voltage appearing at the extremity of a circuit when the other end is grounded.

Here, intentionally, an important part of the circuit has been installed in contact with a vertical grounding conductor into which (part of) the lightning current can flow.

The arrows again show the different layouts sorted in decreasing order of induced voltages.

The complementarity of rule III and IV is now clearly illustrated.

Indeed, in most layouts presented in this figure the circuit shares a common impedance with the lightning down conductor, and hence is de facto installed very close to it; but thanks to the application of rule III, the induced voltages (figure 67 b) remain very similar to those measured with the layouts of figure 65.

The conclusion of this schematic illustration is that whenever the possibility exists to avoid circulation of large currents in grounding conductors it is worth doing it; but this is not always possible; the case of an antenna struck by lightning is the best example. In such a situation, the only thing that can be done is to offer to the disturbance the easiest path (i.e. with the smallest inductance) to earth.
This being said, the principle of keeping sensitive circuits close to grounding elements always applies; and if some doubt remains about the application of rule III and IV, it can be eliminated by installing the different circuits in individual shields or conduit.

5.2.2 Parallel earthed conductor

Of great importance concerning rule III is the value of the transfer impedance between electrical circuits and earthed conductors parallel to them (ECP) specially installed in order to reduce the disturbance level.
The ECP acts to reduce the common mode voltage induced on the cable. This reduction is determined by the transfer impedance Z_t of the ECP with respect to the cable. The high frequency part of Z_t strongly depends on the shape of the ECP, rather than on the total cross-section or the material properties. Moreover once a particular shape is chosen, it should be maintained over its full length and connected to the cabinets at the ends by a grounding element the shape of which has a comparable transfer impedance.
Typical shapes of ECP and corresponding values for the inductive part of Z_t are illustrated in figure 68.

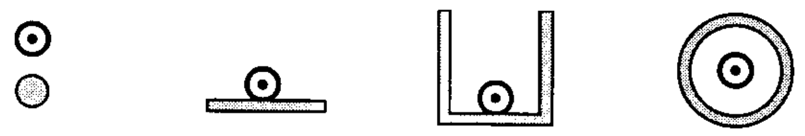


Figure 68 - Transfer inductance of different Parallel Earthed Conductors

Examples of ECP, listed in order of increasing effectiveness are:

- a protective earth (PE) lead;
- a stranded ground wire put in a trench;
- the shielding of other circuits;
- a cable tray;
- a metallic conduit (containing the circuit).

The actual effectiveness achieved by the presence of an ECP in the vicinity of a shielded cable depends on the relative distribution of disturbance currents in both circuits. For a simple ground wire this distribution is practically inversely proportional to the resistance of both circuits. This means that, in order to be efficient, the equivalent cross - section of the ECP must always be larger than that of all cable shields.

For other shapes (plate, U, tube, etc.) skin effect will cause a major part of the high frequency current components to flow in the ECP rather than in the shield of the cable which is to be protected. [9] [25]

This is also the reason why it is better to use a large number of relatively thin ECPs instead of one ECP with the same total cross - section.

It is also important to note that when an equipment grounding conductor (or a cable shield) is not put in the vicinity of an ECP, the division of disturbance currents between this conductor and other ground conductors will be done essentially according to their respective inductances, i.e. their respective length; hence their relative cross-section will play only a secondary part, at least at high frequencies.
This is one more reason for applying rule III of clause 5.2.

Another important feature of the ECP is its ability to play the part of the external shield of a triaxial cable of which, for some specific reason, the internal shield may not be grounded at both ends (see chapter 4, figure 49 f).

5.3 Guidelines for HV substations

5.3.1 Bonding and earthing practices

As proposed in chapter 4, we will use the concept of *bonding network* for all interconnected conductors intended to constitute an equipotential network, and keep the concept of *earth or earth network* for all buried conductors in close contact with the soil.
We will generally use the words *to ground (grounding)* for making a connection to the bonding network (or to the earth) and reserve the words to earth *(earthing)* when we specifically need to take advantage of the main characteristic of the *earth*, i.e. its resistance value. [4], [5]

5.3.1.1 Earth network

The earth network aims to achieve several objectives:

- a low earth resistance;
- limitation of step and touch voltages;
- reduction of HF and LF common mode disturbances;
- ability to withstand large short circuit currents.

In order to meet these objectives a meshed network has to be implemented. Its area must extend to include all the HV equipment and all the buildings in the substation.
The earth resistance R of a meshed network of perimeter p installed in a soil of resistivity ρ can be estimated from the formula: $R = 2\ \rho/p$.
Vertical or inclined driven rods can help to reduce the earth resistance for small substations or when the resistivity decreases with depth. However they are of little use for reducing EM disturbances.
The network shall be buried - when possible - at a depth of at least 50 cm and below the frost line.
The cross section of the conductors is based on the maximum voltage drop allowed as a consequence of fault currents. Values ranging from 1 to 3 V/m are generally accepted. For mechanical reasons, cross sections should not be less than 25 mm^2 for copper stranded cables and 90 mm^2 for corrosion protected steel. In fact, larger cross-sections like copper bars of 50 x 3 mm^2 are common practice.
The reduction of induced disturbances requires meshes not larger than 250 m^2 in a soil of normal resistivity ($\rho \leq 200\ \Omega \cdot m$) and even smaller than 150 m^2 when the resistivity becomes higher than 1000 Ωm.
In order to reduce the surge impedance, the density of the grid meshes should even be reinforced (e.g. 5 m x 5 m) in the vicinity of (HV) equipment, more especially near:

- power transformers;
- capacitive voltage transformers;
- lightning arresters;
- line towers and other supports with ground wires;
- coupling transformers for power line carrier systems.

5.3.1.2 Grounding of high voltage equipment

- HV equipment shall be installed and bonded to the earth network in the vicinity of a node and connected to it by at least 2 (better 4) oppositely arranged conductors, the size of which being determined by the 50 (60) Hz needs.
- The metallic support of HV equipment, i.e. control cubicles, relays, kiosks, should be part of the grounding connection.
- All grounding conductors should be as short as possible.
- Preference will be given to multiple grounding connections separated by more than 10 cm, instead of a single connection of equivalent cross section. Particularly power transformers should be bonded to different nodes of the earth network by several connections.
- Daisy chain grounding of different equipment is to be avoided.
- A grounding conductor (ECP) of at least 50 mm^2 should be installed in each cable trench or concrete cable duct and connected to the earth network at both ends, and also, if possible, at a few other points.
- All the grounding conductors must be interconnected at their crossing points.

5.3.1.3 Interconnection of substation earth networks

Whenever two (or more) substations are located in the vicinity of each other (e.g. step down substation, substations with different voltage plans, substations attached to generating plants) and if measurements, control or telecommunication signals are exchanged between them, the earth networks have to be interconnected by at least two conductors the size of which is determined by the maximum 50 (60) Hz current liable to circulate between substations.

The distance between conductors should be as great as possible. The cable ducts or trenches should be installed close to the ground connections (which can be laid inside the trenches) and should preferably be metallic and grounded at both ends.

5.3.1.4 Grounding of relay rooms (kiosks)

As explained in chapter 4 the grounding of each building containing electronic equipment should aim for implementing an integrated ground plane.

In order to achieve this, a ground bar (or bonding bar) shall be installed following the walls of the room, preferably near the floor.

The size of this bar is not critical but should not be smaller than 50 mm^2 (copper strap or rod). This collector forms a closed loop which has to be connected to the earth network via at least two conductors of the same cross section, installed as far as possible from each other.

The following items are connected to the ground bar:

- all metallic structures or enclosures within the room;
- the ground conductors laid in the cable trenches;
- the shield and spare conductors of the cables leaving the room (if not directly, at least through an extension bar as described below).

It is allowed and recommended to connect to the earth network, either directly or by means of the ground bar, reinforcing rods embedded in concrete.
When different metallic enclosures are installed in a row, an extension of the ground bar must be made starting from one wall, interconnecting all the enclosures and reaching the opposite wall.
Each extension of the bar contributes in this way to the setting up of a ground mesh being, in turn, part of the integrated ground plane.
Every connection to the ground bar should be as short as possible (< 10 cm). The cross section is not critical as far as EMC is concerned. Values between 4 mm^2 and 16 mm^2, depending on the magnitude of the LF currents likely to flow in the conductors, are acceptable, taking into account that four 4 mm^2 links are, by far, better than a single 16 mm^2 connection.

Use of metallic structures as part of the equipotential bonding

As indicated in chapter 4.5.2. it is recommended to interconnect all the cable supports, trays, racks and raceways in order to form a three dimensional ground mesh. This means that, as far as EMC is concerned, bonding the enclosure of equipment or a cable shield directly to this mesh will ensure a better grounding than the use of an isolated copper conductor connected to the earth network or even to the ground bar.
In this sense the ground bar and its extensions can easily be constructed using metallic structures as far as the global copper equivalent cross section remains larger than 50 mm^2 and an uninsulated 16 mm^2 copper conductor clamped to the structure ensures the electrical continuity.

5.3.1.5 Grounding of the control building

In principle, all the recommendations made for the relay rooms are valid for the control building.
However, most important control buildings involve several rooms containing very sensitive equipment (computers).
For this reason some specific measures have to be taken in the realisation of the cabling and more particularly of the grounding connection.
Though a hybrid network can be installed (see chapter 4.5.3) - mainly if the building contains different floors - it seems easier and even more efficient to build a fully meshed network, the density of which is higher in a room containing the most sensitive devices.

5.3.1.6 Cabling and grounding of the telecommunication building

Special attention has to be paid to the cabling and more particularly the grounding of a telecommunication building directly attached to a tower supporting radio antennas.
There are at least three reasons for that:

- the risk of a direct lightning stroke to the tower is high;
- most telecommunication equipment doesn't meet the EMC specifications required for the severe EM environment of HV substations;
- wideband signals (high speed, low levels) are exchanged rendering the EMC problems more acute.

All the basic principles mentioned in subclause 5.3.1.4 are applicable, but more than anywhere else, the concept of a three dimensional ground plane remains valid.

However, as antenna feeders usually enter the building at roof level, it is advisable to install the ground bar and its extensions above the equipment, hanging under the roof instead of lying near the floor (this latter layout being advised when the feeders enter the building at ground level).

This means that all cable supports are fixed to the wall, near the ceiling or to the ceiling itself and the cabling is made at that level and penetrates the different racks and enclosures from above.
With such a cabling layout the equipment forms a cluster hanging from the ceiling of the room without any direct electrical contact with the floor.

Splitting the cabling between top and bottom of the equipment must, in any case, be avoided because this creates loops able to intercept or generate significant magnetic fields in case of lightning stroke.

Taking into account that lightning currents flow from the top of the building to the bottom and that radio connections are mainly based on coaxial links or wave guides with multiple ground connections, the only way to reduce common impedance and inductive coupling is to avoid installing vertical ground conductors near the equipment and, instead, to locate them at all corners.

For the same reason each cable (in particular the coax cables) and its support coming from the tower must be grounded directly at the entrance of the building by means of a conductor of at least 50 mm^2 installed on the outside of the wall and connected to the earth grid of the building.

If possible, all cables (communication, power, or ground cables) linking the telecommunication building with other buildings should enter the building at the same side as those coming from the tower, in order to avoid lightning currents crossing the building.

It is also of great importance to correctly apply the rules listed in clause 5.2 and, in particular, to take into account the discussion of subclause 5.2.1.

In particular it is recommended to avoid installing in the same tray, or in close proximity to each other, cables coming from the antenna tower (e.g. coax feeders, antenna heating cables) and cables remaining inside the building (e.g. 2 Mbit or 8 Mbit pulse code modulation cables between radios and multiplexers, wiring between multiplexers and distributing frames, etc.).

5.3.1.7 Lightning protection

It is usually assumed that the high voltage equipment and more particularly the lightning protection of this equipment acts as a Faraday cage for the LV equipment and the buildings installed within a HV substation with the consequence that no additional external protection is required.

However it remains necessary to check the effectiveness of this protection system following the rules discussed in the general guidelines and standards concerning lightning protection (see subclause 5.4.2.2).

5.3.1.8 Fences

For safety reasons (touch voltages), fences are never connected to the earth network of the substation, unless it is possible for a person to touch both fence and substation equipment or structures. In this case, the earth network must be extended beyond the substation fence.

5.3.1.9 Grounding of Gas Insulated Substations

All the principles stated in the preceding clauses are applicable to GIS.
However a more detailed description of the main grounding practices for GIS can be found in [10].

5.3.2 Auxiliary cabling

Auxiliary cabling includes the general LV cabling of the HV substation associated with:

- measurement (VT, CT);
- control, operation;
- indication, communication;
- LV power supplies (d.c., a.c.).

5.3.2.1 Cable trenches

Auxiliary circuits should be installed as far as possible from the sources of disturbances. In particular avoid:

- parallelism with busbars or keep the separation large;
- proximity to capacitive voltage transformers and to surge arresters.

As already mentioned in subclause 5.3.1.2, a grounding conductor (ECP) of at least 50 mm^2 should be placed in each cable trench.

5.3.2.2 Cable shielding

All the cables leaving or entering a building must be shielded.

With the exception of low level transducers (type 2b signals in subclause 5.1.2 classification) which are not very frequent in substations, all the shields are grounded at both ends.
This grounding can be made either in a distributing frame or directly at the equipment to which the cable is connected. In the first case it is recommended to install the distributing frame along the wall near the entry of the cables and to connect the shields directly to (an extension of) the ground bar.
In the second case, which corresponds more to the practice today, shields are connected to highly conducting surfaces, e.g. cabinet walls, at the point where the cables enter. This connection should be as short as possible, the best one being the true circumferential connection. However pigtails of less than 10 cm give in most situations fair results.

Connectors should constitute electrical continuity between cable shield and cabinet. Avoid coated connectors ensuring the ground connection by a single (or double) pin or by the locking mechanism (fixing, catch).
The cross section of the grounding connection should be equivalent to that of the shield.

Type of shielding

It has been shown in chapter 4 that depending on the type of shielding used different values of transfer impedance can be achieved giving rise to different levels of common mode voltage for a given disturbance.
The following types, listed in increasing order of effectiveness, are most frequently encountered in HV substations:

1. steel sheet (armour) wrapped in helix without coverage, in conjunction with a few copper leads ensuring the electrical continuity.

   Due to the small pitch of the helix the shielding effectiveness is very poor and depends of the thickness of the cable: the smaller the cross-section is, the better the effectiveness will be. Practically, for frequencies not exceeding 100 kHz, it can range from 10 to 20 dB.

   This kind of shielding should be avoided in HV substations;

2. steel wires wrapped in helix with a pitch greater than 20 cm.

   The effectiveness of this kind of armour is slightly better than the former and extends up to a few hundred kHz. Values ranging from 30 to 40 dB have been measured. However these shields are not recommended in general and certainly not in GIS environments;

3. full covering copper wires wrapped in helix with a long pitch and recovered at 50 % by a copper tape wrapped in the opposite direction.

   These shields can be recommended, for instance, in the cabling of voltage and current transformers;

4. single (or double) copper braid with high optical coverage (≥ 80 %).
   (Copper braids are sometimes supplemented by an aluminised plastic foil wrapped on the conductors).

   With optimised braids the good shielding effectiveness (> 40 dB) extends beyond a few MHz.

   This kind of shield can be recommended for the general auxiliary cabling in HV substations.

   For installation in trenches it can be advisable to reinforce the braid with one or two copper (brass) sheets wrapped in helix. This will, of course, not only enhance the mechanical behaviour of the cable but also its transfer impedance;

5. double copper tape wrapped with overlapping in opposite direction.

   Due to the good coverage and the double helix, the shielding effectiveness remains good beyond 10 MHz. However the relative stiffness of this arrangement limits its use to applications requiring small cable size like telecommunication cables;

6. continuous screen formed by a metallic tube (lead, copper) or by an U fold (steel, copper) wrapped around the cable (not in helix) with overlapping.

   In order to remain sufficiently flexible copper shields are usually corrugated.

   Continuous screens present the best shielding effectiveness, mainly at high frequency, leading to residual common mode voltages not exceeding a few tens of volt. They are suitable everywhere and more particularly in GIS substations;

7. multiple layer shields are sometimes used either to achieve very low transfer impedances at low frequencies (shields containing magnetic materials) or to achieve triaxial configurations allowing some diversity in the grounding practice (i.e. inner shield grounded at one end and outer shield grounded at both ends).

All combinations of the above recommended configurations, e.g. shields based on copper wires or tapes reinforced by steel sheets, will of course improve the overall effectiveness.
In particular, the combined action of good cable shielding with metallic and galvanically continuos U shape cable trays (see subclause 5.2.2) can offer reducing factors up to or even higher than 60 dB allowing the undisturbed transmission of practically any kind of signal.

It must be pointed out here that, contrary to generating plants, the quantity of cabling in a HV substation is relatively limited and will even probably decrease in the future with the advent of local area networks and other multiplexing systems. Moreover most of this cabling is associated with high security circuits such as protection.
On the other hand, due to the proximity of HV equipment and to the higher risk of lightning, the EM environment is normally more severe in substations than in generating plants.
The conclusion is that it is worth paying greater attention to the cabling quality (i.e. its shielding effectiveness) in a HV substation than in a generating plant. In other words, the pay back of very good cable shielding is higher for a HV substation than for a generating plant.

5.3.2.3 Cabling inside buildings

Cabling not extending outside a building may remain unshielded except for these carrying type 1 and 2b signals, namely:

- wideband communication circuits (i.e. $\Delta f > 4$ kHz or speed > 20 kbit/s);
- low level analogue circuits (temperature measurements, etc.).

5.3.2.4 Insulation levels

The minimum value of insulation level between wires and between wires and shield depends of the circuit type and configuration, however the dielectric test voltage should never be less than 1000 Veff at 50 Hz (60 Hz). A value of 2000 Veff constitutes a good trade off in accordance with most international standards.

5.3.2.5 Cable bundle

Referring to rule IV of clause 5.2, provision shall be taken to never mix in a same cable (or bundle of unshielded cables), circuits carrying different types of signals (at least if they are very sensitive like type 1 or 2 of subclause 5.1.2).
The same thing applies for circuits crossing an interference barrier (subclause 5.3.6). For example the input and output circuits of a filter or an isolation transformer should never be in the same cable.

5.3.2.6 Secondary circuit of voltage and current transformers

Special attention has to be paid to the cables connecting voltage and current transformers to relay rooms, because they are among the only circuits with direct connection to high voltage equipment. Even if this connection occurs via step-down transformers, the fact is that the reduction factor is only defined at power frequency. The actual HF transfer function of this equipment, in common mode as in differential mode, has little to do with the transformer turns ratio and differs greatly from one to another.
For safety reasons, the secondary circuits have to be grounded at the HV equipment. In order to reduce as much as possible the loop formed by the neutral conductor and the ground connection both circuit and shielding should be grounded to the transformer tank itself and not by means of a separate connection to the earth network (figure 69).

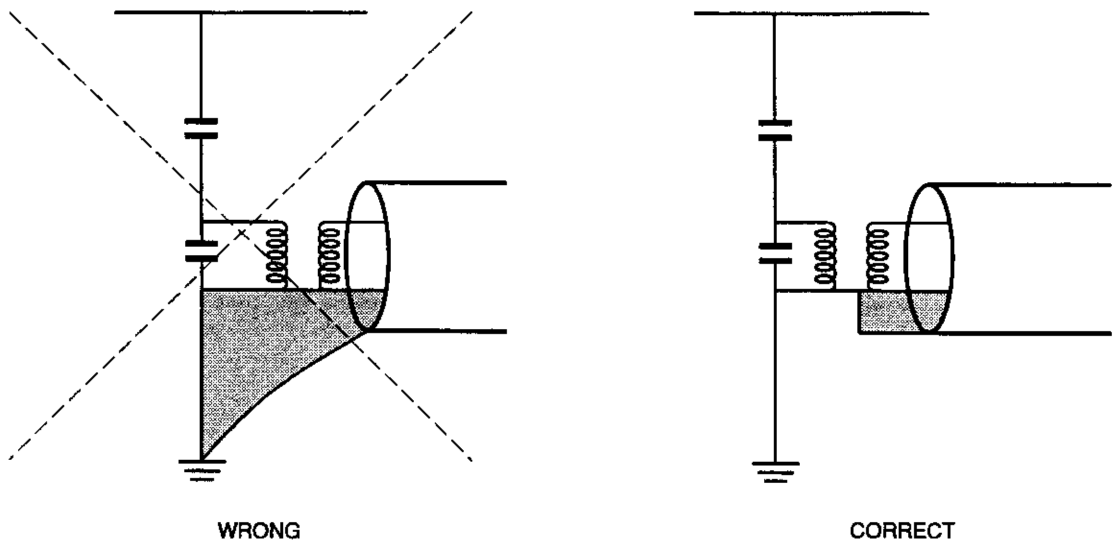


Figure 69 - Grounding of capacitive voltage transformer

The connection between transformers and relay room can be made:

- by separate bipolar cables for each phase (current and voltages);
- by two four conductor cables, one for currents and one for voltages.

In this latter situation a junction box - usually near the central transformer - allows the connection of the different neutral conductors together (figure 70).

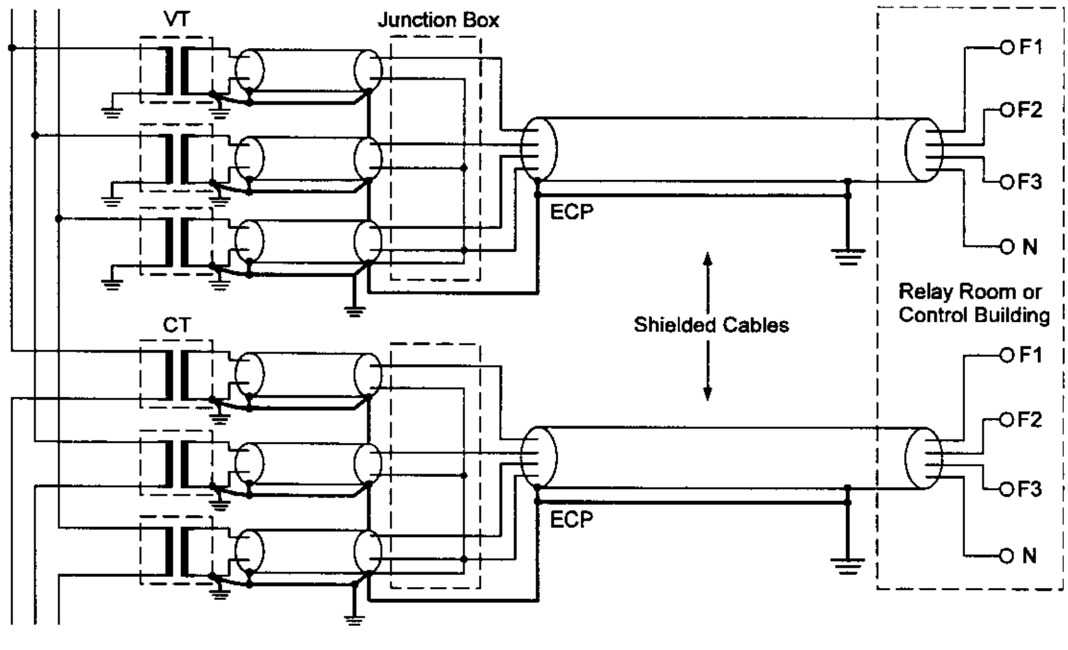


Figure 70 - Grounding of VT_S and CT_S secondary circuits and of connecting cables to relay house

The neutral conductors as well as the shields of all the cables entering the junction box are connected to the box which is, in turn, earthed.
This double grounding of the neutral conductors (at the transformer and at the junction box) has very little influence on the common impedance disturbance level, thanks to the very short length of the bipolar cables between transformer and junction box.
In no case is an additional grounding of the neutral conductor allowed in the relay room.
Sometimes double grounding cannot be avoided when two groups of measuring transformers are connected to the same equipment (e.g. synchronisation circuits). In this case isolation transformers become a necessity.
In any case, it is highly advisable to add to each bipolar cable an ECP of minimum 50 mm^2 cross section.

It is clear however that, if the safety rules allow it, lower disturbance voltages are obtained when the neutral conductors are grounded at only one point e.g. the junction box and not at the transformers as well (figure 71).

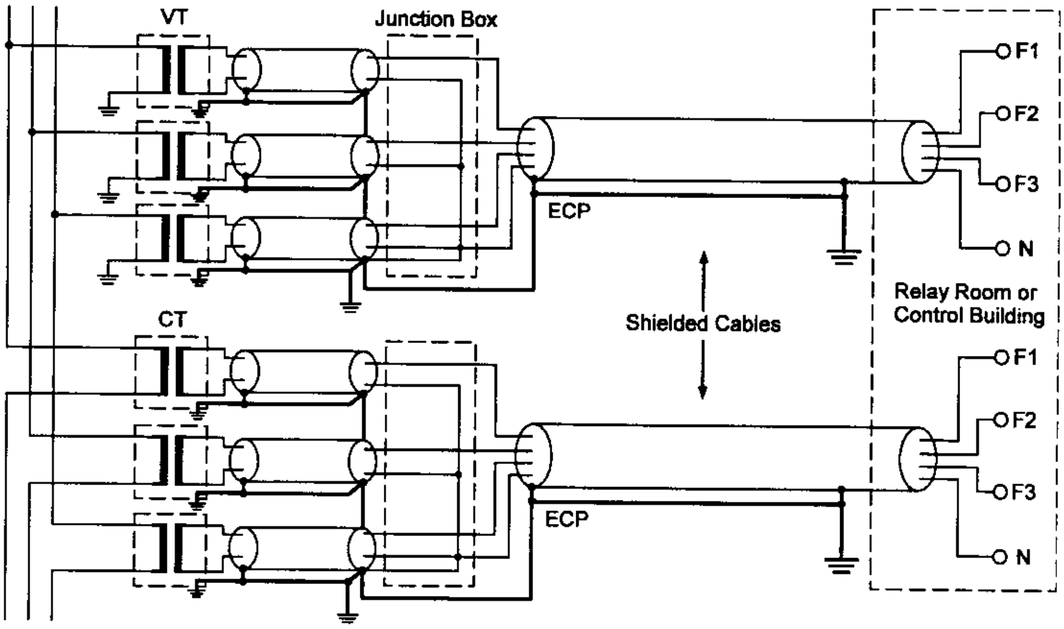


Figure 71 - Modified grounding configuration of VT_S and CT_S secondary circuits for limiting differential transient voltages

5.3.3 Shielding of buildings

The need for shielded building construction can exist when very sensitive equipment like telecommunication equipment or computers is to be protected.
The main sources likely to justify global shielding are, at high frequencies, radiation due to lightning and switching in HV circuits (mainly GIS), and, at low frequencies, significant magnetic fields in the vicinity of power lines and busbars able to disturb video monitors.
Shielding against high frequency disturbances is quite easy when a reasonable performance is required (see chapter 4.4).
Very high shielding performance is not justifiable as a lot of disturbances are conducted and penetrate into the buildings via the cabling.
This being said, one of the easiest ways to realise low cost HF shielding is to put in the walls a grid (lattice) of steel rods (≈ 5 mm diameter) with mesh size of about 10 to 15 cm, each grid being bonded to the following at its edges.
With such a layout magnetic field attenuation ranging from 15 to 30 dB between 10 kHz and 30 MHz can be achieved depending on the care brought to the connection between grids between grids and metallic frames, and to the importance of the apertures (windows, doors, etc.).
Another way to realise low cost HF shielding is to use a wire netting (e.g. "chicken netting").

Power frequency fields

Attenuating VLF (50 Hz, 60 Hz) magnetic fields, necessitated by the use of cathode ray tubes is, in a certain sense, more difficult. The use of steel grids like above will introduce attenuation of only a few dB. Steel plate or sheet is more efficient but difficult to work with. The shielding effectiveness is proportional to the thickness of the sheet and to the root of the permeability, values between 10 and 20 dB can be achieved with 2,5 mm steel sheet with a relative permeability of 1000 when they present a closed magnetic circuit around the source or the victim. When the magnetic circuit doesn't close on itself its reluctance remains high and the resulting effectiveness, for the same conditions, seldom exceeds 10 dB.

Important improvements can be brought by the use of grain oriented steel as used in transformers.

On the other hand, due to the induced eddy currents it is also possible to achieve shielding with aluminium (or copper) plates.

For the same thickness the results are usually better with steel close to the vulnerable equipment, whereas the behaviour of aluminium seems to be better at higher distances (e.g. at a few meters).

Recourse to high permeability alloys (mumetal) allows the attainment of very high shielding efficiencies but their very high cost limits their application to the protection of small equipment.

When the source of disturbance is a busbar, the best mitigation method is increased separation between source and victim or reduced distance between the different phases (replacement by a three phases cable or an insulated busbar, see subclause 5.5.2).

5.3.4 Gas Insulated Substations

All the cabling principles discussed in the preceding paragraphs are applicable to GIS but have to be reinforced to cope with the more severe conditions prevailing here (see subclause 5.5.1.2).
In particular, it is of great importance to achieve good equipotential bonding or an Integrated Ground Plane (IGP).

This IGP may consist of continuous welded steel mats in concrete, gridirons or metal plates at one or several levels.

The steel rods embedded in reinforced concrete can be used to achieve this ground plane and can even form the basis of the IGP if the mesh size is not larger than 5 m x 5 m.

The bonding network resulting from the interconnection of this IGP with the classical protection earth network should have an average mesh size not exceeding 2 m x 2m.

All metallic framework should be grounded at least at two points; in particular, conductive cable trays or ladders should be grounded at both extremities and each time they cross other metallic elements.
The GIS metal enclosure itself will be connected to the bonding network at the base of every support. Those connections must be very short and preferably made via multiple conductors (3 or 4).

5.3.4.1 Junction with overhead lines

At the junction with overhead lines, the metal enclosure of the GIS has to be electrically extended to the IGP. This can be achieved by bonding the metallic enclosure of the GIS to the IGP by means of metal plates of several square meters (low impedance). The tubular GIS enclosure itself is connected to the plates by 6 to 8 short straps distributed around its circumference.

5.3.4.2 Junction with cables

Two cases can be distinguished depending on whether the cable shields may or may not be connected to the local ground.

1. Shield connected to the local earth

   The only way to avoid significant disturbances is to coaxially bond the cable shield to the GIS enclosure.
   If this is not done, i.e. if the cable shields are "only" connected to the earth network, the voltage difference between shield and enclosure can easily exceed 50 kV (in 150 kV substations) and give rise to sparkover.
   The presence of ring current transformers or the necessity to make the connection removable implies that a true coaxial connection is not always possible. In this case, it can be approximated by at least 4 short links (e.g. copper 50 mm x 3 mm) circumferentially distributed.
   Even so, the risk of sparkover exists if the distance between shield extremity and enclosure is smaller than 10 cm.
   In order to avoid uncontrolled discharges it is advisable to install on the cable a "corona" ring (cylindrical spark gap as in figure 72) leaving a small gap of 2 to 5 mm with the enclosure.

   Such a corona ring works as a high pass filter and allows well controlled low energy sparks (the 50 / 60 Hz components flow through the external "coaxial" connection) with little or no influence on the general disturbance level.

   Complete suppression of sparking can be achieved, if necessary, by bridging the gap with a ring of resistors with a total resistance value of a few ohms. [24]

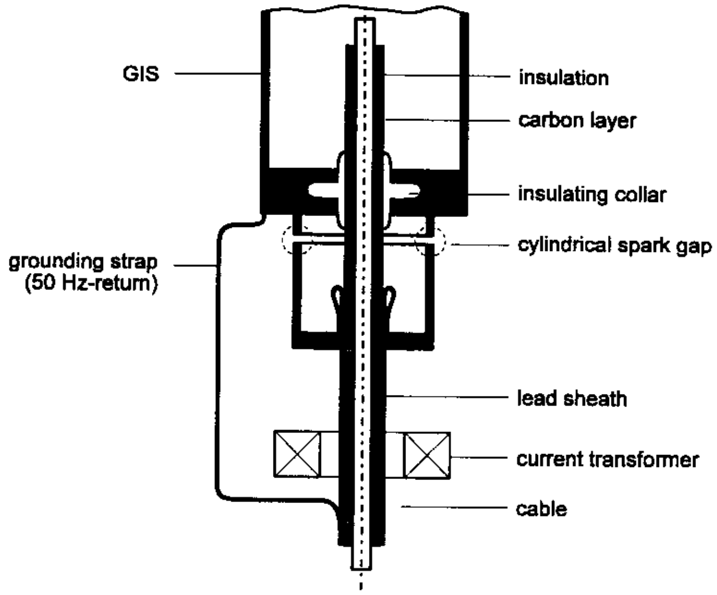


Figure 72 - Simplified sketch of the GIS / cable transition with current-transformer arrangement. Only one of the three cables is shown

2. Shield not connected to earth

   When the cable shields are not connected to the local earth, it becomes necessary to install a crown of surge arresters (e.g. varistors, capacitors or resistors) between shield and enclosure.

   This solution can also be applied for bypassing insulated joints in the metal enclosure.

   In all cases the connections to the by-pass components should be as short as possible.

3. Auxiliary circuits

   As explained in subclause 5.3.2.2, high quality shielded cables have to be used with the shielding coaxially grounded at both ends.
   Special attention should be paid to the paths followed by these cables. The paths should always follow well grounded metallic structures.
   Separate cables should be used for each bay and each type of circuit.

5.3.5 Interference barriers

Besides the general cabling and shielding methods described in the preceding paragraph it will be sometimes necessary to have recourse to **barriers** in order to keep the disturbance level under an acceptable threshold in term of interference, or more often, of dielectric strength.

This occurs mainly whenever a circuit crosses the frontier between different electromagnetic environments.

The interference barriers can be separated into three groups following the two classical strategies:

- galvanic isolation (open circuit strategy);
- overvoltage protection (short circuit strategy);
- filters (both strategies).

5.3.5.1 Galvanic isolations

The most used components offering isolation are described in the following:

- ***electromagnetic and static relays***, usually limited to ON-OFF switching and VLF applications with isolation level not exceeding 2 kVeff (50/60 Hz);

- ***optocouplers***, low cost and widely used (alone or in combination with other electronic circuits). They allow transmission of signals with frequency spectrum extending to the MHz range and isolation levels up to 5 kV.
  The stray capacitance (up to a few pF) between input and output can sometimes severely limit the common mode rejection ratio at high frequency, but good designs, incorporating a screen between input and output, do exist;

- ***isolation transformers*** [9], the most frequently used symmetrical barrier which can easily be added to any existing circuit without special adaptation and which usually don't require any power feed at their output.
  Signals ranging from a few Hz to several MHz can be transmitted across such transformers with insulation levels exceeding sometimes 20 kVeff.
  The stray capacitance between primary and secondary winding is higher than in optocouplers (up to several hundred pF) but can also be compensated by a screen connected to ground.
  Most isolation transformers have windings with a mid-point allowing, among other possibilities like power feeding of phantom circuits, the grounding of the circuit. This is of great importance when dealing with longitudinal and common mode power frequency voltages (see chapter 4).
  Also when the communication equipment presents a high common mode impedance it can happen that the stray capacitance of the transformer allows sparkovers between leads and ground. In this case it becomes necessary to ground the mid-point at the equipment side, either directly or by means of a surge protective device;

- ***fibre optic systems***, of course the best possible barriers against all kind of disturbances.
  However, unless used for the transmission of multiplexed information (e.g. Local Area Networks), their relatively high cost, taking into account the terminating equipment, limits their application to sophisticated systems requiring wideband transmission (e.g. differential digital protection or teleprotection).
  On the other hand, it is worth noting that some low cost (plastic) optical fibres can be of great interest for short distance low frequency applications requiring a very high insulation level (e.g. telephone circuits extending outside HV substations, see subclause 5.3.5.6, and sensors on HV equipment, etc.);

- sometimes it is necessary to have recourse to equipment combining different types of galvanic isolation such as isolation transformers and relays or optocouplers or even optical fibre. This occurs, for instance, with telephone circuits requiring d.c. signalling.

5.3.5.2 Overvoltage protection or Surge Protective Devices (SPDs)

The concept of the surge protective device is completely different from that of galvanic isolation in the sense that, whenever the protection operates a current is diverted to ground and the electrical characteristics of the signal to be transmitted are corrupted during the time that the disturbance lasts (this can be a clamping of the voltage level, a modification of the source impedance or even a short circuit).
Moreover the current diverted to ground, when significant, can sometimes lead to common impedance coupling or to a potential rise causing an interference problem elsewhere.
For that reason, overvoltage protection should be used only on circuits which can be interrupted during the disturbances. It should normally not be used on circuits carrying protection signals.

Three kinds of overvoltage protection are usually encountered (alone or in combination with each other):

- (Gas) arresters;
- (Metal oxide) varistors;
- breakover (avalanche) diodes.

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[9] *In some countries **neutralizing transformers** are used instead of isolation transformers. For more details see [20] vol VII.*

The following table summarises the main features of the three types of components.

Feature	Gas arresters	Varistor	Diodes
current handling capability	high	medium	poor
response time	low	medium	high
protective level (PL)	high (shape dependent)	any (current dependent)	any
dynamic PL /static PL	> 1	≈ 1	≈ 1
capacitance	very low	high	medium
leakage current	no	yes	no
life duration	small	yes	no

Table 5 - Main features of the devices used for overvoltage protection

Gas arresters or gas tubes are mainly used in protection schemes requiring high power handling capability (disturbances due to lightning or to power faults).

Their minimum d.c. sparkover voltage is typically about 90 V while their dynamic sparkover voltage at 1 kV/µs usually exceed 500 V.

Due to this significant level of residual transient overvoltage and due to the level of current that can be diverted to ground, it is usually not recommended to install these components within the equipment. They are better used as primary protection of a whole installation at the cable entry point to building (room).

Varistors present the advantage with respect to gas arresters, that they do not short circuit the signal and they exhibit a good dynamic behaviour. For these reasons they are widely used, mainly on power circuits.
However, due to their high capacitance, they are not suitable for HF applications such as 2 Mbit/s PCM circuits.

Breakover diodes cannot divert significant currents but their clamping voltages can be very low and independent of current. They are therefore used mainly as surge suppressors (secondary protection) close to the equipment or circuit to be protected (see below).

Arrester - Suppressor

The need to protect sensitive equipment against surges has prompted the application of multi-stage cascade protection schemes in which high energy SPD often called ***(Lighting current) arresters*** or ***type I SPDs*** (according to IEC 1312) are installed at the entrance of a building, to divert the major part of the surge energy, and SPD with lower energy handling capability called ***Overvoltage arresters***, ***Suppressors*** or ***Type II SPDs*** are installed near the equipment to be protected [10].

Such a scheme needs some coordination between arrester and suppressor in order to get a good distribution of the surge energy between both components.
The coordination has to take into account the relative clamping voltages, the response times, and the energy capability of the devices, as well as the conductor impedance between them and the impinging surge waveform.
This coordination problem is not always easy to solve.

Guidance can be found in the work done in that field by IEC, mainly in SC37A (Low voltage surge protective devices) and in TC81 (Lightning protection).

[10] *We prefer to use here the terms arrester and suppressor instead of primary and secondary protection to avoid confusion with the usual expressions used in the distribution world where a primary arrester is installed at the MV side of the MV/LV transformer and a secondary arrester at the service entrance of the building.*

5.3.5.3 Filters

Contrary to the two above mentioned methods of protection, filters don't act as dielectric protection but only as interference protection. The main idea related to the use of filters is that the bandwidth used for a circuit should never extend beyond the frequency spectrum of the signals it carries. Many EMC problems arise because disturbances penetrate equipment via circuits and ports whose frequency spectrum handling capability has not been limited.

The best known kind of filter is the low-pass device installed at the power port of most electronic equipment.

This filter has usually two functions:

- attenuation of differential mode disturbances;
- attenuation of common mode disturbances.

While the first function is usually easily achieved (it is directly defined by the transfer characteristics of the filter), the second is often a source of problems because it depends largely on the way the filter is installed and wired within the equipment.

The only way to ensure correct rejection of the common mode conducted disturbances is to install the filter directly at the entrance of the cable into the equipment (or into the framework or cubicle where the equipment is mounted), and to make the ground connection by a *direct contact* between the filter (metallic) case and the framework, *and not* (or at least not only) by a grounding wire.

5.3.5.4 General recommendations

- All type I protection (arresters) should be regrouped into one cubicle or frame separated from the electronic equipment and located as close as possible to the entrance of the room or building.
  Only type II protections (suppressors) are installed within the equipment.
- Cabling has to be made to correspond with the installed barriers. In particular, when using isolation transformers, care must be taken to keep input and output conductors distant from each other in order to respect the isolation level and to reduce the capacitive and inductive coupling.
- As far as possible all the circuits associated with a cable have to be protected in the same way.
  When only some of the circuits are protected by isolation transformers and the others not, or are equipped with surge protective devices, the insulation level between circuits must be at least equal to that provided by the transformers.

5.3.5.5 Specific recommendations

The following table gives examples of recommendations for barrier protection to install on shielded communication circuits extending outside buildings (in accordance with clauses 5.5 and 5.7).

Circuit	Environment		
	same earth network (*)	*different earth networks (**)*	*circuit incorporated in ground wire*
FDM[11]	isolation transf. 2 kV 4 - 108 kHz	isolation transf. 6 kV	isolation transf. 20 kV (***)
2 Mbit/s	isolation transf. 2 kV 6 - 2000 kHz	isolation transf. 6 kV	isolation transf. 20 kV (***)
64 kbit/s (G 703)	isolation transf. 2 kV 6 - 252 kHz	isolation transf. 6 kV	isolation transf. 20 kV (***)
E/M audio	isolation transf. 2 kV 0,3 - 3,4 kHz	isolation transf. 6 kV	isolation transf. 20 kV (***)
E/M signalling, Subscriber interface	Surge Prot. Device or Dedicated equipment	Surge Prot. Device or Dedicated equipment	Surge Prot. Device or Dedicated equipment

(*) With equipment normally intended to be installed in a class B environment as defined in clause 5.7.
Equipment able to withstand class C environments don't need a protection barrier.

(**) Interconnected earth networks belonging to substations with different voltage plans cannot always be considered as forming a single earth network.

(***) If the mid-point of the isolation transformer at the equipment side is grounded through a SPD, this should be able to withstand a 8/20 μs surge current of 10 kA.

Table 6 - Barrier protection recommended on shielded communication circuits extending outside buildings

5.3.5.6 Protection of unshielded circuits extending outside substations

When a lightning stroke hits a substation, the low frequency components of the current lead to a potential rise of the earth network (see subclause 5.5.3.1) which is roughly speaking equal to the product of the current amplitude and the earth resistance.
For earth resistances in the range of 1 Ω or more, the potential rise easily exceeds several tens of kV.
It also extends in the soil outside the earth network where it decreases, following practically a 1/d rule (at distances d higher than twice the length of the earth network) see figure 73.
The result of this is that each circuit entering this potential "cone" (or "crater") is submitted to a potential difference between cores and earth equal to the local potential rise.
In particular, all cable entering the substation supports the entire potential rise.
If this cable is not protected by suitable galvanic isolation (e.g. isolation transformers), or if a break through occurs (SPD sparkover), its circuits will assume the potential of the substation and "transfer" it outside the "crater", creating further disruptions (see figure 74).

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[11] *Frequency Division Multiplexing*

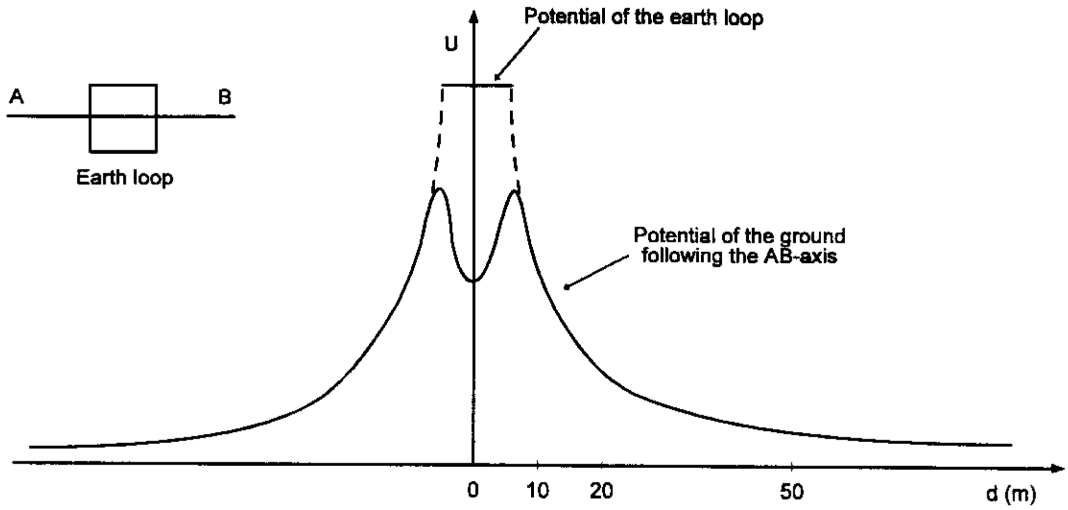

Figure 73 - Earth potential rise due to a lightning stroke

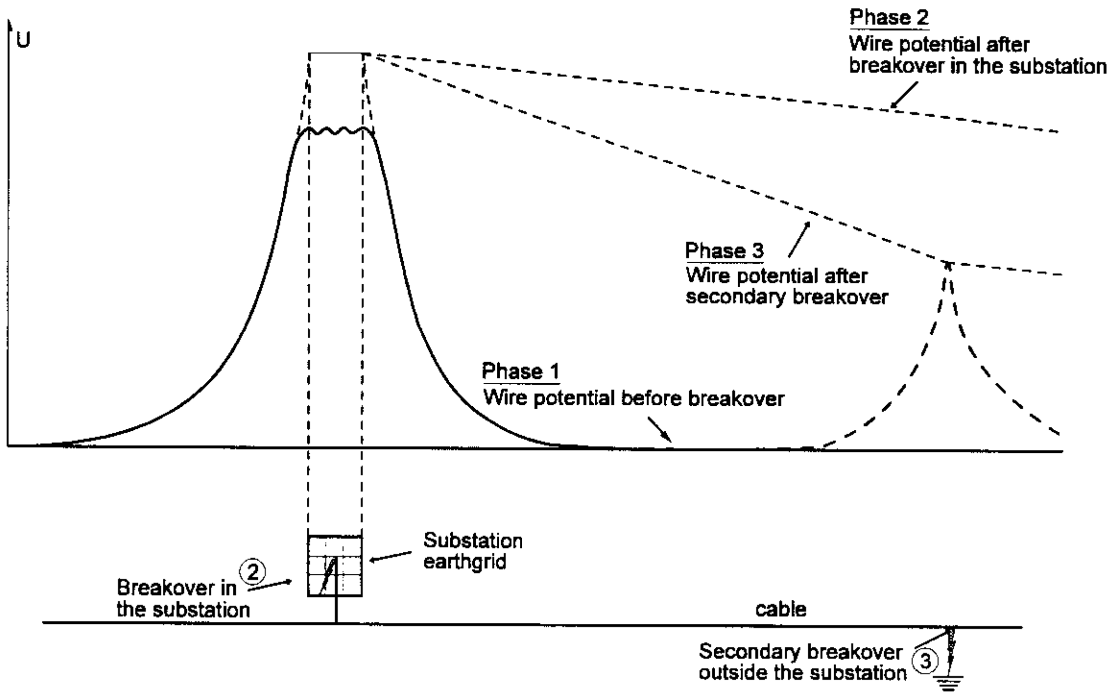

Figure 74 - Transfer of earth potential rise to remote earth networks

This kind of problem is normally handled by CIGRE WG 36 - 02 and ITU-T (CCITT) SG 5.
However, the following mitigation measures give an idea of how to achieve a primary protection scheme:

1. the part of the cable extending inside the potential cone should have a high insulation level (typical breakdown strength: 20 kVeff). The length of this extension cable depends on the soil resistivity, the shape and resistance of the earth network and the protection degree required; typical values range from 50 m to 300 m and up to 1000 m for very large stations;

2. the isolation transformers (or the dedicated equipment like telephone repeaters, in case of d.c. signalling) should also be designed with high dielectric strengths.
   However, it is difficult to design materials with dielectric strengths higher than 20 kVeff (50 Hz) or 50 kV (impulse) because of creepage distance problems.
   Moreover, such equipment should always be installed inside a building or equipped with heating elements in order to prevent condensation;

3. lightning arresters with a high sparkover voltage (e.g. 40 kV) installed in common mode at the cable side of the isolation transformers in order to protect them against excessive voltages. This protection can be a simple air gap (weak point) between pair terminals and earth or between transformer central tap and earth;

4. gas arresters or varistors with normal clamping voltage (e.g. 90 or 230 V) installed in differential mode or between central tap and terminals on the same side of the transformers in order to protect their windings and to avoid excessive voltage between conductors;

5. SPDs with sparkover voltages compatible with the insulation level of the "normal" cable (e.g. PTT cable) or drainage reactors [12], installed in common mode at the junction between "normal" cable and "dedicated" cable.
   This latter protection is meaningless if the local earth resistance is too high (say higher than 10 Ω).

In addition to the previous measures it can be advisable to insert fuses between the isolation transformers and the extension cable. The reason for this is that, in the absence of such protection and in case of sparkover of the lightning arrester, the extension of the GPR outside the well protected installation can cause severe destruction to other cable facilities.
For maximum effectiveness these fuses should have a length of at least 10 cm in order to limit the risk that an electrical arc be maintained. (In fact practical experiences have shown that with currents higher than a few hundreds amps and simultaneously voltages higher than 50 kV, the effectiveness of fuses vanishes).
This latter measure, however, has the drawback of interrupting the circuits following fuse melting, which can be considered unacceptable by some utilities.

Figure 75 shows an example of an installation that satisfies the recommendations described above.

It is worth noting finally that all the previous mitigation measures refer to unshielded cables or to cables with no guaranteed or sufficient shielding continuity (e.g. public telephone cable).
Most cables used by utilities are shielded cables with adequate drainage capability.
In this case, the shielding effectiveness is usually sufficient to allow the use of simple MV isolation transformers (e.g. 6 kV) without the need for other protection.

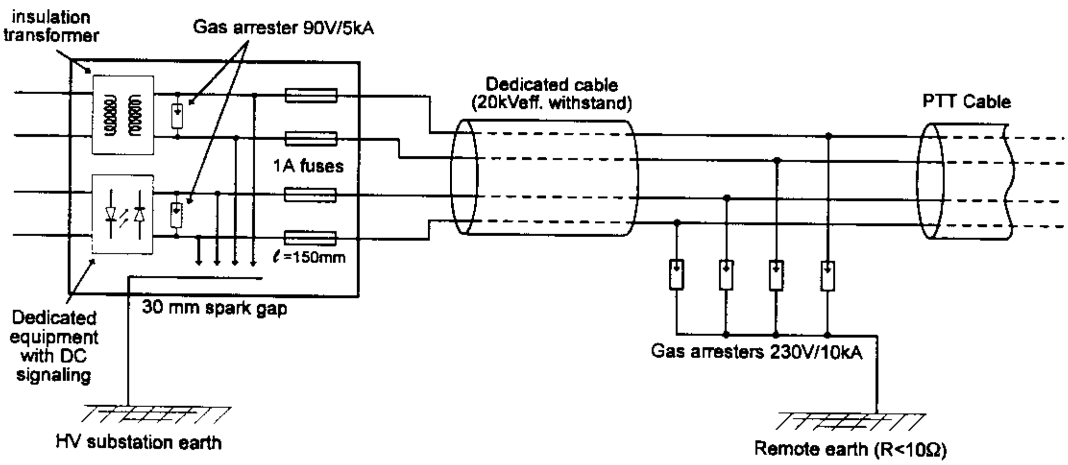

Figure 75 - Example of protection for communication circuits extending outside a substation

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[12] *In some countries it is customary to install between conductors, in addition to SPD's or alone,* drainage reactors *with mid point connected to ground. During voltage surges (50/60 Hz, lightning), they relieve the voltage stress between conductors and force simultaneous operation of the SPD's, thereby minimizing the possibility of noise.*

5.4 Guidelines for generating plants

5.4.1 General grounding and cabling philosophy

All what has been discussed in chapter 4 and in clause 5.2 can of course, without restriction, be applied to generating plants.

5.4.2 Grounding practices

5.4.2.1 Earth network

As in HV substations, the earth network of a generating plant achieves different objectives, the main of which being:

- the limitation of step and touch voltage (safety requirements);
- the ability to intercept short circuit currents;
- the attainment of a good level of EMC.

Notwithstanding the fact that all these objectives are strongly correlated, we will only stress here the EMC needs leaving the requirements for safety to the existing national and international regulations.

In particular, the cross-section of the earthing conductors in the vicinity of HV electrical equipment will normally be specified by the level of the HV fault currents leading to values sometimes exceeding 1000 mm^2 of copper.
For EMC purposes (including lightning), cross-sections of 100 mm^2 in the case of steel strip/rod or 70 mm^2 in the case of copper conductors can be recommended.

An outdoor earth network will be provided over the whole area of the generating plant. Its density will depend on the importance (in terms of vulnerability) of the different equipment installed. Outdoor earthing systems are generally designed with ring type or meshed electrodes laid around each building and buried in soil at a depth of 0,5 m to 1 m.

Foundation earth electrodes are installed in the lower most concrete layer of each building with a mesh size not exceeding 10 m.

These earth electrodes are connected to the main earth grid by at least two buried conductors following different paths.

HV substations in the direct vicinity of the generating plant are also interconnected with the main earth network by at least two conductors. The same is valid for all installations (building, tanks, etc.) which have some electrical connection with the main installation but do not share the same earth network.

5.4.2.2 External Lightning Protection System (LPS)

The external lightning protection can be based on the well known electrogeometric (EG) model which, although partially empirical has been validated by several studies [13]. It will of course take into account other lightning parameters and safety regulations specified by the national and international standards. [11]

The external LPS consists of an air termination system to intercept lightning flashes, and it uses a number of down-conductors to conduct the lightning current to the earth.

The air termination system will basically be a set of conductors forming a meshed Faraday cage, with a spacing between conductors based on the required efficiency of the LPS. This latter depends on the *minimum* value of lightning current likely to be intercepted by the LPS.

Indeed, it is currently admitted that the ***striking distance*** d between the tip of the downward leader and the striking point at the moment at which the upward connecting leader starts, is related to the peak amplitude of the lightning current according to the simplified expression:

$$d = 9{,}4 \cdot I^{2/3} \qquad \text{(d in m, I in kA)}$$

Hence, for a given mesh spacing, the higher the expected current is, the higher the probability that it will be intercepted by the mesh.

Knowing that the probability of a lightning current higher than 8 kA is about 90 % (world mean [11]) and owing to the fact that it is not difficult to protect electrical and electronic circuits inside a generating plant against the direct impact of currents smaller than 8 kA, it seems reasonable to retain this current value for the calculation of the mesh spacing.

The application of the above formula with $I = 8$ kA leads to d = 37 m.

Simplifying the EG model and in order not to repeat the calculation for each particular case, it can be recommended to chose for the mesh a conservative spacing equal to d.

Practically, however, every edge of the building will be provided with an air termination conductor. In addition, every metallic structure such as ventilation equipment, parapets, air conditioning ducts, pipe work reinforcing steel will be bonded to the LPS leading to an actual mesh spacing closer to 20 m.

If necessary, buildings containing very sensitive equipment (or equipment requiring a very high level of security) can be protected with a higher density LPS, with a mesh spacing not larger than 15 m.

Other methods like the rolling sphere method can of course be applied to determine with more accuracy the external lightning protection system.

All the down conductors, which for a given protected structure should exceed two in number, must be connected to the ring earth electrode.
Also, reinforcing concrete walls and columns must be welded or lashed to the foundation electrode or to the ring earth electrode at the bottom and to the meshed grid on the roof at the top. Steel rods can be used as "natural" down conductors.

Importance of the mesh spacing and the number of down conductors

It should be stressed that the mesh spacing of the external LPS not only determines the probability of capturing lightning currents of any amplitude but also plays an important part in determining the division of the lightning current once the external LPS has been struck, and hence the amount of induction within the protected area.

The higher the number of (down) conductors, the smaller the current in each conductor, and the smaller also the magnetic field in the vicinity of these conductors.

On the other hand, as already mentioned in subclause 5.2.1, different theoretical and practical studies have shown that the division of the lightning current between the different branches of a LPS occurs, roughly speaking, in a way which is inversely proportional to the length of the different branches, if their equivalent cross section remains constant.
This important statement can be very useful in calculating the EM level in the vicinity of every ground conductor likely to carry a partial lightning current.

Protection of chimneys

Each chimney will be equipped with two down conductors and at least one ring conductor (air terminal system).

Provision must be made to achieve a good interconnection (at least two 50 mm^2 conductors) between the earth network of the chimney (usually a ring) and that of the main building.

Although they don't need the same protection level as the other buildings, cooling towers will also be equipped with at least two down conductors (better four) and, at the summit, with a ring conductor to which the concrete reinforcing rods are connected.

Protection of chimneys and cooling towers is more to provide general protection for the whole generating plant against significant lightning currents ($I >> 8$ kA) than to provide protection for themselves.

5.4.2.3 Indoor grounding and equipotential bonding

As explained in chapter 4 the general grounding philosophy which is recommended for new generating plants is based on a tridimensional meshed network achieving as far as possible an equipotential bonding between all the equipment.

It is important to stress here the important evolution which has occurred in this field during the last ten years.

For many years electronics was based on the use of low frequency analogue signals and the only kind of known disturbance was at power frequency.

So it seemed natural to try to avoid 50/60 Hz current loops by adopting a star configuration and a so called "separation" between safety, electrical and electronic earths.

Nowadays with the increased speed of modern electronic equipment, and their increased sensitivity to high frequency disturbances, but also with the better knowledge of the mechanisms of influence, this grounding policy is no longer appropriate. On the contrary, its abandonment not only helps tackle EMC problems but also considerably simplifies the cabling and avoids the need for insulating different ground conductors from each other. [15]

In particular the use of separate grounds for d.c. power supplies (reference potential), cable shields and equipment frames or cabinet should be definitively withdrawn (see subclause 5.4.2.4).

The actual realisation of a good equipotential bonding network ensures that "parasitic" currents will always return to their source by the lowest impedance (usually the shortest) path, thereby reducing the risk of common impedance coupling as can arise with current loops.

Indeed a multipoint grounding system will not avoid current loops. However these loops, being by far more numerous and smaller than in a one point (star) grounding system, are not a problem and are even a necessity for fighting against induced disturbances.

The following points are repeated here for convenience:

- in order to reduce high frequency disturbances it is necessary to use multi-grounded cable shields;
- for short length circuits this grounding must be made at both ends whereas for long circuits, thanks to the capacitive return path, it is sometimes sufficient to ground the shields at the most sensitive end of the circuit, i.e. where electronic equipment is installed;
- owing to the fact that, in generating plants, many circuits involve active components at both ends (this situation will increase in the future with the arrival of "smart" transducers and the replacement of all, or part of switchgear and control gear associated auxiliary equipment by electronic devices), it becomes necessary to ground most cable shields (not circuits) at both ends whatever their lengths might be;
- the systematic grounding of all cable shields (except for low level, low frequency circuits like thermocouples and some coaxial links) requires, in turn, the existence of a good equipotential bonding network which will precisely be reinforced by the existence of multigrounded cable shields !

So, even when it is not necessary to ground a cable shield at a particular end (because at that end the equipment is not sensitive to disturbances or cannot be the source of disturbances for other equipment) it remains always advisable to generalise this grounding practice.

The achievement of a good equipotential bonding network requires the electrical connection of all the following items:

- building construction parts such as steel guides and steel columns;
- metallic piping and channels;
- metallic housings of subdistribution boards and switchgear systems;
- metallic cabinets containing electrical equipment and instrumentation;
- desks, cable racks, cable trays, vertical risers, supporting structures, etc..

For cable trays, and more generally, for all metallic components which act as an ECP, it is important to note that not only grounding is needed but also galvanic continuity along its full length.

All the bonds between metallic components must be made, bearing in mind that what is important is not to fix the potential of these components but to allow disturbance currents to flow along them, following the same path as the circuits and, in so doing, keeping the area between active circuits and grounding circuits as small as possible (figure 76).

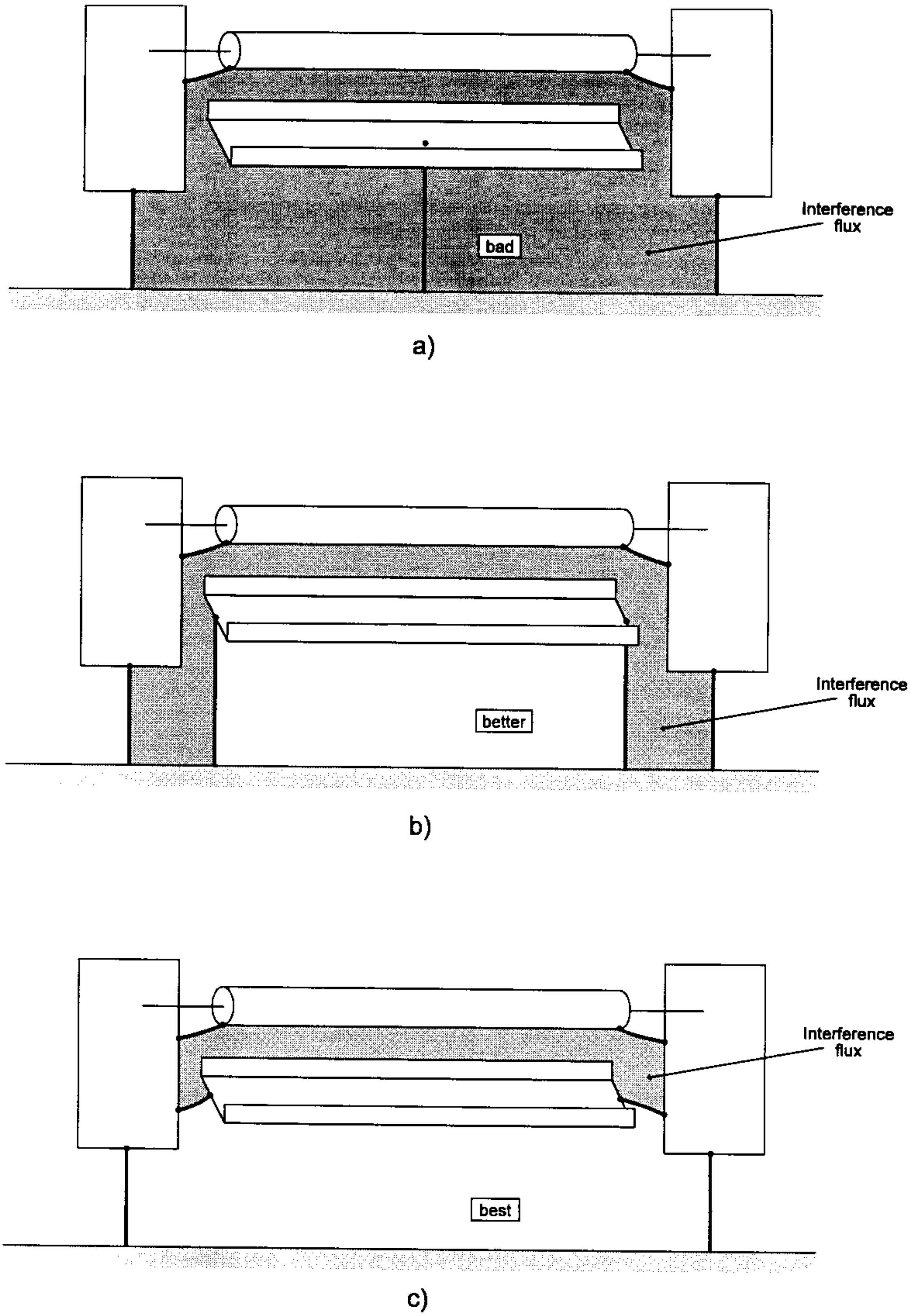

Figure 76 - Grounding of cable trays

Another important point concerns the way the metalwork is bonded to each other.

The best connection involves bolted constructions with direct contact between the different structures. If necessary, serrated washers or lock washers can help ensure good contacts when the protective coating of the metallic surface has not been (sufficiently) removed. Recourse to copper conductors is only needed when direct contact between metal works is not possible.

Depending on the different electromagnetic environments which are a function of the type of equipment installed and the proximity of the external lightning protection system it is possible to split the indoor bonding network (internal LPS) into different zones having different mesh densities. [7]

In particular for sensitive electronic equipment installed in a special room, it may be necessary not only to make good connections between the individual cabinets or between these cabinets and the cable trays but also to provide connections (for instance by means of steel strips) between the cabinet rows (or the cable trays) at regular intervals of e.g. 2 m and to interconnect the whole system to a ring-type grounding bus (bonding bar) installed at the periphery of the room.

Such a grounding bus can be installed at the boundaries of each protection zone and of the whole building, making the multiple interconnections between zones easier.

In the same way the indoor bonding network has to be connected to the safety earthing system and to the outdoor earthing system at multiple points (at least 4).

5.4.2.4 Grounding of battery power supply circuits

It can happen that, in order to be able to detect a single pole earth fault, it is necessary to ground the d.c. power supply circuit at only one point - usually at the battery.
In this situation, the only way to ensure high frequency EMC is to systematically install decoupling capacitors between the supply lines and the frame (from 10 nF to 1 μF depending on the low frequency limit of the disturbance spectrum that has to be covered).
Such a system, however, remains sensitive to switching current surges (e.g. in case of earth faults). Therefore it is more advisable to use a d.c./d.c. converter (with galvanic isolation) in each cabinet in order to be able to locally ground the circuits.

5.4.2.5 Grounding of high-power apparatus or systems

One frequent objection to a meshed bonding network is that this approach results in ground loops and common (ground) impedance coupling between sensitive electronics and high-power systems (motor, welding equipments, etc.).

This objection, in fact, doesn't hold when sufficient provision has been made to achieve a good equipotential bonding network through the interconnection of reinforced concrete, building steel, grounding conductors, cable trays, cable shields, pipes, gutters, supports, frames, etc..

Of course the separation principle described in rule IV of clause 5.2 still applies. For example a motor with a potentially large fault current should not be bonded to the same grounding conductor as sensitive electronics.
Some local reinforcement of the earth network in the vicinity of high-power equipment may also be required.
If necessary a Parallel Earth Conductor (ECP) can be added either to the sensitive circuit or to the (potential) source of disturbance.

More than ever the decoupling principle described in figure 53 of chapter 4 applies: *in a well meshed ground network the disturbance currents will return to their source via the shortest possible path. The more paths created, the smaller the risk of common impedance coupling between source and victim.*

5.4.3 Cabling

5.4.3.1 Internal cabling

The internal cabling includes the auxiliary circuits located in the main building (control-equipment, process) as shown in figure 63.

All the general cabling recommendations made for HV substations are basically valid here.

However some specific features of generating plants will sometimes lead to the choice of other types of cables or to other installation practices.

These main features can be summarised as follows:

1. the general electromagnetic environment of generating plants is normally less severe than that of HV substations;
2. due to the high level of interconnected metallic components, the equipotential bonding network should be of higher quality within the main building of a generating plant than in an (open air) substation;
3. the number of cables used in a generating plant is much larger than in a substation. This means in practice that, for economic reasons, the same level of cable shielding will not normally be possible in a generating plant;
4. the emergence of smart transducers and actuators will lead to an increased decentralisation of the electronics and a greater need for multigrounded cable shielding.

Type of cable

Depending of the type of signal carried (see subclause 5.1.2) different types of cable can be recommended as in the following.

- Type 1a: coaxial or twisted pair cable with a shield quality at least equivalent to point 4. of subclause 5.3.2.2.
- Type 1b: high quality coaxial or triaxial cable possibly protected by a continuous copper tube. Resonances in the shielding circuit can sometimes be avoided by the use of high permeability or high loss materials (ferrite powder, permalloy).
- Type 2: twisted pair cable with a shield made of aluminium foils or aluminium tapes (see chapter 4 - figure 59), or better, a copper braid shield. Very low level circuits like thermocouples should be individually shielded.
- Type 3: twisted pair cable with shielding.
- Type 4: multiconductor cable with or without shielding. One return conductor can be used for several circuits.

Use of cable trays

The installation of the cables on galvanically continuous cable trays can contribute greatly to the reduction of external disturbances.

Depending on the continuity level of the cable tray, the way it is grounded (see figure 76), and whether it is covered or open, the shielding effectiveness will vary greatly (from less than 10 dB to more than 30 dB between 100 kHz and 10 MHz).

Cable trays can also be very helpful in reducing cross-talk between different circuits.

The best layout uses separate trays for cables carrying sensitive signals (subclause 5.1.2 type 1 and 2) and for cables carrying "noisy" signals (type 4, LV - a.c. or d.c. power cable, etc.).

In cases where the same tray is shared by different types of circuits, care should be taken to bundle each cable category separately and to keep the distance between bundles as large as possible.

It should indeed be stressed here that a metallic cable tray offers a certain degree of reduction in the coupling between cables in it, provided the cables are not installed too close to each other.

Grounding of cable shields

As explained in chapter 4.3.3 and with the assumption that a good equipotential bonding network has been achieved, most cable shields should be bonded to the (grounded) metallic cabinets of the apparatus to which they are connected.

The main exception to this rule concerns cables carrying low frequency, low level analogue signals such as for temperature measurement. In this case the shield must be grounded at the end with the highest unbalance or where the circuit itself is grounded.

If the cable involves individual shielded pairs the inner shields are grounded at one end while the other shield is grounded at both ends.

Cables connected to passive transducers or non electronic actuators (relays, motor,.etc.) may sometimes be grounded at only one end (the end opposite to the transducer or actuator), but this practice should normally be avoided as it goes against the achievement of a good equipotential bonding network. Moreover, with single point shield grounding, there is some risk of resonance excited by disturbances at lower frequencies.

Long coaxial cables can normally also be grounded at one point only, but a capacitive HF grounding should be provided at each piece of equipment connected to them.

5.4.3.2 External cabling

External cabling covers all the links to the external auxiliaries (see subclause 5.1.1.2) and also to very exposed parts of the generating plant such as chimneys antennas, electrofilters, ground-lights.

The main problem with the external cabling is of course lightning.

Although the best way to protect external circuits is based on the achievement of good interconnections between the different earth network, no guarantee of complete protection can be given without additional precautions such as SPDs and galvanic isolation. The use of (very well) multigrounded shielded cables is of course a prerequisite.

Metallic trays, or better, metallic conduit, will also greatly help to reduce common mode voltage stresses on the equipment.

Cables coming from outside the main building should be grounded directly near their entrance to the building in order to avoid large transient currents flowing inside the building.

Cables connected to equipment on the chimney should be installed on a cable ladder providing a ground link between the external lightning protection systems of both the building and the chimney, or should be placed underground in metallic conduit.

5.5 Nature and level of the disturbances in HV substations

The objective of this clause is to give, based on the EMC concepts developed in the preceding chapters, an evaluation of the disturbance levels likely to appear in the auxiliary circuits of a substation. [6]

5.5.1 Disturbances due to switching operations, insulation breakdown or sparkover in HV circuits

5.5.1.1 Open-air (Air Insulated) Substations (AIS)

The disturbance levels depend on different parameters, the most important of which are:

- the transient voltages and currents generated by the switching operation;
- the voltage level of the substation;
- the relative position of emitter (source) and susceptor (victim);
- the nature of the earthing network;
- the cable types (shielded or not shielded);
- the way the shields are grounded.

The main coupling modes are:

a) **magnetic (or electromagnetic)** coupling due to the propagation of current and voltage waves on busbars and lines.

   Measurements of transient electric fields carried out underneath the busbar and in the vicinity of voltage transformers have shown typical peak amplitudes in the range of 1 - 10 kV/m.

   The corresponding spectrum depends on the dimensions of the substation and is thus generally inversely proportional to the voltage level. Although frequencies as high as 200 MHz have been recorded, the spectrum usually extends from a few kHz to a few MHz.

The high frequency transients have an overall duration in the range of 1 - 10 µs, but these transients may be repeated a large number of times during one switching operation.

The common mode voltage appearing at one extremity (the other being grounded) of an unshielded cable of about 100 m length lying on the ground under the busbar can reach typically 3 to 4 kV during switching operations in a 150 kV substation and 6 to 8 kV in a 400 kV substation.

The common mode voltage appearing at the extremities of a shielded cable grounded at both ends will depend on the shielding effectiveness (see chapter 4) of the cable and on the frequency spectrum.
Roughly speaking reduction factors ranging from some tens for a steel wire shield to more than one hundred for a very good copper braid shield or a tubular shield can be achieved at frequencies between 200 kHz and 2 MHz (see subclause 5.3.2.2).

The current in the shields can easily reach several tens of amperes.

b) **common impedance coupling and magnetic coupling** due to the current flowing into capacitive loads like voltage transformers (figures 69 and 77).

The common mode voltage induced into the circuits which are in the direct vicinity of capacitive transformers and more particularly into the secondary circuits of these devices can exceed 10 kV in a 400 kV substation.

This voltage will of course be greatly reduced by the use of shielded cables but it remains difficult to get reduction factors as high as mentioned above because of the impossibility of reducing to zero the area of the loop formed by the zero volt conductor, the grounding of the transformer and the grounding of the secondary circuit. Moreover, the stray capacitance between the primary and secondary windings of the measuring transformer results in a high frequency differential voltage appearing on the secondary circuit which can reach several kV. The spectrum of this disturbance can exceed 10 MHz but is usually reduced by the damping of the wiring.

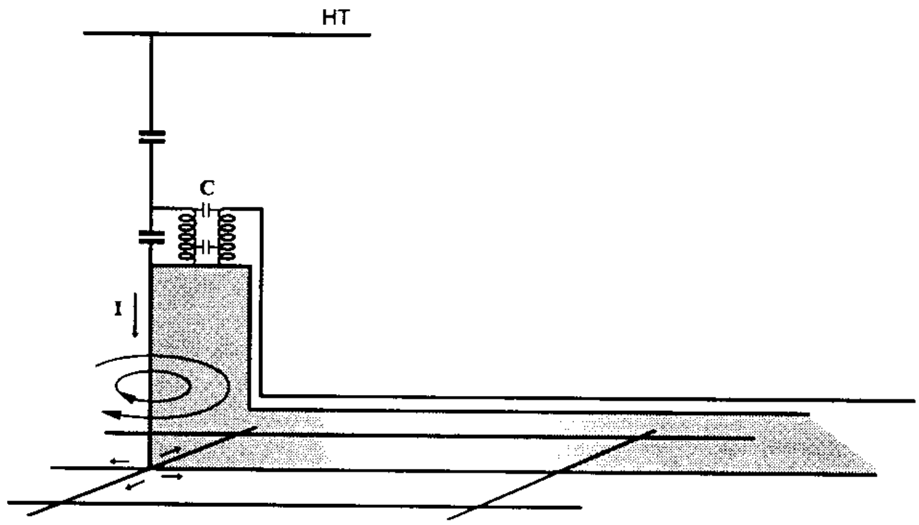

Figure 77 - Common impedance and magnetic coupling due to the grounding connection of voltage transformers

5.5.1.2 Gas Insulated Substations (GIS)

Compared with conventional open air substations, GIS exhibit some fundamental differences:

1. the size of the electrical components is much smaller.
   For this reason, the frequency spectrum of the disturbances, of which a great deal is due to multiple reflections of travelling waves on the busbars, extends at least 10 times higher (see chapter 3);
2. the characteristic impedance of the GIS is about 5 times smaller than that of an open air installation (i.e. ≈ 60 Ω instead of 300 Ω).
   This leads to an important impedance mismatch at the junction of the GIS and overhead lines or open air busbars.

This mismatch is, during switching operations, the origin of a high standing wave ratio and, in particular, of high current waves (the amplitude of the voltage waves depends directly on the voltage level and is comparable to that generated in open air substations, whereas the amplitude of the current waves is inversely proportional to the characteristic impedance).
Whenever the GIS metal enclosure presents a shielding discontinuity, e.g. at the junction with overhead lines or cables, it becomes an important source of radiation, with values sometimes higher than 10 kV/m and 50 A/m.
If the discontinuity is made outside the building in which the GIS is installed, and if the shielding of the building ensures the continuity of the GIS shielding (see subclause 5.3.4.1), this is of little importance.
This is generally what happens with overhead lines. However, when part of the substation is open air or when it is connected to cables with ungrounded (or incorrectly grounded) shields, it will give rise to important disturbances.

The consequence of these features is that, during switching operations, very high potentials are induced in the earth network and in the secondary circuits.
Those potentials are well known in the literature under the not always accurate name (see chapter 4.2.2.1 and subclause 5.5.4.2) of Transient Ground Potential Rise (TGPR). They can be high enough to cause sparkover between metallic grounded elements not in direct contact with each other.

All those problems are rendered more acute by the small distances usually present in GIS between HV equipment and electronic equipment.

5.5.2 Disturbances due to power frequency fields

The influence of capacitively coupled power frequency fields on equipment installed within substations is seldom significant owing to the ability to reduce the electric fields by metallic screens and by not leaving metallic elements floating (ungrounded).

Magnetic fields at power frequency are also very seldom the origin of interference with apparatus, even under fault conditions. There is however one important exception, namely the video monitors (Cathode Ray Tubes) which can be sensitive to fields as low as 1 A/m (or 1 μT).

The best solution to avoid this kind of problem is of course to increase the distance x between source and victim knowing that, for a magnetic field due to a current I in a single long wire, the decrease follows 1/x:

$$H = \frac{I}{2\pi x}$$

for a two or three phase balanced system the decrease follows $1/x^2$:

$$H = k I \frac{d}{x^2}$$

where: d is the distance between conductors (assumed to be much smaller than x)
k is a constant dependent on the layout and approximately equals to 0,2.

For a circuit confined in a limited volume (e.g. transformer, MV - LV substation), the decrease follows almost $1/x^3$ assuming x much greater than the maximum dimension of the volume.

Another solution is to act on the source itself by reducing the distance d between conductors.

If this is impossible, one solution consists of replacing the cathodic ray tubes with liquid crystal displays or other similar devices; another one consists of shielding the cathodic ray tubes or the room where they are installed by appropriate measures (see subclause 5.3.3).

Active compensation by using cancellation fields from controlled current loops can sometimes also be applied to mitigate the interference problem.

Aside from the small influence of power frequency fields on equipment and apparatus it is worth mentioning that inductive and capacitive coupling - mainly during fault conditions - can be the origin of much more important problems on long structures like cables and pipelines, as explained in subclause 5.5.3.2.

5.5.3 Disturbances due to fault currents

High frequency phenomena due to fault currents are not very different from those due to switching operations; a single phase fault gives rise to a rapid change in the busbar voltage with an amplitude equivalent to that of the surges due to switching operations.

The origin of 50 (60) Hz current circulation within the high voltage equipment, the earth network the cable shields (when the density of the earth grid is inadequate) is mainly responsible for the difference in the low frequency phenomena observed during faults. These currents, in turn, induce disturbances in the wiring by common impedance coupling or by inductive coupling.
Maximum values of 500 V can be encountered in classical substations as a consequence of a 50 kA fault current. However a maximum value of 200 V should not be exceeded in a substation having a good earth network and properly installed cabling.

The main problems due to fault currents in substations concern the circuits extending outside the earth grid as they are directly influenced by the ground potential rise.

5.5.3.1 Ground potential rise

When an earth fault occurs in an electrical installation, the current flowing to the earth produces a potential rise of the earth electrode (earth loop, earth grid) and of the neighbouring soil with respect to a remote earth (figures 73 and 78).

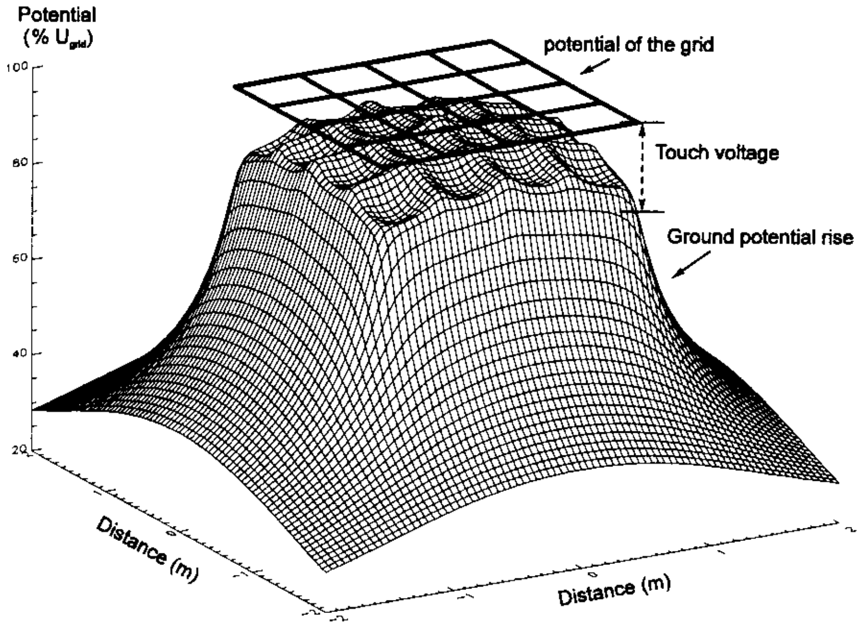

Figure 78 - 50 (60) Hz potential rise in the vicinity of an earth grid

As it can be seen on these figures there are limited differences in GPR between two points on the same earth grid. Hence any circuit installed within the area of this earth grid will be subjected mainly to the inductively coupled disturbances mentioned above.

The situation however is different for a cable entering the "zone of influence" as it is directly exposed to a longitudinal voltage equal to the GPR (see subclause 5.3.5.6).

The value of the GPR is normally equal to the product of the resistance of the earth grid R_g and the current I_g flowing into the earth:

$$U = R_g I_g$$

In the most general situation I_g is smaller than the fault current I. This latter is the sum of:

I_a supplied by the transformers of the substation;

I_b supplied by the overhead lines without ground wire;

I_c supplied by the overhead lines with ground wire;

I_d supplied by the power cables.

The current I_g into the earth doesn't include the components returning to their source via the ground conductors (see chapter 4.2.2.3 - 2).
It is given by an expression of the type [13]:

$$I_g = I_b + I_c \frac{R_c + j\omega(L_c - M_c)}{R_c + j\omega L_c} + I_d \frac{R_d}{R_d + j\omega L_d}$$

where:

R_c and R_d	are the per unit length (p.u.) resistances of the ground wire and of the power cable shielding;
ωL_c and ωL_d	are the p.u. reactances of the different circuits with earth return (about 0,7 Ω/km at 50 Hz);
ωM_c	is the p.u. mutual reactance of the circuit formed by the ground wire and the earth and the circuit formed by the faulted line and the earth (about 0,25 Ω/km at 50 Hz).

For shielded cables with the shielding earthed at both ends the overvoltage U will of course be reduced by the *shielding* factor (see chapter 4.2.2.3 eq. 8):

$$k = \frac{R\ell}{R_g + R'_g + (R + j\omega L)\ell}$$

With R the p.u. resistance of the shielding;

R_g the earth resistance of the substation;

R'_g the earth resistance of the substation at the remote end (supposed here not to be affected by the fault current);

ωL the p.u. reactance of the shielding / earth circuit (≈ 0,7 Ω/km at 50 Hz).

The presence of a ground connection between both substations involves, on the other hand, a current I_2 flowing in the shielding of the cable, and a transfer of part of the GPR to the far end:

$$I_s = \frac{U}{R_g + R'_g + (R + j\omega L)\ell}$$

$$U_g = \frac{U R_g}{R_g + R'_g + (R + j\omega L)\ell} \quad \text{and} \quad U'_g = \frac{U R'_g}{R_g + R'_g + (R + j\omega L)\ell}$$

with U_g the new GPR and U'_g the GPR of the remote substation.

It is advisable to check, particularly for short distances between substations, if these currents and voltages are admissible and if there isn't any risk of saturation of the shielding.

Ground potential rise due to single phase faults can sometimes exceed 5 kV, leading to overvoltages in insufficiently protected circuits.

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[13] *The earth resistance being neglected with respect to the impedance of the conductors with earth return.*

Moreover, if a telecommunication cable follows an overhead line or a power cable over a long distance, it will be inductively influenced by the fault current. This latter CM overvoltage can also reach several kV and depends on a wide range of parameters like the current amplitude, the length of influence, the distance between source and victim and the current division between the earth and the overhead ground wires or shield of the power cables.

5.5.3.2 Influence of power cables and overhead lines on telecommunication cables

This subject, partially concerning substations, is discussed in the framework of a cooperation between CIGRE and ITU-T. All the details about the calculations of influence can be found in [12], Vol II, III, IV.

In order to gain an idea of the possible problems likely to appear in telecommunication circuits, we will summarise here some of the main conclusions of these documents:

- capacitive coupling occurs only between overhead lines and overhead telecommunication circuits. It can become significant when the distance between source and victim is shorter than 50 m;
- the main cause of disturbance is certainly due to inductive coupling under fault conditions. It can occur with overhead circuits as well as with underground circuits.

The length of influence is of particular importance. Values of induced voltage in the range of 10 V/km per kA are typical for telecommunication circuits influenced by a single phase fault with earth return on a HV line at a distance shorter than 200 $\sqrt{\rho}$, (with ρ the soil resistivity in Ω·m).

For an underground power cable in the vicinity of a telecommunication cable the induced voltage can exceed 100 V/km per kA.

Of course in all these situations important reduction factors can be present thanks to the earth wire of the overhead lines ($0,5 \leq k \leq 0,8$), the shielding or the ECP of the underground cable ($0,1 \leq k \leq 0,5$) and / or the shielding of the telecommunication cable ($0,1 \leq k \leq 0,8$).

Note that the total reduction factor is seldom equal to the product of the individual factors.

5.5.4 Disturbances due to lightning

Contrary to normal switching operations lightning can produce destructive effects when there is a direct stroke to the substation. In this case the coupling mechanism will be common impedance (e.g. potential rise of the earth network) or direct induction in sensitive circuits. Coupling by radiation should give rise only to interference.

On the other hand, it is useful to remember here that even if the rise time of a lightning impulse is significatively longer than that of some switching transients (values from 0,25 to 10 µs compared to values from 5 to 50 ns), its amplitude can be two orders of magnitude higher; therefore it leads to dI/dt of the same order of magnitude!

5.5.4.1 Induction in circuits lying close to ground conductors

The direct inductive influence of a lightning current flowing in a ground conductor on a circuit lying in the vicinity has been partly discussed in subclause 5.2.1; the corresponding disturbance levels can be directly estimated using the expressions given in figure 64.
Depending on the relative distances between the conductors, the lengths of influence and the magnitude of the lightning current, the resulting disturbance will vary greatly.

A very important point which is worth repeating here concerns the number of grounding conductors. Indeed it is not sufficient to offer to the lightning current a short path to earth but also to provide multiple paths in order to divide the current and to reduce the amplitude of each component.

5.5.4.2 Direct strike to a substation

As with fault currents the highest disturbance level will be applied to the circuits that extend beyond the earth network. Taking into account the importance of the involved currents, the GPR can easily reach several tens or even hundreds of kV.

But contrary to what happens at low frequency, even inside the area of the earth grid the situation remains complex as the potential of the grid can no more be considered as uniform. This is due to the inductive effects which have to be taken into account when the frequency increases.

If the earth grid was made of insulated conductors or if it was installed above ground (as is the case for the bonding network) and connected to an ideal earth along its edges, it would be rather easy to cope with this situation and to calculate the voltage induced in any circuit installed in the vicinity of the grid, knowing in particular that when the circuit is referred to the grid, the closer it is to it, the smaller the induced voltages will be (see clause 5.2 rule III).
In this case it would be incorrect to speak about (Transient) Ground Potential Rise as the difference of potential between any two points, i. e. the contour integral of the electric field between these points, is largely dependent on the magnetic flux encompassed by this circuit, and hence a function of the path followed to make the measurement. In particular, this voltage difference would be practically zero at the surface of the earth grid because the magnetic flux is then very close to zero and the resistance of the conductor, even taking into account of skin effect, can still be neglected. This is the so called "Voltage drop" or "Scalar difference of potential".

The situation, however is completely different when the earth grid is buried and in contact with a conductive medium like the soil.
Indeed, in this case, due to the dissipation in the conductive medium, the current along every ground conductor decreases with the distance from the current injection point. This is true whatever the frequency is, but at high frequency the conductor reactance increases. As a consequence, the currents tend to dissipate more readily in the spreading resistance of the soil, a path of lesser impedance than that through the ground conductors themselves.

This is illustrated schematically in figure 79 where the earth grid consists of a single horizontal conductor represented by a lumped inductance L between two resistances R_1 and R_2 representing the dissipating resistance of the soil.

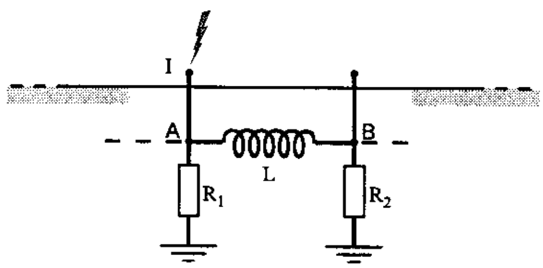

Figure 79 - Simple model of horizontal earth electrode

If we assume in this simple model, for the low frequencies: $\omega L \ll R_1 = R_2 = R$

and for the high frequencies: $\omega L \gg R_1 = R_2 = R$

we have:

$$GPR_{LF} = I\,R/2$$

$$TGPR = GPR_{HF} = I\,R$$

Hence it is easy to understand in an actual situation that the profile of (scalar) potential of the ground near the earth grid will be steeper at high frequency than at power frequency.
This is illustrated in figures 80 and 81 taken from [16] where the scalar potential rise of an earth grid has been calculated when a 1 kA current is injected at the centre of the grid at respectively 0 Hz and 0,5 MHz; the grid is a square of 60m x 60 m with 10 m x 10 m meshes (made of copper conductors with 5 mm radius) buried at a depth of 0,5 m.

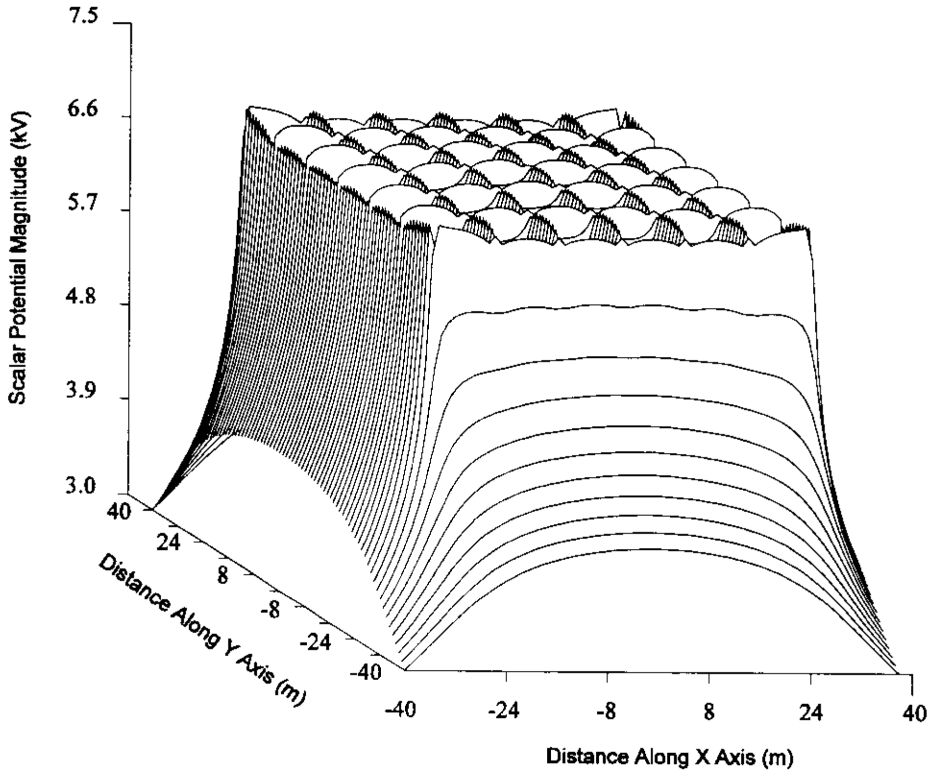

Figure 80 - Earth surface potential for I = 1 kA, f = 0 Hz and ρ = 1000 $\Omega{\cdot}$m

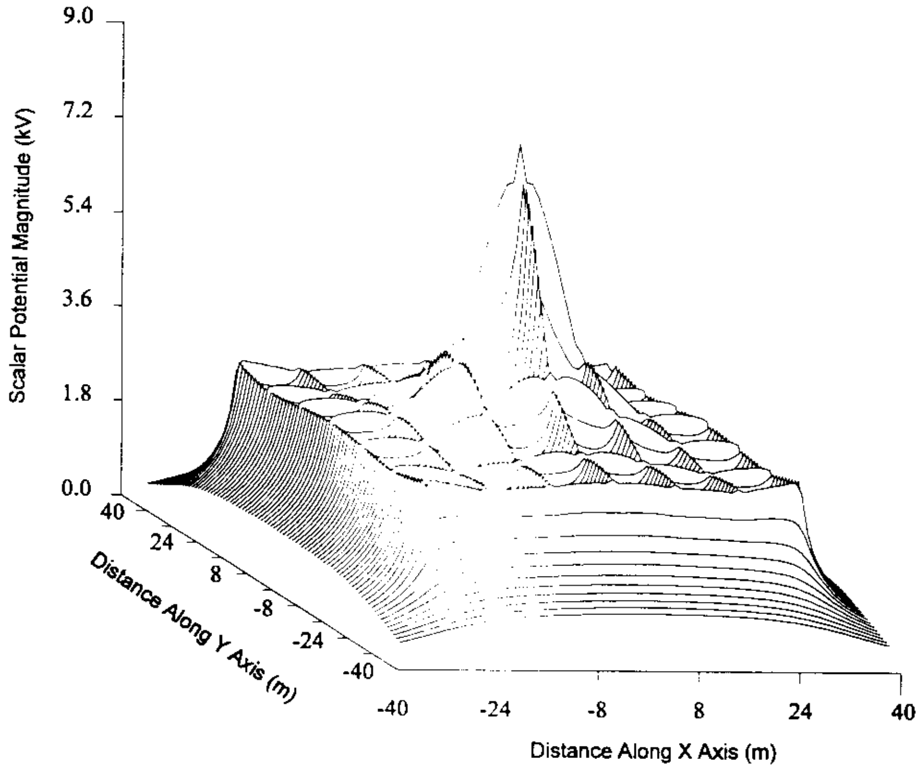

Figure 81 - Earth surface potential for I = 1 kA, f = 0,5 MHz and ρ = 1000 $\Omega{\cdot}$m (ε_r = 10)
(This scalar potential has no direct physical meaning)

The concept of GPR assumes here its full meaning, but this doesn't mean automatically that any circuit installed in the vicinity of such an earth network will be subjected to this GPR, as a strong magnetic coupling can still exist between both circuits.

In order to illustrate this, let's add to the circuit of the above example a new circuit consisting at a single conductor above ground, parallel to the earth conductor and earthed at the point struck by the lightning stroke (figure 82).

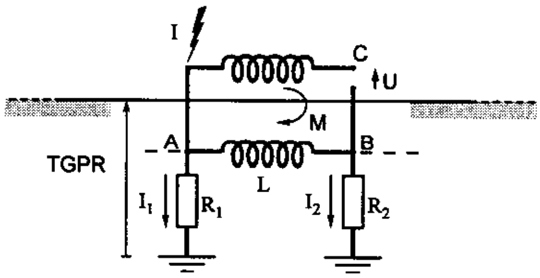

Figure 82 - Simple model of an horizontal conductor parallel to an earth electrode

In this new situation the common mode voltage U applied to the new circuit will be given by (in Laplace form):

$U = s\,(L - M)\,I_2 = R_1 I_1 - R_2 I_2 - s\,M\,I_2;$

or:

$U = \Delta\Phi - s\,M\,I_2;$

with M the mutual inductance between both conductors;

$\Delta\Phi$ the difference of scalar ground potential rise between A and B.

The problem now is to evaluate the relative importance of the two terms of this equation.
In order to estimate these values we need to calculate L and M.
This can be done by first applying expressions similar to those given in Appendices 4.6 and 5.8:

$$L = \frac{\mu_o \ell}{2\pi}\left(\ln\frac{2\ell}{\sqrt{2da}} - 1\right)$$

$$M = \frac{\mu_o \ell}{2\pi}\left(\ln\frac{2\ell}{d+h} - 1\right)$$

where:

a is the radius of the conductor;

h is the height of the conductor above ground;

d is the depth of burial of the earth conductor;

ℓ is the length of influence of the ground conductor, i.e. the length beyond which almost all the current has dissipated into the soil. This length can be assumed to be equivalent to the critical length ℓ_c introduced in appendix 5.8.1.

It turns out from the above expressions that when the distance d + h between conductors is much larger than the radius a of the buried conductor, L remains larger than M and the common mode voltage U is mainly due to the drop of ground potential $\Delta\Phi$.

This is logical since L represents the whole magnetic flux surrounding the earth conductor while L - M represents the part of this flux limited by the conductor above ground.

As the magnetic field decreases rapidly with the distance to the ground conductor, it is evident that the most important part of the flux is that part limited by the loop formed by both conductors.

Note that $L - M = LBAC = \frac{\mu_o \ell}{2\pi}\left(\ln\frac{d+h}{\sqrt{2da}}\right)$ is nothing other than the self inductance of the loop formed by both conductors, as derived from chapter 4.6 and taking into account an "equivalent radius" for the buried conductor equal to $\sqrt{2da}$.

According to equation 4 of chapter 4.2.2.2, (L - M)/ℓ can also be considered as being the transfer inductance of the ground conductor.

Very important also is the concept of length of influence or critical length ℓ_C: indeed, the higher the frequency and the lower the soil resistivity, the smaller this length will be and thus also the greater the contribution of the GPR will be with respect to the magnetic coupling.

For all these reasons, and although the common mode voltage U is not exactly equal to the difference of GPR between A and B, it is usual to take this latter value as the upper bound of U.

On the other hand, when the distance between source and victim is of the same order of magnitude as the diameter of the ground conductor or when this ground conductor is not a bare conductor in contact with the earth (with the consequence that the current cannot dissipate in the soil and thus that the length of influence is much longer than the critical length), in other words when the ground conductor is the shield of a cable or a Parallel Earthed Conductor, the above approximation is no longer valid and the (T)GPR doesn't represent any more the actual common mode voltage appearing at the end of an earthed circuit.

This is a very important statement because it means practically that ***the part played by the "above ground" earthing network, the so called "bonding network", is not the same as the part played by the "underground" earthing network (the earth grid or earth electrode) in reducing the disturbance level.***

The bonding network is by far the most important for high frequency (or transient) phenomena.

In all the situations where a cable is protected by an ECP or a shielding it remains possible to get an estimation of the level of disturbance by splitting the problem into three steps:

- calculate (or measure) the CM voltage U' in the absence of ECP or shielding;
- calculate the current flowing in the ECP or the shielding by dividing U' by its impedance;
- calculate the resulting CM voltage U by using the transfer impedance concept.

An example of this calculation is given in appendix 5.8.2.

The method proposed here to estimate the importance of the common mode level of disturbance is of course very approximate. It employs the circuit theory which is rather a bad tool for making calculations at high frequencies and in a dissipative medium.
This is due to the fact that the propagation effects appear at much lower frequencies in the soil than in the air (at 1 MHz, for ρ = 100 Ω·m, the wavelength in the soil is equal to 22 m, whereas it is equal to 300 m in the air).

A much more rigorous approach based on the antenna theory can be found in [23] where the relative importance of the difference of transient potential (TGPR) and of the path dependent voltage (magnetic induction) is emphasised.

The following example, taken from [23], illustrates some of the previous conclusions [14].

A surge of current with a rise time of 0,25 µs and a half amplitude duration of 100 ms is fed at the corner of an earth grid identical to that of figures 80 and 81, but buried at 0,8 m depth in a soil with ρ = 1000 Ω·m and ε_r = 9.
A cable, earthed at one end, is buried at 0,3 m depth (figure 83). Two alternative cable routes are considered, one following the earth grid conductors (1–2–3) and the other going directly from point 1 to point 3 (1–3).

As pointed out previously (equation relating to figure 82 and chapter 4.2.2.1), the CM voltage appearing at the unearthed end, may be expressed as the sum of two terms:

$$V_T = \Delta\Phi + V_\ell$$

where $\Delta\Phi$ is the difference of TGPR and is uniquely defined between points 1 and 3, and V_ℓ is the path dependent term due to time-varying field.

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[14] *The symbols used are those taken from ref. [23].*

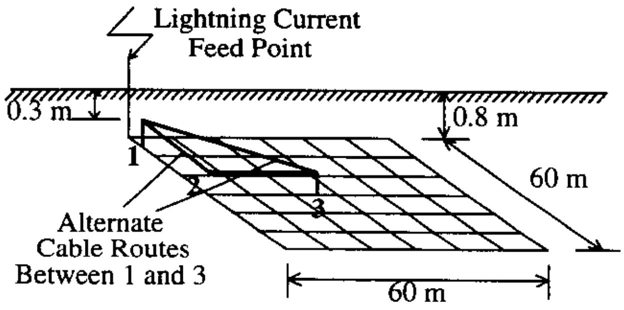
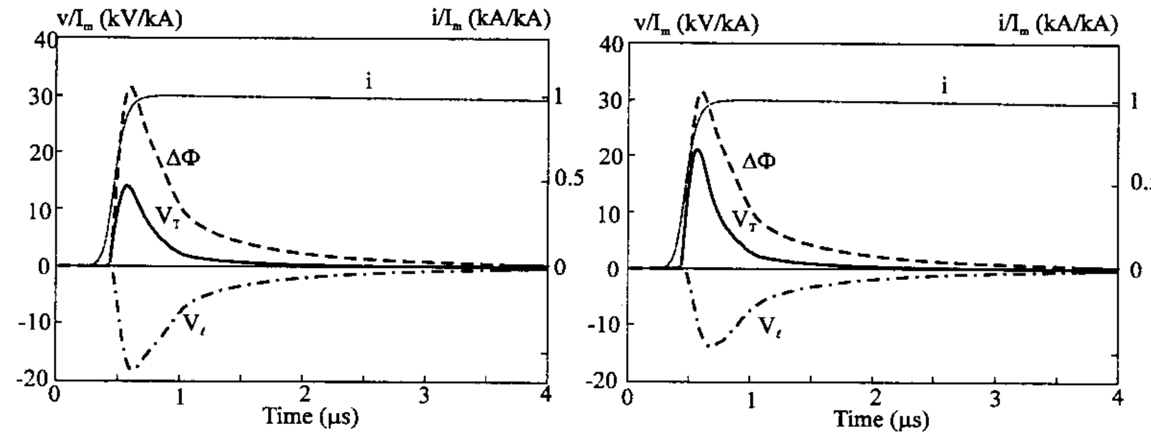


Figure 83 - Earth grid with two different cable routes

The following figure 84 illustrates the total value and both components of the transient voltage, for both routes, 1-2-3 in (a) and 1–3 in (b).



a) Cable route 1–2–3

b) Cable route 1–3

Figure 84 - Transient voltages at the end of the cable

It can be seen, as forecast by the circuit theory, that the effects of TGPR are partially cancelled by the induced e.m.f. due to the flux variation. This cancelling is larger when the cable follows the earth grid conductors (principle of the Parallel Earthed Conductor introduced in subclause 5.2.2).

Many parameters can affect the intensity and the wave shape of the transient voltages in practical situations.

Some factors have a dominant influence on both components of the voltage (i.e. on the TGPR and on the induced components); for example:

- the shape of the lightning current;
- the earth conductivity.

Some factors influence mainly the TGPR; for example:

- the location of the lightning current feed point;
- the mesh density of the earth grid around the lightning current feed point;
- the location of the earthing points of the cable (or of the cable shielding).

Other factors influence more the induced components; for example:

- the cable routing;
- the distance between cable and earth grid;
- the presence of an ECP or an ***Above Ground Bonding Network*** (AGBN).

There are also a lot of other parameters which may be taken into consideration, such as: earthing system shape and size, depth of burial, conductor material, ground rods, etc..

Detailed parametric analysis, that enables variation of these parameters has been made available recently thanks to the use of numerical codes. Some examples of these codes are listed in appendix 4.6.4 of chapter 4.

5.5.4.3 Direct strike to a high voltage line

Although this kind of event is very frequent, its consequences are certainly of lesser importance than those due to a direct strike to a substation.
However, as explained in chapter 3.3, the occurrence of a direct stroke to a high voltage line can be the origin of an insulation breakover and hence gives rise to very steep voltage waveforms with a much higher frequency spectrum than that of the lightning stroke itself.
In this case the disturbance level can be comparable to what happens in case of insulation breakdown or switching operations of HV equipment installed within the substation (see subclause 5.5.1).

5.5.5 Electrical fast transients due to switching operations in low voltage circuits

As discussed in chapter 3.6, very fast transients of a few kV can be generated by switching operations in LV (e.g. 48 - 110 - 230 V) inductive circuits such as breaker or isolator command circuits, but also on all other very low voltage (e.g. 12 - 24 V) circuits incorporating relays.

Coupling to sensitive circuits occurs by common impedance in power feeding circuits or by direct crosstalk (capacitive coupling) and inductive coupling between circuits (i.e. between wires of the same cable or between unshielded cables in the same bundle).

Fortunately, owing to the steepness of the transients, damping occurs rather quickly and disturbances are normally limited to neighbouring circuits.

Aside from electromechanical relays, solid state relays like thyristors and switching of lighting circuits (gas discharge) can also be the origin of interference.
These latter, although more frequent than the fast transients produced by mechanical switching, are normally much less severe.

5.5.6 Electrostatic discharges

Electrostatic discharges are disturbances that can be encountered everywhere and which are not specific to HV substations.
However as the climatic environment (temperature, humidity) of a classical substation is generally less controlled than that existing in a generating plant or a control centre, and due to the fact that vehicles (furniture) can sometimes be moved within a substation, it is admitted that a risk of higher level discharges can occur in a substation.

5.5.7 Disturbances due to radio transmitters

Portable transceivers are widely used by control and maintenance teams in substations when they are working in the field or in the buildings.
In such situations it often happens that walkie-talkies are used in the direct vicinity of sensitive electronic equipment which can be left unprotected by their cabinet when operating with an open door.

Knowing that the E field of a 5 W transmitter can easily exceed 10 V/m at 50 cm and 30 V/m at 20 cm, it is easy to understand the risk posed to this kind of direct radiative coupling within instruments (e.g. unwanted tripping).

Coupling of RF disturbances via signal or power supply cables is less frequent in substations when the cabling is correctly done.

5.6 Nature and level of the disturbances in generating plants

Generally speaking EMC problems will be less severe in generating plants compared with those in HV substations. The main reason for this is the larger distance that exists between HV equipment and LV equipment and the existence of a better earth network.

In particular lightning strokes and switching operations in the HV yard adjacent to a generating plant will very seldom be the origin of interference within the generating plant itself while they are the most important cause of EMC problems in HV substations.

However, contrary to the usual situation in substation, it happens more often in generating plants that sensitive electronics is present at both extremities of cables (e.g. electronic-smart-transducers at one end, instrumentation at the other end) rendering the cabling and shielding practices sometimes more critical.

We now survey the main sources of disturbances in generating plants bearing in mind that for a lot of them (e.g. power frequency magnetic fields and fast transients in low voltage circuits), all that has been said in the preceding clause remains valid.

5.6.1 Fault currents

The maximum value of fault current in a low- or medium-voltage distribution system will probably be not higher than 10 to 20 kA. However fault currents of the order of 100 kA can occur on generator busbars (this being the sum of the currents from the two sides of the fault).

It is clear that the earth grid in the vicinity of the generator or the transformer is always reinforced in order to satisfy all safety regulations. This means in particular that these currents will return to their source by a very short path and should not influence circuits which are not in the direct vicinity of this equipment.

Care should be taken however to limit the currents likely to flow in the shields of the signal cables which are connected to them. This can be done by the use of bonding conductors (ECP) or cable trays.

5.6.2 Lightning

The consequences of a lightning strike to a generating plant will depend on the point of strike.

Normally if the main buildings have been correctly protected with an external lightning protection system as described in subclause 5.4.2.2 there should be no major disturbances induced in the internal wiring.

Things are a little bit different when lightning strikes a remote part of the generating plant not on the main earth grid. In this case significant ground potential rises can occur and affect some specific circuits (see subclause 5.5.4.2).

5.6.3 Switching operations in low voltage circuits

The presence of a large number of power regulation circuits, variable speed drives, and other electronic converters makes the probability of generating repetitive transient disturbances higher than in substations. This implies that special attention must be paid to the general wiring of sensitive circuits (capacitive and inductive coupling) and to the filtering of power supplies (common impedance coupling).

In particular, the use of different cable trays supporting circuits (cables) carrying different types of signal is a good way to avoid this kind of disturbance and also improves the bonding network (figure 85).

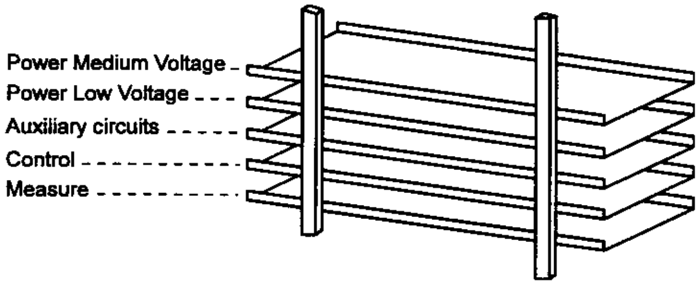


Figure 85 - Example of stacking of trays containing different types of cable. The trays should be electrically connected to the (grounded) vertical supports

5.6.4 Radio transmitters

As in substations, portable transmitters are very insidious sources of disturbance as they can be present anywhere without any correlation with environment classes.

Fixed radio installations like paging systems may sometimes also affect the normal operation of instrumentation when their antenna is installed close to low level circuits.

The RF field associated with the above are unlikely to have any direct effects on single components, such as integrated circuits, transistors, diodes, but will be coupled into various conductors and the resulting voltages and currents will produce undesired effects on electronic modules and equipment such as:

- thermocouple amplifiers producing incorrect outputs;
- malfunctioning of control systems;
- instrumentation signal transmitters producing incorrect signal levels;
- electronic d.c. power supplies being affected such that the stabilised output is disturbed.

In most instruments [8] the normal signals are d.c. or low frequency a.c. and the coupled RF disturbance occurs at frequencies far removed from the operational range of the amplifiers. However the induced RF disturbances can produce interference effects by different mechanisms:

a) overload of a high gain amplifier;

b) rectification of the RF voltage by a non-linear element (e.g. a semiconductor junction) and interference produced by the resulting d.c. voltage or current;

c) demodulation of a modulated carrier at a semiconductor junction and interference effects caused by the LF voltage;

d) transient effects produced by switching a transmitter on or off.

5.6.4.1 Direct coupling within instruments

The RF field produced by a local transmitter may penetrate instrument cases with very little attenuation if the cases are non-metallic or where there are apertures exceeding about 1/10 wavelength in metallic cases or where the sides of a metal case are not adequately bonded together.

5.6.4.2 Coupling via signal cables

The coupling of RF into instrumentation via signal cables is likely to be the dominant effect in many installations where interference is experienced, since the injection occurs at a sensitive point in the system. This is particularly true where low-level signals are used and where there is no buffering or filtering at the input. Even with balanced amplifiers, and where the induced RF is common mode, interference can still be caused since the common mode rejection of the active devices usually decreases at high frequencies and/or for high levels of common mode voltage.

Fortunately the types of instrument cables in general use will normally include dielectric materials which have appreciable losses at VHF and UHF, and therefore have significant attenuation at these frequencies. The attenuation on the inner conductors of a 10 meter length of cable could be typically 10 dB at 30 MHz, 20 dB at 100 MHz and increasing to about 60 dB at 400 MHz.

For this reason and also owing to the usual existence of metalwork and other screening elements in the proximity, the effect of radiated fields will normally tend to be very local and quite easy to detect.

However for the frequency range under consideration (e.g. 470 MHz) many earth conductors associated with electronic instrumentation are not "electrically short".

In particular, wherever the bonding between cable shields and instrumentation cabinets is not made coaxially, the risk of interference exists.

This is particularly the case with some transducers (e.g. pressure transducers) connected to instrumentation by a 4-20 mA loop with remote d.c. power feeding. The common mode induction of a few volts on the transducer wiring can easily affect the converter operation and modify the d.c. current in the loop.

Some servo-mechanisms are also very sensitive to these kinds of disturbance.

For all these reasons the maximum permitted power level of hand held radio transmitters is very often restricted to 200 mW or even less in nuclear generating plants, and in some countries they are completely forbidden.

5.6.5 Other sources of disturbances

5.6.5.1 Welding

Among the other possible causes of interference it is worth mentioning welding which, like 50/60 Hz faults, can inject significant currents into the bonding network. However, and contrary to some wide spread habits, the solution is to ensure that the bonding network is a well meshed network and not a star network in order to permit the injected currents to return to their source by the shortest path, thereby avoiding the risk of common impedance coupling.

Aside from that kind of low frequency disturbance, welding ignition systems due to the high frequency oscillations of "plasma type" guns can be source of radiated disturbances.

5.6.5.2 Radar

At the other extremity of the spectrum are radar emissions.

As generating plants are generally installed near busy water-ways it is not impossible that radar beams from ships are intercepted by sensitive electronic apparatus.

Although we have not been informed of the actual occurrence of such disturbances, some interference to microwave radio system correlated with the passage of ships has been reported.

5.7 EMC environment

Based on the description of the sources of disturbances (chapter 3) and on the way they can be coupled to sensitive circuits (chapter 4), general guidelines concerning the cabling and related mitigation methods have been given in clauses 5.2 and 5.4.
The resulting levels of disturbance likely to appear in the different kinds of circuits have been analysed in clauses 5.5 and 5.6.

The present clause is a natural continuation of the previous ones in the sense that it tries to evaluate the maximum disturbance level applied to each equipment and so to quantify its specific EMC environment.

This environment depends on the nature of the disturbance, on its coupling mode, on the location of the equipment and on the way it is connected to other devices.
For that reason it is usually established on a port-by-port basis.

Due to the enormous quantity of parameters that are involved in the calculation of the resulting disturbance levels, it is impossible to give precise values. Preference is therefore given to a division of the disturbance levels into several classes which can then lead to the specification of immunity tests.

According to IEC. five to six environment classes can be selected, ranging from class 0 (very well protected) to class 4 (heavily disturbed) or even class X (special).

UNIPEDE [14] however proposes to distinguish four classes to characterise conducted disturbances appearing on signal ports (see figures 62, 63 and table 7).

Class	Definition	Port connected to
A	Protected	equipment installed in the same protected room, i.e. where special mitigation methods have been applied
B	Local	other equipment within the same building except equipment related to the process or close to HV equipment
C	In field	other equipment located on the same earth network except high voltage equipment
D	To HV equipment	HV equipment, telecommunication network or equipment located on a different earth network

Table 7 - Classes of signal ports with different disturbance levels

These environment classes do not make any distinction between whether the equipment itself is installed in a generating plant, a substation or other premises. This is because many sources of conducted disturbances (lightning, fast transients in LV circuits) are not related to the type of installation and also because mitigation methods are normally applied in premises where the sources of disturbance are well known (e.g. fast transients due to switching operations in HV substations). [3]

On the other hand it has been assumed that disturbances that are directly radiated or induced into the equipment (enclosure port) could be more severe in HV substations than in other locations but they should not depend significantly on the position of the equipment within a substation or a generating plant.

Also for power supplies the environment of substations has been considered to be more severe than that of all the other premises, but, again, no distinction has been made between the different locations within the plant, as it is assumed that a common power supply system can feed all the equipment.

In order to have an idea of the different environment levels that are likely to be encountered, a list of some typical values of *test levels* used to qualify the equipment is given below (see tables 8 to 10). It is clear that these values include an important margin with respect to the actual interference levels, not only because they are test values but also because they are based on the assumption that only minimum mitigation measures are applied.

It is also important not to confuse the environment classes, which refer to the equipment (ports), with the severity test levels which, for a given port, can differ from one test to another.

SIGNAL PORTS					
Class	**50/60 Hz fault**	**Lightning surge**	**Oscillatory transients**	**Fast transients**	**Radio frequency**
B	100 V	1 kV	-	1 kV	10 V
C	300 V	2 kV	1 kV	2 kV	10 V
D	300 V	4 kV	2,5 kV	4 kV	10 V

Table 8 - Typical test levels adopted to test signal ports

a.c. AND d.c. POWER PORTS					
Class	**Lightning surge**	**Oscillatory transients**	**Fast transients**	**Radio frequency**	**Voltage interruptions**
Generating plant	2 kV	1 kV	2 kV	10 V	a.c.: 0,1 s
HV substation	4 kV	2,5 kV	4 kV	10 V	d.c.: 0,05 s

Table 9 - Typical test levels adopted to test a.c. and d.c. power ports

ENCLOSURE PORT					
Class	**50/60 Hz transient field**	**50/60 Hz permanent field**	**Transient HF magnetic field**	**Radio frequency field**	**Electrostatic discharge (air)**
Generating plant	100 A/m	100 A/m	30 A/m	10 V/m	8 kV
HV substation	1000 A/m	100 A/m	100 A/m	10 V/m	15 kV

Table 10 - Typical test levels adopted to test the enclosure port of equipment

5.8 Appendix

5.8.1 Behaviour of earth electrodes when lightning current is injected

Many theoretical and experimental studies have shown that it is possible to model single conductor earth electrodes by a series - parallel equivalent circuit similar to that of a transmission line (figure 86).

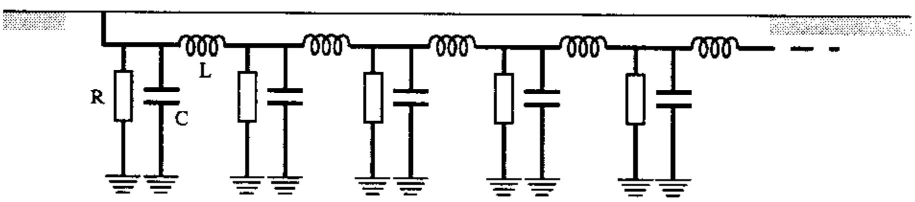


Figure 86 - Circuit theory model of a horizontal earth electrode

An additional spark gap connected in parallel with part of the resistance can also be considered in order to take into account soil ionisation.

It has been shown however [17] that soil ionisation is not instantaneous: soil resistivity decreases with a time constant of about 2 µs. This value is rather high compared with the time constants associated with most negative subsequent strokes. Moreover if soil ionisation occurs it will always have as consequence a reduction of the ground potential rise. So ignoring this phenomenon always gives conservative results.

For these reasons we will consider here only the linear components of the impedance.

Although different authors diverge in determining the per unit length values of R, L and C, the discrepancies obtained remain usually small with respect to the approximations introduced for seasonal variations of soil resistivity or lack of soil homogeneity.

The classical expressions for R, L, C are [17]:

$$R = \frac{\rho}{2\pi} A$$

$$L = \frac{\mu_o}{2\pi} A$$

$$C = \frac{2\pi\varepsilon}{A}$$

$$\text{with } A = \ln\frac{k\ell}{a} - 1$$

In this expressions:

ℓ is the rod length in m;

a is the equivalent mean geometric radius of the rod in m;

ρ is the soil resistivity in Ωm;

$\mu_o = 4\pi 10^{-7}$ H/m;

ε is the soil permittivity (typical value: $\varepsilon = 10\,\varepsilon_o$ with $\varepsilon_o = 8{,}85\ 10^{-12}$ F/m).

The choice of k is not straightforward but is usually chosen between 1 and 4 depending on the layout.

The most used expressions are due to Sunde [19], with:

for a vertical rod: $A = \ln\frac{4\ell}{a} - 1$

for a buried horizontal rod: $A = \ln\frac{2\ell}{\sqrt{2da}} - 1$

(with d the depth of burial and a the radius of the rod).

Based on the above per unit length values, the equivalent lumped elements are:

$R_g = R / \ell$, $L_g = L\,\ell$, $C_g = C\,\ell$

In order to highlight the main parameters determining the high frequency behaviour of the earth impedance the values of the time constants $\tau_L = L_g / R_g$ and $\tau_c = R_g C_g$ can be computed and compared with the minimum risetime τ_r of the lightning current waveform.

Taking into account $\tau_r \geq 0{,}2$ µs ($f \leq 1{,}4$ MHz), it is often claimed [17], [18] that the capacitive effects can be neglected as τ_c is always much smaller than τ_r for earth resistivities lower than 100 Ω·m. With this assumption and assimilating an earth rod with an open-circuited transmission line it is possible to calculate the surge impedance Z_g of the line and to compare it to R_g.

Achieving this, most of the authors come to the conclusion that the ratio Z_g / R_g remains more or less constant up to some ***characteristic frequency*** which, for small earth electrodes like that of HV towers, is usually in the range of 100 kHz or above. At higher frequencies an increase proportional to $\sqrt{f}$ [17], [18] or to f [21], is generally observed. However when capacitive effects are taken into account [21], [22] a decrease seems to occur for short (horizontal) conductors buried in a soil of medium (100 Ω·m) to high resistivity.

The characteristic frequency at which Z_g / R_g starts to increase is always inversely proportional to τ_L.

Starting from this statement it is possible to calculate the ***critical length*** ℓ_c of the electrode for each characteristic frequency. This parameter ℓ_c is the maximum length for which the ratio Z/R remains close to 1 - or in other words, *the maximum length beyond which the efficiency of the earth conductor doesn't increase further.*

For a single horizontal electrode the expressions for ℓ_c have been respectively derived from [17] [18]. They are very similar:

$$\ell_c \approx 0.6\left[\frac{\rho\ (\Omega\cdot m)}{f\ (MHz)}\right]^{0,5} \qquad \text{according to [17]}$$

$$\ell_c \approx \left[\frac{\rho\ (\Omega\cdot m)}{f\ (MHz)}\right]^{0,54} \qquad \text{according to [18]}$$

For a single vertical rod or a conical electrode arrangement the value of ℓ_c seems to be slightly shorter. [17]
Assuming now the simplified formula:

$$\ell_c \cong \sqrt{\frac{\rho(\Omega\cdot m)}{f\,(MHz)}},$$

this means that for soil resistivities extending from 10 Ω·m to 1000 Ω·m, the maximum length of an earth electrode ensuring a constant impedance up to 1 MHz varies from 3 m to 30 m.

For longer electrodes the surge impedance will be higher than the earth resistance leading to a higher transient ground potential rise.

Inversely, starting from knowledge of the critical length it is possible to calculate for any frequency the value for the earth impedance Z_g of a given earth electrode by calculating the expression of R_g and L_g in which ℓ has been replaced by ℓ_c and assuming that $Z_g = R_g + j\omega L_g$.

This leads to the following expressions:

$$R_g = \frac{\sqrt{\rho f}}{2\pi}\left(\ln\sqrt{\frac{\rho}{d a f}} - 1\right)$$

$$L_g = \sqrt{\frac{\rho}{f}}\left(\ln\sqrt{\frac{\rho}{d a f}} - 1\right)$$

where f is the frequency in MHz

For multiple electrode arrangements, earth loops and earth grids the calculations are more complex, but due to the relatively lower value of the earth resistance of such arrangements the characteristic frequency will normally be smaller than for a single rod.

An important conclusion that can be derived from the above statements is that although the maximum level of disturbance increases with the value of the soil resistivity ρ the difference in behaviour between "high frequency" phenomena and "low frequency" phenomena decreases.

This can be illustrated by comparing figure 87 presenting the scalar potential rise of an earth grid (square of 60 m x 60 m with meshes of 10 m x 10 m buried in a soil of 100 Ω·m resistivity) under the influence of an HF current (1 kA, 0,5 MHz) injected at its centre, with figure 81 presenting the same phenomenon under almost the same conditions except for the soil resistivity (1000 Ω·m) and for the permittivity (which, according to the above discussion, plays a secondary role in the results).

In other words, *the absolute value of the d.c. resistance of an earth grid is not so important in determining the level of HF disturbance due to phenomena like lightning.*
For those phenomena, as already explained at chapter 4, the best solution lies always in the achievement of a good bonding network (above ground, in cable trenches or underground).

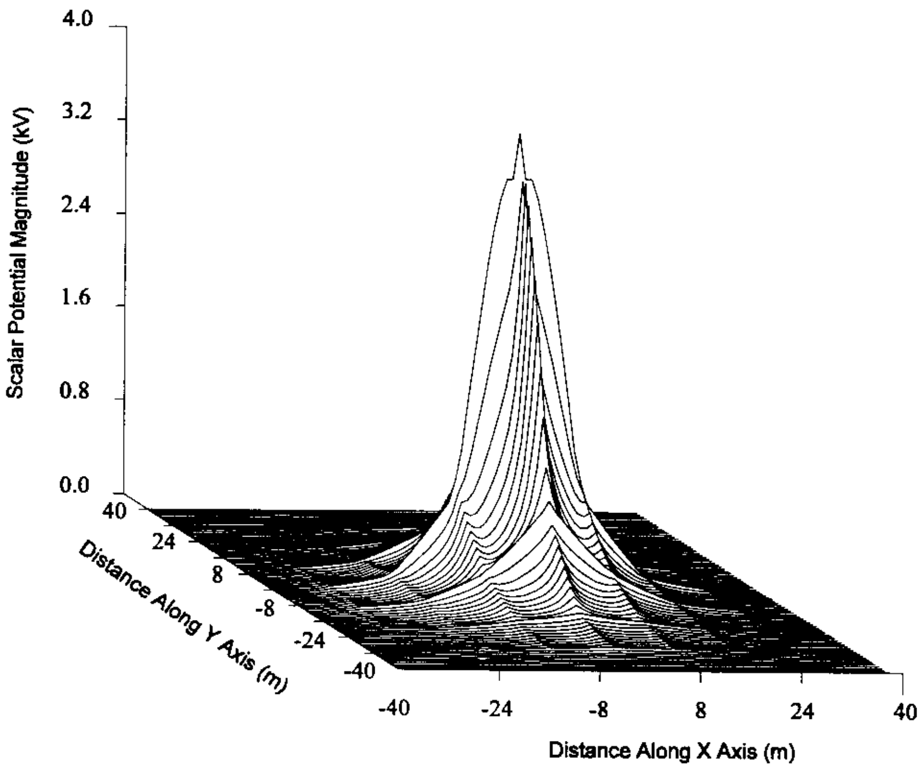


Figure 87 - Earth surface scalar potential for I = 1 kA, f = 0,5 MHz and ρ = 100 Ω·m (ε_r = 50)

5.8.2 Lightning induced voltages in a shielded circuit - Calculation example

A 100 m signal cable is to be installed in a trench between a telecommunication building (with antenna tower) and an auxiliary kiosk situated on the same earth network of a HV substation.

The question raised is: what will be the common mode voltage appearing at one end of this cable (the other end earthed) when lightning strikes the telecommunication tower?

As the cable has a steel armouring (type 1. in the subdivision of subclause 5.3.2.2) its transfer impedance can be modelled as follows:

$Z_t = R_t + j\omega L_t$;

with R_t = 1 mΩ/m;

L_t = 20 nH/m.

The earth impedance Z_g of the telecommunication building has been measured in the time domain (e.g. by injection of an 8/20 μs impulse current or in the frequency domain at 25 kHz).

Both measurements led to approximately the same result:

R_g = 0,1 Ω

L_g = 2,5 μH

These relatively small values are due to the high density of the earth mesh and to the low value of the soil resistivity: ρ = 10 Ω·m.
These parameters are in fact frequency dependent, but this evaluation is sufficient for the present purpose [15]. Note that it would also be possible to estimate them directly by applying the formulas given in appendix 5.8.1.

[15] *A more realistic evaluation would have been to measure R_g at a lower frequency and L_g at a higher frequency, taking into account that R_g is mainly responsible of the LF GPR due to the LF components of the lightning current, whereas L_g is responsible of the TGPR due to the HF components.*

Now we can write: $GPR(t) = (R_g + L_g\, d/dt)\, i(t)$

or after Laplace transformation: $GPR(s) = (R_g + s\, L_g)\, I(s)$

The lightning current i(t) will be modelled by the classical double exponential function:

$i(t) = I_o\,(e^{-\alpha t} - e^{-\beta t})$

with, assuming a 1 / 50 µs wave-shape: $\alpha = 1{,}4\ 10^4$ and $\beta = 2\ 10^6$

The current flowing in the shield of the signal cable is given by:

$I_c(s) = GPR(s) / (R_c + s\, L_c)\, \ell$

with: ℓ the length of the cable

$R_c + sL_c$ the per unit impedance of the cable shield with ground return

We can assume: $R_c \approx R_t = 1\ m\Omega/m$

$L_c = 1 \mu H/m$

Hence the common mode voltage becomes:

$U(s) = I_c(s)\, Z_t\, \ell$

When the inverse Laplace transform is taken we finally get:

$$u(t) = I_o \frac{L_g}{L_c}\left[\beta L_t e^{-\beta t} + R_t\left(K_1 e^{-Rc\, t/Lc} - K_2 e^{-\alpha t}\right)\right]$$

with

$$K_1 = \left(\frac{R_g}{L_g} - \frac{R_c}{L_c}\right) \Big/ \left(\alpha - \frac{R_c}{L_c}\right)$$

$$K_2 = \left(\frac{R_g}{L_g} - \alpha\right) \Big/ \left(\alpha - \frac{R_c}{L_c}\right)$$

The first term of the above expression is a high frequency component due to the front of the lightning wave-shape. It is by far the most important one when the transfer impedance exhibits a significant inductive component (L_t). The other two terms are low frequency components depending of the tail of the wave-shape. They can often be neglected in the evaluation of the maximum peak value of the CM induced voltage.

This means that U_{peak} is practically a linear function of the steepness β of the lightning current, the equivalent self inductance L_g of the earthing network and the transfer inductance L_t of the cable shield.

With the values assumed in the example, we have:

$u(t) = I\,(0{,}1\ e^{-2\ 10^6\, t} + 0{,}0075\, e^{-10^3\, t} - 0{,}05\ e^{-1{,}4\ 10^4 t})$.

In other words, in this example U_{peak} can reach 100 V per kA of lightning current.

This calculation is of course very approximate since it doesn't take into account either propagation effects (reflections), or the influence of the cable shield on the GPR.
However, it can certainly be used in order to understand what the most important parameters influencing the coupling are, and to give a first approximation of what will be the resultant disturbance level.
It is clear, of course, that a complete computer simulation would produce more accurate results.

If correct protective measures are taken (e.g. by using shielded cables and ECP) and if the equipment is correctly designed to withstand the relevant test levels, lightning should not be the origin of material destruction, as in most practical situations the voltage appearing in common mode at the extremities of a correctly earthed shielded cable will seldom exceed 2 kV.

For soils of very high resistivity the use of an ECP in the form of a metallic conduit can lead to an important reduction in the CM voltages thanks to the very low value of the transfer impedance. An interesting discussion on that subject can be found in [20].

5.9 References

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6 Electromagnetic interference on automation and control systems

6.1 General

The effects and consequences of the different classes of electromagnetic phenomena on electronic systems installed in HV and MV substations, generating stations, control centres, etc., are directly related to the different kinds of functions carried out by a specific control system, and to the process involved.

In the evaluation of these effects and consequences, it is useful to identify the "main functions" of the electrical plant's apparatus and systems. The approach described in the following is consistent with the UNIPEDE report 23005Ren9523, January 1995 [16].

The following functions are considered of particular relevance to electronic equipment and systems:

- protection and teleprotection;
- on-line processing and regulation;
- counting;
- command and control;
- supervision;
- man-machine interface;
- alarm;
- data transmission and telecommunication;
- data acquisition and storage;
- metering;
- off-line processing;
- monitoring;
- self-diagnosis.

Combinations of different functions are in general present in the apparatus and systems.

Depending on the types of electromagnetic phenomena (conducted and radiated, low and high frequency) and the equipment port involved, the effect (interference) may be limited to one function or to an unforeseeable number of them.

The total effect of the electromagnetic phenomena on electronic equipment and systems, and the related consequences on the process, can therefore be described as a collection of possible influences on the different functions involved.

The electromagnetic disturbances relevant in HV substations and power plants can be classified as continuous phenomena, transient phenomena with high occurrence and transient phenomena with low occurrence, as in the following Table 11.

[16] *Environmental influences other than electromagnetic disturbances (e.g. temperature, humidity, etc.) can also affect the correct operation of the electronic equipment. This subject is not here considered; however, a similar approach could be adopted to carry out a general evaluation of the compatibility of a control system with its environment.*

On-line processing and regulation

On-line processing and regulation systems give the process working condition as defined by control/telecontrol systems or by operators. The optimum running of the process is achieved by these functions taking into account relevant process parameters.

Degradation of on-line processing and regulation could occur due to lack of immunity of the equipment and related input/output interfaces and process instrumentation involved. A possible consequence is unnecessary stress or damage of the process and degradation of performance.

The immunity of on-line processing and regulation systems to electromagnetic phenomena, including transient phenomena with low probability of occurrence, is of particular importance.

Counting

The function of counting electrical energy generated or passing through an electrical plant as well as fuel supplies, can be of particular significance due to the contractual aspects which may be involved.

This applies to traditional watt-hour meters for electrical energy measurement, and to similar equipment based on advanced technology, having a capability for setting operating conditions and storing data.

This function shall be highly reliable and therefore immunity against continuous and transient phenomena is mandatory.

Command and control

Command and control functions are important to all operating conditions of electrical plants, including partial operation of the plant or temporary out of service conditions.

Electrical equipment is controlled by dedicated units/equipment with different level of complexity which are connected as necessary to other systems in order to provide full automated control, or manual control by direct action of the operator. The coordination of all sources of command and control actions is ensured by the provision of priority levels.

Insufficient reliability of the command and control functions due to lack of immunity could result in:

- improper operation of electrical equipment, involving safety aspects;
- wrong operation sequence or procedure, with possible damage/over stress of the controlled equipment;
- unavailability of the process equipment and then of the process or part of it.

Command and control units are required to operate properly in actual environmental conditions, e.g. for continuous phenomena or high occurrence transient phenomena.

Spurious operation of remote controlled switch gear is unacceptable.

Electromagnetic phenomena with a low probability of occurrence, having only minor influence, may be observed on a control system and accepted. For example: a delay in the execution of a command may be insignificant compared to the time constant of the controlled process, so that the main function is not affected.

Supervision

Supervision systems collect data from the process and related equipment for diagnostic purposes, for maintenance programme purposes and evaluation of the process. They generally do not interact with the process itself.

The performance degradation or temporary unavailability of the supervision system causes loss of information on the process and deviation in the event scheduling time. These effects can occasionally be accepted, e.g. in the case of transient phenomena with low probability of occurrence affecting acquisition of cycling measurements.

The acquisition of event data shall however be recorded in actual sequence.

Man-machine interface

The man-machine interface function allows the operators to directly interact with the process from operator desks or to manage the information from the plant. Control and regulation systems interface with the process, and the manual command to process equipment has higher priority.

This function may be activated by the operator by using this interface. High priority commands to the running process are generally available, and are given by the operator through the use of dedicated devices.

The absolute immunity of this function to transient phenomena having a low probability of occurrence can therefore be considered as not binding; the operator presence allows manual restoration.

Alarm

The alarm function includes all local or remote indications able to give information on any kind of temporary or not temporary degradation of the operating conditions of apparatus and systems.

Alarms can have different urgency, depending on whether there is the need of immediate intervention or if the system can still operate in an acceptable mode (e.g. thanks to redundancy).

In case of self-recovery after temporary degradation, the alarm may disappear. Whenever, according to the product specification, a chronological list (trace) of the alarms is automatically created, the alarm function may not be affected by the electromagnetic phenomena.

Data transmission and telecommunication

Data transmission and telecommunication functions are auxiliary functions to other ones. They allow the data acquisition and the remote control of systems installed within an electrical plant. The control functions of the process are controlled by local systems.

Through data transmission and telecommunication, the telecontrol systems can coordinate the operating condition of different electrical plants, improving the overall efficiency of the electrical network.

Interference on data transmission and telecommunications has the effect of delaying the transfer of command and control, affecting the telecontrol efficiency.

Depending on the telecommunication link adopted, electromagnetic phenomena can influence the ongoing communication or affect the terminal equipment, producing a bit error rate degradation; full immunity against electromagnetic phenomena can be obtained only with particular communication supports, e.g. optical fibre.

Temporary loss of the communication function for a short period is occasionally tolerated, provided that the link is automatically restored within an acceptable time. However the receipt of corrupted data cannot be tolerated.

Data acquisition and storage

Data acquisition and storage of relevant parameters from electrical plants allow, by data processing, an off-line analysis, comparison with reference condition and computation, etc.. These functions are generally assigned to "in-field" equipment, and are complementary to supervision.

Proper design of the data acquisition system interfaces, including hardware and/or software filtering actions, gives to data acquisition the required immunity to electromagnetic phenomena.

Temporary deviation from precise analogue data acquisition and incorrect time allocation of digital data, due to transient phenomena, are sometimes acceptable due to the possibility of identifying these effects through data validation.

No corruption of locally stored data is allowed.

Metering

Metering of some relevant parameters of the process gives direct evidence of their values and trend. This function is carried out by using analogue or digital instruments. These instruments are located for example on a control system panel, display panels or in the proximity of electrical equipment.

Temporary deviation of analogue or digital indications as a consequence of a transient disturbance can be accepted; no degradation due to continuous phenomena is allowed.

Off-line processing

Off-line processing functions allow, for example, simulation of the process, planning of power generation, study of models and analysis of critical working conditions. This function implies the use of data coming from the process or stored data. It does not interact with the on-line process itself.

Temporary degradation of this function due to transient phenomena is accepted in principle, on condition that it does not involve the on-line activities and that no corruption of stored data or processing accuracy occurs.

Monitoring

The process is monitored on displays, showing the entire setting and operating condition of the plants. Information technology equipment with CRT monitors or other devices are used to represent the process and its parameters at different levels of detail.

Temporary degradation of this function (e.g. in the image quality) can be accepted, provided that the consistency of the monitoring with the process condition is resumed.

Temporary loss of display with restoration within a given time, e.g. a few seconds, allowing for possible intervention by operators, can also be accepted; an example would be the jitter of the image on a CRT display caused by transient power frequency magnetic fields.

Self-diagnosis

Self-diagnosis capability is increasing in complex electronic systems, and becomes of particular relevance for the credibility of the system itself.

Self-diagnosis test cycles are generally assigned low priority in the tasks sequence.

Temporary loss of the self-diagnostic function can generally be considered as acceptable if it is self recovered within the system working cycle and if it gives rise only to a delay in warning an operator of a system failure condition. Such a loss of function should also not produce spurious alarm conditions which could necessitate attendance at unmanned remote locations.

<table>
<tr><th rowspan="2">Functions (*)</th><th colspan="3">Functional requirements versus nature of electromagnetic phenomena</th></tr>
<tr><th>Continuous phenomena</th><th>Transient phenomena with high occurrence</th><th>Transient phenomena with low occurrence</th></tr>
<tr><td>Protection and teleprotection (**)</td><td colspan="3" rowspan="3">Normal performance within the specification limits</td></tr>
<tr><td>On-line processing and regulation</td></tr>
<tr><td>Counting</td></tr>
<tr><td>Command and control</td><td colspan="2" rowspan="3"></td><td>short delay (1)</td></tr>
<tr><td>Supervision</td><td>temporary loss, self recovered (2)</td></tr>
<tr><td>Man-machine interface</td><td>stop and reset (3)</td></tr>
<tr><td>Alarm</td><td rowspan="7"></td><td colspan="2">short delay (4), temporary wrong indication</td></tr>
<tr><td>Data transmission and telecommunication (***)</td><td>no loss, possible bit error rate degradation (5)</td><td>temporary loss (5)</td></tr>
<tr><td>Data acquisition and storage</td><td colspan="2">temporary degradation (2) (6)</td></tr>
<tr><td>Metering</td><td colspan="2">temporary degradation, self recovered (7)</td></tr>
<tr><td>Off-line processing</td><td>temporary degradation (6)</td><td>temporary loss and reset (6)</td></tr>
<tr><td>Monitoring</td><td>temporary degradation</td><td>temporary loss</td></tr>
<tr><td>Self-diagnosis</td><td colspan="2">temporary loss, self recovered (8)</td></tr>
</table>

NOTES

* *For the application of the assessment criteria to apparatus with multiple functions, as well as for concurrent functions (e.g. supervision and monitoring), the performance related to the most critical function applies.*

** *For teleprotection using power line carrier the "normal performance" in occasion of the switching of HV isolators may need an appropriate validation procedure.*

*** *Used in automation and control systems as auxiliary function to other ones, e.g. to implement co-ordination.*

1. *A delay of a duration which is insignificant compared to the time constant of the controlled process is acceptable.*
2. *Temporary loss of data acquisition and deviation in event scheduling time is accepted, but correct events sequence shall be maintained.*
3. *Manual restoration by operators is allowed.*
4. *With respect to the degree of urgency (not to the process).*
5. *Temporary bit error rate degradation can affect the communication efficiency; automatic restoration of any stoppage of the communication is mandatory.*
6. *No effect on stored data or processing accuracy.*
7. *Without affecting the metering accuracy of analogue or digital indication.*
8. *Within the system diagnostic cycle.*

Table 12 - Assessment criteria for the different functions (in descending order of criticality)

7 Design criteria of equipment and systems

7.1 Introduction

When electronic systems working in HV substations or power plants have to meet electromagnetic compatibility immunity requirements, several actions can be adopted to reduce the influence of the electromagnetic disturbances.

Interference can be normally mitigated according to the following practical rules:

- operating directly on the source of interference, trying to suppress, or at least to reduce, the disturbances;
- mitigating the coupling mechanism between sources and "victims" and evaluating the disturbances affecting the electronic systems, characterising their working environment;
- designing equipment and systems to include the immunity requirements related to the actual electromagnetic environments.

In the previous chapters of this Guide information is given about the typical sources of disturbances affecting auxiliary systems in electrical installations (chapter 3), the mechanism of interference coupling on cables and equipment and the related mitigation methods (chapter 4), the practical implementation and the interference levels in various types of installations (chapter 5).

As many concepts applied to reduce the influence of the electromagnetic disturbances in plants and installations can also be used for equipment and systems, in this chapter only the main concepts are reported and their efficiency discussed.

7.2 Grounding and bonding

The general approach followed in applying grounding and bonding techniques in EMC has been already presented in the previous chapters of this Guide, in particular in chapter 4.5. As the same criteria are also applicable to circuits of electronic equipment and systems which are to be connected to the ground or together, only the principal concepts are given here.

Concerning the grounding technique, there are two common reasons for grounding a circuit:

- for safety;
- to provide an equipotential reference for signal voltages.

Signal grounds generally fall into one of two classes: single point grounds (series or parallel connections) and multipoint grounds.

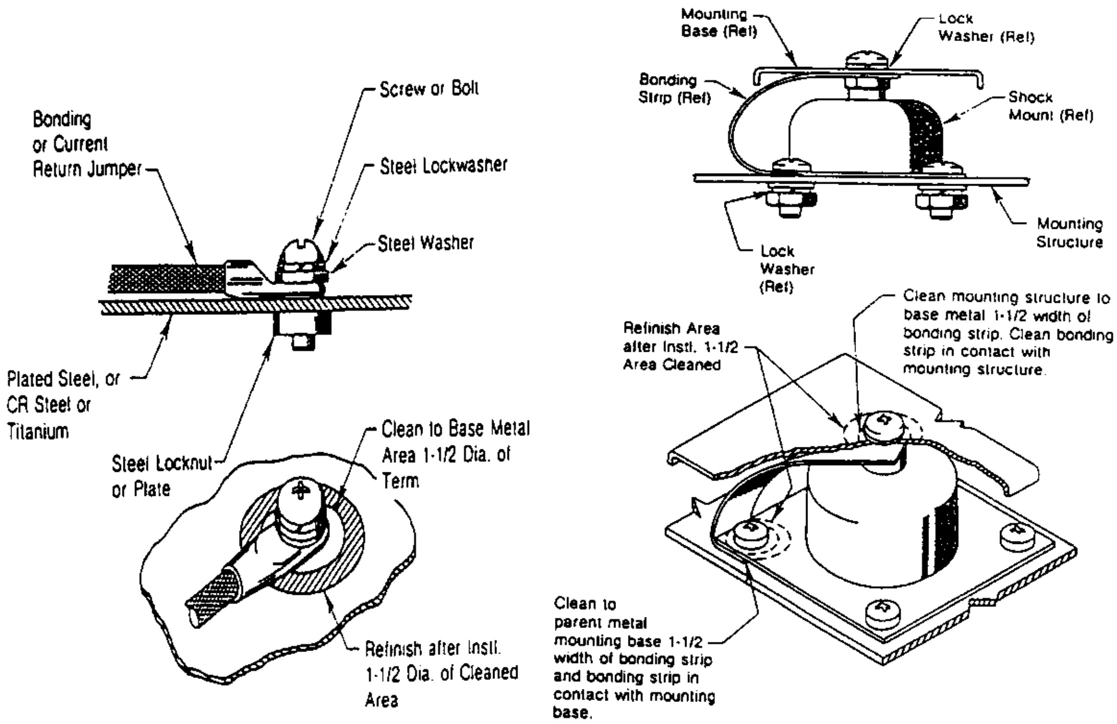
In the past, the preferred approach related to the grounding layout of pieces of equipment and systems demanded insulated structures connected to the ground at a single point by means of a unique connection.

As modern electronic circuits are very sensitive to high frequency disturbances, the recent design techniques make use of distributed ground points and ground connections, in particular to guarantee efficient grounding in presence of high frequency disturbances.

Electrical bonding refers to the process in which components or modules of an assembly, equipment or subsystems are electrically connected by means of a low impedance conductor.

The purpose of bonding is to make the structure homogenous with respect to the flow of radio-frequency currents. This mitigates potential differences which could produce disturbances among metallic parts.

Figure 88 shows some examples of arrangements for bonding connections.



a) b)

a) Examples of typical bonding hardware configuration

b) Bonding shock mounts: a flexible metal strap is used because relative motions between parts is foreseen [1]

Figure 88 - Examples of arrangements of bonding connections

7.3 I/O ports

The conducted disturbances transferred to I/O ports of equipment and/or systems can be mitigated by selecting suitable I/O interfaces, which are to be correctly bonded and grounded. In this situation, the following general design criteria can be applied:

- balancing techniques;
- use of isolation transformers;
- use of optoisolators.

A discussion about interference barriers is also given in chapter 5.3.5.

7.3.1 Balancing techniques

A balanced I/O port is a two-conductor circuit in which both terminals have the same impedance with respect to ground and to all other conductors. This type of I/O port enables the common mode currents to be neutralised. A detailed description of balanced circuits is reported in chapter 4.2.2.2.

Balancing techniques include the use of ***twisted pair*** (or multi-core cables) to minimise the disturbances among different apparatus.

7.3.2 Isolation transformers

The I/O interfaces can include isolation transformers which provide a galvanic separation between the electronic equipment and the field. Isolation transformers can be used both in signal and in a.c. power circuits. Isolation levels of some kV can be reached.

The transformers have a stray capacitance between the primary and secondary windings. This coupling can be eliminated by providing a screen connected to the ground, as shown in figure 89.

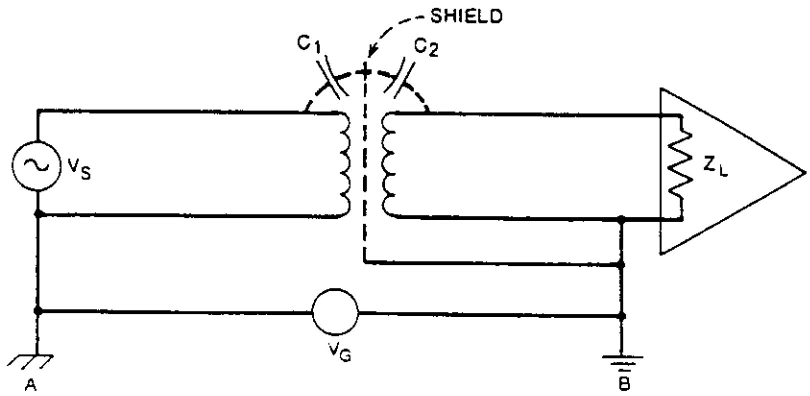


Figure 89 - Isolation transformer with a screen connected to the ground. The reported configuration is suitable to protect the I/O interface of the equipment [2]

The main disadvantage of using transformers in signal circuits is due to the limited bandwidth. In particular, when signal at direct current or very low frequency continuity is required, an isolation transformer is not practical.

7.3.3 Optoisolators

The I/O interfaces also include optoisolators which can provide a good galvanic separation between the electronic equipment and the field.

The basic optical coupler consists of a light source, usually a photo diode, driven by one circuit closely coupled by a transparent insulator to a receiver. Both devices are contained in the same package, as shown in figure 90.

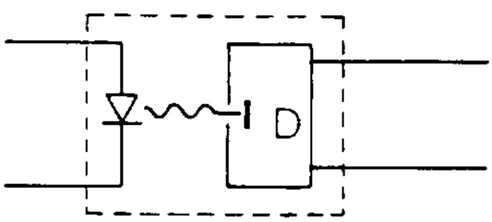


Figure 90 - Schematic diagram of an optoisolator

Optoisolators are especially useful in digital circuits; for analogue devices they are less suitable because linearity through the coupler is not always satisfactory. Isolation levels up to 5 kV can be reached.

During implementation, care should be taken to ensure that interference is not introduced via the power supply input to the device.

7.4 Filtering

Protection against conducted disturbances is based on the use of filters or other suppression devices. Filters, that are useful both on signal and on power lines, can attenuate common mode or differential mode disturbances. In this Guide filters are described in Chapter 5.3.5.3.

The main characteristic of a filter is its insertion loss, which represents the ratio of output voltages before and after filter insertion in a 50 Ω circuit, as a function of the frequency.

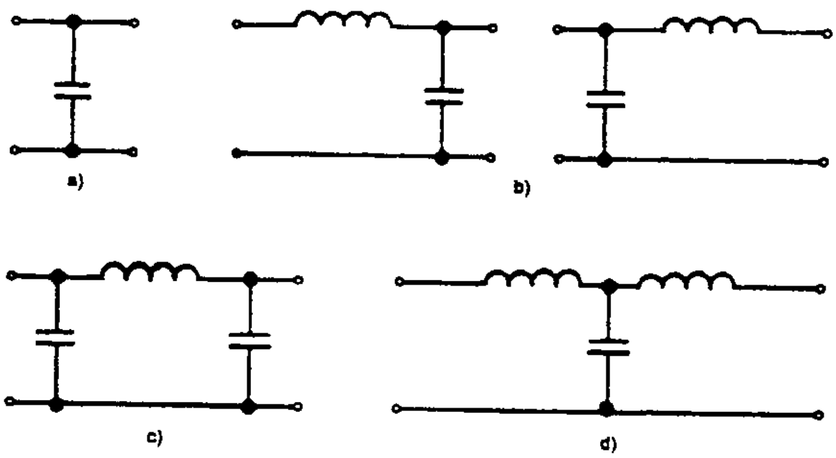
Mainly for power filters, actual attenuation may differ from the insertion loss because the impedances of both the source and the loads of real-life installations may be significantly different from 50 Ω. Since the frequency response of a filter is impedance-level dependent, the insertion loss is useful to compare filters on a relative basis.

The following parameters are very important in the choice of suitable filters:

- the maximum mismatch has to be reached between the input impedance of the filter and the line carrying the disturbance;
- the voltage/current ratings and the insulation resistance must be properly evaluated.

Figure 91 shows different low pass filters according to the different types of circuits which are to be protected. As the maximum mismatch has to be reached, the following configurations are possible:

- the capacitive input (output) must be connected with the source (load) at high impedance (> several ohms);
- the inductive input (output) must be connected with the source (load) at low impedance (< several ohms).



a) capacitor; b) L filter;

c) π filter; d) T filter.

Figure 91 - Different circuit solutions of filters, based on different input impedances

A typical power line filter structure is schematically represented in figure 92.

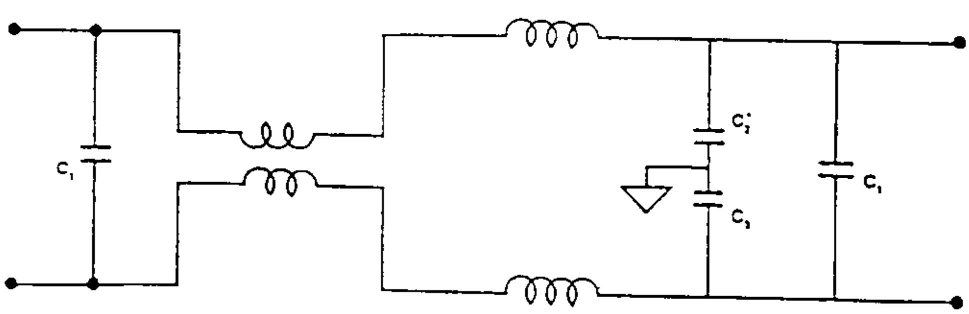


Figure 92 - Typical power line filter layout

Since the filter must provide a high impedance (to achieve high insertion loss) any stray capacitance (or mutual inductance) between the input and the output leads could provide a low impedance bypass cancelling the effect of the filter as shown in figure 93 a).

It is therefore very important to keep the output connections well away from the input to any filter. In situations where a noise current is diverted to a shield, as in the case of the T network shown in figure 93 b), the quality of the shield connection becomes crucial.

As shown in figure 93 c), any impedance Z_g will deteriorate the filter performance.

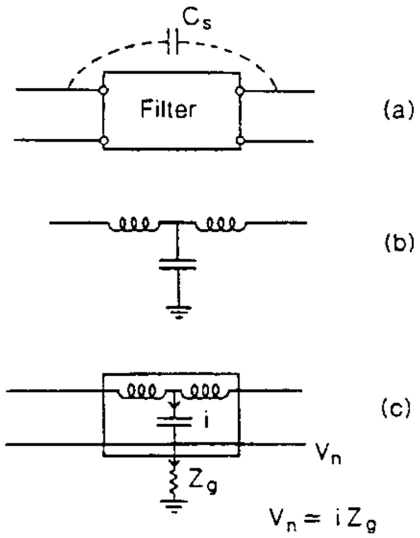


Figure 93 - Some common faults with filter installation [3]

The common faults reported for filters are easily applicable to any I/O interface devices (isolation transformers, optoisolators, etc.) because the correct positioning is very important. For example, if I/O interfaces are to be connected to ground, the impedances of the connections must be minimised to guarantee the efficiency of the devices.

7.5 Surge protective devices

Suppressor devices work by presenting a high impedance to ground until the transient overvoltage appears, at this moment they rapidly become essentially a short circuit to ground so diverting the incoming energy.

The three main types of suppressor devices are the following (more details are given in chapter 5.3.5.2):

- transient suppressor diodes (fast switching speeds; for protection of low voltage circuits-up to 400 V). For high voltages, avalanche/zener diodes are used. They work well but can only deal with small pulse currents. They also have a large capacitance (500 - 2000 pF);
- varistors (slower speeds than avalanche diodes; higher voltages than diodes: up to 2 kV; they can degrade easily). Varistors are non-linear resistive elements made of sintered blocks of zinc oxide (mixed with some other metallic oxides). Repetitive exposure to peak ratings lowers performance. Varistors, like diodes, have large capacitance (100 - 4000 pF depending on rating);
- gas arresters or spark gaps (very slow speed; highest voltages: up to 10 kV). These devices are small sealed spark gaps containing rare gases (argon, neon). As a voltage pulse arrives at the arrester (above the protection level) a gas breakdown is initiated. Unfortunately, this can take a little time to start and then develop a low impedance. As a consequence fast rising pulses will break down at higher value than more slowly rising pulses. Very low capacitance (1 - 3 pF).

Because all the various suppressor devices have different performance in different ranges, it is sometimes useful to combine them to provide a good protection system.

For example, figure 94 shows a 10 kV surge applied to a 24 V line protected first by a spark gap; then a varistor and finally a diode. The figure shows how the surge is attenuated as it passes along the combination of protective devices.

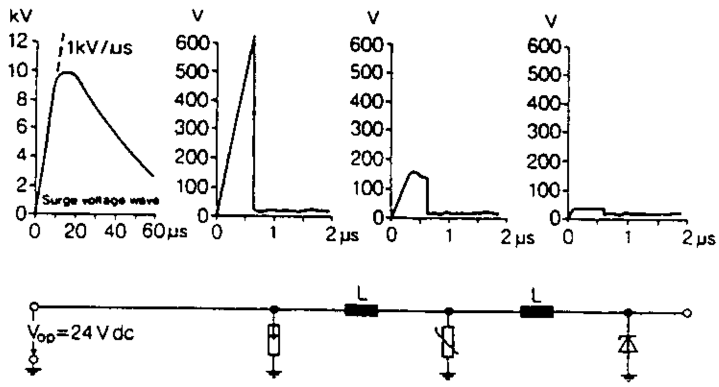


Figure 94 - Attenuation of a 10 kV pulse by a combination of surge protective devices [3]

The same considerations about the correct positioning and the minimum impedance of the ground connections of filters and I/O interface devices are also valid for surge protective devices.

If the protection devices are used for signal circuits, care should be paid to minimise the differential mode disturbances by using a protection device working in an "integrated" way on the different conductors.

7.6 Shielding

Protection against radiated disturbances is based on the use of shielding techniques. These techniques, which are described in detail in chapter 4.4, are also applicable to efficiently protect pieces of electronic equipment and systems.

Table 13 shows the absorption and reflection loss of a number of different and very large materials, which may be used for shielding devices.

Permeable materials	Frequency	Absorption Loss All Fields	Reflection Loss		
			Electric Fields	Magnetic Fields	Plane Waves
Magnetic $\mu \geq 1000$	Low < 1 kHz	Bad	Excel.	Fail	-
	Medium 1-100 kHz	Good	Good	Bad	Fair
	High > 100 kHz	Excel.	Fair	Poor	Fair
Non-Magnetic $\mu = 1$	Low < 1 kHz	Fail	Excel.	Bad	-
	Medium 1- 100 kHz	Bad	Excel.	Poor	Good
	High > 100 kHz	Good	Good	Fair	Fair
Assumptions - Material Thickness: 8 mm; Source Distance: 3 m; Radio Frequency: as shown					

Attenuation Scores					
Excellent: > 150 dB	Good: 100-150 dB	Fair: 50-150 dB	Poor: 30-50 dB	Bad: 10-30 dB	Fail: < 10 dB

Table 13 - Qualitative summary of shielding (solid shield, no holes or seams)

The previous calculations of shielding effectiveness have assumed a solid shield with no seams or holes. In practice, however, most shields are not solid because there can be access covers, doors, holes for conductors, ventilation, switches, meters and mechanical joints and seams.

Shield discontinuities usually have more effect on magnetic field leakage than on electric field leakage, but minimising techniques are normally suitable both for magnetic and electric field. The effects of metallic enclosures are reported in chapter 4.4.3.

The maximum dimension (not area) of a hole or discontinuity determines the amount of leakage. In addition, a large number of small holes result in less leakage than a larger hole of the same area. This is the reason why honeycomb ventilation covers, which are showed in figure 95, are so widely used. In honeycomb structures the emerging field from each hexagonal cell coherently combines with its neighbour.

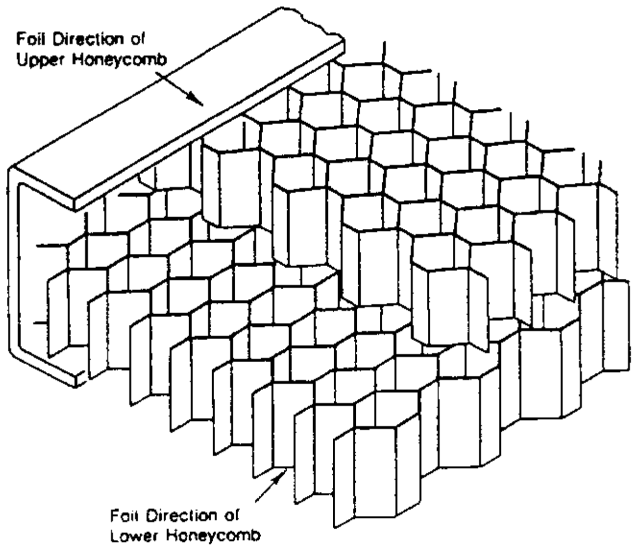


Figure 95 - Typical honeycomb construction

7.7 References

[1] W.G. Duff: "Fundamental of Electromagnetic Compatibility", Control Technologies, Inc. Gainsville, Virginia 1988

[2] H.W. Ott: "Noise Reduction Techniques in Electronic Systems", John Wiley & Sons, 1976

[3] P.A. Chatterton, M.A. Houlden: "EMC Electromagnetic Theory to Practical Design", John Wiley & Sons, 1992

8 Laboratory tests and in field tests

8.1 General

A useful method to achieve electromagnetic compatibility is provided by EMC conformance tests (type tests) on automation and control systems, performed in the laboratory.
The type tests of electronic equipment are generally based on a dedicated test plan, specifying the test procedures, the test levels and the acceptance criteria. In particular, the test procedures can be based on international standards (e.g. IEC publications) or, if necessary, on a dedicated specification defined by the manufacturer or by the user.

The general approach when testing equipment, takes into account the traditional architecture of the electronic systems and the typical location of the equipment in the control rooms or dedicated areas within a plant.
Different options are now available in the configuration of advanced systems based on information technology, including solutions with distributed systems where the electronic units can be located in field (e.g. in the switchyard area).
Of course, these new configurations may not be clearly covered by the consolidated test procedures, and must be considered when revising or developing the future EMC standards.

At the same time, proper mitigation methods should be considered in the design of the installation to suitably limit the effect on the process of the severe environmental conditions in the location of remote control units.

In addition to the laboratory tests, in field tests can be considered during the assembling of an installation or as final check. These tests have a different scope from the type tests, e.g. to verify the efficiency of specific EMC provisions (e.g. bonding and shielding actions) or to verify the installation EMC margin.

8.2 Laboratory tests on electronic equipment and systems

A complete set of EMC tests should cover emission and immunity aspects, both radiated and conducted. The relevant phenomena simulated can include low frequency and high frequency disturbances, both transient and continuous.

A variety of approaches and procedures have been adopted in the past by the different technical bodies dealing with electronic equipment in the definition of the EMC requirements and tests. Furthermore, dedicated EMC specifications and test procedures have in some cases defined by the manufacturers or by the utilities.
In the past, these activities have not been systematically co-ordinated and harmonised.
A significant contribution in improving this situation has been provided by the recent standardisation progress within the IEC. In fact, the different phenomena relevant in the definition of the immunity requirements of an electronic system are now covered by a series of "basic EMC documents", published or in progress (see 8.2.1); each document gives a specific test procedure, and a general guide for the selection of a test level.
The availability of these reference documents now makes it easier to achieve harmonisation of the EMC requirements of different products.

The general policy for testing automation and control systems takes into consideration different categories of test:

- type test, carried out on a representative sample in order to verify the EMC performance at the design level;
- routine test, carried out during production to confirm that each individual apparatus has been correctly manufactured;
- sample test, repeated at appropriate time intervals on representative samples in order to assess the uniformity of the manufacturing process.

This approach should be applied to the EMC tests with some caution; in fact, the application of some immunity tests can produce a degradation of the tested equipment.

The type tests include the most complete list of EMC tests, and are carried out on a dedicated sample; for the reason above specified concerning the risk of degradation, this sample should not be installed, unless properly revised.
The routine tests of course include a limited number of tests and generally do not include the most severe immunity tests (e.g. tests with high energy transients).

Due to the statistical nature of the electromagnetic disturbances, the test procedures with the associated severity may not cover critical or atypical environmental conditions. In this case, the adoption of appropriate EMC margins can reduce the risk of interference.

In the context of conformance testing on electronic equipment, a specific activity is sometimes carried out to investigate the self-diagnostic performance and "credibility" of a system. During these tests single failures are injected into the electronic modules and related connections, to simulate possible failure conditions of components. The reaction of the system and self-diagnostic capability is then detected, including possible consequences on the controlled process. This specific procedure could, in some way, integrate with the EMC evaluations, and could help to detect the behaviour of a system under interference conditions.

8.2.1 Immunity requirements and test procedures

A survey of the standardised procedures commonly used to carry out laboratory tests is given in the following. For each test the normative reference is indicated, together with the scope and the related phenomena.
The list is based on the publication IEC 1000-4-1: "Overview of immunity tests", 1992.
Some indications are given about the priority and relevance of the tests for equipment and systems operating in HV substations and power plants.

a) *Harmonics and interharmonics*

Conducted test, to be carried out on a.c. power ports of electronic equipment to detect the possible effects of harmonic distortion characterising the low voltage power supply networks. The typical values of harmonics and interharmonics, to be considered for the definition of the test levels, are discussed in IEC 1000-2-1 and IEC 1000-2-2.
A dedicated test procedure is under consideration and will be published as IEC 1000-4-13.

b) *Voltage dips, short interruptions and voltage variations*

Conducted tests, to be carried out on a.c. and d.c. power ports of electronic equipment to verify its immunity level, or the possible degradation of performances, when subjected to disturbances characterising the power network.
A dedicated test procedure for the a.c. power ports is published as IEC 1000-4-11. An additional procedure relating to d.c. power ports is under consideration and will be published as 1000-4-29.

Tests a) and b) are related to low frequency disturbances, and are recommended when the equipment is not supplied from a dedicated power source but is connected to a distributed power supply network.

c) *Surges*

Conducted test, to be carried out on the different ports of the equipment (power and signals) to verify its immunity or functional degradation when subjected to unidirectional transients (induced voltage surge: 1,2/50 µs at open circuit test generator, induced current surge: 8/20 µs at short circuited generator). These disturbances are caused by switching phenomena or faults in the power network and lightning strokes.
The test procedure is defined in IEC 1000-4-5.

d) *Oscillatory waves (repetitive transients and single ring waves)*

Conducted test, to be carried out on the different ports of the equipment (power and signals) to verify its immunity when subjected to repetitive oscillatory transients at 1 MHz and ring waves at 100 kHz. These disturbances are caused by switching HV isolators and circuit breakers.
The test procedure is defined in IEC 1000-4-12.

e) *Electrical fast transient/bursts*

Conducted test, to be carried out on the different ports of the equipment (power, signals and earth) to verify its immunity when subjected to bursts of fast pulses, with rise time of 5 ns and duration 50 ns. The transients, having low energy and high repetition rate, simulate the switching of inductive loads or relay contacts bounce.
The test procedure is defined in IEC 1000-4-4.

Tests c), d) and e) refer to transient phenomena of different nature. High priority is generally given to these tests as they are particularly relevant to electrical plant both in HV substations and power plants.

The surge test with 1,2/50 µs pulse and the 100 kHz ring wave test can be considered redundant. However, sometimes they may give complementary results due to the higher energy content of the surges and the voltage polarity changes of the ring waves.

The test with oscillatory transients at 1 MHz is very efficient to simulate the EM environment of open air substations, but it is not appropriate to accurately simulate the electromagnetic environment in GIS installations, characterised by transients with oscillation frequency in the range of tens of MHz. A revision of the related basic document is in progress to cover this specific aspect more satisfactorily.

f) *Conducted disturbances induced by radio-frequency fields in the range 150 kHz - 80 MHz*

Conducted test, to be carried out on the different ports of the equipment (power, signals and earth) to verify its immunity when subjected to common mode disturbances at radio-frequency. This test, in the specified frequency range, can replace the traditional test with radiating the equipment with electromagnetic fields.
The test procedure is defined in IEC 1000-4-6.

g) *Conducted common mode disturbances in the range d.c. - 150 kHz*

Conducted test, to be carried out on the different ports of the equipment (power and signals) to verify its immunity when subjected to common mode disturbances at power frequency, including harmonics and interharmonics, and higher frequencies generated by power circuits and power equipment.
The test procedure is under consideration and will be published as IEC 1000-4-16.

h) *Power frequency magnetic field*

Test related to the enclosure of the equipment, to be carried out to verify its immunity against magnetic fields originating from power conductors, power transformers, HV circuits, etc..
The test procedure is defined in IEC 1000-4-8.

i) *Pulse and damped oscillatory magnetic field*

Test related to the enclosure of the equipment, to be carried out to verify its immunity against transient fields originating from lightning currents and switching of HV circuits by isolators.
The test procedure is defined in IEC 1000-4-9 and 1000-4-10.

The tests with power frequency magnetic field and transient magnetic field are of general interest for equipment to be installed in electrical plants. The test at power frequency is of particular relevance for equipment, CRT or similar items which are intrinsically susceptible to magnetic fields.

j) *Radiated radio frequency electromagnetic field*

Test related to the enclosure of the equipment, to be carried out to verify the immunity of the equipment against electromagnetic fields, radiated by radio frequency emitters. This test generally covers the frequency range 80 MHz to 1 GHz; the lower frequency range is covered by the conducted test IEC 1000-4-6.
The test procedure is defined in IEC 1000-4-3.

k) *Electrostatic discharge*

Test related to the enclosure of the equipment, to be carried out to verify the immunity of the equipment against the electrostatic discharges produced by operators touching the equipment or other objects in the proximity.
The test procedure is defined in IEC 1000-4-2.

In addition to the test procedure listed above, the standardisation product committees, the manufacturers of electronic equipment or the users, can define the specific EMC requirements.

An example of immunity requirements of particular interest for the electrical plants is given by UNIPEDE (International Union of Producers and Distributors of Electrical Energy), with the publication of the Technical Report 23005Ren9523 "Automation and control apparatus for generating stations and substations - Electromagnetic compatibility - Immunity requirements", January 1995. This report gives the EMC requirements of automation and control systems for use in generation, transmission and distribution of electricity, and related telecommunications.

8.2.2 Emission limits and test procedures

The possible electromagnetic emission of electrical and electronic equipment includes low frequency disturbances, injected into the power networks, and conducted and radiated disturbances at radio frequency.

Specific low frequency emission limits are defined for the a.c. power port, including the related test procedures. They are generally applied to commercial equipment with nominal current up to 16A, in order to avoid degradation of the public network power quality.

The emission limits and test procedures are defined in IEC 1000-3 series, as in the following.

a) *Limits of emission of harmonic current* for equipment with rated current up to 16 A per phase

   The requirements and the test procedure are defined in IEC 1000-3-2.

b) *Limits of emission of voltage fluctuations and flicker* for equipment with rated current up to 16 A per phase

   The requirements and the test procedure are defined in IEC 1000-3-3.

Other IEC publications of the series 1000-3 are dedicated to the definition of limits and evaluation criteria to be applied to equipment with higher rated current.
The emission limits of the publications above can appear not to be directly applicable to automation and control systems in power plants and HV substations, where d.c. power supply network and preferential a.c. power supply network are generally used for electronic equipment.

The low frequency emission limits should in any case be considered for automation and control systems, particularly in the case of use of a preferential a.c. distribution network supplied by an Uninterruptible Power Supply Systems (UPS). In fact, due to the relatively high output impedance of the UPS, the harmonics and the inrush current generated by the electronic equipment can affect the power quality of the network and reduce the power available to a portion of the nominal power of the UPS.

Radio frequency emission limits (conducted and radiated) are applied to the equipment to avoid interference to the broadcasting services and telecommunications.
Limits and test methods are specified by CISPR publications. The limits are defined for different categories of product, taking into account their intended use and location (e.g. industrial areas, domestic/residential areas, etc.). Examples of CISPR publications relevant for the electrical equipment and control systems of electrical plants are the following.

a) *Limits of conducted radio frequency disturbances*

   The measurements are generally specified in the frequency range 0,15 to 30 MHz.
   The limits are defined in CISPR 11 (dedicated to Industrial, scientific and medical radio-frequency equipment) and CISPR 22 (dedicated to Information Technology Equipment). The basic test procedures are specified in CISPR 16.

b) *Limits of radiated radio frequency disturbances*

   The measurements are generally specified in the frequency range 30 MHz to 1 GHz.
   The limits are defined in CISPR 11 and CISPR 22. The basic test procedures are specified in CISPR 16.

The radio frequency emission limits for equipment and control systems installed in substations and power plants, where necessary, could be derived from the less severe limits used in industrial environment.

Particular attention is addressed to the radio interference emission of overhead power lines and high voltage equipment. This subject is covered by specific CISPR publication series 18. These publications describe the phenomena, the method of measurement and the procedure for determining limits and the code of practice for minimising the generation of radio noise.

8.3 In field tests on the complete installations

In field tests on a complete installation could represent a final step of the EMC design, e.g. for checking the specific mitigation methods or the final EMC margins. These tests could also be carried out for investigation purposes during the exercise of the installation.

In field EMC tests can be carried out with different influence on the service conditions of the plant, as in the following.

- Investigation of the steady-state EM environment in the normal operating condition of the plant. In this case there is no relevant influence on the operating conditions of the installation.
- Investigations related to the effects of specific operating conditions of some equipment or systems (e.g. load configuration, plant layout, etc.). A moderate influence is requested on the operating conditions of the plant.
- Investigations on the effects of switching operations of power equipment, investigation related to transient operating conditions of the process. In this case the in field-activities must be co-ordinated with the operative planning of the plant.
- Experiments and investigation related to source of disturbances with low frequency of occurrence, e.g. faults of power circuits or lightning. In this case it may be necessary to coordinate the field activity with an outage of a part of the plant.

In addition to specific in field measurements, in order to collect data about possible interference conditions in a plant some automation and control systems could be partially dedicated to monitor the electromagnetic influences on a continuous and statistical basis. To this purpose, the manufacturer and the user of the electronic systems can agree upon dedicated hardware and software solutions for logging different disturbances, e.g. due to lightning, switching operations, faults, etc.. This feature is easily available with the use of modern electronic equipment versus electromechanical apparatus.

8.3.1 Testing the efficiency of specific mitigation methods

The verification of specific mitigation methods and EMC provisions applied in a plant (e.g. shielding solutions, signal cable protection, etc.), can be of particular interest to compare the actual efficiency of different practical implementations. The collected data could also be used as basis for periodical verification and subsequent checking of the installation's ageing.

Examples of possible investigations and related aim are listed below.

- Measurement of the efficiency of the bonding between metallic structures, parts of cable trays, ground conductors, etc., by means of proper low impedance measuring system. Possible effects of corrosion and degradation of electrical connections can be detected with periodical repetition of these measurements.
- Inspection and verification of the grounding efficiency of control system cabinets and screens of related cables to check for grounding connections and the risks of bad contacts due to corrosion, deteriorated crimping, etc..
- Measurement of the efficiency of filters, protective devices, isolation transformers and other EMC interfaces assembled outside the equipment cabinet e.g. in a dedicated unit. Measurements could be carried out using a continuous or transient disturbance simulator, with particular caution to avoid risk to degrade the interfaces involved and the protected equipment. Considering that varistors can suffer degradation with surges energy, these devices should be periodically verified using a proper monitor, basically a 1 mA generator with a voltmeter.

- Measurement of the shielding efficiency of protected areas. In case of a shielded room, a periodical verification of the shielding efficiency is recommended to check its integrity. Specific measurements can be carried out with the application of standardised test methods for measuring the shielding efficiency, taking special care when using radiated electromagnetic energy for the test. Special attention must be paid to the gaskets, shielded doors and other provisions used for maintaining the integrity of the Faraday cage.

8.3.2 Monitoring of continuous disturbances

In order to check the steady-state electromagnetic environment, the continuous disturbances affecting the power and signal cables of automation and control systems, as well as the electromagnetic field in their proximity, could be monitored for a sufficient period of time and for different operating conditions of the process. Spectrum analyser, oscilloscope, power quality monitoring unit and other instrumentation can be used.

The measurement can be finalised to monitor:

- the quality of the power distributed to the automation and control systems and the related disturbances: voltage fluctuation and short interruptions, harmonic content on a.c. power supply, ripple on d.c. power supply, common mode noise, etc.;
- the low frequency and high frequency noise induced in control and signal cables (common mode and differential mode disturbances);
- the efficiency of communication links: pattern generators and error detector could be used to check the signal to noise ratio of the communication;
- the power frequency magnetic field in different areas of the plant, particularly where CRT video terminal screens are used.

The measurement results, related to operating conditions of the plant and compared to the data of other similar plants, can help in the final evaluation of the environmental condition.

Specific measurements could be carried out to investigate the corona effect and the radio noise field radiated from HV equipment and overhead power lines. The measurement procedures are described in the publication CISPR 18.

8.3.3 Measurements of conducted and radiated transient disturbances due to switching

As previously discussed, the switching operation of HV isolators and circuit breakers in open air and GIS substations can induce significant disturbances into the auxiliary circuits. This cause of disturbances should be investigated with high priority to achieve a comprehensive evaluation of the electromagnetic environment. Proper transient recorders and oscilloscopes with sufficient bandwidth, and voltage and current probe, are to be used.

The generating stations are characterised by frequent switching operation of HV and LV power loads. The related transient disturbances induced into the control and signal cable are not severe if proper provision is made for the separation of the different cable categories. Sometimes, LV switching of inductive loads may induce relevant fast transients into digital and analogue signal cables and shall be investigated.

Significant transient electromagnetic fields are also radiated by the switching operations, up to the surrounding area outside the substation. The characterisation of these fields are difficult due to their transient nature, the wide band covered and their high level. Specific investigations can be carried out by using special (and expensive) measurement systems, and are to be considered only in special cases.

8.3.4 Evaluation of transient disturbances with low occurrence

Transient disturbances with low frequency of occurrence may be generated by faults in the power networks, or by lightning stroke on HV lines, towers, chimneys and other structures. Due to the rare and unpredictable nature of these phenomena, direct investigations are quite difficult. Transient recorders should be installed in significant locations for a sufficient period of time to have good probability of monitoring these disturbances.

A reduced scale simulation of these phenomena can help the investigation and give some indications for the characterisation of the electromagnetic environment.

The simulation of fault conditions of power circuits involving the earth system could be carried out by injecting earth currents at power frequency directly into those metallic structures and ground conductors which have a significant risk of being involved in a fault. During this simulation the ground potential rise and the induced voltages on auxiliary circuits can be measured and, using a scale factor, referred to the actual fault current.

More difficult is the simulation of lightning phenomena on structures.
A possible test set up is represented in figure 96. A transient generator, realised by a high voltage d.c. source and a capacitor bank is installed far away from the plant under investigation. A significant transient current can be injected on ground conductors and metallic structures by means of an HV line and a spark-gap.

The efficiency of the simulation is related to the test generator capability and to the layout of the test set-up. The reported experience has indicated that transient current in the order of some kA, giving a 1/10 reduced scale simulation, can be obtained using a 100 kV test generator.

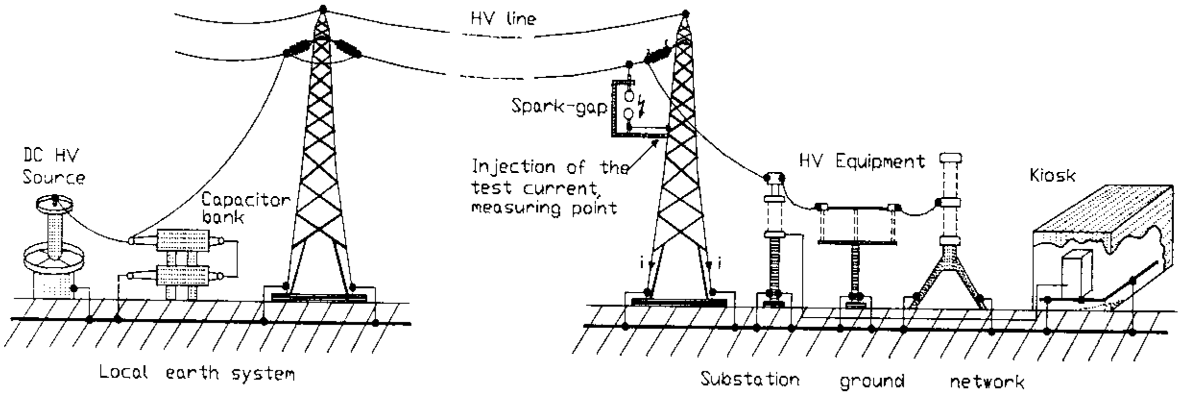


Figure 96 - Example of test set up for investigating the effects of direct lightning involving an HV substation

9 Economical considerations

9.1 General

The best technical-economical compromise in achieving EMC can be based on a proper balancing of actions at the installation level (reduction of the emission of disturbances at the sources and prevention of unwanted coupling) and the actions on sensitive equipment (increase immunity performance).

At the design stage of the installation it is necessary to take into consideration some technical and political aspects as follows.

- Some essential EMC actions and provisions should be considered in the design level of the installation rather than defined at later stages, in order to get better results and reduce the costs.
- In principle, a dedicated set of EMC provisions could be precisely defined for each plant, trying to limit the costs as much as possible. However, this implies a complete knowledge of the EM environment.
  Due to the complexity of the subject and the number of parameters involved, a detailed EMC analysis may require theoretical evaluations, based on models, and expensive field investigations.
- For the reason above, a simplified approach is generally preferred with the application, at the design stage, of a consolidated set of provisions (see chapter 5); consequently, different EMC margins can be obtained depending on the actual conditions of the different installations.
- The EMC requirements of automation and control systems are to be considered as design parameters. They must be defined or agreed within the commissioning and qualification stages of the equipment, with the advantage of a clear definition of responsibility limits between equipment designers and power plants/substations designers.
- The EMC of automation and control systems can allow the original expected life of the equipment to be achieved, avoiding degradation due to EM disturbances.

In conclusion, EMC measures should be included in a "standardised" design of installations and equipment, rather than defined in a "case by case" approach.

For automation and control systems, additional support for the application of standardised EMC measures is provided by the legal value sometimes assigned to the EMC requirements. This is the case of the essential requirements defined by the European EMC Directive 89/336/EEC, related to the free circulation of goods within the European Union.

9.2 Costs of electromagnetic compatibility

a) *Costs at installation level*

The mitigation of electromagnetic disturbances in HV substations and power plants involves additional costs at the design level and in the assembly stage.
Some of the economic parameters related to the mitigation methods that can be applied in new plant are discussed below.

- *Improvement of the earth network and earthing connections of HV and power equipment.*
  The cost of this measure is represented by some additional ground/earth conductors and their assembling in the plant (in practice a very small portion of the cost of the earthing system).
- *Adoption of shielded cables for carrying the signal circuits in HV substations.*
  Depending on the cables involved and the type of shield, the additional cost, compared to unshielded cables, can range from 10% to 20%.
- *Protection of low level signal cables in generating stations.*
  The shielding actions are generally realised on cable grouping, e.g. by using metallic trays. Because cable trays are in any case used, the additional cost is generally limited to the improvement of the bonding conditions of the metallic parts of these trays, including dedicated metallic covers.

- *Use of optical links for signal connections.*
  These solutions are generally adopted to give better functional performance; their additional cost should only be partially charged to the EMC aspects.

In case where commercial equipment designed for residential environments are to be installed in HV substations or generating stations, special provisions may be necessary due to their insufficient EMC performance. In particular cases, a dedicated "protected area" can be realised within the plant, provided with shielding and filtering properties. This kind of solution is very expensive, implies periodical maintenance, and therefore should be considered only in case of systems with special performance; a dedicated economical evaluation, comparing alternative solutions, is suggested.

Provisions for the reduction of electromagnetic disturbances can be difficult to apply to old plant. The opportunity should be taken of using an upgrade which is planned for more general reasons, to also include the EMC aspects and to introduce mitigation methods as would be used for a new installation.

Sometimes some investigations and actions to mitigate electromagnetic disturbances may be triggered by EMI problems. The related costs can be very high, as they include expensive in-field investigations as well as the resulting improvements. The economical evaluation should be carried out case by case.

b) *Additional costs of the electronic systems*

Automation and control systems for industrial applications are generally designed on the basis of EMC requirements covering both immunity and emissions aspects. A more complete set of immunity requirements is necessary for the electronic equipment intended to be used in electrical plant, due to the more complex electromagnetic environment.
To fulfil these immunity requirements, specific solutions are adopted by the manufacturers, including dedicated I/O interfaces, shielding and filtering actions, etc..

Specific EMC provisions, as well as being integrated in the design stage, could be implemented also in the assembly stage of electronic equipment. This is the case when Programmable Logic Controllers, designed for general applications in residential and industrial environment, are to be used in HV substations or power plants.

The additional costs concern the design of the automation system as well as the conformance tests.
The adoption of EMC provisions on a large scale can allow a manufacturer to optimise the design and reduce the associated additional cost.
A similar comment may apply to EMC type tests. On this subject, it is to be considered that the continuous revision of the electronic systems, for the introduction of new technologies and solutions, can imply the repetition of conformance tests. These additional costs shall be taken into consideration by the manufacturers in the definition of the policy for updating their production.

Post installation actions on electronic systems affected by interference can be very expensive compared with the costs of measures at the design stage, due to the difficulty to integrate into an installed system special EMC provisions like filtering, additional interfaces or protection units, etc..

To emphasise this concept, figure 97 represents the feasibility of EMC measures within the design and life period of an automation system (design stage, prototype improvement, production and working period) and the trend of the related costs.

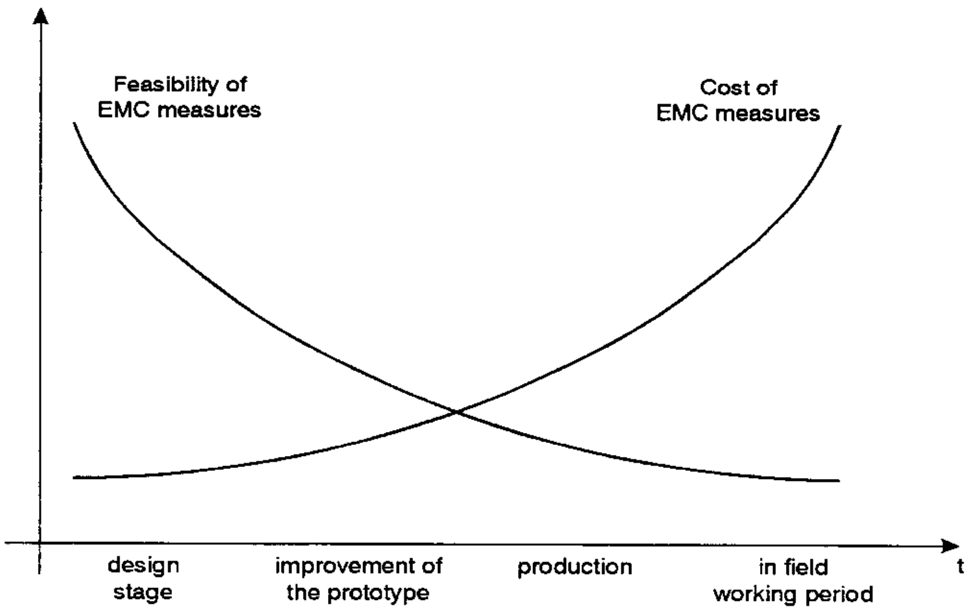


Figure 97 - Feasibility and cost of the EMC measures within the design and life period of an automation system

9.3 EMC management and risks related to EMC deficiencies

The risks associated with a poor EMC design must be evaluated case by case. Examples of evaluation steps are reported in the following.

- The most severe disturbances transferred to automation and control systems are generally associated with phenomena having low frequencies of occurrence, like lightning strokes in the plant area, ground fault and short circuit conditions. As a consequence of these phenomena, the integrity of the systems can be affected. Furthermore, interference conditions can occasionally appear not to have a clear cause.
  In critical situations, relevant functions assigned to electronic equipment could fail, with risks for the efficiency and safety of the plant.
- In the case of poor EMC design, the disturbances with high frequency of occurrence, e.g. produced by switching operations, use of walkie-talkie, etc., can affect the operating condition of the automation and control system.
  Periodical inspections and checks could be necessary in this case to assure their correct operation. The associated additional costs can be of particular relevance for telecontrolled plants.
- Occasional interference can produce insufficient reliability of electronic systems and affect the confidence of the operators in the automatic control and telecontrol of the plants. As a consequence, the automation and control systems could be excluded by the operators and replaced by manual control.

A complete approach of the electromagnetic compatibility implies proper education and training of the technicians involved. In fact, a proper background is necessary to define the appropriate strategy for achieving EMC at the design level, for assuring the expected quality on the products and for checking the assembling of equipment and components in the installation.

To this purpose, several handbooks and literature are now available, dealing with the different aspects of the EMC. These handbooks generally emphasise specific aspects, like the electronic design, testing in laboratories, etc., and must be selected accordingly.

Technical references on EMC installation guidelines, design criteria, tests procedures, etc., are published by different international organisations (IEC, ITU, UIE, CIRED, etc.) as technical reports, standards or guidelines.

Training courses are available within Universities, by competent bodies and by EMC laboratories.
Broad band courses are formulated for a general introduction to the subject, but more detailed courses are also available for specific needs of the industry operators.

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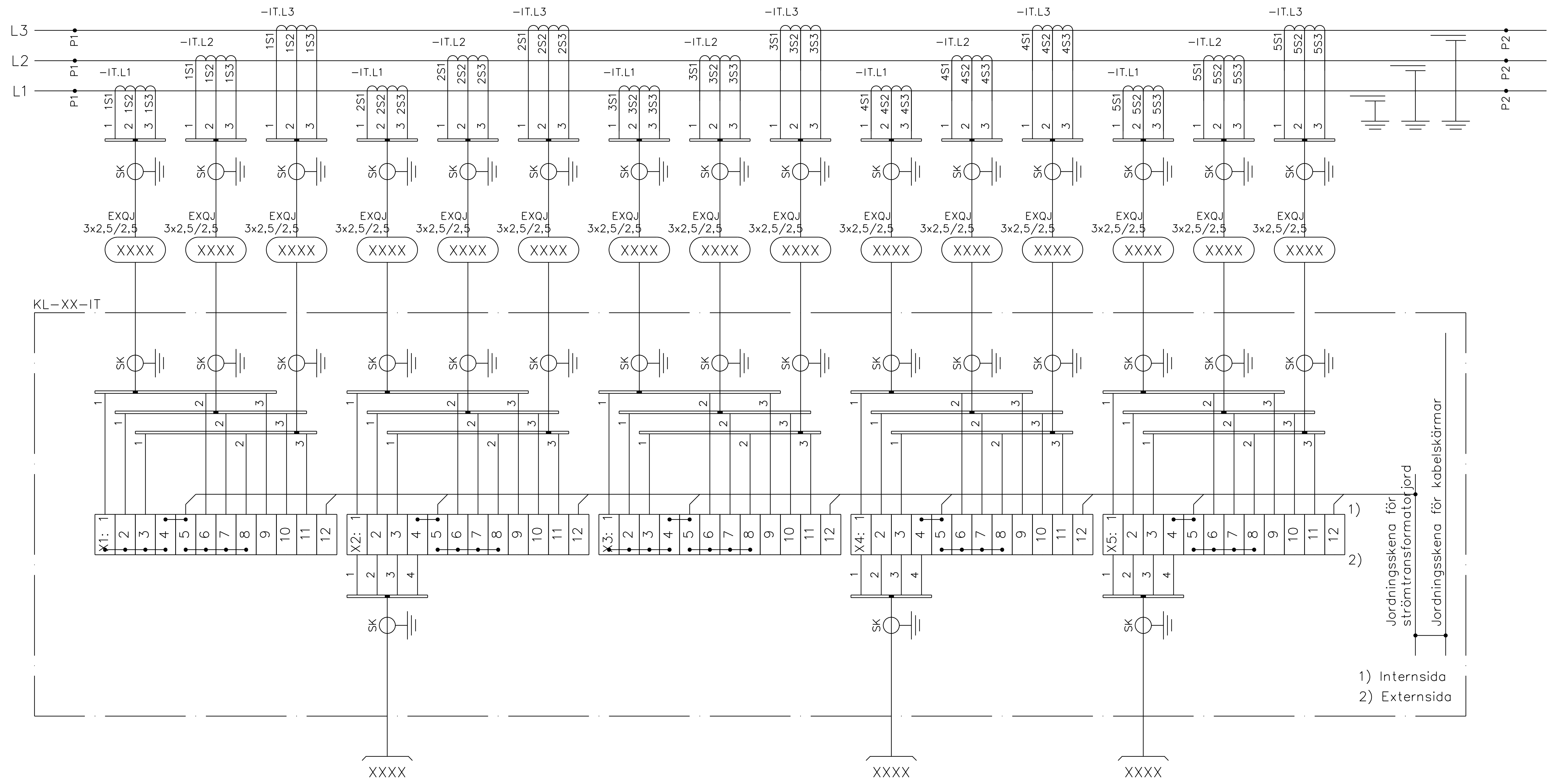

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VATTENFALL

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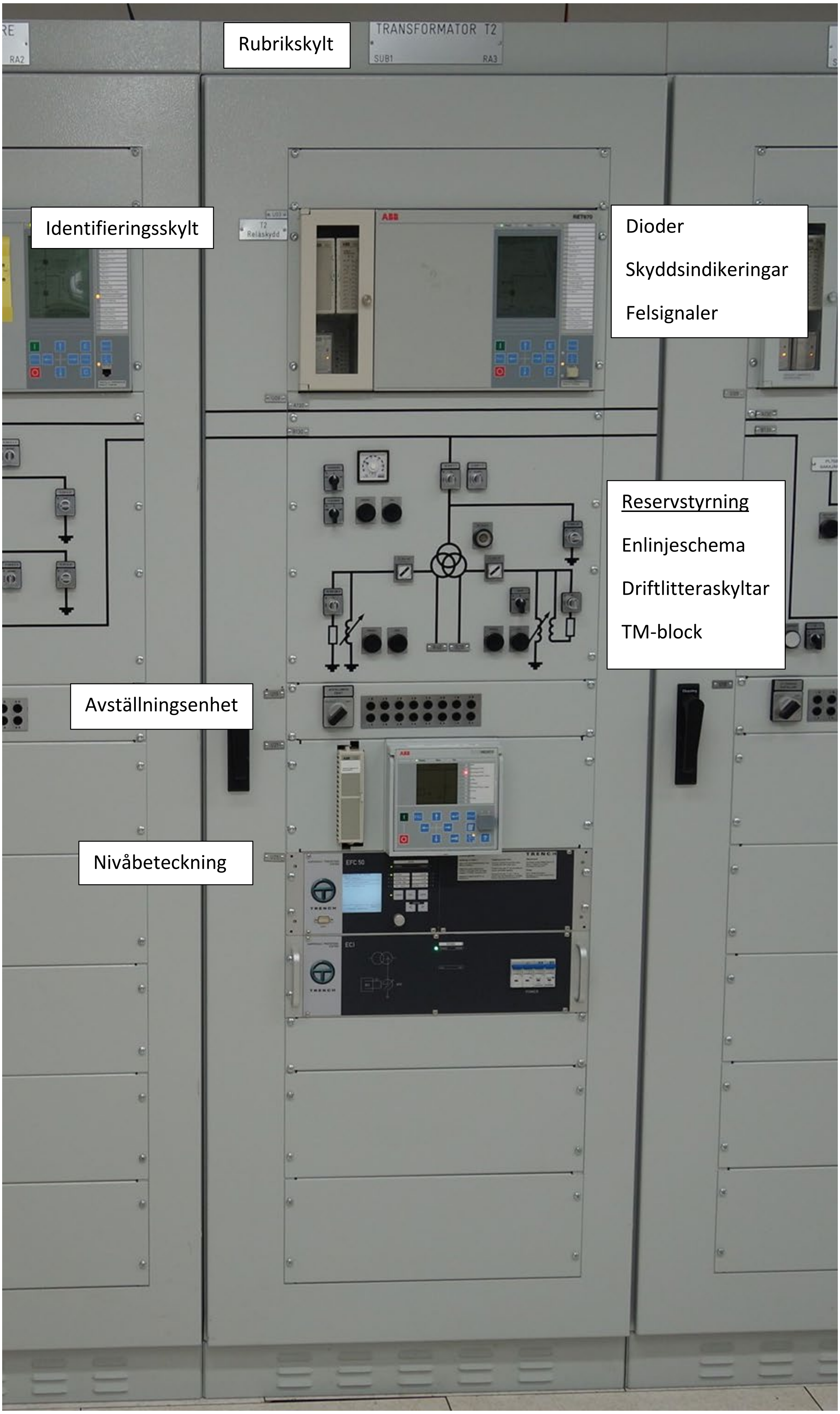
VTR02-08 Bilaga 1: Exempel skyltning kontrollskåp framsida



Idrifttagningsanvisning

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Innehållsförteckning

1. Allmänt

Detta dokument innehåller anvisningar för vilka kontroller och prov som skall utföras före och i samband med idrifttagning av nya eller ändrade anläggningar ägda av Vattenfall Eldistribution AB.
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Idrifttagningsprovens ändamål är att säkerställa att anläggningen uppfyller i kontraktet ställda krav.
Detta dokument är endast ett förtydligande av de prov och kontroller som skall utföras och utgör ingen inskränkning i entreprenörens ansvar enligt kontraktet.

Personal som utför idrifttagning av Vattenfall Eldistribution AB anläggningar skall känna till innehållet i detta dokument samt skall ha flerårig vana av idrifttagning, felsökning och underhållsprovning i aktuell typ av anläggning.

Beställaren eller annan entreprenör till denne skall i varje skede av idrifttagningen beredas möjlighet att delta i provningen.

All idrifttagningsprovning skall redovisas. En provplan/kontrollplan (ITP-Inspection and Test Plan) bestående av checklistor och protokoll skall fyllas i. Där så anges i ITP skall prov redovisas i särskilda protokoll. Övriga prov och kontroller redovisas i separat kretsschema (ej fabriksritningar) och övrig dokumentation s.k. ”Provex”.
I samband med avslut av projekt skall dokumentation överlämnas enligt i beställningen ställda krav.

Anvisningen är upplagd så att prov som skall utföras är uppställda punktvis (kolumnen: prov) i checklistor.
I samband med ett nytt projekt skall entreprenören ta fram en prov/kontrollplan ITP som skall godkännas av beställaren.

ITP består av valda delar av dessa checklistor. Vissa checklistor kan förekomma i flera exemplar i planen. I ett projekt med tre nya brytare skall alltså checklista för brytare finnas med i tre exemplar, varje exemplar märkt med brytarens littera. De prov som skall utföras i det aktuella projektet markeras genom att i kolumnen ”utförs av” föra in vem som skall utföra provet. Prov som inte behöver utföras i det aktuella projektet markeras med streck i kolumnen ”utförs av”.
I planen skall också framgå namnet på den person hos entreprenören som i det aktuella projektet är huvudansvarig för att provplanen följs.
I kolumnen ”utfört/sign” skriver den som utfört provet datum och signatur. I kolumnen ”anmärkning” görs speciella noteringar om avvikelser eller dyl.
Exempel på en prov/kontrollplan (ITP) finns i bilaga.

Entreprenören skall uppvisa ifyllda checklistor för godkännande av beställaren före spänningssättning av ny/ändrad anläggning. Avgröning skall ske på omritat kretsschema, inte fabriksriktningar.
Efter idrifttagen och besiktigad anläggning återlämnas planen med ifyllda checklistor och provningsprotokoll tillsammans med slutdokumentation till beställaren.

För prov som skall redovisas i protokoll är denna punkt markerad i checklistan: (protokoll)
Exempel på protokollblanketter finns som bilaga. Typ och fabrikat av utrustning samt provningsmetod m. m. avgör hur protokollet skall se ut. Detta bestäms i varje enskilt fall.

Entreprenören kan använda egna checklistor i provplanen och protokollblanketter om dessa innehåller samma uppgifter och <u>godkänns av beställaren</u>. Provplanen kan även innehålla prov som inte finns med i dessa checklistor, anläggningens utförande eller entreprenörens interna kvalitetskontroll kan innebära att ytterligare prov utförs och redovisas. Denna checklista visar vilka prov som minst måste utföras.
I de fall utrustning saknas i denna checklista ansvarar entreprenören för att skapa en egen checklista/provplan för utrustningen, relevanta delar från liknade objekt skall användas

2. Ritningsgranskning/konstruktion

Kontroll att anläggningen ur allmän drift-, underhålls- och säkerhetssynpunkt är ändamålsenligt och föreskriftsenligt utförd och dimensionerad

Nr	Prov	Utförs av	Utfört/Sign	Anmärkning
2.1	Kontroll att kretsschema är ändamålsenligt utförda ur allmän drift- och funktionsmässig synpunkt.			
2.2	Intern konstruktionsgranskning av entreprenör är utförd och redovisad på kretsschema			
2.3	Apparater och andra anläggningsdelar är dimensionerade med hänsyn till driftström, kortslutningseffekt och klimatförhållanden samt har tillräckliga isolationsavstånd i alla kopplingslägen.			
2.4	Fasta jordningsanordningar finns på erforderliga ställen och är rätt placerade och dimensionerade			
2.5	Nollpunktsjordningen är utförd med hänsyn till systemjordningens utformning i nätet.			
2.6	Lokalanläggningen är lämpligt utförd och dimensionerad bl.a. med hänsyn till nödvändigheten av säker funktion hos manöver- och felbortkopplingsutrustningen			
2.7	Utlösningsvillkoret beräknat för likströmsanläggningen			
2.8	Utlösningsvillkoret beräknat för växelströmsanläggningen			
2.9	Kablar inom anläggningen är av godkänd typ och är riktigt dimensionerade med hänsyn till belastning, spänningsfall m. m.			
2.10	Kopplingsapparater, avledare och mättransformatorer är lämpligt dimensionerade och placerade med hänsyn till skyddsobjekt och skyddsområde (risk för förbikoppling av mättransformatorer, osymmetri vid kopplingar)			
2.11	Anläggningen är lämpligt utförd ur betjänings- och underhållssynpunkt (apparatplacering, avstånd, utrymme, förväxlingsrisk, belysning m. m.)			
2.12	Skyltlista med skyltar för identifiering av betydelsefulla anläggningsdelar. Text, färg och placering är riktig			

Noteringar:

3. Jordtag och jordningar

Nr	Prov	Utförs av	Utfört/Sign	Anmärkning
3.1	Uppmätning av jordtagsresistans (protokoll)			
3.2	Jordningskontroll i sammanhängande jordkabelnät (protokoll)			
3.3	Uppmätning av steg- och beröringsspänningar (protokoll)			
3.4	Uppmätning av spänningar vid direktjordat system mot: ☐ Tele (Skanova) (protokoll) ☐ Trafikverket (protokoll) ☐ Lågspänningsnät (protokoll)			
3.5	Kontroll att skyddsjordningar av skåp, kopplingslådor och stativ m. m. är utförda enligt jordningsschema.			
3.6	Grind och staket är skyddsjordade enligt anvisning			
3.7	Byggnader är skyddsjordade enligt anvisning			
3.8	Fasta jordningspunkter finns på erforderliga ställen			
3.9	Arbetsjordningar är rätt dimensionerade och placerade			

Noteringar:

4. Ställverk med apparater (avsnitt nedan gäller även kapslade ställverk samt GIS-ställverk och skall utföras på SITE)

4.1 Brytare		Littera:		
Nr	Prov	Utförs av	Utfört/Sign	Anmärkning
4.1.1	Okulär besiktning			
4.1.2	Mekaniska och elektriska prestanda uppfylls enligt kravspecifikation.			
4.1.3	Indatablad ifyllt för inläggning i underhållssystemet			
4.1.4	Skyltning / märkning			
4.1.5	Kontrolldragning av bultförband			
4.1.6	Kontroll att jordningen av stål och stativ är rätt utförd (shuntning över fasta förbindningar för att förhindra radiostörningar)			
4.1.7	Polaritet på motormatning			
4.1.8	Mätning av motorström och uppspänningstid			
4.1.9	Kontroll av larmkontakter: ☐ Ospänd fjäder ☐ Densitetsvakt ☐ Utlöst motorskydd/dvärgbrytare ☐ Värmefel			
4.1.10	Kontroll av mekanisk/elektrisk blockering (gäller frånskiljande brytare DCB)			
4.1.11	Till/frånslagstider			
4.1.12	Uppmätning av resistansen över brytaren			
4.1.13	Fingeravtryck på hastigheten på brytelementet (m/s)			
4.1.14	Täthetsprov (prova att apparaten ej läcker)			
4.1.15	Lokalmanöver vid brytardon			
4.1.16	Mekaniskt frånslag			
4.1.17	Mekanisk blockering (gäller frånskiljande brytare DCB)			
4.1.18	Värme och ventilation i manöverdon			
4.1.19	Manöverprov inklusive antipumpfunktion (lokalt, fjärr)			
4.1.20	Leverantörsdokumentation (kontrollera att det är rätt dokument och rätt antal)			

Noteringar:

4.2 Frånskiljare (F)		Littera:		
Nr	Prov	Utförs av	Utfört/Sign	Anmärkning
4.2.1	Okulär besiktning			
4.2.2	Mekaniska och elektriska prestanda uppfylls enligt kravspecifikation.			
4.2.3	Indatablad ifyllt för inläggning i underhållssystemet			
4.2.4	Skyltning / märkning			
4.2.5	Kontrolldragning av bultförband			
4.2.6	Kontroll att jordningen av stål och stativ är rätt utförd (shuntning över fasta förbindningar för att förhindra radiostörningar)			
4.2.7	Mätning av motorström vid slutning, öppning och slirning			
4.2.8	Stickprovskontroll med låsta strömbanor (kontroll att det ej slirar i länkar och leder)			
4.2.9	Uppmätning av övergångsresistenser			
4.2.10	Indikeringskontakter ger säkra lägesinformationer Öppen – Sluten (manövrering, optisk kontroll)			
4.2.11	Kontroll av mekaniska/elektriska förreglingar enligt förreglingsschema			
4.2.12	Värme och ventilation i manöverdon			
4.2.13	Manöverprov vid motormanövrerade frånskiljare (lokalt, fjärr) Blockering av motormanöver vid handmanöver			
4.2.14	Vind och islastprov (tillägg som specas separat) Prov på en i anläggningen monterad frånskiljare som visar att den uppnår sina ändlägen i öppet och slutet läge			
4.2.15	Leverantörsdokumentation (kontrollera att det är rätt dokument och rätt antal)			

Noteringar:

4.3 Jordningsfrånskiljare (-JF)		Littera:		
Nr	Prov	Utförs av	Utfört/Sign	Anmärkning
4.3.1	Okulär besiktning			
4.3.2	Indatablad ifyllt för inläggning i underhållssystemet			
4.3.3	Skyltning / märkning			
4.3.4	Indikeringskontakter ger säkra lägesinformationer Öppen – Sluten (manövrering, optisk kontroll)			
4.3.5	Montering enligt anvisning			
4.3.6	Kontrolldragning av skruvförband			
4.3.7	Manöverprov (lokalt/avstånd)			
4.3.8	Kontroll av mekaniska/elektriska förreglingar enligt förreglingsschema			
4.3.9	Jordningen från jordkniven är ordentligt ansluten till jordlinenätet (shuntad över alla delarna i stativet)			
4.3.10	Uppmätning av övergångsresistansen			
4.3.11	Vind och islastprov (tillägg som specas separat) Prov på en i anläggningen monterad jordningsfrånskiljare som visar att den uppnår sina ändlägen i öppet och slutet läge			
4.3.12	Leverantörsdokumentation (kontrollera att det är rätt dokument och rätt antal)			

Noteringar:

4.4 Spänningstransformator (-UT)		Littera:		
Nr	Prov	Utförs av	Utfört/Sign	Anmärkning
4.4.1	Okulär besiktning			
4.4.2	Indatablad ifyllt för inläggning i underhållssystemet			
4.4.3	Skyltning / märkning			
4.4.4	Belastningsmotstånd			
4.4.5	Ej använda kärnor är **inte** kortslutna. Ej använda lindningar är jordfixerade i en punkt.			
4.4.6	Isolations och jordningskontroll av hela sekundärkretsen lindning för lindning			
4.4.7	Kopplingslåda: ☐ Plintdisposition ☐ Åtkomlighet för mätning vid normal drift ☐ Kontroll att KL är direktjordad till marklinenätet ☐ Ventilation ☐ Skyltning			
4.4.8	Omsättningsprov (protokoll)			
4.4.9	Riktningsprov/fasriktighet (primär = sekundär) hela vägen till reläskydd (protokoll)			
4.4.10	Utlösningsprov aut./säkringar, kontrollera signal			
4.4.11	Leverantörsdokumentation (kontrollera att det är rätt dokument och rätt antal)			

Noteringar:

4.5 Strömtransformator (-IT)		Littera:		
Nr	Prov	Utförs av	Utfört/Sign	Anmärkning
4.5.1	Okulär besiktning			
4.5.2	Indatablad ifyllt för inläggning i underhållssystemet			
4.5.3	Skyltning / märkning			
4.5.4	Montagekontroll (jämför vändning av P1-P2 mot ritningar)			
4.5.5	Samtliga **ej** använda strömkärnor är kortslutna och jordade			
4.5.6	Kapacitiva mätuttag för spänning (kondensatorbelägg): ☐ Kontroll att ej använda uttag är jordade i uttagslådan. Om uttagen används skall överspänningsskydd finnas och vara rätt justerade.			
4.5.7	Isolations- och jordningskontroll av hela sekundärkretsen lindning för lindning			
4.5.8	Skärm är återdragen genom kabelströmtransformator			
4.5.9	Kopplingslåda: ☐ Plintdisposition ☐ Åtkomlighet för mätning vid normal drift ☐ Kontroll att KL är direktjordad till marklinenätet ☐ Strömkärnornas sekundära jordning är direkt (ej seriejordade via stativ eller bultförband) ☐ Ventilation ☐ Skyltning			
4.5.10	Efterdragning av samtliga plintar, framförallt strömkretsar			
4.5.11	Omsättningsprov (protokoll)			
4.5.12	Riktningsprov / fasriktighet (primär = sekundär) hela vägen till reläskydd (protokoll)			
4.5.13	Magnetiseringskurvor Fabriksprov godkänns. Verifiering av vad som är relä- och mätkärnor skall provas på plats. (protokoll)			
4.5.14	Bördamätning (protokoll)			
4.5.15	Verkningsgradsprov (kärna för JS) (protokoll)			
4.5.16	Obefogad disymmetri (vid summaströmkopplat JS) (protokoll)			
4.5.17	Lågspänningsprov (vid diffskydd för krafttransformator) (protokoll)			
4.5.18	Omsättningsprov för ev. mellanströmstransformatorer (protokoll)			
4.5.19	Leverantörsdokumentation (kontrollera att det är rätt dokument och rätt antal)			

Noteringar:

4.6 Ventilavledare (-V)		Littera:		
Nr	Prov	Utförs av	Utfört/Sign	Anmärkning
4.6.1	Okulär besiktning			
4.6.2	Indatablad ifyllt för inläggning i underhållssystemet			
4.6.3	Skyltning / märkning			
4.6.4	Montering			
4.6.5	Leverantörsdokumentation (kontrollera att det är rätt dokument och rätt antal)			

Noteringar:

4.7 Krafttransformator	Littera:			
Nr	**Prov**	**Utförs av**	**Utfört/Sign**	**Anmärkning**
4.7.1	Okulär besiktning			
4.7.2	Indatablad ifyllt för inläggning i underhållssystemet			
4.7.3	Skyltning/ märkning			
4.7.4	Kontroll av protokoll från fabriksprovning			
4.7.5	Kopplingslåda: ☐ Kontroll att KL är direktjordad till marklinenätet ☐ Värme och ventilation ☐ Märkning ☐ Skyltar ☐ Samtliga plintar är åtdragna			
4.7.6	Fuktindikator/torkapparat funktion/felsignal testade Vid elektrisk torkapparat kontrolleras signaler från denna.			
4.7.7	Isolationskontroll med 5 kV-megger (protokoll)			
4.7.8	Omsättningsprov, alla LK-lägen (protokoll)			
4.7.9	Fasriktighet (primär=sekundär)			
4.7.10	Lågspänningsprov transformator (protokoll) • 400 VAC (3-fas) ansluts på uppsidan, 3-fasig kortslutning anbringas utanför diffzon på nedsidan. • Kontroll av differentialskydd (Idiff = 0, Istab > 0) • Kontrolleras för samtliga LK-lägen. • Vid parallella kabelförband uppmäts även strömfördelning mellan kablar i samband med lågspänningsprovet (utförs vid det LK-läge som ger den högsta strömmen).			
4.7.11	Lågspänningsprov transformator (protokoll) • 400 VAC (2-fas) ansluts på uppsidan, 3-fasig kortslutning anbringas utanför diffzon på nedsidan. • Kontroll av jordströmsdifferentialskydd (Idiff = 0, Istab > 0)			
4.7.12	Prov av gasvakt (utlösning och larm)			
4.7.13	Prov av tryckvakt (utlösning och larm)			
4.7.14	Prov av tempvakt olja och lindning (utlösning och larm).			
4.7.15	Övriga signaler och vakter: ☐ Oljenivå ☐ Oljegropsnivå ☐ Utlöst aut. säkring ☐ Övrigt: ____________________________________			

Forts. på nästa sida

4.7.16	Fläktar: ☐ Rotationsriktning ☐ Utlösningsprov av motorskyddet (2 faser) ☐ Start från vakter ☐ Signaler			
4.7.17	Pumpar: ☐ Rotationsriktning ☐ Utlösningsprov av motorskyddet (2 faser) ☐ Start från vakter (oftast går pumparna alltid) ☐ Signaler			
4.7.17	Övrigt: ☐ Kranar och ventiler i rätt läge ☐ Gasvakt ej förbikopplad ☐ __________			
4.7.18	Oljeprov (Garanti att transformatorn är PCB fri)			
4.7.19	Gasanalys enligt schema (1 mån / 3 mån / 6 mån / 1 år) efter drifttagning.			
4.7.20	Kontroll av transformatorns placering över oljegrop			
4.7.21	Omsättning på ok-lindning/Lokalkrafttransformator (protokoll)			
4.7.22	Kontroll att ok-lindningen el. lokalkrafttransformatorns lågspänningsnolla (systemjordning) är inkopplad till ställverket enligt anvisning (TN-S alt. TN-C)			
4.7.23	Isolationsprov med 1 kV-megger av ok-lindning eller lokalkrafttransformator.			
4.7.24	Leverantörsdokumentation (kontrollera att det är rätt dokument och rätt antal)			

Noteringar:

4.8 Lindningskopplare (-LK)		Littera:		
Nr	Prov	Utförs av	Utfört/Sign	Anmärkning
4.8.1	Motordon: ☐ Rotationsriktning ☐ Utlösningsprov av motorskydd (2-fas)			
4.8.2	Lägesindikator: LK visar rätt läge genom hela området ☐ Lokalt ☐ Närkontroll ☐ Fjärrkontroll			
4.8.3	Handvev fungerar			
4.8.4	Manöverprov (lokalt, fjärr)			
4.8.5	Manöver från automatik (spänningsreglering)			
4.8.6	Lindningskopplaren kopplar utan avbrott			
4.8.7	Kontroll av överströmsblockering			
4.8.8	Leverantörsdokumentation (kontrollera att det är rätt dokument och rätt antal)			

Noteringar:

4.9 Nollpunktsbildare (NT)		Littera:		
Nr	Prov	Utförs av	Utfört/Sign	Anmärkning
4.9.1	Okulär besiktning			
4.9.2	Indatablad ifyllt för inläggning i underhållssystemet			
4.9.3	Skyltning / märkning			
4.9.4	Montage			
4.9.5	Prov av gasvakt (utlösning och larm)			
4.9.6	Kontroll av övriga vakter och signaler			
4.9.7	Isolationsprov med 1 kV-megger			
4.9.8	Kontroll av nollpunktsbildarens placering över oljegrop			
4.9.9	Leverantörsdokumentation (kontrollera att det är rätt dokument och rätt antal)			

Noteringar:

4.10 Nollpunktsmotstånd (-NM)		Littera:		
Nr	Prov	Utförs av	Utfört/Sign	Anmärkning
4.10.1	Okulär besiktning			
4.10.2	Indatablad ifyllt för inläggning i underhållssystemet			
4.10.3	Skyltning / märkning			
4.10.4	Montage			
4.10.5	Hjälpkontakter			
4.10.6	Värme och termostat i manöverdon			
4.10.7	Manöver/ Indikering (lokalt/fjärr) av motståndsbrytaren			
4.10.8	Lågspänningsprov (protokoll)			
4.10.9	Kontroll att motståndbrytare ligger kvar vid hjälpspänningsbortfall (mekanisk självhållning)			
4.10.10	Signal: utlöst temp-skydd			
4.10.11	Leverantörsdokumentation (kontrollera att det är rätt dokument och rätt antal)			

Noteringar:

4.11 Nollpunktsreaktor (-NX)		Littera:		
Nr	Prov	Utförs av	Utfört/Sign	Anmärkning
4.11.1	Okulär besiktning			
4.11.2	Indatablad ifyllt för inläggning i underhållssystemet			
4.11.3	Skyltning / märkning			
4.11.4	Montage			
4.11.5	Prov av gasvakt (utlösning och larm)			
4.11.6	Kontroll av övriga vakter och signaler			
4.11.7	Värme och termostat i manöverdon			
4.11.8	Manöver/ Indikering (lokalt/fjärr)			
4.11.9	Manöver från automatik (NX-aut.)			
4.11.10	Lågspänningsprov, samtliga inställningslägen (protokoll)			
4.11.11	Kontroll av reaktorns placering över oljegrop			
4.11.12	Leverantörsdokumentation (kontrollera att det är rätt dokument och rätt antal)			

Noteringar:

4.12 Kondensatorbatteri (EK)		Littera:		
Nr	Prov	Utförs av	Utfört/Sign	Anmärkning
4.12.1	Okulär besiktning			
4.12.2	Indatablad ifyllt för inläggning i underhållssystemet			
4.12.3	Skyltning / märkning			
4.12.4	Montage			
4.12.5	Jordning			
4.12.6	Lågspänningsprov (protokoll) (även med en enhet kortsluten för kontroll av osymmetri)			
4.12.7	Leverantörsdokumentation (kontrollera att det är rätt dokument och rätt antal)			

Noteringar:

4.13 Högspänningssäkring (-Y)		Littera:		
Nr	Prov	Utförs av	Utfört/Sign	Anmärkning
4.13.1	Funktionskontroll av utlösningsmekanismen			
4.13.2	Kontroll av säkringens märkström mot transformator storlek och fabrikantens rekommendation.			
4.13.3	Kontroll av slagstiftets riktning.			

Noteringar:

4.14 Högspänningskabel		Littera:		
Nr	Prov	Utförs av	Utfört/Sign	Anmärkning
4.14.1	Kabelns historia (hur den har förvarats från tillverkare tills den har blivit förlagd)			
4.14.2	Identifiering av kabelns faser i ”andra änden” (batterispänning 4,5 – 9 – 13 VDC kan användas)			
4.14.3	Kabelskärmar är anslutna till jord, skärmavledare finns vid jordning i ena änden. Skärm är återdragen genom kabelströmstransformator i förekommande fall			
4.14.4	Uppmätning av strömfördelning vid parallella kraftkabelförband			
4.14.5	Mantelprov (protokoll)			
4.14.6	Isolationsprov med 1 kV megger (protokoll) (alt. 5 kV megger om högspänningsprov ej utförs)			
4.14.7	Kablar genom väggar har tätats med brandklassad metod			
4.14.8	Kontroll att isoleringen inte har och inte kan skadas av ”vassa” oisolerade föremål/kanter vid kabelgenomföringar (genom väggar, in i ställverksutrymmen eller motsvarande)			
4.14.9	Leverantörsdokumentation (kontrollera att det är rätt dokument och rätt antal)			

Noteringar:

5. Hjälpsystem

5.1 Likströmssystem

Nr	Prov	Utförs av	Utfört/Sign	Anmärkning
5.1.1	Okulär besiktning. (föreskriftsenlig installation)			
5.1.2	Indatablad ifyllt för inläggning i underhållssystemet			
5.1.3	Skyltning / märkning			
5.1.4	Celler märkta enligt VTR02-05			
5.1.5	Laddningsutrustning, kontrollera inställning av : ☐ Hålladdningsspänning ☐ Snabbladdningsspänning ☐ Strömgräns ☐ Signalgräns för batterispänning			
5.1.6	Jordfelsövervakning: Högohmigt jordfel lägges på plus- och minussidan för kontroll av indikering och signal.			
5.1.7	Motorskydd: Driftströmmarna uppmäts och inställningarna samt i förekommande fall felsignalerna kontrolleras			
5.1.8	Kontroll av gruppcentral och nollspänningsreläer			
5.1.9	Kontroll av ventilation och fläkt för batterirum			
5.1.10	Kontroll av skyddsutrustning i batterirum			
5.1.11	Kontroll av förläggning av batterikabel (polseparerad)			
5.1.12	Kontroll av att likspänningsgrupper är separerade			
5.1.13	Kontroll ev. sub-uppdelning			
5.1.14	Mätning av växelström med tångamperemeter på plus- och minussidan för kontroll av att rippelström ej förekommer			
5.1.15	Kontroll av hålladdningstillstånd. Uppmätning av hålladdningsspänning totalt och för varje cell eller block av celler.			
5.1.16	Kontroll av syradensitet i varje cell			
5.1.16	Kapacitetsprov på batteri utfört. (protokoll) Urladdningsprov, som utförs på fulladdat batteri med 5-timmarsström i 5 timmar. Värden enligt VTR02-05 skall innehållas för att provet skall vara godkänt.			
5.1.18	Belastningsprofil skall kontrolleras på fulladdat batteri med i beställningen angiven belastningsprofil. (Utförs ej på batterier med beställt specificerat Ah-värde.) Värden enligt VTR02-05 skall innehållas. Urladdningsförloppet skall redovisas i kurvform och omfatta både ström och spänning			
5.1.19	Kontroll korrosion, läckage och elektrolytnivå			
5.1.20	Kontroll åtdragningsmoment hos polbultar			
5.1.21	Kontroll övergångsmotståndet i samtliga anslutningar			
5.1.22	Leverantörsdokumentation (kontrollera att det är rätt dokument och rätt antal)			

5.2 Växelströmssystem

Nr	Prov	Utförs av	Utfört/Sign	Anmärkning
5.2.1	Okulär besiktning. (föreskriftsenlig installation)			
5.2.2	Matning av växelströmscentral. Säkringarnas storlek resp. överströmsskyddens inställning kontrolleras.			
5.2.3	Funktionskontroll av överkopplingsautomatik (protokoll)			
5.2.4	Kontroll av växelriktare: ☐ Matning ☐ Nätsynk ☐ Överkopplingsswitch			
5.2.5	Kontroll av jordfelsbrytare inkl. signal			
5.2.6	Okulärkontroll av värme- och belysningsinstallation			
5.2.7	Kontroll att temperaturkrav uppfylls (framför allt i batterirum men även i övriga utrymmen)			
5.2.8	Leverantörsdokumentation (kontrollera att det är rätt dokument och rätt antal)			

Noteringar:

5.3 Brandskydd/Brandlarm/Inbrottslarm

Nr	Prov	Utförs av	Utfört/Sign	Anmärkning
5.3.1	Okulär besiktning			
5.3.2	Märkdata och tillverkningsnummer			
5.3.3	Skyltning / märkning			
5.3.4	Funktionskontroll			
5.3.5	Signal till DC / Larmcentral			

Noteringar:

6. Kontrollanläggning

6.1 Allmän montagekontroll

Nr	Prov	Utförs av	Utfört/Sign	Anmärkning
6.1.1	Kontroll av apparatbestyckning mot apparatlista			
6.1.2	Kontroll att skåp, lådor, apparater, stativ och övriga metalldelar är jordade enligt montageanvisning			
6.1.3	Kontroll att teleutrustning, antenn, master, m. m. är jordade enligt montageanvisning			
6.1.4	Kontroll av kabelförläggning, kablar på stegar separat fästa/najade			
6.1.5	Kontroll av att skärmar för kraft- och kablar är jordade			
6.1.6	Kontroll av tätningar och mekaniska skydd			
6.1.7	Kontroll av skyltning (även att skyltar för *Arbete pågår*, *Arbete med spänning* finns)			
6.1.8	Kontroll av att kablar, kabelparter och reservparter är märkta och åtkomliga			
6.1.9	Reservparter är isolerade med ändhylsa			
6.1.10	Polaritetskontroll och etappvis spänningssättning av hjälpkretsar utförd			
6.1.11	Montage- och funktionskontroll av hjälpreläer och hjälpkretsar mot kretsschema och tabeller s.k. ”grönritning”			
6.1.12	Kontroll att biledningar sitter fast och är rätt kopplade			

Noteringar:

6.2 Stationsbuss/Processbuss

Nr	Prov	Utförs av	Utfört/Sign	Anmärkning
6.2.1	Kontroll att kopplingar/anslutningar är hela och fungerar			
6.2.2	Kontroll av funktionalitet inkl. korrekt adressering			
6.2.3	Kontroll av tidsfördröjning för typiska meddelanden			
6.2.4	Kontroll av tidsynk (alla enheter omfattas) Sommartid skall ställas in automatiskt.			
6.2.5	Switchar, servrar och klienter inkopplade enligt specifikation och systemlayout			
6.2.6	Kontroll av övervakning/signaler			
6.2.7	Kontroll av funktion med enhet ”utslagen”			
6.2.8	Prestandaprov			
6.2.9	Leverantörsdokumentation (kontrollera att det är rätt dokument och rätt antal och att ev. SCD-fil är korrekt och läsbar i beställarens verktyg)			

Noteringar:

6.3 Reläskydd	Littera (och ev. SUB-tillhörighet):			
Nr	**Prov**	**Utförs av**	**Utfört/Sign**	**Anmärkning**
6.3.1	Kontroll av provdon: ☐ Samtliga strömmar, spänningar, utlösningar, m. m. är dragna via provdonet ☐ Rätt kontakttyp används till resp. funktion ☐ Lossa täcklisterna på framsidan och kontrollera att kortslutningsbleck för strömkretsar är korrekt monterade			
6.3.2	Kontroll att samtliga biledningar sitter fast och är rätt kopplade (identifikationskontroll, grönritning)			
6.3.3	Kontroll av märkdata på ingående apparater inkl. utlösningskombination			
6.3.4	Kontroll av märkning			
6.3.5	Kontroll av montering			
6.3.6	Kontroll att samtliga anslutningar är åtdragna			
6.3.7	Kontroll av ström- och spänningsriktning (vid riktningsberoende skydd)			
6.3.8	Kontroll att optokopplingar eller motsv. är hela och fungerar			
6.3.9	Injustering av inställningsvärden: Ström, spänning, tid, impedans, m. m. enligt selektivplan Verifiering av reläskyddens karakteristik (protokoll)			
6.3.10	Prov av samtliga funktioner: ☐ Utlösning ☐ Blockeringar ☐ Starter (ÅI-start…) ☐ Larmer/övervakning			
6.3.11	Prov av ev. fjärrutlösning, reläskyddskommunikation, längsdiffkommunikation			
6.3.12	Prov att utlösningsimpuls löser rätt objekt			
6.3.13	Kontroll av eventuell avställningsenhet			
6.3.14	Kontroll av tripkrets-övervakning			
6.3.15	Kontroll av störnings och händelseregistrering			
6.3.16	Kontroll av tidsynk Sommartid skall ställas in automatiskt.			
6.3.17	Kontroll att kommunicerande utrustning fungerar till avsedd plats STINA			
6.3.18	Indatablad ifyllt för inläggning i underhållssystemet			
6.3.19	Leverantörsdokumentation (kontrollera att det är rätt dokument och rätt antal)			

Noteringar:

6.4 Ljusbågsvakt		Littera:		
Nr	Prov	Utförs av	Utfört/Sign	Anmärkning
6.4.1	Kontroll av provdon (rätt kontakttyp till resp. funktion)			
6.4.2	Kontroll att samtliga optokopplare, optofibrer är hela och rätt monterade (skall vara skyddade mot mekanisk åverkan).			
6.4.3	Kontroll att samtliga biledningar/kabelparter sitter fast och att plintar är åtdragna			
6.4.4	Prov av funktioner (samtliga sensorer): ☐ Utlösning ☐ Frigivningar ☐ Blockeringar ☐ Detektorer ☐ Larmer			
6.4.5	Kontroll att utlösningsimpulser löser rätt objekt vid varje driftläggning			
6.4.6	Injustering av inställningsvärden (ström-frigivning)			
6.4.7	Leverantörsdokumentation (kontrollera att det är rätt dokument och rätt antal)			

Noteringar:

## 6.5 Mätning/Instrument		Littera:		
Nr	Prov	Utförs av	Utfört/Sign	Anmärkning
6.5.1	Kontroll av skalfaktor på instrument och mätvärdesomvandlare med hänsyn till anslutna mättransformatorer			
6.5.2	Okulär kontroll av inkoppling instrument/mätvärdesomvandlare			
6.5.3	Okulär kontroll av inkoppling debiterings/kontrollmätning			
6.5.4	Okulär kontroll av inkoppling elkvalitetsmätare			
6.5.5	Kontroll av signaler			
6.5.6	Kontroll av hjälpspänningsmatning			
6.5.7	Kontroll av ström- och spänningsinstrument i samband med bördamätning av mättransformator			
6.5.8	Prova instrument för lägesindikering			

Noteringar:

6.6 Debiteringsmätning		Littera:		
Nr	Prov	Utförs av	Utfört/Sign	Anmärkning
6.6.1	Kontakta mätinsamlingen (010 4730690) innan åtgärd			
6.6.2	Kontrollera modem och antenn samt att kommunikation fungerar (med mätinsamling 010 4730690) innan anläggningen tas i drift			
6.6.3	Kontrollera att hjälpspänning finns fram till energimätaren			
6.6.4	Kontrollera att mätspänning finns i alla 3 faser fram till energimätaren			
6.6.5	Kontrollera att samtliga strömkretsar är anslutna till energimätaren (ingen krets är öppen) och att biledningar sitter fast			
6.6.6	Kontrollera att strömriktning är rätt ansluten till energimätaren, aktiv förbrukning skall registreras på register 1 på mätaren, detta ger ström in på 1, 4 och 7 på mätaren.			
6.6.7	Vid konstkopplade mätare kontrollera särskilt att strömmen i mittfasen är rätt inkopplad			
6.6.8	Kontrollera att ström och spänning för samma fas ligger ihop (U1 & I1, U2 & I2, U3 & I3)			
6.6.9	Kontrollera att cos fi är rimligt			
6.6.10	Kontrollera samtliga larmfunktioner från energimätaren			
6.6.11	Kontroll av märkning/märkskyltar			
6.6.12	Kontroll av montering			
6.6.13	Kontroll att samtliga anslutningar är åtdragna			
6.6.14	Kontroll av spänningsval			
6.6.15	Om pulsutgångar används kontrollera att dom fungerar			
6.6.16	Om pulsingångar är inkopplade kontrollera att dom fungerar och lämna ev. pulsvärde till mätinsamlingen			
6.6.17	Kontrollera att energiupplösningen på registren och timvärden (lastprofil) är korrekta för kategorin (antal, heltal och decimaler)			
6.6.18	Gör okulär kontroll av omsättningar för ström och spänningstransformatorer, notera om det ej är läsbart			
6.6.19	Efter åtgärd/provning m. m. kontakta mätinsamlingen och utför insamlingskontroll (kontrollera uttag mot föregående timvärde)			
6.6.20	Om mätarkonfiguration ändrats skall den nya sparas ned och lämnas in under anläggningsmappen			
6.6.21	Upprätta dokumentationen. Rödändringar skall införas i kretsschema/tabeller och originaldokumentationen uppdateras. Nytt renritat exemplar skall distribueras till stationen och bladas in i stationspärm snarast.			
6.6.22	Utför kontroll av mätsystem enligt SWEDACS föreskrifter och enligt särskilda krav från Vattenfall Eldistribution (separat protokoll)			

Noteringar:

6.7 Felsignaler

Nr	Prov	Utförs av	Utfört/Sign	Anmärkning
6.7.1	Kontroll av övervakning på signalslingorna och internt fel			
6.7.2	Prova samtliga larmpunkter med fördröjning och ev. gruppering enl. specifikation och hela vägen: Kontakt – signalterminal/central/stations-HMI – driftcentral – reservlarm			
6.7.3	Kontroll att signal avges vid ny signal inom samma grupp			
6.7.4	Leverantörsdokumentation (kontrollera att det är rätt dokument och rätt antal)			

Noteringar:

6.8 Störnings- och händelseregistrering

Nr	Prov	Utförs av	Utfört/Sign	Anmärkning
6.8.1	Kontroll av funktion			
6.8.2	Kontroll att mätvärden har rätt skalning, samt att texter är rätt.			
6,8.3	Kontroll av övervakning			
6.8.4	Störningsfiler lagras på avsedd plats lokalt i stationen (filer i RTU)			
6.8.5	Kontroll att kommunicerande utrustning fungerar till avsedd plats STINA			
6.8.6	Leverantörsdokumentation (kontrollera att det är rätt dokument och rätt antal)			

Noteringar:

## 6.9 Automatik	Littera:

- ☐ PS (Parallellning/Spänningssättningsdon)
- ☐ FPS (Fasningsdon)
- ☐ ÅI-aut. (Återinkopplingsautomatik)
- ☐ LK-aut. (Spänningsreglering)
- ☐ Uo-aut. (Nollspänningsautomatik)
- ☐ NM-aut. (Nollpunktsautomatik)
- ☐ NX-aut. (Avstämningsautomatik)
- ☐ ÖK-aut. (Överkopplingsautomatik)
- ☐ AFK (Automatisk förbrukningsfrånkoppling)
- ☐ EXA (Extremspänningsautomatik)

- ☐ ____

Nr	Prov	Utförs av	Utfört/Sign	Anmärkning
6.9.1	PLC-realiserade automatiker provas i en FAT (= fabrikstest) före montage (prov protokollförs)			
6.9.2	Kontroll av ingående apparater, hjälpspänningsmatning, larmer			
6.9.3	Injustering av inställningsvärden: ström, spänning, tid m.m. (protokoll)			
6.9.4	Prov av samtliga funktioner enligt spec. Om möjligt som fullskaleprov (vissa prov protokollförs) ☐ Utlösning ☐ Blockeringar ☐ Starter ☐ Larmer/övervakning			
6.9.5	Kontroll av eventuell avställningsenhet			
6.9.6	Indatablad ifyllt för inläggning i underhållssystemet			
6.9.7	Leverantörsdokumentation (kontrollera att det är rätt dokument och rätt antal)			

Noteringar:

6.10 Manöver/Indikering/Blockering/Förregling/Val

Realiserade i konventionell reläteknik med kontrolltavla eller i PLC-teknik med en stationsdator

Nr	Prov	Utförs av	Utfört/Sign	Anmärkning
6.10.1	Alla PLC-realiserade funktioner provas i en FAT (= fabrikstest) före montage (vissa prov protokollförs)			
6.10.2	Manöver och indikering provas från Driftcentral (om möjligt som fullskaleprov)			
6.10.3	Manöver och indikering provas från Stations-HMI (som fullskaleprov)			
6.10.4	Manöver och indikering provas från Reservstyrning (som fullskaleprov)			
6.10.3	Kontroll av att spegelreläer och valutrustning följer brytare och frånskiljare. Valutrustning funktionsprovas med samtliga förekommande driftläggningar. Kontroll av signal spegelrelä felläge och avvikande läge. (om möjligt som fullskaleprov)			
6.10.4	Kontroll av blink-/fast sken-funktion på eventuell kontrolltavla			
6.10.5	Prov av förreglingar och blockeringar funktion enl. spec. (om möjligt som fullskaleprov)			

Noteringar:

6.11 Fjärrkontroll, stations-HMI och kommunikation

<table>
<tr><th>Nr</th><th colspan="2">Prov</th><th>Utförs av</th><th>Utfört/Sign</th><th>Anmärkning</th></tr>
<tr><td>6.11.1</td><td colspan="2">Godkänd FAT</td><td></td><td></td><td></td></tr>
<tr><td>6.11.2</td><td colspan="2">Godkänd SAT</td><td></td><td></td><td></td></tr>
<tr><td>6.11.3</td><td rowspan="3">Driftcentral, kontroll och prov enl. signallista av:</td><td>Analoga mätvärden (protokoll)</td><td></td><td></td><td></td></tr>
<tr><td>6.11.4</td><td>Manöver/indikering (protokoll)</td><td></td><td></td><td></td></tr>
<tr><td>6.11.5</td><td>Felsignaler (protokoll)</td><td></td><td></td><td></td></tr>
<tr><td>6.11.6</td><td rowspan="3">Stations-HMI, kontroll och prov enl. signallista av:</td><td>Analoga mätvärden (protokoll)</td><td></td><td></td><td></td></tr>
<tr><td>6.11.7</td><td>Manöver/indikering (protokoll)</td><td></td><td></td><td></td></tr>
<tr><td>6.11.8</td><td>Felsignaler (protokoll)</td><td></td><td></td><td></td></tr>
<tr><td>6.11.9</td><td colspan="2">Kontroll av manöverrättighet DFO Fjärr/När/Reservmanöver</td><td></td><td></td><td></td></tr>
<tr><td>6.11.10</td><td colspan="2">Kontroll och prov av Reservlarmfunktion</td><td></td><td></td><td></td></tr>
<tr><td>6.11.11</td><td colspan="2">Kontroll av kommunikation (fjärrkontroll)</td><td></td><td></td><td></td></tr>
<tr><td>6.11.12</td><td colspan="2">Kontroll och prov av kommunikation (tele)</td><td></td><td></td><td></td></tr>
<tr><td>6.11.13</td><td colspan="2">Kontroll av bilder i stations-HMI</td><td></td><td></td><td></td></tr>
<tr><td>6.11.14</td><td colspan="2">Kontroll av larmgränser i DC</td><td></td><td></td><td></td></tr>
<tr><td>6.11.15</td><td colspan="2">Kontroll av Stations-HMI signal, omstart m. m.</td><td></td><td></td><td></td></tr>
<tr><td>6.11.16</td><td colspan="2">Kontroll tidsynk</td><td></td><td></td><td></td></tr>
<tr><td>6.11.17</td><td colspan="2">SCD-fil</td><td></td><td></td><td></td></tr>
<tr><td>6.11.18</td><td colspan="2">Service-PC
Samtliga programvaror inkl. applikationer inlagda</td><td></td><td></td><td></td></tr>
<tr><td>6.11.19</td><td colspan="2">Leverantörsdokumentation
(kontrollera att det är rätt dokument och rätt antal)</td><td></td><td></td><td></td></tr>
</table>

Noteringar:

7. Idrifttagningsprov

7.1 Slutprov före spänningssättning

Besiktning av alla kontrollskåp och ställverk

Nr	Prov	Utförs av	Utfört/Sign	Anmärkning
7.1.1	Kontrollera att inga strömtransformatorkretsar är öppna och anslutningar är åtdragna			
7.1.2	Kontrollera att inga arbetsjordningar, kortslutningar eller obehöriga föremål glömts kvar i närheten av spänningsförande delar.			
7.1.3	Kontrollera att isolationsporslin är rengjorda och hela			
7.1.4	Kontrollera att bultförband i skenskarvar och kabelanslutningar är dragna			
7.1.5	Kontrollera att alla reläskydd och utlösningsvägar är intakta			
7.1.6	Kontrollera ev. Längsdiffkommunikation, reläskyddskommunikation och fjärrutlösning är i drift			
7.1.7	Utlösningsprov från samtliga skydd			
7.1.8	Återställ alla indikering/flaggor och signaler i kontrollanläggningen			
7.1.9	Radera alla störningsfiler i skydden som härrör från provning			
7.1.10	Kontrollera att automatiker är ur drift			

Noteringar:

7.2 Slutprov efter spänningssättning

Nr	Prov	Utförs av	Utfört/Sign	Anmärkning
7.2.1	Efter spänningssättning kontrollera att allt verkar normalt i ställverket (ev. missljud el. lukt)			
7.2.2	För krafttransformator. Kontrollera: ☐ Att fläkt och pumpautomatik fungerar ☐ Fasföljd och faslikhet mot övrigt nät (även lokalkraft) ☐ Spänningsändring vid lindningskopplarkörning ☐ Temperaturhöjning för olja och lindning ☐ Lufta oljan efter att krafttransformator varit spänningssatt utan last i 1 dygn. ☐ Kontrollera strömfördelning i kraftkablar med belastad transformator.			
7.2.3	För spänningstransformator: ☐ Kontrollera att sekundärspänningar är de tänkta ☐ Mät nollpunktsspänning ☐ Kontrollera faslikhet mot andra spänningssatser (protokoll)			
7.2.4	Kontroll av att instrument och mätvärden i station och DC visar rimliga värden och riktningar			
7.2.5	Kontroll av mätare, debitering och kontroll (rotation, utslag)			
7.2.6	Kontroll av ström och spänning till reläskyddsingångar (protokoll)			
7.2.7	Kontroll av cirkulations- och differentialströmmar i differentialskydd och samlingsskeneskydd (protokoll)			
7.2.8	Kontroll av nollpunktsspänning till riktade jordfelsskydd och nollpunktsspänningsskydd (protokoll)			
7.2.9	Riktningsprov med belastningsström eller primärt jordfel på riktningskännande reläskydd			
7.2.10	Injustering av värde för spänningsreglering			
7.2.11	Automatiker tas i drift av DC			

Noteringar:

VTR02-09 Bilaga 2 – Exempel SAT-program

A	**Signalprov hjälpkraft och allmänt**	Utfört	Godk
A1	Anbringa jordfel på LS samtliga system, kontrollera signaler HMI, reservlarm, DC		
A2	Avlägsna LS-säkring samtliga system (LS-separation, Sub1 resp Sub2) kontrollera signaler HMI, reservlarm, DC		
A3	Simulera larm från likriktare och ev växelriktare, kontrollera signaler HMI, reservlarm, DC		
A4	Kontrollera batteriövervakning map spänning, kontrollera signaler HMI, reservlarm, DC		
A5	Utför utlösningsprov på samtliga LS-system, kontrollera funktionalitet		
A6	Kontrollera överkopplingsautomatik lokalkraft, simulera avbrott på matning, kontrollera funktion samt signaler HMI, reservlarm, DC		
A7	Simulera Brand resp Inbrott, kontrollera signaler HMI, reservlarm, DC		
A8	Kontrollera övriga allmänna signaler och indikeringar enligt signallista (Nödlarm, GPS, DFO m fl) till HMI, reservlarm och DC		
A9	Kontrollera att larmklockor endast ringer i läge ”När” och ”Reservmanöver”		
A	**Signalprov objekt; brytare, jordningsfrånskiljare och spänningstrafo m fl**		
A10	Simulera signaler från brytare -S, kontrollera signaler HMI, reservlarm, DC		
A11	Kontrollera på någon brytare att manöver blockeras vid ”ospänd fjäder”		
A12	Simulera signaler från jordningsfrånskiljare –JxF, kontrollera signaler HMI, reservlarm och DC		
A13	Injicera spänning i resp trefasgrupp, ta bort en fas, kontrollera signaler HMI, reservlarm och DC		
A	**Signalprov objekt transformator**		
A14	Simulera signaler från transformator enligt signallista, kontrollera signaler HMI, reservlarm och DC		
A	**Signalprov objekt nollpunktsreaktor och motstånd**		
A15	Simulera signaler från nollpunktsreaktor och motstånd enligt signallista, kontrollera signaler HMI, reservlarm och DC		
A	**Signalprov objekt kontrollutrustning/terminal**		
A16	Simulera signal IRF från samtliga terminaler, kontrollera signaler HMI, reservlarm och DC		
A17	Simulera signaler från resp objekts skydds-, automatik-, signal- och fackterminal enligt signallista , kontrollera signaler HMI, reservlarm och DC		
A18	Simulera mätvärden, kontrollera mätvärde och effektriktning till HMI och DC		

B	**Manöverprov HMI (ink blockering/förregling)**	Utfört	Godk
B1	Kontrollera att manöver endast kan utföras med DFO i läge ”När”, ej i läge ”fjärr” eller ”reservmanöver”		
B2	Manövrera brytare -S ”till” resp ”från” kontrollera indikering		
B3	Manövrera brytare –A-F-S ”Blockerad” resp ”Deblockerad” kontrollera indikering		
B4	Manövrera –JxF ”sluten” resp ”öppen” kontrollera indikering. Brytare ska vara blockerad, för jordningsfrånskiljare på samlingsskena ska samtliga brytare vara blockerade		
B5	-A-F-S ”deblockerad”, manövrera –JxF slut (ska ej gå)		
B6	-A-F-S eller –B-F-S ”till”, manövrera –JxF slut (ska ej gå)		
B7	Manövrera brytare via (F)PS, kontrollera funktionalitet		
B8	Manövrera ”Rak manöver”, kontrollera automatisk återgång till FPS. Kontrollera att Rak Manöver måste väljas för varje brytarmanöver		
B9	Manövrera ”FPS annullera”		
B10	-JxF ”sluten”, manövrera –A-F-S ”deblockera” (ska ej gå)		
B11	-JxF ”sluten”, manövrera –A-F-S ”till” (ska ej gå)		
B12	Simulera spänning, manövrera –JxF slut (ska ej gå)		
B13	Simulera utl säkring, manövrera –JxF slut (ska ej gå)		
B14	Manövrera SÅi ”ur drift(i drift”, kontrollera indikering		
B15	Manövrera FÅi ”ur drift/i drift”, kontrollera indikering		
B16	Kondensatorbatteri: Kontrollera att tillslag av brytare endast kan utföras vid ”urladdat batteri”		
B17	Transformator: Kontrollera att tillslag av brytare inte kan ske vid ”Inkopplingsförbud”		
B18	Spänningsreglering: Manövrera spänningsreglering ”Hand/Aut” kontrollera indikering		
B19	Spänningsreglering: Manövrera öka/minska, kontrollera att det endast går i läge ”Hand”		
B20	Spänningsreglering: kontrollera blockeringsnivå och funktion (öka endast vid låg spänning resp minska endast vid hög spänning)		
B21	NX-aut: Manövrera ”Hand/Aut” kontrollera indikering		
B22	NX-aut: Manövrera öka/minska, kontrollera att det endast går i läge ”Hand”		
B	**Manöverprov reservmanöver**		
B23	Kontrollera att manöver endast kan utföras i DFO läge ”Reservmanöver” ej i läge ”När” eller ”fjärr”		
B24	Manövrera brytare -S ”till” resp ”från” kontrollera indikering		
B25	Manövrera brytare –A-F-S ”Blockerad” resp ”Deblockerad” kontrollera indikering		
B26	Manövrera –JxF ”sluten” resp ”öppen” kontrollera indikering		
B27	Transformator: Kontrollera att tillslag av brytare inte kan ske vid ”Inkopplingsförbud”		
B28	Spänningsreglering: Manövrera ”Hand/Aut” kontrollera indikering		
B29	Spänningsreglering: Manövrera öka/minska, kontrollera att det endast går i läge ”Hand”		
B30	NX-aut: Manövrera ”Hand/Aut” kontrollera indikering		
B31	NX-aut: Manövrera öka/minska, kontrollera att det endast går i läge ”Hand”		

B	**Manöverprov DC**	Utfört	Godk
B32	Utförs enl separat Punkt till Punkt-plan		
B33	Kontrollera att manöver endast kan utföras med DFO i läge ”Fjärr” ej i läge ”När” eller ”Reservmanöver”		
C	**Ledning: Utlösningsprov ZS med SÅi+FÅi (vid sub-uppdelning: utförs från sub1 resp sub2 separat/säkringar för resp sub urtagna)**		
C1	Slå till brytare		
C2	Simulera fel på ledning ZS (samtliga steg, olika faskombinationer)		
C3	Kontrollera att endast felaktig lednings brytare löser (-F-S)		
C4	Kontrollera att Såi slår till brytare		
C5	Simulera fel på ledning ZS (kvarstående fel)		
C6	Kontrollera att Fåi slår till brytare		
C7	Kontrollera händelser och indikeringar till HMI och DC		
C8	Kontrollera ev RSK-SS		
C9	Kontrollera BFS start för -F-S		
C10	Tvåbrytare: Slå till båda brytare, simulera fel med Såi och simulera ett nytt fel innan –B-F-S går till, kontrollera att endast –A-F-S återinkopplas		
C11	Tvåbrytare: Slå endast till –A-F-S, simulera fel och kontrollera att endast –A-F-S återinkopplas		
C12	Tvåbrytare: Slå endast till –B-F-S, simulera fel och kontrollera att endast –B-F-S återinkopplas		
C	**Ledning: Utlösningsprov JS/NUS med SÅi+FÅi (vid sub-uppdelning: utförs från sub1 resp sub2 separat/säkringar för resp sub urtagna)**		
C13	Slå till brytare		
C14	Simulera fel på ledning (samtliga steg)		
C15	Kontrollera att endast felaktig lednings brytare löser (-F-S)		
C16	Kontrollera att Såi slår till brytare		
C17	Simulera fel på ledning (kvarstående fel)		
C18	Kontrollera att Fåi slår till brytare		
C19	Kontrollera händelser och indikeringar till HMI och DC		
C20	Kontrollera ev RSK-SS		
C21	Kontrollera BFS start för -F-S		
C	**Ledning: Utlösningsprov LDS med SÅi+FÅi (vid sub-uppdelning: utförs från sub1 resp sub2 separat/säkringar för resp sub urtagna)**		
C22	Slå till brytare		
C23	Injicera ström, ta ur fiber, kontrollera att skyddet blockeras och signal till HMI, reservlarm och DC		
C24	Simulera fel på ledning LDS		
C23	Kontrollera att endast felaktig lednings brytare löser (-F-S)		
C24	Kontrollera att Såi slår till brytare		
C25	Simulera fel på ledning (kvarstående fel)		
C26	Kontrollera att Fåi slår till brytare		
C24	Kontrollera händelser och indikeringar till HMI och DC		
C26	Kontrollera BFS start för -F-S		

D	**Kondensator: Utlösningsprov I> (vid sub-uppdelning: utförs från sub1 resp sub2 separat/säkringar för resp sub urtagna)**	Utfört	Godk
D1	Slå till samtliga brytare		
D2	Simulera utlösning via I>		
D3	Kontrollera att endast felaktigt objekts brytare löser (-S)		
D4	Kontrollera händelser och indikeringar till HMI och DC		
D5	Kontrollera BFS start för -S		
D	**Kondensator: Utlösningsprov I>> (vid sub-uppdelning: utförs från sub1 resp sub2 separat/säkringar för resp sub urtagna)**		
D6	Slå till samtliga brytare		
D7	Simulera utlösning via I>>		
D8	Kontrollera att endast felaktigt objekts brytare löser (-S)		
D9	Kontrollera händelser och indikeringar till HMI och DC		
D10	Kontrollera BFS start för -S		
D	**Kondensator: Utlösningsprov JS (utförs från sub1 resp sub2 separat/säkringar för resp sub urtagna)**		
D11	Slå till samtliga brytare		
D12	Simulera utlösning via JS/NUS		
D13	Kontrollera att endast felaktigt objekts brytare löser (-S)		
D14	Kontrollera händelser och indikeringar till HMI och DC		
D15	Kontrollera BFS start för -S		
D	**Kondensator: Utlösningsprov obalans (EKx-IT0)**		
D16	Slå till samtliga brytare		
D17	Simulera utlösning via obalans		
D18	Kontrollera att endast felaktigt objekts brytare löser (-S)		
D19	Kontrollera händelser och indikeringar till HMI och DC		
D20	Kontrollera BFS start för-S		
E	**Transformator: Utlösningsprov DS**		
E1	Slå till samtliga brytare		
E2	Simulera utlösning via DS		
E3	Kontrollera att endast felaktigt objekts brytare löser (-S upp/nedsida)		
E4	Kontrollera Inkopplingsförbud		
E5	Kontrollera händelser och indikeringar till HMI och DC		
E6	Kontrollera BFS start för -S (upp/nedsida)		
E	**Transformator: Utlösningsprov JDS**		
E7	Slå till samtliga brytare		
E8	Simulera utlösning via JDS		
E9	Kontrollera att endast felaktigt objekts brytare löser (-S) (upp/nedsida)		
E10	Kontrollera Inkopplingsförbud		
E11	Kontrollera händelser och indikeringar till HMI och DC		
E12	Kontrollera BFS start för -S (upp/nedsida)		

E	**Transformator: Utlösningsprov vakter**	Utfört	Godk
E13	Slå till samtliga brytare		
E14	Simulera utlösning via samtliga vakter		
E15	Kontrollera att endast felaktigt objekts brytare löser (-S upp/nedsida)		
E16	Kontrollera Inkopplingsförbud		
E17	Kontrollera händelser och indikeringar till HMI och DC		
E18	Kontrollera BFS start för både –A-F-S och –B-F-S (upp/nedsida)		
E	**Transformator: Utlösningsprov ZS/I> (vid sub-uppdelning: utförs från sub1 resp sub2 separat/säkringar för resp sub urtagna)**		
E19	Slå till samtliga brytare		
E20	Simulera utlösning via ZS /I>(samtliga steg, olika faskombinationer)		
E21	Kontrollera att endast felaktigt objekts brytare löser (-S upp/nedsida)		
E22	Kontrollera händelser och indikeringar till HMI och DC		
E23	Kontrollera BFS start för -S (upp/nedsida)		
E	**Transformator: Utlösningsprov JS/NIS (vid sub-uppdelning: utförs från sub1 resp sub2 separat/säkringar för resp sub urtagna)**		
E24	Slå till samtliga brytare		
E25	Simulera utlösning via JS/NIS		
E26	Kontrollera att endast felaktigt objekts brytare löser (-S upp/nedsida)		
E27	Kontrollera händelser och indikeringar till HMI och DC		
E28	Kontrollera BFS start för –S (upp/nedsida)		
F	**Utlösningsprov BFS**		
F1	Slå till samtliga brytare		
F2	Ta bort utlösning till -S		
F3	Simulera utlösning från skyddsfunktion ZS eller JS eller annat		
F4	Kontrollera att samtliga –S anslutna till skena med felaktig brytare löser. För tvåbrytafack: kontrollera fackets ”tvilling-S” löser		
F5	Kontrollera ev BFS Retrip		
F6	Ledning: Kontrollera att Åi blockeras		
F7	Kontrollera händelser och indikeringar till HMI och DC		
G	**Utlösningsprov Uo-auto**		
G1	Slå till samtliga brytare		
G2	Simulera driftspänning, sänk till under funktionsvärde,		
G3	Kontrollera att rätt brytare löser (-S)		
G4	Ledning: Kontrollera att Åi inte startas		
G5	Kontrollera att BFS inte startas		
G6	Kontrollera händelser och indikeringar till HMI och DC		
H	**Samlingsskena utlösningsprov Samlingsskeneskydd**		
H1	Slå till samtliga brytare		
H2	Simulera ”öppen strömkrets”, kontrollera signal till HMI, reservlarm och DC		
H3	Simulera utlösning via SS i något fack		
H4	Kontrollera att endast felaktigt objekts brytare löser (samtliga -S)		
H5	Kontrollera händelser och indikeringar till HMI och DC		
H6	Kontrollera BFS start för resp samlingsskena –A-F-S resp –B-F-S		

H	**Samlingsskena/fack utlösningsprov Ljusbågsvakt**	Utfört	Godk
H7	Slå till samtliga brytare		
H8	Simulera ljusbåge via något fack, kontrollera att felaktigt objekts brytare löser (samtliga -S)		
H9	Kontrollera att endast felaktigt objekts brytare löser (samtliga -S)		
H10	Kontrollera inkopplingsförbud		
H11	Kontrollera händelser och indikeringar till HMI och DC		
I	**Kommunikation STINA, stationsbuss mm**		
I1	Hämta fil från några fack till Vattenfalls störningsanalysfunktion/enhet (olika typ/fabrikat)		
I2	Kontrollera tidsynk till samtliga utrustningar		
I3	Töm samtliga störningsskrivare på störningsfiler från provning		
I4	Kontrollera att Vattenfall Elkvalitetsfunktion/enhet kan kontakta elkvalitetsutrustningen		
I5	Kontrollera att Vattenfall Mätinsamlingsfunktion/enhet kan kontakta energimätare		
I6	Kontrollera stationsbuss-HSR, ta bort fiber kontrollera händelser och indikeringar till HMI och DC		
I7	Kontrollera övervakning RTU/stations-HMI kontrollera händelser och indikeringar till HMI, reservlarm och DC		
I8	Kontrollera att kontakt kan upprättas med samtliga utrustningar från service-PC		