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ADVERTÊNCIA:

Numerical Distance Protection

Principles and Applications

Gerhard Ziegler
Gustav Steynberg

Numerical Distance Protection – Course program

Part	1: Fundamentals and operation principles	26-11	9:30-11:00 Break 11:30-13 Lunch
Part	2: Teleprotection using distance relays		14:30-15:30 Break
Part	3: Power swing blocking/tripping (out-of-step protection)		16:00-17:00
Part	4: Distance protection of parallel lines	27-11	8:00-9:30
Part	5: Distance protection of series-compensated lines		9:30-10:00 Break
Part	6: Distance protection of three-terminal and tapped lines		10:30-11:15
Part	7: Auto-reclosure (ARC)		11:15-11:45
Part	8: Setting of distance protection		11:45-13:00 Lunch
Part	9: Current and voltage transformer requirements		14:30-16:00
Part	10: Connection, commissioning and maintenance		16:30-17:00
Part	10: Distance protection in the transmission system	28-11	8:00-9:00
Part	12: International practices and recent trends		9:00-9:30
Part	13: Modern numerical relay design and integrated functions		9:30-10:00 Break
Part	14: Integration in Substation automation with IEC 61850		10:30-12:00
Final Discussion			12:00-13:00 End

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Modern Relay Design
and
Integrated Functions

Power System Protection:
Relay design

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Uniform Design Trend

SIPROTEC4 Relay Series

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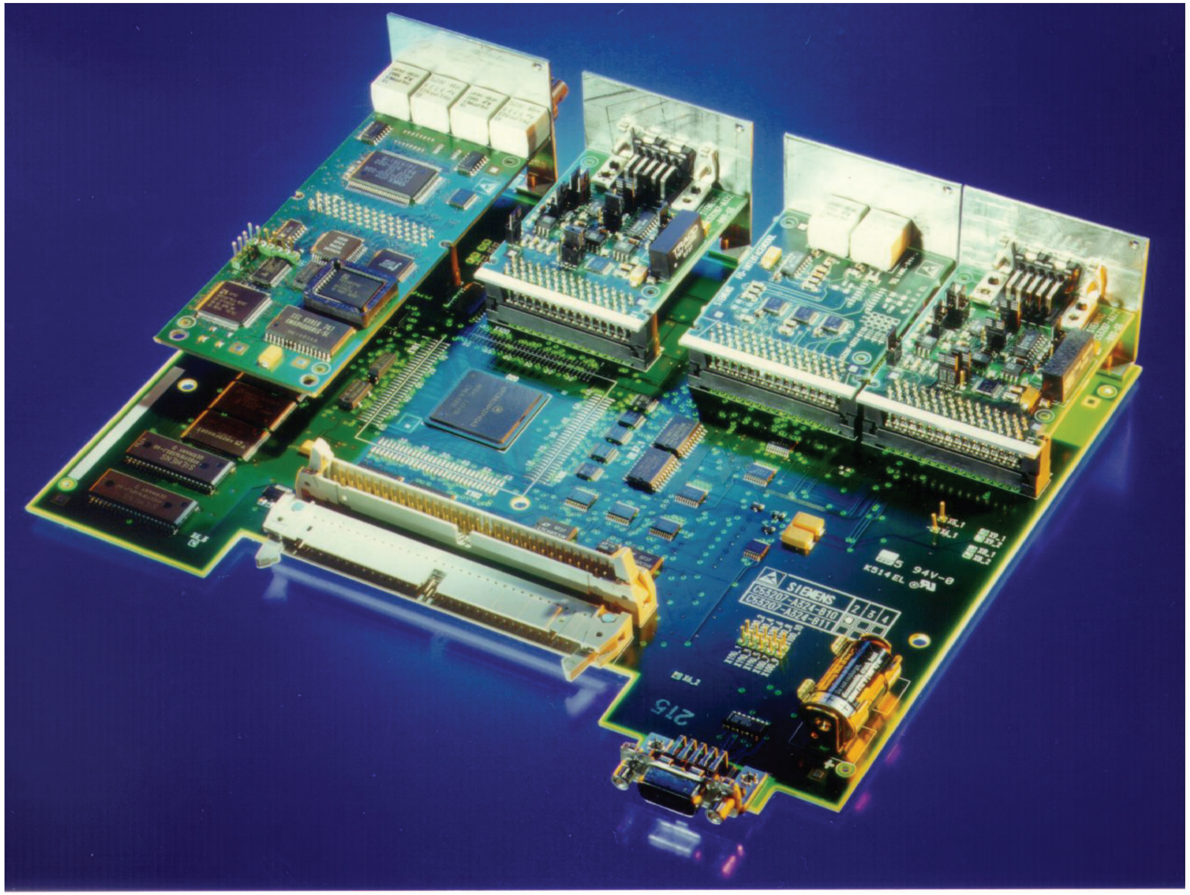
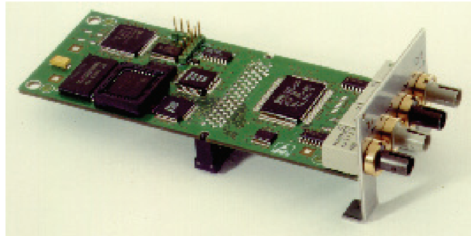
Modern IED processing and communication board



O.F. Double ring



Exchangeable communication modules

Wired IEC61850 Ethernet 100 Mbit

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Development of processing hardware

Begin of delivery	Relay generation	Memories RAM/EPROM	Bus width	Clock frequency	Processing power
1992	SIPROTEC 3	256/512 k	16 bit	16 MHz	1.0 MIPS
2000	SIPROTEC 4	512k/4MB + 4MB D-RAM	32 bit	80 MHz	35 MIPS

SIPROTEC 4 Data aquisition

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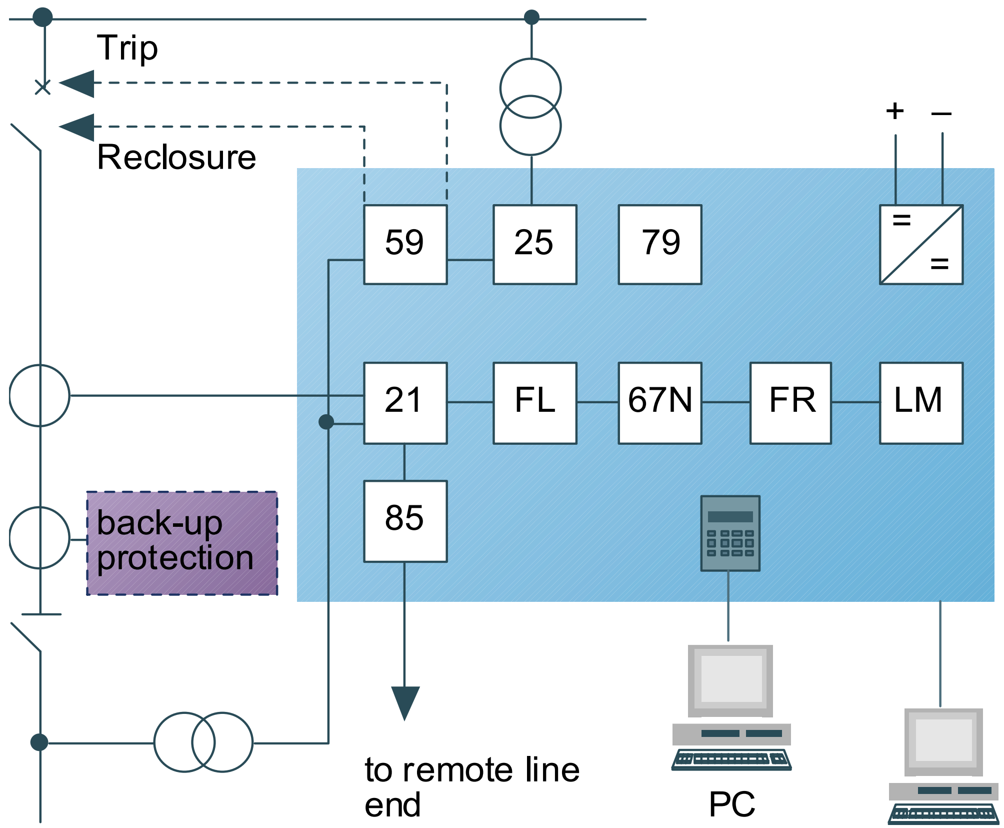
Sampling rate:	1000 Hz (1200 Hz with 60 Hz nominal frequency)
Samples per period:	20
Anti-aliasing filter:	500 Hz (600 Hz) limiting frequency
A/D-conversion:	16 bit, corresponding to 65536 steps
Measuring value storage:	15 s
Program language:	C/C++

Multifunction relays

Example: Line Protection



Continuing function integration

59	Overvoltage protection
25	Synchro-check
79	Autoreclosure
21	Distance protection
FL	Fault locator
67N	Directional earth fault protection
FR	Fault recording
LM	Load monitoring
85	Carrier interface

7SA6: Communication interfaces

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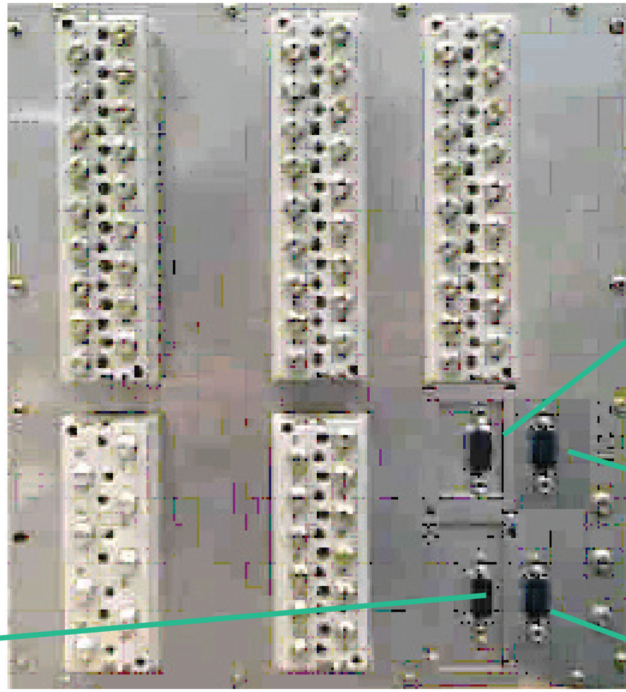
PC-interface,
front side
⇨electric RS 232



Analog output 20 mA or
teleprotection interface
⇨electric or optic

Service interface
⇨electric RS232 / RS485
⇨DIGSI 4 / modem

Time synchronisation
⇨GPS (IREC-B)
⇨or DCF-77

System interface
⇨electric or optic
⇨IEC60870-5-103,IEC61850, Profibus FMS, DNP3.0
or Modbus;
alternatively analog output 20 mA

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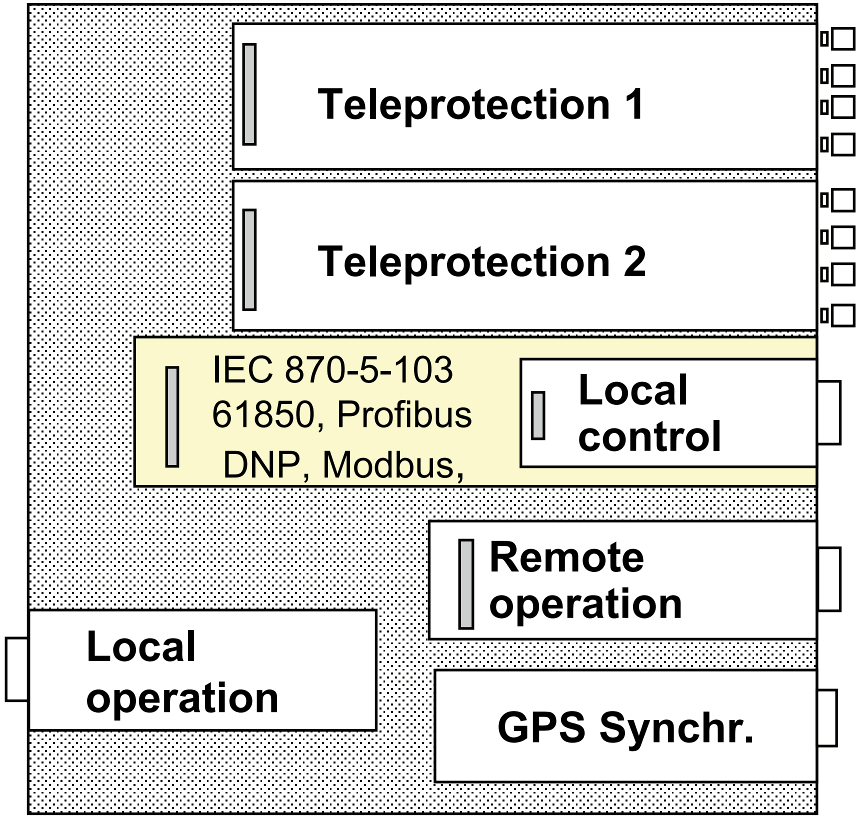
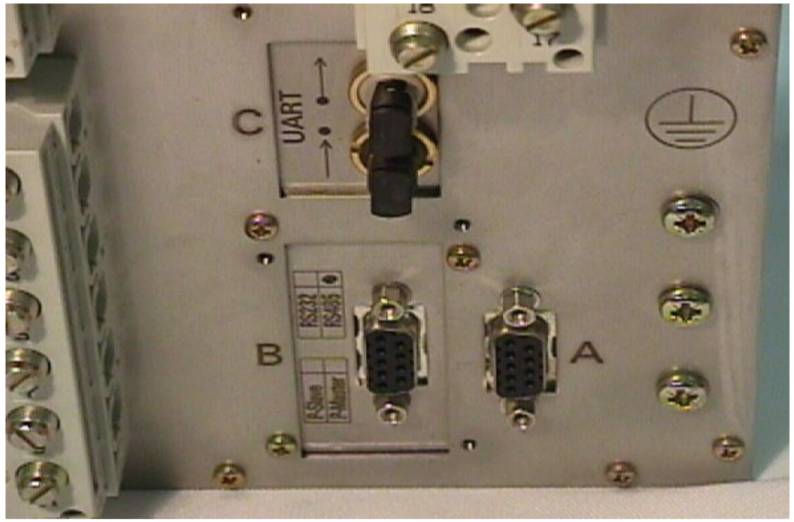

Teleprotection 1
Teleprotection 2
IEC 870-5-103
61850, Profibus
DNP, Modbus,
Local
control
Remote
operation
Local
operation
GPS Synchr.


C
UART
B
A

Modems for relay communication

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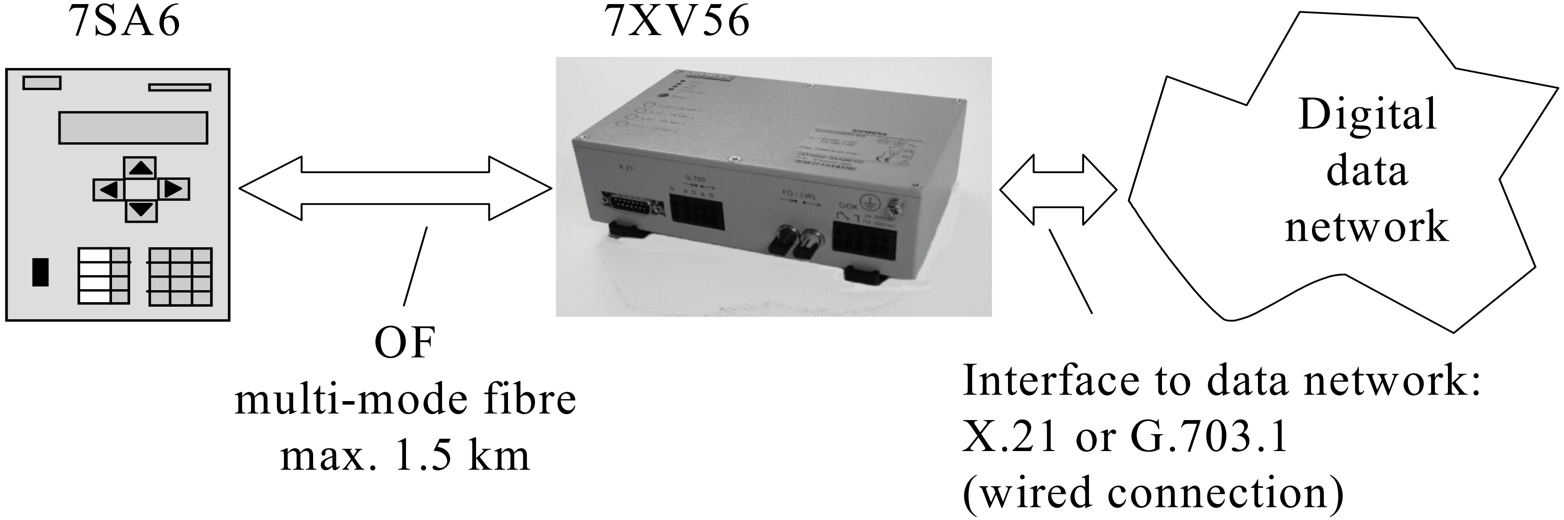

21 & 87 Relay

United full scheme distance and differential protection

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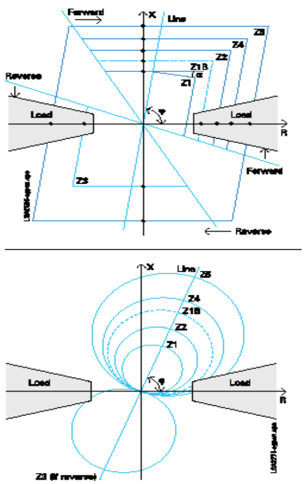

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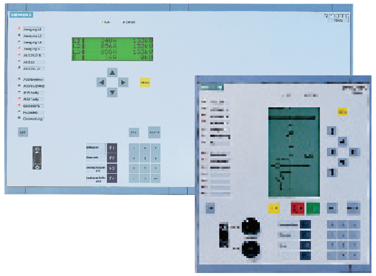
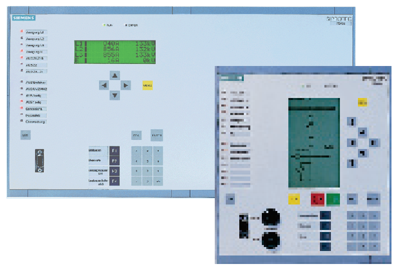


Copy of well proven features

21, 21N 67N 68, 68T	85 - 21 85 - 67N
79 59 49 51/51N	25 27 81 50 BF

87

21 & 87



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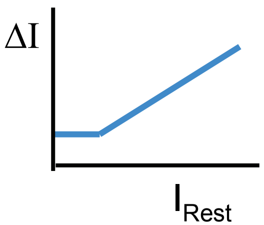
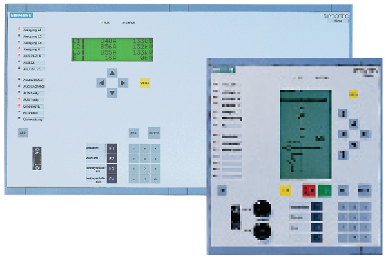
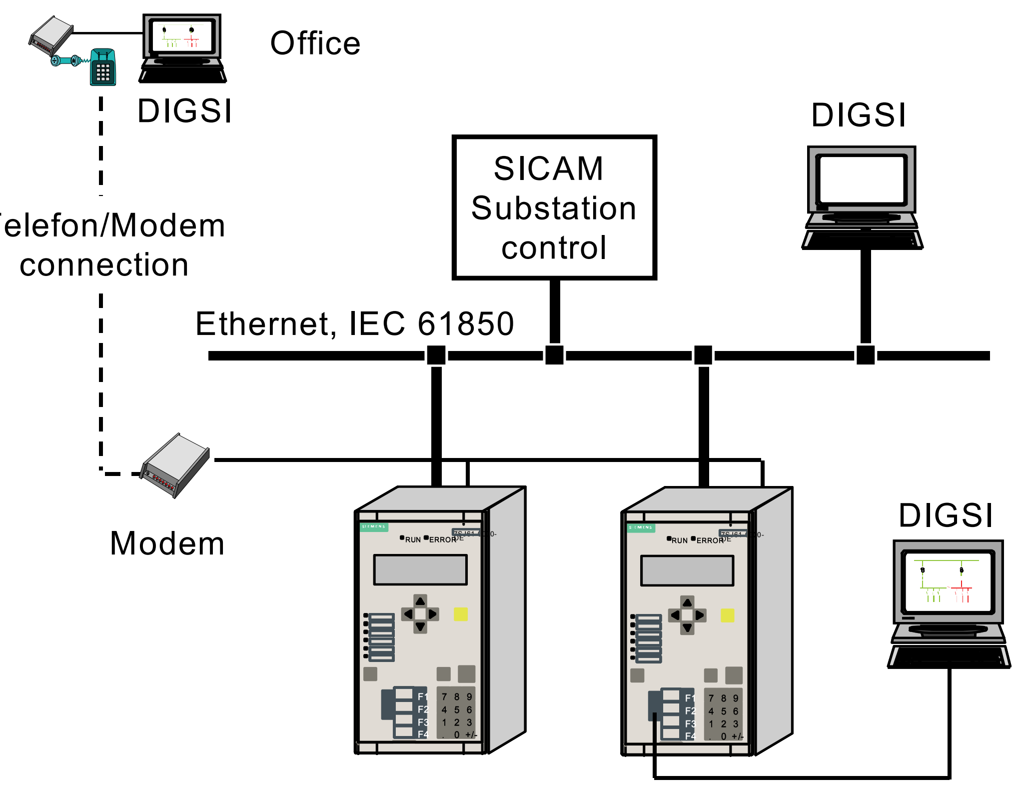




Modern Substation Automation



Software marshalling matrix

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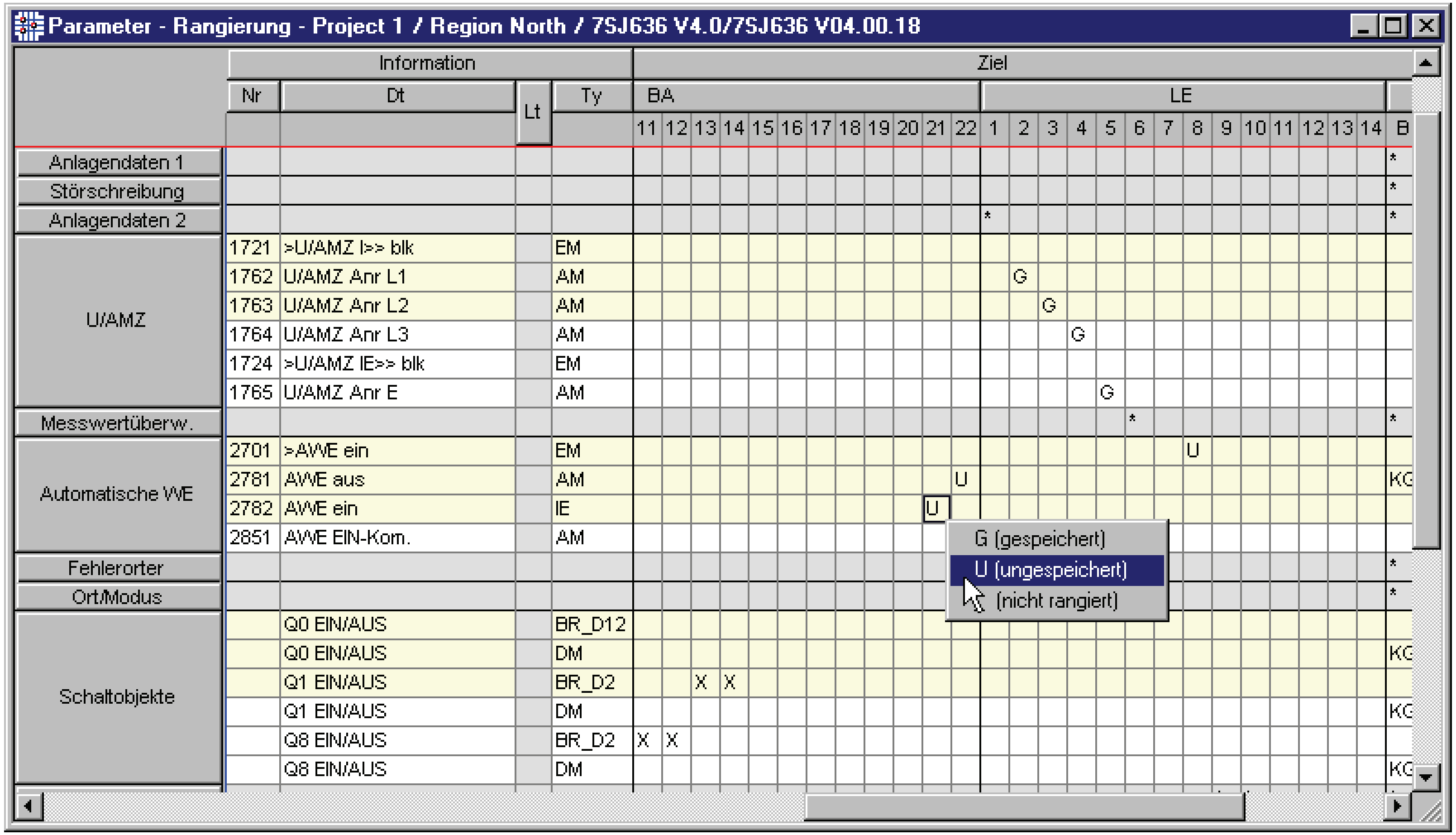

PLC (Progammable logic control)

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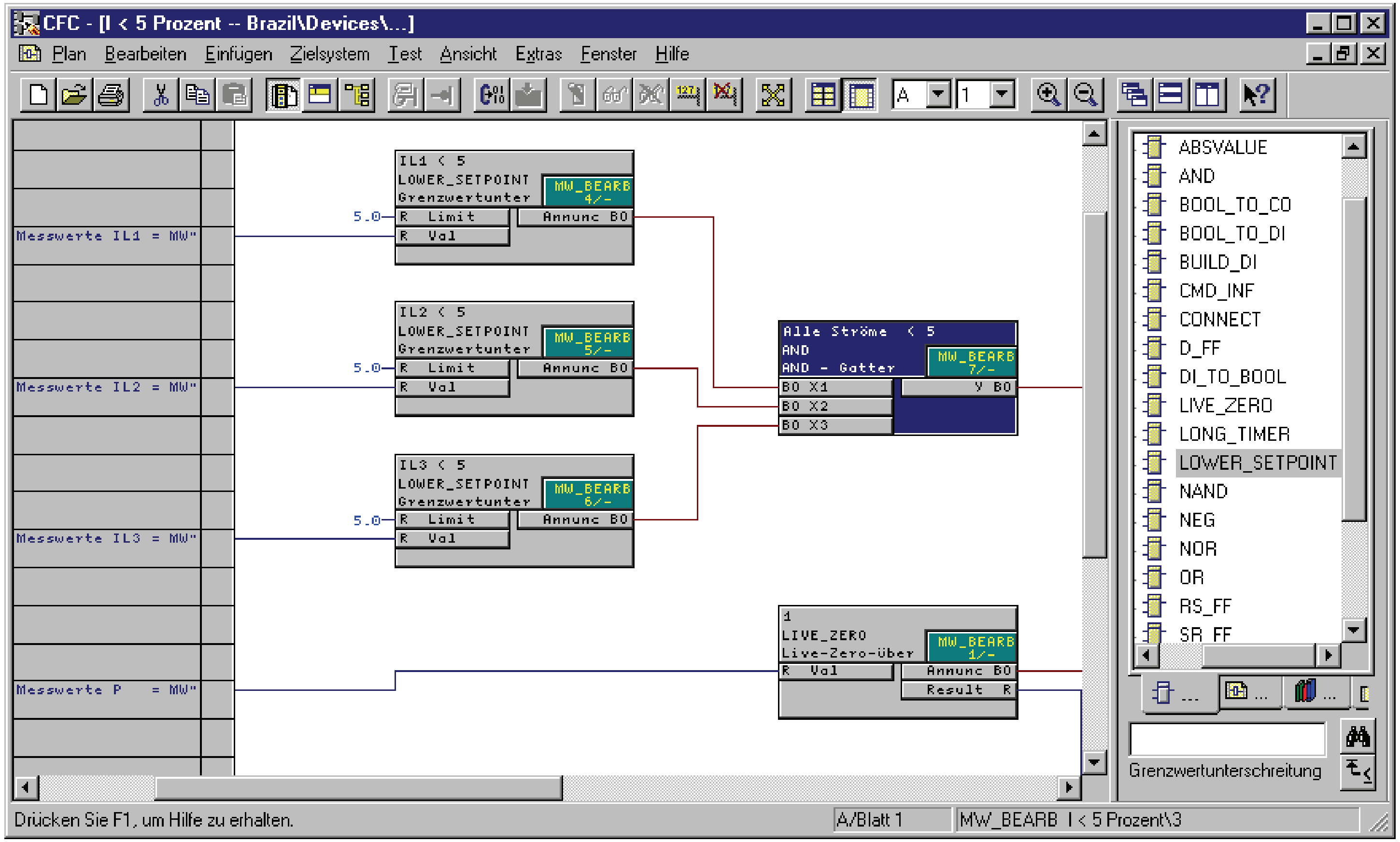

Distribution Switchgear Innovation

One IED replaces a conglomeration of “black box” devices

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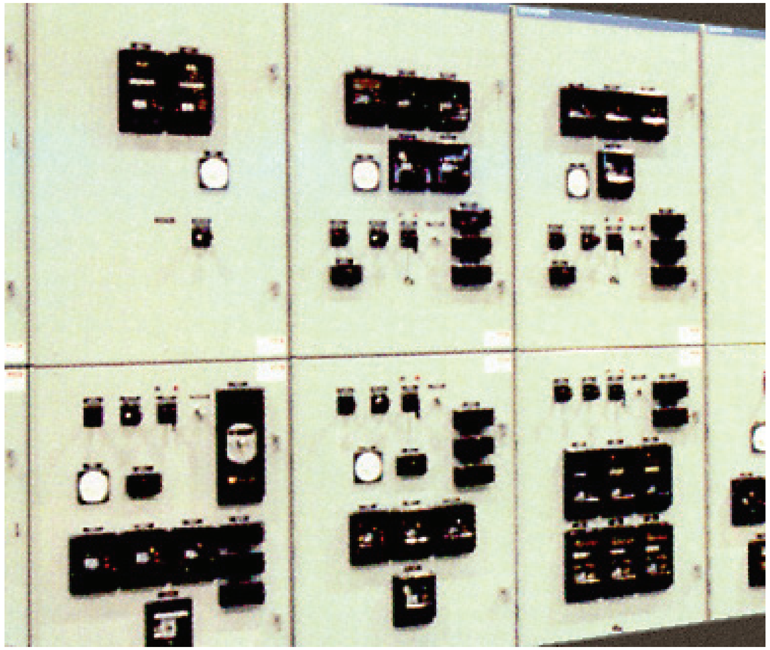
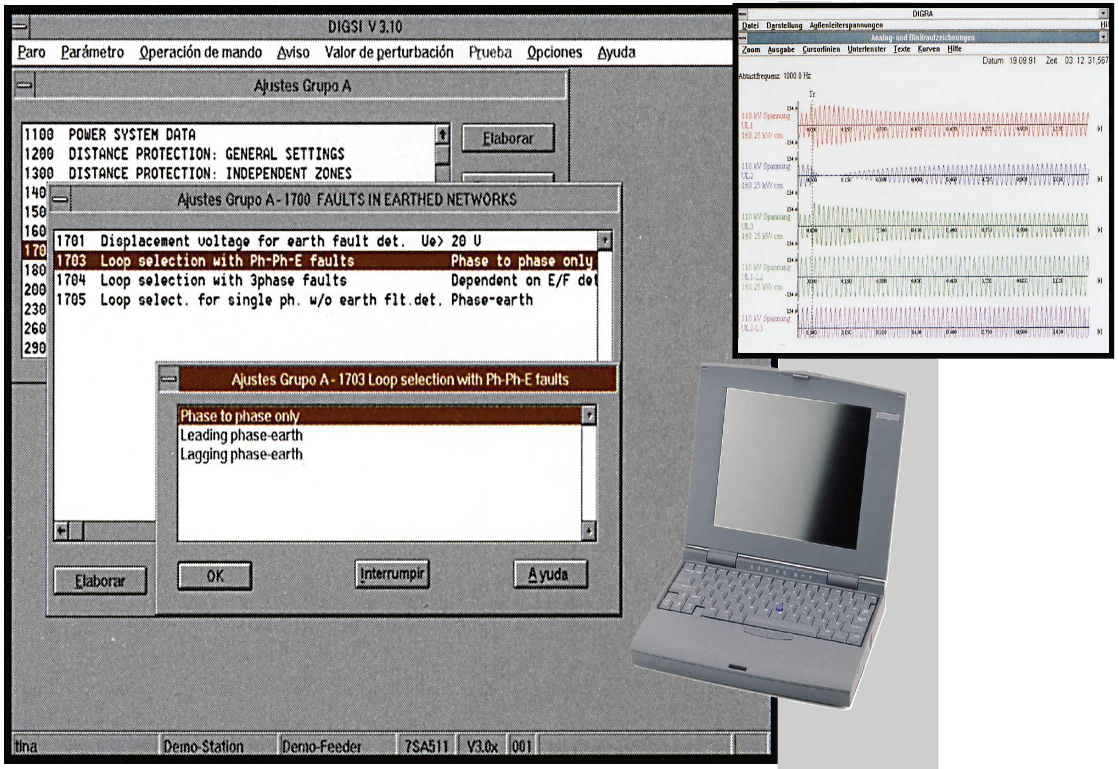
Traditional panels with mechanical relays and control

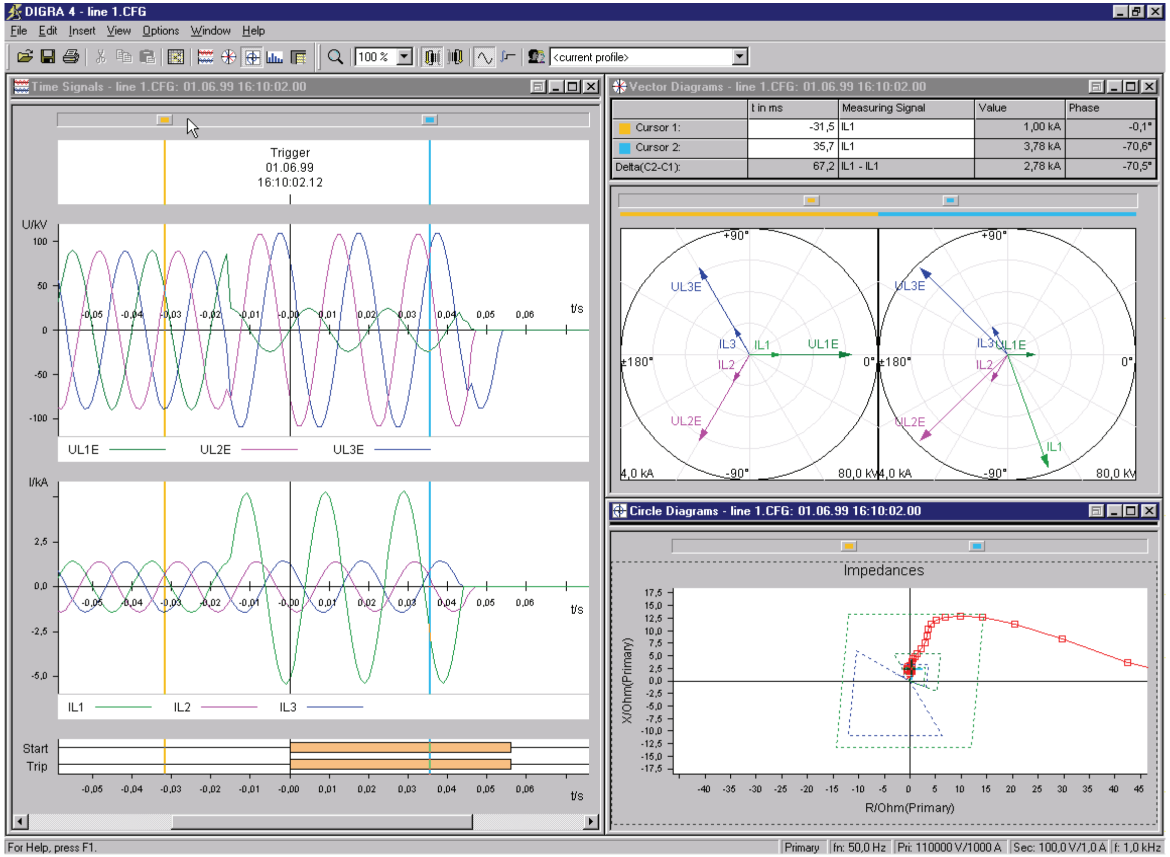


Modern panels with
digital multifunction relay

State-of-the-art:
Windows Based Relay Operating Programs



A New Quality of Fault Analysis



Powerful PC Tools

Calculation of phasors, sequence components, impedances, harmonics, and more

Jul-06
Author

Power Transmission and Distribution

Valuation of integrated functions in protection relays
Utility survey, Germany 2003

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Integrated functions	Valuation: 0	1	2	3	4	5
Flexible setting					X	
Higher selectivity				X		
Shorter operating time			X			
Lower CT and VT requirements		X				
Integrated fault recording						X
Integrated load monitoring (U, I, P, f)		X				
Remote retrieval of fault records						X
Remote setting			X			
Self-monitoring						X
Remote diagnosis				X		
Programmable logic functions					X	
Free assignment of I/O interfaces					X	

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IEC 61850 - Basics and trends of numerical communication in substations

Power Transmission
and Distribution

Today's Communication Standards within and outside of Substations

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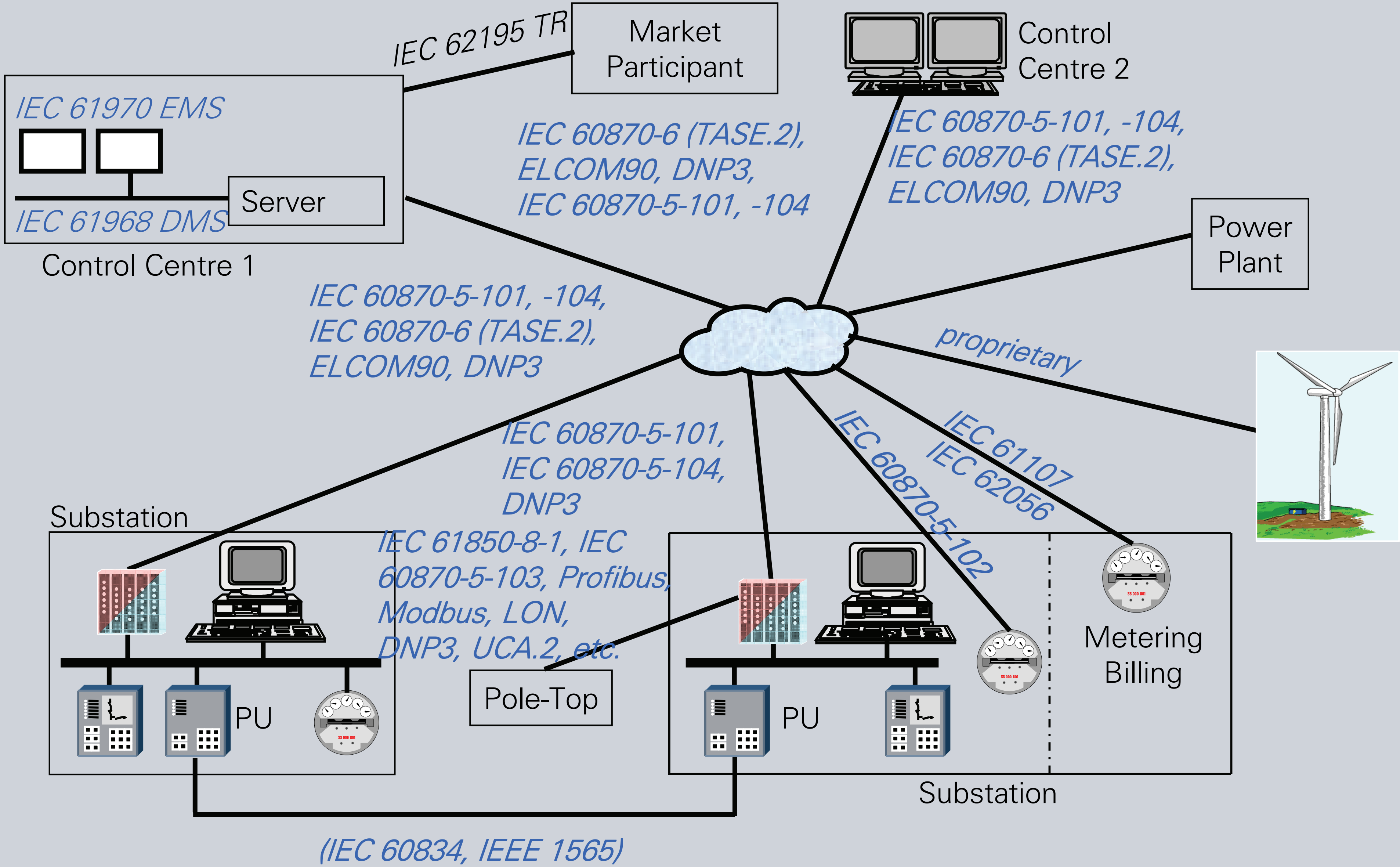
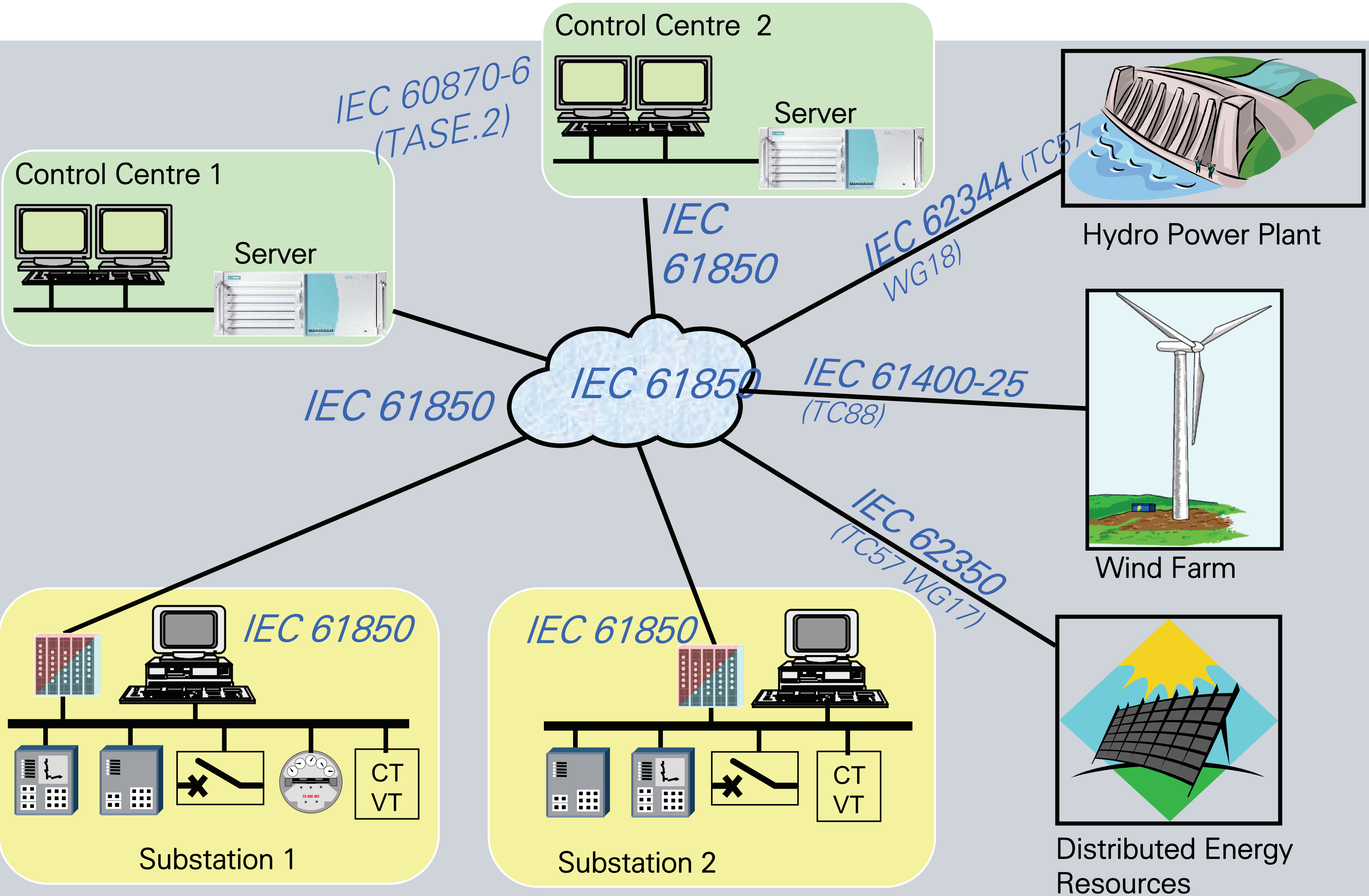


Trend in the future



What‘s so special about IEC61850?

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Features	Benefits
Interoperability e.g. IEDs talks to each other	Combine diff. manufacturers **no converters, inter-bay interlockings w/o master**
Separation of Application (e.g. protection) Services (e.g. control, reports) Communication (e.g. TCP/IP, Ethernet)	Future proof investment **Even if communication technology changes, the data and service model remains the same (standardized)** **Use standard infrastructure Speed (100Mbps → 1Gbps)**
	No communication master
Inter-device Communication	Shorter response times **no more master/slave bottle-necks**
Support of Client-Server Architecture	Manageable Complexity **standardized exchange of engineering data**

Interoperability ≠ Interchangeability

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Interoperability
is the ability of two or more IEDs
from the same vendor, or different vendors,
to exchange information and uses that information for correct co-operation.

Interchangeability
ability to replace a device supplied by one manufacturer with a device supplied by another manufacturer, without making changes to the other elements in the system.

IEC 61850 Part 1
"Interchangeability is beyond this communication standard."

Interoperability

What is needed for interoperability

- Data model
- Service model
- Mapping to a real protocol
- Communication medium
- Data exchange between engineering tools
- Conformance test

IEC 61850 standardized these needs

The idea behind IEC 61850: Separation

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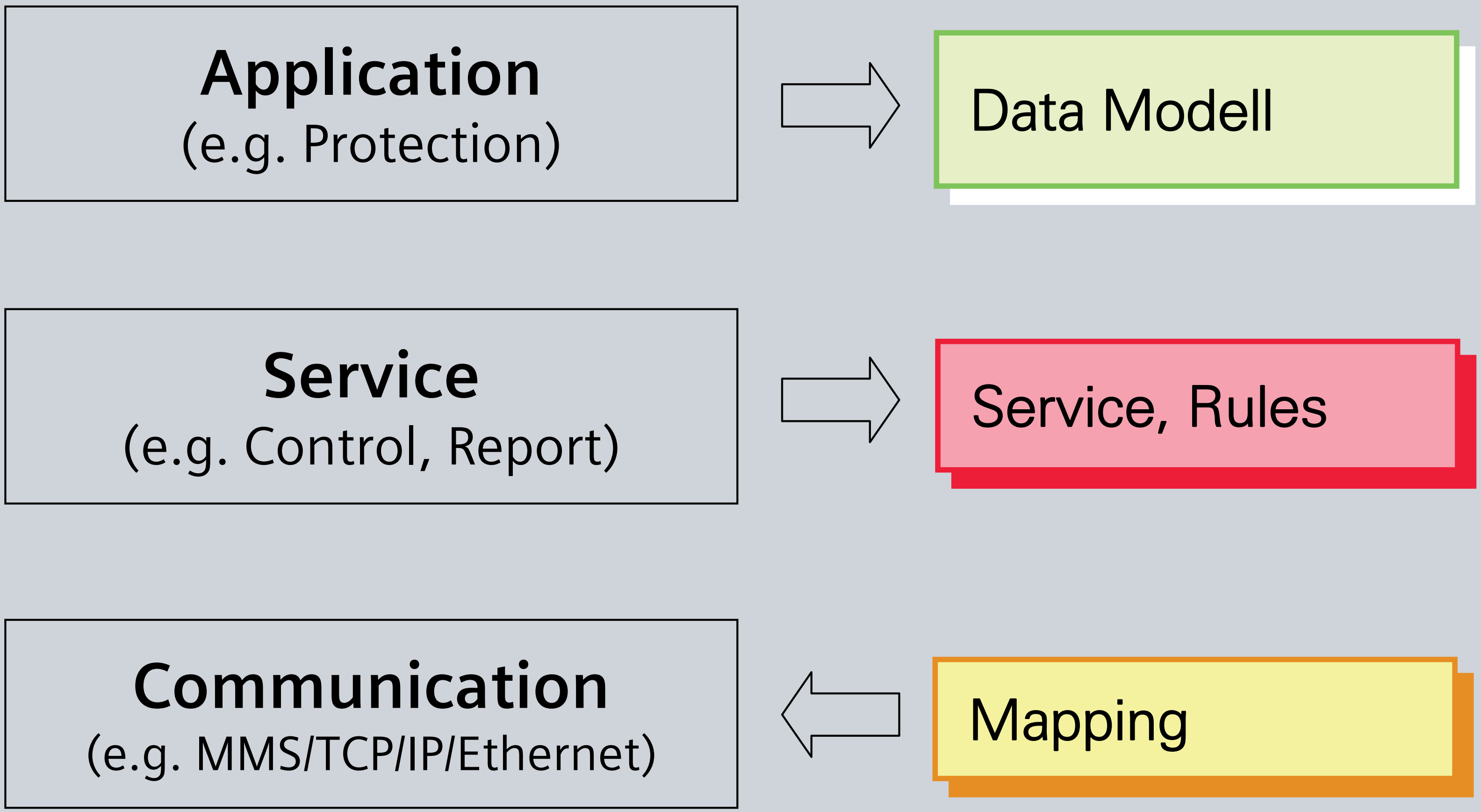
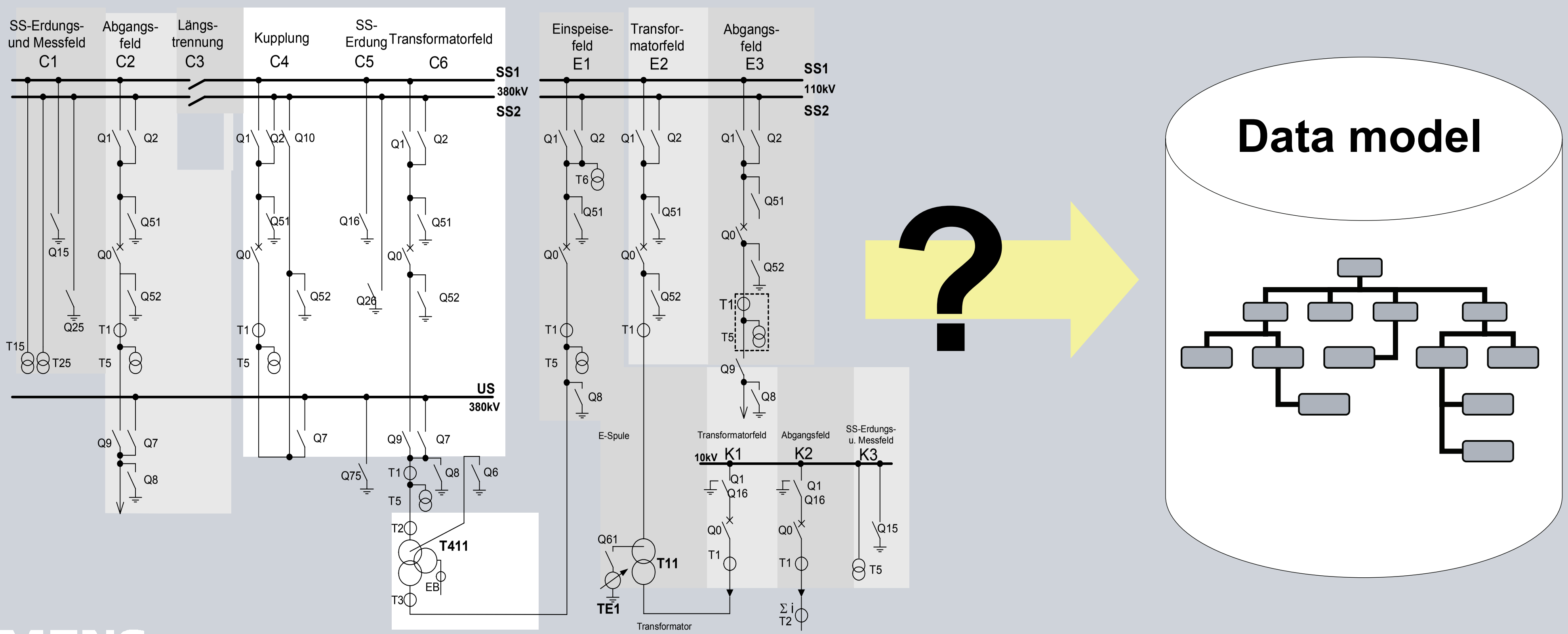


because Data did not change and will not change
but the communication technology will

Data model

Data model How are the data of switchgear and control modeled considering the functionality according to the IEC 61850?

How does this influence your data and specification?



Basis of the data model

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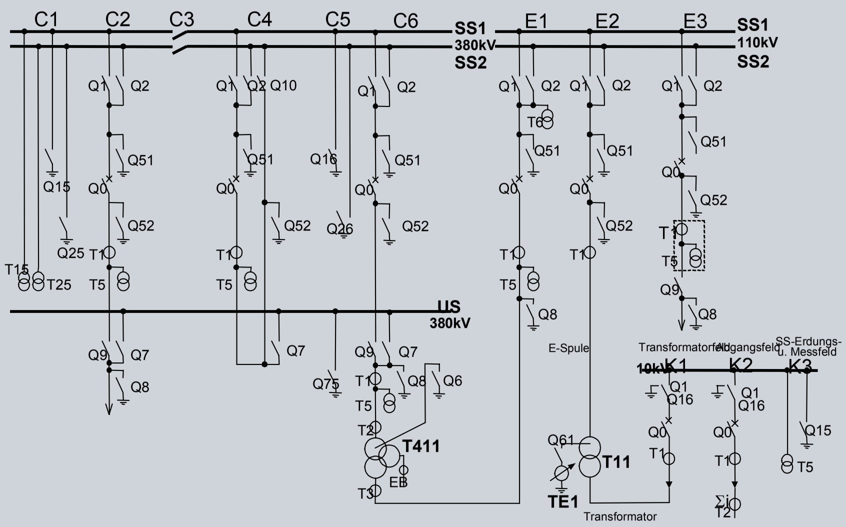

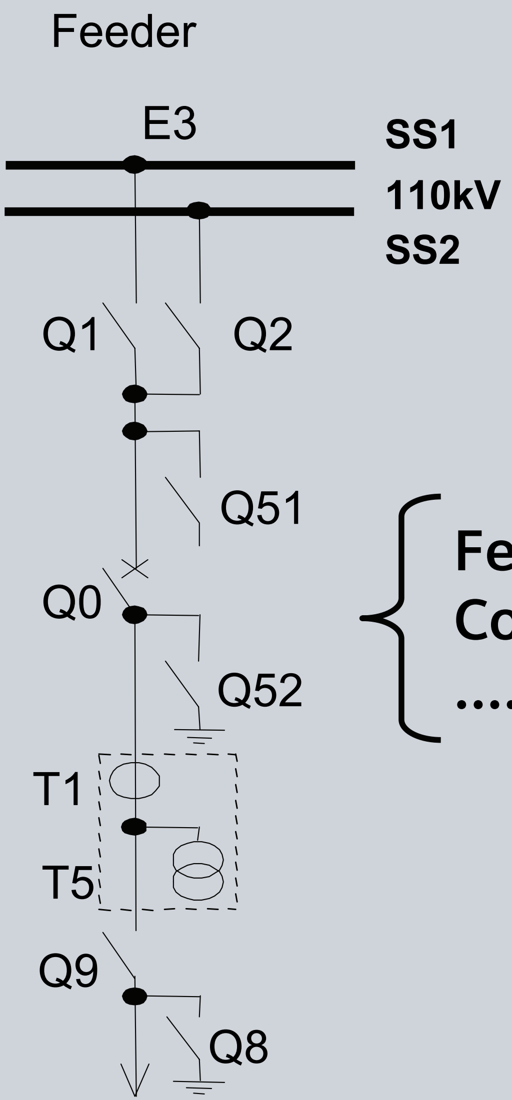

Feedback signal CBR
Control command CBR
....

IEC 61850: Data Attribute – Data Object

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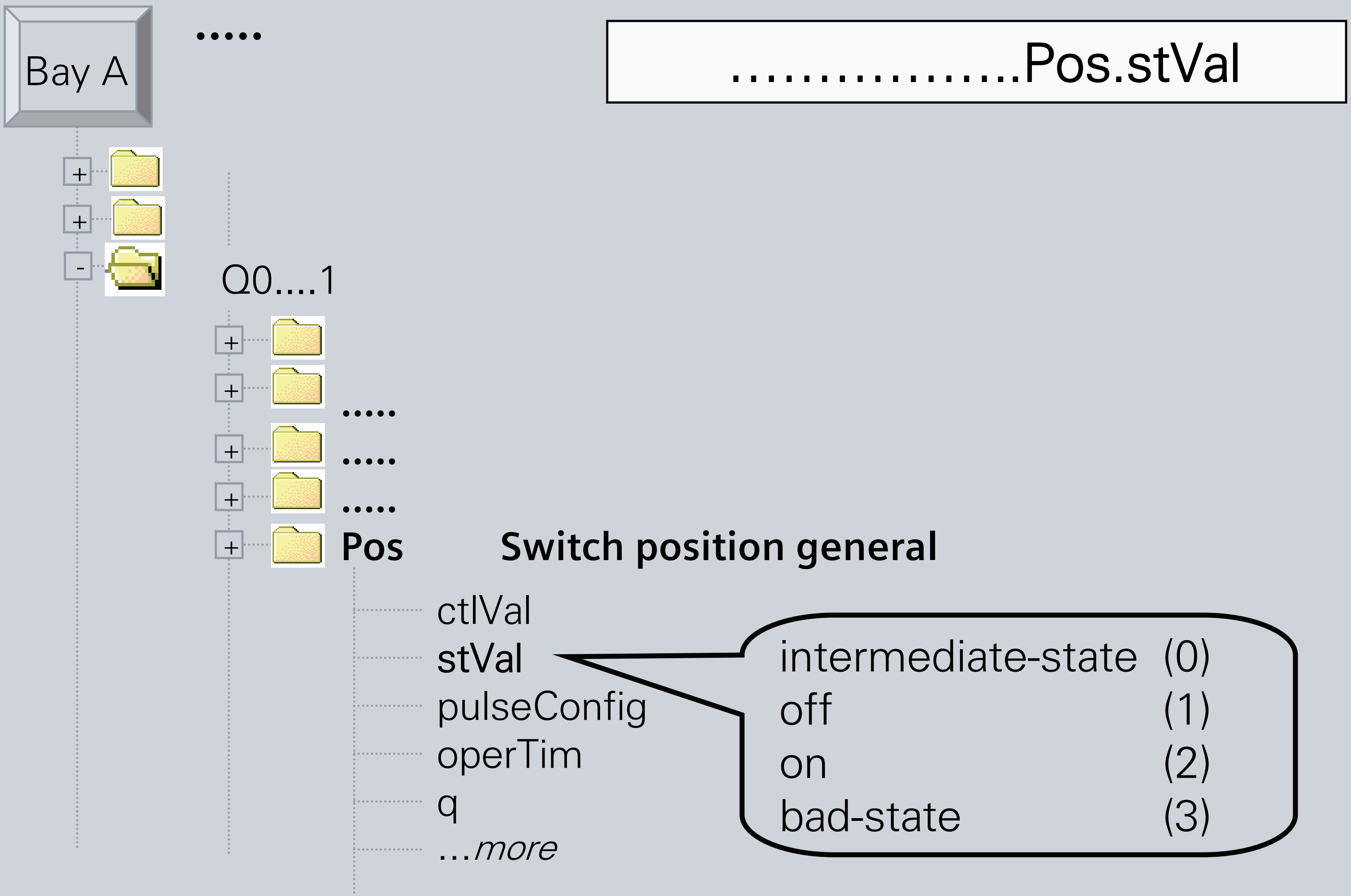


IEC 61850: Data Objects – Logical Node

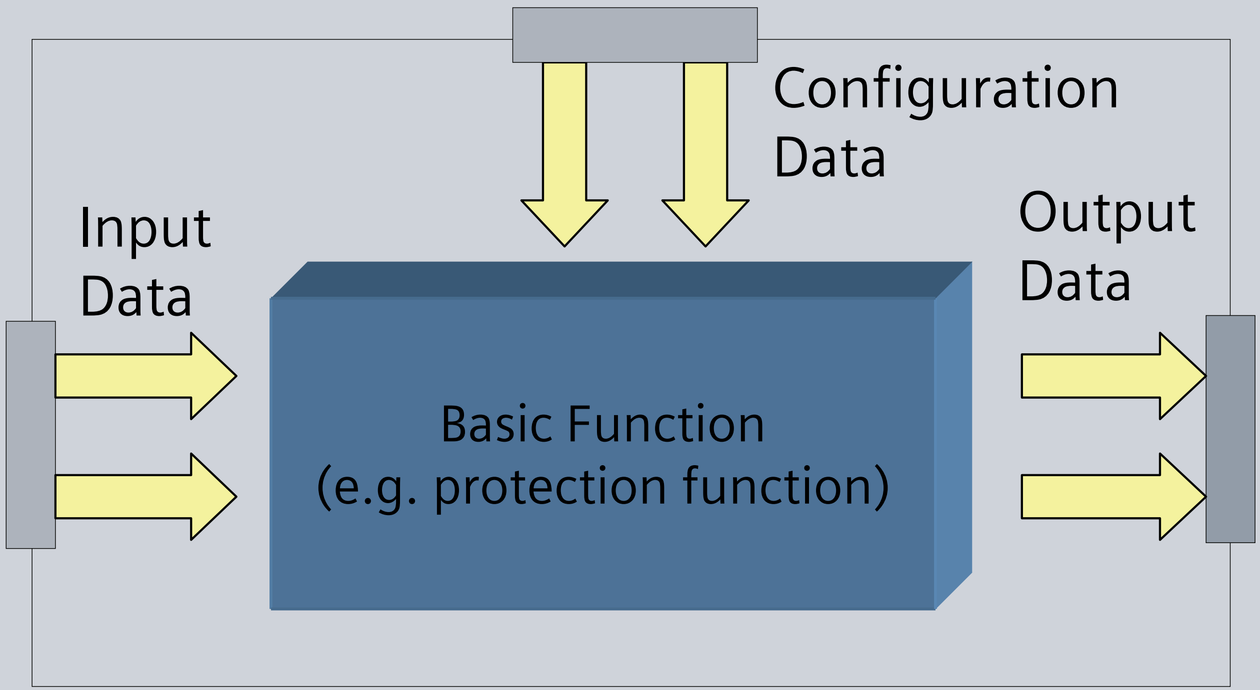
....../Q0XCBR1.Pos.stVal

- Bay A
  - ....
  - ....
  - ....
  - Q0XCBR1

Data object	Description
Mode	Mode
Beh	Behavior
Health	Health
NamePlt	Name plate
Loc	Local operation
OperCnt	Operation counter
Pos	**Switch position general**
....	
OpOpn	Operation “open switch”
OpCls	Operation “close switch”

Logical Node

Concept of a Logical Node



- Functions still remain vendor specific
- Data exchange becomes standardized

IEC 61850: Logical Node – Logical Device

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BayA/Q0XCBR1.Pos.stVal

Bay A

Bay Unit

PTOC	(Time Over Current)
RREC	(Autorecloser)
Q0**XCBR**1	(Circuit Breaker)
Q1XSWI1	(Isolator Q1)
Q2XSWI1	(Isolator Q2)
Q0CILO1	(Interlocking Q0)
Q1CILO1	(Interlocking Q1)
Q2CILO1	(Interlocking Q2)
IPIOC1	ANSI51

Logical Node: There are about 90 classes

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Group Indicator	Logical node groups
A	Automatic Control
C	Supervisory control
G	Generic Function References
I	Interfacing and Archiving
L	System Logical Nodes
M	Metering and Measurement
P	Protection functions
R	Protection related functions
S	Sensors
T	Instrument Transformer
X	Switchgear
Y	Power Transformer
Z	Further (power system) equipment

M:

MMXU	Measuring (Measurand unit)
MMTR	Metering
MSQI	Sequence and Imbalance
MHAI	Harmonics and Interharmonics
MDIF	Differential Measurements

P:

PDIF	Differential protection
PTEF	Transient Earth Fault
PTOC	Time overcurrent protection
PDIS	Distance protection
…more	

S:

SIMG	Insulation medium meas unit
SARC	Monitoring and diagnostics for arcs
SPDC	Monitoring and diagnostics for partial discharge

X:

XCBR	Circuit Breaker
XSWI	Circuit Switch

Logical Node for Circuit Breaker - LN XCBR

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IEC 61850-7-3

Mandatory /Optional

XCBR class				
Attribute Name	**Attr. Type**	**Explanation**	**T**	**M/O**
LNName		Shall be inherited from Logical-Node Class (see IEC 61850-7-2)		
Data				
Common Logical Node Information				
		LN shall inherit all Mandatory Data from Common Logical Node Class		M
Loc	SPS	Local operation (local means without substation automation communication, hardwired direct control)		M
EEHealth	INS	External equipment health		O
EEName	DPL	External equipment name plate		O
OpCnt	INS	Operation counter		M
Controls				
Pos	DPC	Switch position		M
BlkOpn	SPC	Block opening		M
BlkCls	SPC	Block closing		M
ChaMotEna	SPC	Charger motor enabled		O
Metered Values				
SumSwARs	BCR	Sum of Switched Amperes, resetable		O
Status Information				
CBOpCap	INS	Circuit breaker operating capability		M
POWCap	INS	Point On Wave switching capability		O
MaxOpCap	INS	Circuit breaker operating capability when fully charged		O

Data: There are about 350 classes

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Data Classes	Number
System information	13
Physical device inform.	11
Measurands	66
Metered values	14
Controllable Data	36
Status information	85
Settings	130
	355

Types: DPC, SPC, INC….

Pos – Switch position
TapChg – Change voltage (stop, higher, lower)
FanCtl – Fan control
More…..

Types: DPS, SPS, INS. ACT….

OP – Operate
Loc – Change voltage (stop, higher, lower)
OpCnt – Operation counter
More…..

They are assigned to 28 common data classes in Part 7-3, e.g. DPC, SPC...

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Common data class - Controllable double point (DPC)

control value

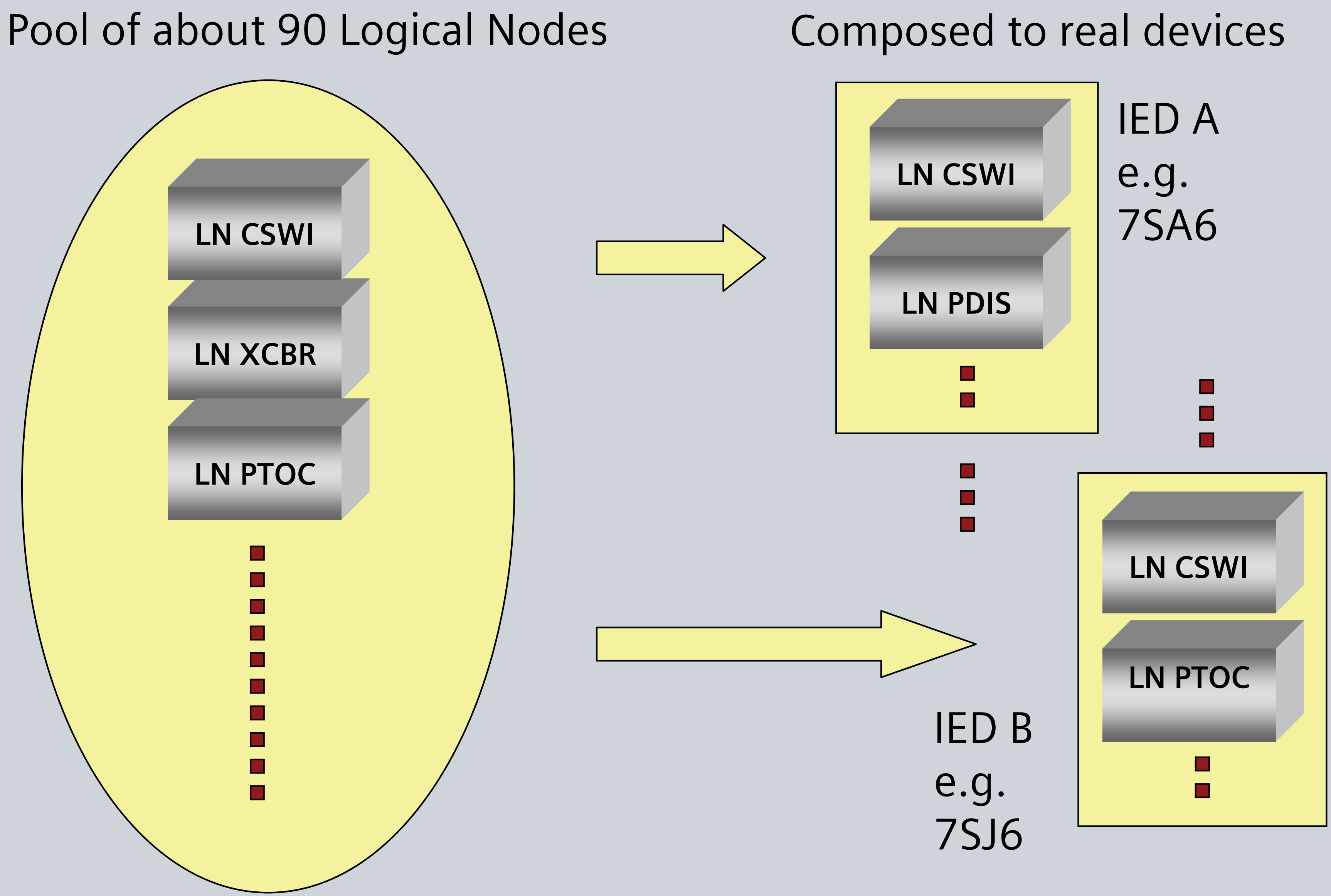
status value

basic types

functional contraint

DPC class					
Attribute Name	**Attribute Type**	**FC**	**TrgOp**	**Value/Value Range**	**M/O/C**
DataName	Inherited from Data Class (see IEC 61850-7-2)				
DataAttribute					
				control and status	
ctlVal	BOOLEAN	CO		off (FALSE) | on (TRUE)	AC_CO_M
operTm	TimeStamp	CO			AC_CO_O
origin	Originator	CO, ST			AC_CO_O
ctlNum	INT8U	CO, ST		0..255	AC_CO_O
stVal	CODED ENUM	ST	dchg	intermediate-state | off | on | bad-state	M
q	Quality	ST	qchg		M
t	TimeStamp	ST			M
stSeld	BOOLEAN	ST	dchg		AC_CO_O
				substitution	
subEna	BOOLEAN	SV			PICS_SUBST
subVal	CODED ENUM	SV		intermediate-state | off | on | bad-state	PICS_SUBST
subQ	Quality	SV			PICS_SUBST
subID	VISIBLE STRING64	SV			PICS_SUBST
				configuration, description and extension	
pulseConfig	PulseConfig	CF			AC_CO_O
ctlModel	CtlModels	CF			M
sboTimeout	INT32U	CF			AC_CO_O
sboClass	SboClasses	CF			AC_CO_O
d	VISIBLE STRING255	DC		Text	O
dU	UNICODE STRING255	DC			O
cdcNs	VISIBLE STRING255	EX			AC_DLNDA_M
cdcName	VISIBLE STRING255	EX			AC_DLNDA_M
dataNs	VISIBLE STRING255	EX			AC_DLN_M

Vendors compose real protection and control devices



IEC 61850-7: Addressing “Circuit Breaker”

BayA1/Q0XCBR1.Pos.ctlVal

Attribute Name (fixed)

Data Object Name (fixed)

Logical Node Name Suffix (free)

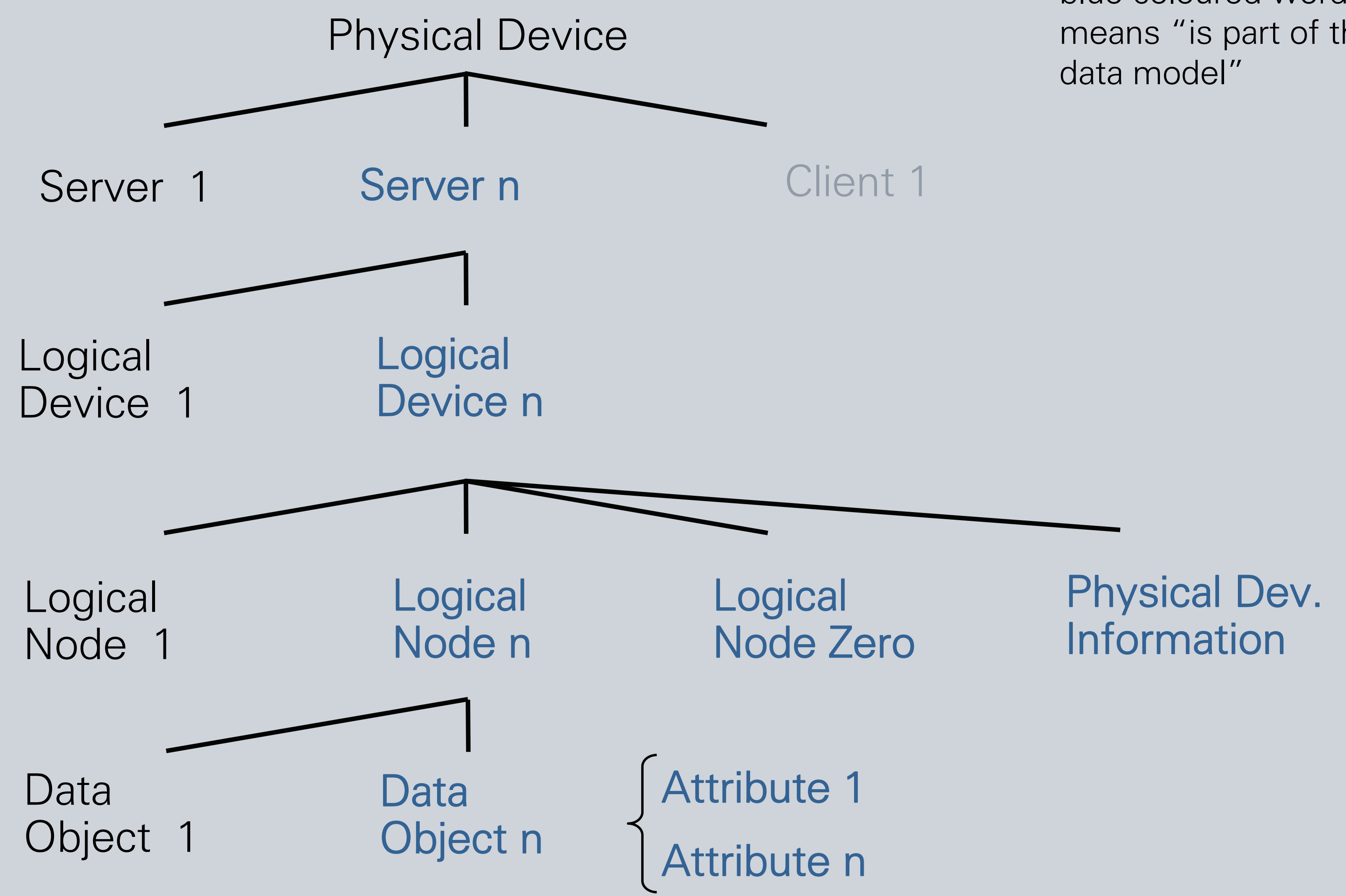
Logical Node Class (fixed)

Logical Node Name Prefix (free)

Logical Device Name (free)

Hierarchy of the Data Model

blue coloured words means "is part of the data model"



Service Model

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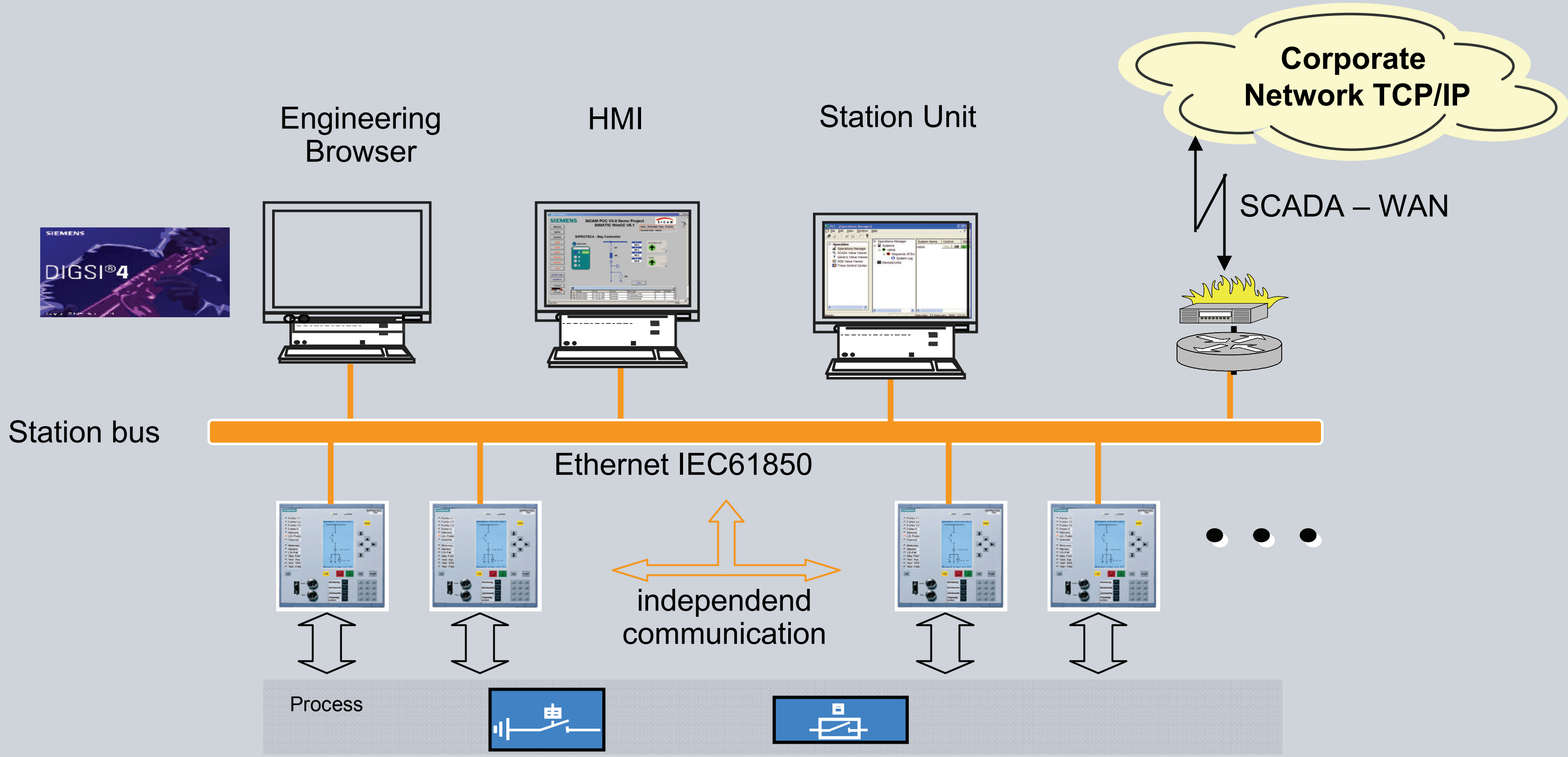
distributed intelligence

- no more classic Master/Slave configuration and no bottle neck.
- Client / Server architecture
- Peer-to-peer (publisher / subscriber) architecture

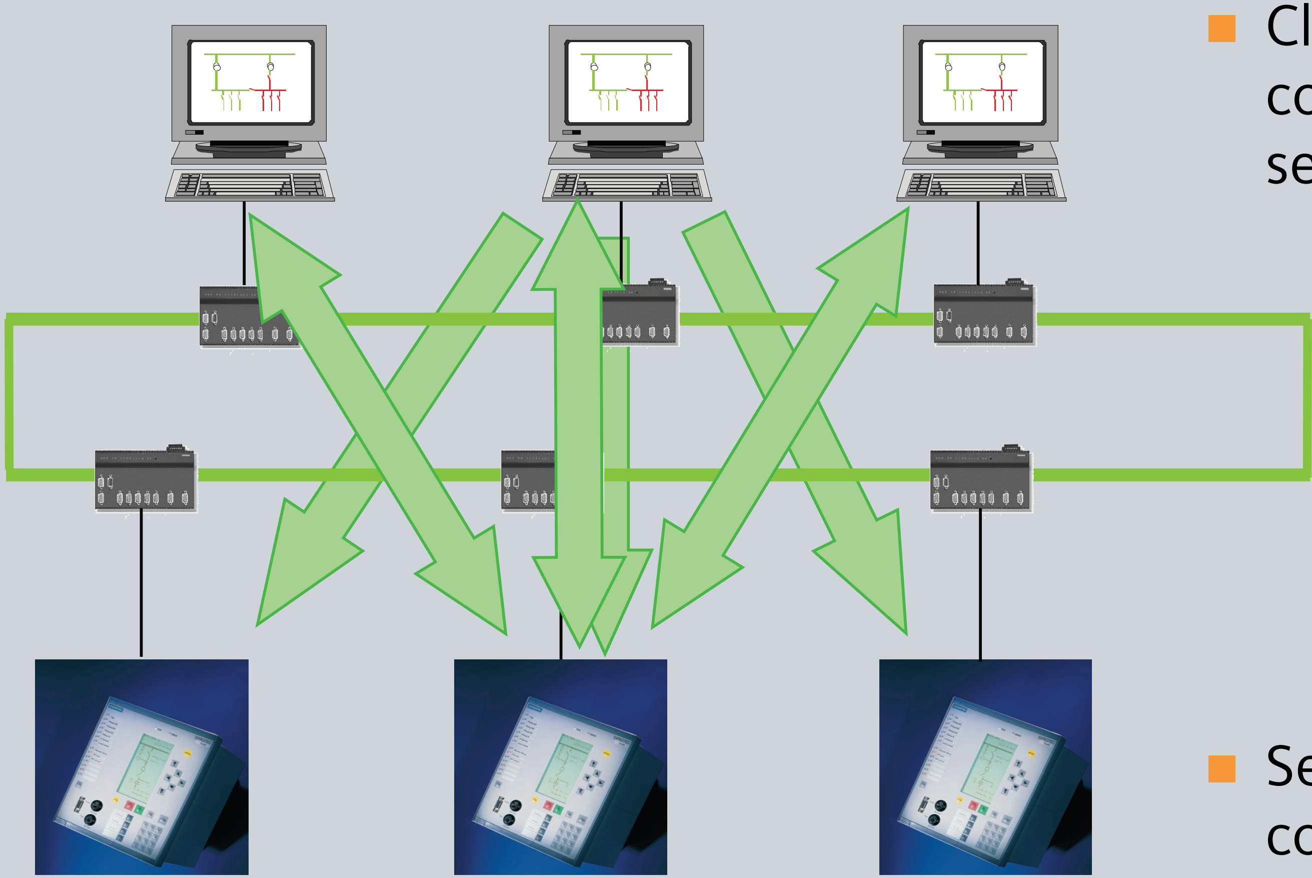


Services in IEC 61850-7-2

- Control
- Buffered and Unbuffered Information Report
- Logging
- GOOSE (for fast inter-device communication)
- Substitution
- Setting Group
- Sampled Value
- Time Synchronisation (SNTP)
- File Transfer (MMS-File Transfer, FTP)

GOOSE –Generic Object Oriented Substation Event

Client / Server architecture



- Client keeps connection to several servers.
- Server supports connection to several clients simultaneous.

- Report is more efficient than polling
- Report is transmitting data based on a condition being met: change of state, value, quality attribute, time-out

Control models in IEC 61850

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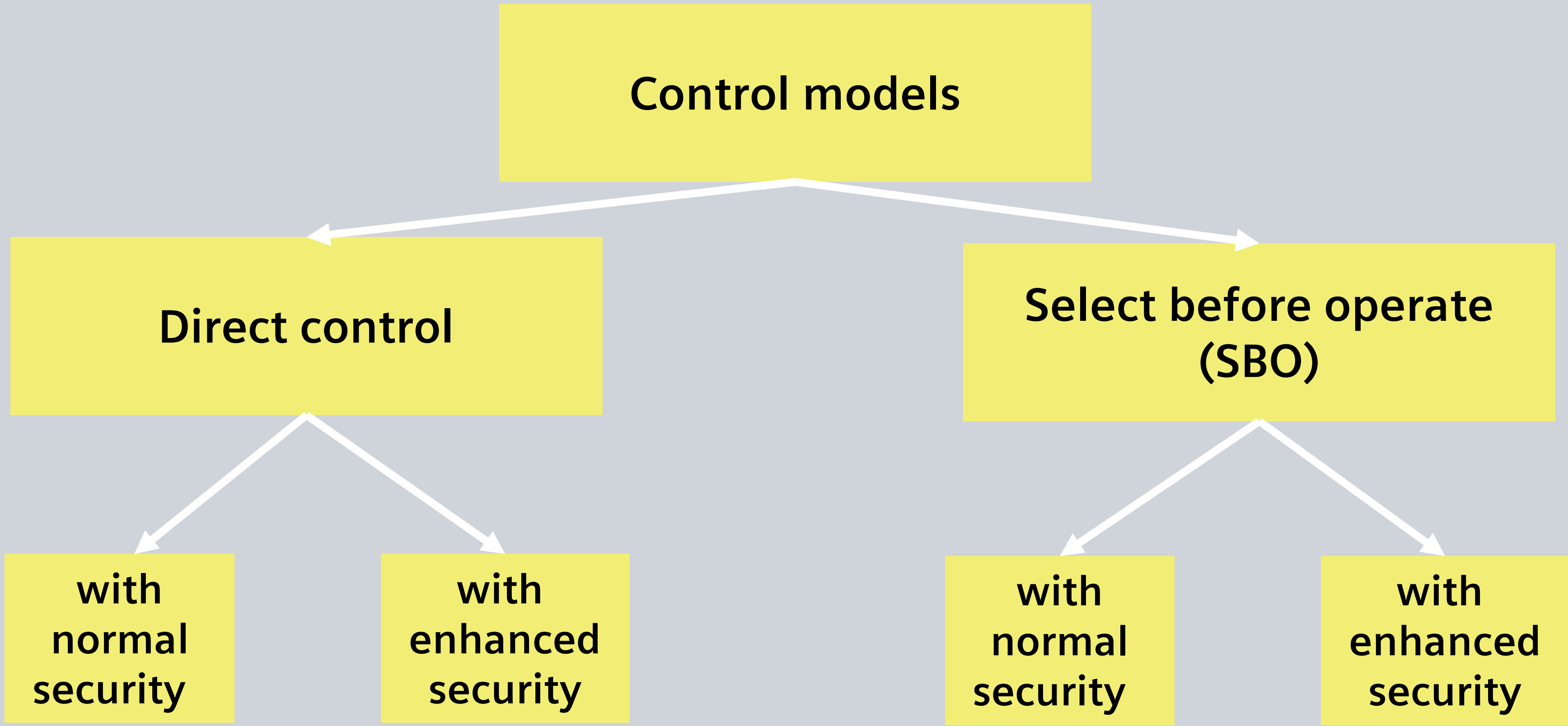

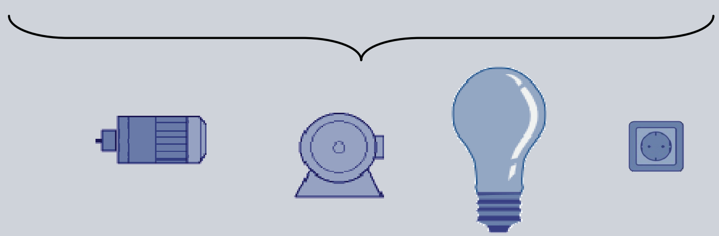

Publisher-Subscriber-architecture

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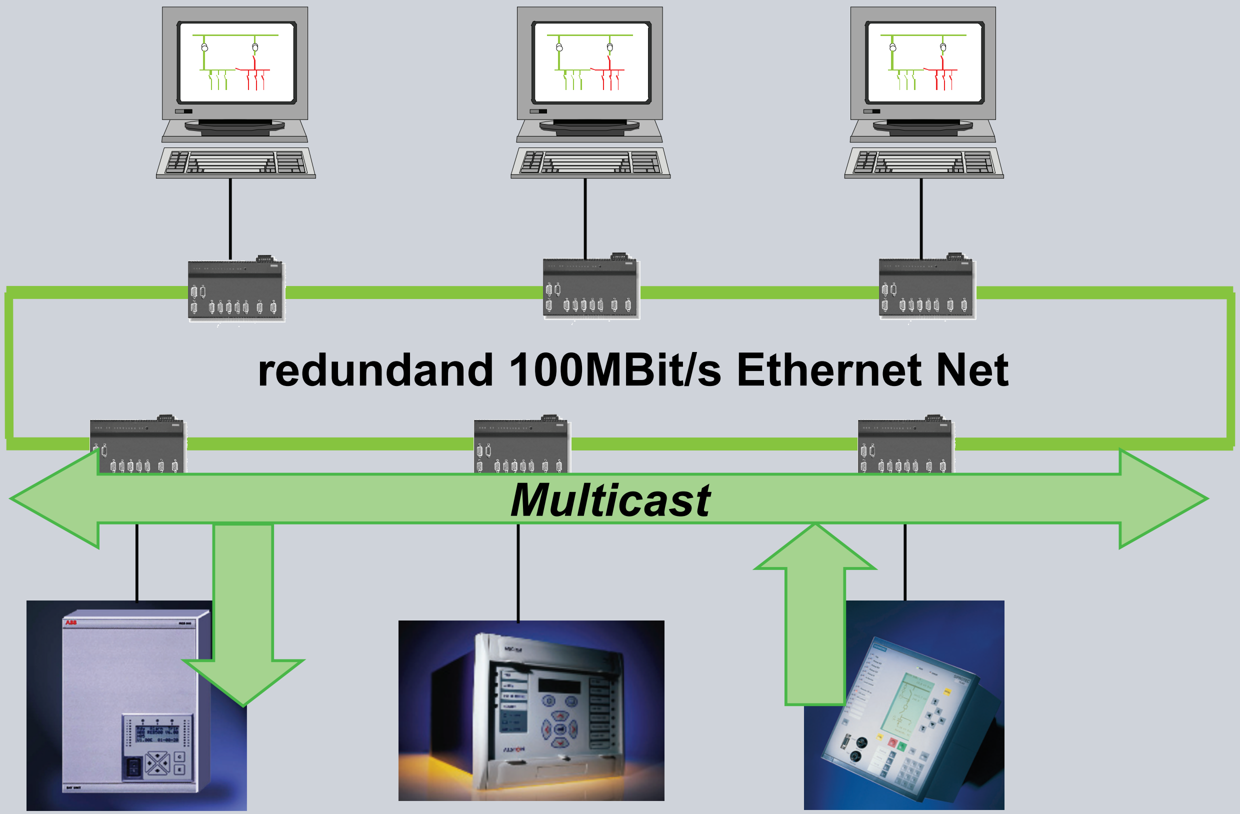
Fast Inter-Device Communication (GOOSE)

A device sends the published information by multicast .
A subcriber receives this message.



GOOSE –Generic Object Oriented Substation Event

IEC 61850 – GOOSE principle

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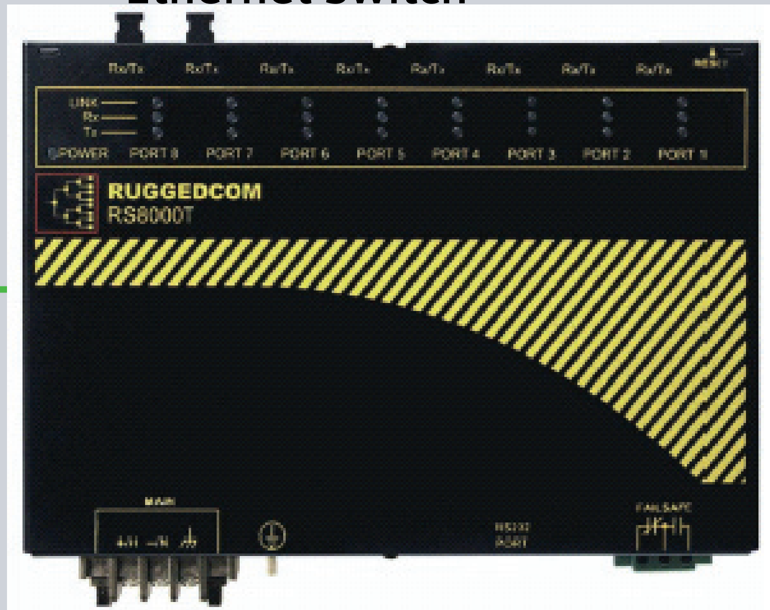
Prioritization (tagging) of GOOSE-Telegrams

Ethernet Switch

fast

GOOSE

Normal Telegrams



Only IEC 61850 uses the possibilities of the modern 100 MBIT-Ethernet.

Not UCA2.0, not DNP, not T104 !

Transfer time in IEC 61850-5

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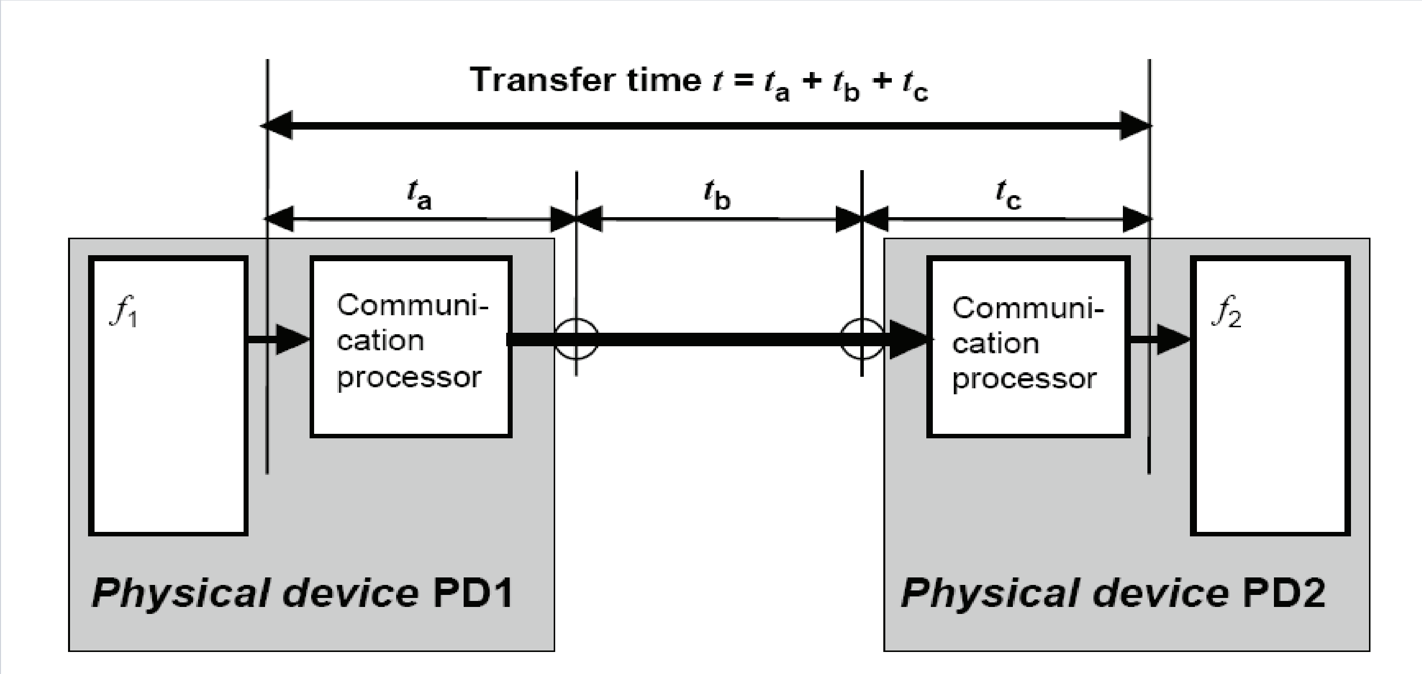
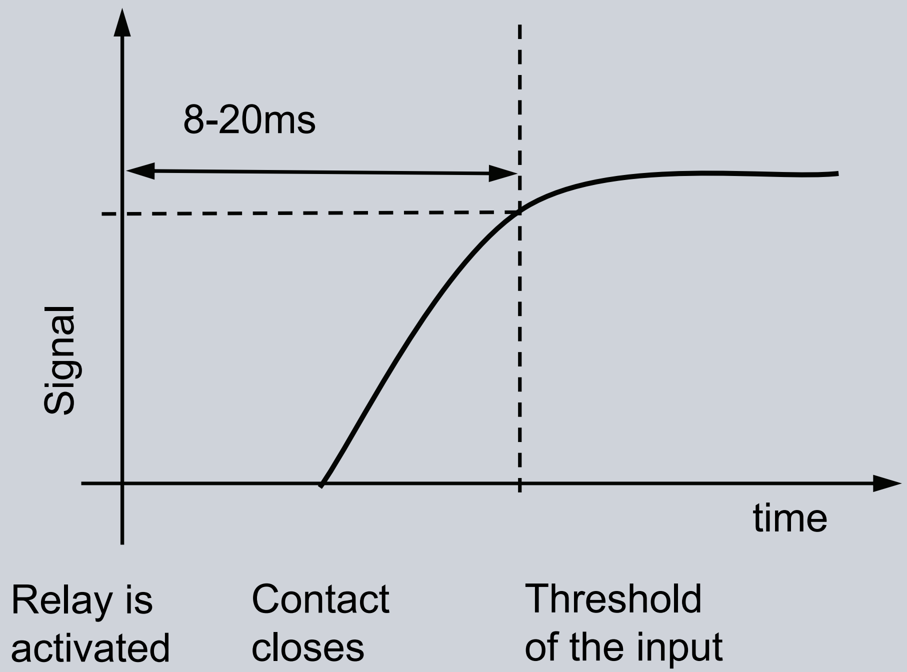


(from IEC 61850-5)

	Fast messages: Trip	Fast messages: others	Medium speed messages	Low speed messages
Distribution (P1)	10ms	100ms	100ms	500ms
Transmission (P2/P3)	3ms	20ms		

Hardwired signal transmission between bays

Output- / Input Signal (schematic)



Transmission with network communication between bays

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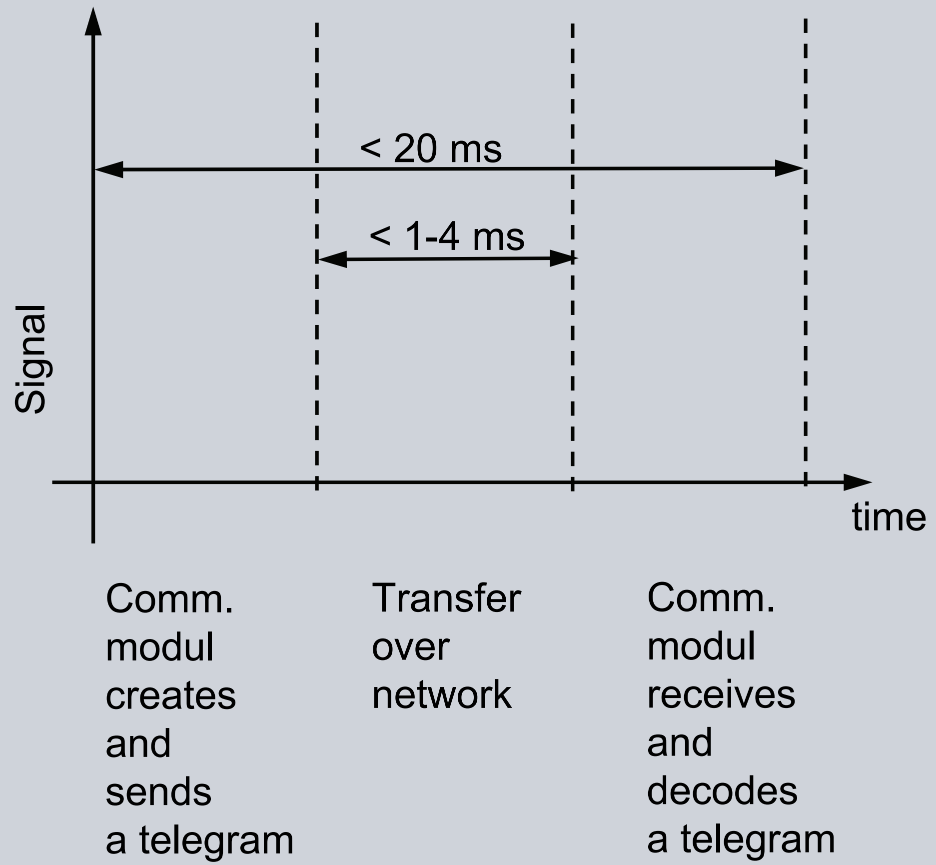
Use of GOOSE with prioritizing and multicast filtering (principle)



Example for IEC 61850–GOOSE
Principle of reverse interlock

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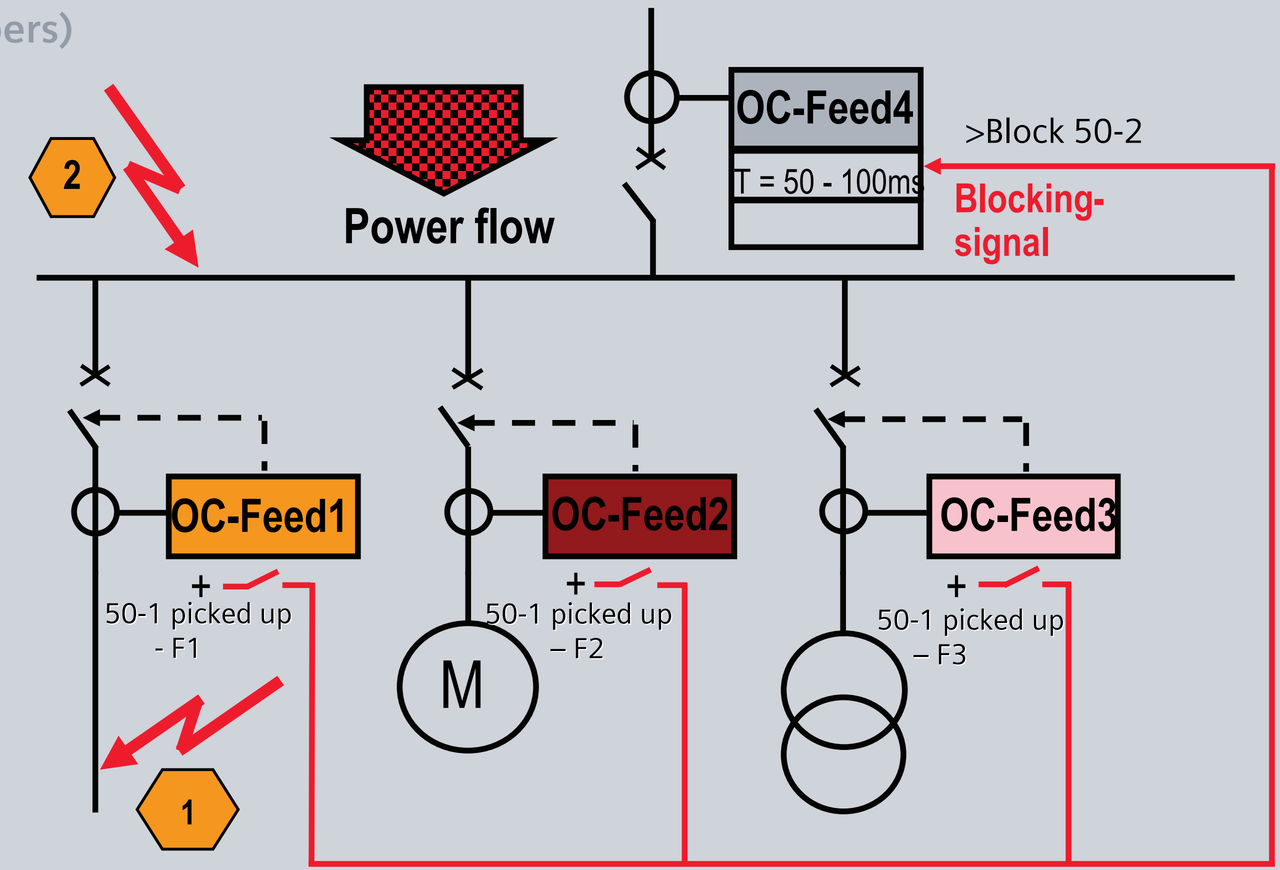
Principle of reverse interlock
(ANSI – numbers)



1 Overcurrent protection of outgoing feeders blocks the 50-2 stage (I>>) of the overcurrent protection of the incoming feeder (OC-Feed4) with the pick-up signal of OC-functions 50-1 (I>).

2 50-2 (I>>) stage of the overcurrent protection of the incoming feeder sends a trip signal after 50-100 ms, when no blocking signal is received from one or more overcurrent protection of the outgoing feeders.

Exchange of binary information (single messages) between devices
Contacts -> Binary input (wiring between the devices)

Example on IEC 61850–GOOSE
Topology of Ethernet Station-bus

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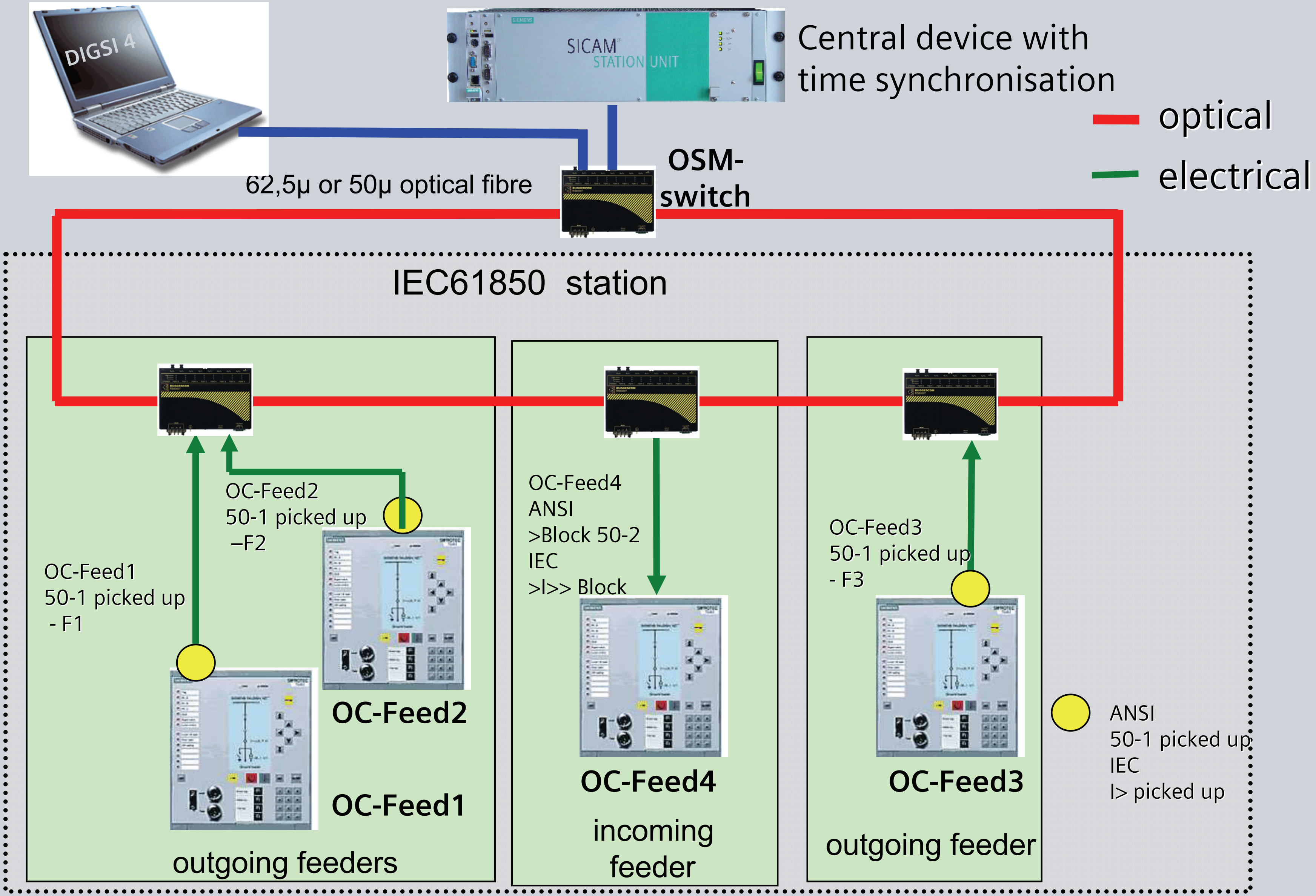

How GOOSE works according to IEC 61850: Cyclic and spontaneous GOOSE messages

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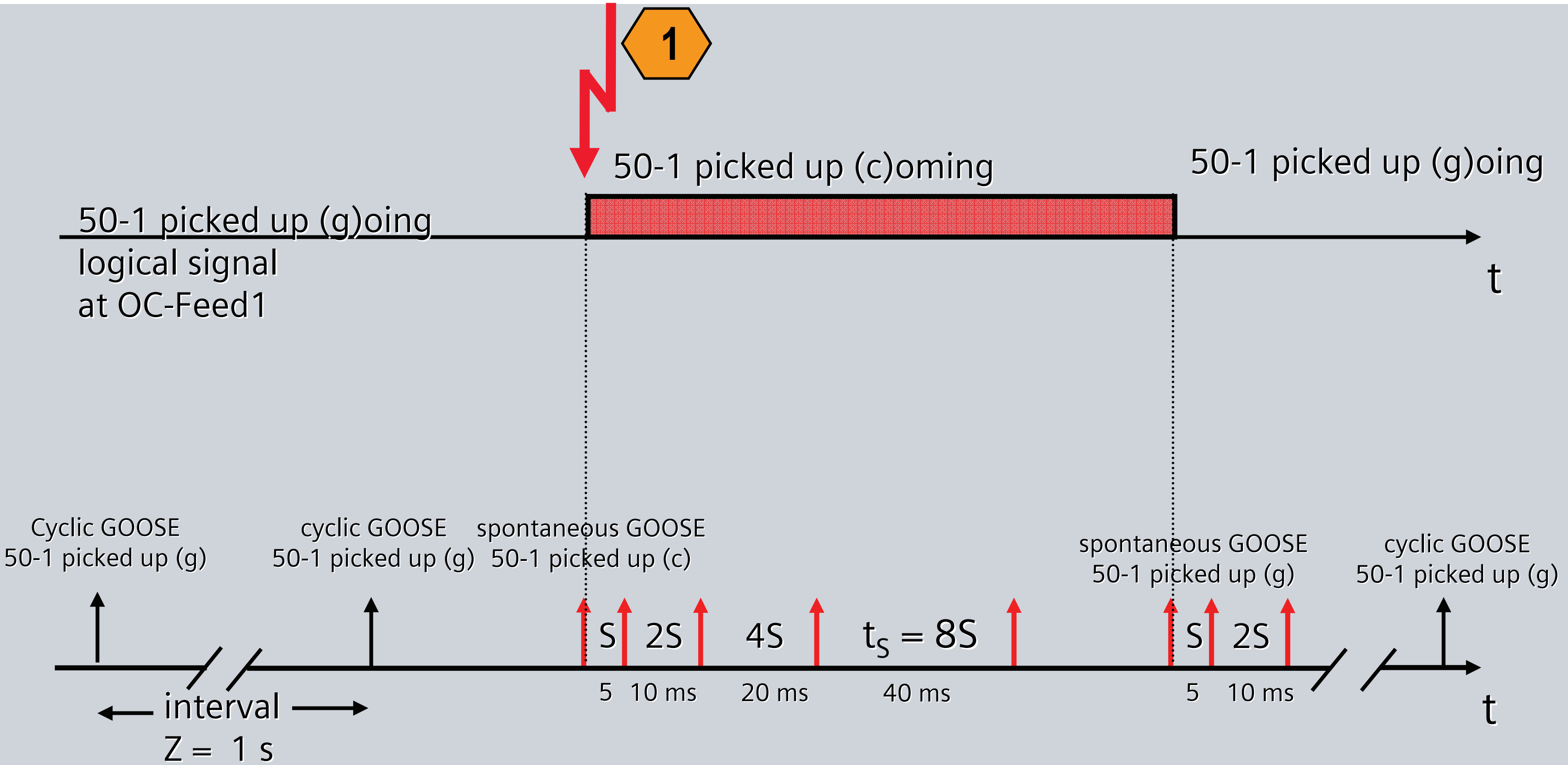
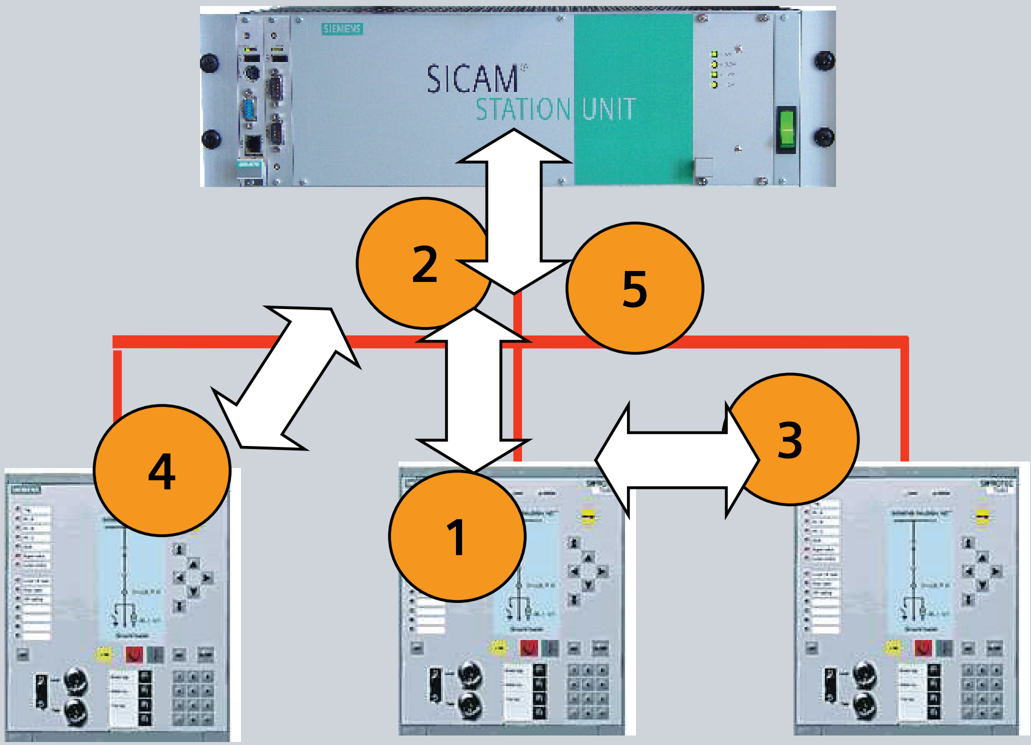


- cycle interval e.g. Z = 1 s (for monitoring of the status of received GOOSE messages at the receiver: here OC-Feed4)
- switch from cyclic to spontaneous when signal changes (50-1 pick up (c))
- N spontaneous repeats $t_S = 2^N * S$ (N=0,1,2,3…for $t_S < Z$, S = 5 ms)
- switch from spontaneous to cyclic when $t_S > Z$

IEC 61850 - Services in SIPROTEC4 and SICAM PAS



1. Control
   - Select before Operate (SBO) with enhanced security → all commands to the HV-process
   - Direct Control with normal security → all auxiliary controls
2. Information Report
   - all information in monitoring direction to the PAS-substation controller
3. GOOSE
   - Inter-device communication → Interlocking, Blocking etc.
4. File Transfer
   - Alarm lists, Event lists, SOE
   - Transmission of fault records
5. Time Synchronisation

etc.

Use of Services for SAS-Applications (1)

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SAS-Application	Service in IEC 61850-7-2	Mapping IEC 61850-8-1	Remarks
Control	Select before operate (SBO) with enhanced security Direct control with normal / enhanced security	MMS-Write MMS-InformationReport	SBOwES necessary for HV equipment for of safety reasons
Monitoring, Reporting, SCADA	Unbuffered reporting	MMS-InformationReport	InformationReport controls by change of state, value, qua-lity for spontenous change of informa-tion; with polling loss of information
Interbay communicaton for e.g. exchange of status information for interlocking, blocking of protection functions etc.	GOOSE	Direct on Ethertype	Multicast messaging with priorization by tagging in the Ethertypes

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Use of Services for SAS-Applications (2)

SAS-Application	**Service in IEC 61850-7-2**	**Mapping IEC 61850-8-1**	**Remarks**
Change of parameter sets	Substitution Activation of parameter sets	MMS-Write	
Time synchonisation	Standardized Services	SNTP	
Transmission of fault records with file transfer	GetFile GetFileAttributeValues, GetDirectory	MMS-fileRead, MMS-Optainfile	
General interrogation	Unbuffered Reporting	MMS-InformationReport	
Self Monitoring of SAS	-	IEC 61850-Keep alive process for servers GetDomainList for clients	Automatically checked
Engineering	OPC-server (like in MMS-explorer) can only be configured online (real devices while engineering are necessary, IEC61850 defines engineering with substation configuration description language (SCL) with the systemconfigurator-tool		

SICAM PAS
Redundant Communication

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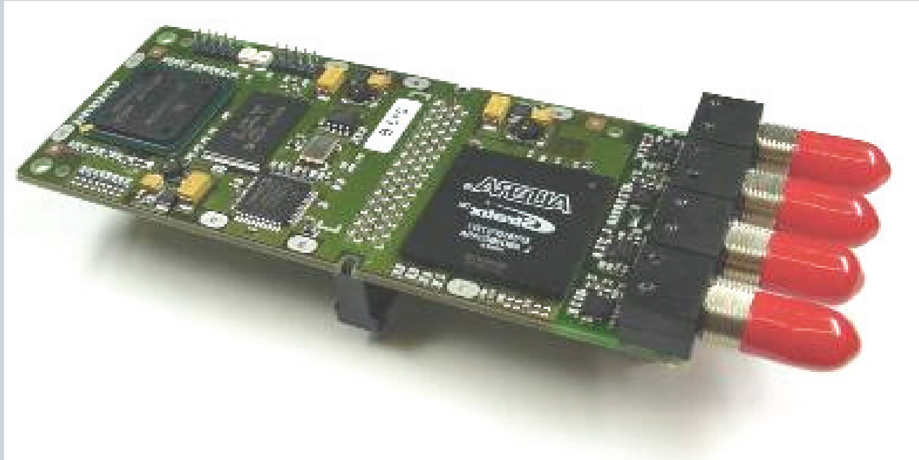
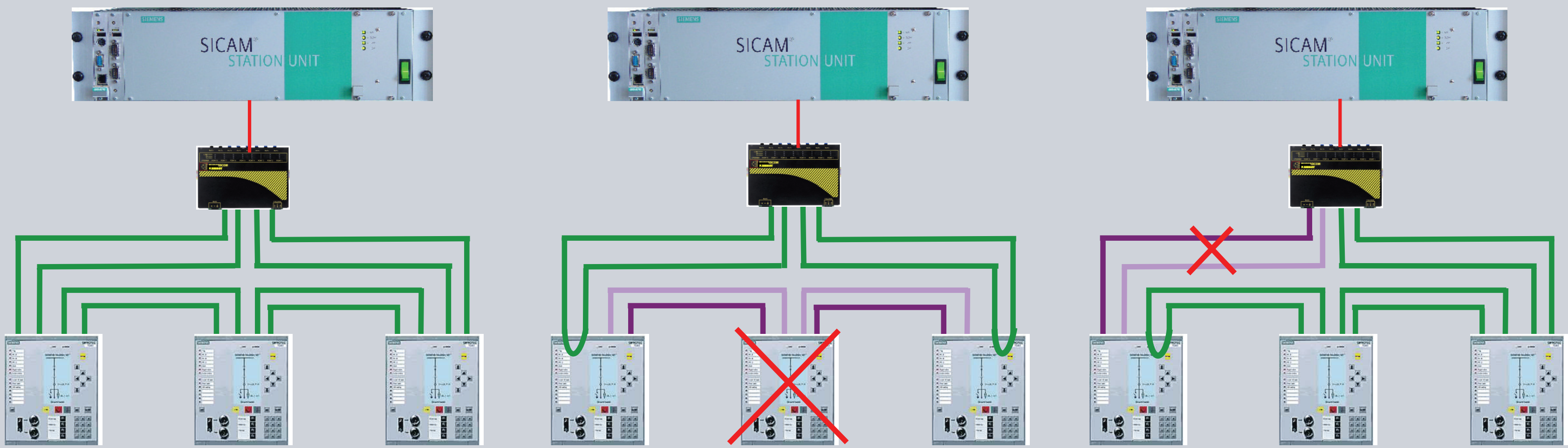
Fully redundant →
optimized for communication to bay controller / Protection relays

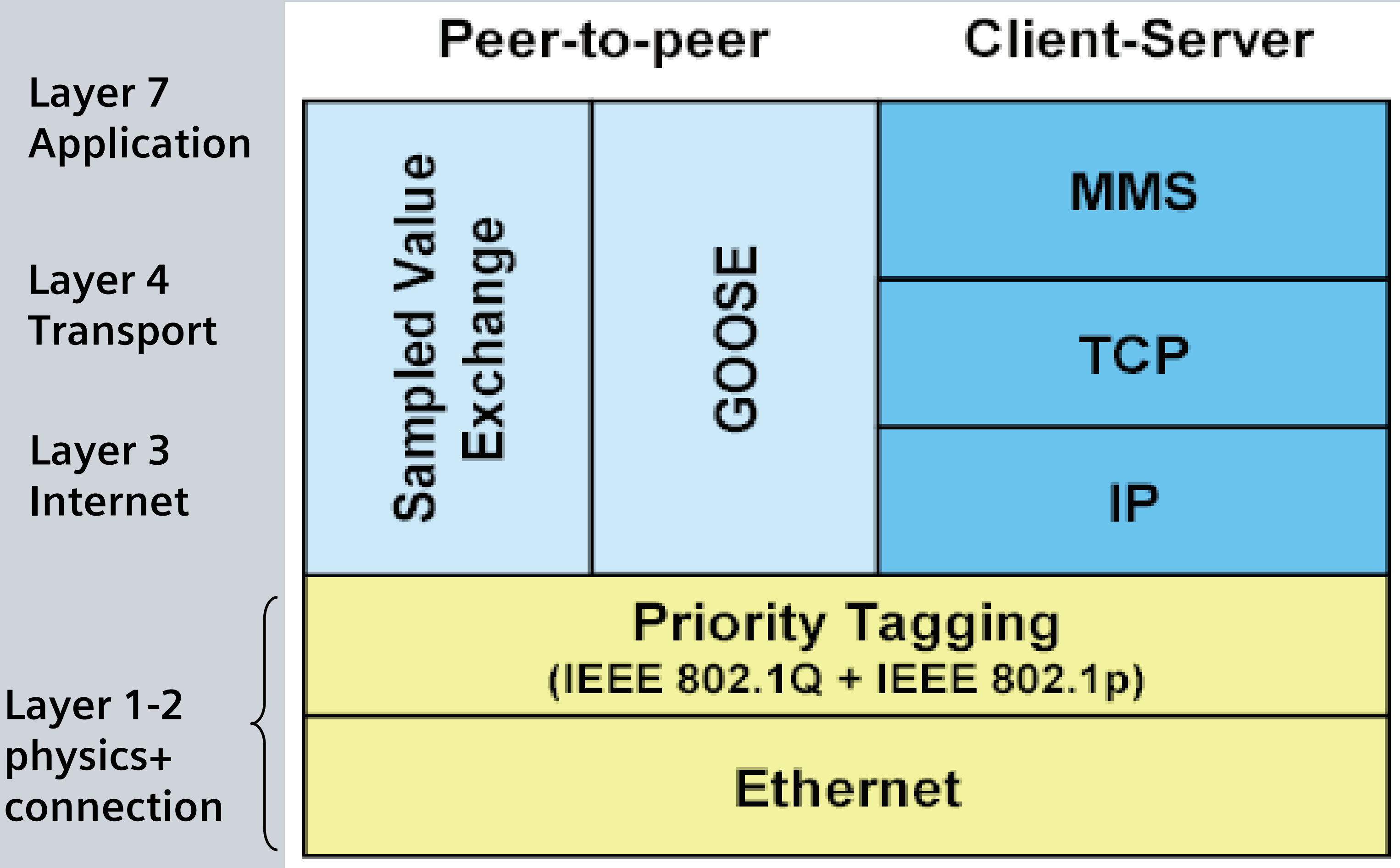
Self healing mechanisms for high relaibility



- OFC Ring (fullduplex)
- Device failure
- OFC failure



Protocol stack of IEC 61850



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Benefits of IEC 61850-9-2 Process Bus

- Standardized communication interface on Ethernet
- Enabling Non Conventional Instrument Transformer Technology
- Saves cables and other hardware structures
- Saving engineering efforts
- Eases installation and maintenance
- Base for intelligent switchgear and extended monitoring features

Transmission of Sampled Values: basic system

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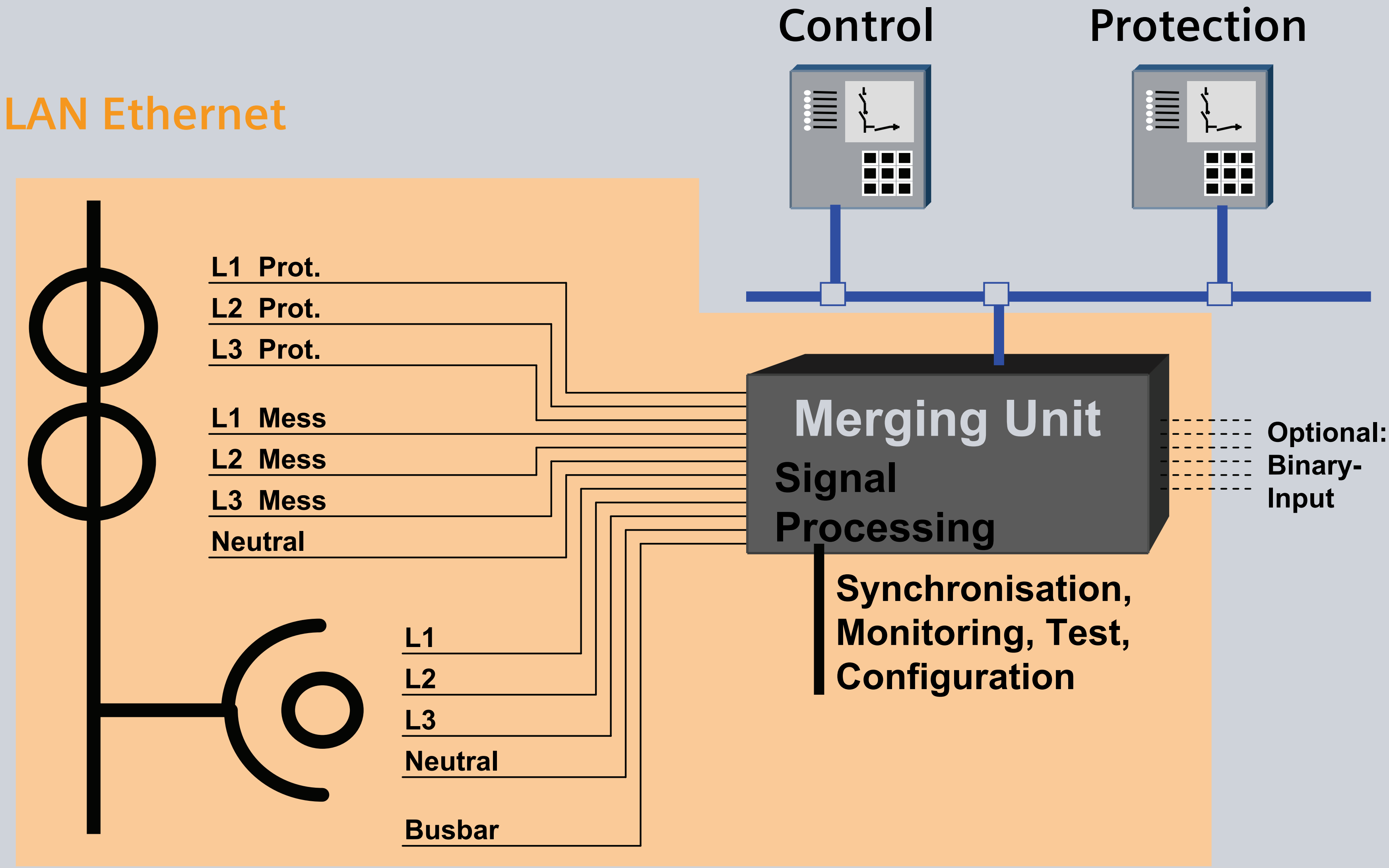

System architecture with station bus (ring) and process bus (possible conventional configuration)

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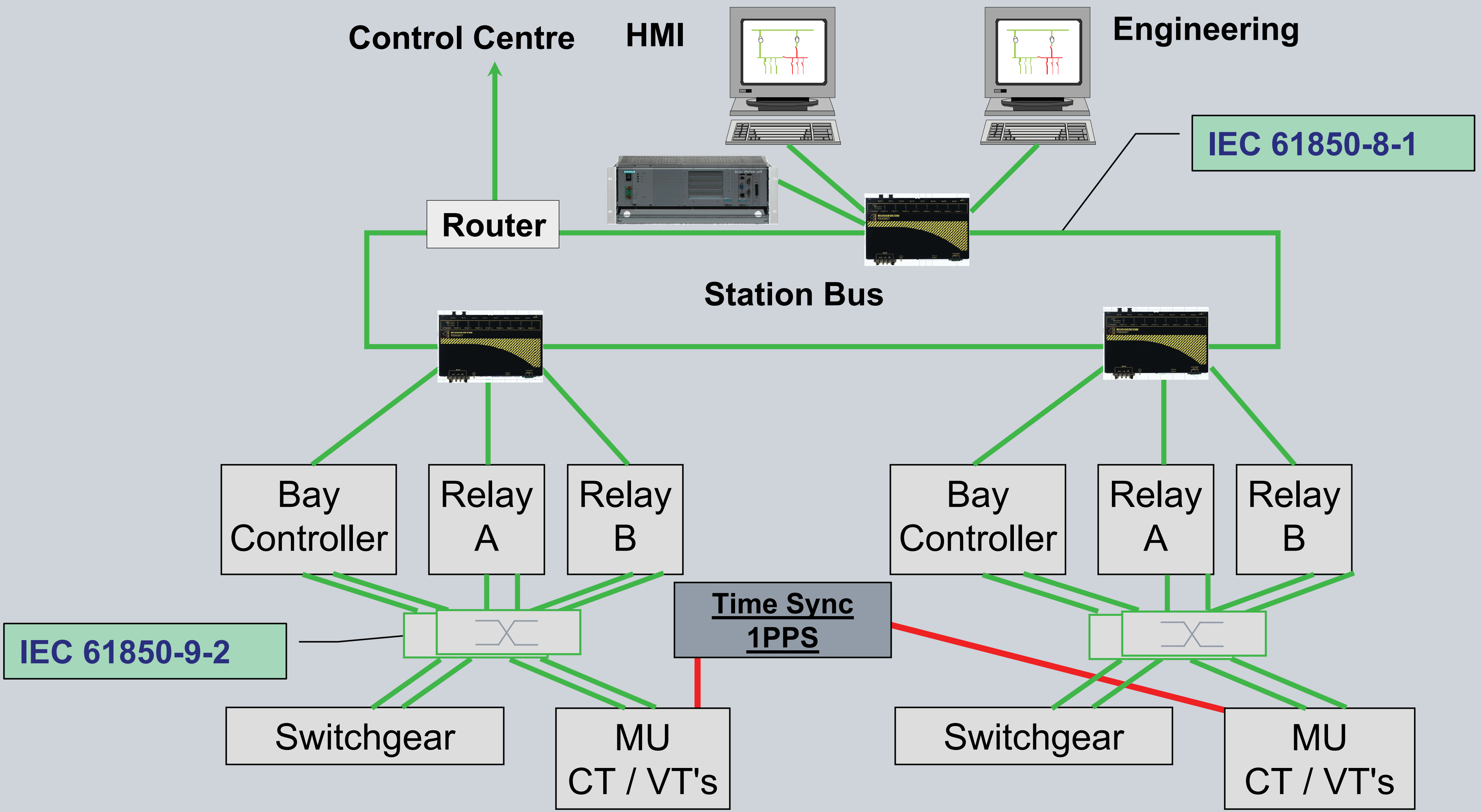

Benefits of IEC 61850-9-2 based on Real Time Ethernet

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- **Real Bandwidth Reservation**
  Guaranteed response times

- **No-Dropout Ring Redundancy**
  In the case of interruption not even one telegram gets lost

- **< 1µs Time Sync via the Ethernet**
  IEEE 1688 Precision Time Protocol
  20ns time sync jitter pro switching hop
  Redundancy for the time sync as well

- **Real Time and non-Real-Time (TCP/IP) on the same wire/fiber**
  Monitoring and Controls as well as SV and Trip-GOOSE

System architecture with station bus (ring) and process bus (Real Time Ethernet)

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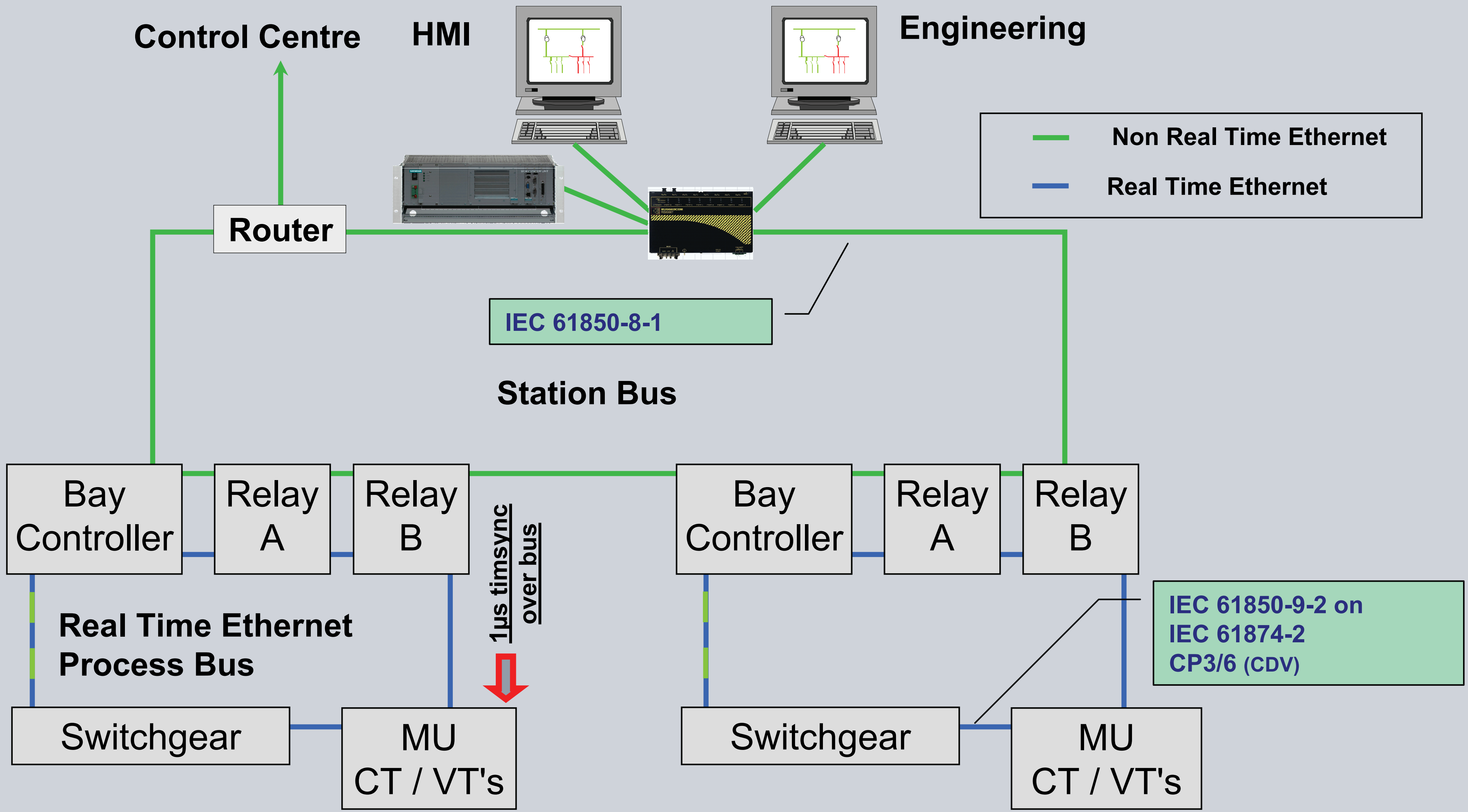
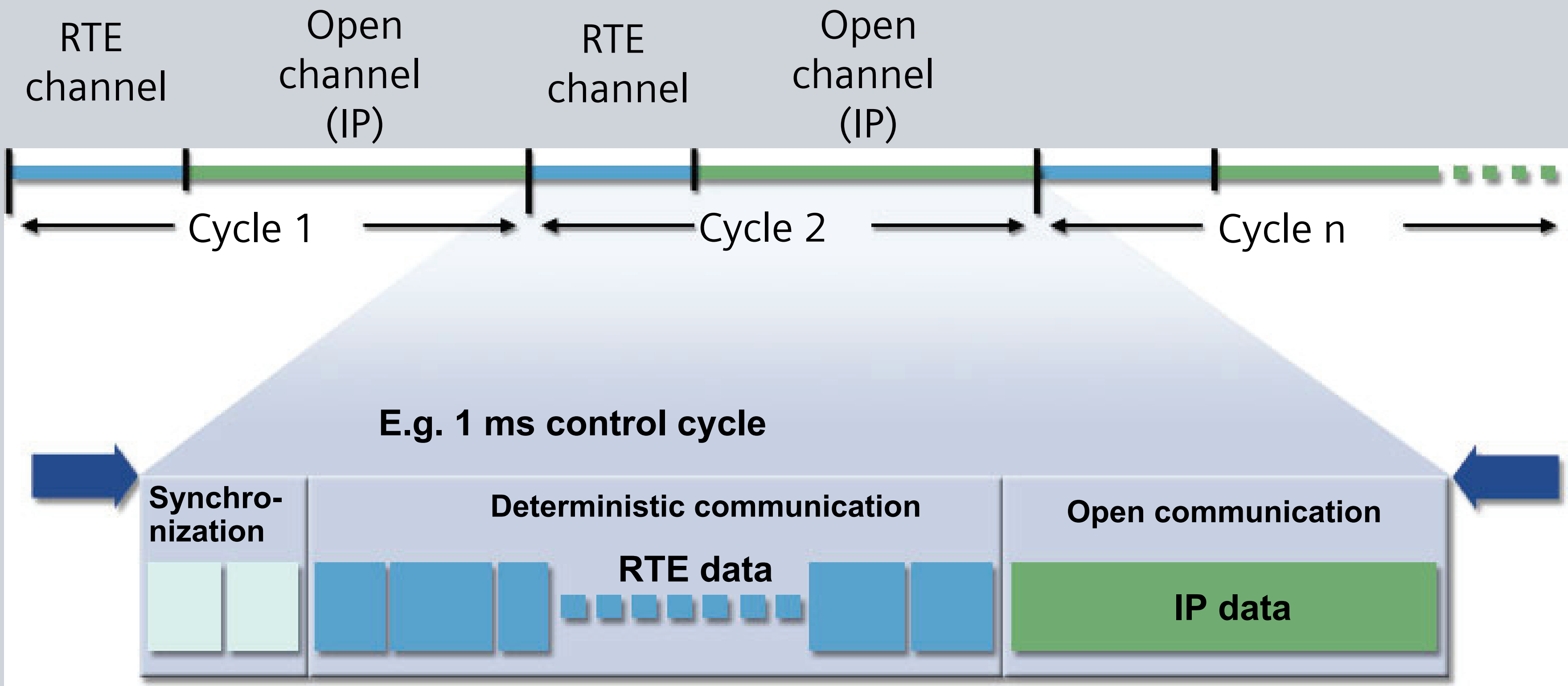


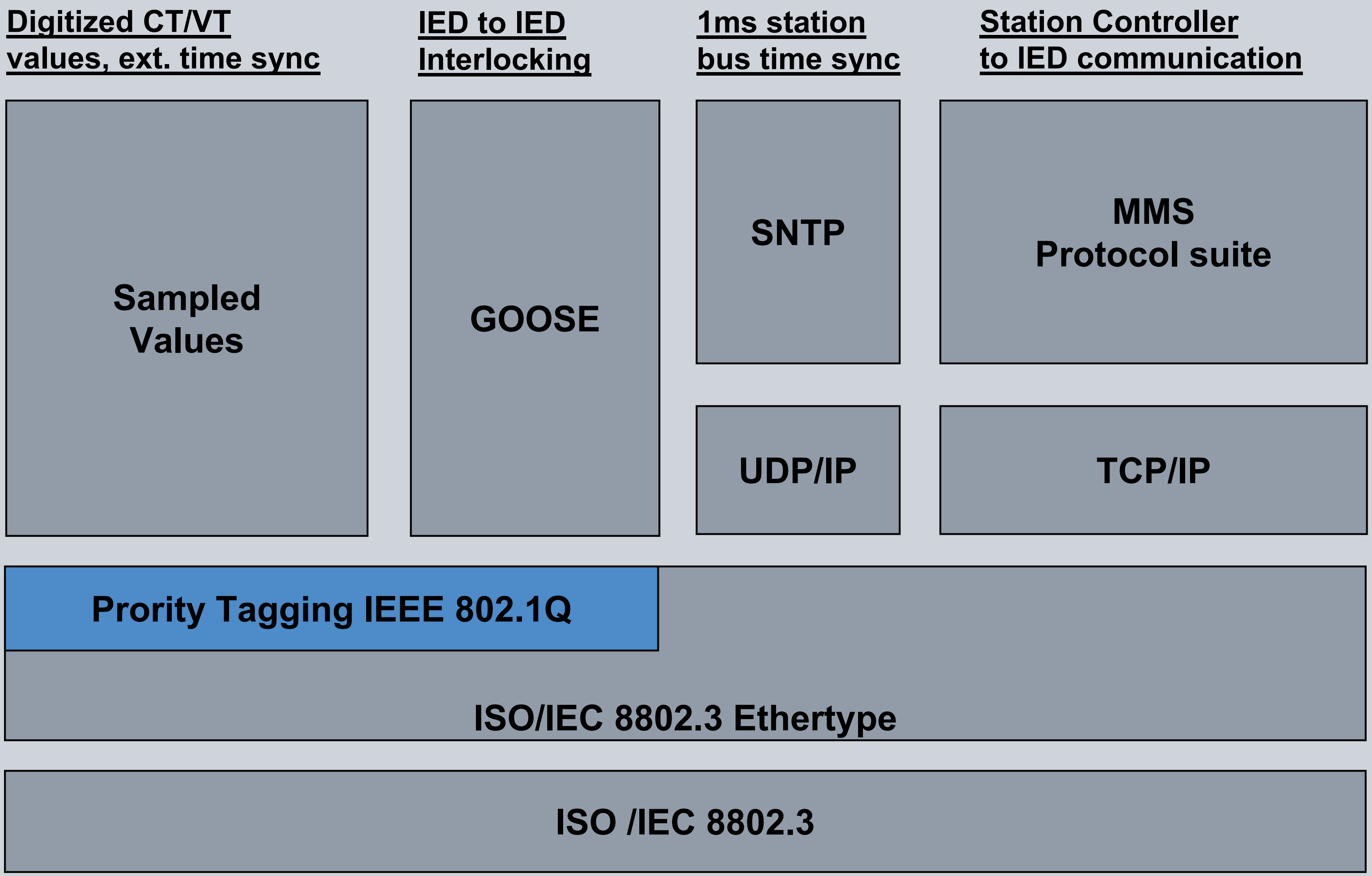
What is new with Real Time Ethernet?

Communication system scheduling

- separate time domains for real-time and non-real-time -

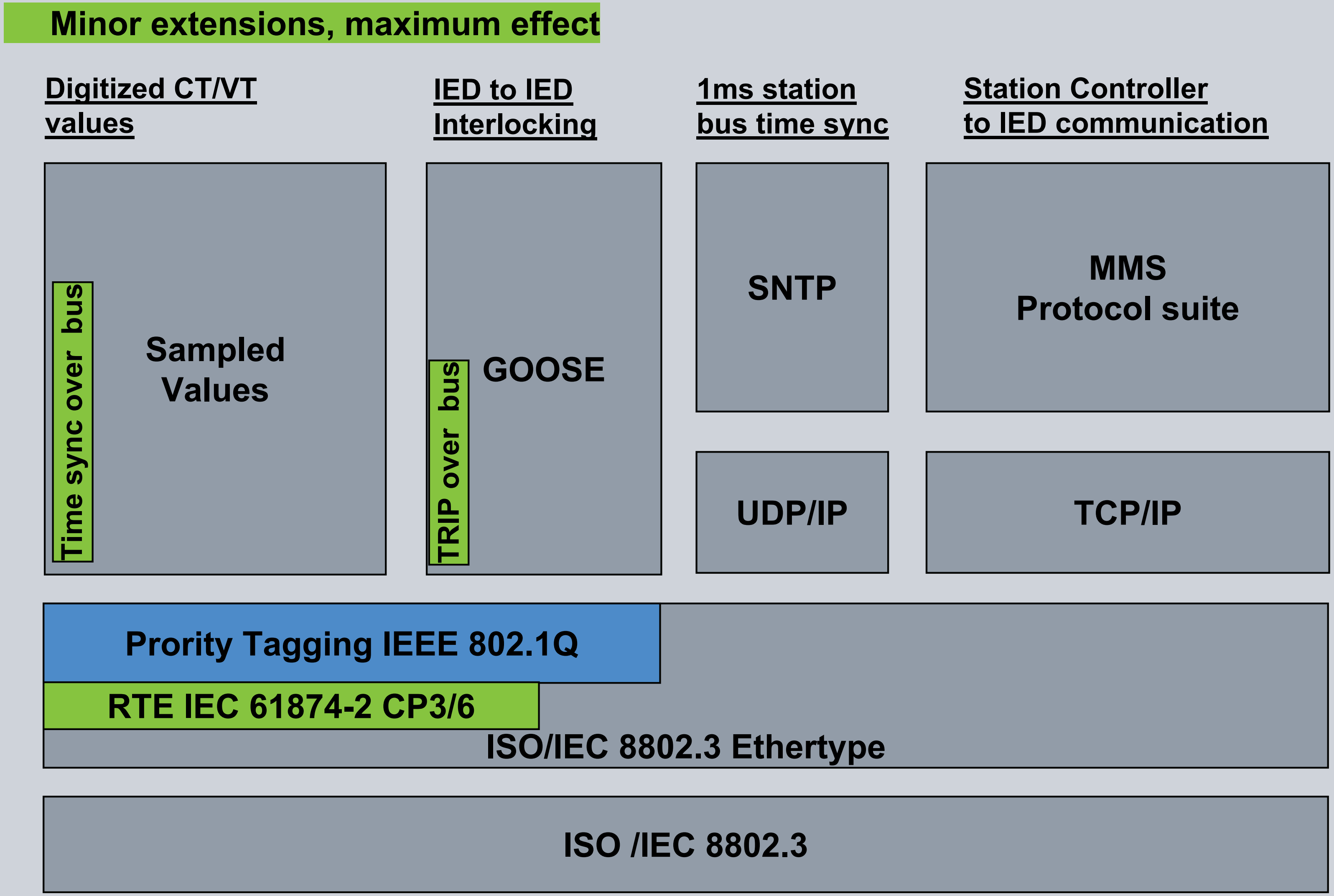


Recent IEC 61850 Protocol Stack

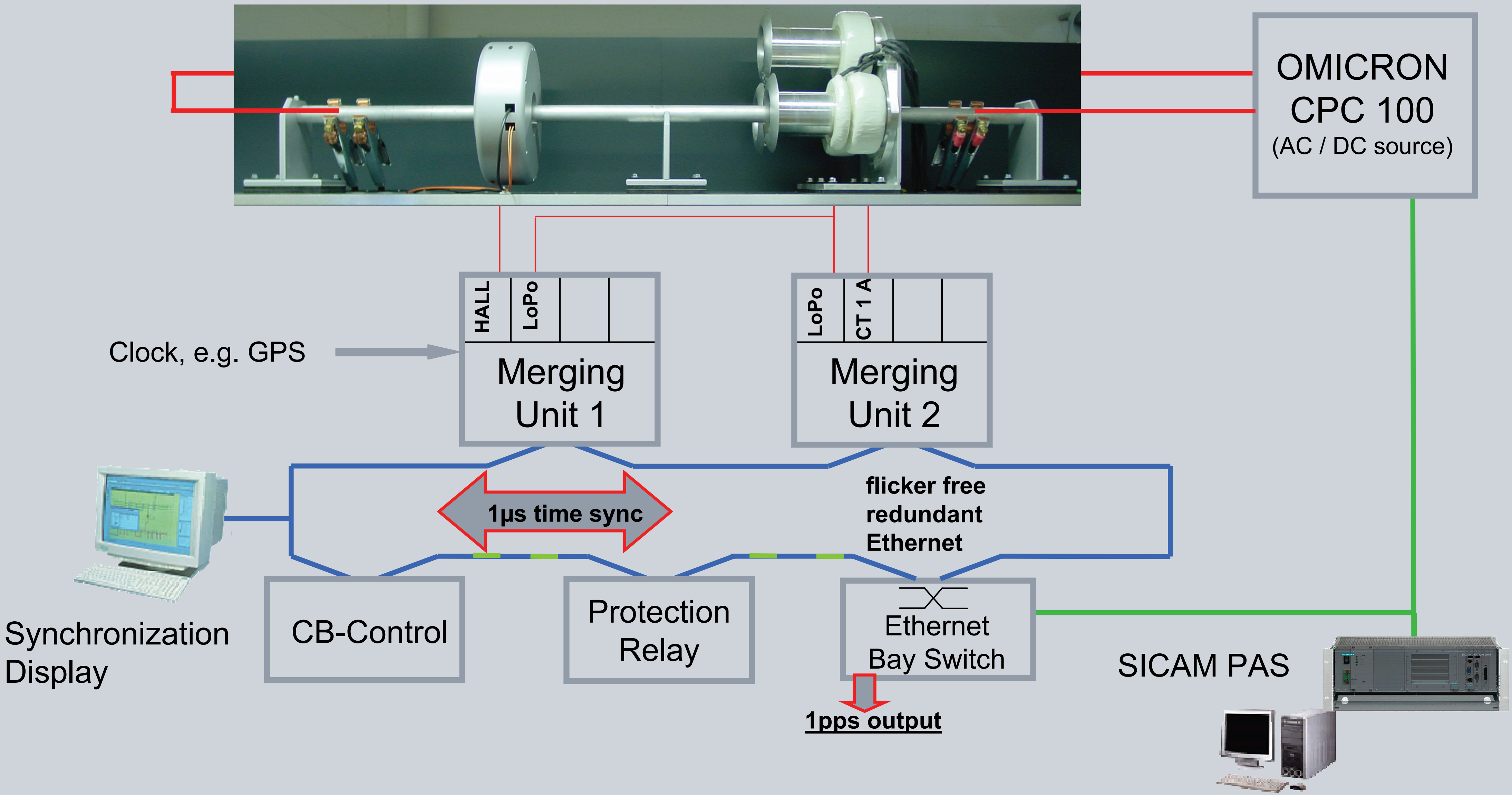


GSSE („UCA-Goose) on LLC
MMS optional on LLC

IEC 61850 Protocol Stack combined with RTE



Demo Siemens Stand CIGRE 2006



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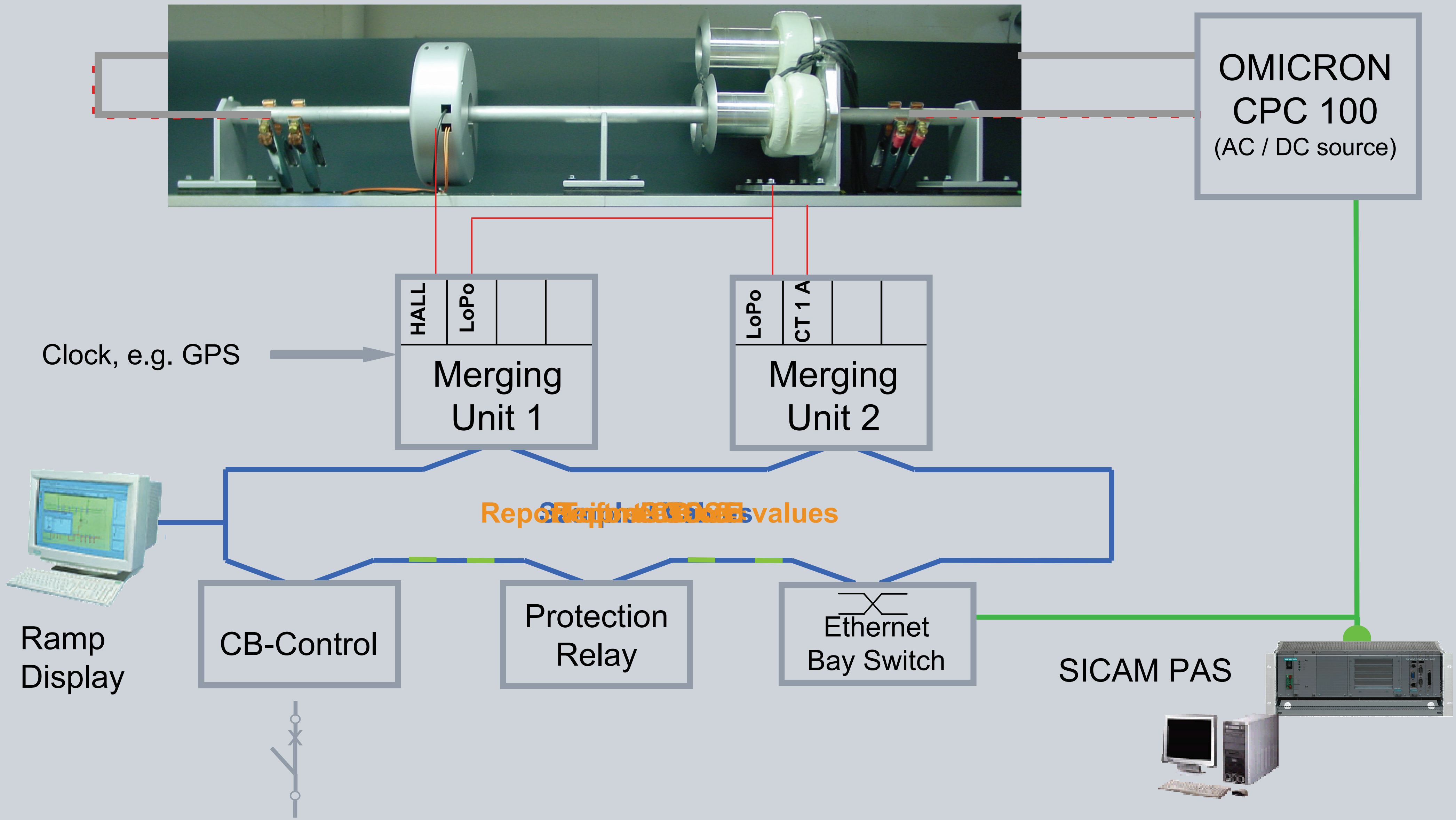
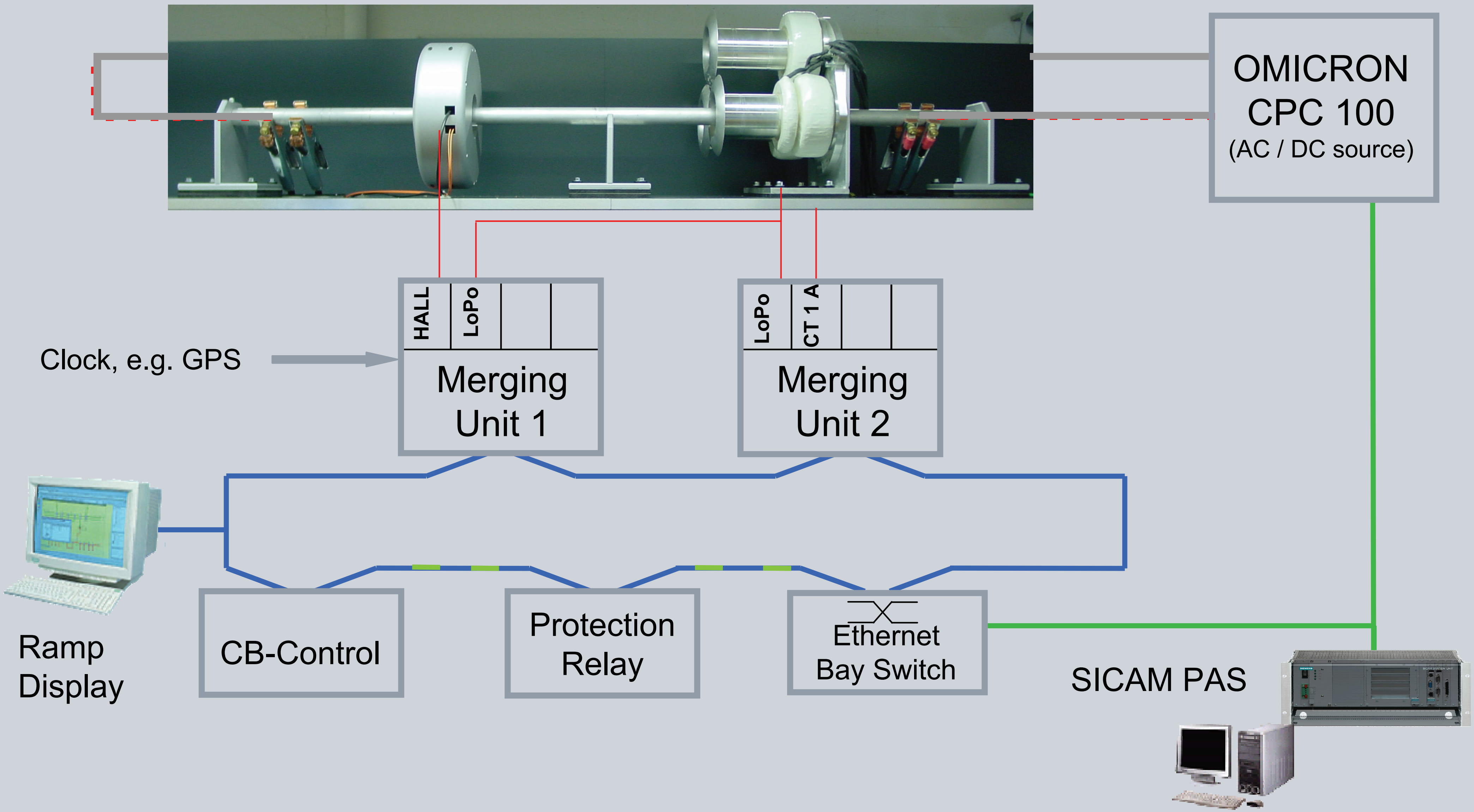
Process Bus Demo Application

- Close CB by a IEC 61850-8-1 control signal from SICAM PAS
- Closing the CB starts the sequence of Omicron stepwise increasing the current, 300 to 1500 A
- Conventional, LoPo and Hall Sensor connected to both MU's measure the current LoPo is connected to both of the MU's
- Sampled Current is transmitted via IEC 61850-9-2 LE to the relay. Relay reports RMS measures to SICAM PAS
- Protection device sends a Trip-GOOSE to CB Controller at 1200 A; Omicron de energizes the line
- CB sends a report to SICAM PAS

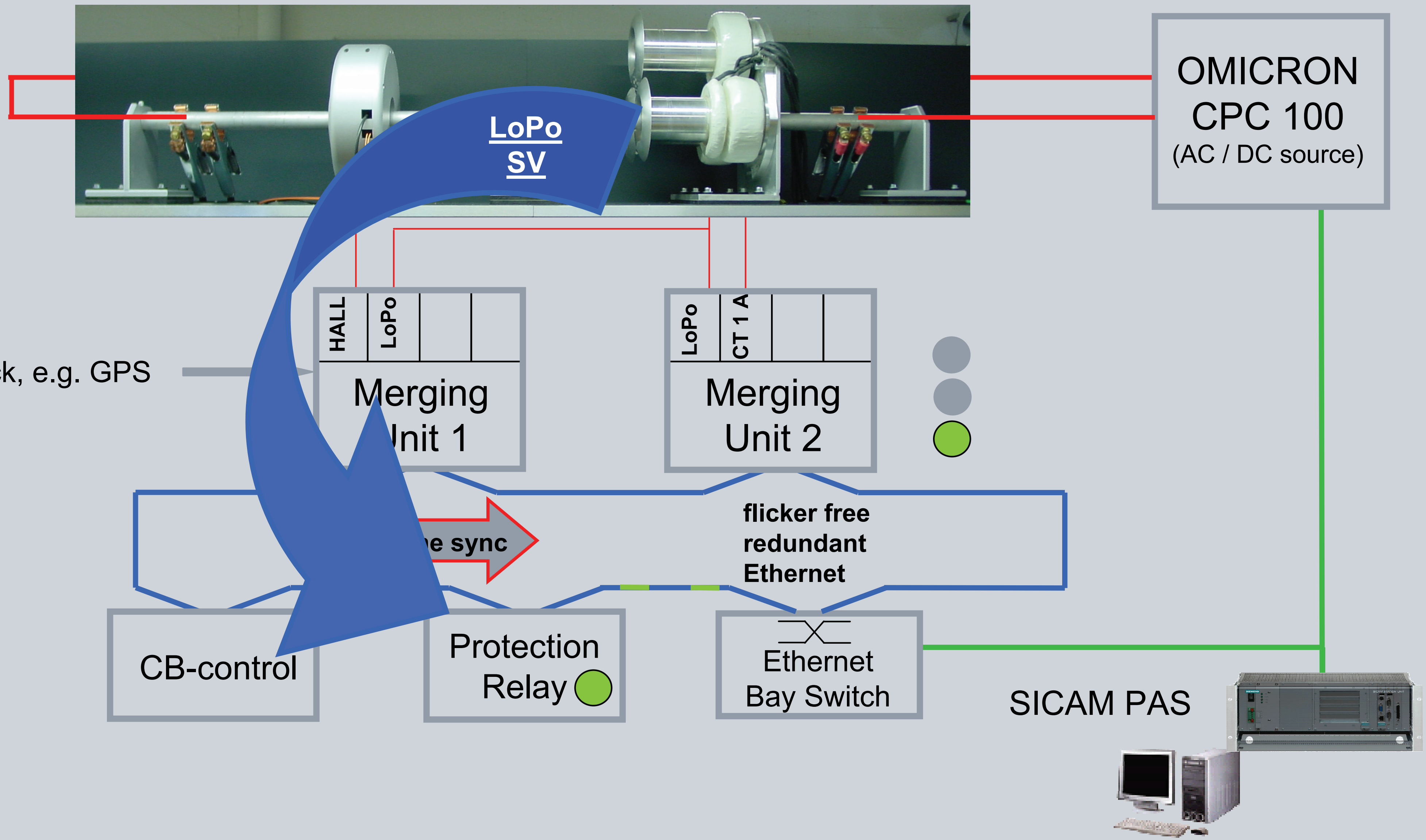
Demo Siemens Stand CIGRE 2006



Demo Siemens Stand CIGRE 2006



Evidence: Redundancy:
Transmission of LoPo Values to Relay



Evidence Redundancy: Normal Operation

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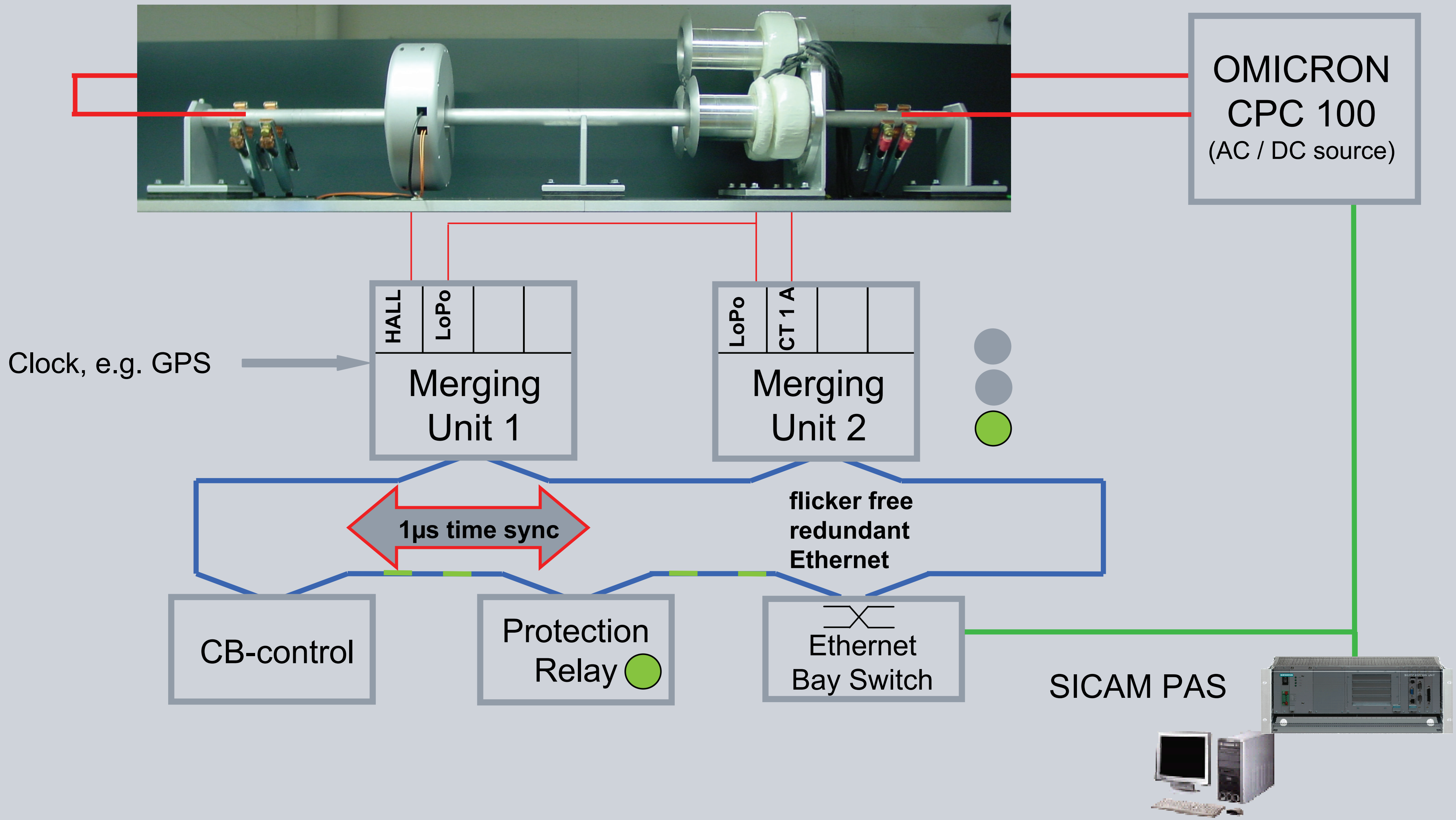

Evidence Redundancy:
Bus cut, relay shows no effect

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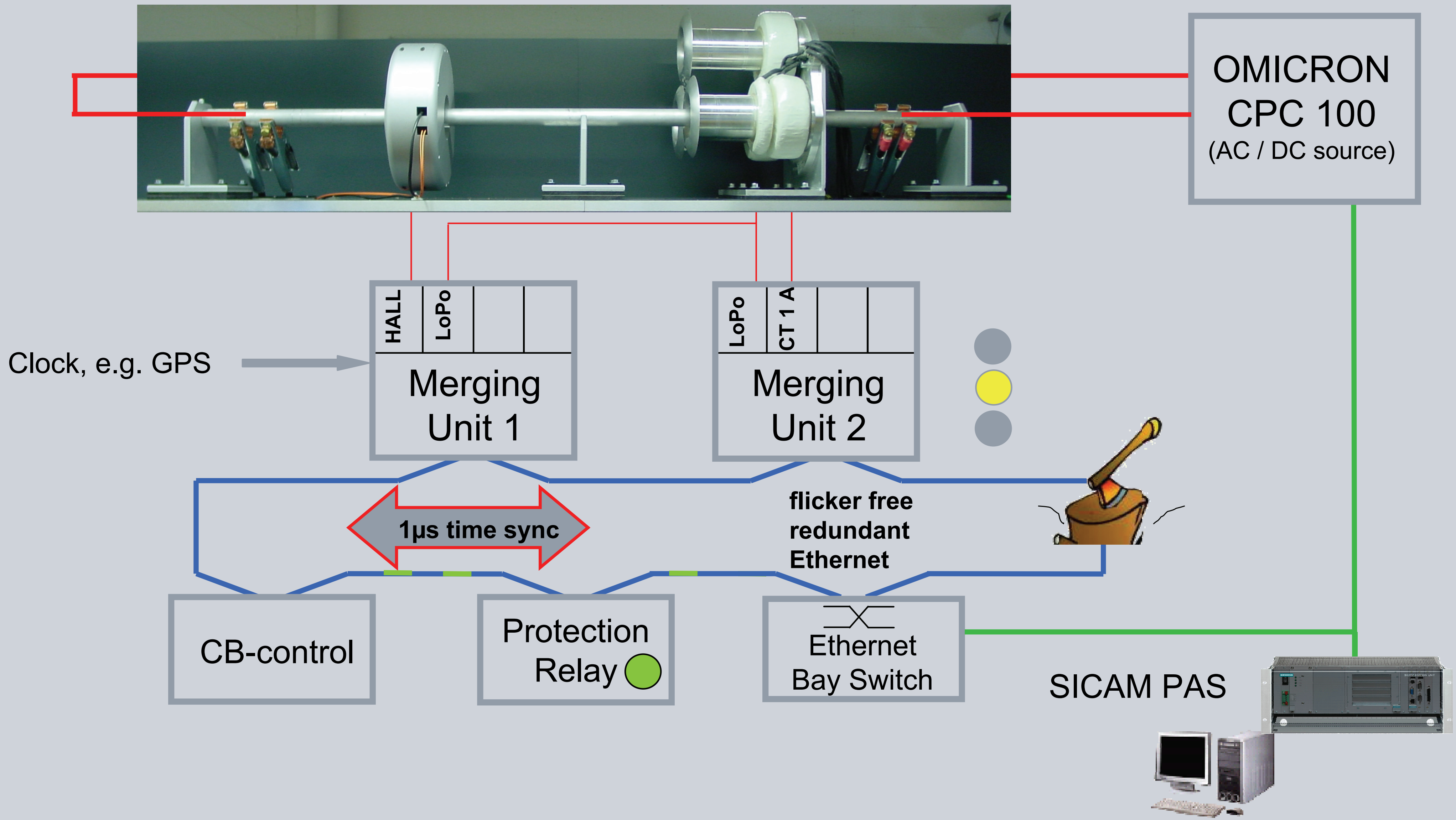

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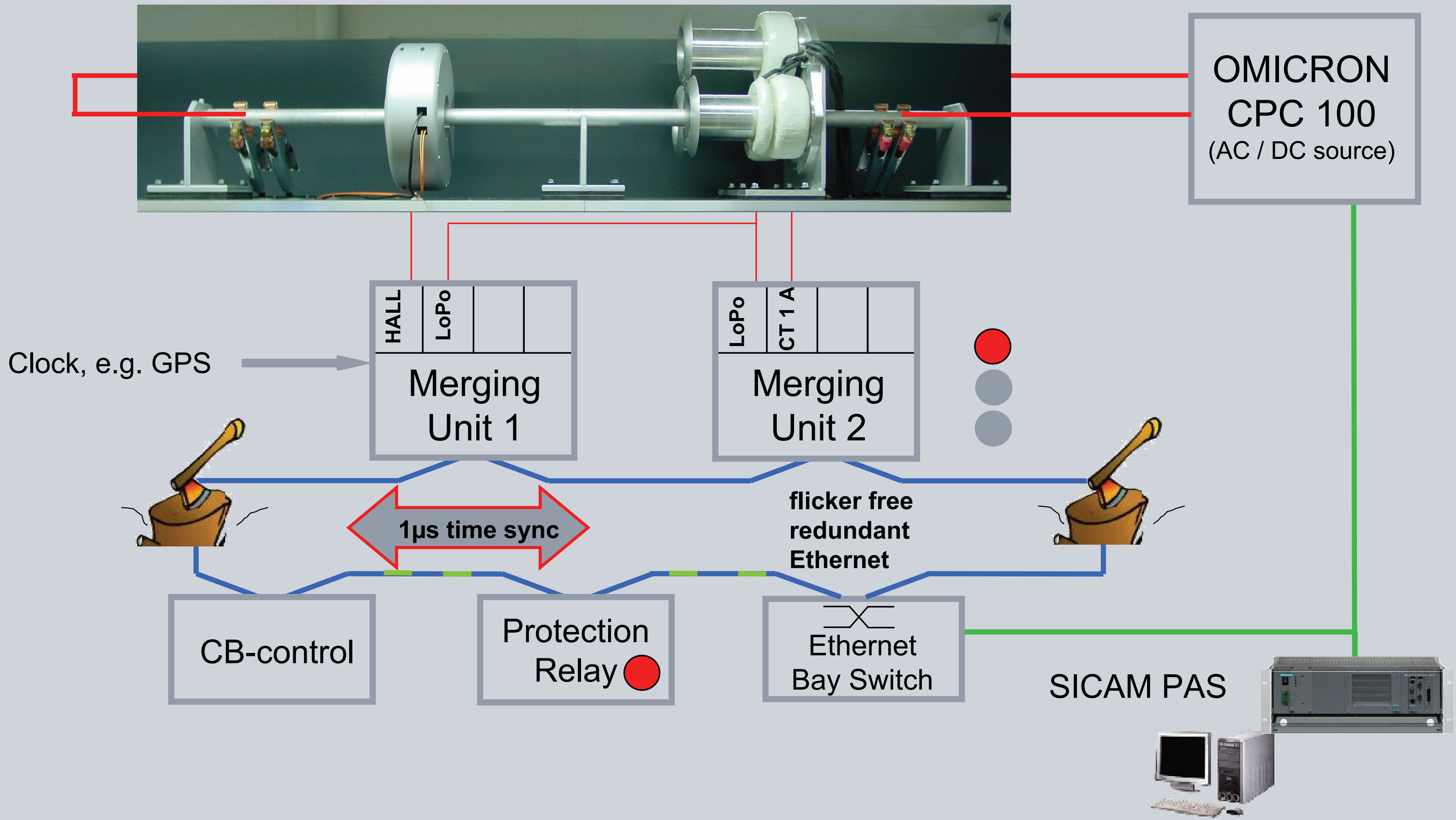
Evidence Redundancy:
Second bus cut (n-2) , relay shows error



Presentation of Prototyp with Real Time Ethernet CIGRE conference Paris 2006

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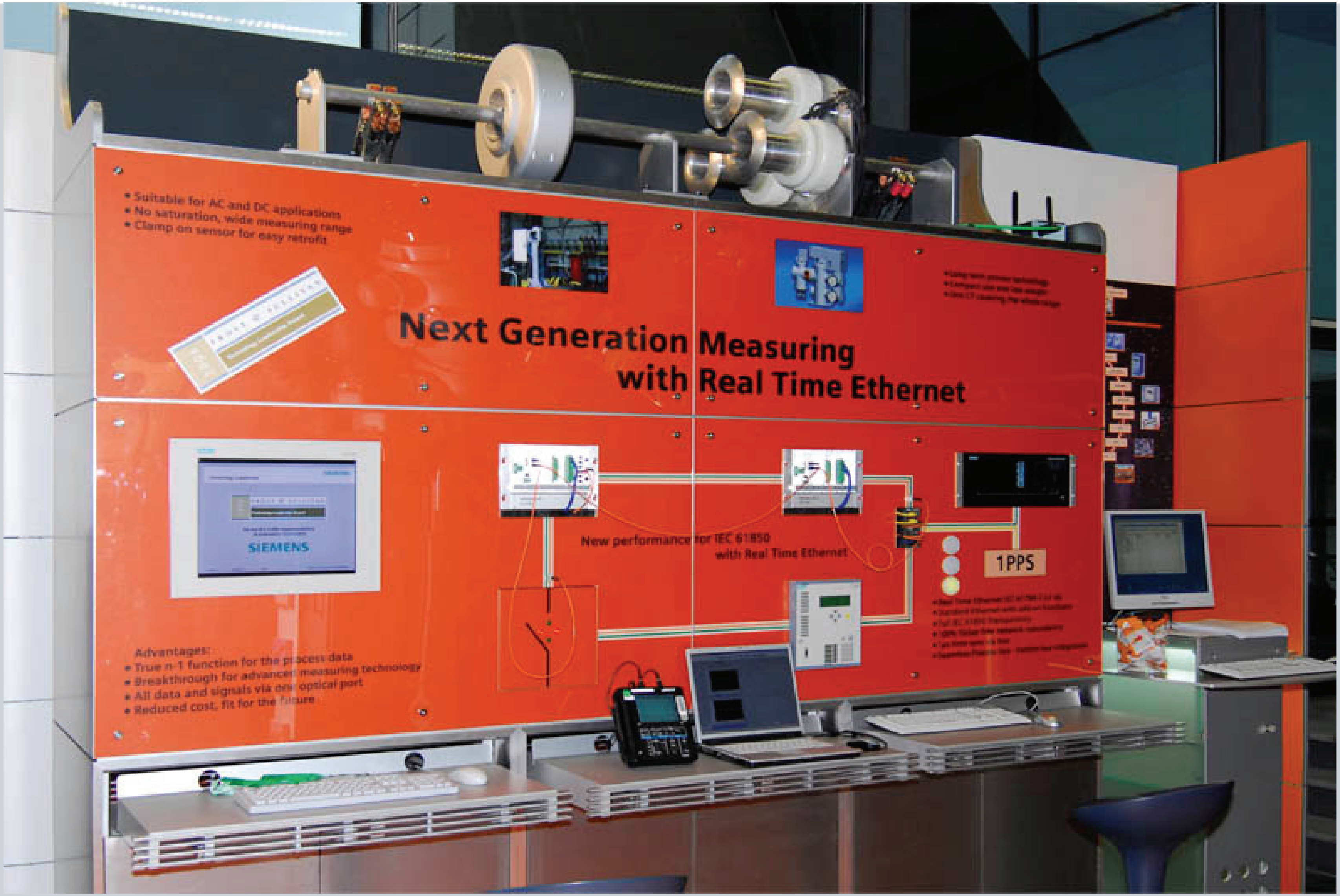
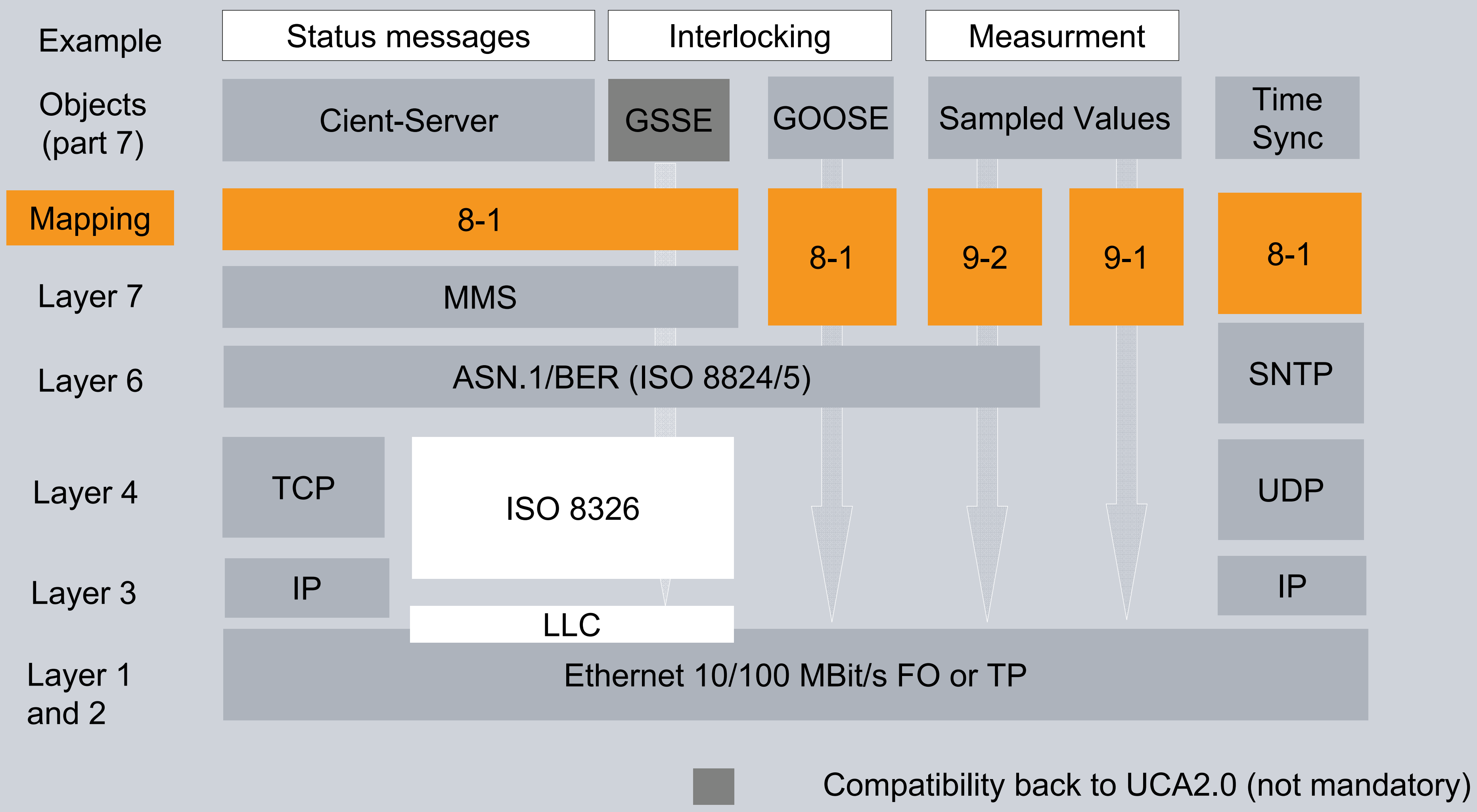


Protocol stack of IEC 61850

Assignment Functions, Services and Protocols



System configurator for managing the exchange of information on the station bus

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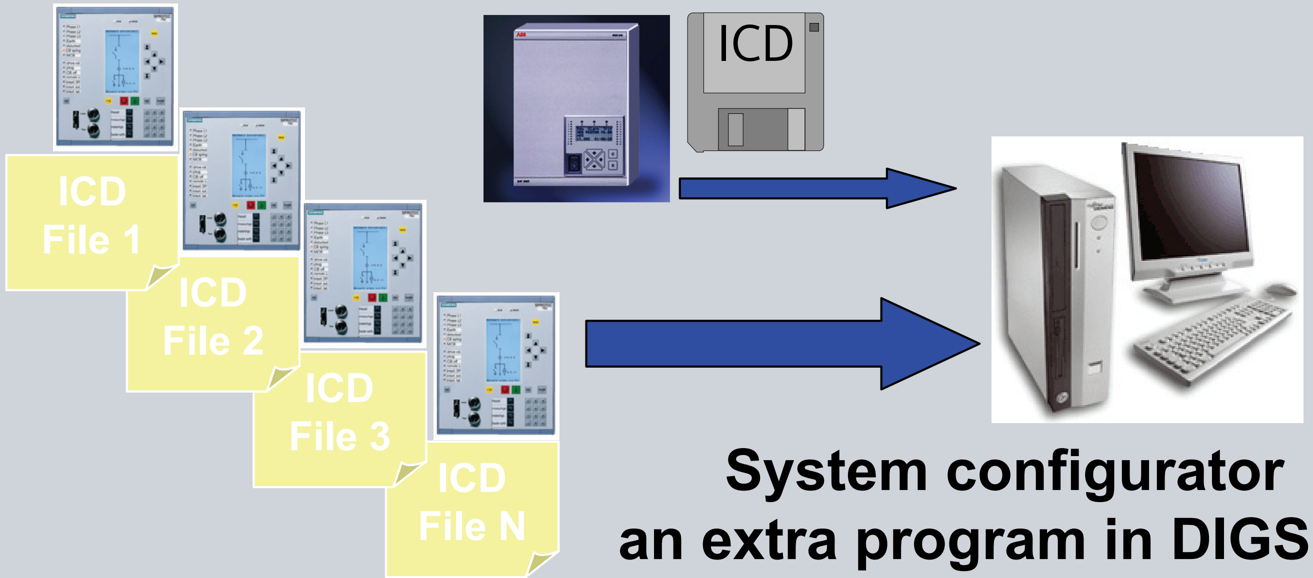


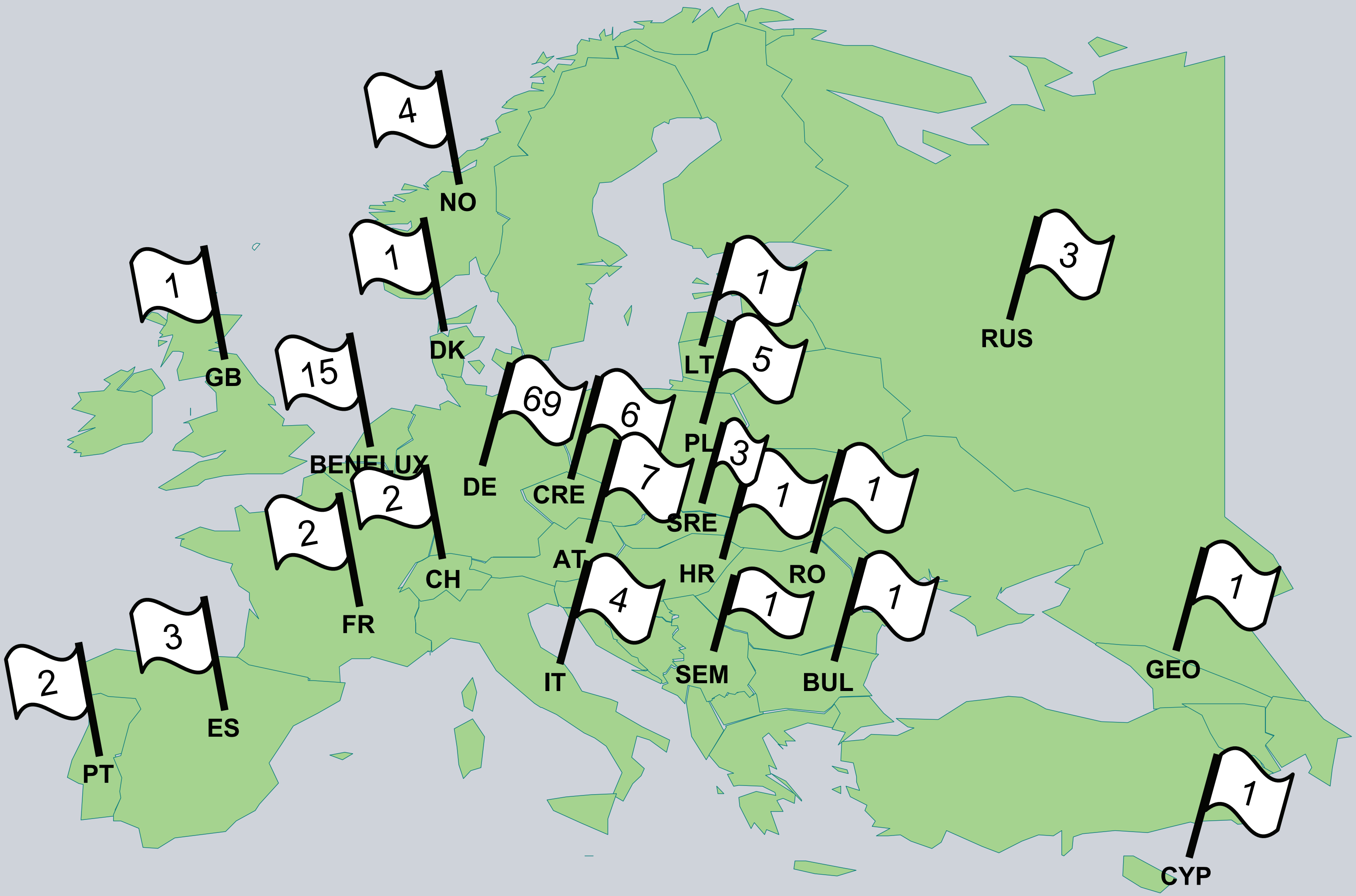
SCL – Substation Configuration Language

System configurator
an extra program in DIGSI 4

- ICD and SCL according to Part 6 of IEC 61850
  - Description of logical nodes of a device confirming to the standard (ICD): (protection functions, control commands and measured values etc.)
  - Full description of substation and communication relationships (SCD)

In DIGSI 4 information for the system interface is assigned and logical plans are designed in the CFC-logic editor.
In the System Configurator, information between devices is assigned.

Our Experience:
IEC 61850 Projects - Europe



Our Experience:
IEC 61850 Projects – World without Europe

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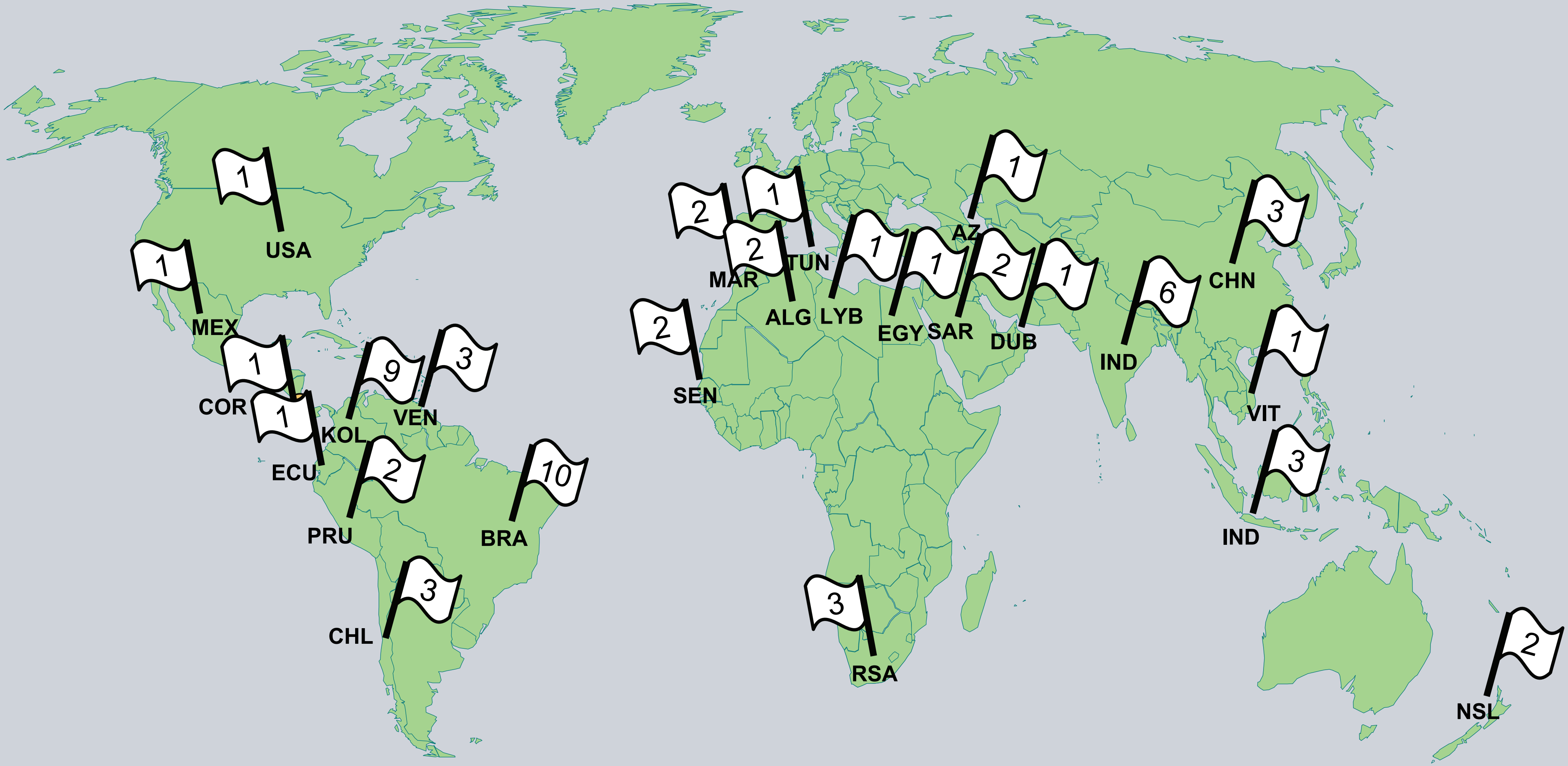

Reference list

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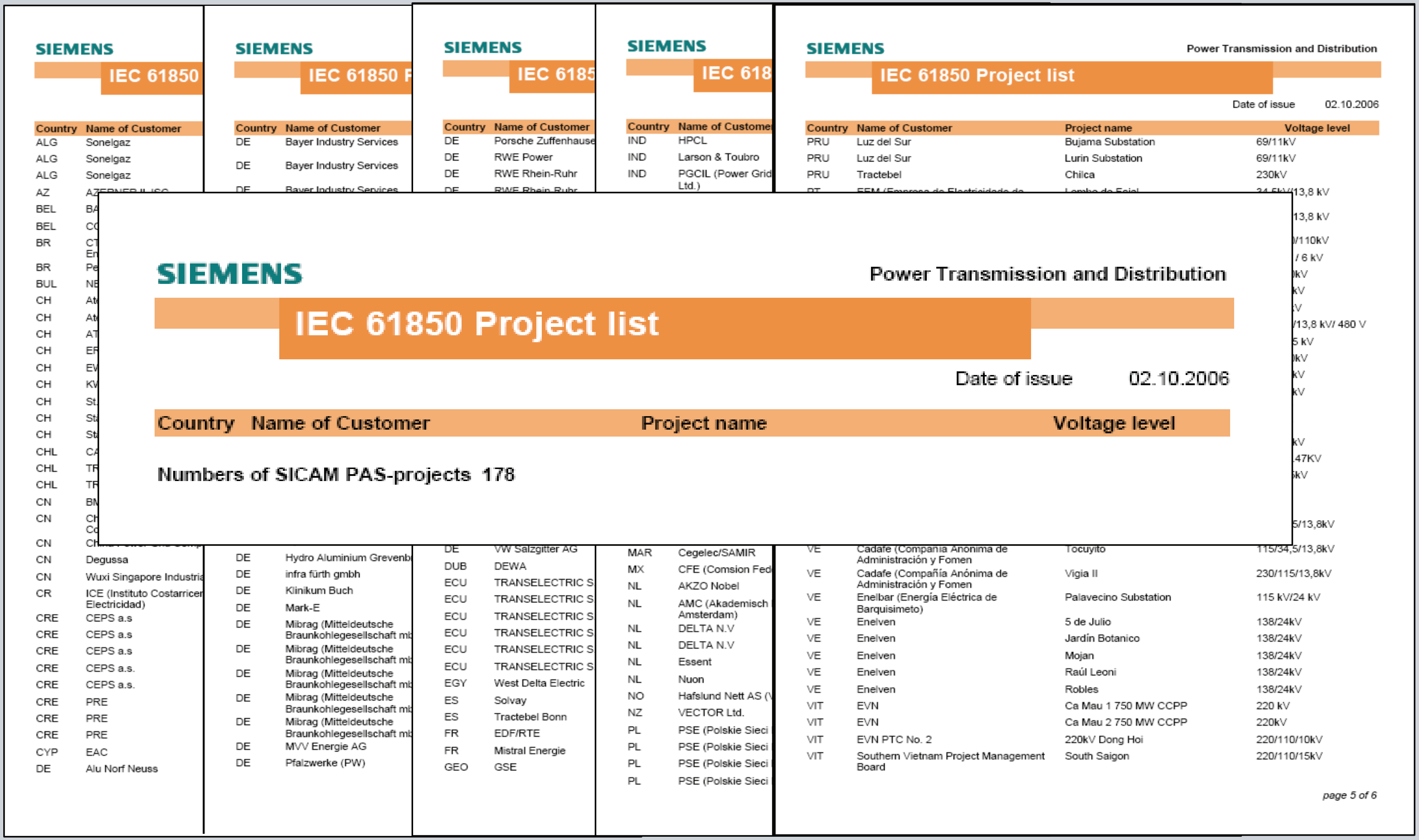

Project Opencast mining Garzweiler II, Germany

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- Customer: **RWE Power**
- Contract Award: **summer 2003**
- Main part in operation: **April 2005**
- Substation: **110, 25 & 6kV**
  - Number of bays: **134**
  - Application: power for **opencast mines** delivering coal to 4 power stations

Project Opencast mining Garzweiler II, Germany

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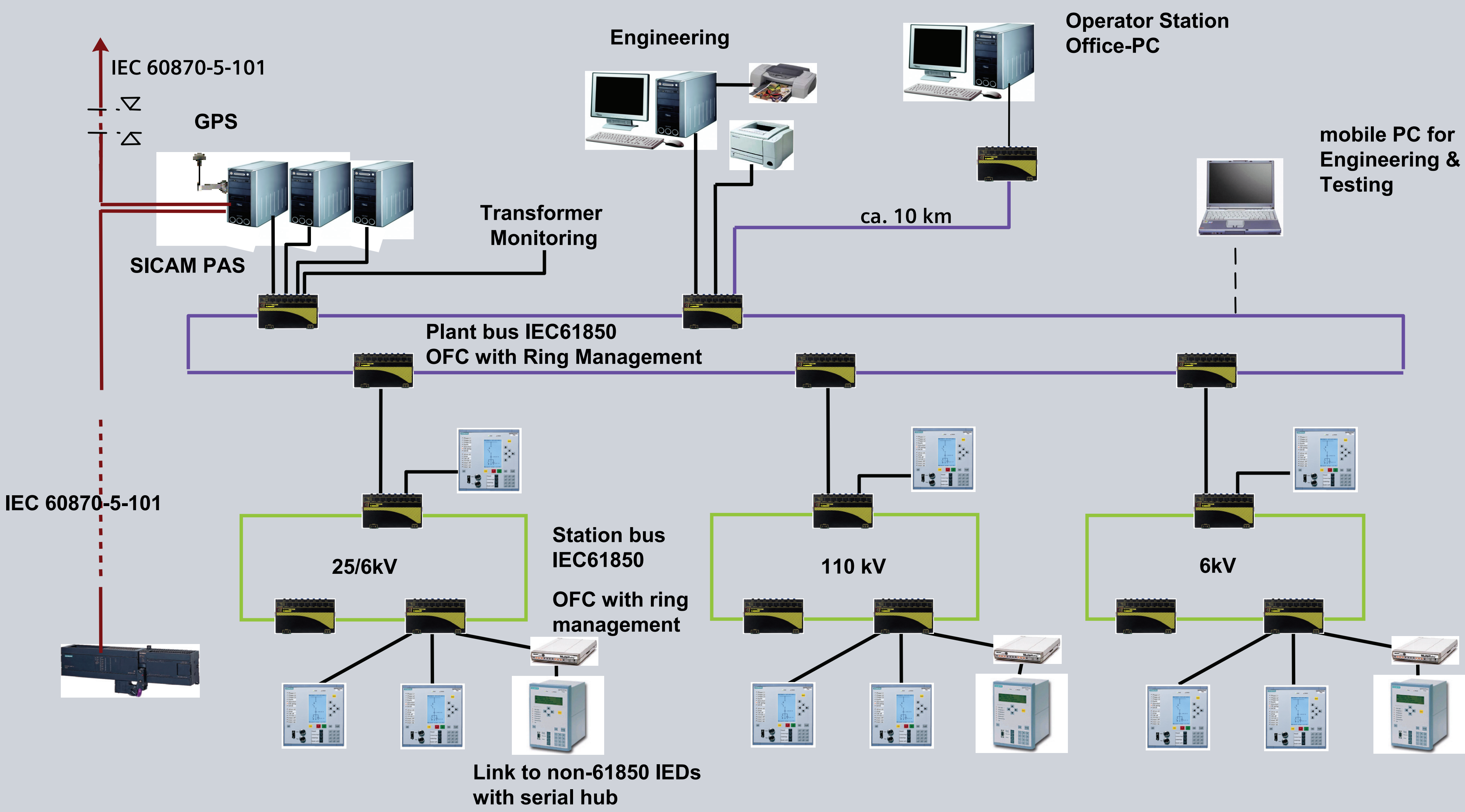

Project Opencast mining Garzweiler II, Germany

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Project start: summer 2003   Commissioning: April 2005

SICAM PAS & IEC 61850
500kV Nanqiao Substation

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- costumer: Shanghai Extra High Voltage Company
- Sign of the contract: December 2004
- in operation: November 2005
- Switchgear
  - 500, 220 & 35kV
  - ca. 40 Bays
  - 82 IEC 61850 Devices

SICAM PAS & IEC 61850
500kV Nanqiao Substation

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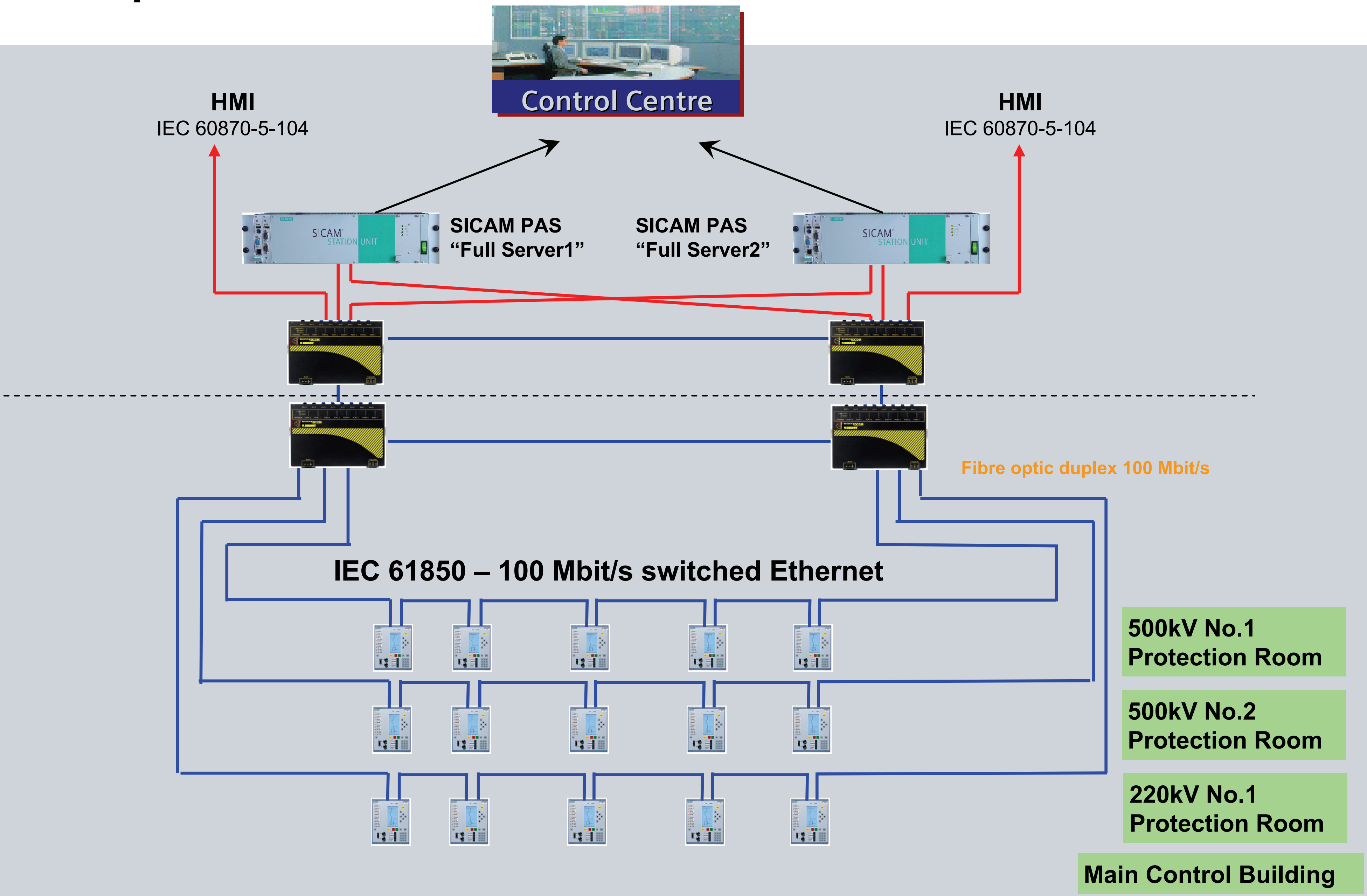

IEC 61850 Network configuration
Large System with EN100 Moduls

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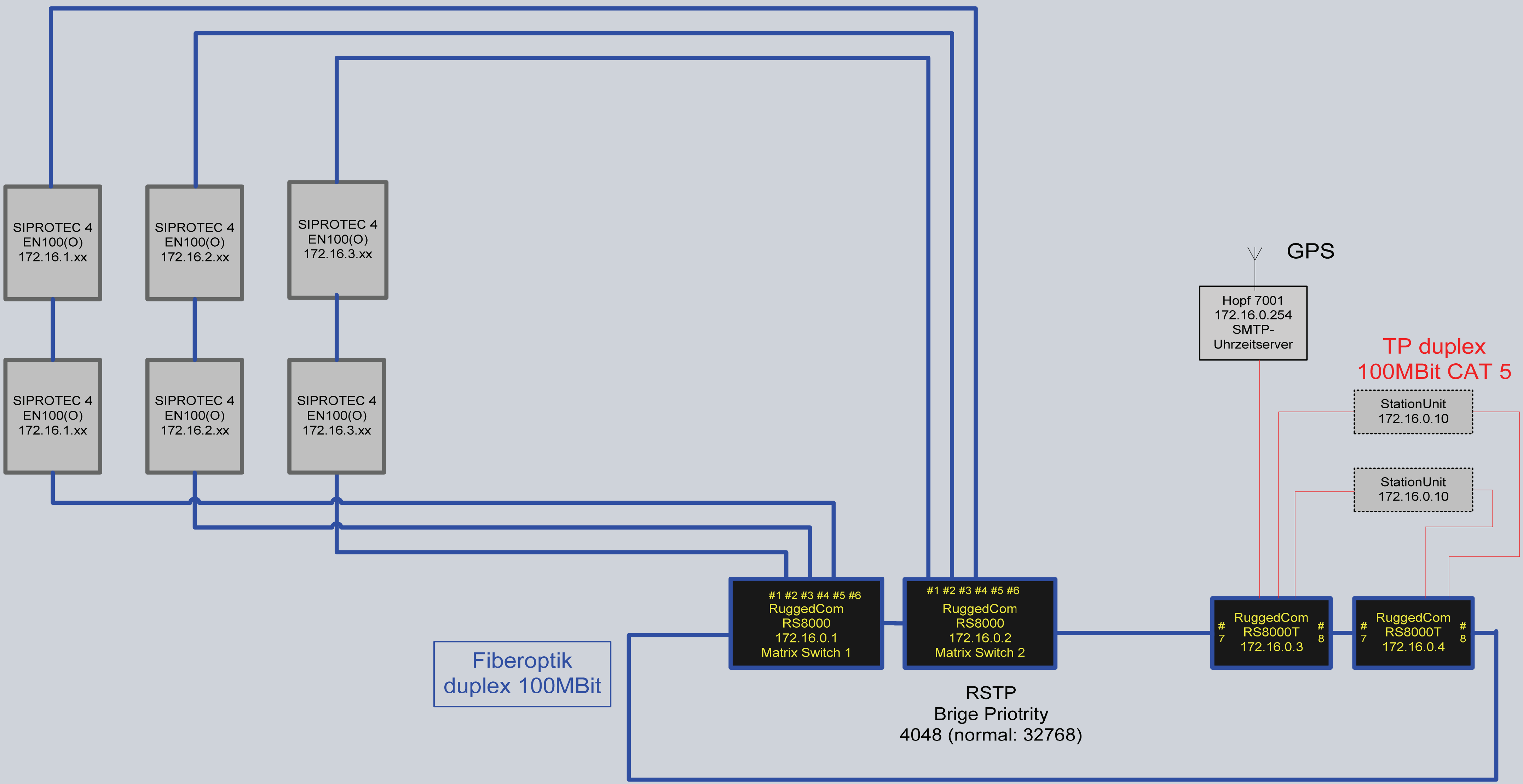

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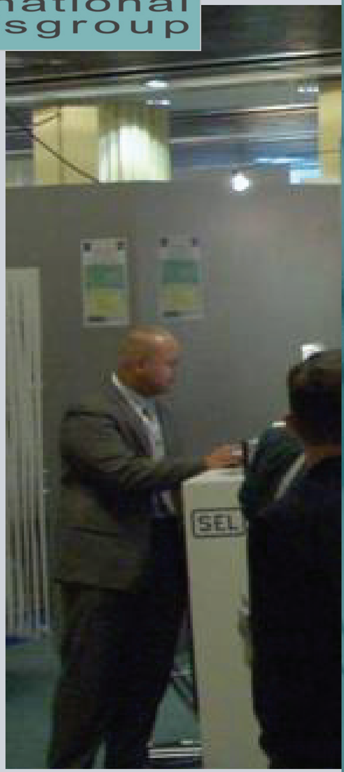

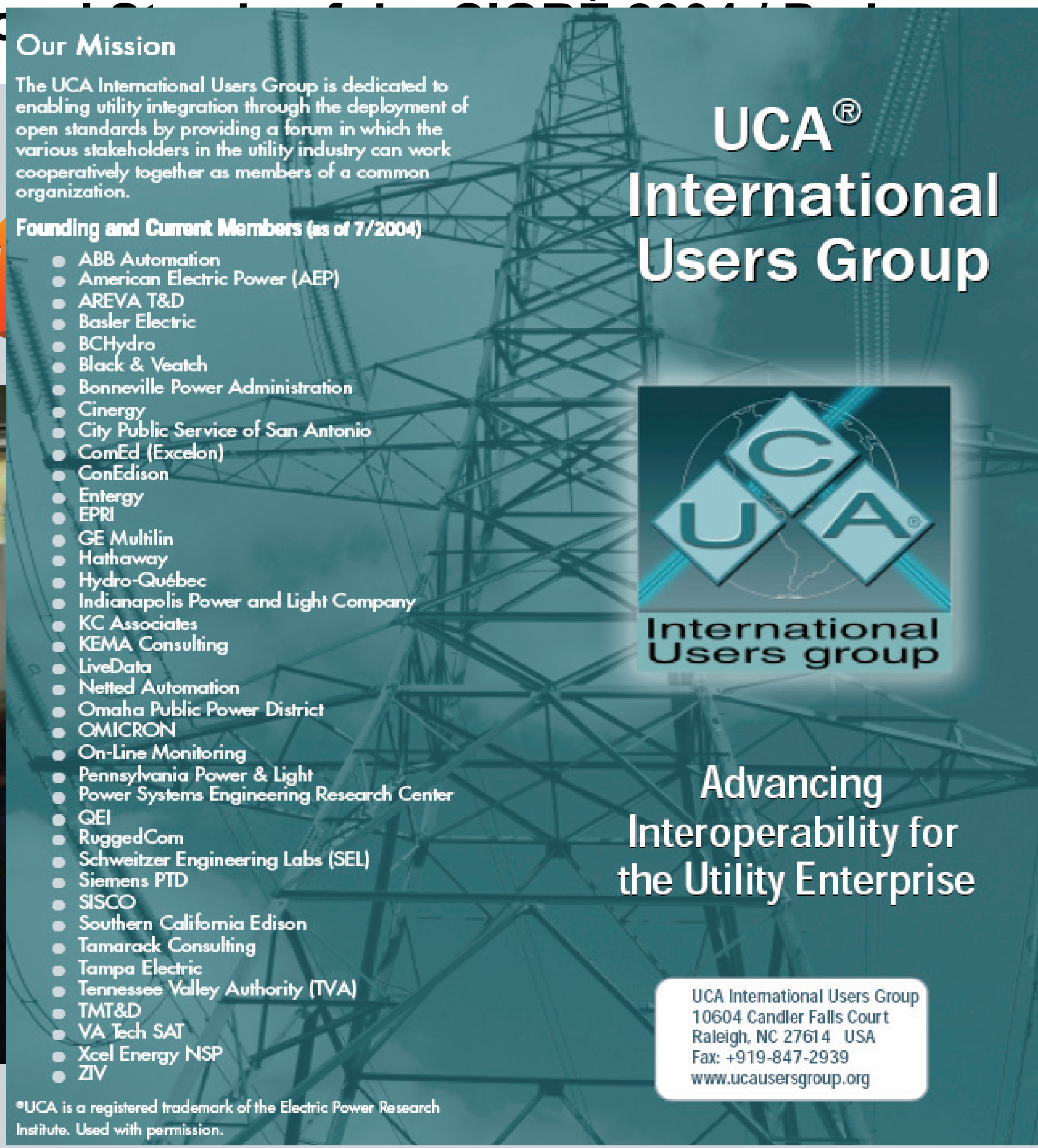

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Distance Protection of Tapped Lines

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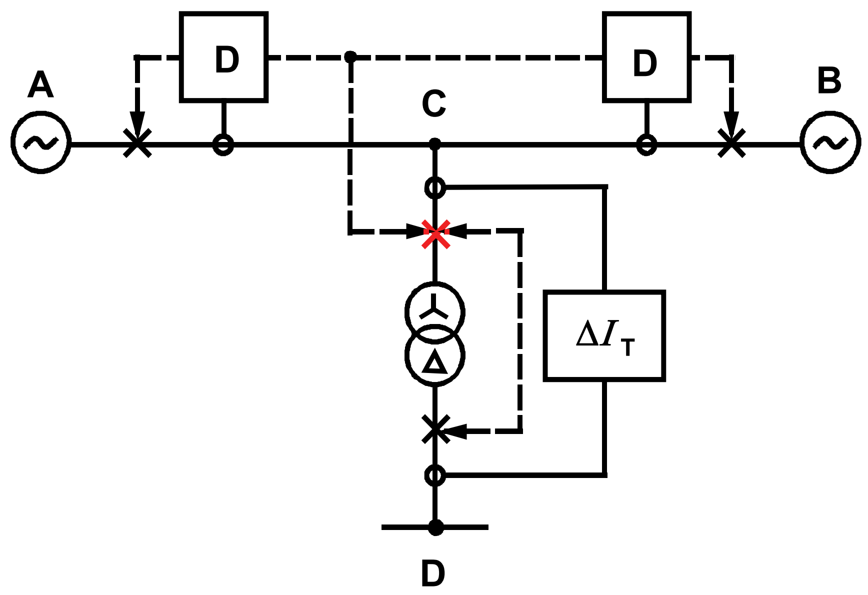
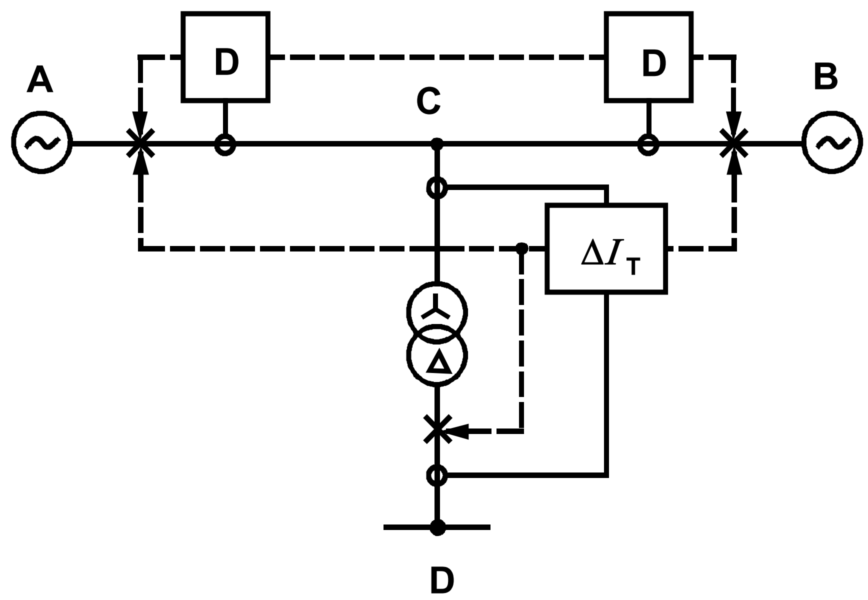
Distance protection of tapped lines
Basic tap configurations

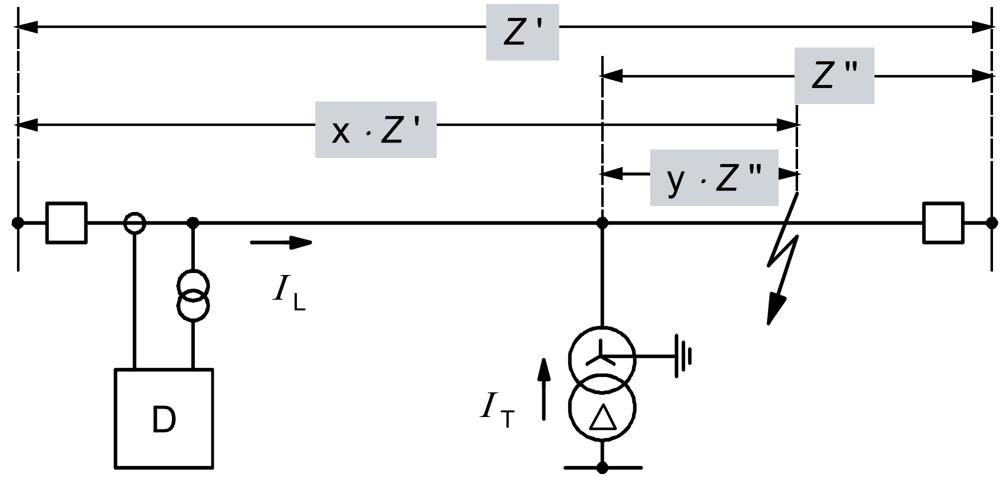


With circuit breaker at the tap



Without circuit breaker at the tap

Tapped line, Distance measurement during Ph-E fault
Influence of earthed transformers (1)



$$V_{L1\text{-}Relais} = x\,[I_{L1\text{-}L}\cdot Z_1' + I_{E\text{-}L}\cdot Z_E'] + y\,[I_{L1\text{-}T}\cdot Z_1'' + I_{E\text{-}T}\cdot Z_E'']$$

$$= x\cdot Z_1'\left[I_{L1\text{-}L} + I_{E\text{-}L}\cdot\frac{Z_E'}{Z_1'}\right] + y\,[I_{L1\text{-}T}\cdot Z_1'' + I_{E\text{-}T}\cdot Z_E'']$$

$$Z_{L1\text{-}Relay} = \frac{U_{L1\text{-}Relay}}{I_{L1\text{-}L} + k_0\cdot I_{E\,L}}$$

With k_0 set to : $\frac{Z_E'}{Z_1'}$

$$Z_{L1-R} = x\cdot Z_1' + \underbrace{y\cdot Z_1'\cdot\frac{I_{L1-T}\cdot Z_1'' + I_{E-T}\cdot Z_E''}{I_{L1-L}\cdot Z_1' + I_{E-L}\cdot Z_E'}}_{\text{Measuring error}}$$

Measuring error

Tapped line, Distance measurement during Ph-E fault
Influence of earthed transformers (2)

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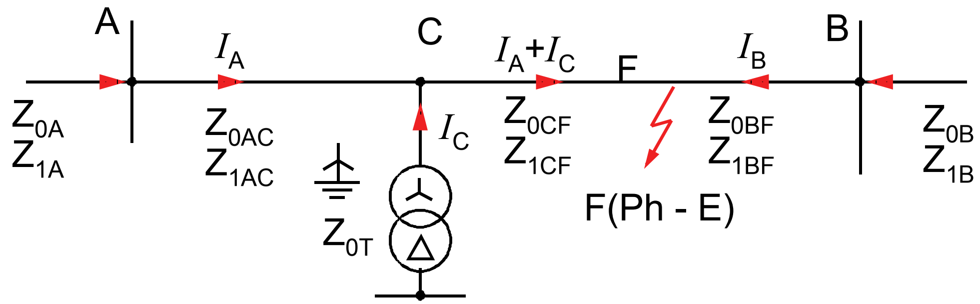
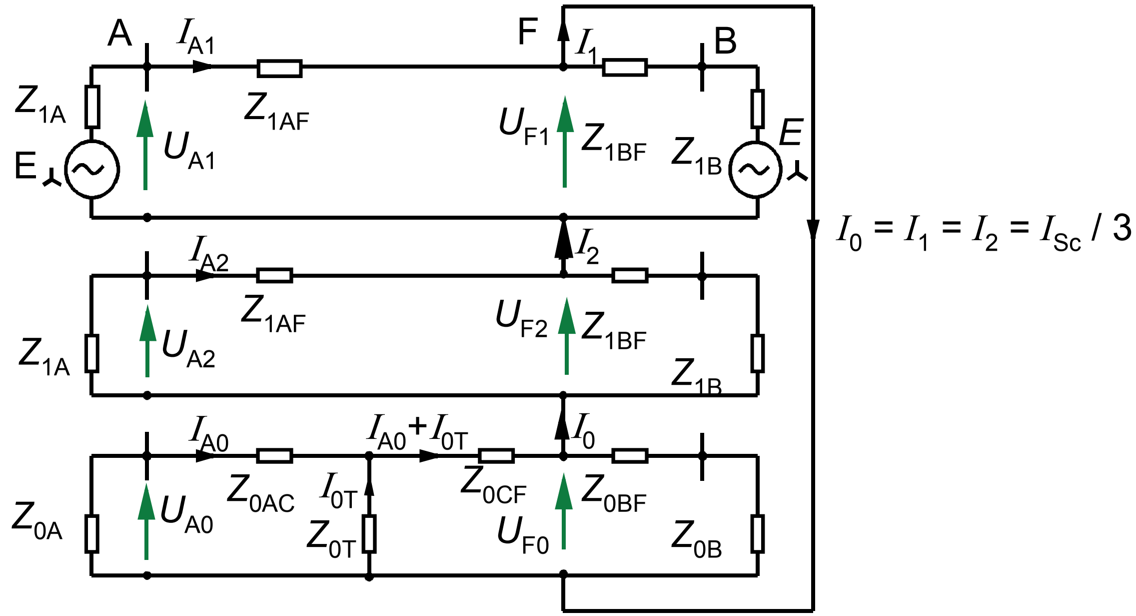
a) Single-phase equivalent circuit



b) Equivalent circuit with symmetrical components



Tapped line, Distance measurement during Ph-E fault
Influence of earthed transformers (3)

$$U_{A0} = U_{F0} + Z_{0CF} \cdot (I_{A0} + I_{0T}) + Z_{0AC} \cdot I_{A0}$$

$$U_{A1} = U_{F1} + Z_{1AF} \cdot I_{A1}$$

$$U_{A2} = U_{F2} + Z_{1AF} \cdot I_{A2}$$

with $U_{F0} + U_{F1} + U_{F2} = 0$ und $Z_{0AC} + Z_{0CF} = Z_{0AF}$:

$$U_A = Z_{0AF} \cdot I_{A0} + Z_{0CF} \cdot I_{0T} + Z_{1AF} \cdot (I_{A1} + I_{A2})$$

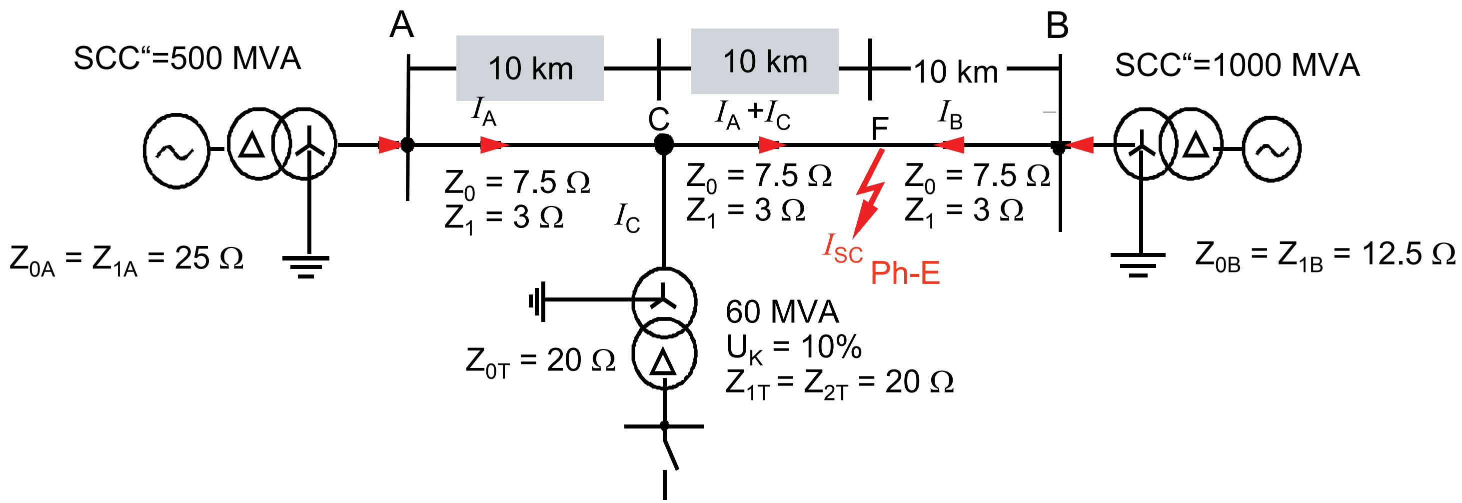
$$I_A = I_{A0} + I_{A1} + I_{A2}$$

Symmetrical component currents :

$$I_{A0} = \frac{Z_{0T}}{Z_{0T} + Z_{0A} + Z_{0AC}} \cdot \frac{Z_{0B} + Z_{0BF}}{Z_{0B} + Z_{0BF} + Z_{0CF} + \frac{Z_{0T}(Z_{0A} + Z_{0AC})}{Z_{0T} + Z_{0A} + Z_{0AC}}} I_0$$

$$I_{A1} = I_{A2} = \frac{Z_{1B} + Z_{1BF}}{Z_{1B} + Z_{1BF} + Z_{1A} + Z_{1AF}} I_0$$

Tapped line, Distance measurement during Ph-E fault
Influence of earthed transformers, example



True positive sequence impedance to fault point: $Z_{1A\text{-}F} = 6\ \Omega$

Measuring error = 2 Ω:
The fault appears 6.7 km further away.

There is an underreach of about 33%.

$Z_{0F} = 10\ \Omega$

$Z_{1F} = Z_{2F} = 10.3\ \Omega$

$I_0 = I_1 = I_2 = 110\text{ kV}/\left(\sqrt{3}(10+2 \cdot 10.3)\ \Omega\right) = 2.1\text{ kA}$

$I_{SC} = I_0 + I_1 + I_2 = 6.3\text{ kA}$

$I_{A0} + I_{T0} = 0.5\ I_0 = 1.05\text{ kA}$

$I_{A0} = 0.4\text{ kA}$; $I_{0T} = 0.65\text{ kA}$; $I_{AE} = 3 \cdot I_{A0} = 1.2\text{ kA}$

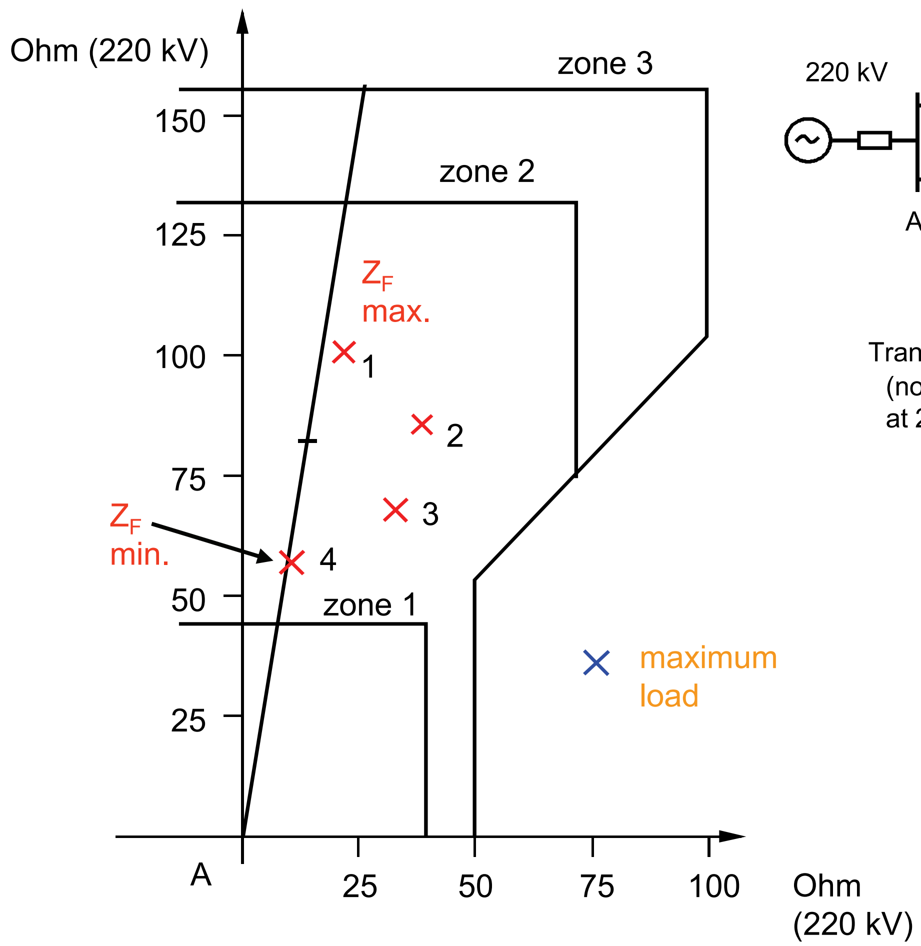
$I_{A1} = I_{A2} = 0.33\ I_0 = 0.7\text{ kA}$

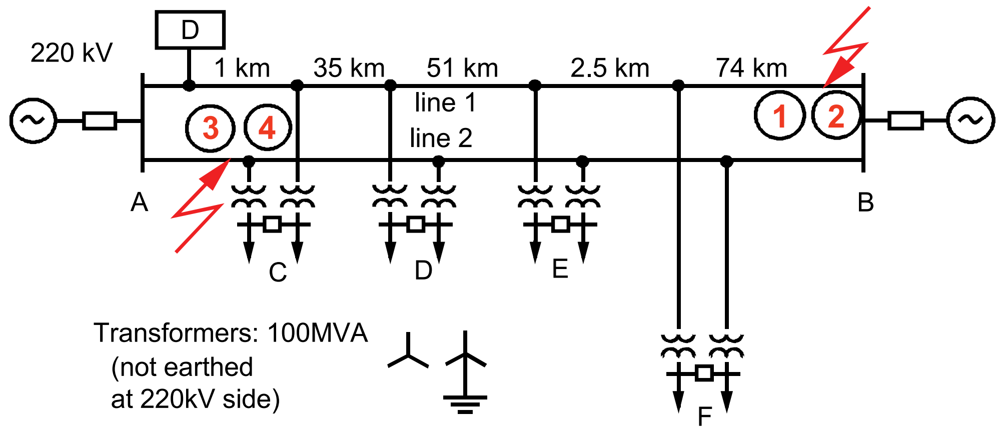
$U_A = 7.5\ \Omega \cdot 0.4\text{ kA} + 7.5\ \Omega \cdot 1.05\text{ kA} + 6\ \Omega \cdot 0.7\text{ kA} + 6\ \Omega \cdot 0.7\text{ kA} = 19{,}3\text{ kV}$

$I_A = 0.4\text{ kA} + 2 \cdot 0.7\text{ kA} = 1.8\text{ kA}$

$Z_{mA} = U_A/(I_A + k_0 \cdot I_{AE}) = 19.3\text{ kV}/(1.8\text{ kA} + 0.5 \cdot 1.2\text{ kA}) = 8\ \Omega$

Multiply tapped double circuit line (220 kV)
Distance protection setting





R-X diagram, relay in A, line 1

Point 1	Fault at B on line 1 with cross feed via tap stations (bus couplers closed).
Point 2	Fault in B with maximum load at taps (line 2 out of service).
Point 3	Fault on neighbouring line 2 at C and line 2 open at B.
Point 4	As 3 but line 2 switched off at both ends

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Fault locator with 2 ended measurement

Power Transmission
and Distribution

Consultant Power System Protection

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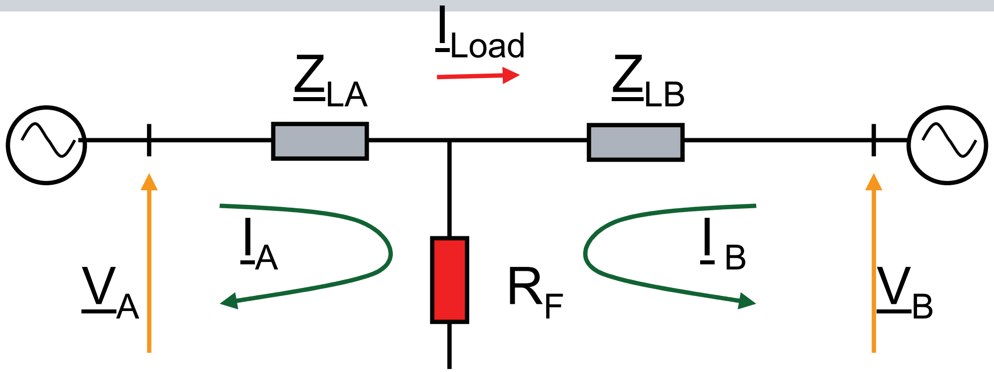
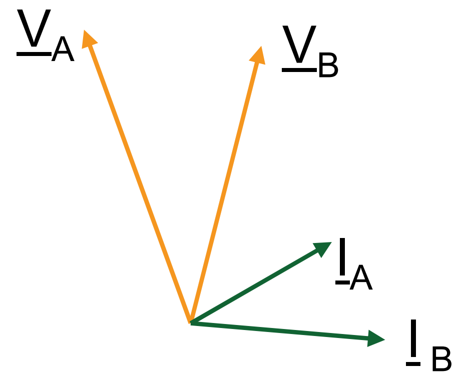
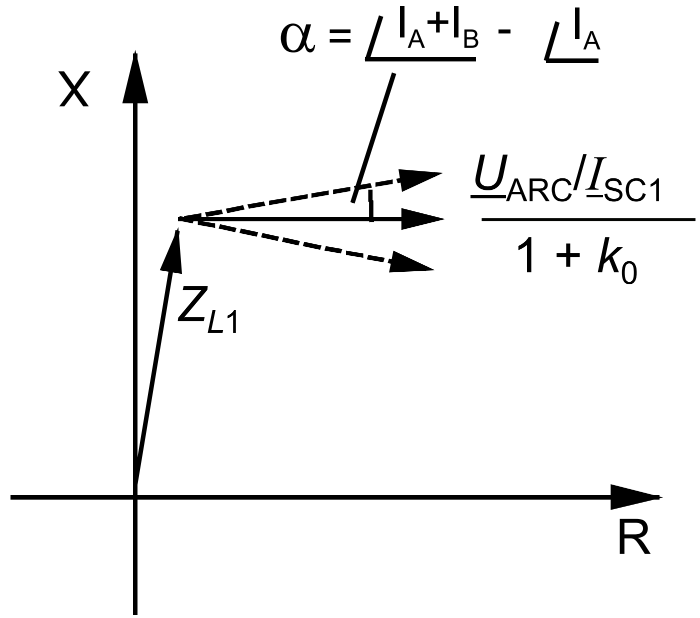
Fault Locator: Load and Fault Resistance



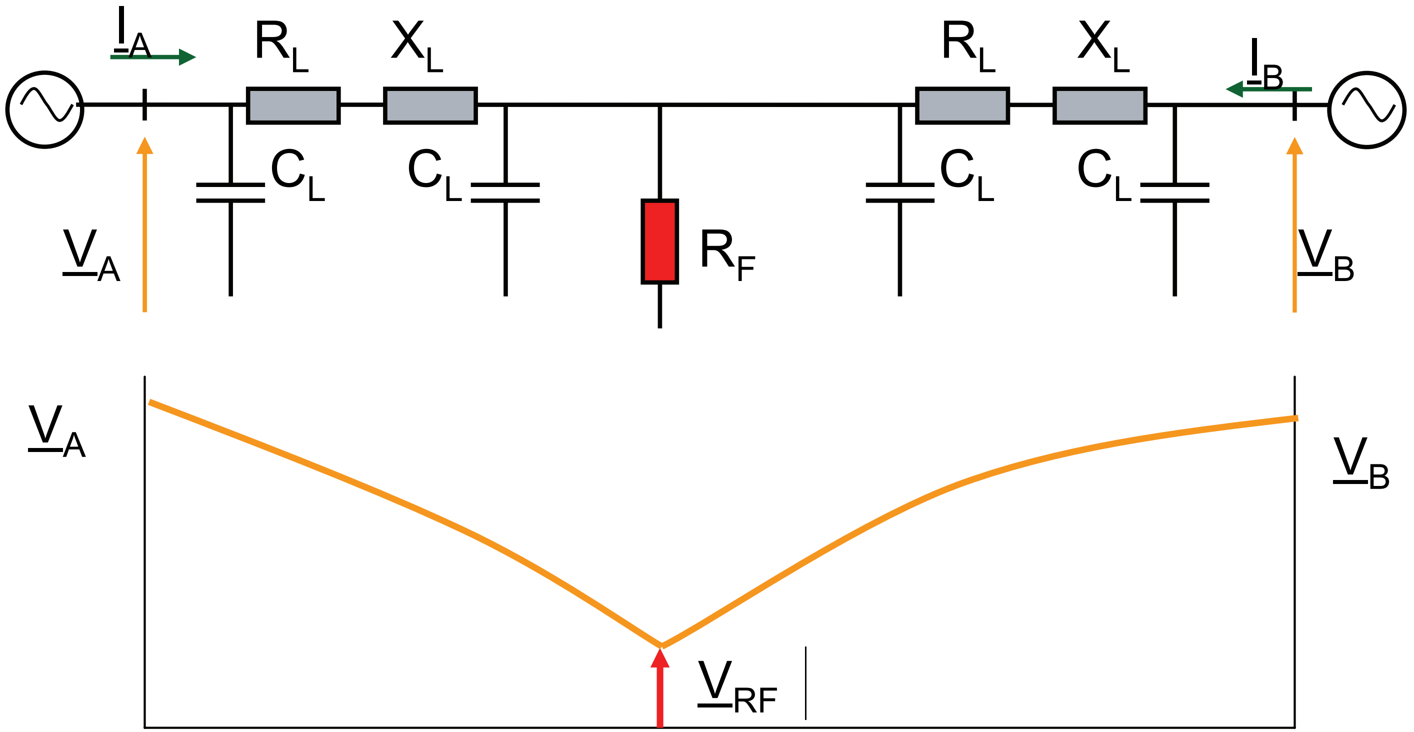


Due to load current there is an angular displacement between the voltages. This angle and possible differences in the source impedance angle cause the angular displacement between current IA and IB. As a result, the voltage drop accross RF is affected by this angle between the currents.

The single ended measurement cannot compensate for this.



Fault Locator: 2 ended with transmission line equation



R_L X_L C_L

are distributed positive sequence line resistance, inductance and capacitance

Based on measured positive sequence voltage and current from both line ends, the positive sequence voltage drop along the line upto the fault location is calculated. At the fault location the calculated voltages from end A and end B are equal.

Data from both ends are required for the computation.

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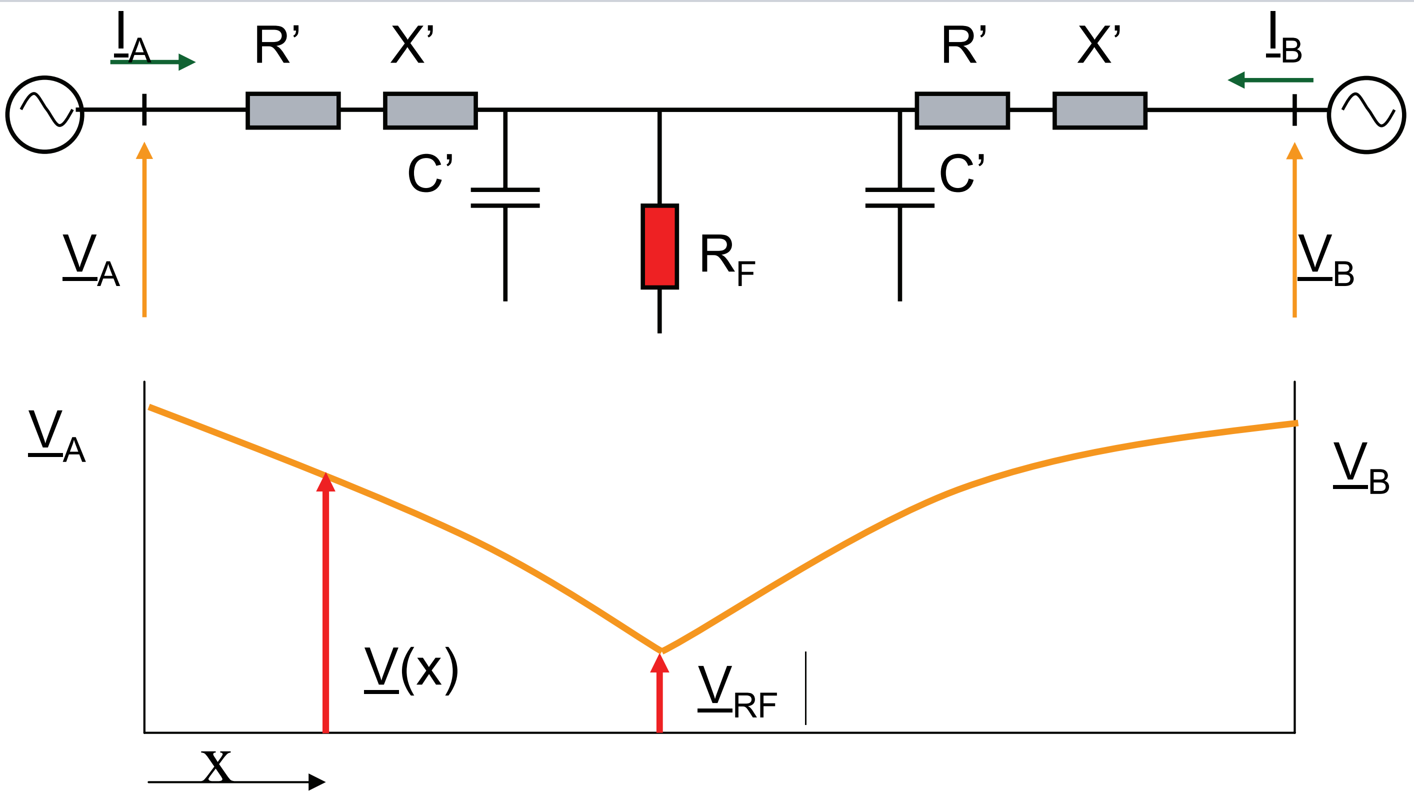
Fault Locator: 2 ended with transmission line equation



R' X' C'

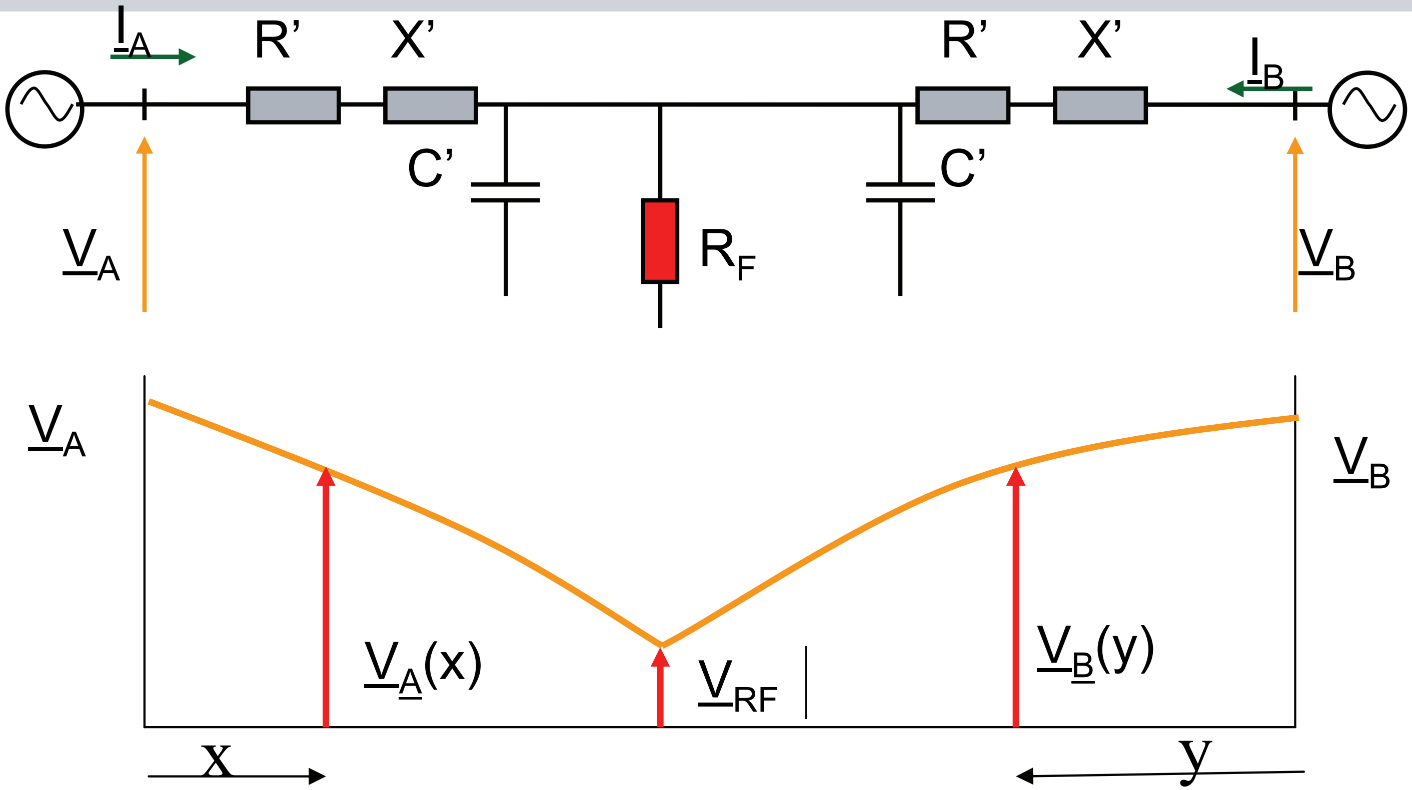
are positive sequence line resistance, inductance and capacitance per km

$$\underline{V}(x) = \underline{V}_A \cdot \cosh(\underline{\gamma} \cdot x) - \underline{Z} \cdot \underline{I}_A \sinh(\underline{\gamma} \cdot x)$$

$$\underline{\gamma} = \sqrt{(R' + j\omega L') \cdot j\omega C'}$$ Propagation constant

$$\underline{Z} = \sqrt{\frac{R' + j\omega L'}{j\omega C'}}$$ characteristic impedance

Fault Locator: comparison of results from both line ends



The measured current and voltage signals at end A and B are transmitted via communication interface and then synchronised at each line end.

$$\varepsilon(x,y) = \underline{V}_A \cdot (x) - \underline{V}_B(y)$$

$$ideally : \varepsilon(x,y) = 0$$

By minimising the error ε the fault location (x,y) is obtained

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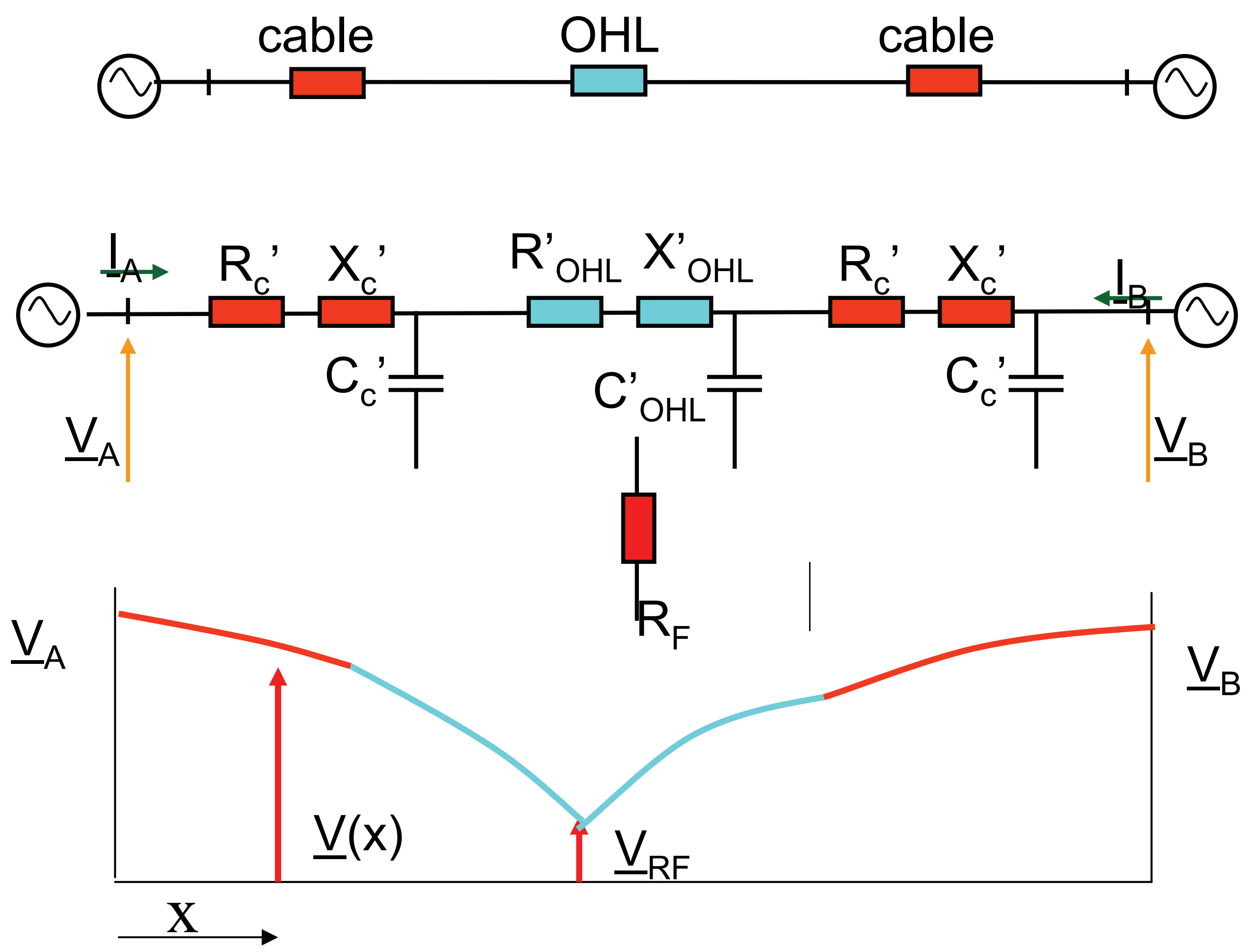
Fault Locator: multiple feeder sections



R’ X’ C’

line/cable resistance, inductance and capacitance per km for each line section must be set

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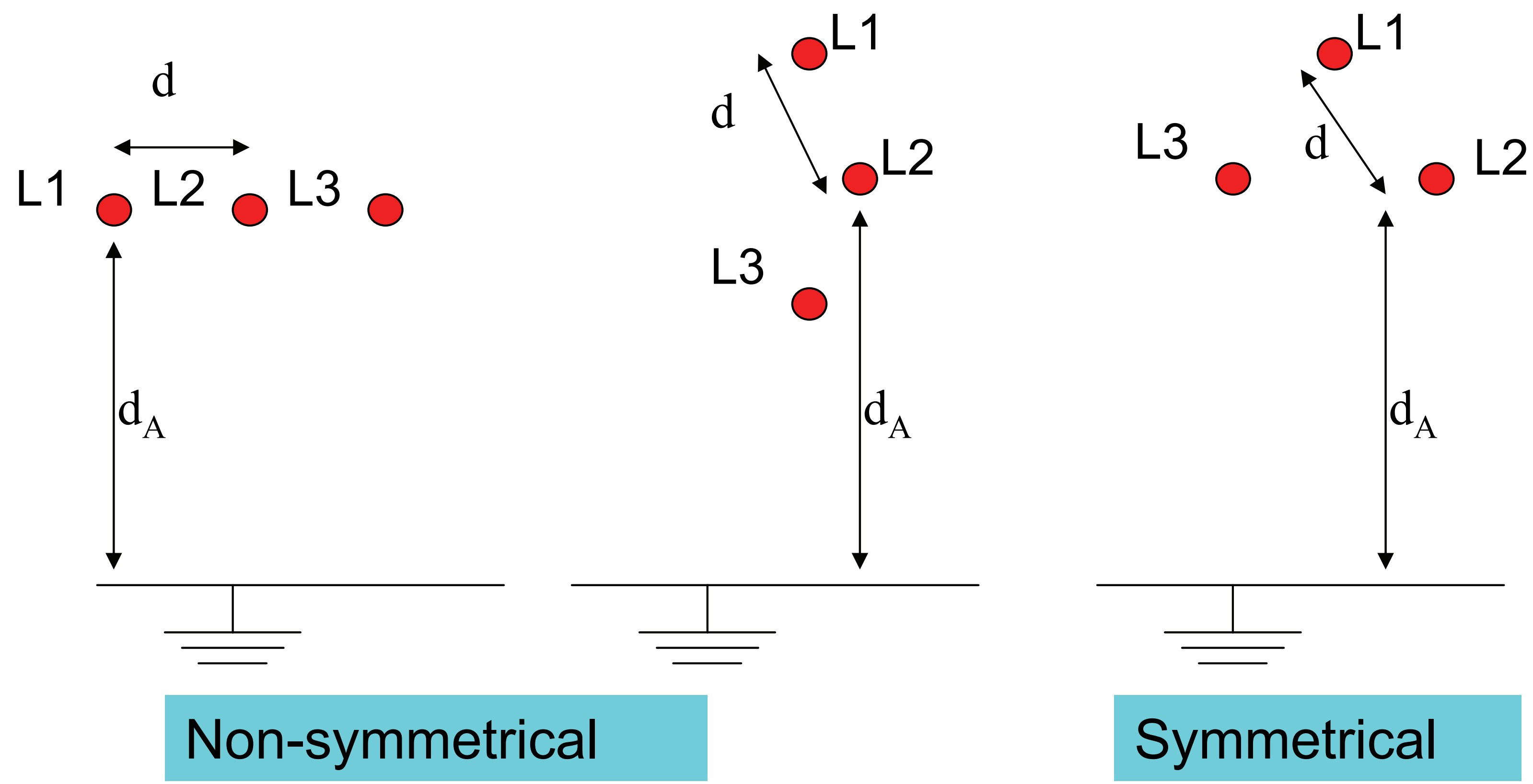
Fault Locator: Non-symmetrical and Non-transposed lines



The coupling impedances of the three phases are not the same. By defining the centre conductor (in this case L2), the impedance non-symmetry can be considered in the calculation of the voltage profile.

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Fault Locator: advantage of 2 ended method

- The measurement is not dependant on zero sequence system data (XE/XL, RE/RL etc.)
- Fault resistance and load current do not affect the accuracy
- Coupling of parallel lines only has a negligible effect on the measurement
- Fault location accuracy is also achieved on non-symmetrical and non-transposed lines

Example: Single and 2 end fault locator – Influence of load current and fault resistance

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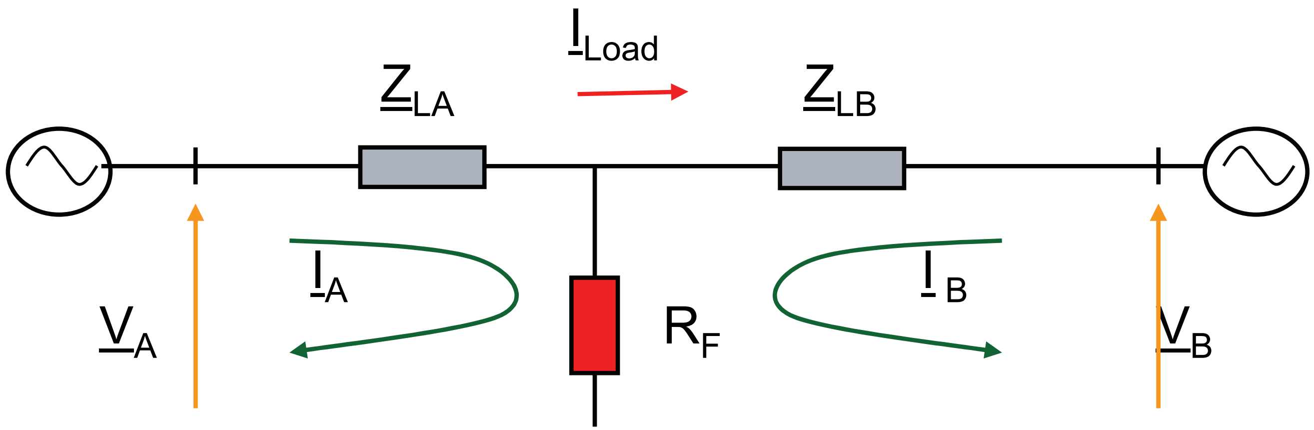

R_F = 30 Ohm

I_{Load} = 300 A (10° between sources)

ZLA = ZLB = 2 + j15 Ohm (fault at 50%)

Line length = 100 km

Measured single end fault location (L1-G with fault resistance 30 Ohm and load current 300 A)

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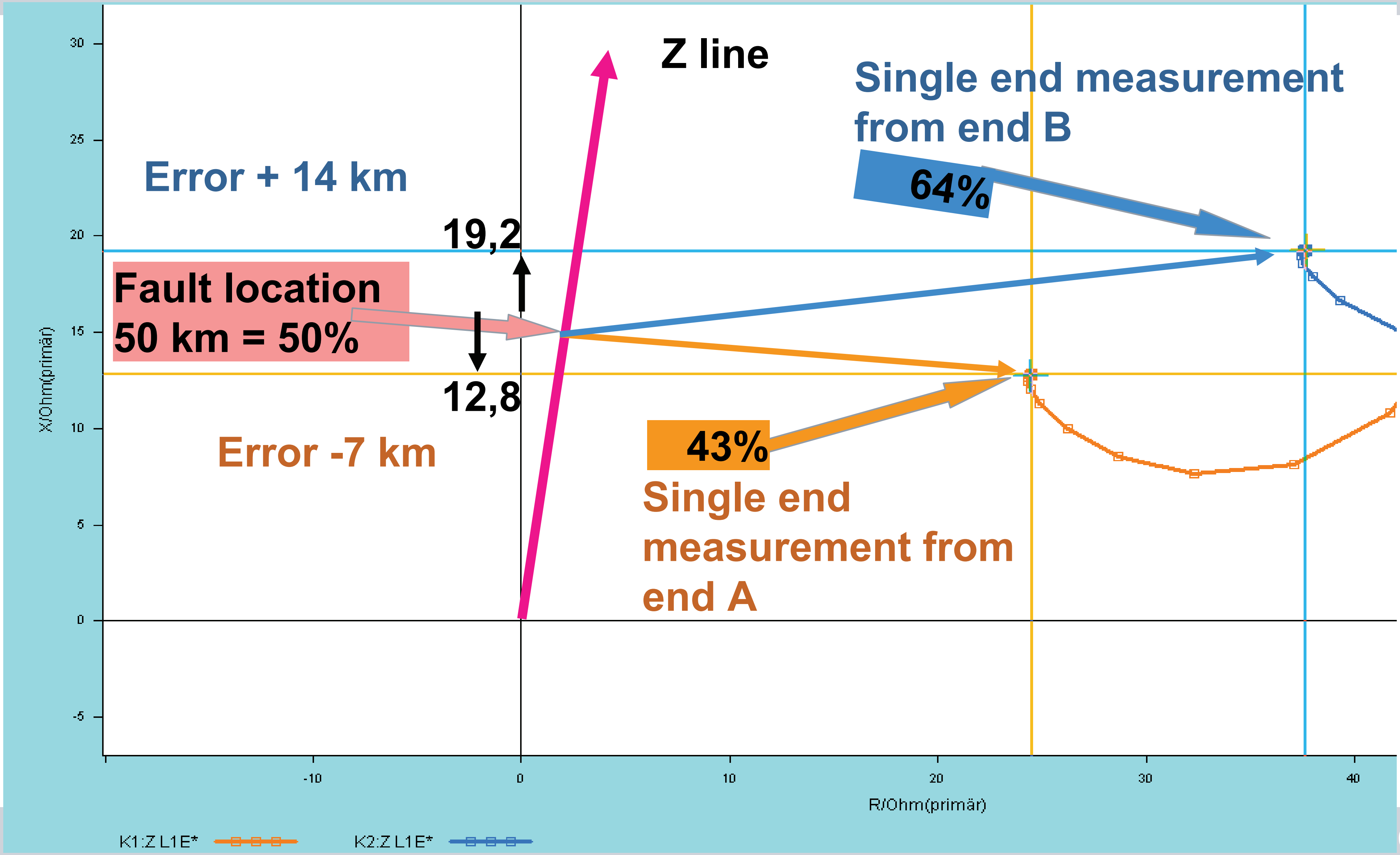

Measured 2 end fault location (L1-G with fault resistance 30 Ohm and load current 300 A)

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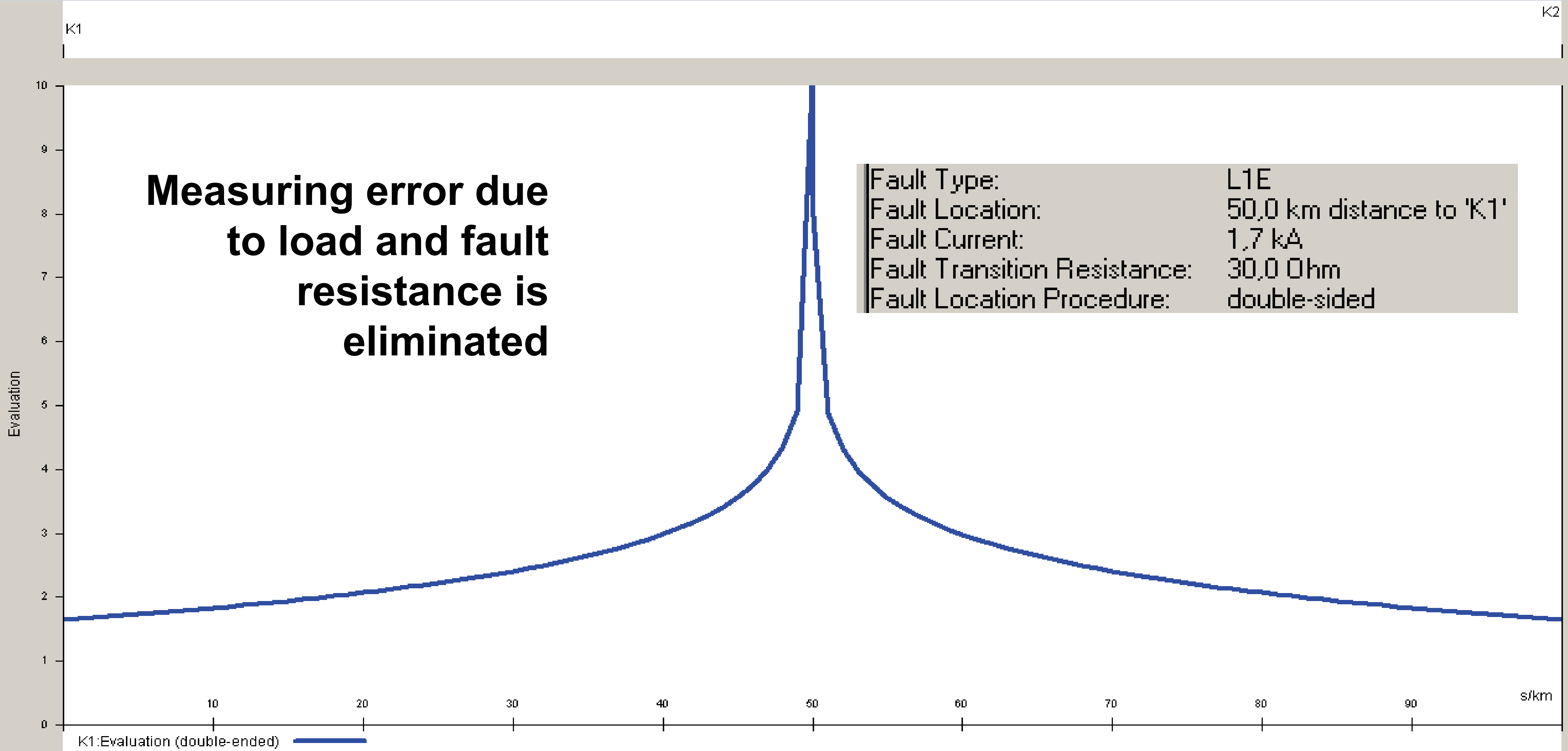

Measuring error due to load and fault resistance is eliminated

Example: Single and 2 end fault locator – Influence parallel line (mutual coupling of zero sequence)

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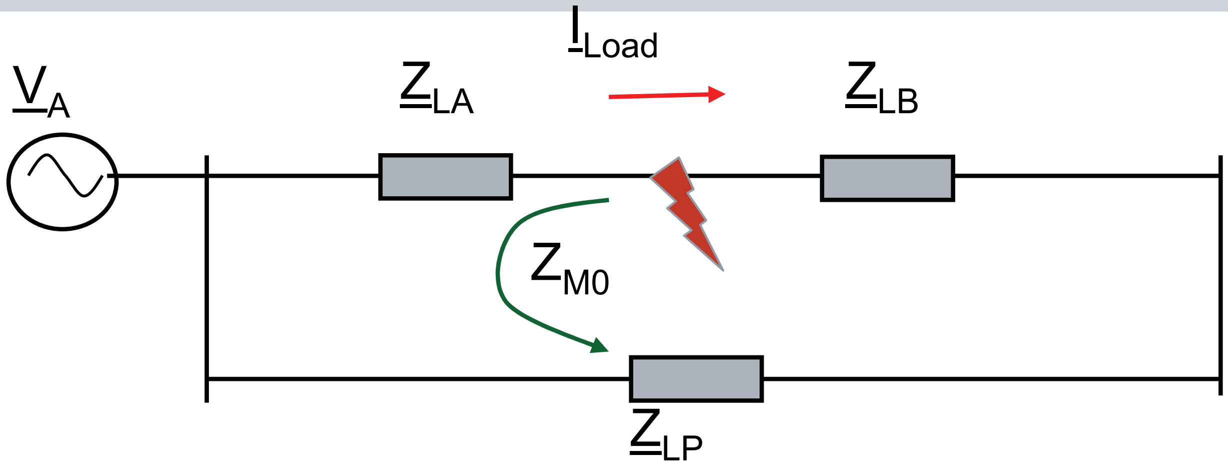

ZM0 = 15 + j100

I_{Load} = 300 A (10° between sources)

ZLA = ZLB = 2 + j15 Ohm (fault at 50%)

Line length = 100 km

Measured single end fault location (L1-G with zero sequence mutual impedance of parallel line)

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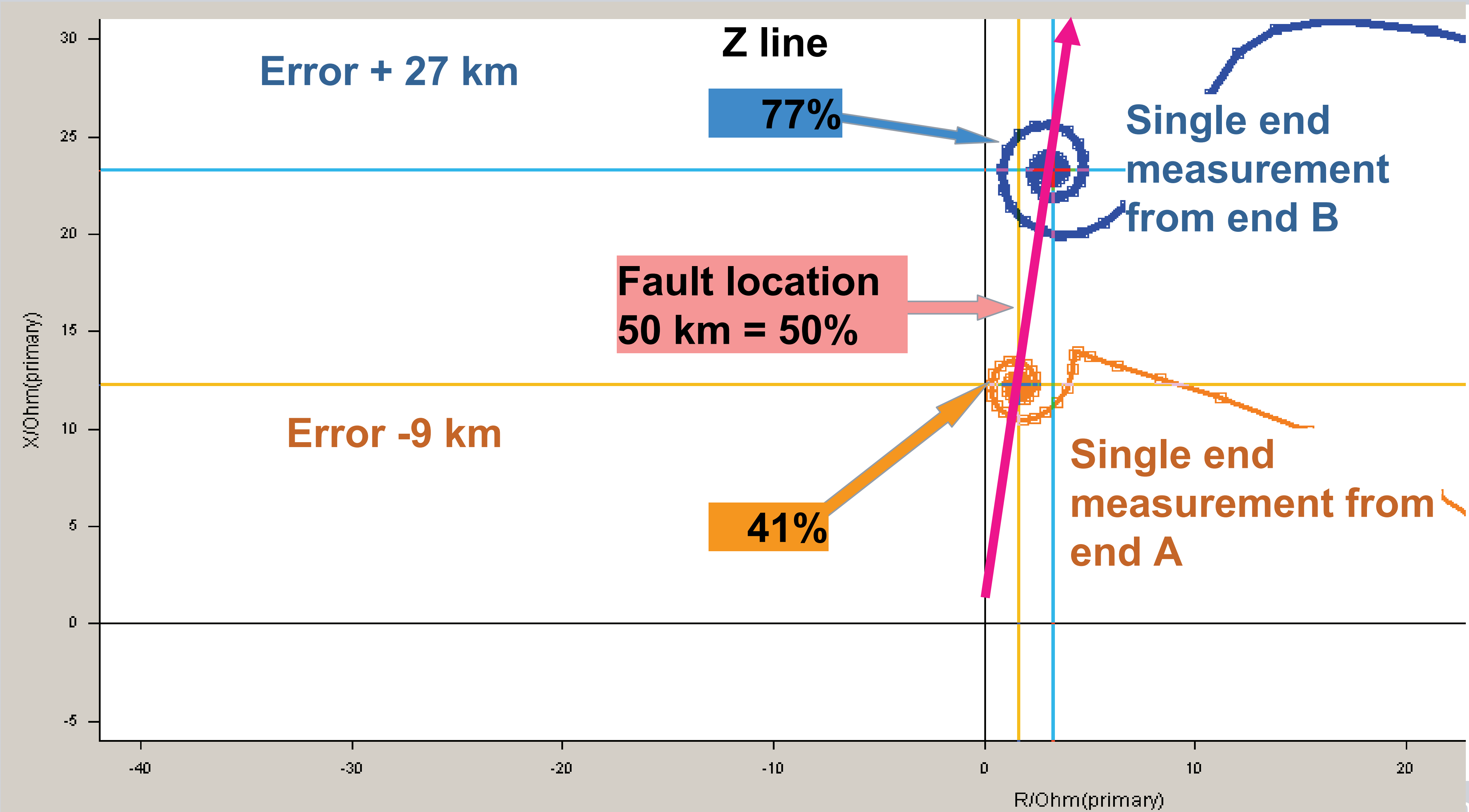

Measured 2 end fault location (L1-G with fault resistance 30 Ohm and load current 300 A)

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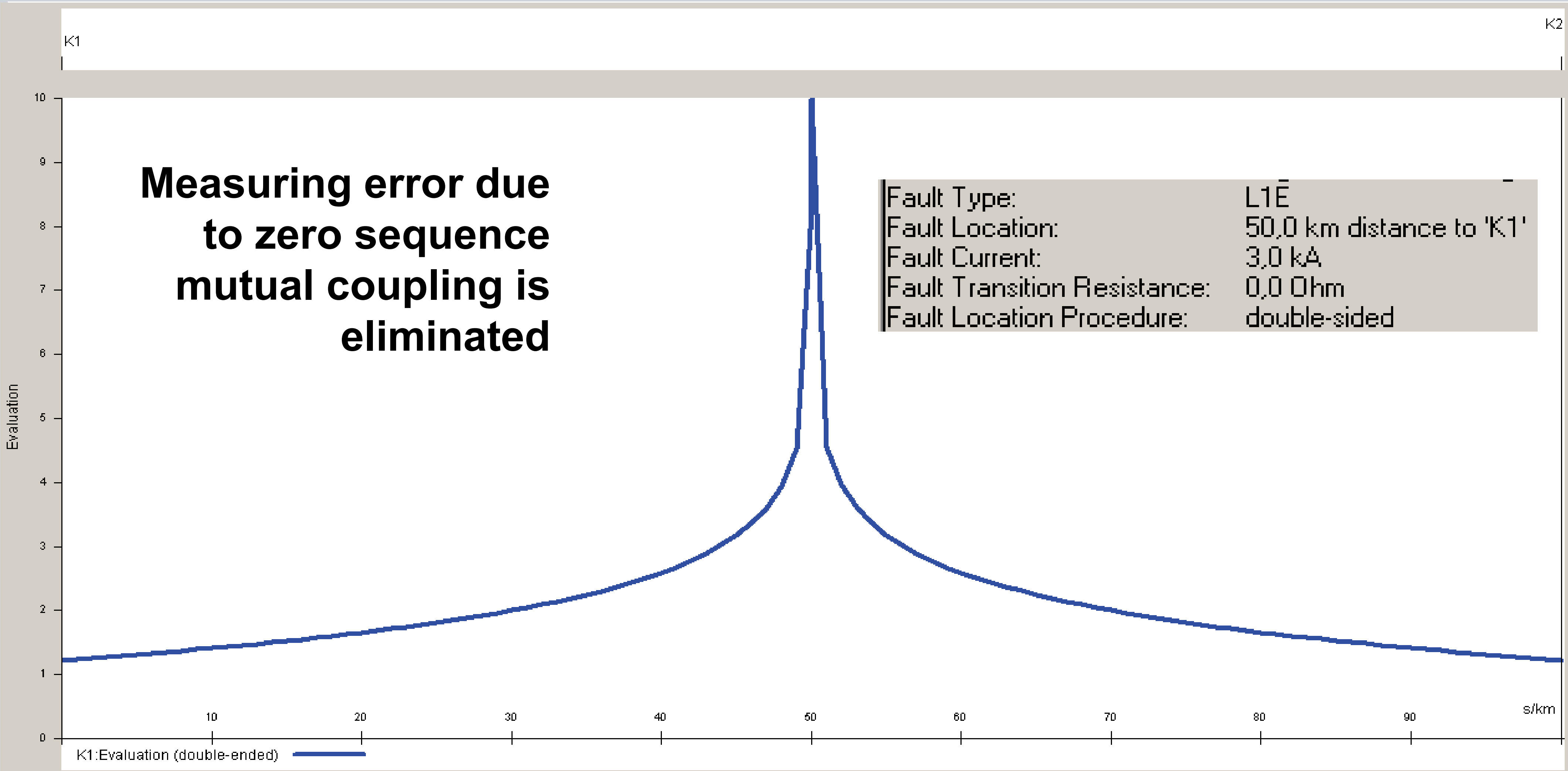

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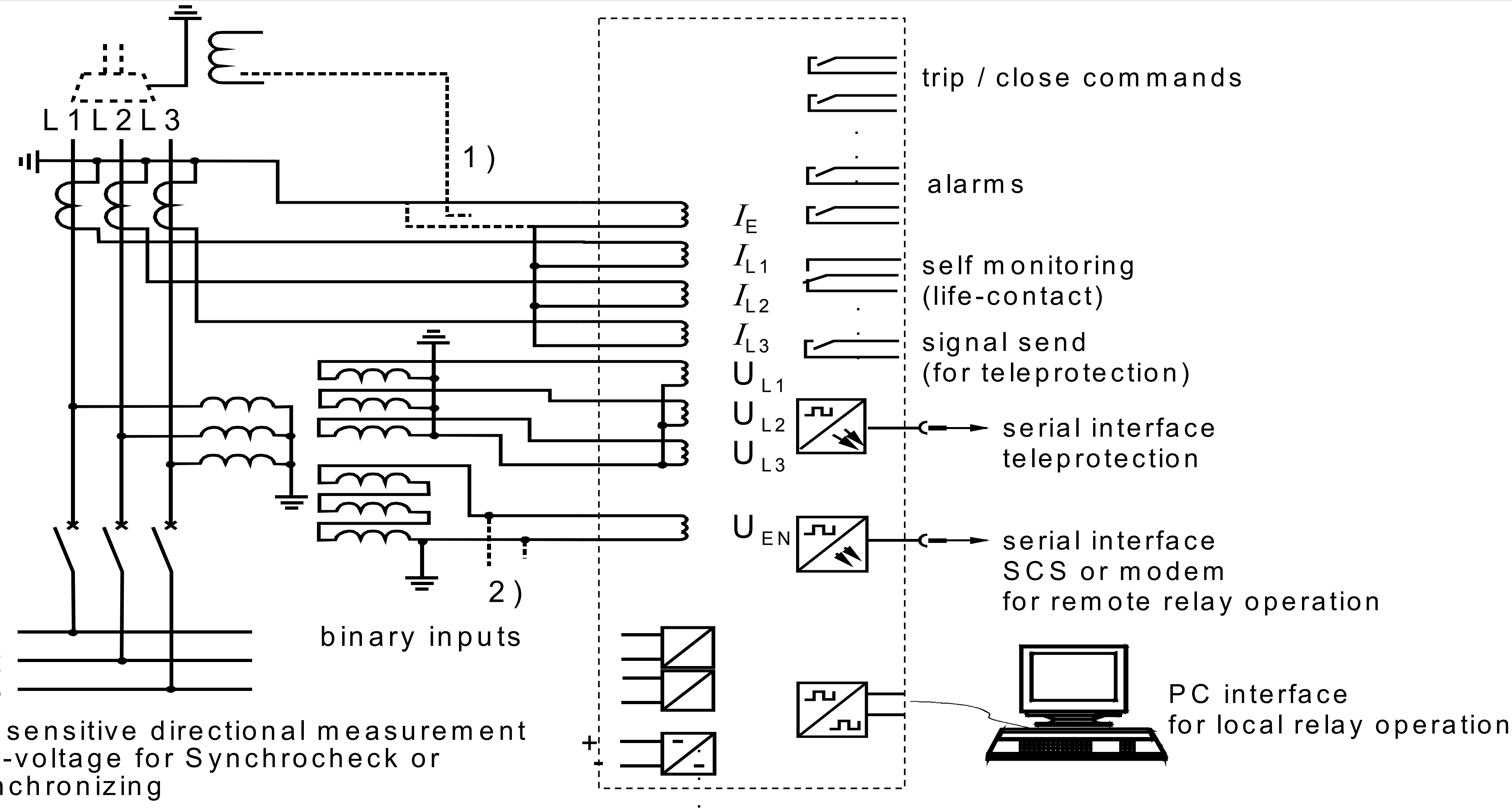
Distance Protection

Connection, Commissioning, Maintenance

Distance protection
Connection



1) for sensitive directional measurement
2) BB-voltage for Synchrocheck or synchronizing

Directional test using load current
Sign of measured impedance R+jX

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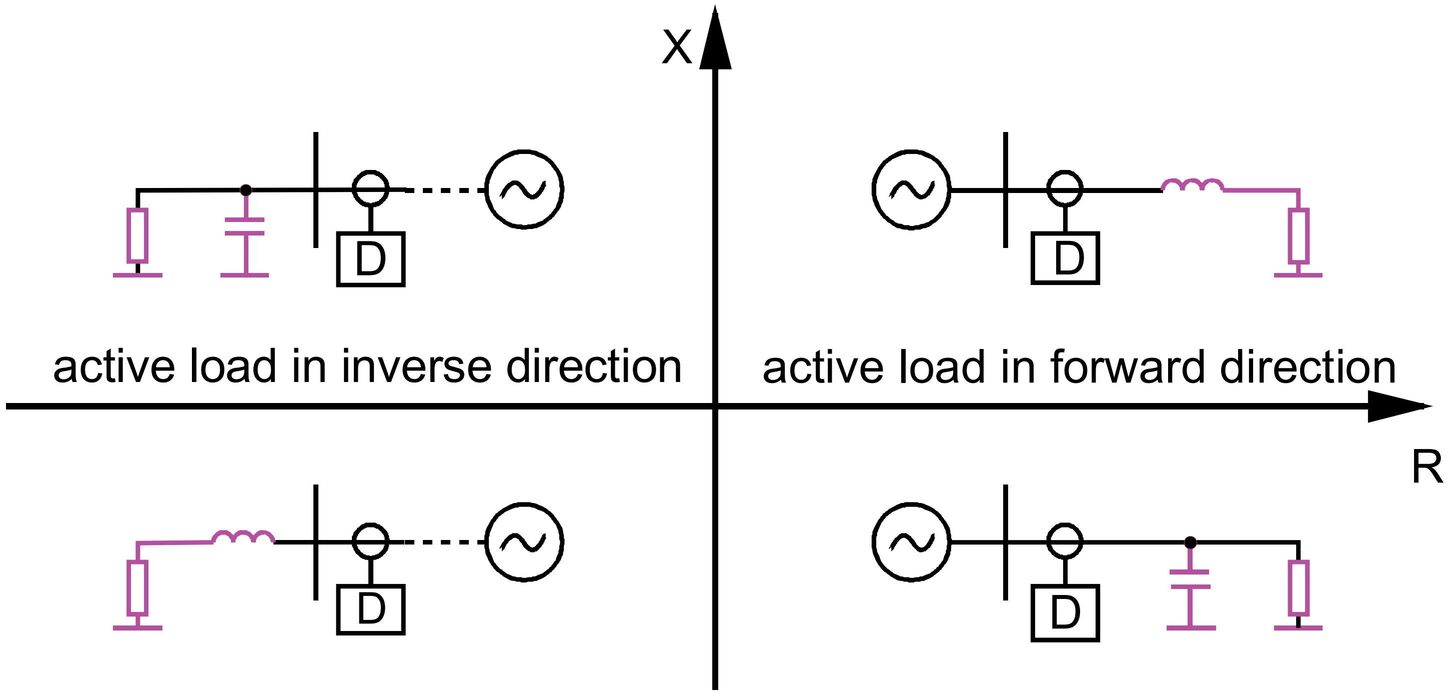
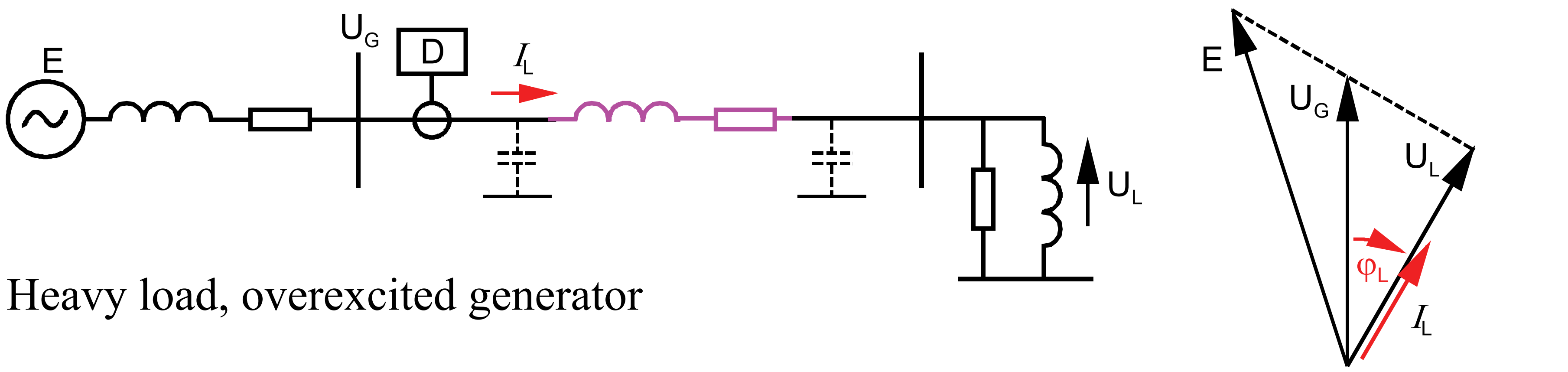
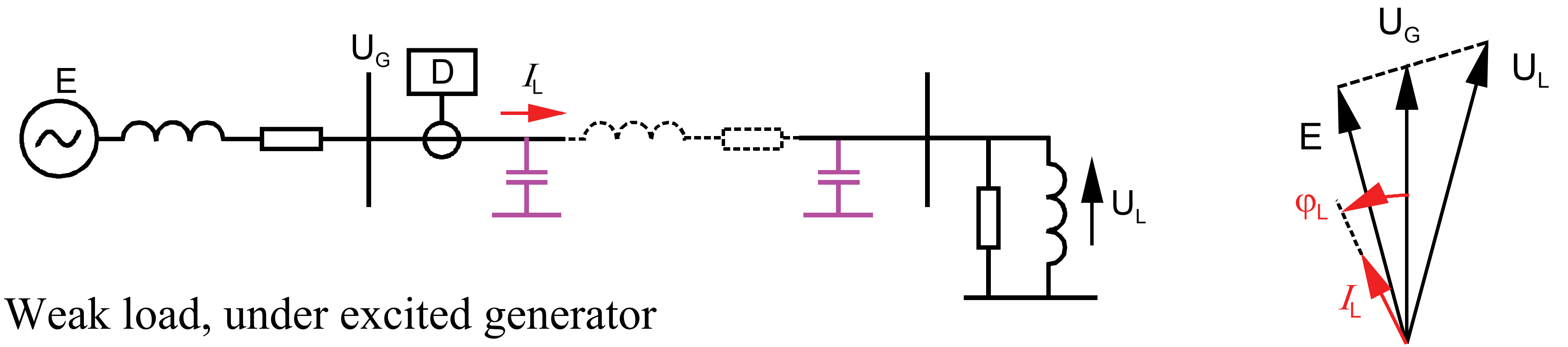
$$R = \frac{U_N^2 \cdot P_{active}}{P_{active}^2 + P_{reactive}^2} \qquad X = \frac{U_N^2 \cdot P_{reactive}}{P_{active}^2 + P_{reactive}^2}$$



Infeed to a network
Load angle at the relay



Heavy load, overexcited generator



Weak load, under excited generator

Reactive power demand of a transmission line

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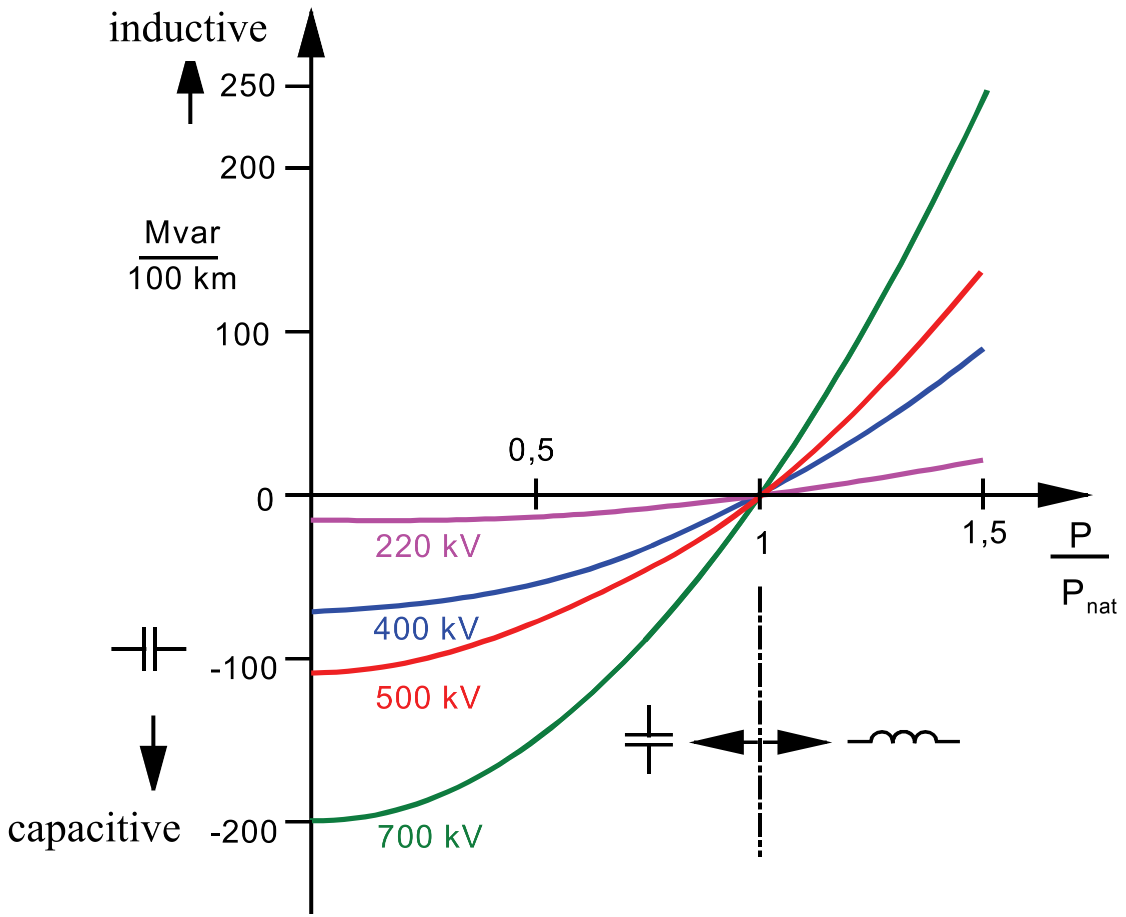

Protection availability, influence of self monitoring

(values in brackets were assumed as an example)

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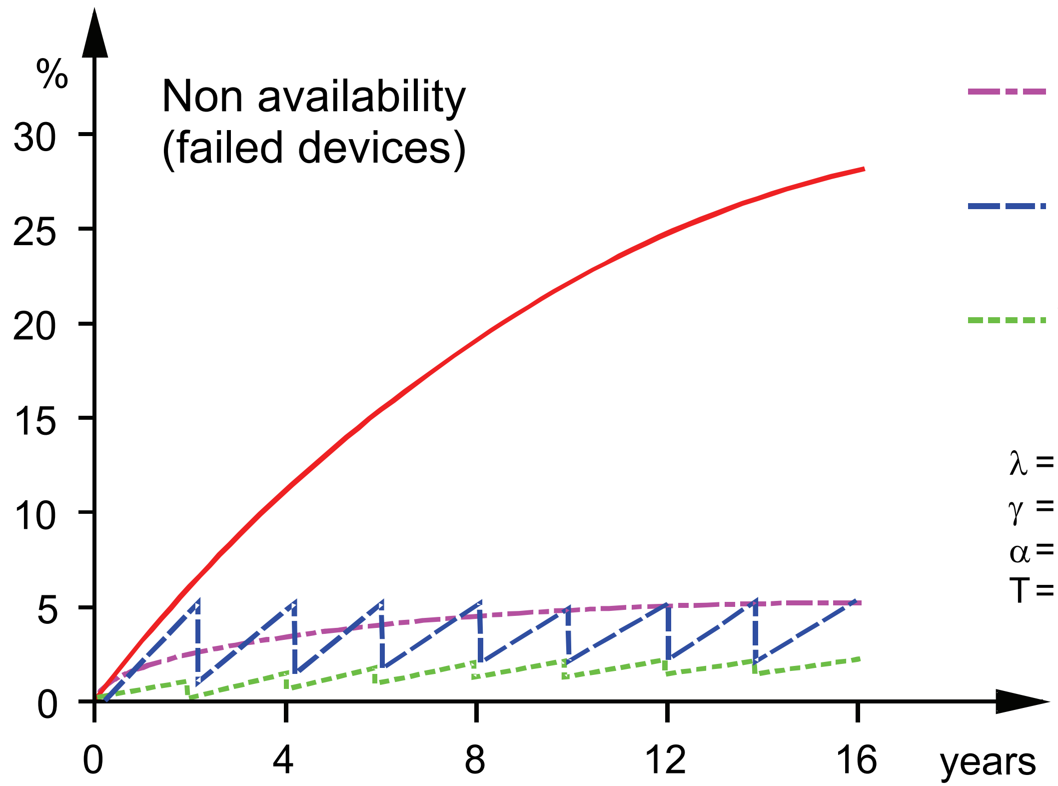

- Without routine maintenance, without self-monitoring
  $U_1 = 1 - e^{-\lambda \times t}$
- With self-monitoring
  $U_3 = 1 - e^{-\lambda (1-\alpha) t}$
- With routine maintenance
  $U_2\ (t) = 1 - e^{-\lambda (1-\gamma) t} \cdot e^{-\lambda\gamma (t - n \times T)}$
- With self-monitoring and routine maintenance
  $U_4\ (t) = 1 - e^{-\lambda \times t (1-\alpha)(1-\gamma)} \cdot e^{-\lambda \cdot (t-\alpha) \cdot \gamma \cdot (t - n \cdot T)}$

λ = failure rate (2%)
γ = fault detection rate of the routine maintenance (95%)
α = fault detection rate of the self-monitoring (80%)
T = test interval (2 years)

assumed repair time
T_R = 2.5 days

Current and Voltage Transformers Performance Requirements

Equivalent current transformer circuit

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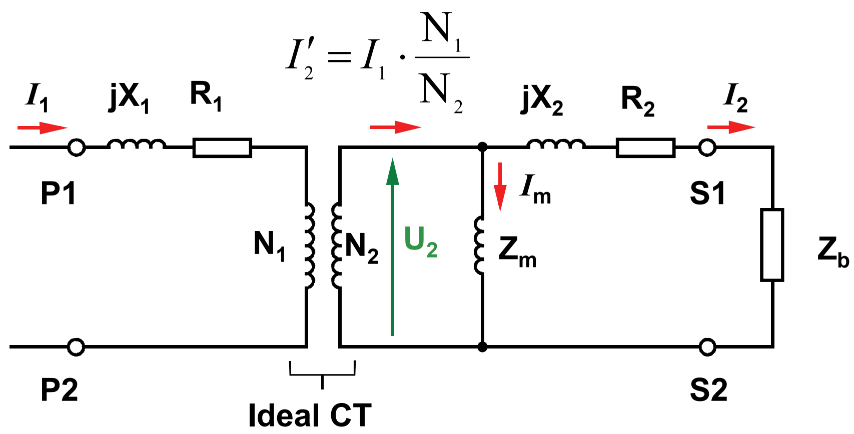

X_1 = Primary leakage reactance
R_1 = Primary winding resistance
X_2 = Secondary leakage reactance
Z_0 = Magnetizing impedance
R_2 = Secondary winding resistance
Z_b = Secondary load

Note: **Normally the leakage fluxes X_1 and X_2 can be neglected**

Current transformer, simplified equivalent circuit

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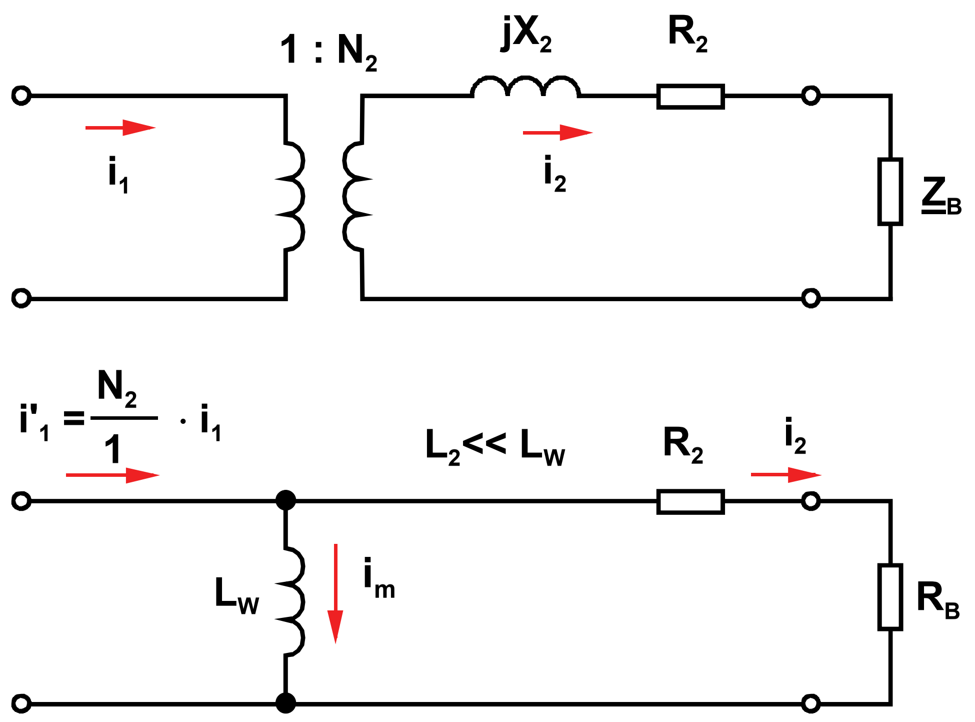

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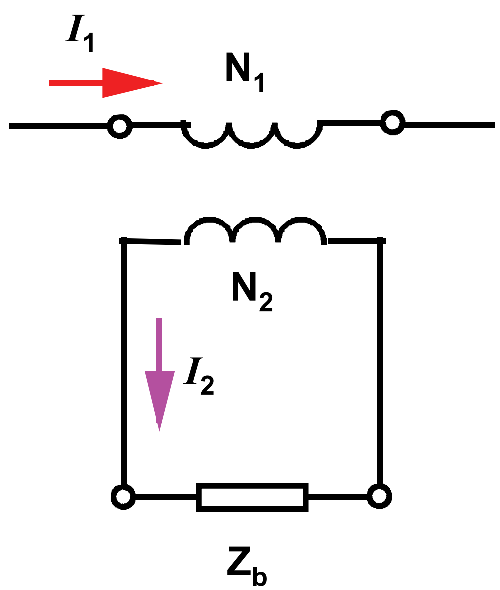
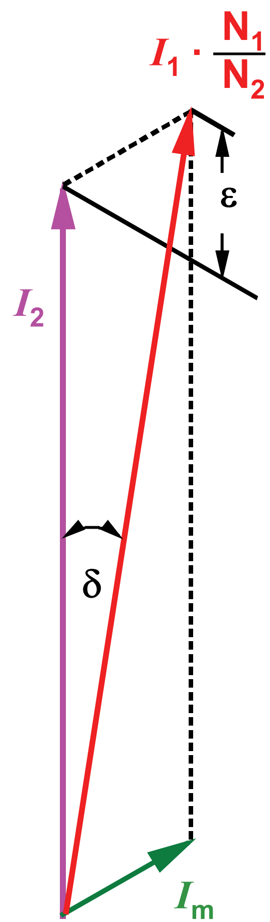
Current transformer:
Phase displacement (δ) and current ratio error (ε)





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Current transformer, Standard for steady-state performance

IEC 60044-1 specifies the following classes:

Accuracy class	Current error at nominal current (In)	Angle error δ at rated current In	Total error at n x In (rated accuracy limit)
5P	± 1 %	± 60 minutes	5 %
10P	± 5%	——	10 %

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Current transformers, Standard for transient performance

IEC 60044-6 specifies four classes:

Class	Error at rated current		Maximum error at rated accuracy limit	Remanence
	Ratio error	Angle error		
TPX (closed iron core)	± 0,5 %	± 30 min	$\hat{\varepsilon} \leq 10\%$	no limit
TPY with anti-remanence air gap	± 1,0 %	± 30 min	$\hat{\varepsilon} \leq 10\%$	< 10 %
TPZ linear core	± 1,0 %	± 180 ± 18 min	$\hat{\varepsilon} \leq 10\%$ (a.c. current only)	negligible
TPS closed iron core	Special version for high impedance protection (Knee point voltage, internal secondary resistance)			No limit

Current transformer saturation

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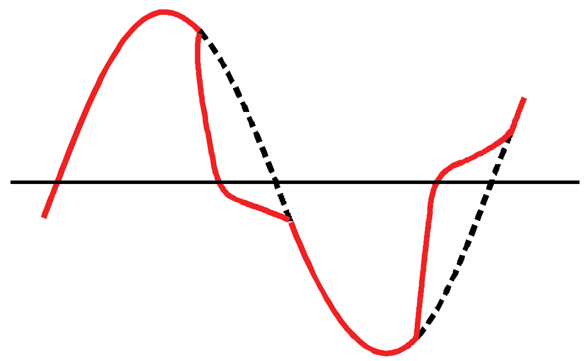
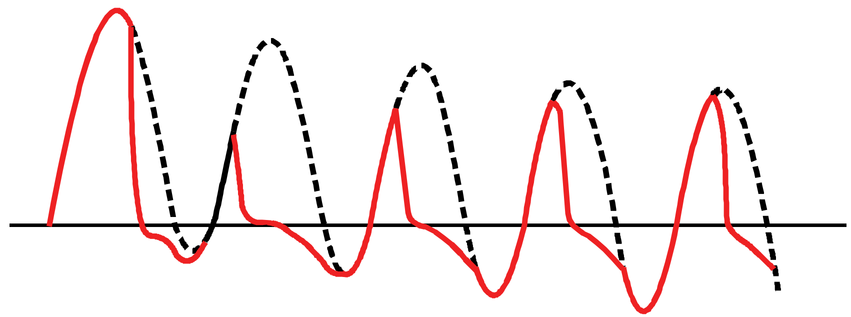
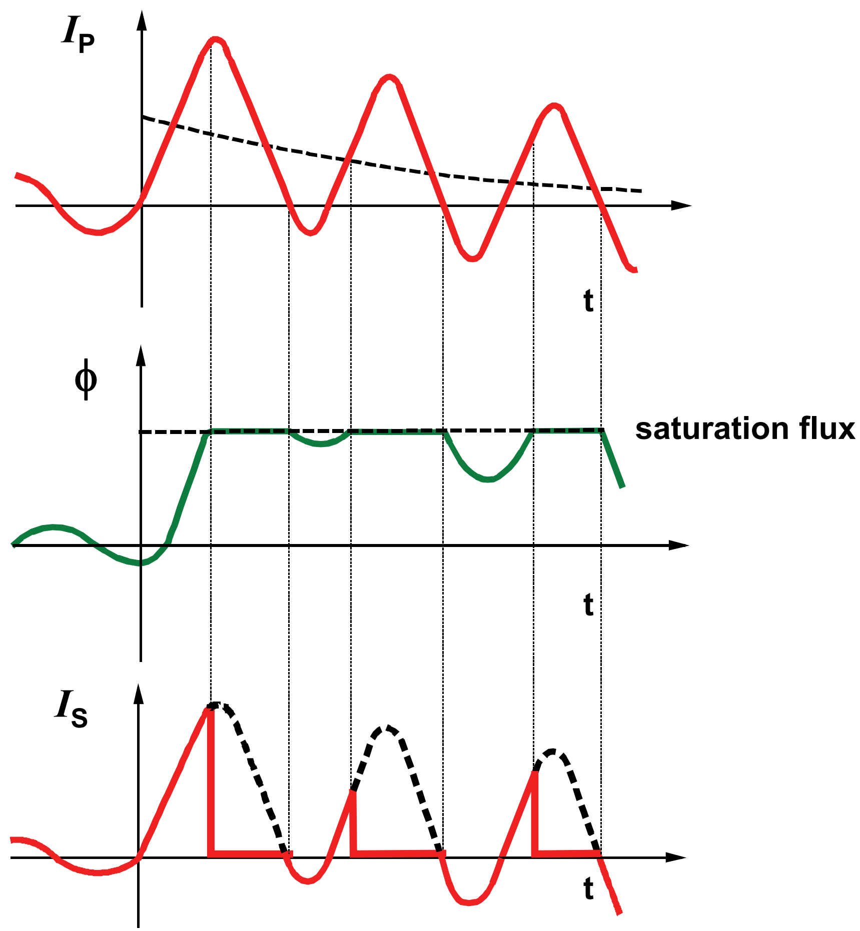


Steady-state saturation with AC current



Transient saturation with offset current

CT saturation
Currents and magnetising



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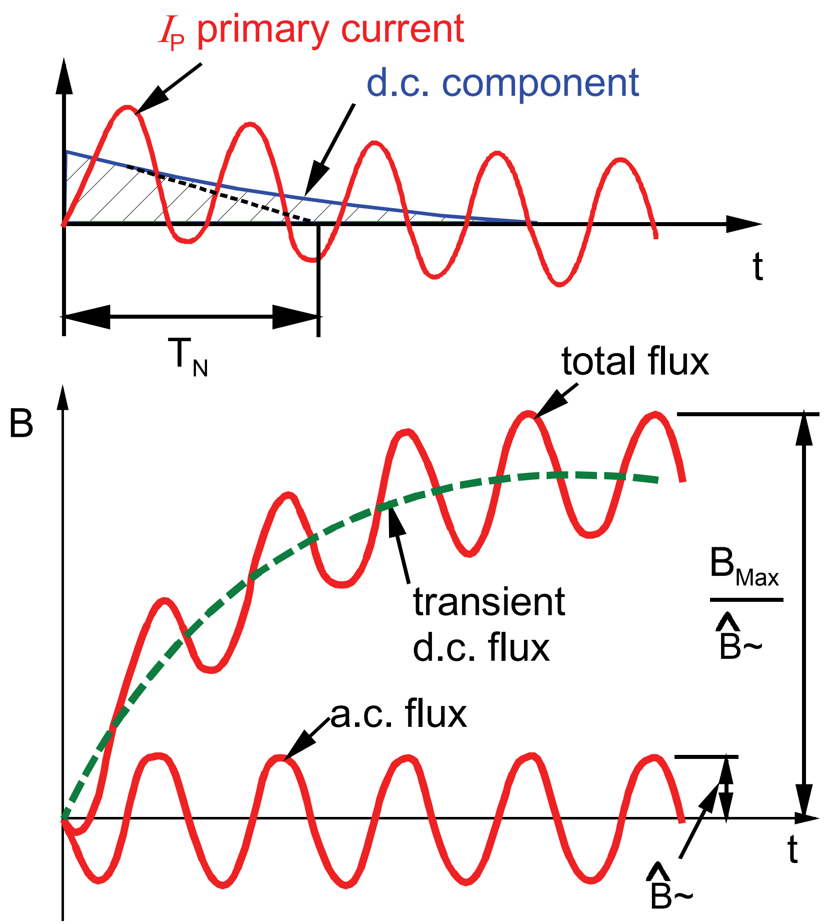
Course of CT-flux during off-set short-circuit current



$$\frac{B}{\hat{B}_\sim} = 1 + \frac{\omega \cdot T_N \cdot T_S}{T_N - T_S}\left(e^{-\frac{t}{TN}} - e^{-\frac{t}{TS}}\right)$$

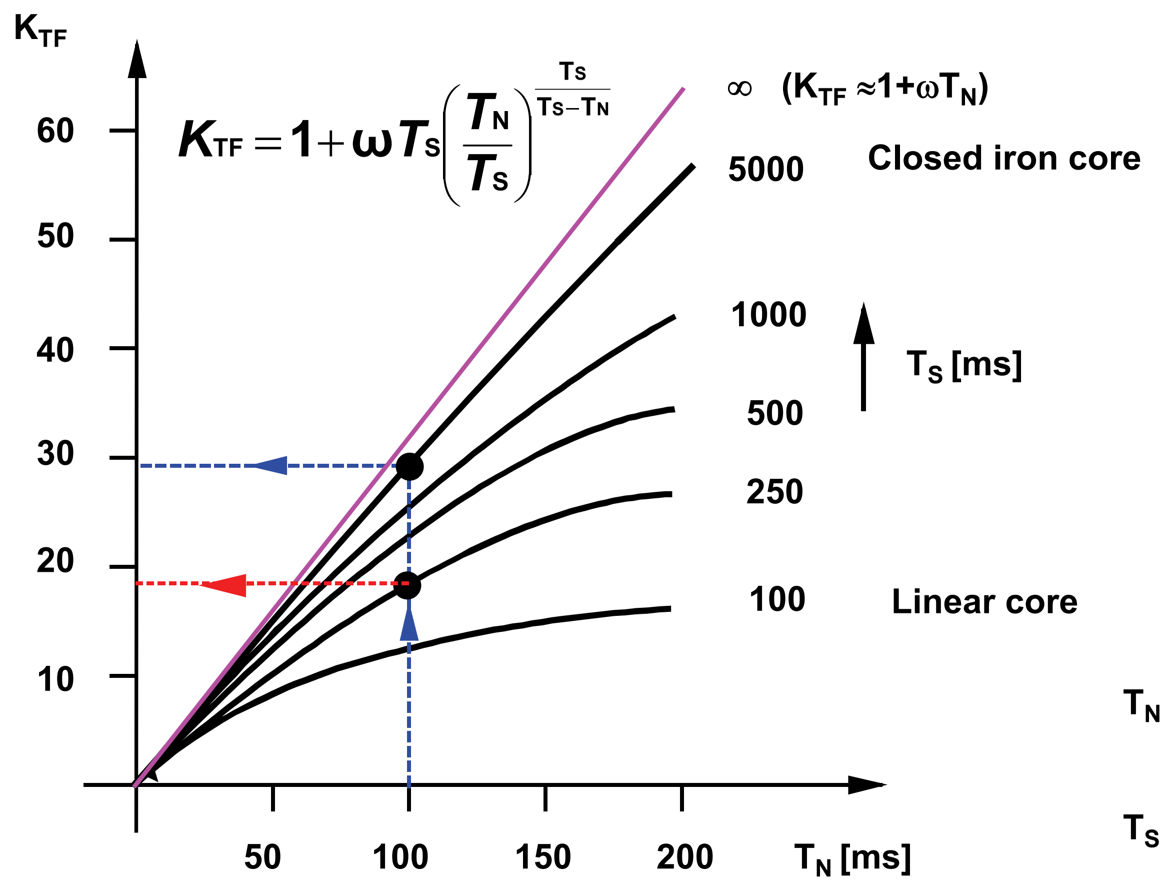
$$\frac{B_{Max}}{B\sim} = 1 + \omega \cdot T_S \cdot \left(\frac{T_N}{T_S}\right)^{\frac{TS}{TS-TN}}$$

$$t_{B\,Max} = \frac{T_N \cdot T_S}{T_S - T_N} \cdot \ln\frac{T_S}{T_N}$$

$$T_S = \frac{L_W}{R_i + R_B} = \frac{1}{\omega \cdot \tan\delta}$$

For 50 Hz: $T_S = \frac{10900}{\delta_{[min]}}[ms]$

CT transient over-dimensioning factor K_{TF}



T_N = network time constant (short-circuit time constant)

T_S = CT secondary time constant

CT with closed iron core, Over-dimensioning factor for a specified time to saturation (T_M)

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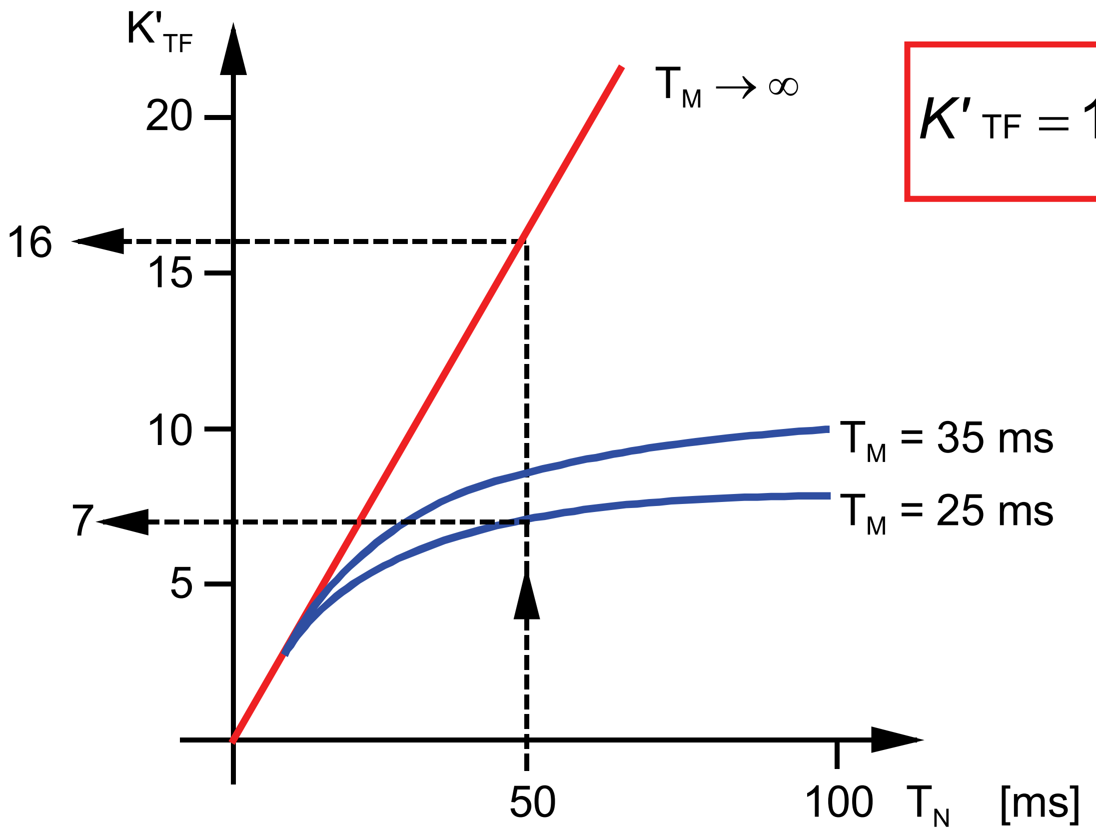
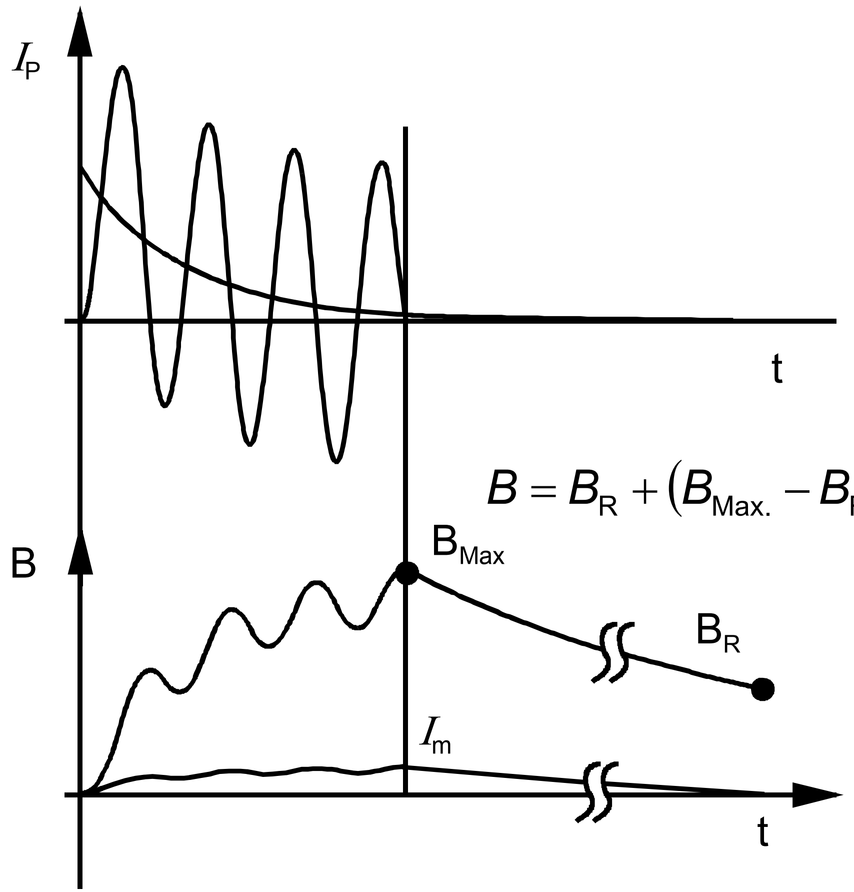


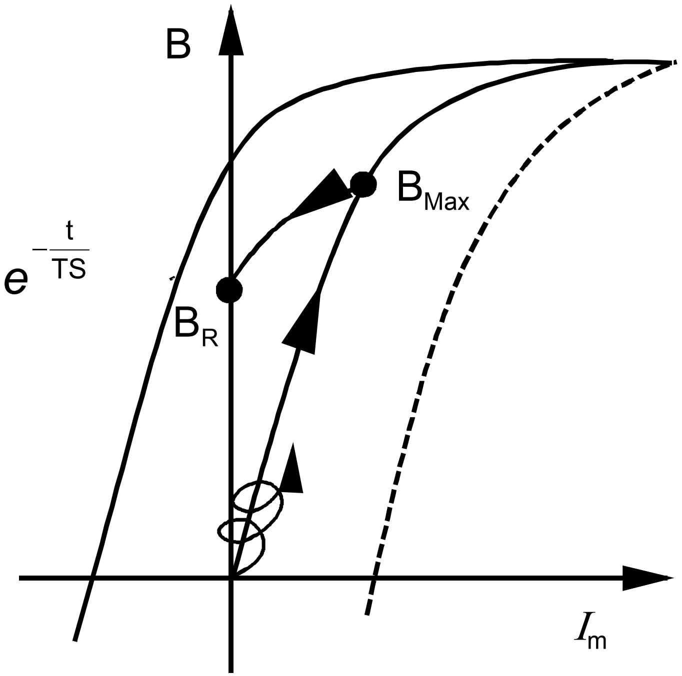
$$K'_{TF} = 1 + \omega T_N = 1 + \frac{X_N}{R_N}$$

$$K'_{TF} = 1 + \omega T_N \left(1 - e^{-\frac{TM}{TN}}\right)$$

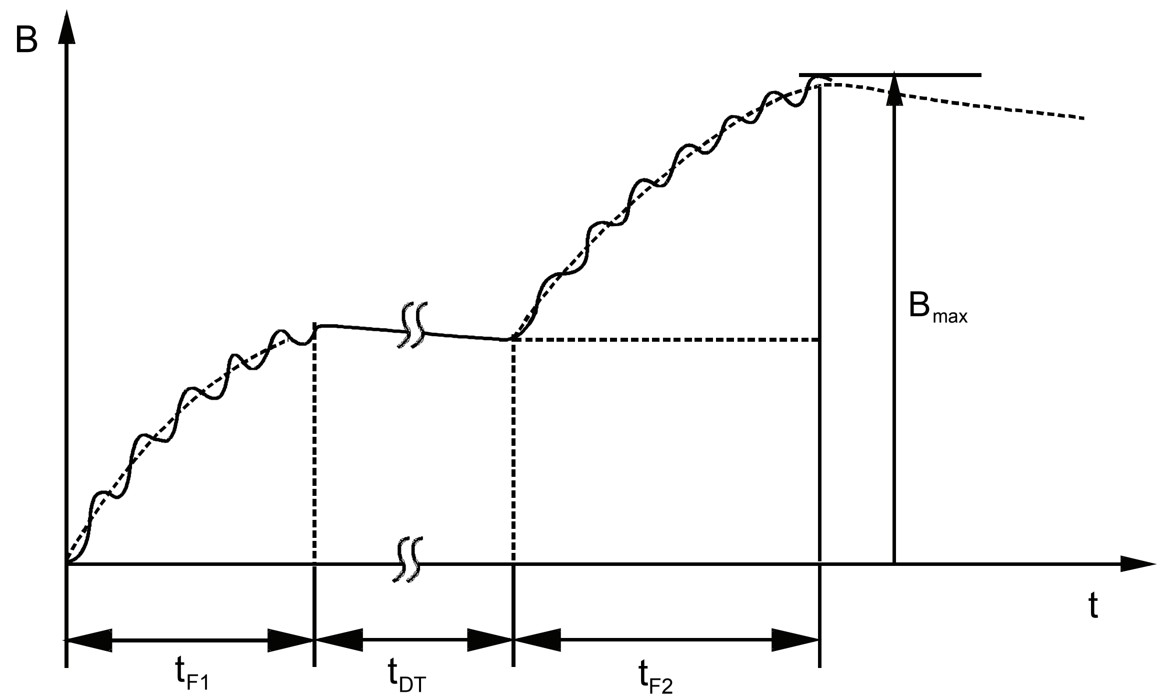
Current transformer
magnetising and de-magnetising



$$B = B_R + (B_{Max.} - B_R) \cdot e^{-\frac{t}{TS}}$$



Current transformer
Course of flux in the case of non-successful auto-reclosure



t_{F1} = duration of 1st fault

t_{DT} dead time

t_{F2} =duration of 2nd fault

$$\frac{B_{max}}{\hat{B}_{\sim}} = \left[1+\frac{\omega \cdot T_N \cdot T_S}{T_N - T_S}\left(e^{-\frac{t_{F1}}{T_N}} - e^{-\frac{t_{F1}}{T_S}}\right)\right] \cdot e^{-\frac{t_{DT}+t_{F2}}{T_S}} + \left[1+\frac{\omega \cdot T_N \cdot T_S}{T_N - T_S}\left(e^{-\frac{t_{F2}}{T_N}} - e^{-\frac{t_{F2}}{T_S}}\right)\right]$$

Current transformer
magnetising curve and point of remanence

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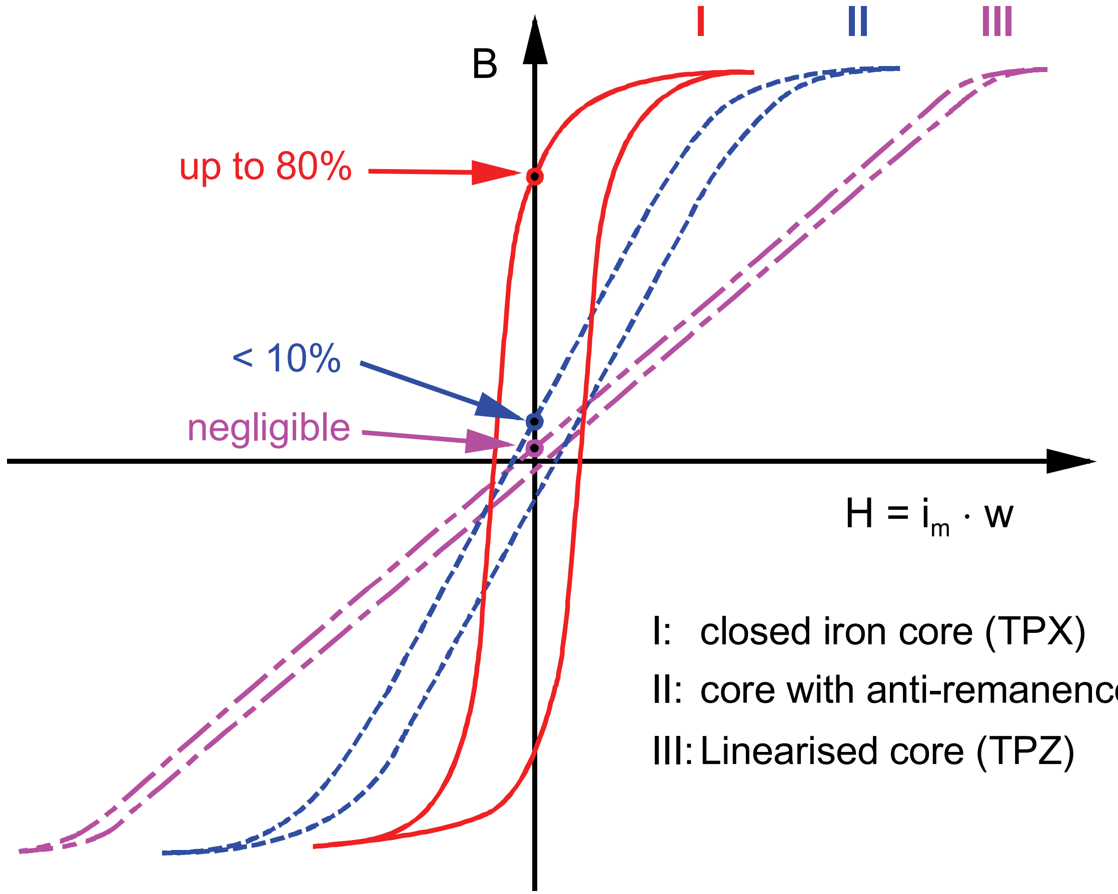
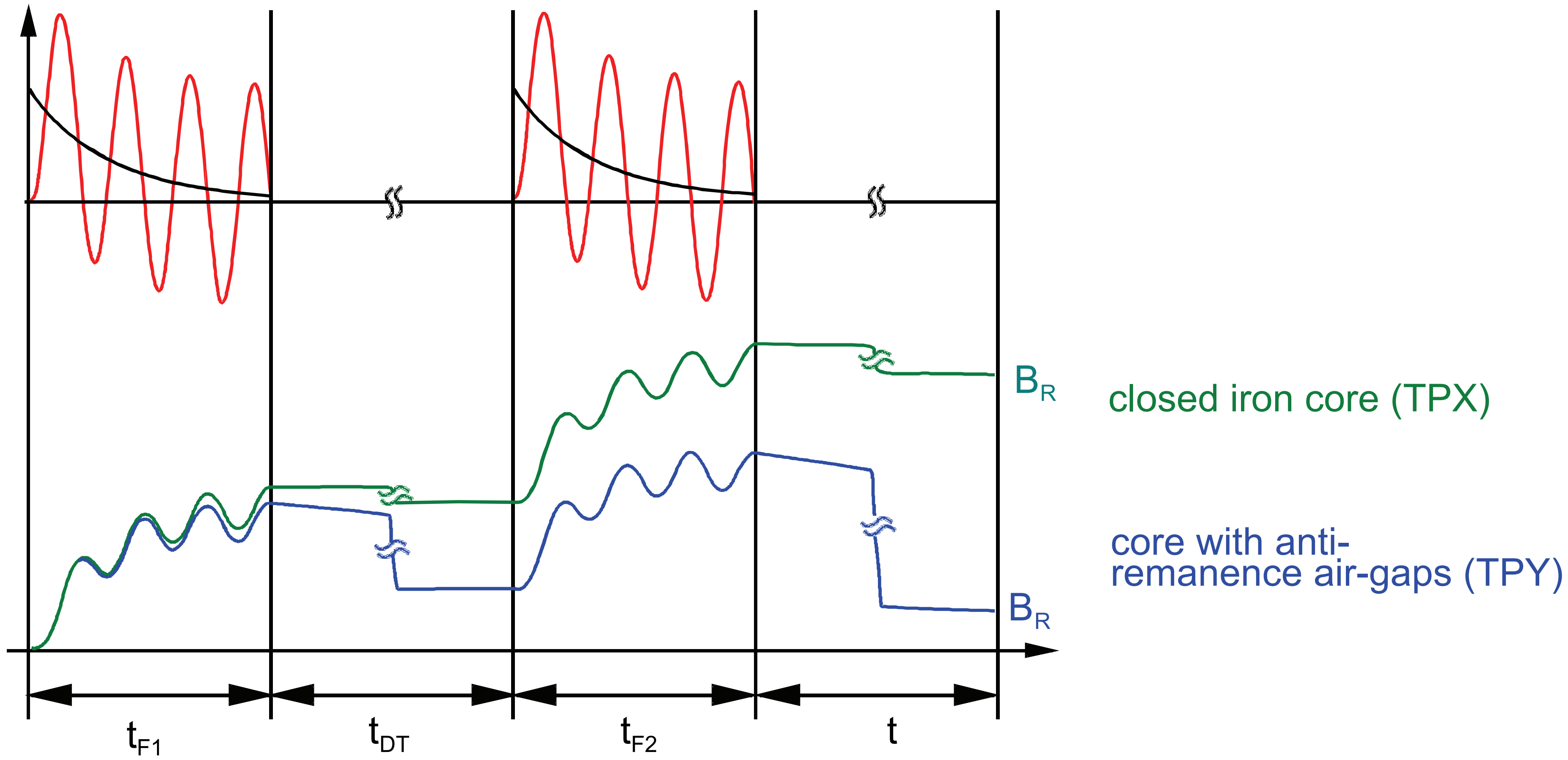


I: closed iron core (TPX)

II: core with anti-remanence air-gaps (TPY)

III: Linearised core (TPZ)

Current transformers TPX und TPY
Course of the flux with non-successful auto-reclosure



Current transformer with linear core (TPZ), Course of the flux with non-successful auto-reclosure

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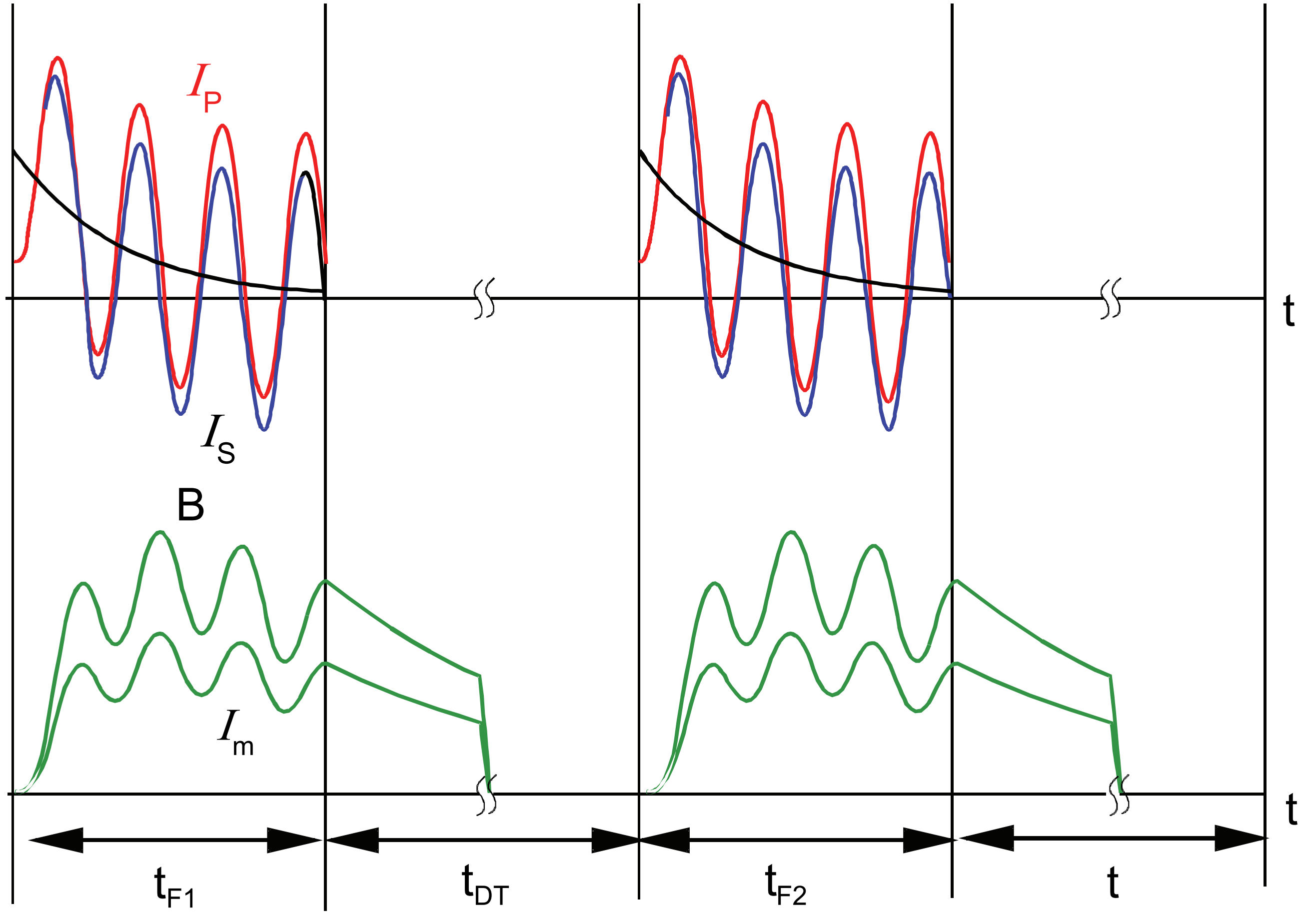

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Standards of voltage transformers

VT classes to IEC 60044-2

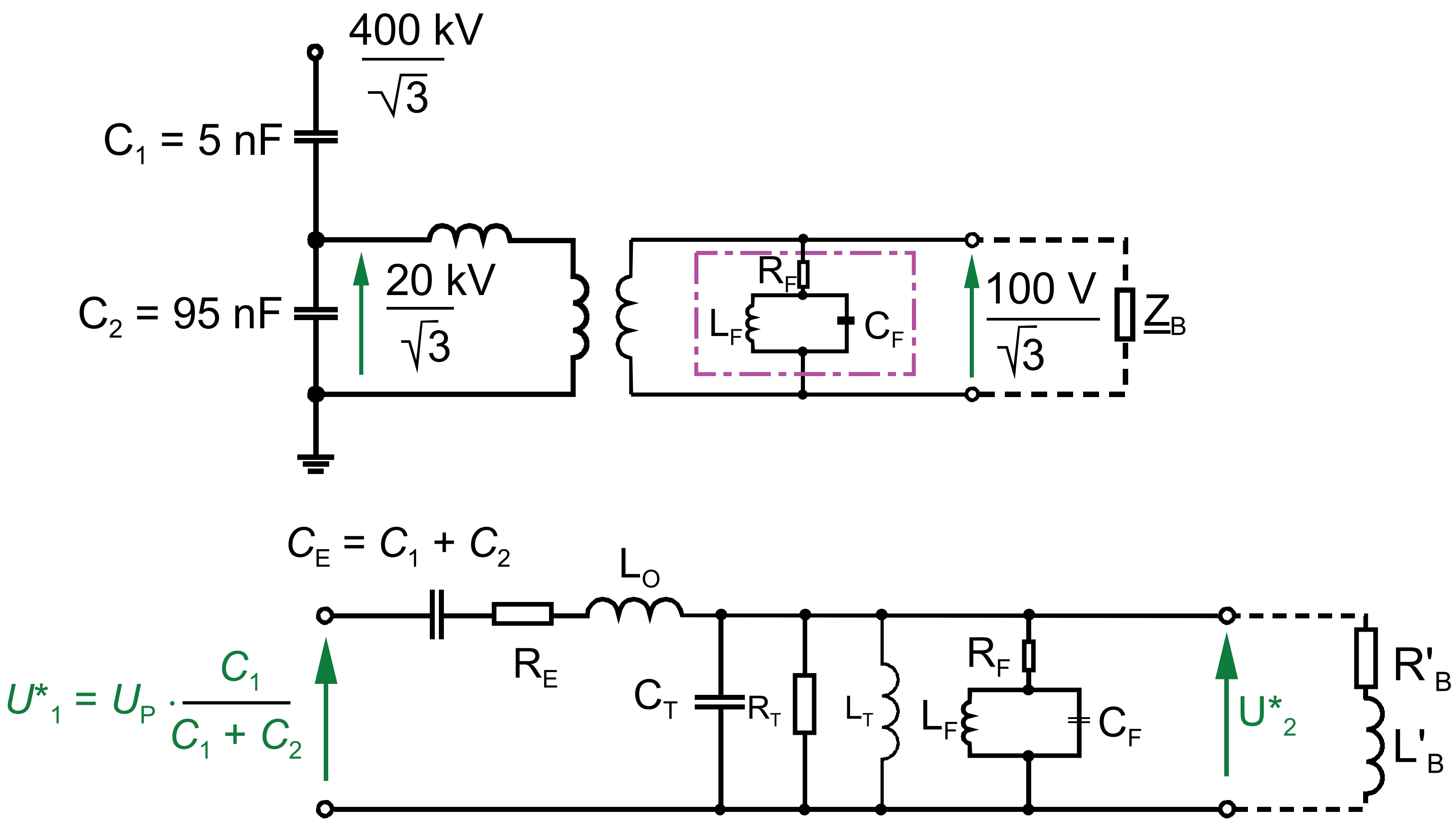
Class designation	Permissible error at $0.05 \cdot U_N$ and $1.0 \cdot U_N$	
	Voltage error F_U	Angle error δ
3P	± 3.0 %	120 minutes
5P	± 6.0 %	240 minutes

All 3P and 5P protection CTs must additionally comply with one of the below VT metering classes!

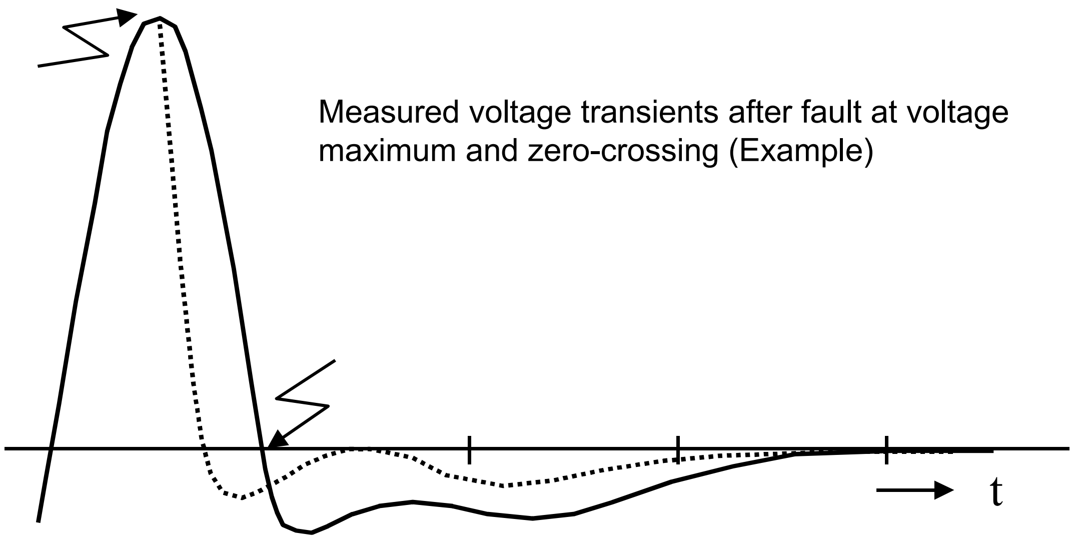
VT classes for measurement IEC 60044-2

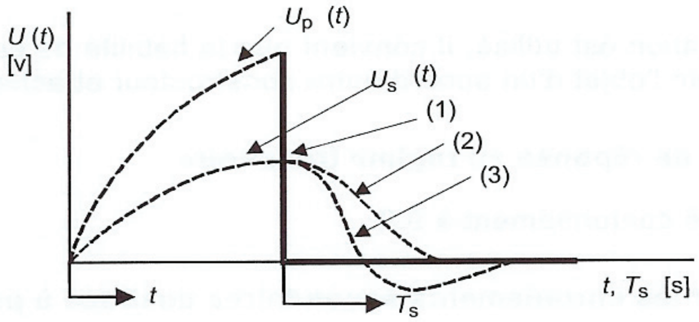
Class designation	Permissible voltage error in % at $1.0 \cdot U_N$	Permissible angle error in minutes at $1.0 \cdot U_N$
0.1	0.1	5
0.2	0.2	10
0.5	0.5	20
1	1	30
3	3	Not determined

Capacitive voltage transformer, Equivalent circuit



Transient performance of CVTs, Recommendations acc. to IEC 60044-5





Legend:

$U_P(t)$ Primary voltage

$U_S(t)$ Secondary voltage

(1) Fault inception

(2) Aperiodic damping of $U_S(t)$

(3) Periodic damping of $U_S(t)$

Time Ts in ms	Ratio $\frac{U_S(t)}{\sqrt{2} \cdot U_S} \cdot 100\%$ Classes		
	3PT1 6PT1	3PT2 6PT2	3PT3 6PT3
10	---	≤ 25	≤ 4
20	≤ 10	≤ 10	≤ 2
40	≤ 10	≤ 2	≤ 2
60	≤ 10	≤ 0.6	≤ 2
90	≤ 10	≤ 0.2	≤ 2

Recommendations to IEC 60044-5

CT dimensioning

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$$ALF' = ALF \cdot \frac{P_i + P_{BN}}{P_i + P_B} = ALF \cdot \frac{R_{CT} + R_{BN}}{R_{CT} + R_B}$$

$$ALF = ALF' \cdot \frac{P_i + P_B}{P_i + P_{BN}} = ALF' \cdot \frac{R_{CT} + R_B}{R_{CT} + R_{BN}}$$

rated CT burden: P_{BN}

internal burden of the CT: $P_i = R_i \cdot I_{2N}^2$

Actual connected burden : $P_B = R_B \cdot I_{2N}^2$

$R_B = R_l + R_R$ = burden resistance

R_l = resistance of connecting cables

R_R = burden resistance of the relay

with $ALF' \geq K_{OD} \cdot \frac{I_K}{I_N}$

$$K_{OD} \geq K_{TF} \cdot K_{Rem}$$

$$K_{Rem} = \frac{1}{1 - \frac{\%\ Remanence}{100}}$$

Theory:

No saturation for the total short-circuit duration: $K'_{TF} = \frac{B_{Max}}{\hat{B}_{\sim}} = 1 + \omega T_N = 1 + \frac{X_N}{R_N}$

No saturation for the specified time t_M: $K''_{TF} = \left[1 + \frac{\omega \cdot T_N \cdot T_S}{T_N - T_S} \left(e^{-\frac{t_M}{T_N}} - e^{-\frac{t_M}{T_S}} \right) \right]$

Practice: Use of K_{TF} - values recommended by vendors

Distance relays, practical CT requirements
Transient over-dimensioning factors K_{TF} (ARC not considered)

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7SA513

- Close-in fault: $K_{TF} \geq 2$
- Fault at balance point:
  - $K_{TF} \geq 5 \quad if \quad T_N < 50ms$
  - $K_{TF} \geq 10 \quad if \quad T_N \geq 50ms$

7SA6

- Close-in fault: $K_{TF} \geq 2 \quad (\geq 1 \ if \ T_N < 30ms)$
- Fault at balance point: $K_{TF} \geq 5$

7SA6 / 7SA522: Operating time with CT saturation
Influence of CT dimensioning

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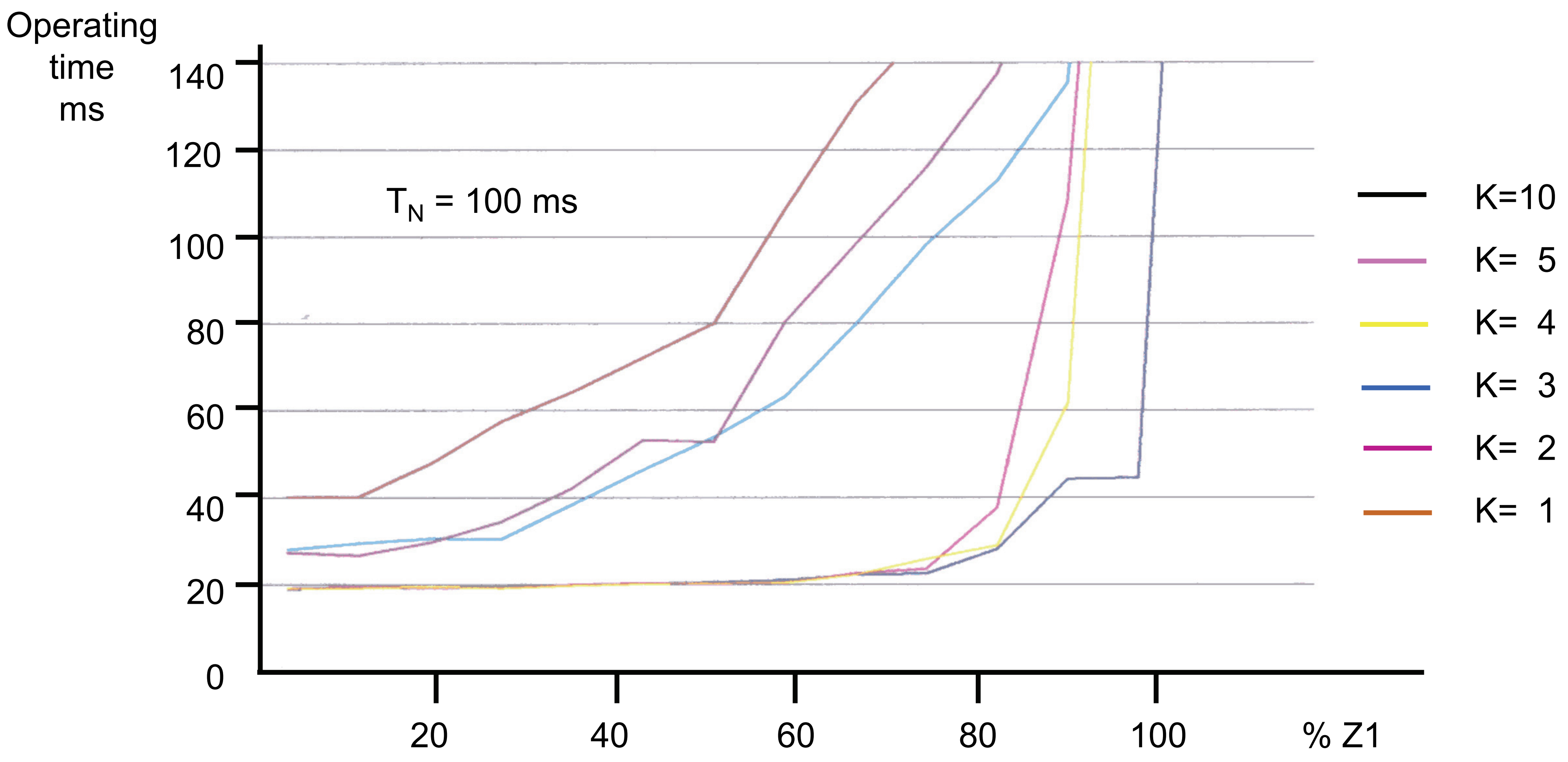

Distance protection, practical CT requirements
Over-dimensioning factor K_{TF} including ARC

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General:

$$K_{TF-ARC} = \left[1+\frac{\omega \cdot T_N \cdot T_S}{T_N - T_S}\left(e^{-\frac{t_{F1}}{T_N}} - e^{-\frac{t_{F1}}{T_S}}\right)\right] \cdot e^{-\frac{t_{DT}+t_{F1}}{T_S}} + \left[1+\frac{\omega \cdot T_N \cdot T_S}{T_N - T_S}\left(e^{-\frac{t_{F2}}{T_N}} - e^{-\frac{t_{F2}}{T_S}}\right)\right]$$

This formula is applicable **with TPY type CTs** where T_S is in the range of some 100 ms resulting in a considerable induction decay during the dead time. (see IEC 60044-6).

With TPZ type CTs, this formula is not applicable because T_S is only about 100 ms and the flux is completely decaying during the dead time. The auto-reclosure must therefore not be considered with dimensioning of TPZ current transformers.

With **closed iron core CTs** ($T_S >> T_N$):

$$K'_{TF-ARC} = 1+\omega \cdot T_N \cdot \left(1-e^{-\frac{T_{F1}}{T_N}}\right) + K_{TF\text{ - without ARC}}$$

CT dimensioning for distance protection
Calculation example (1)

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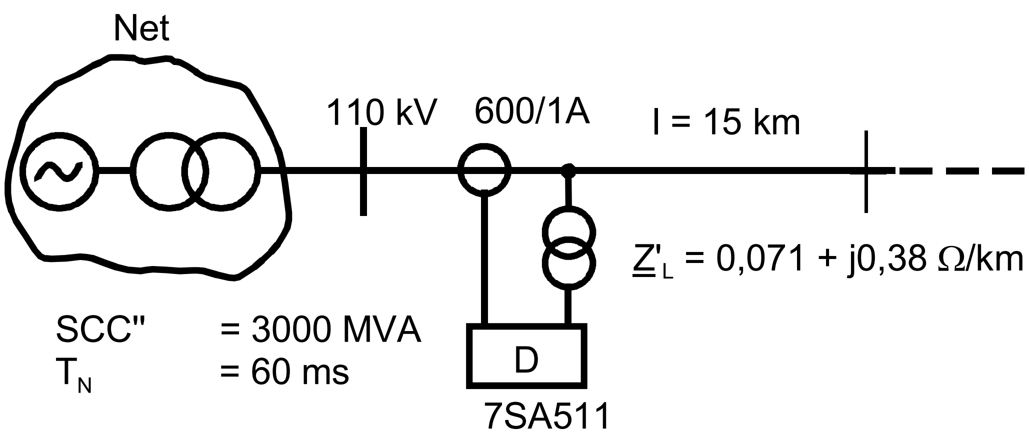

Given:

line-configuration, see above

CTs: 600/1

Connecting leads CT to relay: 80 m one way, 2,5 mm^2 Cu

Searched:

1. Rated accuracy limiting factor of the CTs (Type TPX, 5P, 30 VA)

2. Rated accuracy limiting factor when the auto-reclosure cycle COCO is considered (circuit breaker operating time: 60 ms, dead time: 0.4 s))

CT dimensioning for distance protection
Calculation example (2)

SIEMENS

Condition 1): Close-in faults withiut ARC

The maximum short-circuit current is:

$$I_{K\,Max.} = \frac{S_N''}{1.1 \cdot \sqrt{3} \cdot U_N} = \frac{3000\,\text{MVA}}{1.1 \cdot \sqrt{3} \cdot 110} = 14.4\,\text{kA}$$

For relay 7SA511 with T_N= 60 ms: $K_{TF}=3$.

Therefore we get:

$$ALF' = 3 \cdot \frac{14400}{600} = 72$$

Condition 2): Fault near line end without ARC

The source impedance is

$$X_S \approx Z_S = \frac{1.1 \cdot U_S}{\sqrt{3} \cdot I_S} = \frac{1.1 \cdot 110\,\text{kV}}{\sqrt{3} \cdot 14.4\,\text{kA}} = 4.85\,\Omega$$

$$T_N = \frac{L_S}{R_S} = \frac{X_S/\omega}{R_S}$$

Herewith: $R_S = \frac{X_S}{\omega \cdot T_N} = \frac{4.85}{314 \cdot 0.06} = 0.26\,\Omega$

Fault at the balance point (85% line length):

X_L = 0.85 · 15 · 0.38 = 4.8 Ω

R_L = 0,85·15·0.071= 0.91 Ω

The corresponding fault current is:

$$I_{F\text{-Balance point}} = \frac{1.1 \cdot U_N/\sqrt{3}}{Z_S + Z_L} \approx \frac{1.1 \cdot U_N/\sqrt{3}}{X_S + X_L} = \frac{1.1 \cdot 110/\sqrt{3}}{4.85 + 4.8} = 7.24\,\text{kA}$$

Time constant of the short-circuit current:

$$T_N = \frac{(X_S + X_L)/\omega}{R_S + R_L} = \frac{(4.85 + 4.8)/314}{0.26 + 0.91} = 26\,\text{ms}$$

$$K_{TF2}' = 1 + \omega \cdot T_N \cdot \left(1 - e^{-\frac{T_S}{T_N}}\right) = 7.0 \quad \text{and} \quad ALF' = 7.0 \cdot \frac{7240}{600} = 84$$

The CT has to be designed for condition 2).

CT dimensioning for distance protection
Calculation example (3)

SIEMENS

Resistance of connecting leads CT to relay:

$$R_L = 2 \cdot \frac{\rho \cdot l}{Q} = \frac{0.0179 \cdot 80}{2.5} = 1.15\ \Omega$$

Burden of relay 7SA511: R_R=0.1 Ω
Total burden: R_B=1.25 Ω
for the accuracy limit factor, we get:

$$ALF \geq \frac{6+1.25}{6+30} \cdot 84 = 16.9$$

Chosen: n=20

Condition 3): Close-in fault with ARC

1st short-circuit duration (protection +breaker time: T_{F1} =35+60 =95 ms

Herewith and with T_N=60 ms:

$$K_{TF3}' = 1 + \omega \cdot T_N \cdot \left(1 - e^{-\frac{T_{F1}}{T_N}}\right) + a = 16 + 3 = 119$$

$$ALF_3' = K_{TF3}' \cdot \frac{I_{F\_max\_line\ beginning}}{I_N} = 19 \cdot \frac{14400}{600} = 456$$

Condition 4): Fault at balance point with ARC

With T_{F1}=95 ms, T_N=26 ms und T_M=35 ms:
K_{TF4}'= 9+7=16

$$K_{TF4}' = \left[1 + \omega \cdot T_N \cdot \left(1 - e^{-\frac{T_{F1}}{T_N}}\right)\right] + \left[1 + \omega \cdot T_N \cdot \left(1 - e^{-\frac{T_M}{T_N}}\right)\right]$$

$$= 9 + 7 = 16$$

$$ALF_4' \geq K_{TF4}' \cdot \frac{I_{F\_max\_line\ end}}{I_N} = 16 \cdot \frac{7240}{600} = 193$$

Design for the case with ARC to condition 3), close in fault:

$$ALF \geq \frac{6+1.25}{6+30} \cdot 456 = 92$$

Here, a larger CT would have to be taken, e.g. 60 VA (15 VA internal burden) with a doubled ratio, e.g. 1200/1 A.
The accuracy limit factor would then be: n>49 (50)

CT dimensioning for distance protection
Calculation example (4)

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Design of TPY type CTs for the ARC C-O-C-O cycle

$$K_{TF-ARC} = \left[1 + \frac{\omega \cdot T_N \cdot T_S}{T_N - T_S}\left(e^{-\frac{t_{F1}}{T_N}} - e^{-\frac{t_{F1}}{T_S}}\right)\right] \cdot e^{-\frac{t_{DT}+t_{F1}}{T_S}} + \left[1 + \frac{\omega \cdot T_N \cdot T_S}{T_N - T_S}\left(e^{-\frac{t_M}{T_N}} - e^{-\frac{t_M}{T_S}}\right)\right]$$

It is sufficient when the short-circuit current is transmitted till the end of the relay measuring time T_M.

Given:
TPY type CT with T_S=0.5 s
Dead time: T_{DT}=0.4 s

Solution:

Condition 1): Close-in fault with ARC
With T_N =60 ms, T_{F1} =95 ms and T_M =35 ms:

$$K_{TF\,1}' = [14.3] \cdot 0.42 + [9] = 15$$

$$ALF_1' = 5 \cdot \frac{14400}{600} = 360$$

Condition 2): Fault at balance point with ARC
With T_N =26 ms, T_{F1} =95 ms and T_M =35 ms:

$$K_{TF\,2}' = [7.9] \cdot 0.42 + [6.8] = 10$$

$$ALF_2' = 10 \cdot \frac{7240}{600} = 121$$

The CT has to be designed for the close-in fault:

$$ALF \geq \frac{6 + 1.25}{6 + 30} \cdot 360 = 73 \quad \text{(chosen 80)}$$

Comparison with closed iron core CT, i.e. T_S = 5.0 instead of 0.5 s leads to the following result:
$K_{TF\,1}'$=[16] · 1+ [9]=25. (40% smaller core cross section)

CT dimensioning for distance protection
Calculation example (5)

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Design of TPZ type CTs (linear CTs)

As a rule, the CT is dimensioned so that the maximum short-circuit current with d.c. offset can be transmitted saturation free:

$$K_{TF}^{**} = 1 + \omega \cdot T_S \cdot \left(\frac{T_N}{T_S} \right)^{\frac{T_S}{T_S - T_N}}$$

Example:
The CT shall be designed to IEC 60044-6 with a phase displacement of $\delta = 3^{\circ}$ at rated burden.

$$T_S = \frac{10900}{\delta_{[min]}} = 61\,\text{ms}$$

The short-circuit time constant is: $T_N = 60$ ms.
Herewith we get: $K^{**} = 7$.

It results a very low over-dimensioning factor, which is also valid for the non-successful ARC, as the CT is completely demagnetised during the dead time.
In comparison, the following reductions in core cross section can be achieved:
–by (1– 7/25), i.e. 72% compared to the TPX type CT,
–by (1– 7/15), i.e. 53% compared to the TPY type CT.

However, the higher core fixing cost have to be considered.

Distance Protection Setting

Reichweite der Distanzzonen

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General objectives of distance zone grading:

1st Zone: 85 to 90% of the protected line

Overreach zone : About 120% of the protected line (150% in case of parallel lines)

2. Zone: At least 15 - 20% over the following busbar (Busbar back-up protection), up to about 50% of the shortest following line

3.Zone:
- 10 to 20% over the longest following line considering intermediate infeeds
- R-reach must allow maximum emergency line loading according to NERC recommendations

Setting of impedance type fault detectors

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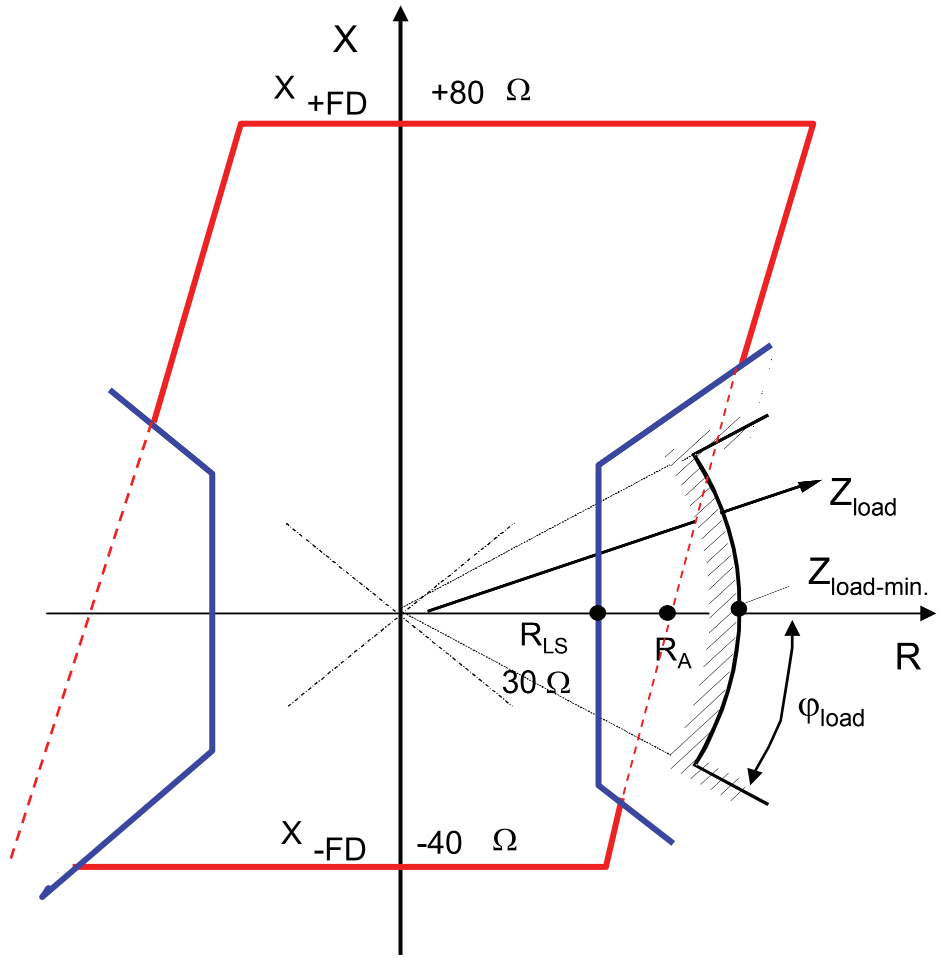


$$Z_{load} = \frac{U_{N\,Ph-Ph}}{I_{load}\cdot\sqrt{3}} = \frac{U_{N\,Ph-Ph}^{2}}{P_{app}}$$

$$R_{load} = Z_{load}\cdot\cos\varphi_{load} = Z_{load}\cdot\frac{P_{act}}{P_{app}} = \frac{U_{N\,Ph-Ph}^{2}\cdot P_{act}}{P_{act}^{2}+P_{react}^{2}}$$

$$X_{load} = Z_{load}\cdot\sin\varphi_{load} = Z_{load}\cdot\frac{P_{react}}{P_{app}} = \frac{U_{N\,Ph-Ph}^{2}\cdot P_{react}}{P_{act}^{2}+P_{react}^{2}}$$

$$P_N = U_N\cdot I_N\cdot\sqrt{3}$$

Example :

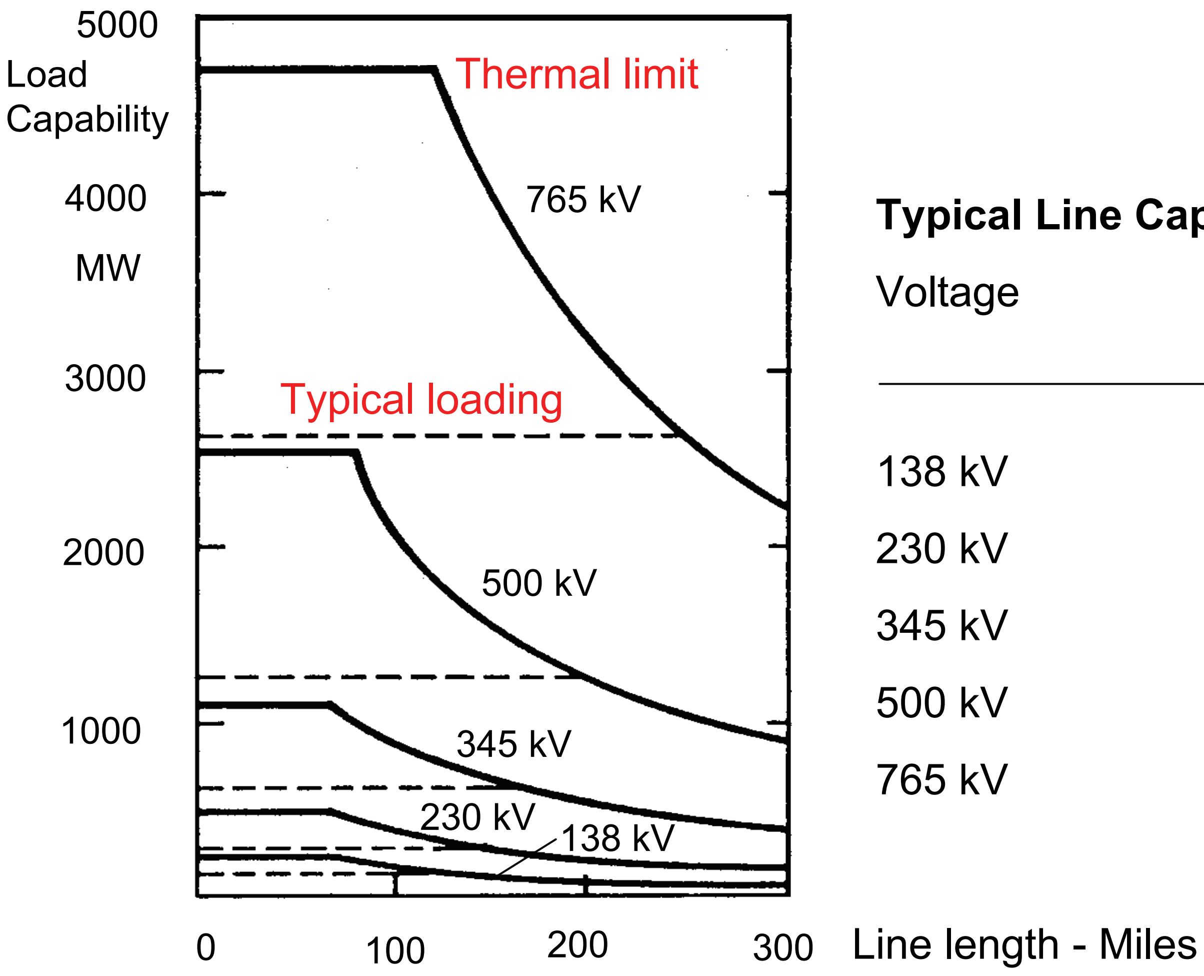
$U_N = 230kV$ *and* *CT - ratio 1200/1*

$P_N = 230kV\cdot 1200A\cdot\sqrt{3} = 478\ MVA$

During this load, the relay measures a secondary load impedance of:

$$Z_{N\,(Sec.)} = \frac{U_{N\,(Sec.)}/\sqrt{3}}{I_{N\,(Sec.)}} = \frac{100\ V/\sqrt{3}}{1\ A} = 57{,}7\ \Omega$$

Line loading



Typical Line Capabilities (about natural load):

Voltage	Load Capability	Load Impedance
138 kV	100 MW	190 Ohm
230 kV	250 MW	212 Ohm
345 kV	600 MW	198 Ohm
500 kV	1200 MW	208 Ohm
765 kV	2500 MW	234 Ohm

August 14, 2003 Northwest USA and Canada blackout
Third zone tripping due to overload and undervoltage

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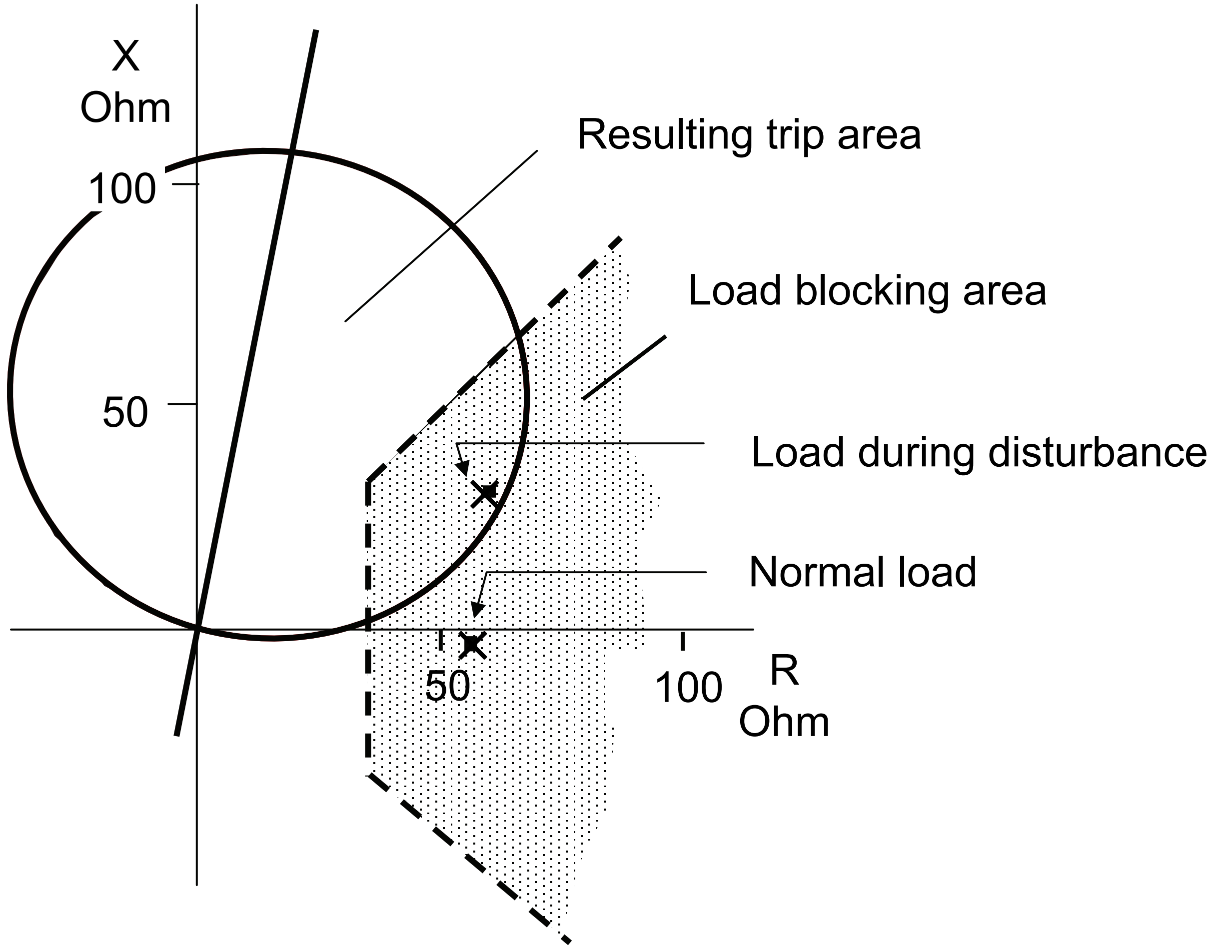

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August 14, 2003 Blackout
NERC Actions to prevent cascading blackouts (February 10, 2004)

NERC (**N**orth **A**merican **E**lectric **R**eliability **C**ouncil):

Recommendation 8a:

Evaluate zone 3 settings for the purpose of verifying that zone 3 relay is not set to trip on load under extreme emergency conditions. *)

*) Zone 3 relay should not operate at or below 150% of the emergency ampere rating of a line, assuming 0.85 per unit voltage and a line phase angle of 30 degrees

Set zone 3 relay to allow 20 min overloading (System operators need 20 min to shed load once a problem has been recognized.

- Distance relays should not be used to provide overload protection
- Relay should be set to ride through all recoverable swings

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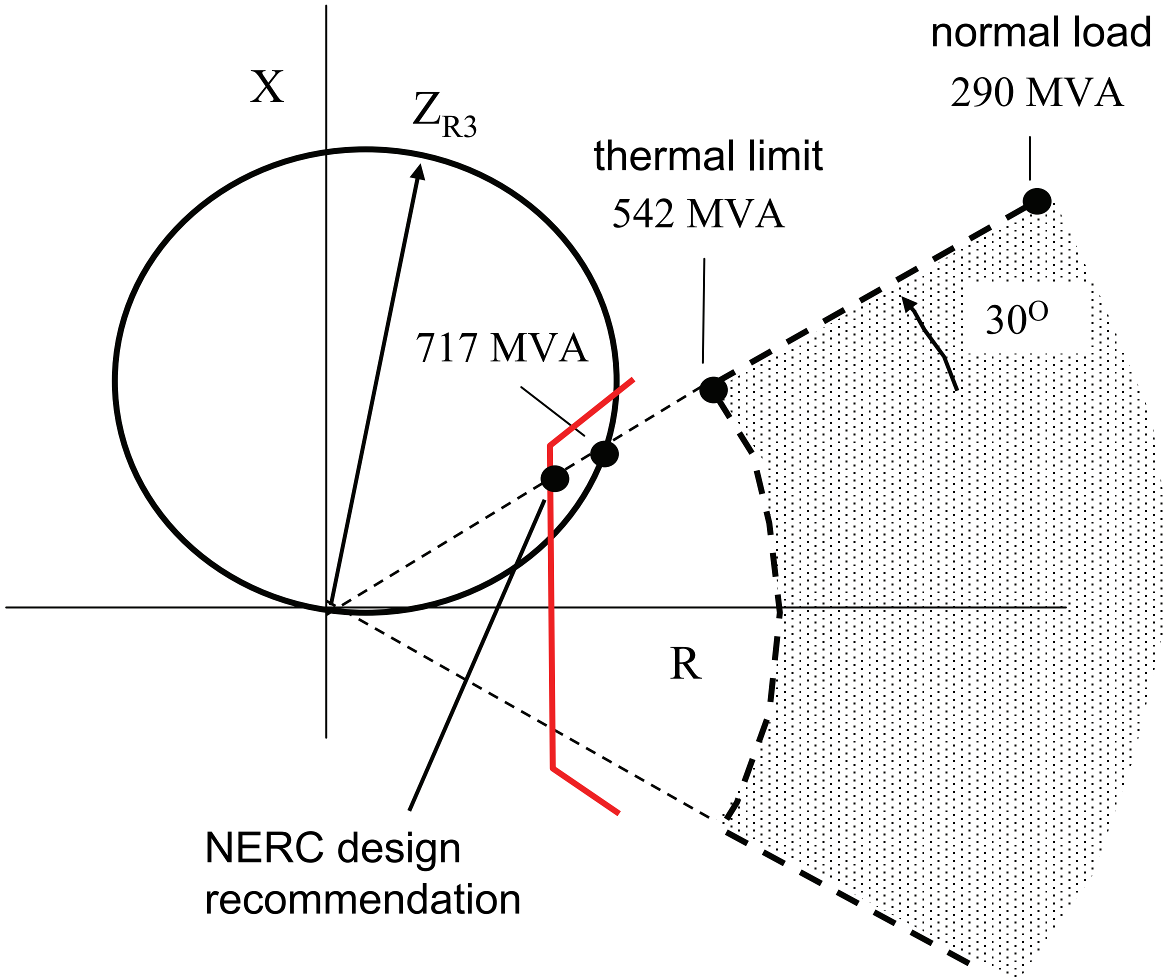
Setting of load encroachment section



Setting of impedance fault detector
Example (1)

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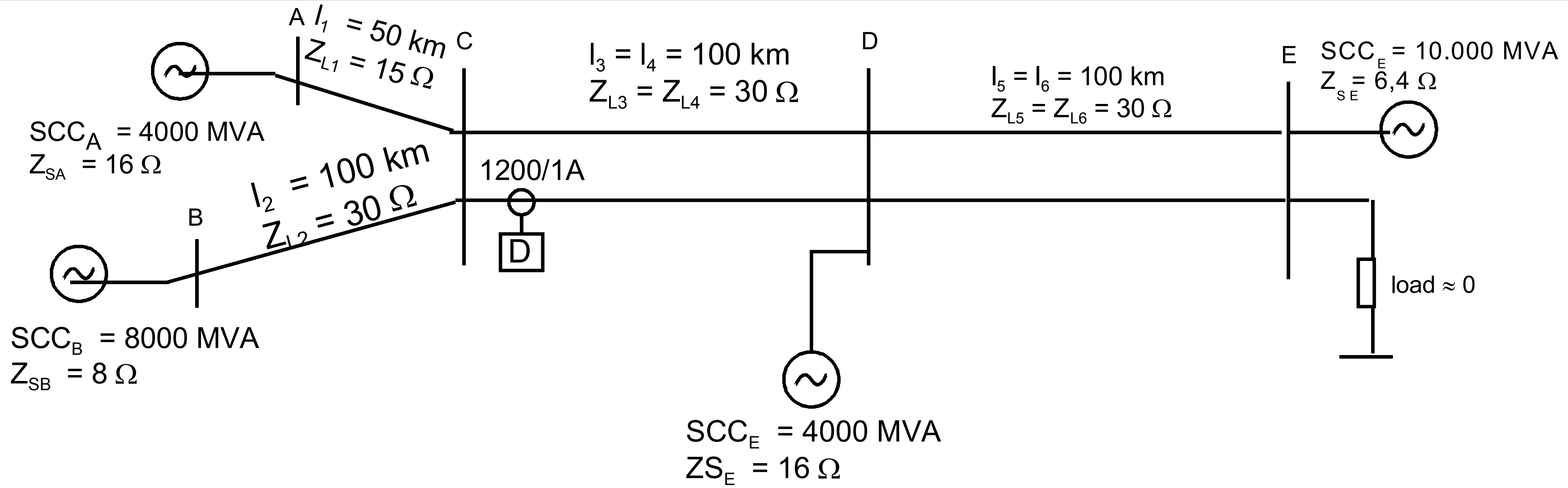

For each 400 kV single line from C to D, the natural load is $P_{Nat,}$ = 460 MW

$$I_{load} = \frac{P_{Nat}}{\sqrt{3} \cdot U_N} = \frac{460\ \text{MW}}{\sqrt{3} \cdot 400\ \text{kV}} = 664\ \text{A}$$

$$Z_{load} = \frac{400.000\ \text{V}/\sqrt{3}}{664\ \text{A}} = 348\ \Omega$$

$$Z\text{-}ratio = \frac{CT\text{-}ratio}{VT\text{-}ratio} = \frac{1200/1}{400/0.1} = 0.3$$

$$R_{FD\,secondary} = 0.3 \cdot \frac{348}{2} \cdot 0.7 = 36.5\ \Omega$$

Setting of impedance fault detector Example (2)

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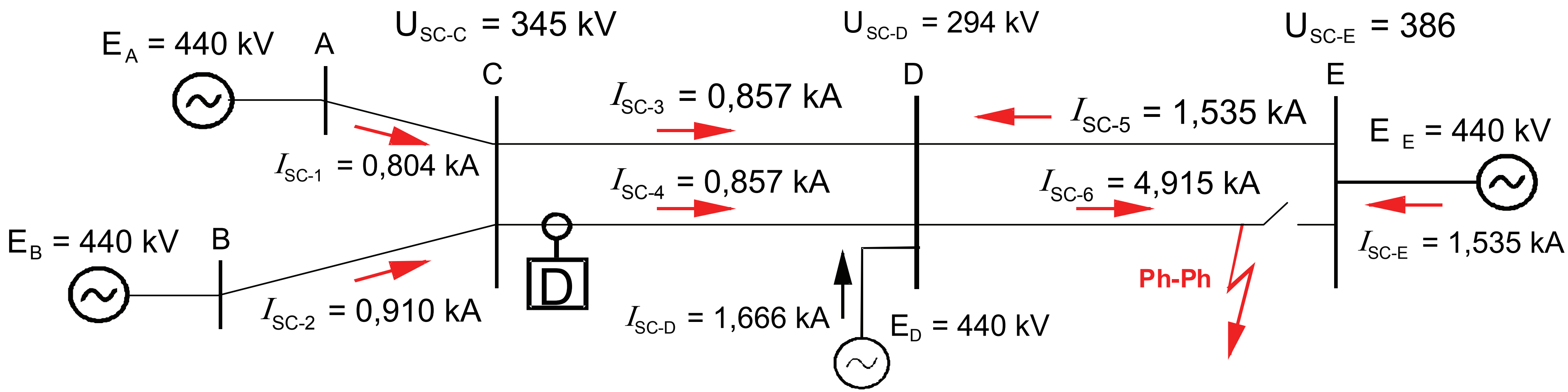

$$Z_{Ph-Ph} = \frac{U_{Ph-Ph}}{I_{Ph1} - I_{Ph2}} = \frac{U_{Ph-Ph}}{2 \cdot I_{Ph}} = \frac{345.000V}{2 \cdot 857A} = 201\Omega$$

$$Z\text{ - ratio} = \frac{\text{CT - ratio}}{\text{VT - ratio}} = \frac{1200/1}{400/0.1} = 0{,}3$$

$$X_{+A\ primary} = 1{,}3 \cdot 201 = 261\Omega$$

$$X_{+A\ secondary} = 0{,}3 \cdot 261 = 78\Omega, \quad chosen \quad 80\,\Omega$$

Setting of impedance fault detector Example (3)

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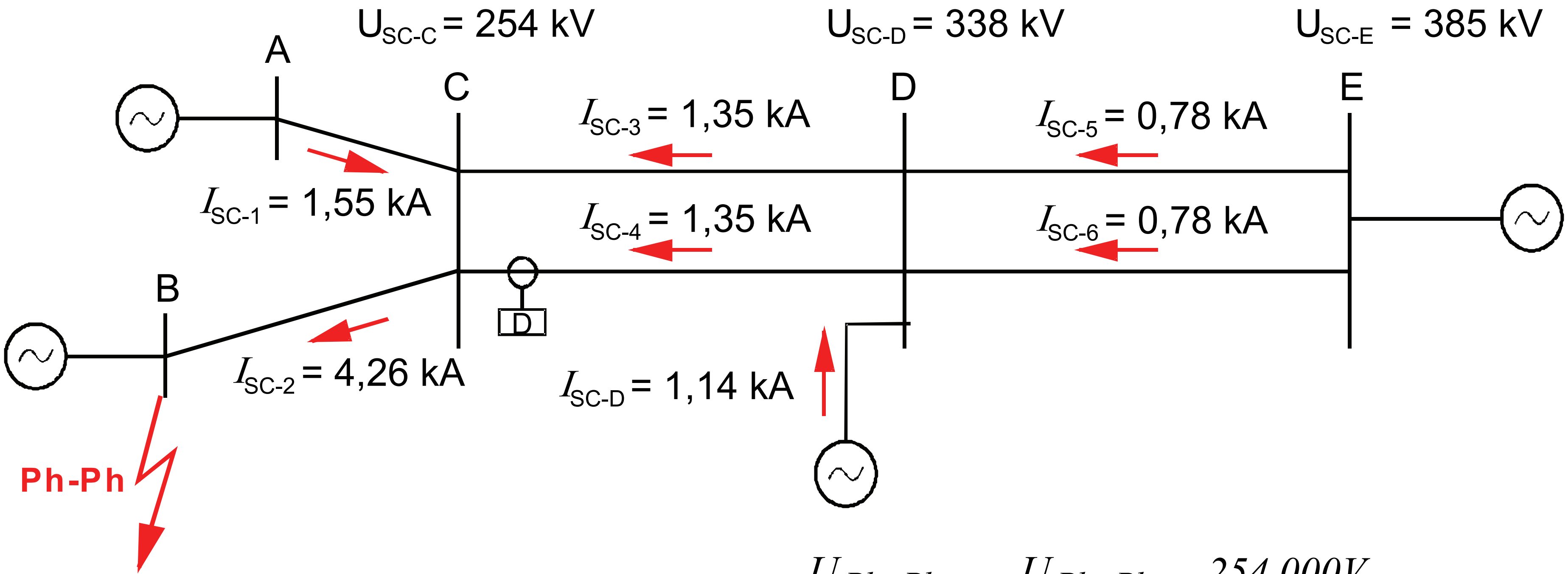

$$Z_{Ph-Ph} = \frac{U_{Ph-Ph}}{I_{Ph1} - I_{Ph2}} = \frac{U_{Ph-Ph}}{2 \cdot I_{Ph}} = \frac{254.000V}{2 \cdot 1350A} = -94\Omega$$

$$X_{-A\,secondary} = 1{,}3 \cdot (-94) = -122\,\Omega$$

$$X_{+A\,secondary} = 0{,}3 \cdot (-122) = -36{,}6\,\Omega, \quad chosen\text{ - }40\Omega$$

R-setting of distance zones (arc compensation)

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Voltage level:	Avarage distance of ph-conductors	Arc resistance	
		at I_{SC}=1000 A	at I_{SC}=10.000 A
380 kV	11 m	27,5 Ω	2,75 Ω
220 kV	7 m	17,5 Ω	1,75 Ω
110 kV	3,5 m	7,5 Ω	0,75 Ω
20 kV	<1 m	<2,5 Ω	<0,25 Ω

Protected cable/line	R/X-ratio of zone setting
Short cables (ca. 0.5 to 3 km)	3 to 5
Longer cables > 3km	2 to 3
Short overhead lines < 10 km	2 to 5
Overhead lines < 100 km	1 to 2
Long overhead lines 100 to 200 km	0.5 bis1
Long EHV lines >200 km	≤ 0.5

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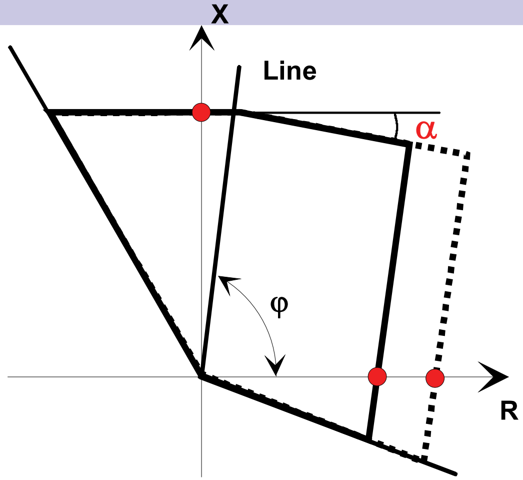
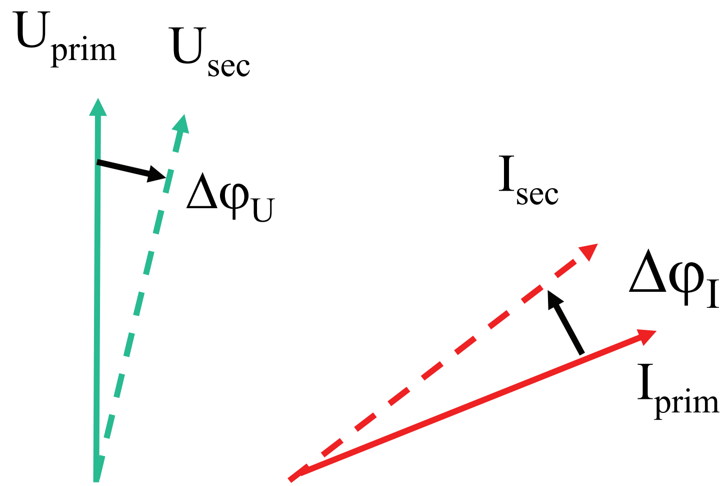
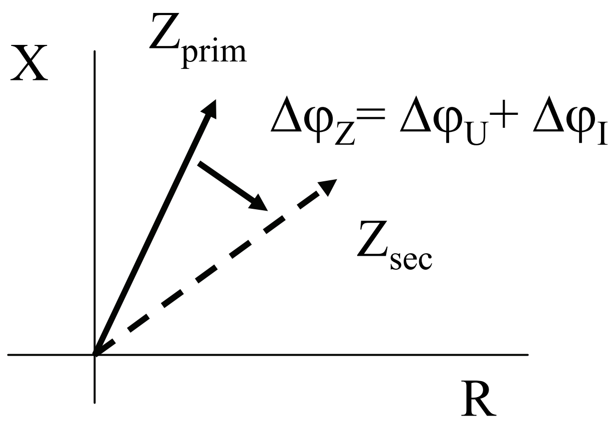
Influence of CT and VT errors on zone reach setting



If setting R/X >1:

- Reduce zone from 90 % to
  STF ≤ [1– (R/X)·tg (δ_U +δ_I)]·93,5%
  (e.g. with R/X=3 setting to 84%
  if $\Delta\varphi_U$=1° and $\Delta\varphi_I$=1°)
- or setting of α to -(δ_U +δ_I)
  (possible with 7SA522 and 7SA6)





Resistive faults:
Impact of line loading on distance measurement

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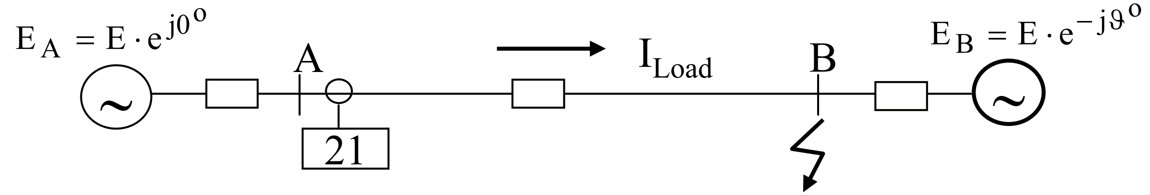
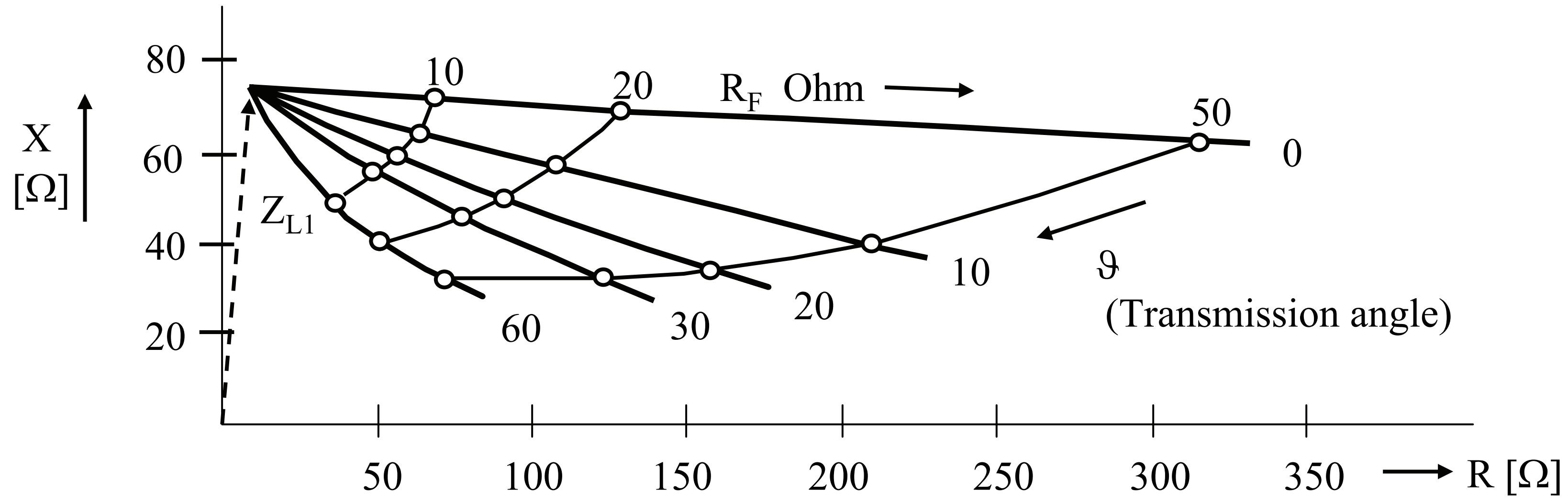


SCC_A= 10 GVA
Z_{1SA}= 0.8 + j16Ohm
Z_{0SA}/Z_{1SA}= 1

400 kV, l= 300 km
Z_{L1}= 7.5 + j75 Ohm
Z_{L0}/Z_{L1}= 4

SCC_B= 10 GVA
Z_{1SB}= 0.8+j16Ohm
Z_{0SB}/Z_{1SB}= 1



Tilting of 1st zone top line to avoid overreach in case of resistive faults with line loading (load exporting end)

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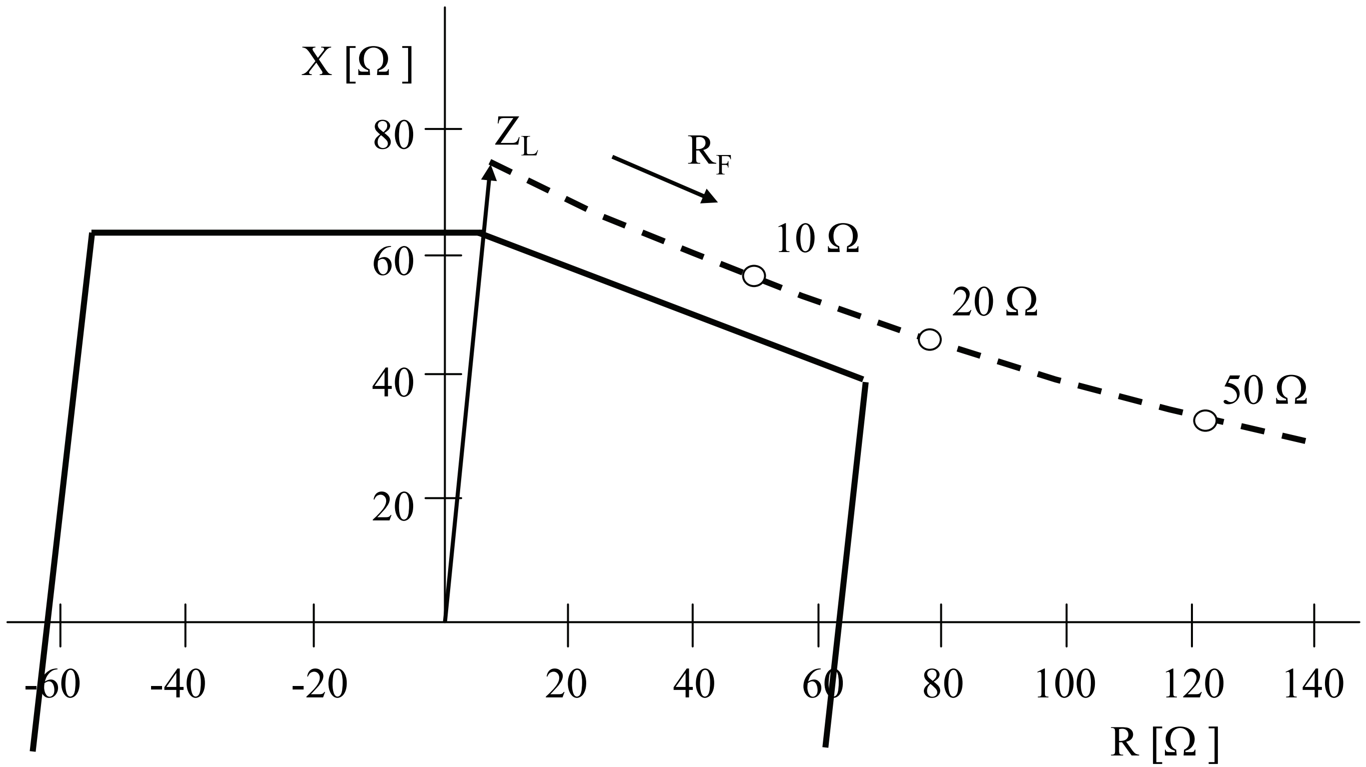

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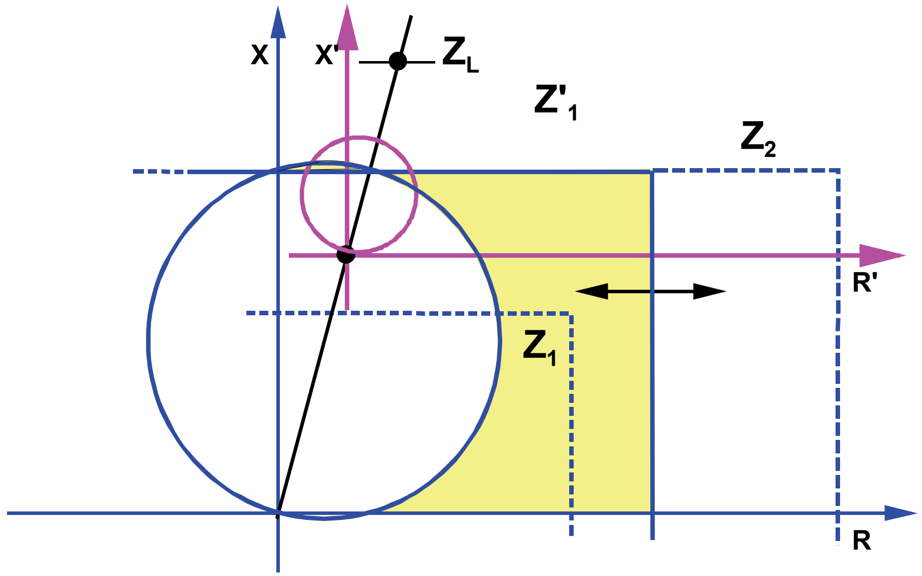
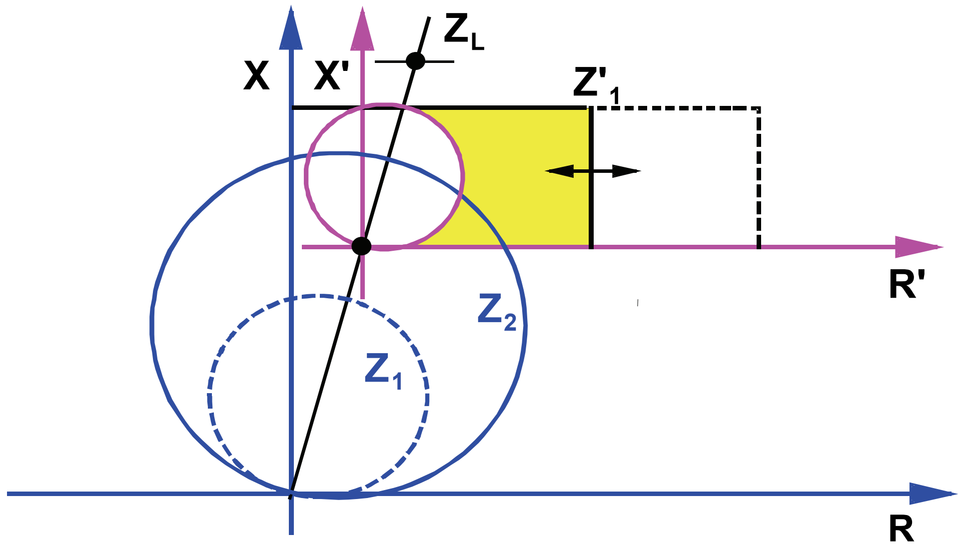
Grading of quadrilateral and circle characteristics



Difference of quadrilateral and MHO-circle in the 2nd zone



Difference of quadrilateral and MHO-circle in the 1st zone

Distance zone setting for a double-circuit line: System data for the calculation example

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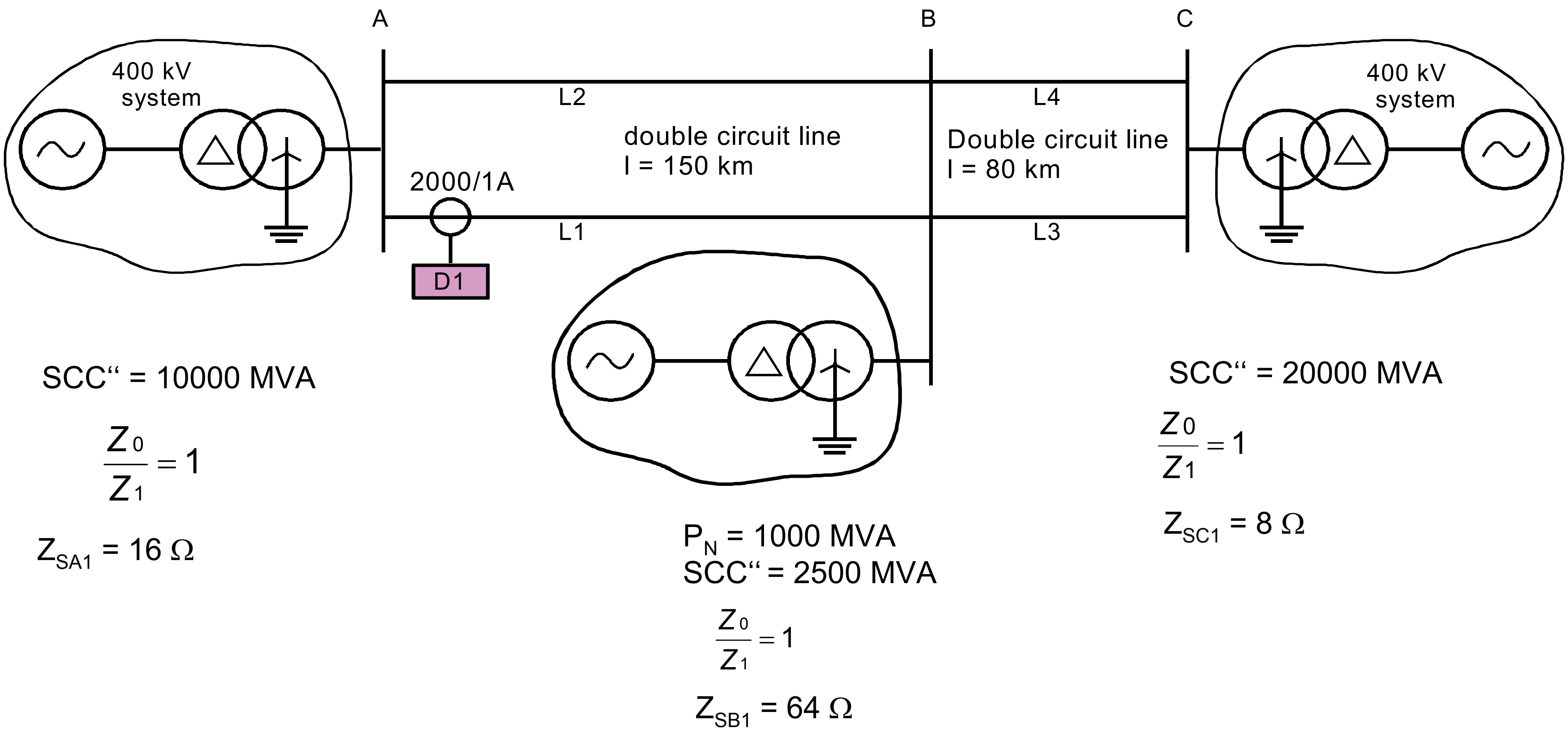

Distance zone setting for a double-circuit line: Classical setting of back-up zones

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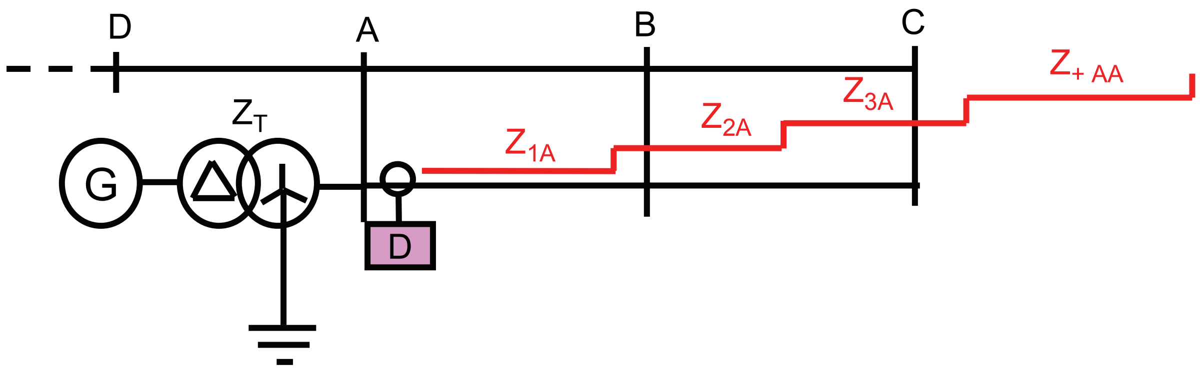

$$Z_{2A} = GF_2 \cdot (Z_{A\text{-}B} + 0.5 \cdot Z_{B\text{-}C})$$

$$Z_{3A} \geq 1.1 \cdot (Z_{A\text{-}B} + Z_{B\text{-}C})$$

$$Z_{+FD} \geq 1.1 \cdot (Z_{A\text{-}B} + 2 \cdot Z_{B\text{-}C})$$

$$Z_{-FD} \geq 1.1 \cdot Z_{A-D} \;\; or \;\; 0.5 \cdot Z_T$$

As a rule, high zone reach should be achieved even with intermediate infeed

Reach setting must consider load flow including a 20 - 30 % safety margin .

Double circuit line
Setting of the back-up zones

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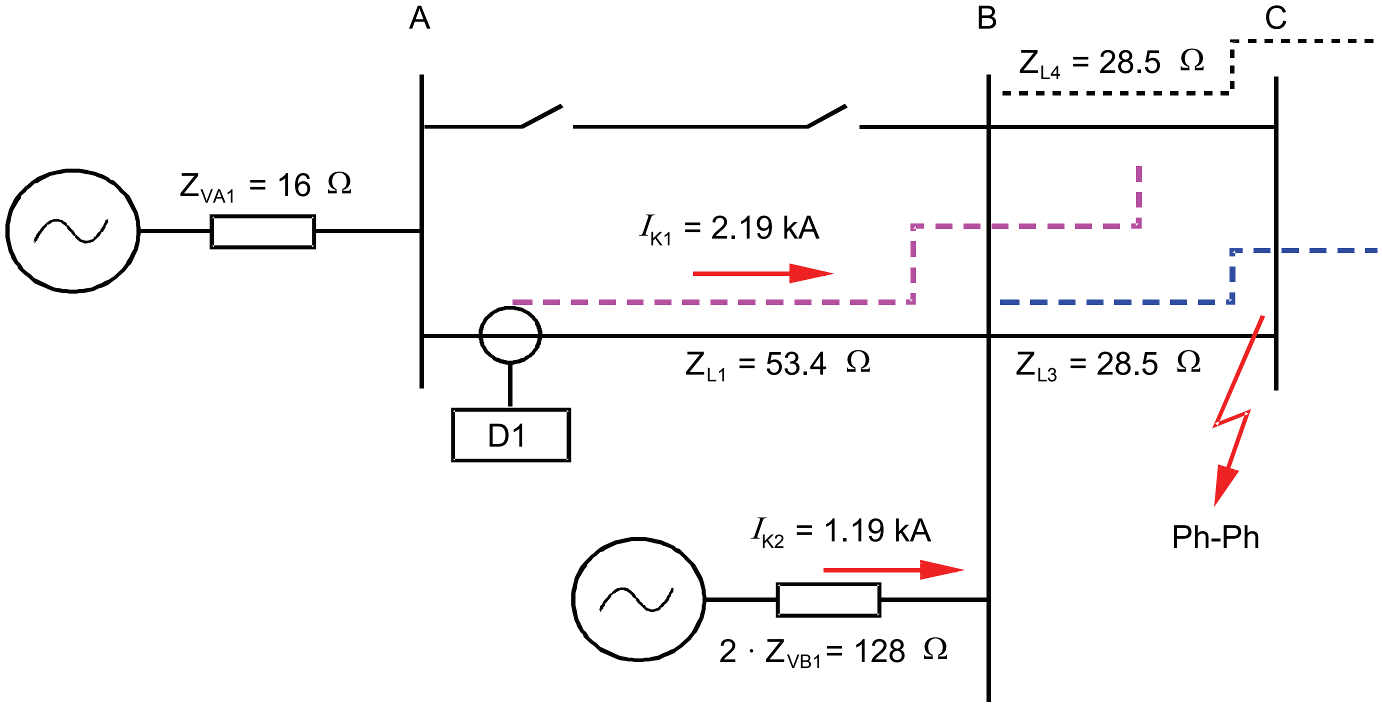

$$X_2 = \left[53.4 + \frac{28.5}{2} \cdot \left(1 + \frac{1.19}{2.19}\right)\right] \cdot 0.85 = 64\ \Omega = 120\%\ X_{L1}$$

$$X_3 = (53.4 + 28.5) \cdot 1.1 = 90.1 = 169\,\%\, X_{L1}$$

Double circuit line
Setting of the fault detection zone

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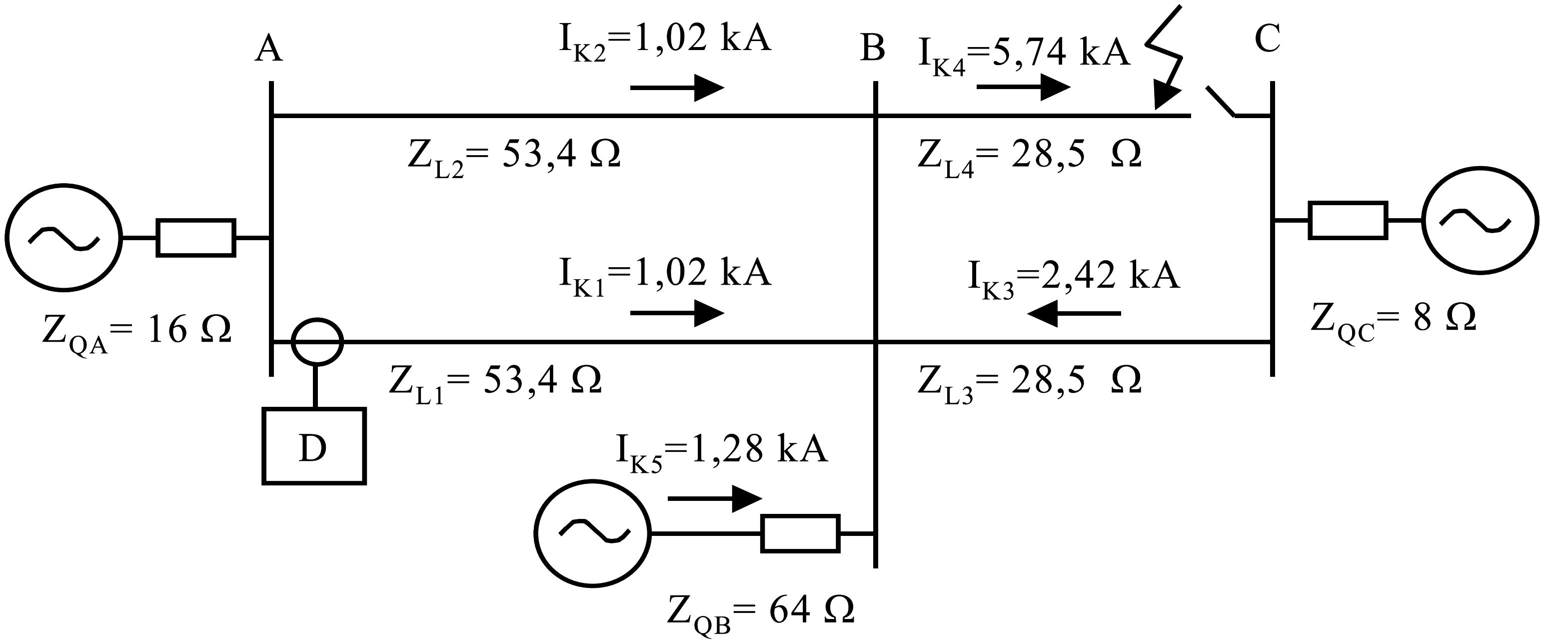

$$X_{+A} = \left[53{,}4 + 28.5 \cdot \frac{5{,}74}{1{,}02}\right] \cdot 1{,}1 = 214\ \Omega = 400\%\ X_{L1}$$

$$X_{-A} = X_{+A}$$

Double circuit line
Set zone characteristics

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$$Z_{Load\text{-}max.} = \frac{U_N^{\,2}}{P_{Nat.}} = \frac{400^2}{518} = 309\ \Omega$$

$$R_{A1} = 0{,}8 \cdot \frac{309}{2} \cdot \cos 30^{O} = 107\ \Omega$$

Expected fault resistances:

$I_{SC\text{-}min.}$ = 1000 A

Insulator Length: 4 m

Arc resistance:
2500 kV/m x 4 m / 1 kA= 10 Ω

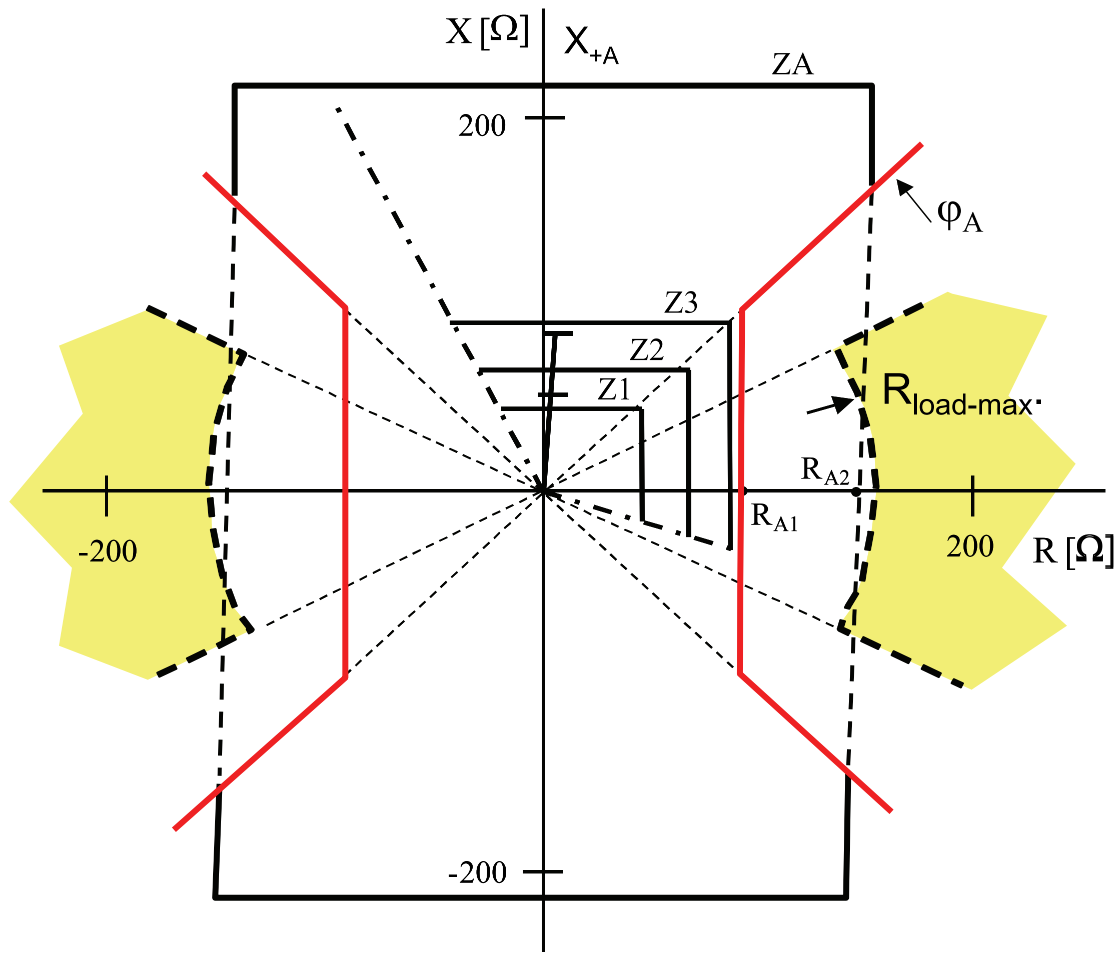
Tower footing resistance: R_{TF}= 5 Ohm

$I_{remote}/I_{local} = 5$

Apparent R_{TF}= (1+5)x5= 30 Ohm

Total Fault resistance $R_{F\text{-}tot}$= 35 Ohm

Chosen: R_{A1}= 100 Ω



Double circuit line: Setting of the back-up zones
Reach check considering all infeeds

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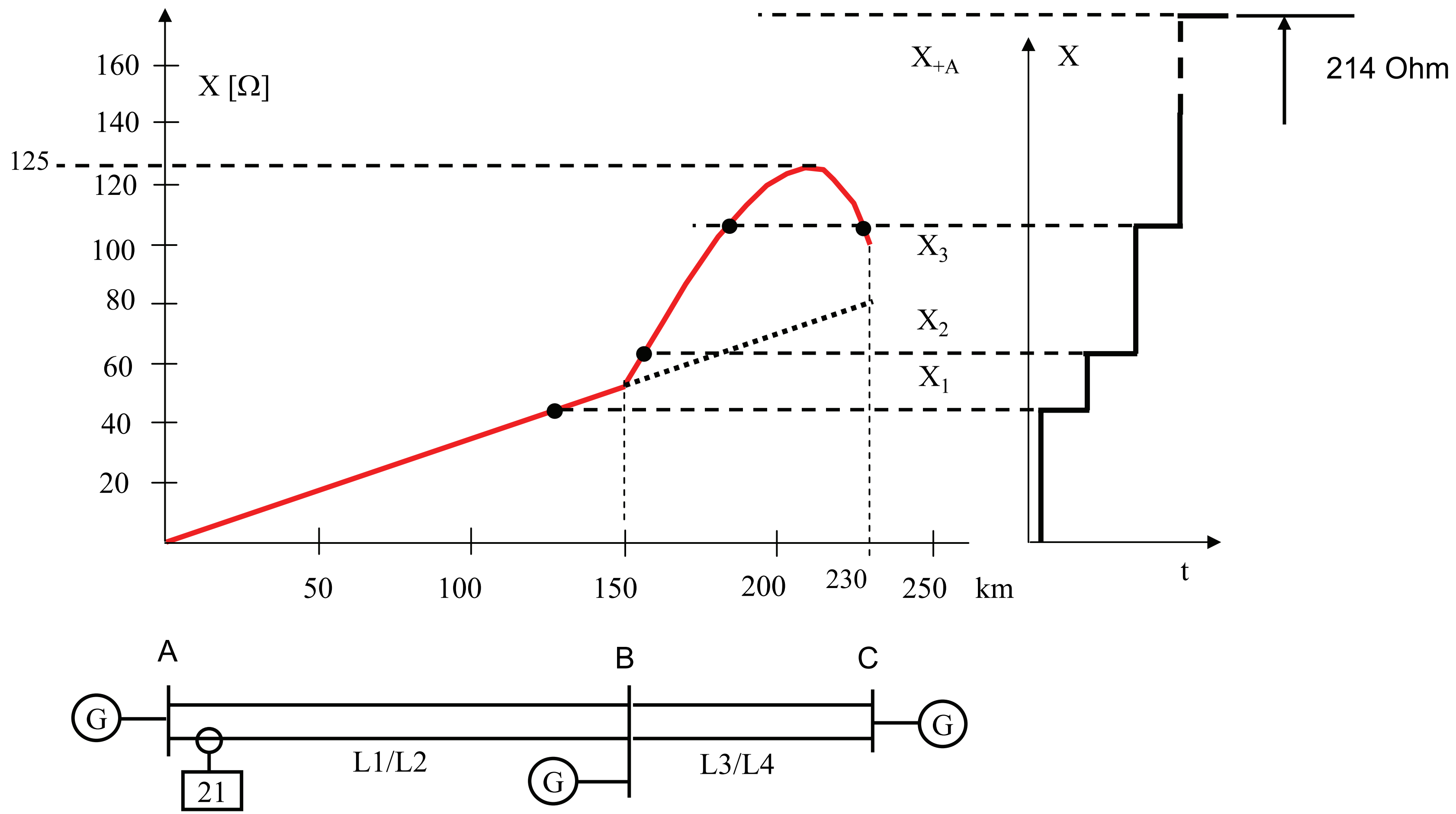

Double circuit line, Distance measurement with earth faults:

Reach dependent on setting of $k_{XER} = \left(\frac{X_E}{X_L}\right)_{relay}$ and switching state

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ⓐ valid for $\frac{x}{l} \leq 1.$

If $\frac{x}{l} > 1,$

then : $\frac{GF_1(1+k_{XER}) + k_{XEM} \cdot \frac{X'_{0M}}{X'_{0L}}}{1+k_{XEL}}$

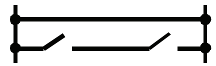
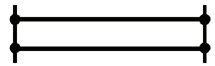
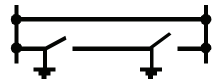
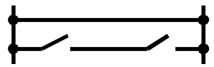
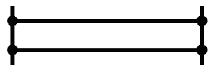
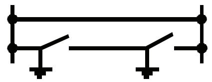
$X'_{0M} = 0.72\ \Omega/km$
$X'_{0L} = 1.11\ \Omega/km$
$X'_{1L} = 0.356\ \Omega/km$

$k_{XEL} = \left(\frac{X'_{EL}}{X'_{1L}}\right)_{line}$

$k_{XEL} = 0.71$

$k_{XEM} = \left(\frac{X'_{0M}}{3 \cdot X'_{0L}}\right)_{line}$

$k_{XEM} = 0.64$

Relay settings	Reach x/l in case of Ph-E faults		
GF1 = 0.85 $k_{XER}=$	 $\frac{x}{l} = GF_1 \cdot \frac{1+k_{XER}}{1+k_{XEL}}$	 $\frac{x}{l}$ = see Equ. (205)	 $\frac{x}{l} = \frac{(1+k_{XER}) \cdot GF_1}{1+k_{XEL} - k_{XEM} \cdot \frac{X'_{0M}}{X'_{0L}}}$ ⓐ
 , $k_{XER} = \frac{1+k_{XEL}}{GF_1} \cdot \frac{x}{l} - 1 = 0.71\ (0.5)$	85% (75%)	71% (64%)	108% (98%)
 $k_{XER} = \frac{1+k_{XEL} + k_{XEM} \cdot \frac{x/l}{2-x/l}}{GF_1} - 1 = 1.18$	108%	85%	132%
 $k_{XER} = \frac{1+k_{XEL} + k_{XEM} \cdot \frac{X'_{0M}}{X'_{0L}}}{GF_1} \cdot \frac{x}{l} - 1 = 0.31$	65%	56%	85%

Double circuit line, Distance measurement with earth faults
Reach in case of single side infeed

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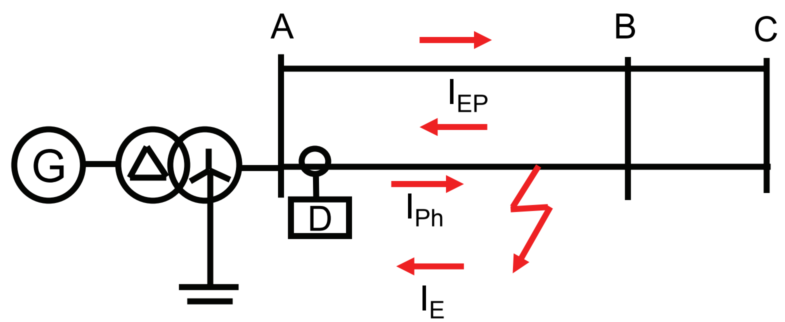
$$\underline{U}_{Ph\text{-}E} = \frac{x}{l}\underline{Z}_L \cdot \underline{I}_{Ph} + \frac{x}{l}\underline{Z}_E \cdot \underline{I}_E + \frac{x}{l}\frac{\underline{Z}_{0M}}{3} \cdot \underline{I}_{EP}$$



With single side infeed:

$$I_{Ph} = I_E \quad \text{and} \quad I_{EP} = \frac{x/l}{2 - x/l} \cdot I_E$$

$$\underline{Z}_{Ph\text{-}E} = \frac{\underline{U}_{Ph\text{-}E}}{\underline{I}_{Ph} + \underline{k}_{ER} \cdot \underline{I}_E} = \frac{x}{l} \cdot \frac{\underline{Z}_L + \underline{Z}_E + \frac{\underline{Z}_{0M}}{3} \cdot \frac{x/l}{2 - x/l}}{1 + \underline{k}_{ER}}$$

$$X_{Ph\text{-}E} = \frac{U_{Ph\text{-}E} \cdot \sin\varphi_K}{I_{Ph} + k_{XER} \cdot I_E} = \frac{x}{l} \cdot X_L \cdot \frac{1 + \frac{X_E}{X_L} + \frac{X_{0M}}{3 \cdot X_L} \cdot \frac{x/l}{2 - x/l}}{1 + k_{XER}}$$

$$\textit{With :} \quad X_{Ph-E} = X_{Ph-Ph} = X_1 = SF_1 \cdot X_L\,, \quad \text{and} \quad k_{XEL} = \frac{X_E}{X_L} \quad \text{und} \quad k_{XEM} = \frac{X_{0M}}{3 \cdot X_L} :$$

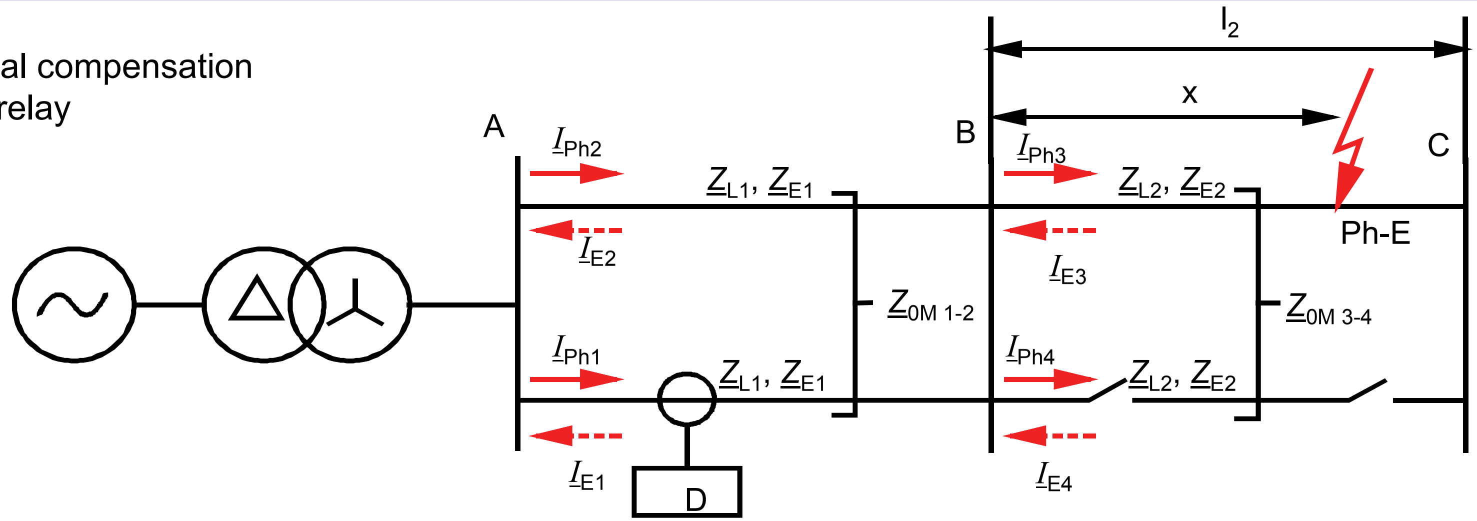
$$k_{XER} = \frac{1 + k_{XEL} + k_{XEM} \cdot \frac{x/l}{2 - x/l}}{SF_1} \cdot \frac{x}{l} - 1$$

$$x/l = \frac{[SF_1 \cdot (1 + k_{XER}) + 2(1 + k_{XEL})] - \sqrt{[..]^2 - 8(1 + k_{XEL} - k_{XEM}) \cdot (1 + k_{XER}) \cdot SF_1}}{2 \cdot (1 + k_{XEL} - k_{XEM})}$$

Double circuit line:
Zone reach with earth fault on following line (single side infeed)

SIEMENS

$\underline{k}_{XER}$ is the residual compensation factor, set at the relay



$$\underline{U}_{Ph-E} = \underline{Z}_{L1}\cdot\underline{I}_{Ph1} + \underline{Z}_{E1}\cdot\underline{I}_{E1} + \frac{\underline{Z}_{0M1-2}}{3}\cdot\underline{I}_{E2} + \frac{x}{l2}\underline{Z}_{L2}\cdot\underline{I}_{Ph3} + \frac{x}{l2}\cdot\underline{Z}_{E2}\cdot\underline{I}_{E3}$$

with: $k_{XEL1} = \frac{X_{E1}}{X_{L1}}$, $k_{XEM1-2} = \frac{X_{0M1-2}}{3\cdot X_{L1}}$ and $k_{XEL3} = \frac{X_{E2}}{X_{L2}}$ and $\underline{I}_{Ph1}=\underline{I}_{E1}=\underline{I}_{E2}=\underline{I}_k$ und $\underline{I}_{Ph3}=\underline{I}_{E3}=2\cdot\underline{I}_F$:

$$X_{Ph-E\,(measured)} = \frac{U_{Ph-E}\cdot\sin\varphi_K}{I_{Ph1}+k_{XER}\cdot I_{E1}} = \frac{1+k_{XEL1}+k_{XEM1-2}}{1+k_{XER}}\cdot X_{L1} + 2\cdot\frac{x}{l_2}\cdot\frac{1+k_{XEL3}}{1+k_{XER}}\cdot X_{L2}$$

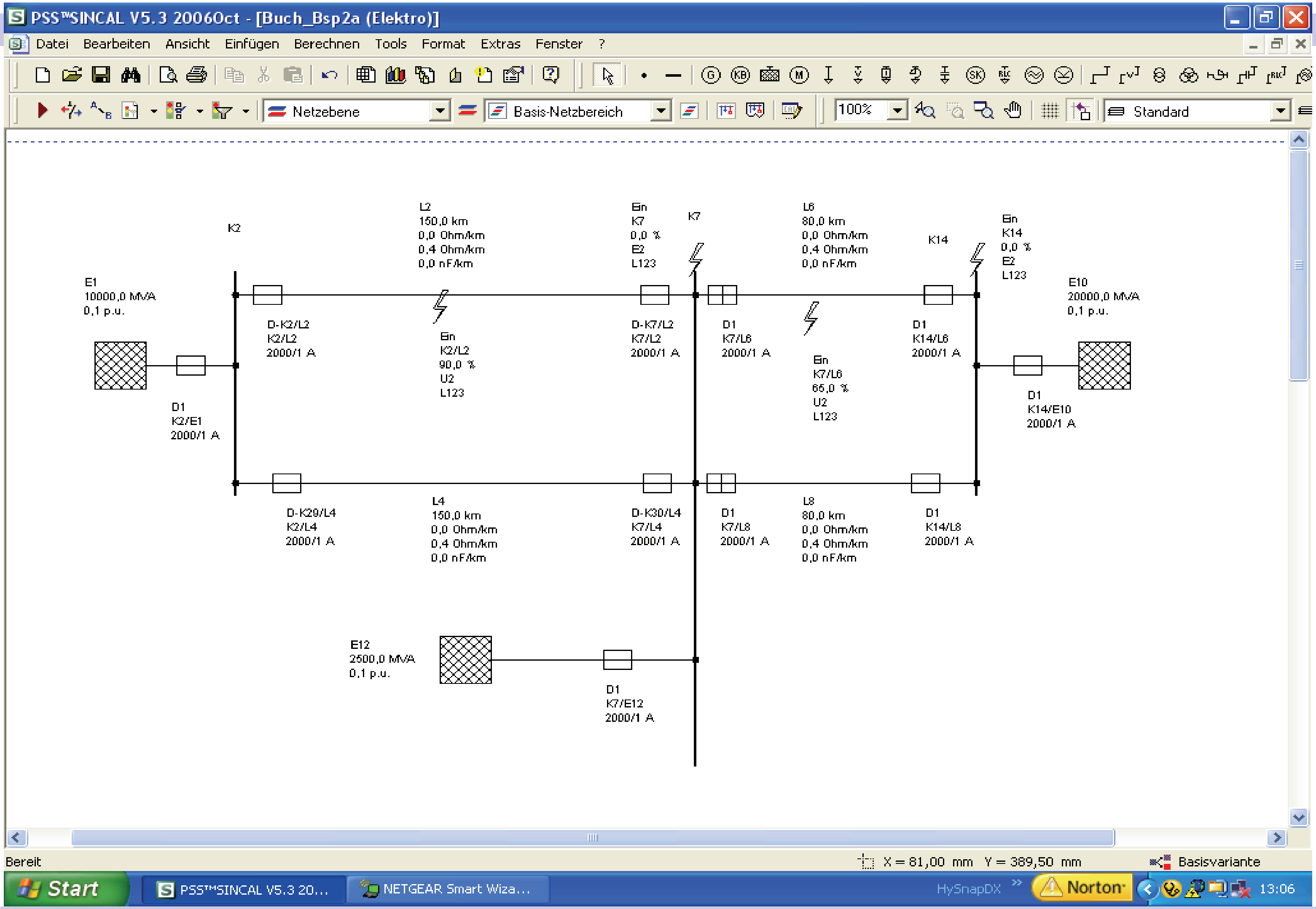
➡ With $\underline{X}_{Ph-E\ (measured)} = \underline{X}_{Zone}$ (zone limit):

$$\frac{x}{l_2} = \frac{(1+k_{XER})\cdot X_{Zone} - (1+k_{XEL1}+k_{XEM1-2})\cdot X_{L1}}{2\cdot(1+k_{XEL2})\cdot X_{L2}}$$

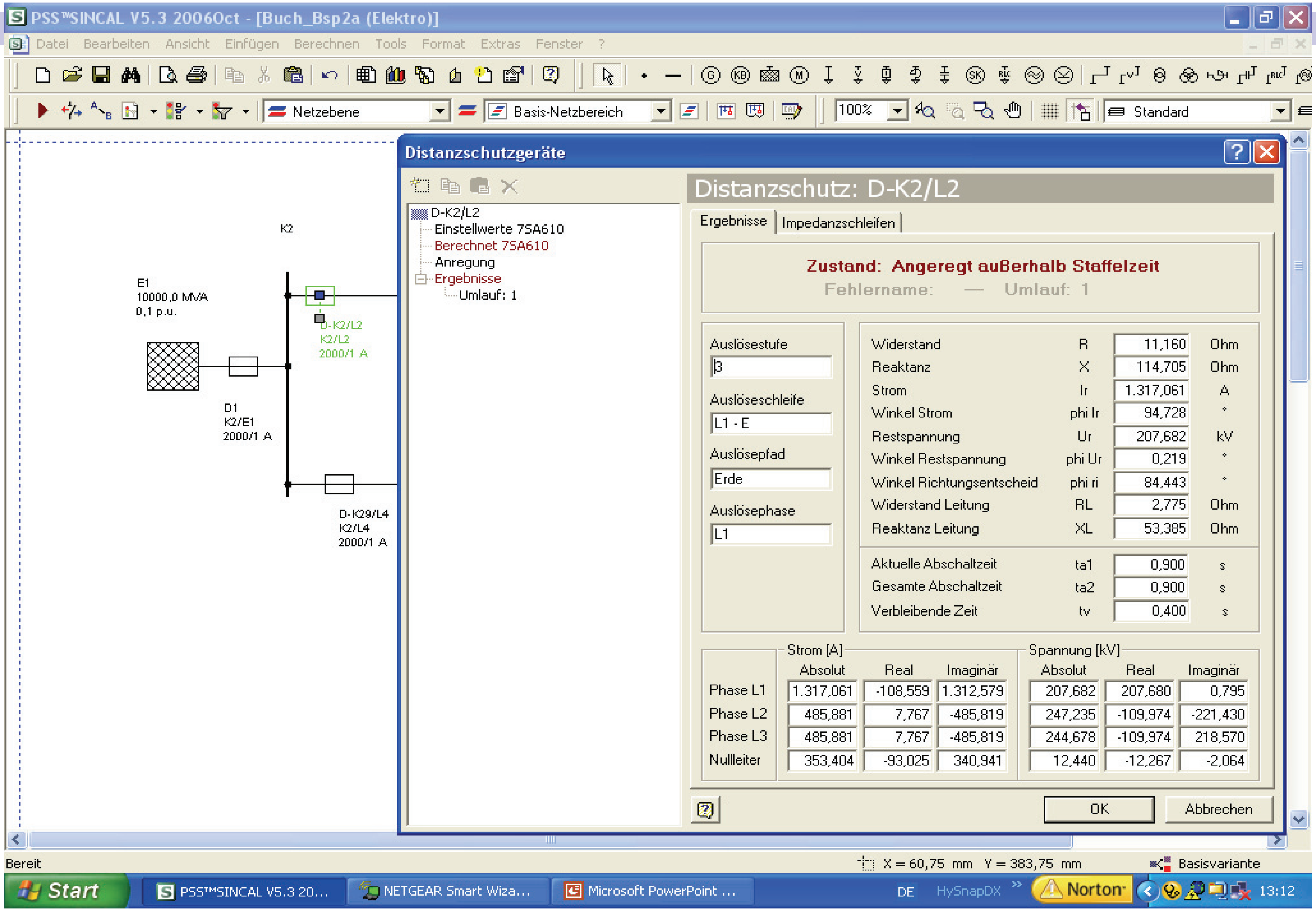
In the example: at x/l=0: $X_{Ph-E} = \frac{1+0.71+0,64}{0.71} = 1.37\cdot X_{L1}$

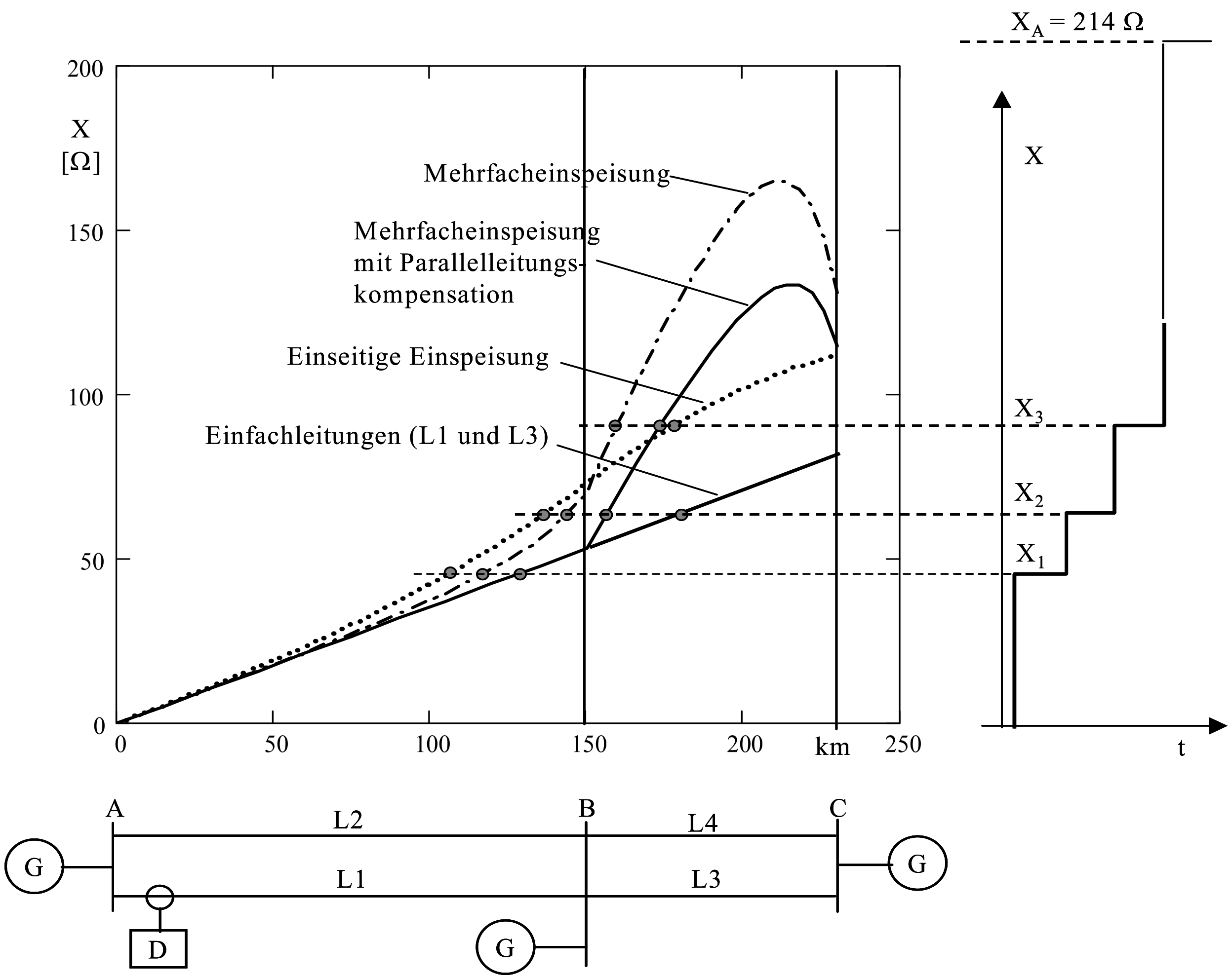
In the example: with X_3=169%X_1: x/l = 29%!

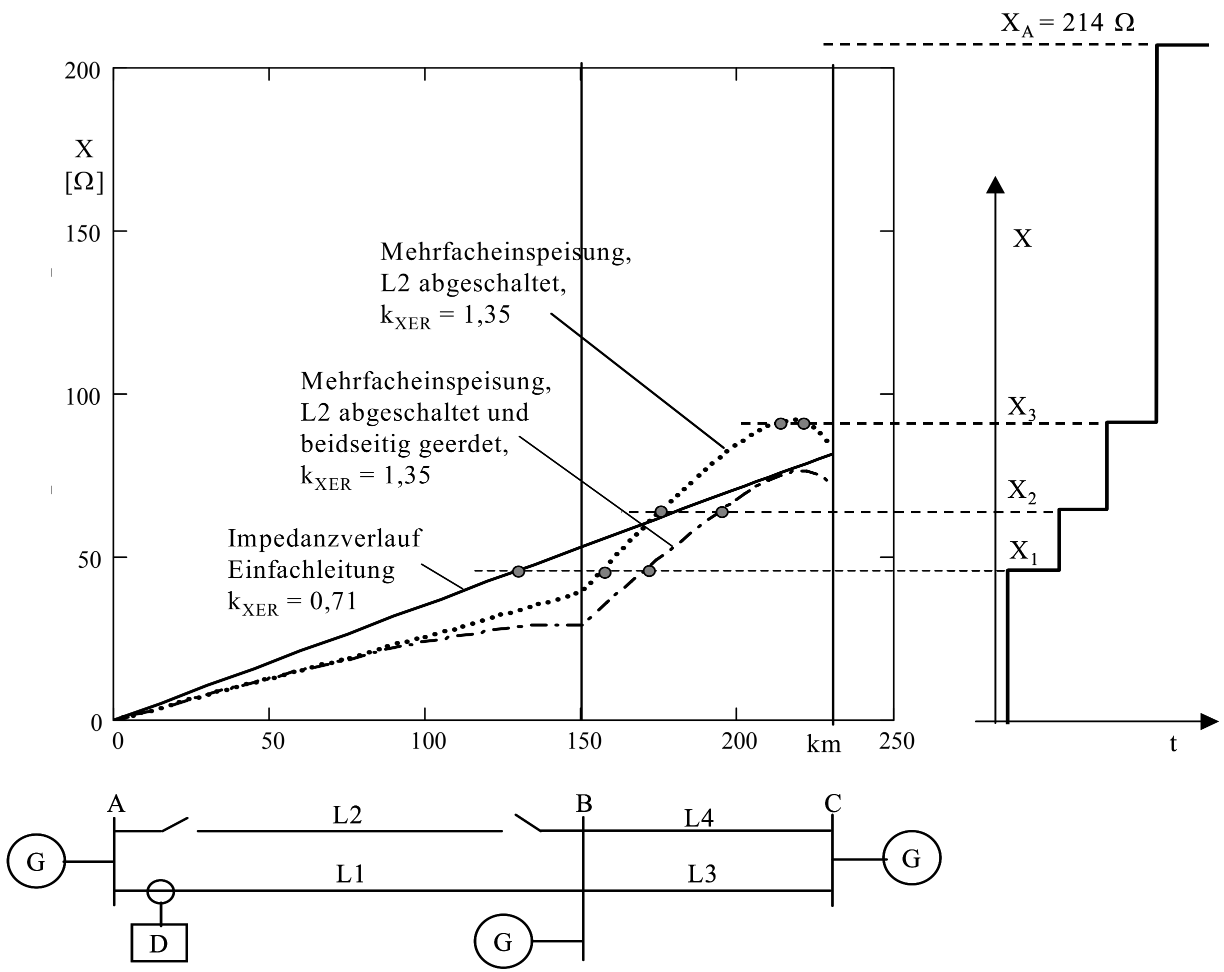
Load-flow and short-circuit calculation based relay coordination (Program SINCAL) (1)



Load-flow and short-circuit calculation based relay coordination (Program SINCAL) (2)




X [Ω]
200
150
100
50
0
Mehrfacheinspeisung
Mehrfacheinspeisung mit Parallelleitungs-kompensation
Einseitige Einspeisung
Einfachleitungen (L1 und L3)
0
50
100
150
200
km
250
A
B
C
L2
L4
L1
L3
G
G
G
D
X_A = 214 Ω
X
X_3
X_2
X_1
t


X [Ω]
200
150
100
50
0
0
50
100
150
200
km
250
Mehrfacheinspeisung,
L2 abgeschaltet,
kXER = 1,35
Mehrfacheinspeisung,
L2 abgeschaltet und
beidseitig geerdet,
kXER = 1,35
Impedanzverlauf
Einfachleitung
kXER = 0,71
XA = 214 Ω
X
X3
X2
X1
t
A
B
C
L2
L4
L1
L3
G
G
G
D

Double circuit line protection:

Check of zone reach for earth faults considering all infeeds

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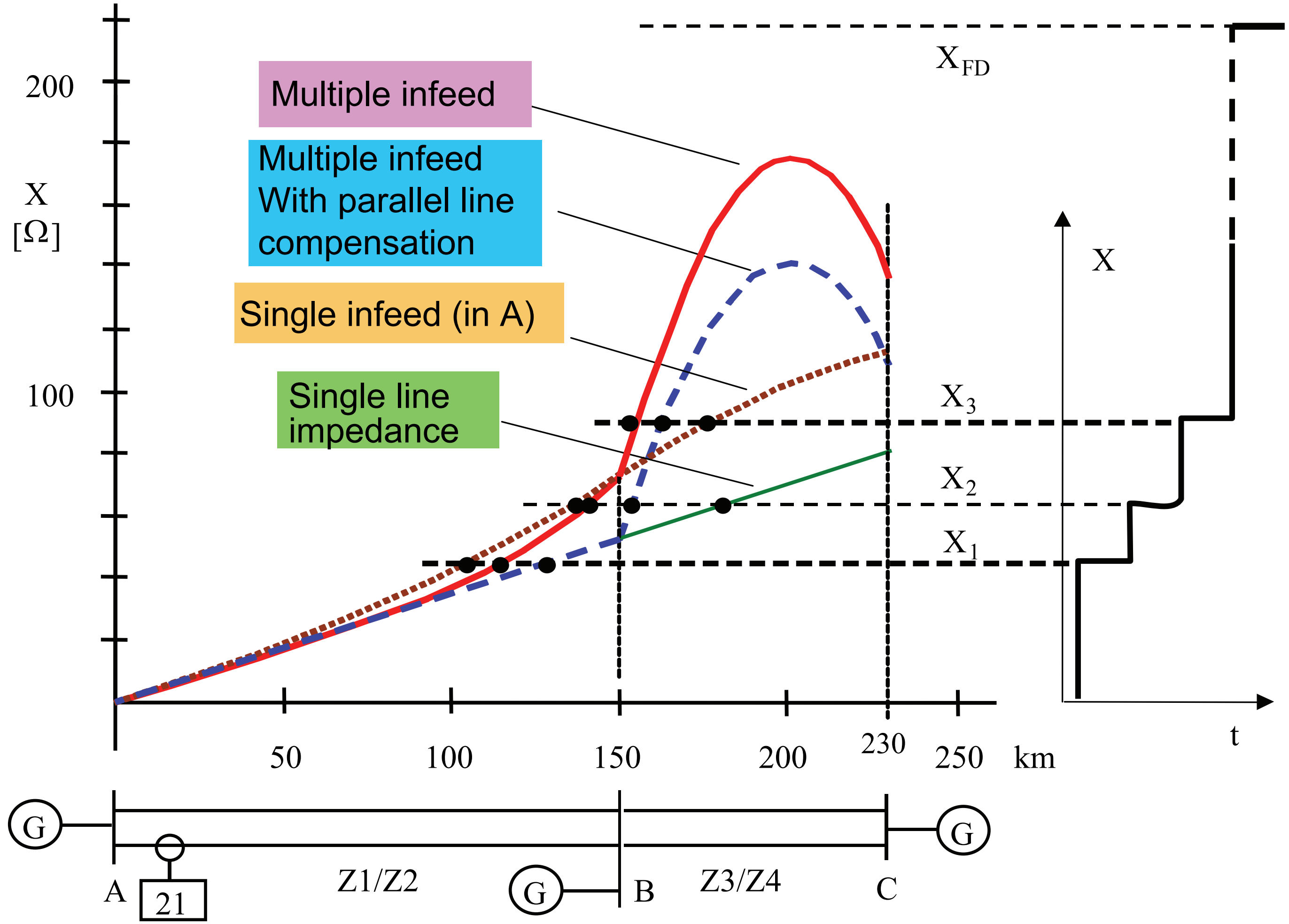
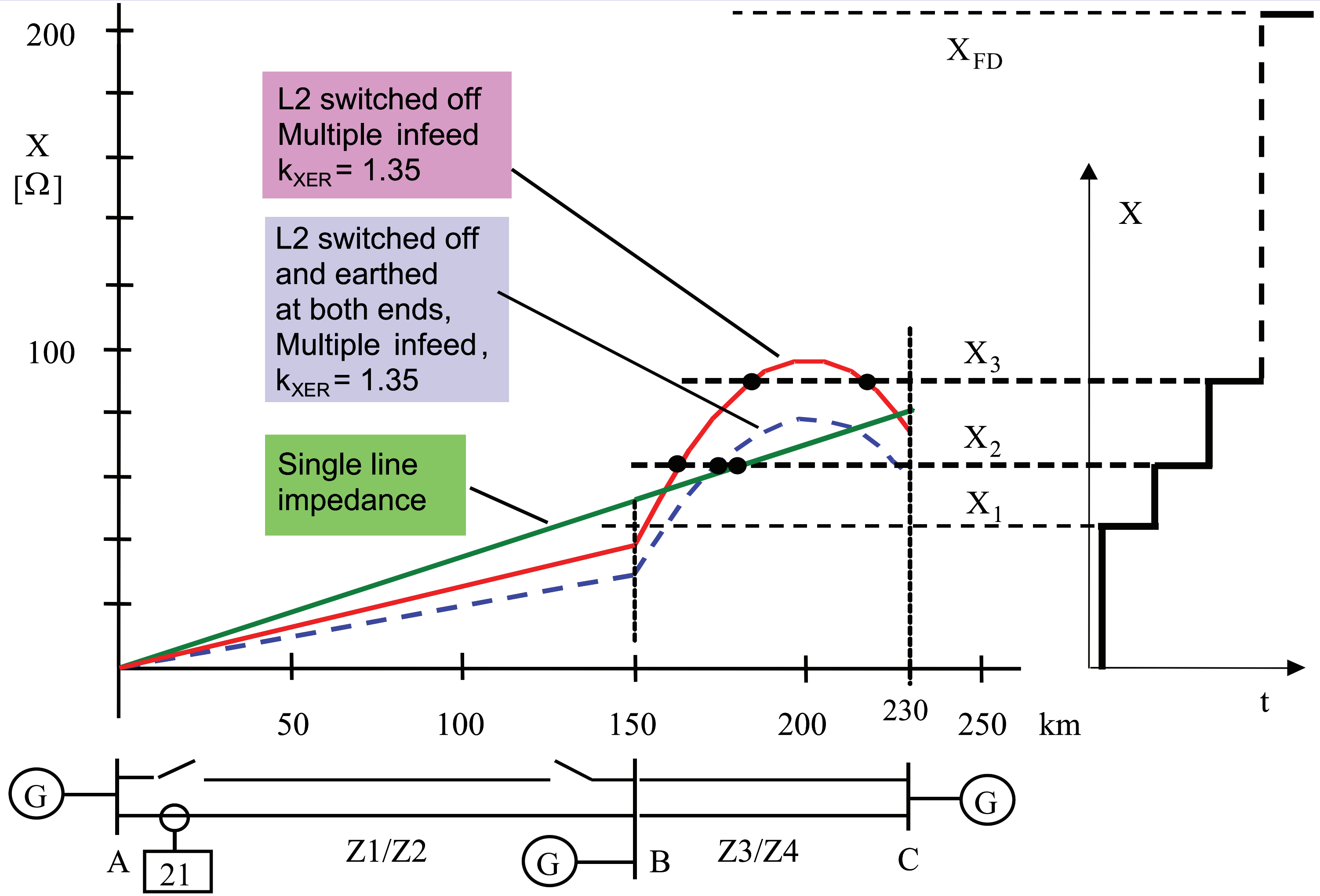


Setting of a separate k_{XE2} = k_{XE1}+ k_{XEM} = 1.35 instead of k_{XE1} = 0.71 would have the same influence on overreaching zones as parallel line compensation.

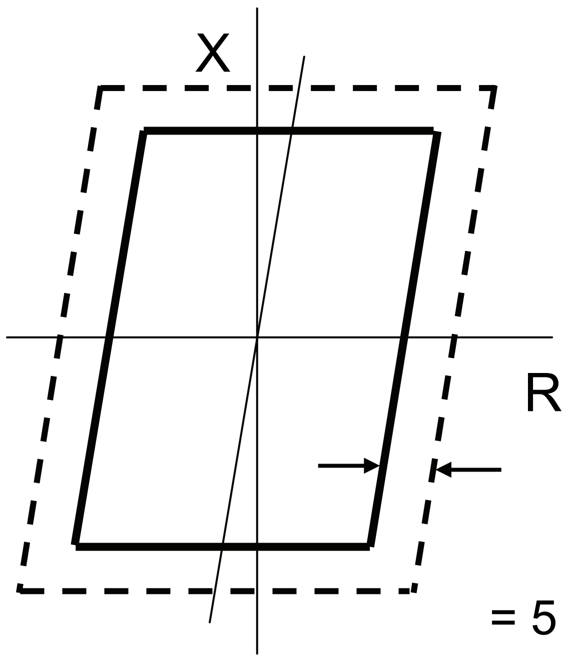
Check of zone reach for earth faults considering all infeeds
Use of the independent k_{XER}-factor for overreaching zones

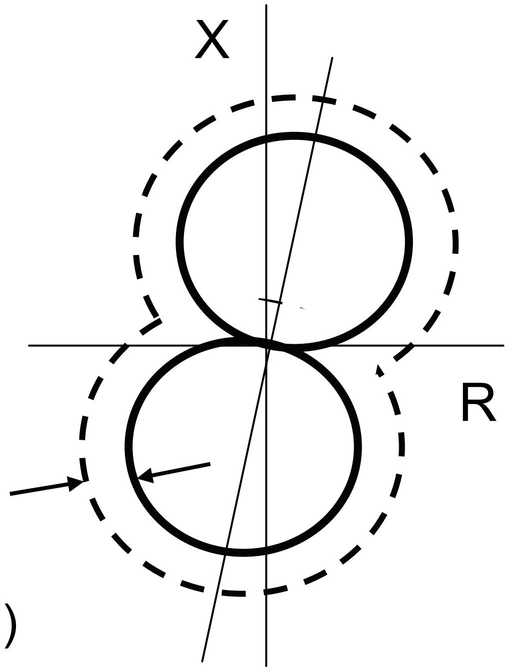
SIEMENS



Setting free power swing blocking function

SIEMENS





ΔZ

= 5 Ω (1 A)

= 1 Ω (5 A)

fixed value

Auto-reclosing (ARC)

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Fault Statistics

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Relative number of different type of faults on transmission lines:

Fault type	H.V. Percent	E.H.V. (500 kV)
single phase-to-earth	70	93
phase-to-phase	15	4
double phase-to-earth	10	2
Three-phase	5	1
Total	**100**	**100**

Autoreclosure
Practised Versions

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High speed three-pole AR

- typical dead time: 0.3...0.5 s
- synchro-check normally not required

Single-pole AR

- always high speed
- typical dead time: 0.6...1.2 s
- AR only with single phase-to-earth faults
- some times also with phase-to-phase faults
- C.B.'s must have phase segregated trip mechanisms
- Protection must operate phase selective

Single- and three-pole AR

- single-pole AR with single-phase-to-earth faults
- tree-pole AR with all other faults
- in case of sequential faults during the single-pole dead time: change-over to three-pole AR or definite three-phase tripping

Delayed AR

- only three-pole for all fault types
- dead-time: 5 s and more
- requires synchro-checking function

Auto-reclosure with zone extension

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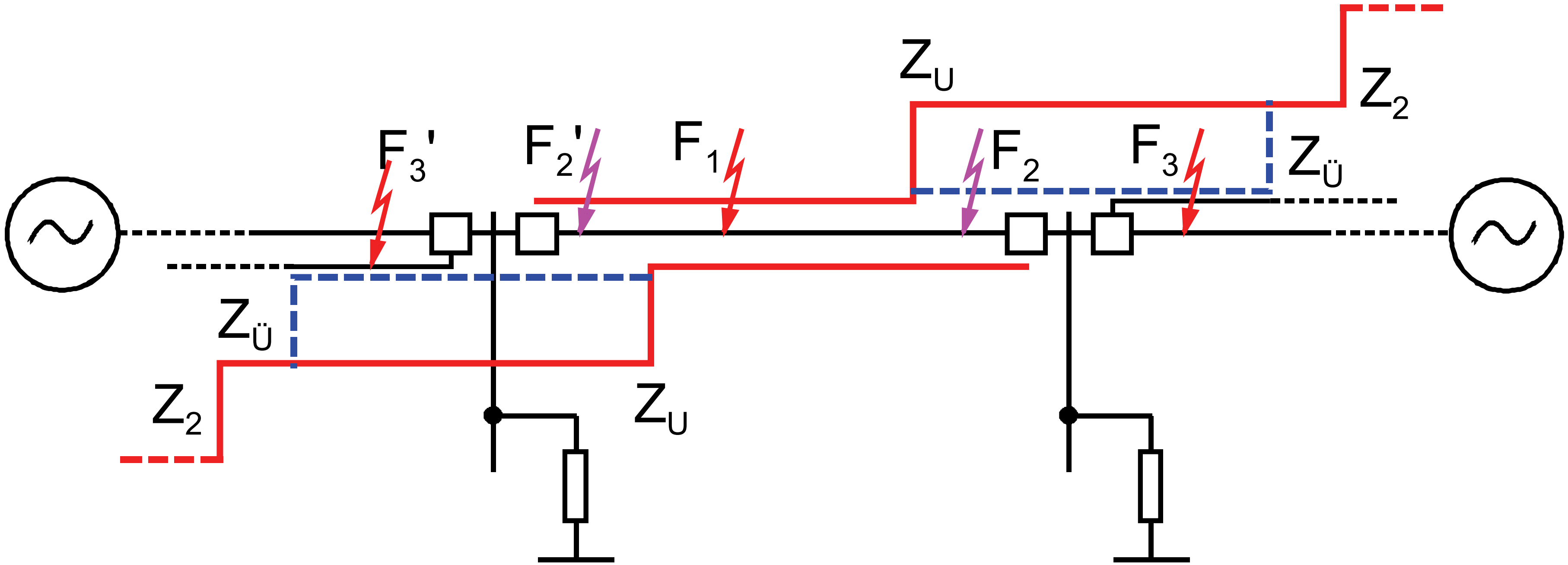

Single-pole auto-reclosure
Influenced and induced secondary arc currents

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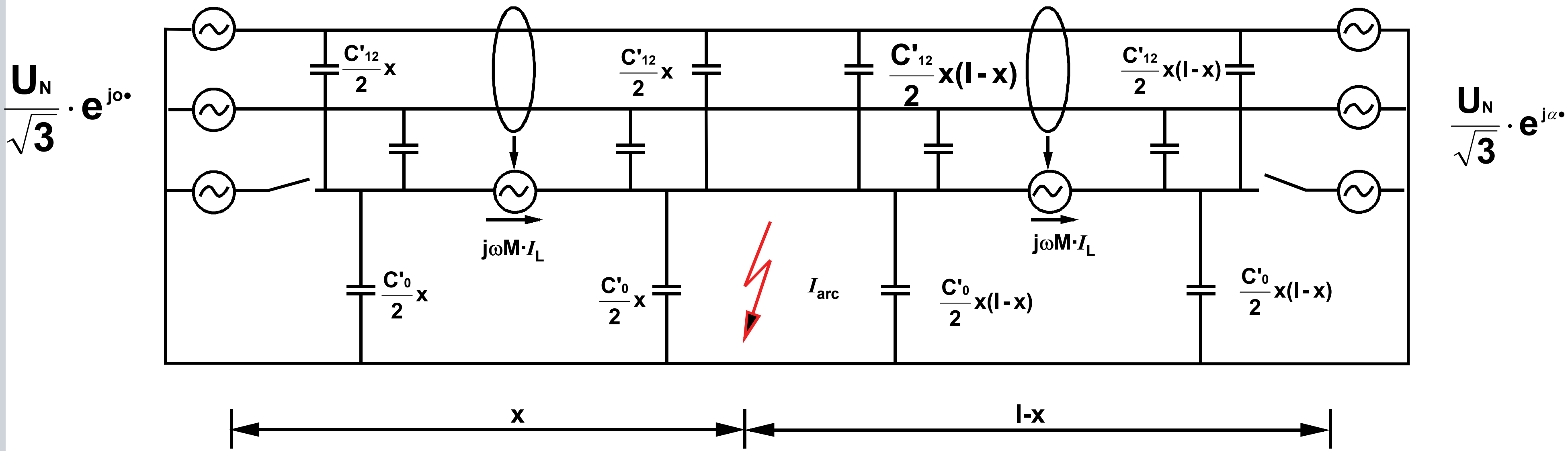


$$I_{ARC\,c} \approx \frac{U_N}{\sqrt{3}} \cdot \omega \cdot C'_{12} \cdot l$$

$$I_{ARC\,L} \approx I_L \cdot \omega M' \left(\frac{1}{2} - x \right) \cdot \omega \cdot (C'_0 + 2 \cdot C'_{12}) \cdot l$$

De-ionizing times

Three-pole reclosing

$$t_{3\text{-pole}} > 10.5 + \frac{kV}{34.5}\,\text{cycles}$$

50Hz:

$$t_{3\text{-pole}} > 210 + 0.58 \cdot kV \cdot [ms]$$

$$500\,kV\,(50\,Hz): t = 0.5\,s$$

Single-pole reclosing

for lines up to about 500 km:

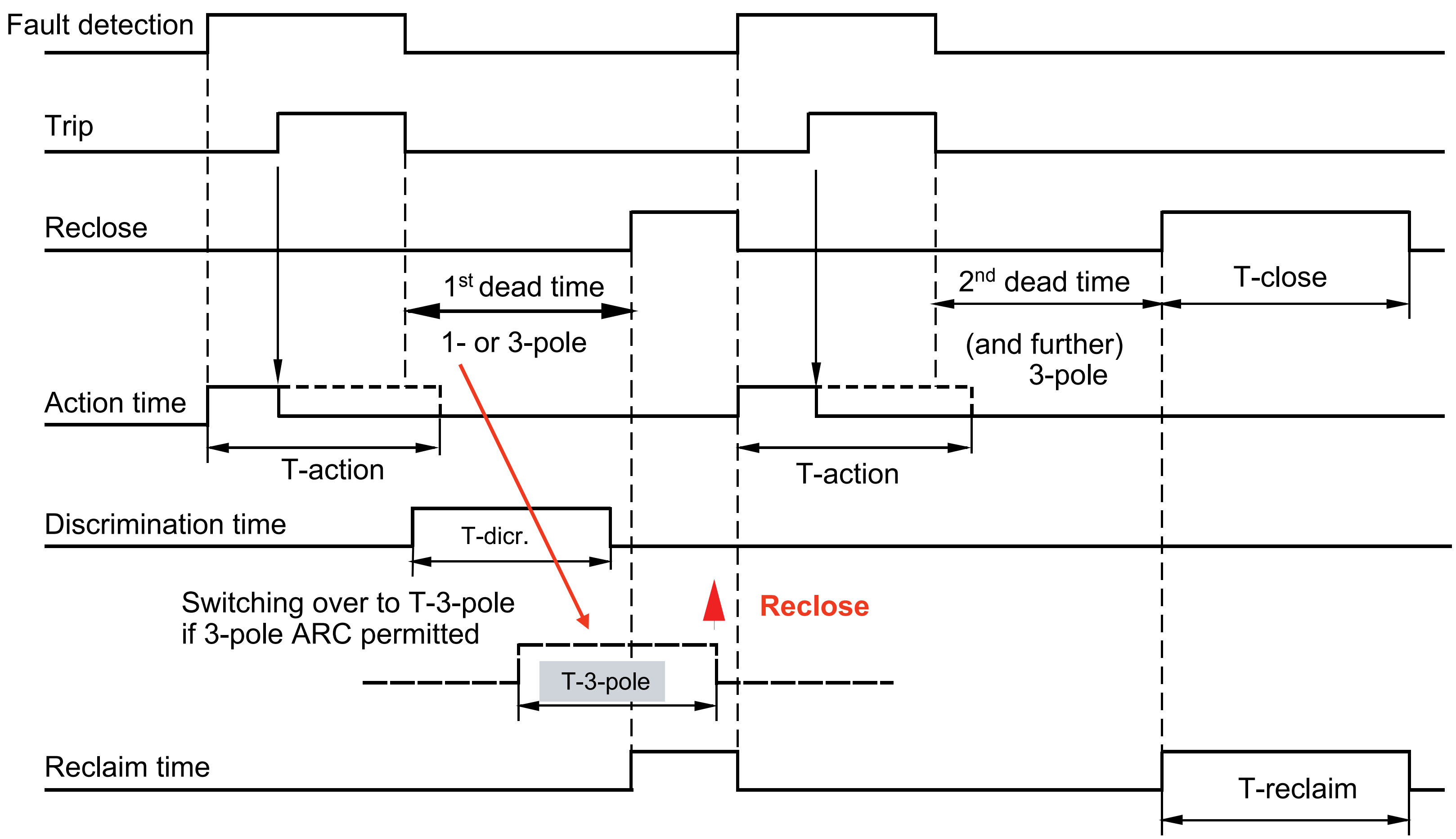
The AR will be successful with high probability if the secondary arc current is kept below following value

$$\frac{I_{Arc}}{A} = 43\left(\frac{t_{dead\text{-}time}}{s} - 0.2\right)$$

Line lengths for single-pole AR without supplemental arc extinction devices, e.g. shunt reactors

Line-to-line Voltage (kV)	Successful Range (km)	doubtful Range (km)
765	0-80	80-130
500	0-100	100-160
345	0-230	230-420
230	0-480	480-800

Auto-reclosure, Signal Sequence



Reduced Dead Time (RDT)

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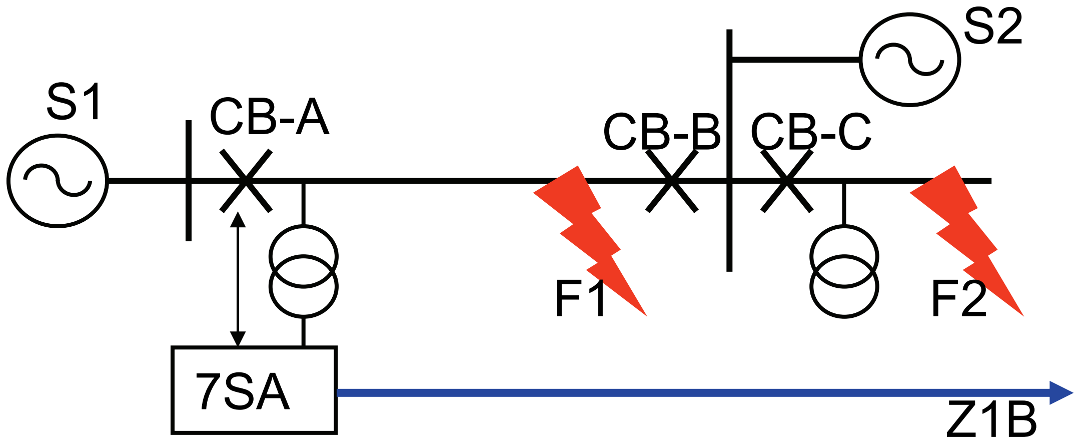
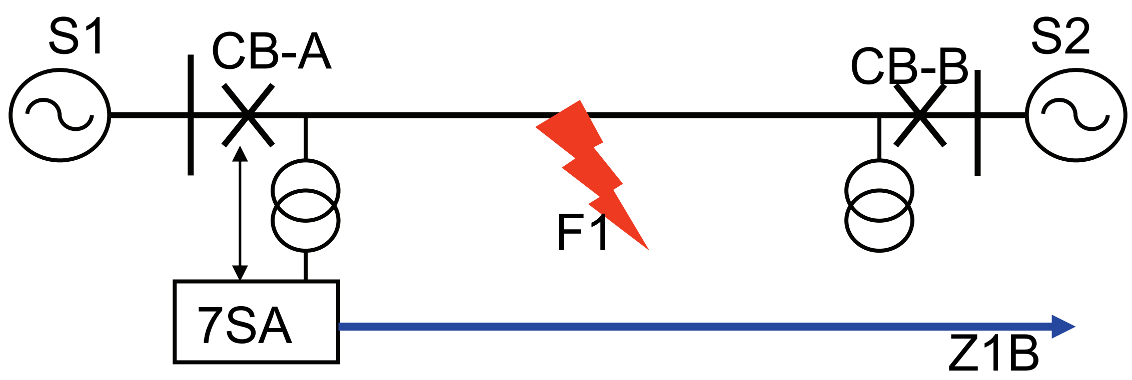


- At A the Z1B is released prior to 1st AR cycle (para 1357)
- All faults (F1) along line A-B are tripped without delay with Z1B at CB-A
- Non-selective trip for external fault (F2) is possible, but AR will be carried out
- With RDT, the dead time following non-selective trip can be minimised. CB-A is reclosed when return voltage from S2 via CB-B is detected at A after CB-C opens.

Adaptive Dead Time (ADT)

SIEMENS



- At A and B faults along the line are cleared by stepped distance and tele-protection
- At B the AR is applied with a fixed dead time
- At A the AR is applied with ADT
- When return voltage is detected at A from S2 via CB-B following successful reclosure at B, the reclose command to CB-A is given
- If the AR at B is not successful because fault F1 is permanent, the ADT will not detect return voltage at A and reclosure onto the fault is prevented at A

Dead Line Check (DLC)

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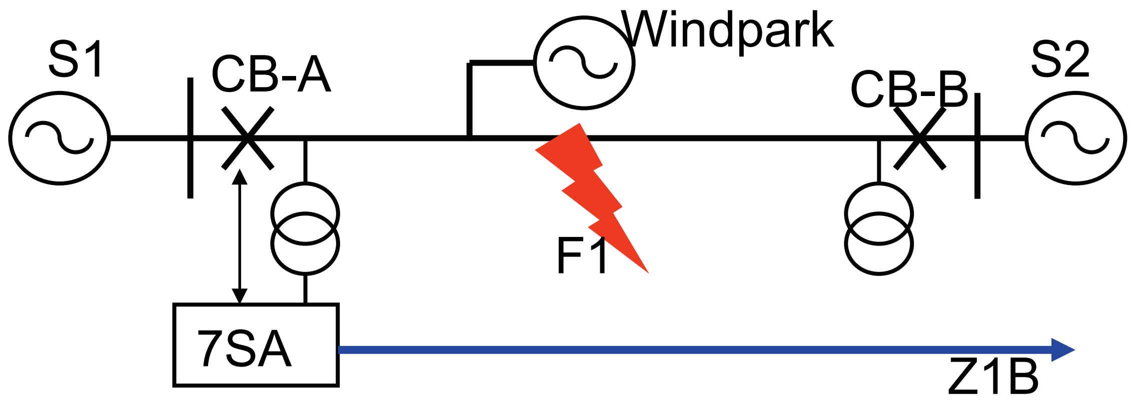
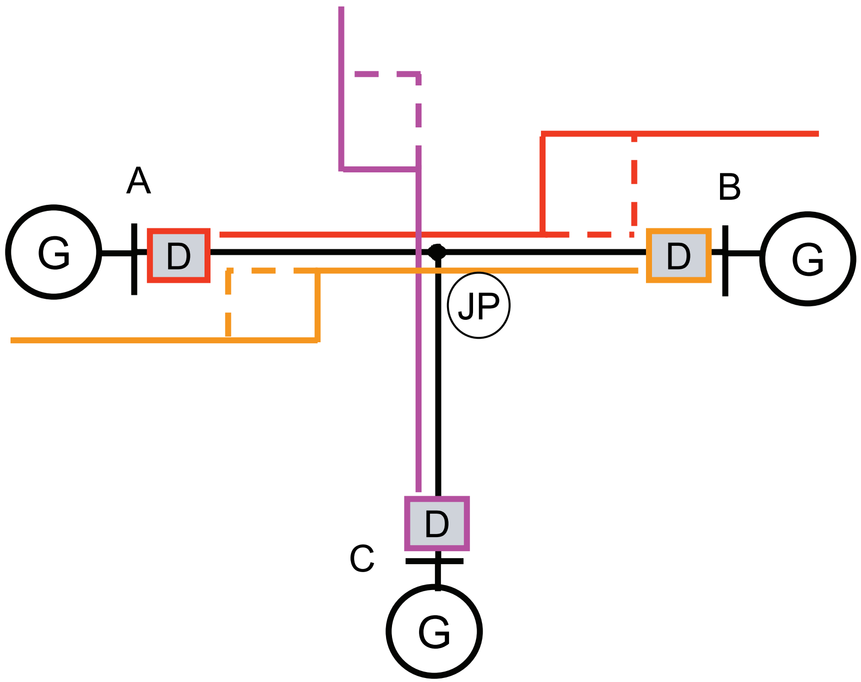


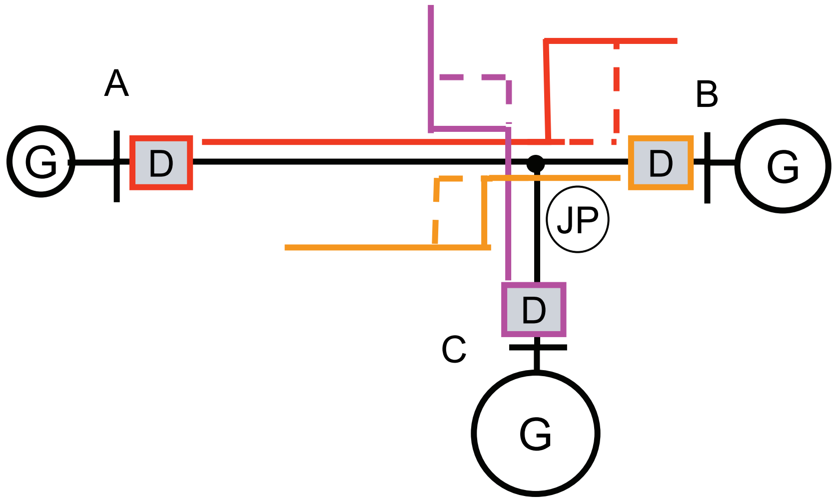
- The Fault F1 is cleared by the protection at A and B. The Windpark must disconnect itself by undervoltage detection.
- Reclosure at A and B may only occur if the Windpark is disconnected – un-synchronised closure will damage Windpark
- At A and B the DLC feature will only allow reclosure following a dead line condition (no voltage) for set time (para 3438)

Distance Protection of Three-terminal Lines

Three-terminal line
Distance protection without communication



Ideal case:
Equal line lengths
Equal infeeds (SCCs“)



Normal case:
Unequal line lengths
Unequal infeeds (SCCs“)

→ **Reach of zones too short!**

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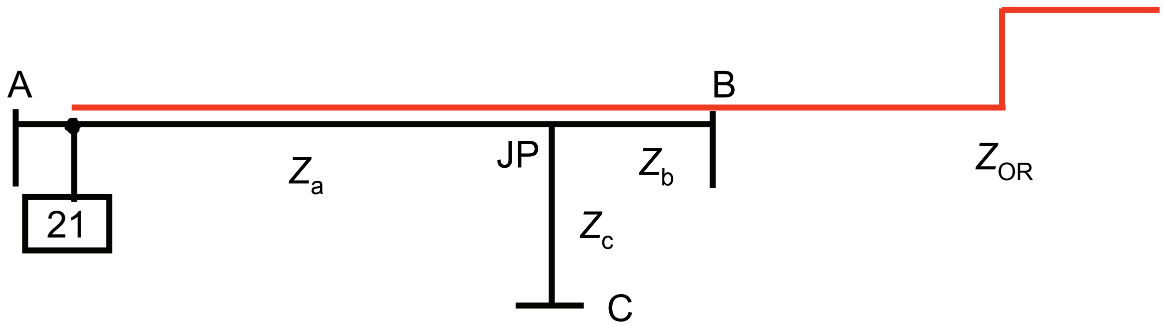
Three-terminal-lines
Setting of overreaching zones



Factor-2 Formula:

$$Z_{OR} = (Z_X + 2 \cdot Z_Y) \cdot k_{OR}$$

with:

Z_X = Impedance from relay to junction point (JP)

Z_Y = Impedance from junction point to (JP) to farthest line end

k_{OR}= Grading factor (z.B. 1,2)

Three-terminal line
Teleprotection in POTT mode

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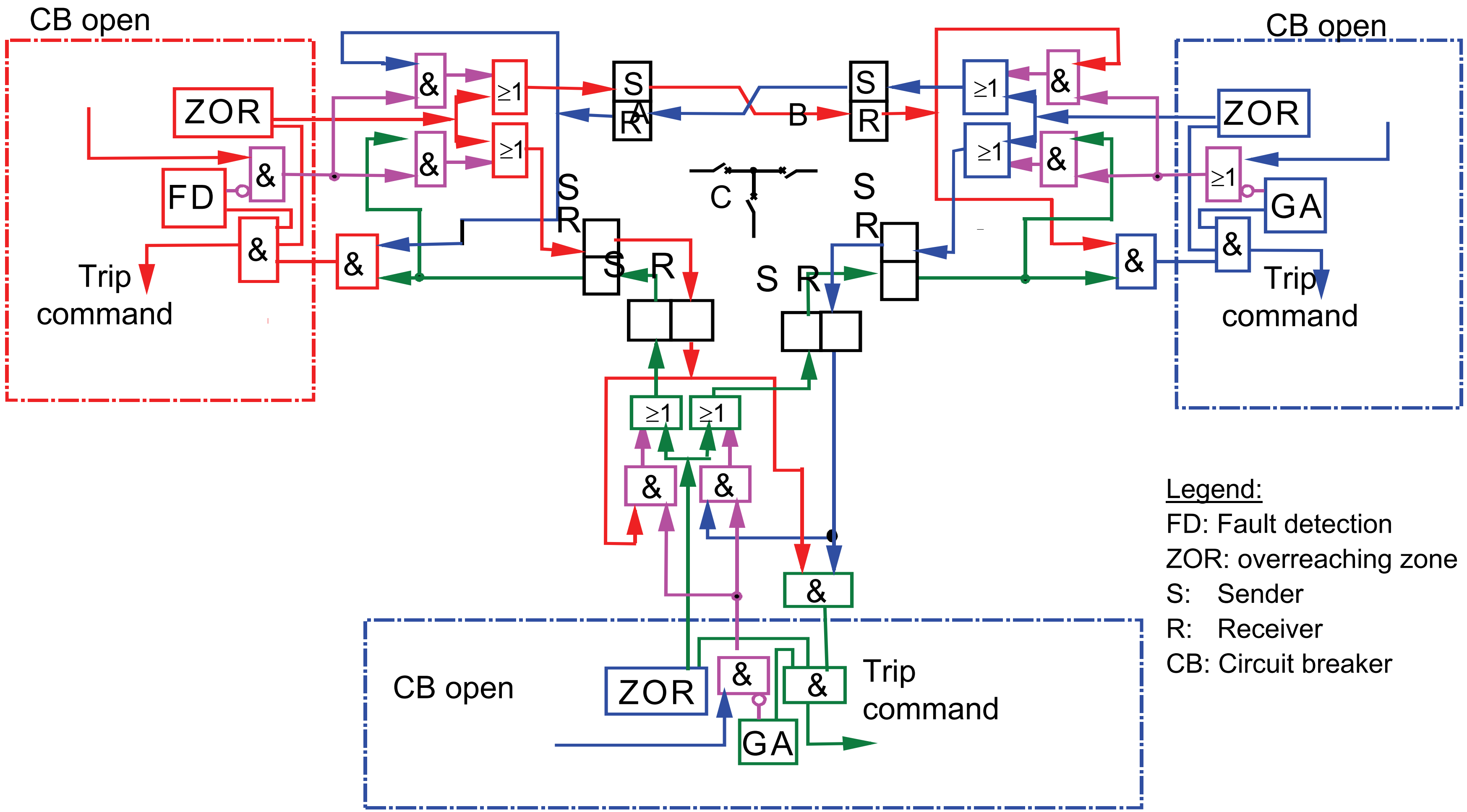

Legend:
FD: Fault detection
ZOR: overreaching zone
S: Sender
R: Receiver
CB: Circuit breaker

Distance protection of a three-terminal line
PUTT or POTT scheme using digital communication

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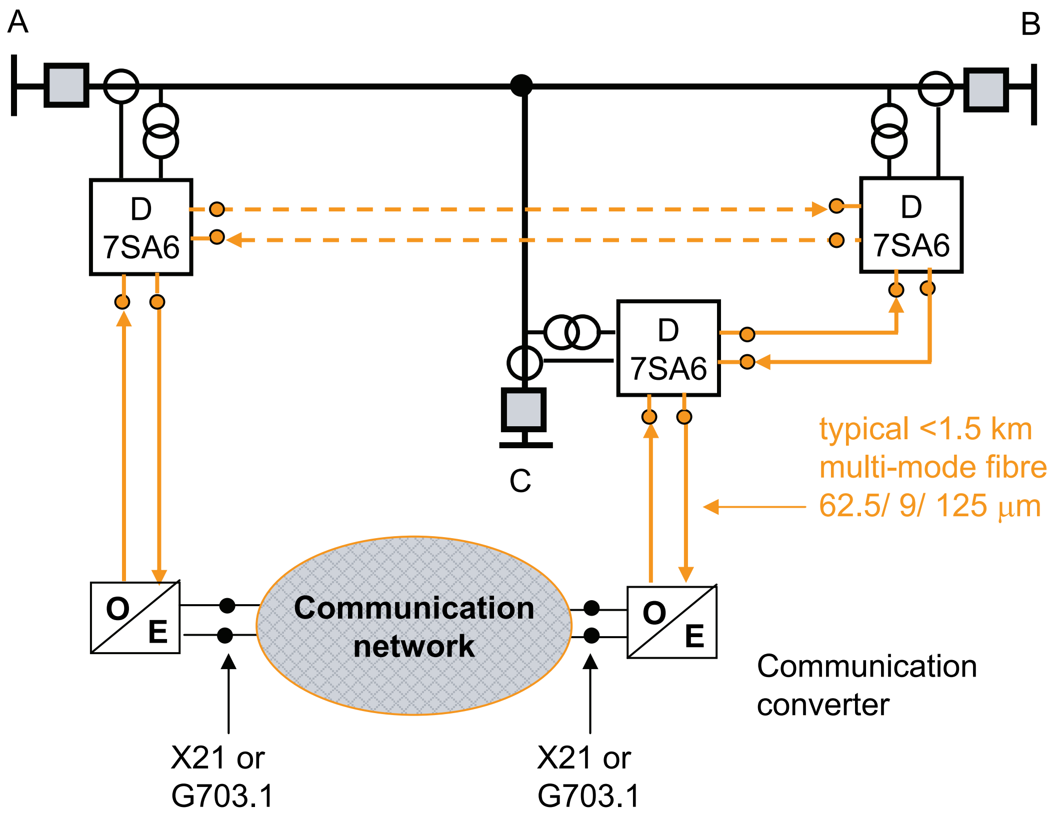
Chain topology or

redundant ring topology

Communication via direct relay-relay connection

Fibre type	optical wave length	permissible attenuation	maximum distance
Multi-mode 62.5/125 µm	820 nm	16 dB	ca. 3.5 km
Mono-mode 9/ 125 µm	1300 nm	18 dB	ca. 35 km



Distance protection of three-terminal lines (1)
Computation example

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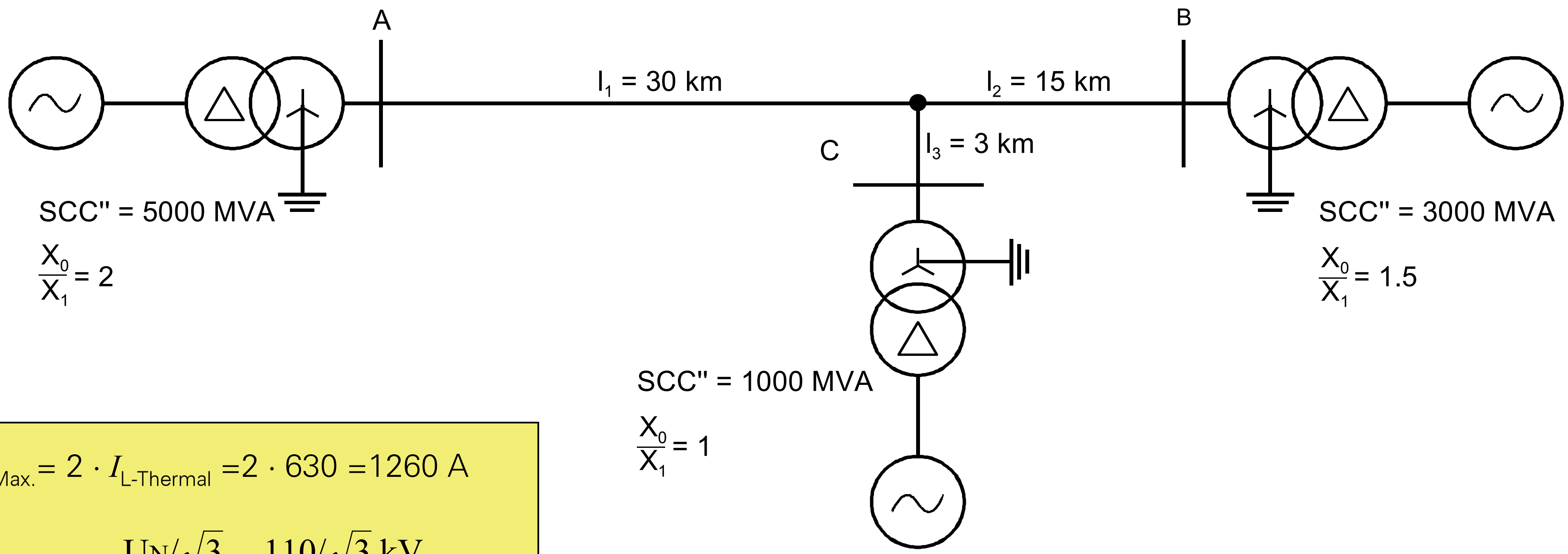
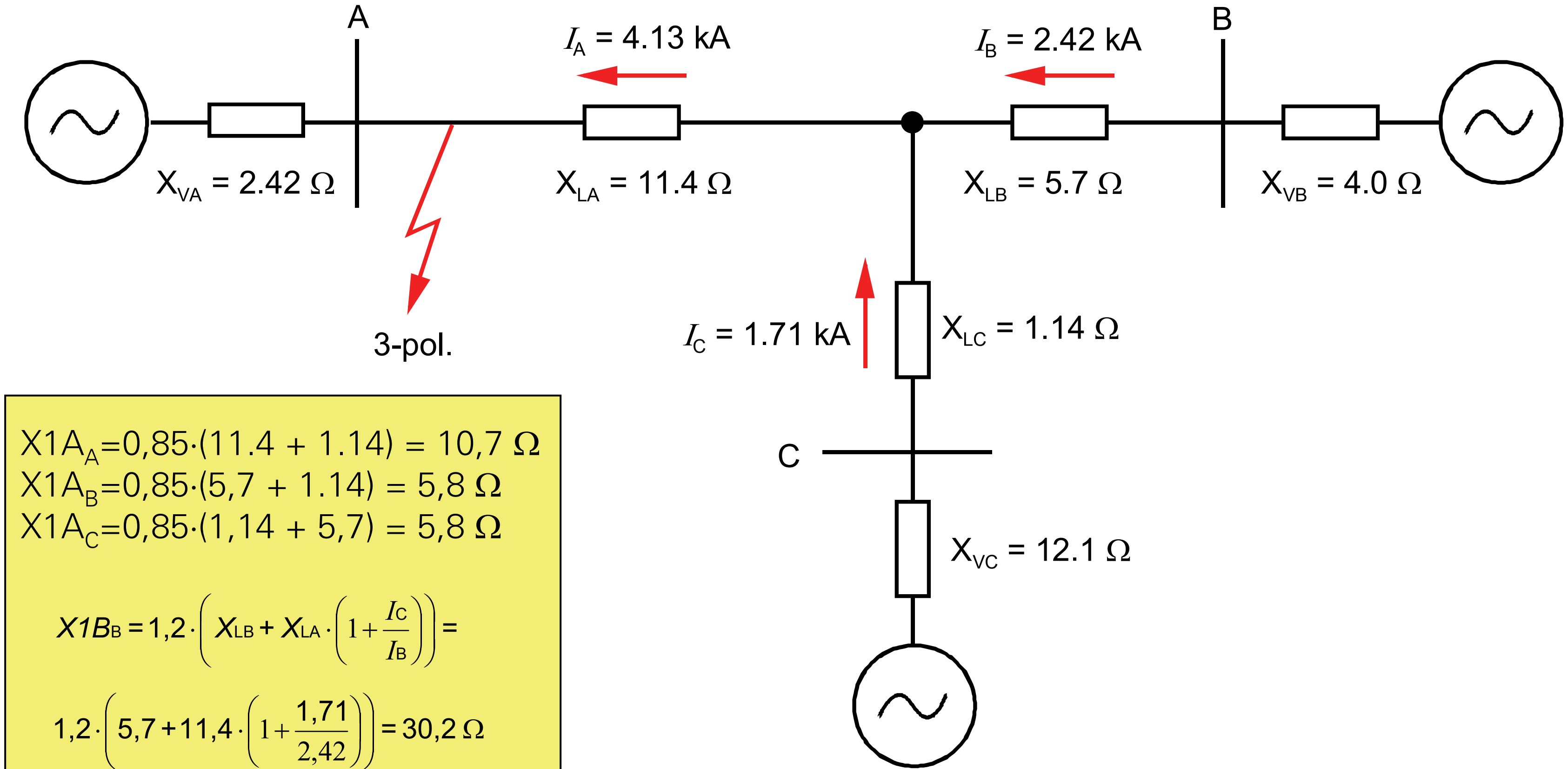


$$I_{L\text{-}Max.} = 2 \cdot I_{L\text{-}Thermal} = 2 \cdot 630 = 1260\ \text{A}$$

$$Z_{\text{load - min.}} = \frac{U_N/\sqrt{3}}{I_{L\text{ - max.}}} = \frac{110/\sqrt{3}\ \text{kV}}{1{,}260\ \text{kA}} = 50\ \Omega$$

Distance protection of three-terminal lines
Computation example (2)

SIEMENS



$X1A_A = 0{,}85 \cdot (11.4 + 1.14) = 10{,}7\ \Omega$

$X1A_B = 0{,}85 \cdot (5{,}7 + 1.14) = 5{,}8\ \Omega$

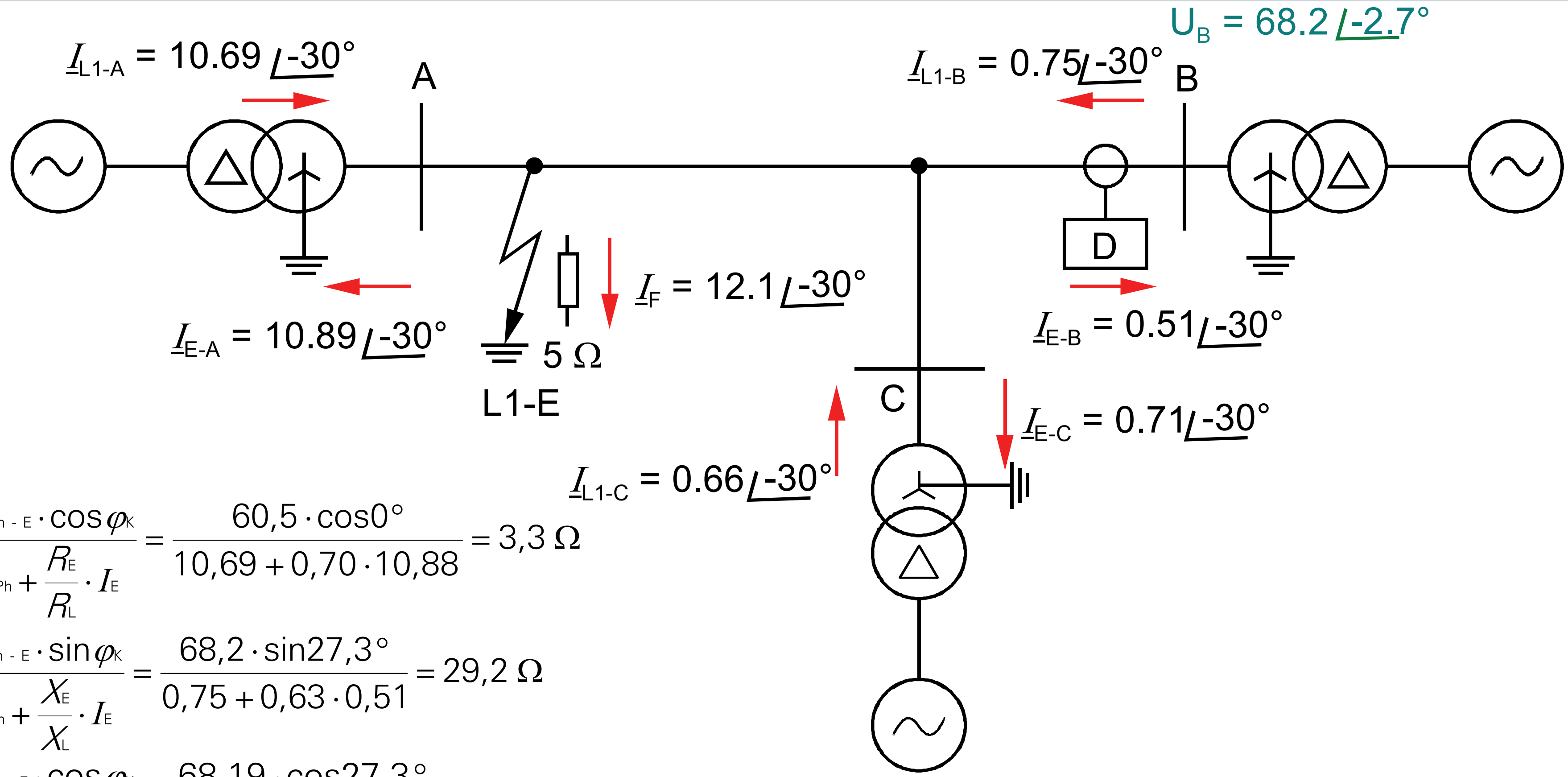
$X1A_C = 0{,}85 \cdot (1{,}14 + 5{,}7) = 5{,}8\ \Omega$

$$X1B_B = 1{,}2 \cdot \left(X_{LB} + X_{LA} \cdot \left(1 + \frac{I_C}{I_B} \right) \right) =$$

$$1{,}2 \cdot \left(5{,}7 + 11{,}4 \cdot \left(1 + \frac{1{,}71}{2{,}42} \right) \right) = 30{,}2\ \Omega$$

Distance protection of three-terminal lines
Computation example (3)

SIEMENS



$$(X_{L1\text{-}E})_A = 0$$

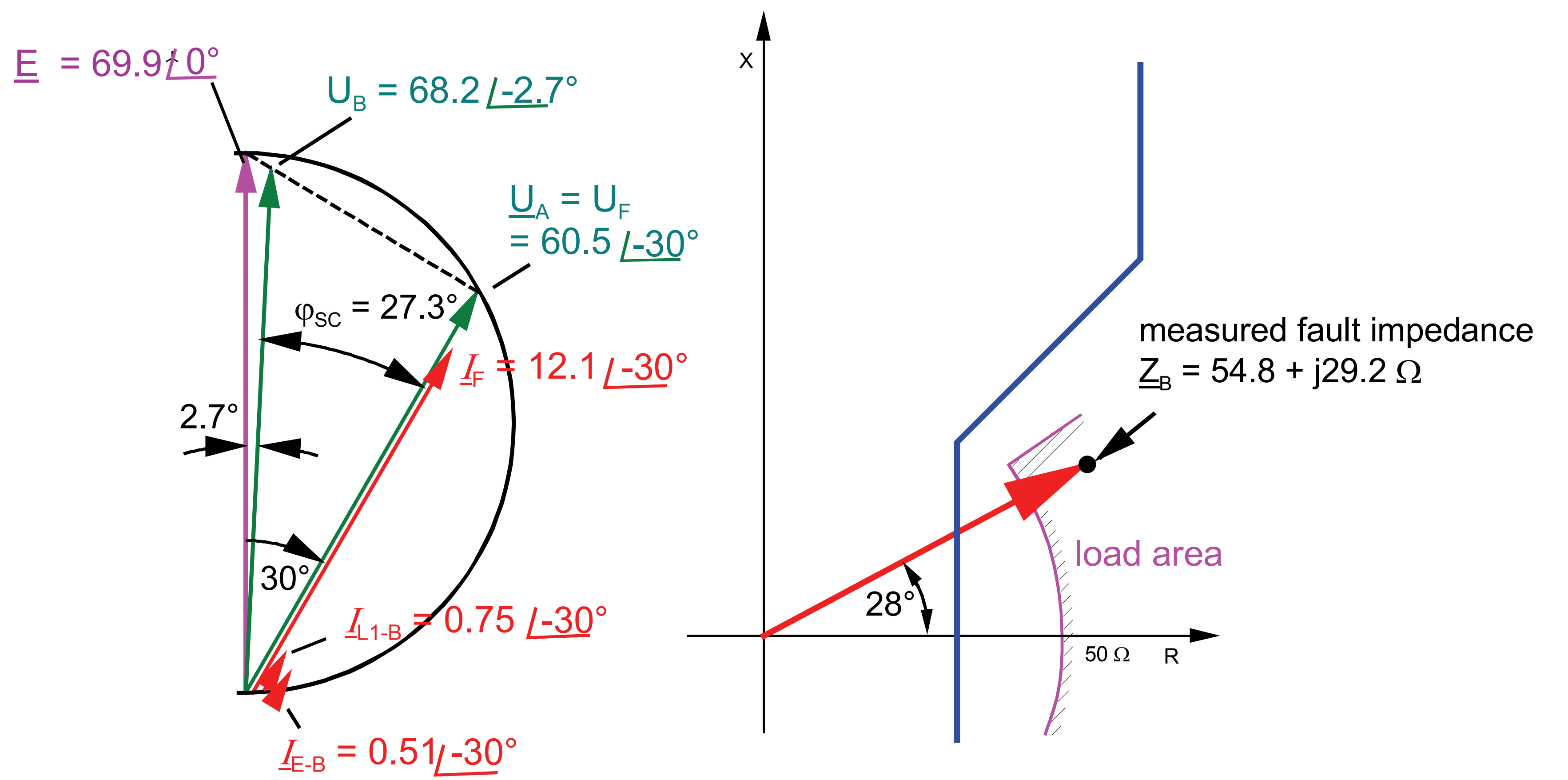
$$(R_{L1\text{-}E})_A = \frac{U_{Ph\text{-}E} \cdot \cos\varphi_K}{I_{Ph} + \frac{R_E}{R_L} \cdot I_E} = \frac{60{,}5 \cdot \cos 0°}{10{,}69 + 0{,}70 \cdot 10{,}88} = 3{,}3\ \Omega$$

$$(X_{L1\text{-}E})_B = \frac{U_{Ph\text{-}E} \cdot \sin\varphi_K}{I_{Ph} + \frac{X_E}{X_L} \cdot I_E} = \frac{68{,}2 \cdot \sin 27{,}3°}{0{,}75 + 0{,}63 \cdot 0{,}51} = 29{,}2\ \Omega$$

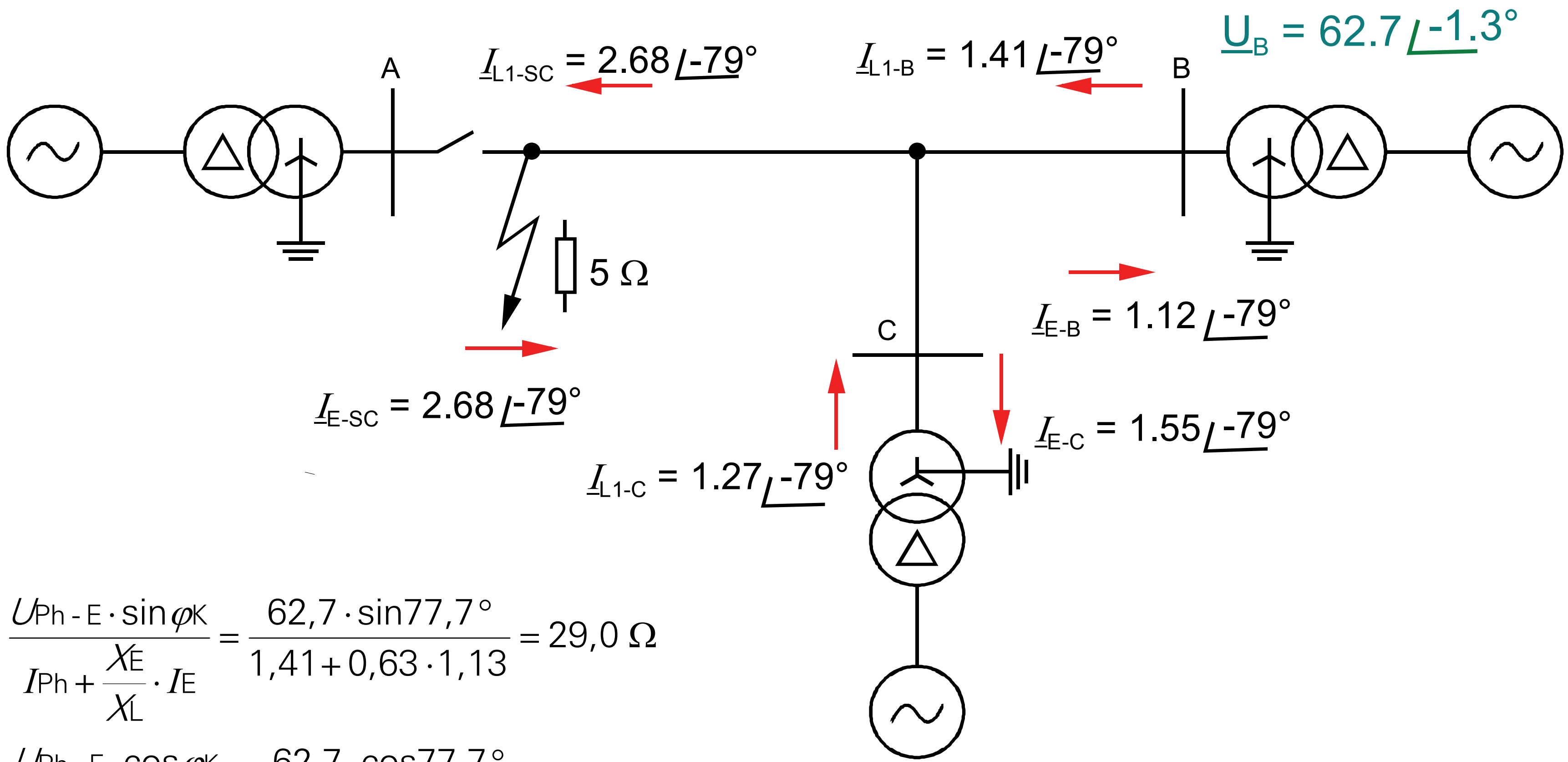
$$(R_{L1\text{-}E})_B = \frac{U_{Ph\text{-}E} \cdot \cos\varphi_K}{I_{Ph} + \frac{R_E}{R_L} \cdot I_E} = \frac{68{,}19 \cdot \cos 27{,}3°}{0{,}75 + 0{,}70 \cdot 0{,}51} = 54{,}8\ \Omega$$

Distance protection of three-terminal lines, Computation example (4)
Fault Ph-E with R_F, measured values after fault inception

SIEMENS



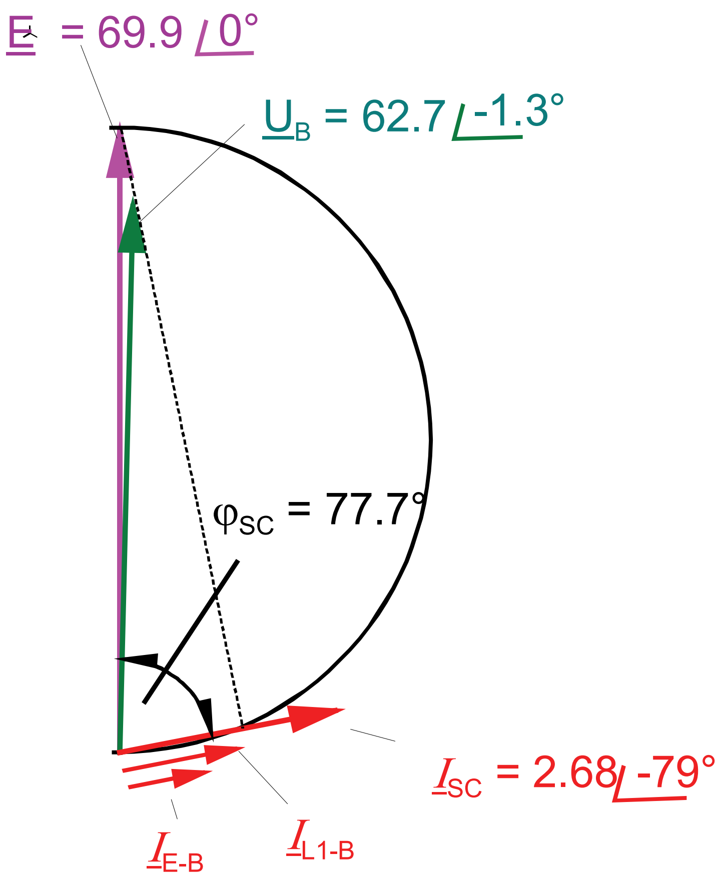
Distance protection of three-terminal lines, computation example (5)
Fault Ph-E with R_F, measured values at B after tripping at A

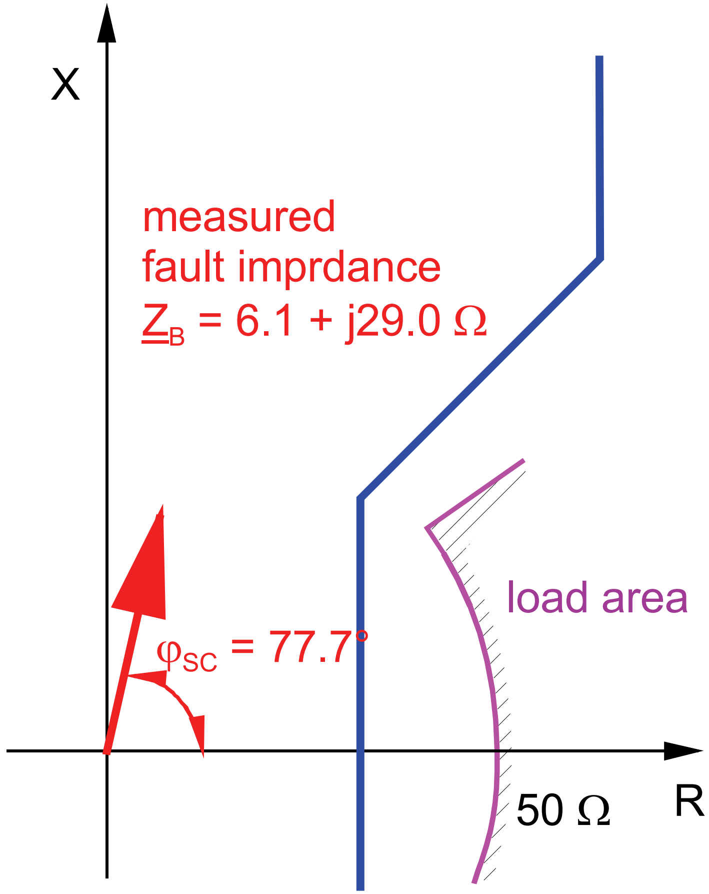


$$(X_{Ph\text{-}E})_B = \frac{U_{Ph\text{-}E} \cdot \sin\varphi_K}{I_{Ph} + \frac{X_E}{X_L} \cdot I_E} = \frac{62{,}7 \cdot \sin 77{,}7°}{1{,}41 + 0{,}63 \cdot 1{,}13} = 29{,}0\ \Omega$$

$$(R_{Ph\text{-}E})_B = \frac{U_{Ph\text{-}E} \cdot \cos\varphi_K}{I_{Ph} + \frac{R_E}{R_L} \cdot I_E} = \frac{62{,}7 \cdot \cos 77{,}7°}{1{,}41 + 0{,}70 \cdot 1{,}13} = 6{,}1\ \Omega$$

Distance protection of three-terminal lines, computation example (6)
Fault Ph-E with R_F, measured values at B after tripping A





Distance Protection of Series Compensated Lines

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Short-circuit voltage and current on series compensated lines

case 1

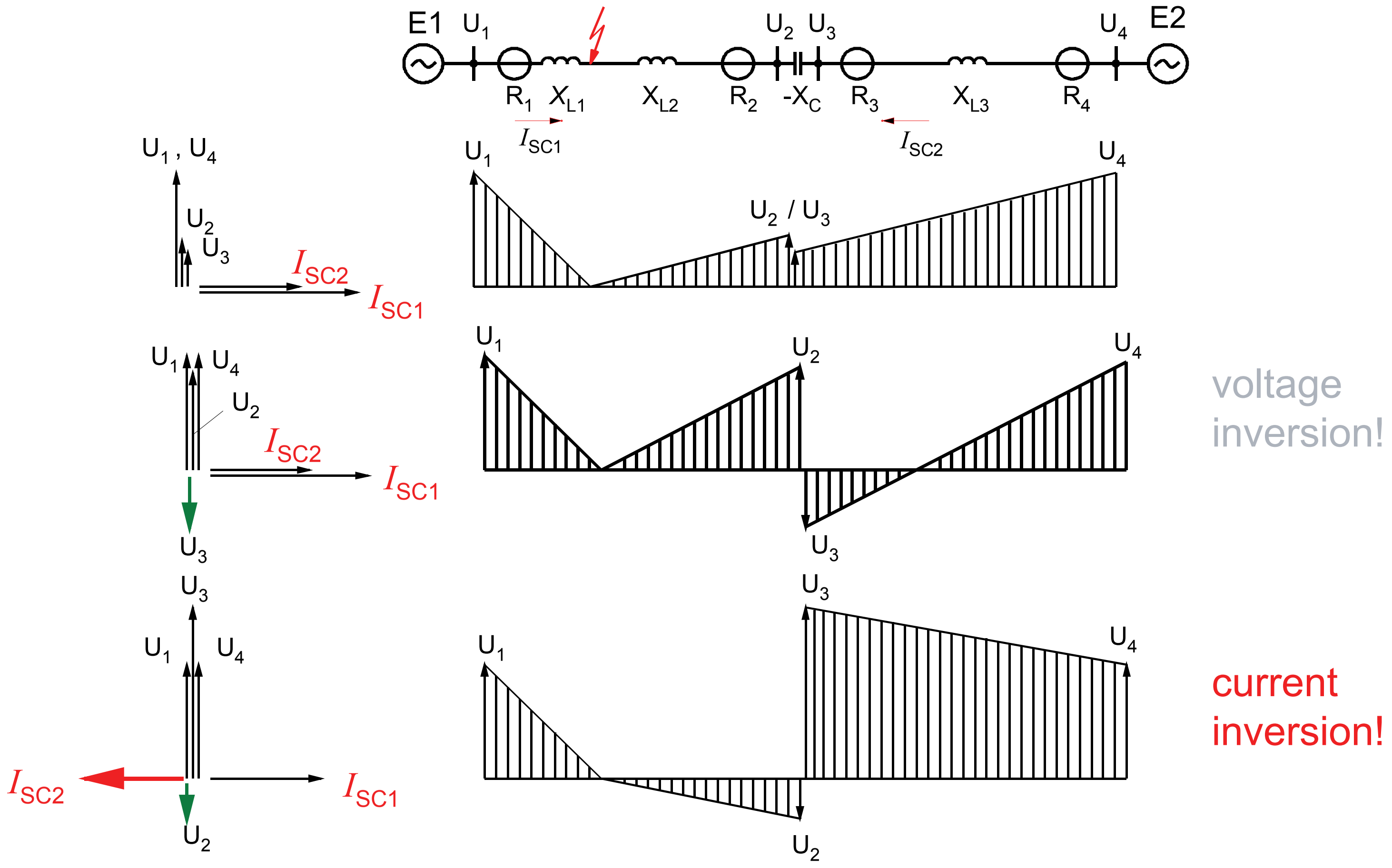
$X_C < X_{L2} + X_{L3}$
$X_C < X_{L2}$

case 2

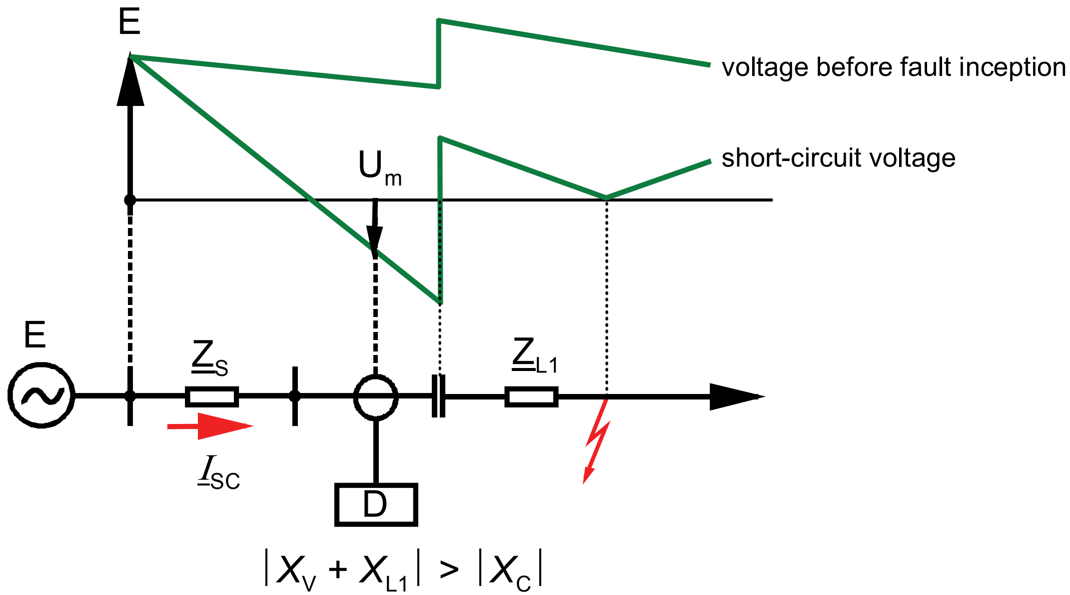
$X_C < X_{L2} + X_{L3}$
$X_C > X_{L2}$

case 3

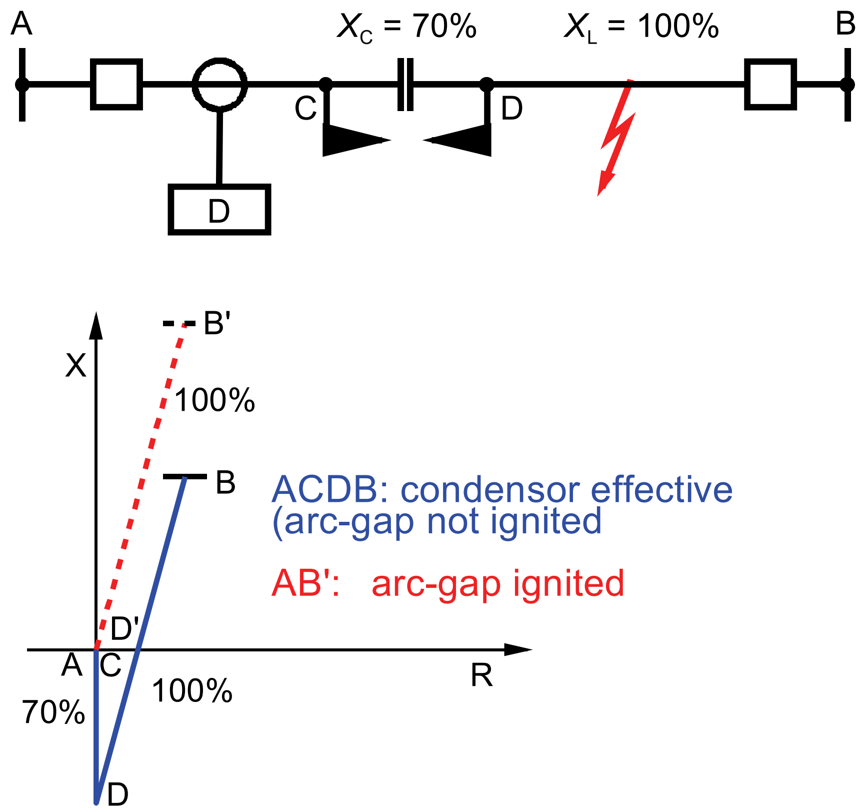
$X_C > X_{L2} + X_{L3}$
$(X_C < X_{L2})$



Distance protection of series compensated lines
Voltage inversion and apparent impedances

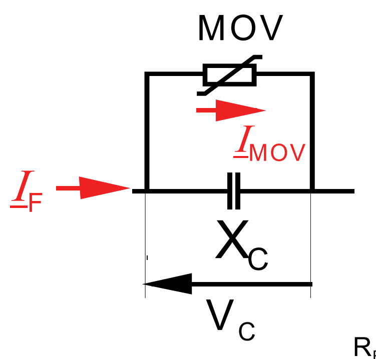


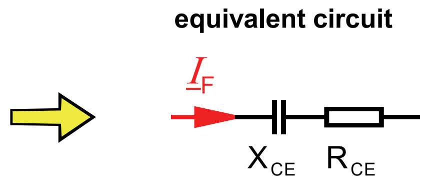
Voltage inversion!

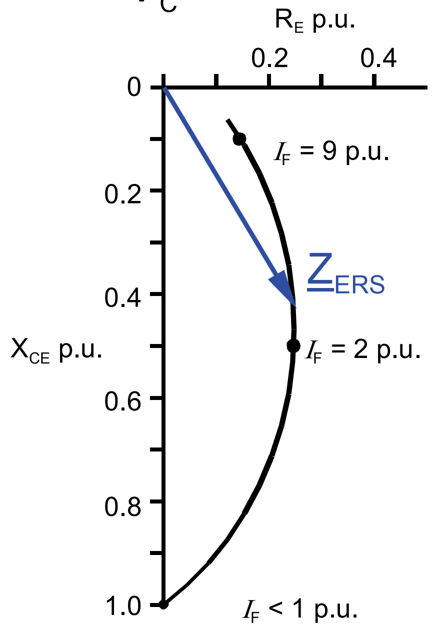


Measured relay impedances
(condensor at the beginning of the line)

Distance protection of series compensated lines
Influence of the voltage limiter (MOV) at the series capacitor





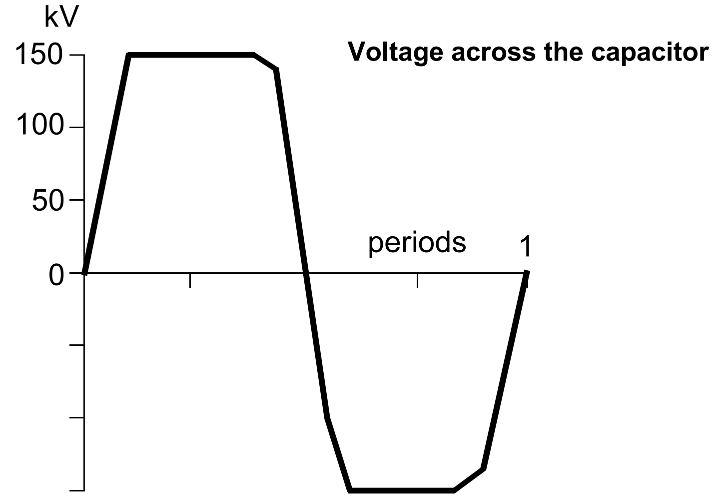


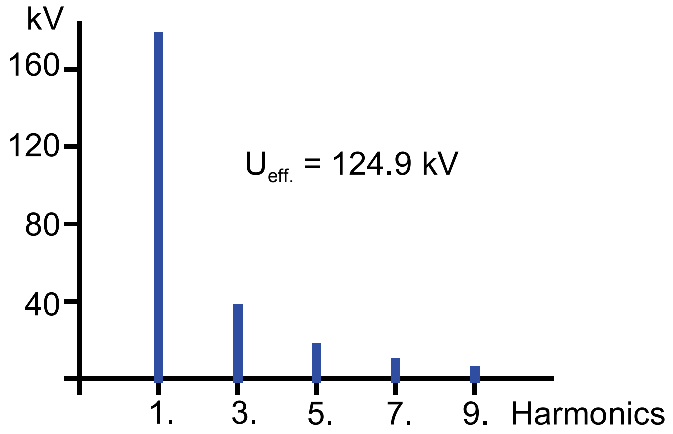
I_F p.u. $= \frac{I_F}{I_{MOV}}$

X_{CE} p.u. $= \frac{X_{CE}}{|X_C|}$

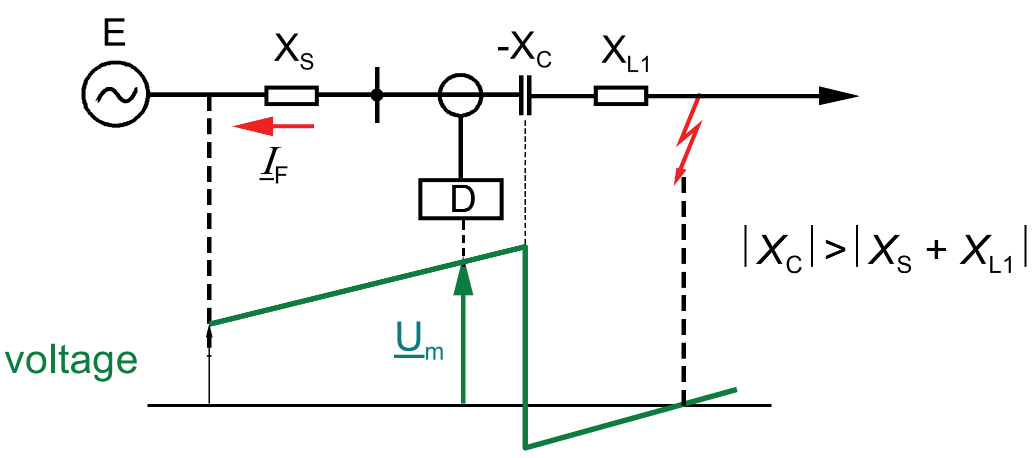
R_E p.u. $= \frac{R_E}{|X_C|}$

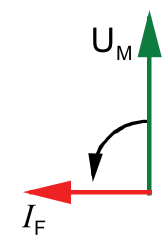
$\underline{Z}_{ERS} = R_E + jX_{CE}$



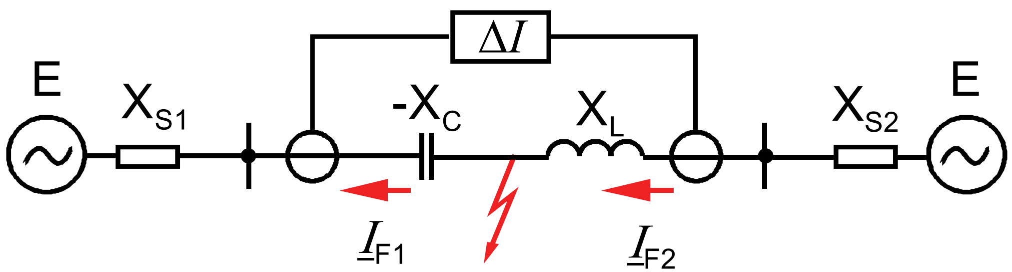


Distance protection of series compensated lines impact of current inversion

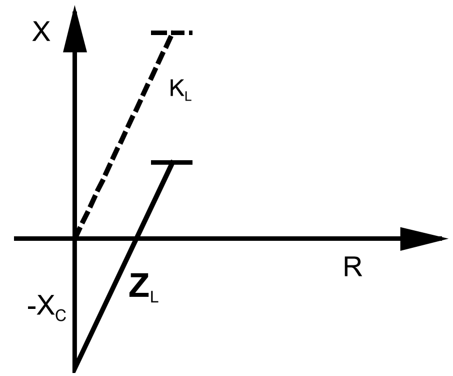




Leading short-circuit current I_F
⇒ false directional decision
even with voltage memory



False through fault condition appears!
Even differential protection may not operate!



relay measures negative impedance

Protection of series compensated lines
Use of healthy phase / memorised voltages

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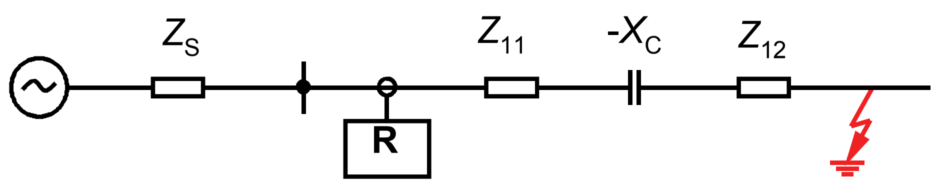
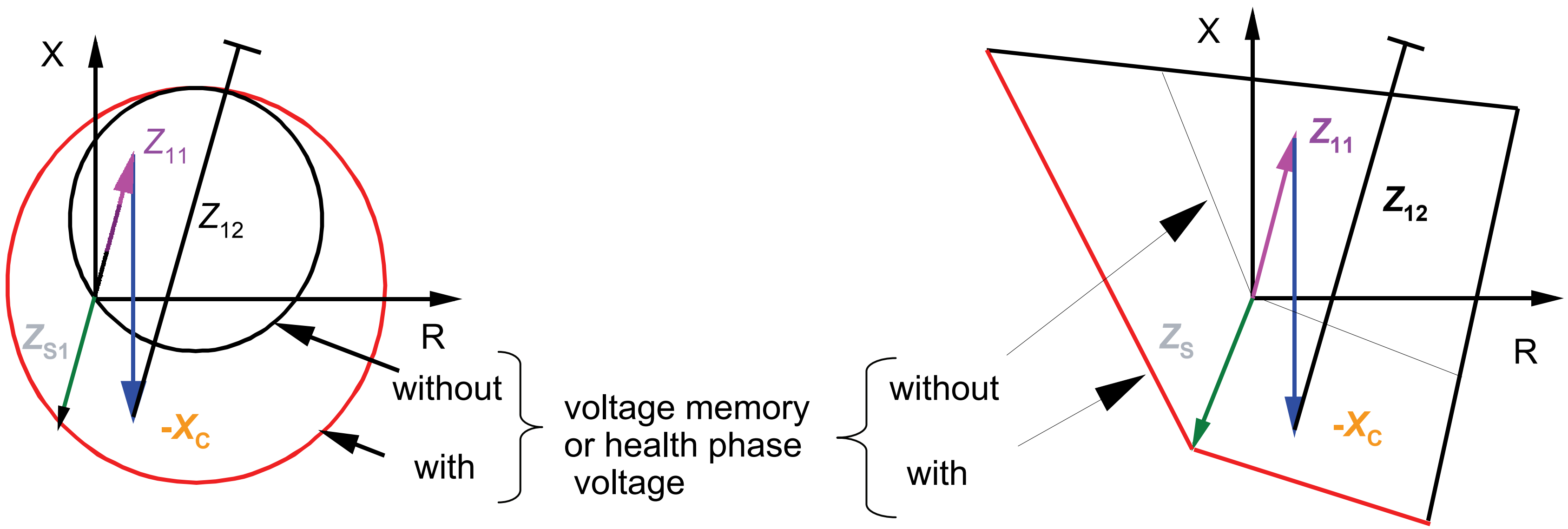
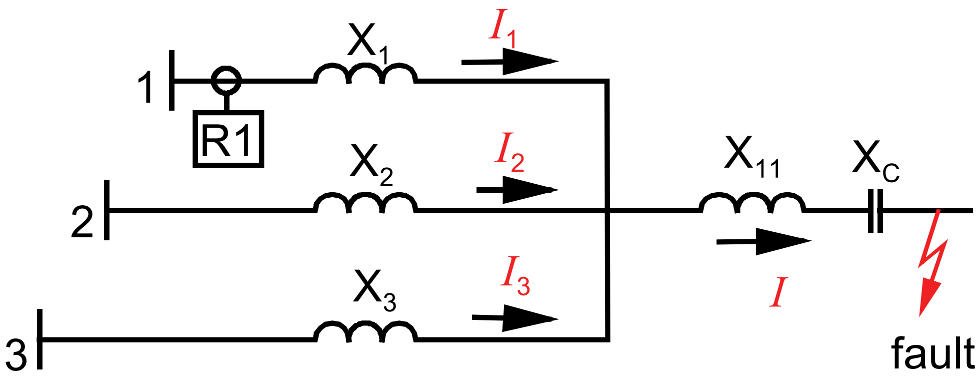


$$|X_S + X_{11}| > |X_C|$$



Distance protection of series compensated lines
Impact of series capacitors on adjacent lines



With: $[X_C] > [X_{11}]$:

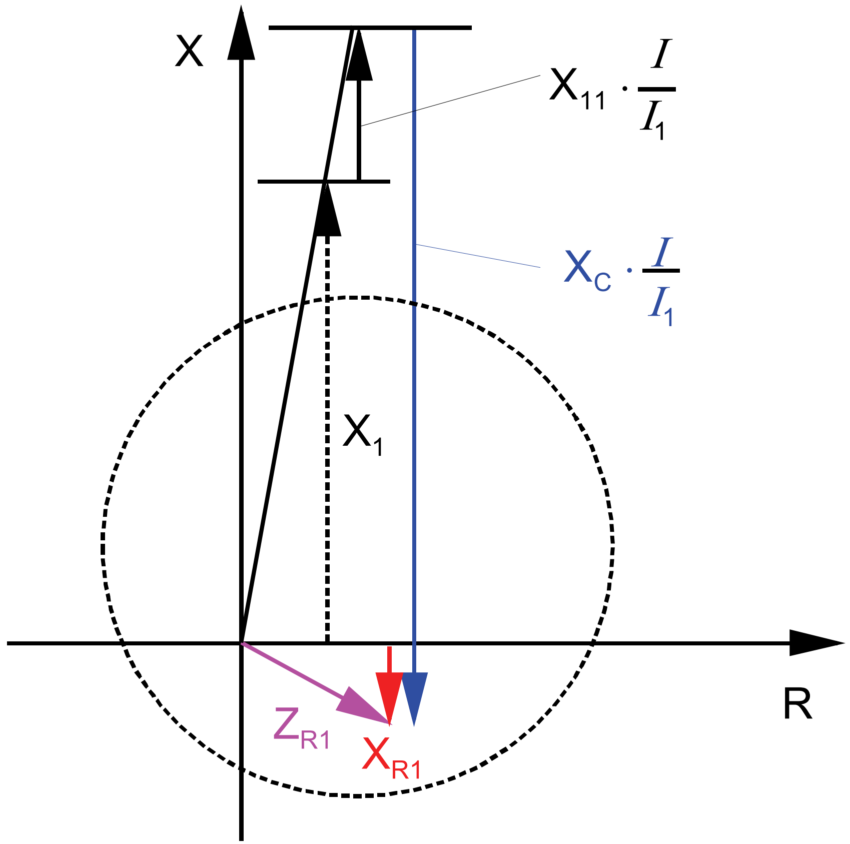
$$X_{R1} = X_1 - \frac{I}{I_1} \cdot (X_C - X_{11})$$

$$X_{R2} = X_2 - \frac{I}{I_2} \cdot (X_C - X_{11})$$

$$X_{R3} = X_3 - \frac{I}{I_3} \cdot (X_C - X_{11})$$

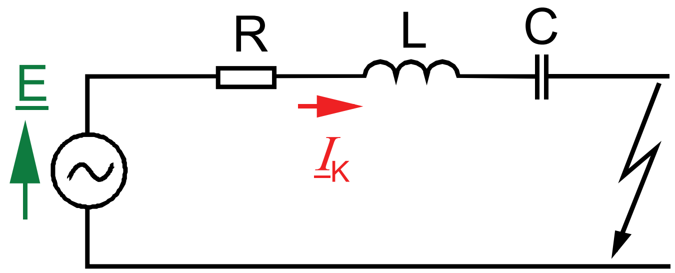
$$I_1 + I_2 + I_3 = I$$

$X_{R1,2,3}$ = reactances seen by the relays in station 1, 2 and 3



X_{R1}: reactance seen by relay in station 1

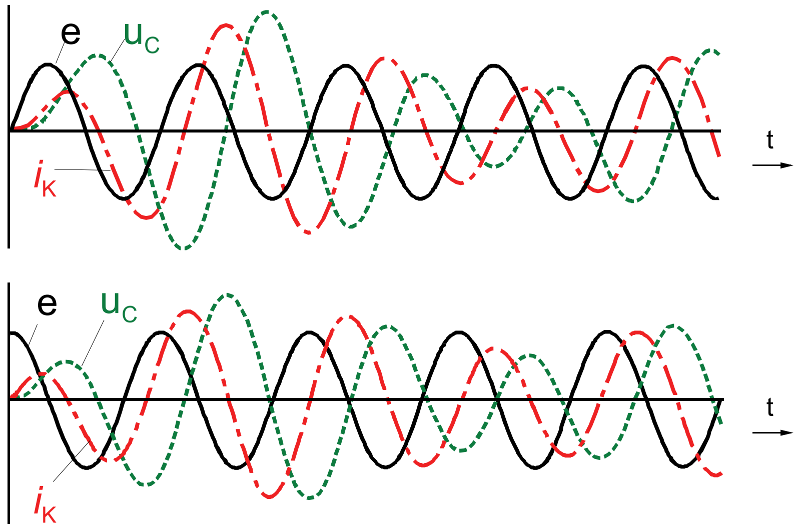
Series compensated lines
Transient fault current



Short-circuit loop of a series compensated line

$$\hat{E}\cdot\sin(\omega t+\lambda)=L\frac{di_{SC}}{dt}+R\cdot i_{SC}+\frac{1}{C}\int i_{SC}dt$$

$$i_{SC}=\hat{I}\cdot\sin(\omega t+\lambda-\Theta)+e^{-\alpha t}(K_1\cos\beta t+K_2\sin\beta t)$$



Short-circuit at voltage zero crossing

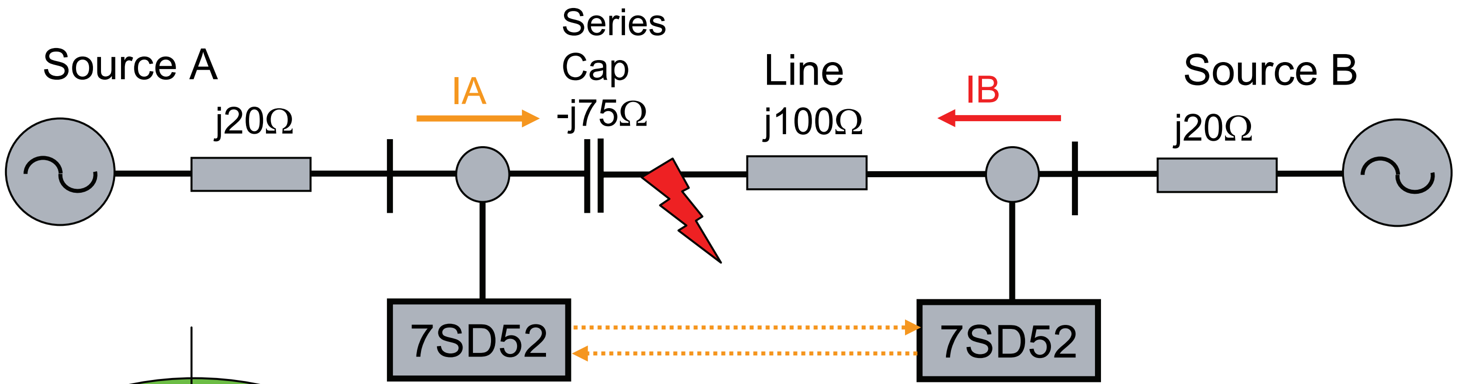
Short-circuit at voltage maximum

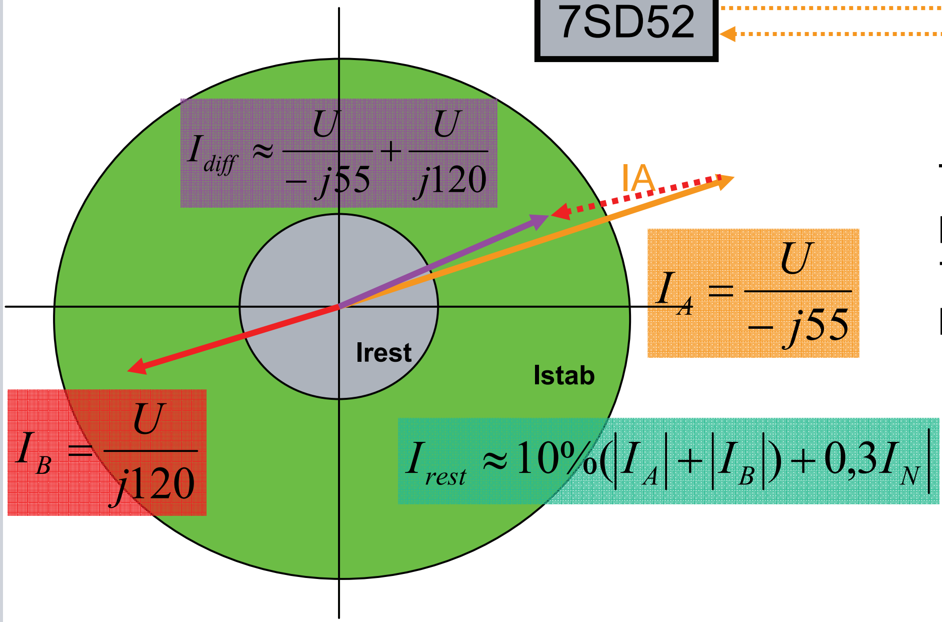
compensation degree:

$$k_C=\frac{X_C}{X_L}=50\%$$

$$k_{Trans}=\frac{1}{1+\hat{U}_{gap}/(\sqrt{2}*E)}$$

Current Inversion and 7SD52 Differential Protection (example)





The restraint current used by 7SD is calculated based on predicted errors:

7SD52 will trip (I_{diff} > I_{rest}) even with current inversion due to high sensitivity.

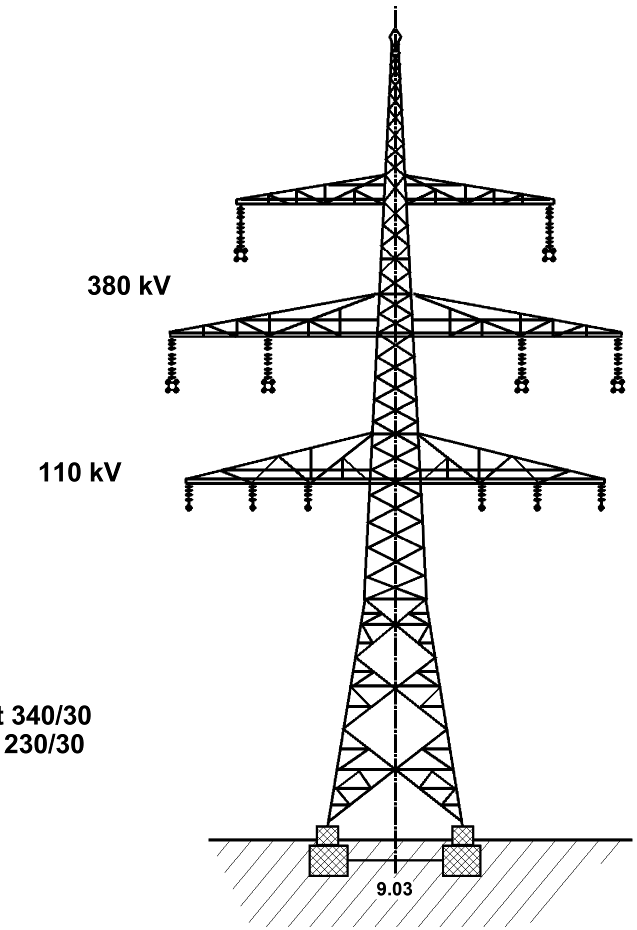
Conventional Diff Protection for example uses the following stabilising current:

$$I_{stab} \approx 50\%(|I_A| + |I_B|)|$$

The conventional diff protection will not trip due to current inversion.

Distance Protection of Parallel Lines

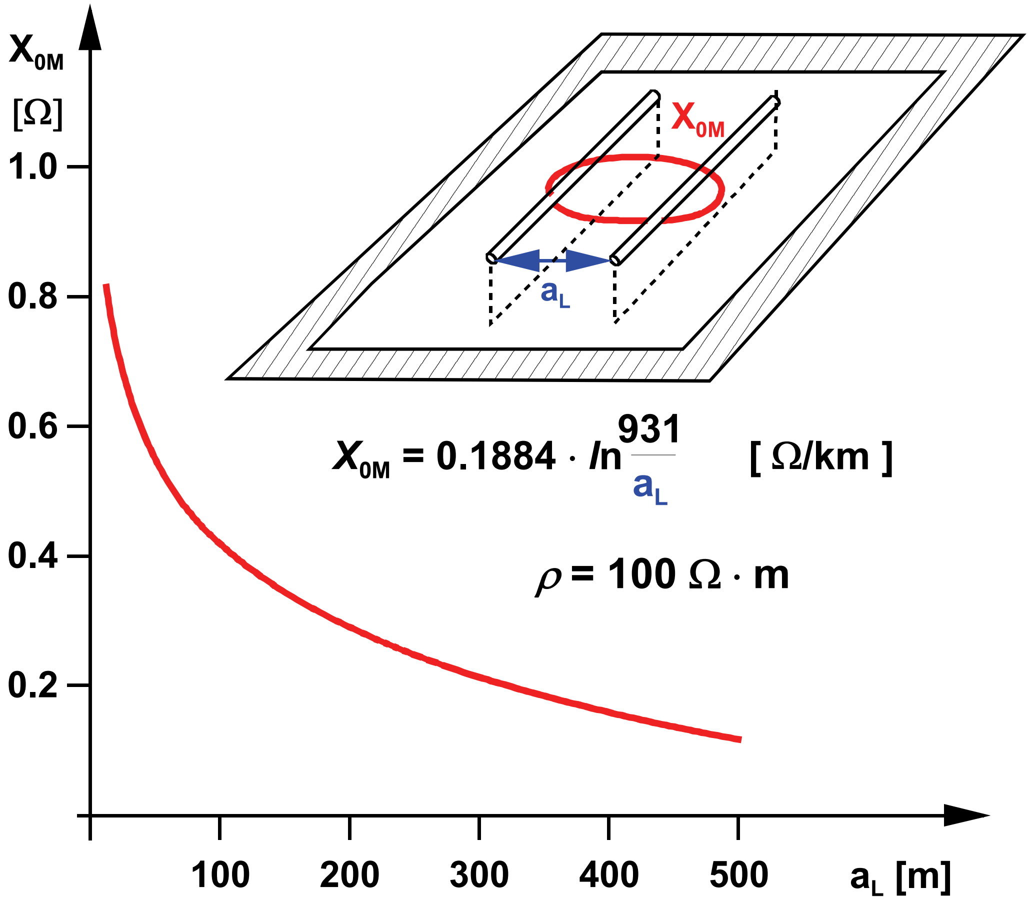
Multiple circuit OH-line tower (Germany)



Phase conductors
380 kV: 2x3x4 Al/St 340/30
110 kV: 2x3 Al/St 230/30

Earth-wire
ESLK Al/St 120/70

Mutual reactance of two conductor-earth loops



$$X_{0M} = 0.1884 \cdot \ln \frac{931}{a_L} \quad [\Omega/km]$$

$$\rho = 100\ \Omega \cdot m$$

Calculation of line impedances
Parallel line (transposed)

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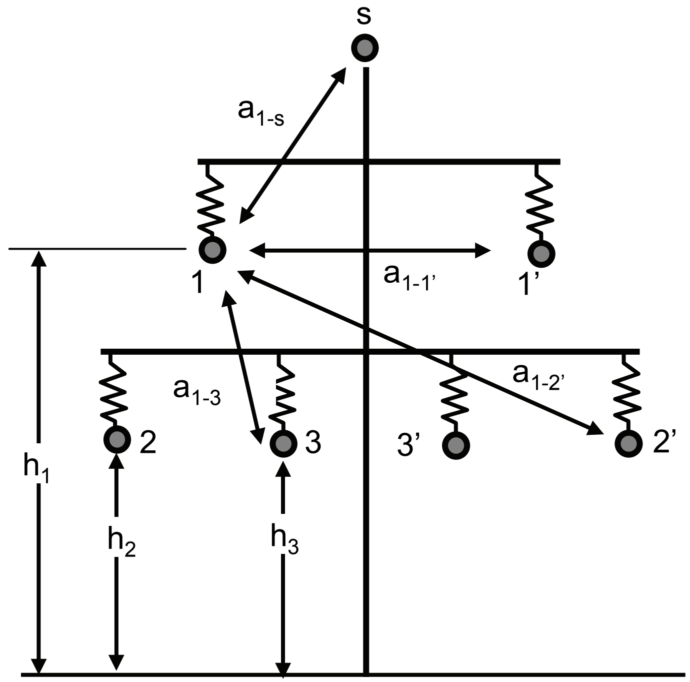


$$A = \sqrt[3]{a_{1-2} \cdot a_{2-3} \cdot a_{3-1}}$$

$$A' = \sqrt[3]{a_{1-2'} \cdot a_{2-3'} \cdot a_{3-1'}}$$

$$A'' = \sqrt[3]{a_{1-1'} \cdot a_{2-2'} \cdot a_{3-3'}}$$

$$A_s = \sqrt[3]{a_{1-s} \cdot a_{2-s} \cdot a_{3-s}}$$

$$A_L = \sqrt[3]{A'^2 \cdot A''}$$

Parallel line **without** earth wire

$$\underline{Z}'_{M0} = 3 \cdot R'_E + j\omega \cdot 10^{-4} \cdot 6 \cdot \ln \frac{\delta}{A_L} \quad \Omega/\text{km}$$

Parallel line **with** earth wire

$$\underline{Z}'_{M0E} = \underline{Z}'_{M0} - \frac{3 \cdot \underline{Z}'^2_{1s}}{\underline{Z}'_s} \quad \Omega/\text{km}$$

with: $\underline{Z}'_{1s} = R'_E + j\omega \cdot 10^{-4} \cdot 2 \cdot \ln \frac{\delta}{A_s} \quad \Omega/\text{km}$

$$\underline{Z}'_s = R'_s + R'_E + j\omega \cdot 10^{-4} \cdot \left(2 \cdot \ln \frac{\delta}{r_s} + 0.5 \cdot \mu_1 \right) \quad \Omega/\text{km}$$

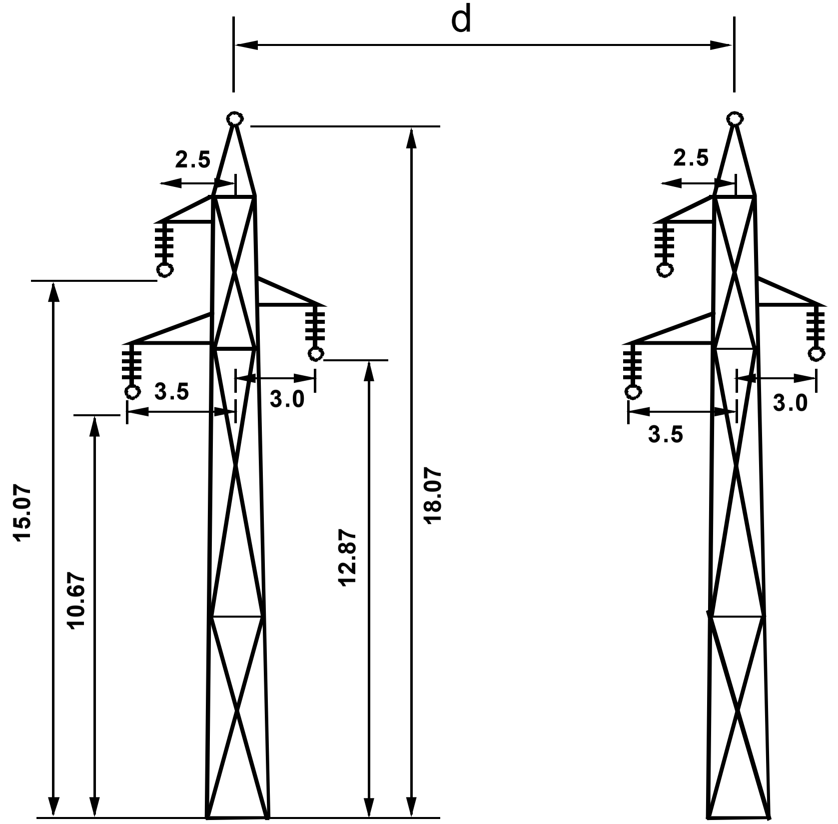
$$\delta = 1650 \cdot \sqrt{\frac{\rho}{\omega}} \quad m \qquad und \qquad R'_E = \frac{\pi}{2} \cdot \omega \cdot 10^{-4} \quad \Omega/km$$

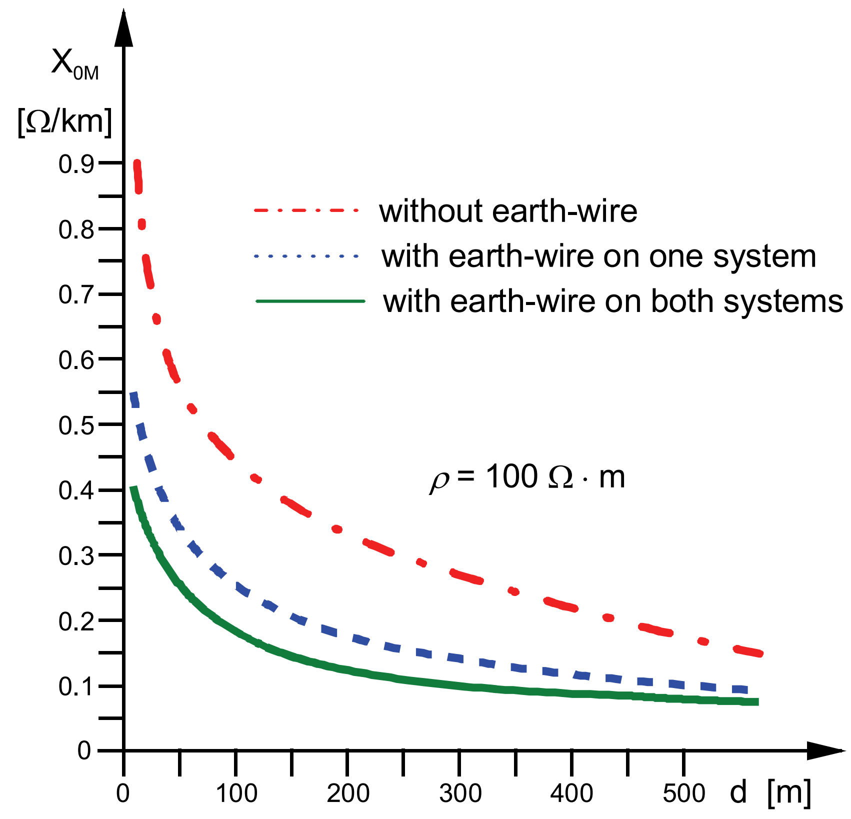
ρ : Earth resistivity in Ωm
100 for wed soil, 500 for dry soil

μ_1 : relative Permeability (1 for Cu and AL)

Calculated mutual reactance of two 110 kV lines

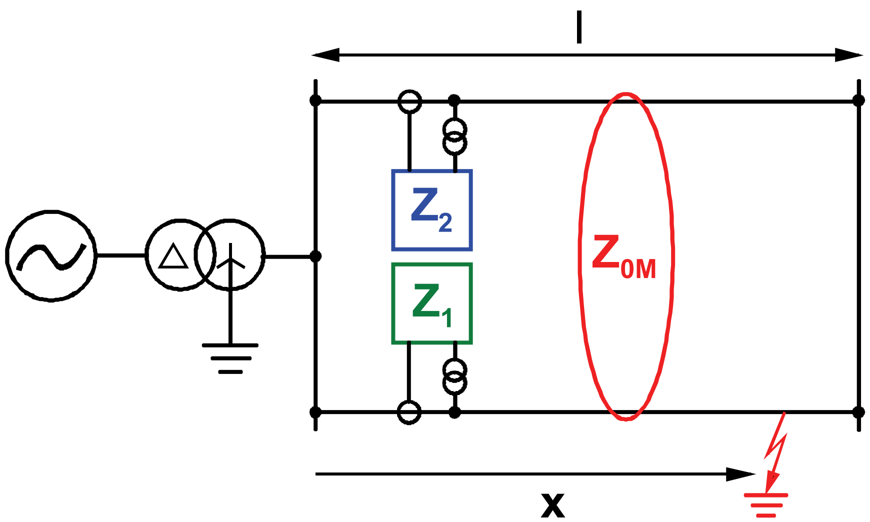
SIEMENS





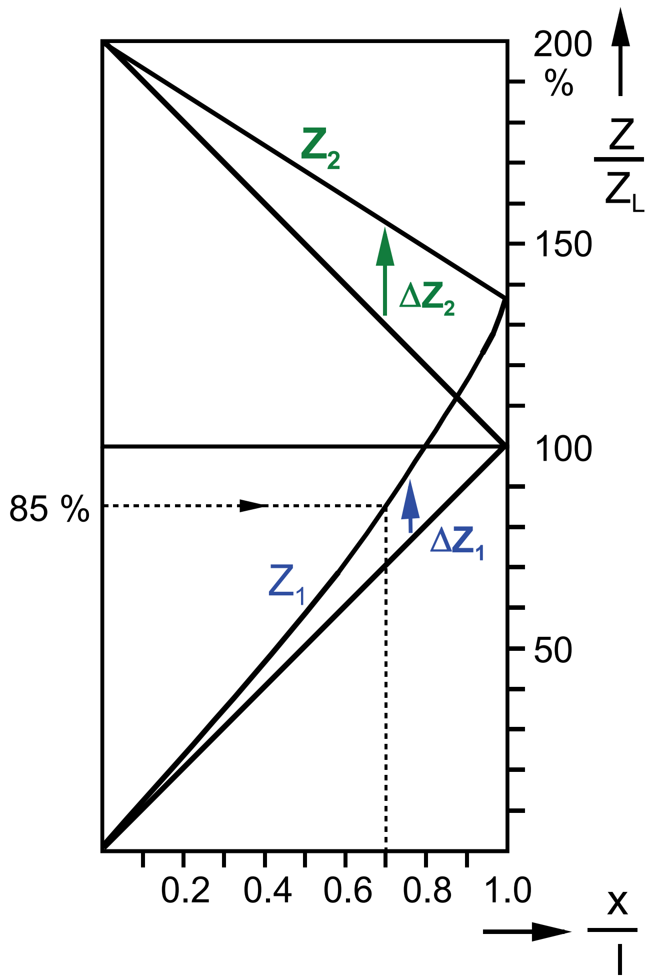
Distance measuring error on a double-circuit line with single-ended infeed

SIEMENS



$$\frac{Z_E}{Z_L} = 0.86$$

$$\frac{Z_{0M}}{3 \cdot Z_L} = 0.65$$

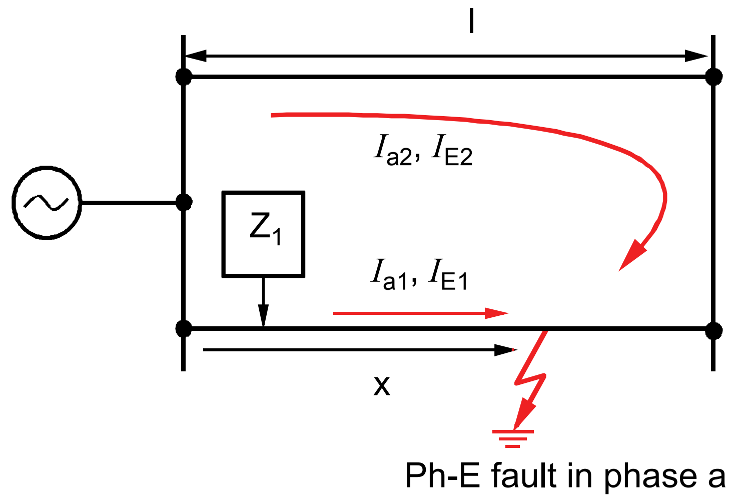


Influence of the zero sequence coupling of the parallel line (Relay on the faulted line **without** compensation)

$$Z_1 = \frac{U_a}{I_{a1} + k_{01} \cdot I_{E1}}$$

$$Z_1 = \frac{x\left[Z_L \cdot I_{a1} + Z_E \cdot I_{E1} + \frac{Z_{0M}}{3} \cdot I_{E2}\right]}{I_{a1} + \frac{Z_E}{Z_L} \cdot I_{E1}} \qquad Z_E = \frac{Z_0 - Z_1}{3}$$

with $I_{E2} = \frac{x}{2l - x} \cdot I_{E1}$ and $I_{a1} = I_{E1}$



$$Z_1 = x \cdot Z_L + \underbrace{x \cdot Z_L \frac{\frac{Z_{0M}}{3 \cdot Z_L} \cdot \frac{x}{2l - x}}{1 + \frac{Z_E}{Z_L}}}_{\text{measuring error}}$$

Influence of the zero sequence coupling of the parallel line
(Relay on the healthy line **without** compensation)

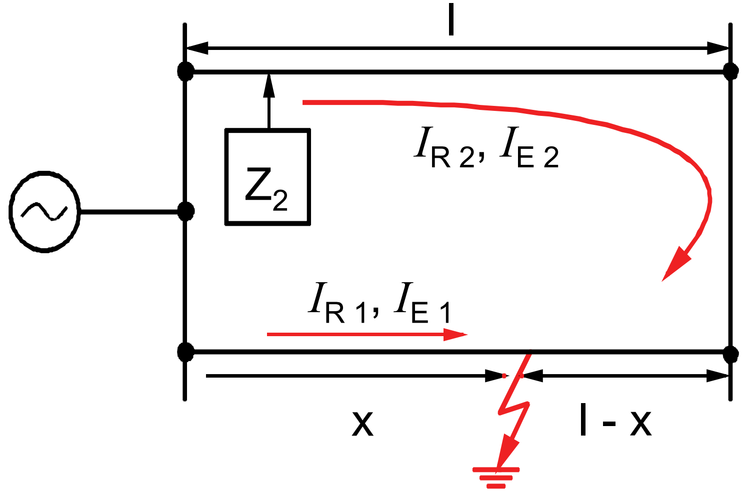
SIEMENS

$$Z_2 = \frac{U_R}{I_{R2} + \frac{Z_E}{Z_L} \cdot I_{E2}}$$

$$I_{R2} = I_{E2}$$

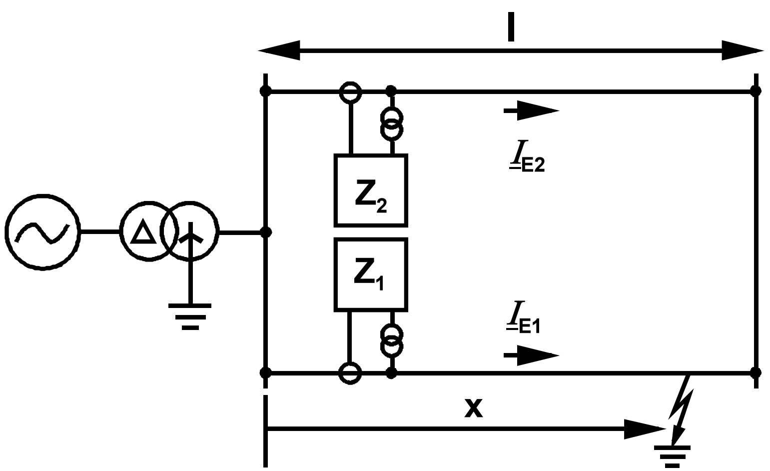
$$I_{E1} = \frac{2 \cdot l - x}{x} \cdot I_{E2}$$

$$Z_2 = Z_L \frac{(2l - x)\left(1 + \frac{Z_E}{Z_L}\right) + x \cdot \frac{Z_{0M}}{3 \cdot Z_L}}{1 + \frac{Z_E}{Z_L}}$$



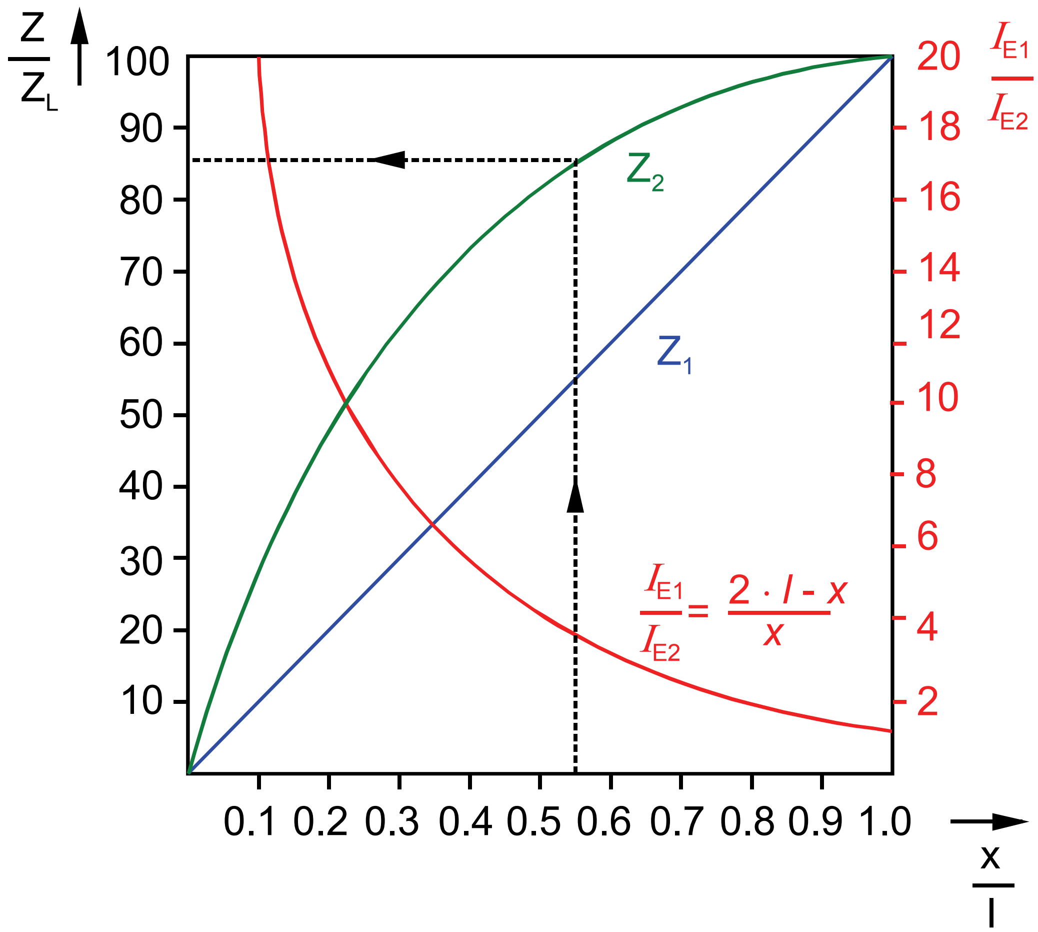
$$Z_2 = Z_L \frac{(2l - x)\left(1 + \frac{Z_E}{Z_L}\right)}{1 + \frac{Z_E}{Z_L}} + \underbrace{\frac{x \cdot \frac{Z_{0M}}{3 \cdot Z_L}}{1 + \frac{Z_E}{Z_L}}}_{\text{measuring error}}$$

Measured impedances **with** parallel line compensation

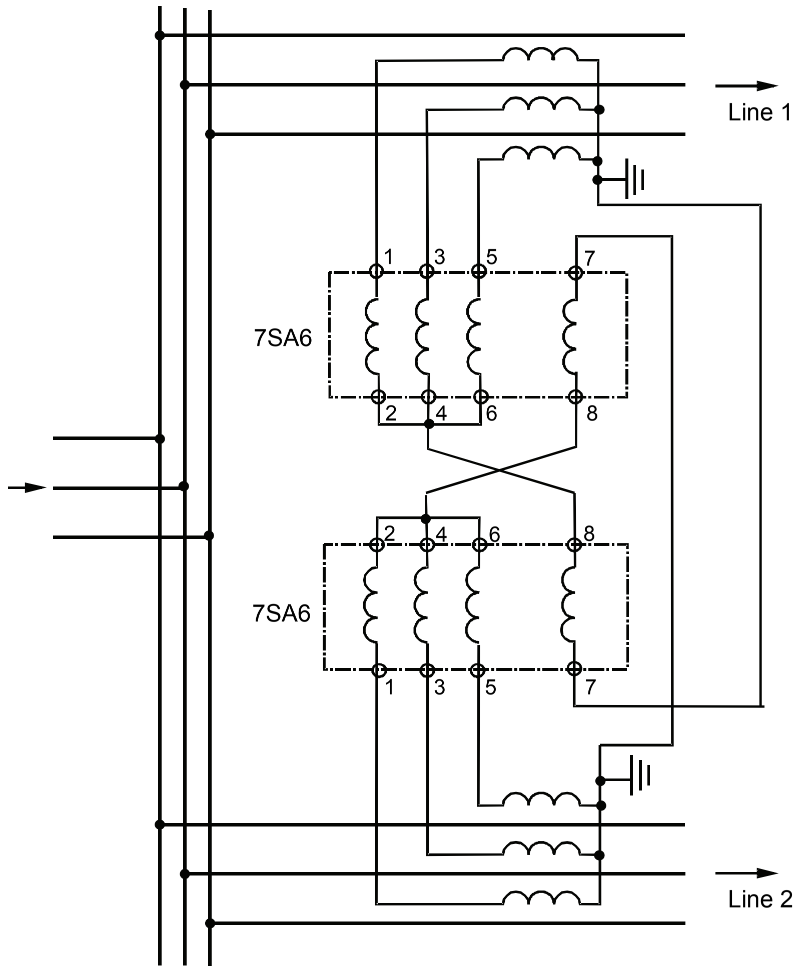


Z_L = line impedance

$$\frac{Z_E}{Z_L} = 0.86 \text{ und } \frac{Z_{0M}}{3 \cdot Z_L} = 0.65$$



Parallel line compensation,
Connection of distance relays 7SA6



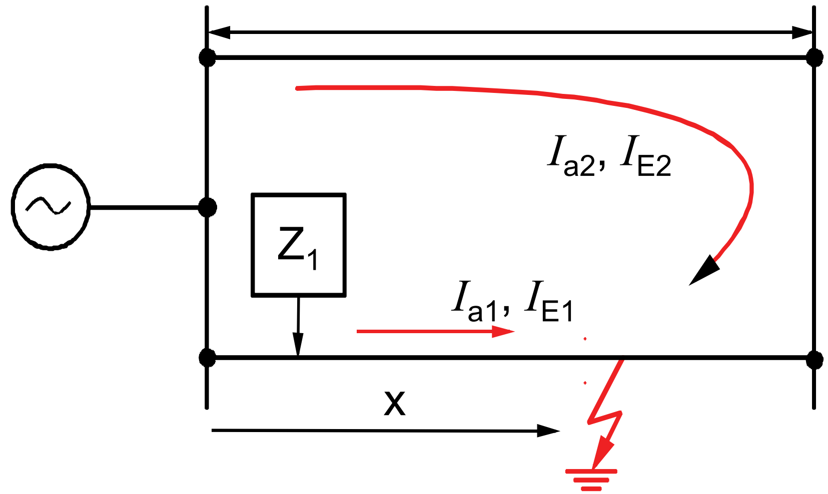
Influence of the zero sequence coupling of the parallel line (Relay on the faulted line **with** compensation)

SIEMENS

$$Z_1 = \frac{U_R}{I_{R1} + k_{01} \cdot I_{E1} + \underbrace{k_{02} \cdot I_{E2}}_{\text{compensation}}}$$

$$k_{02} = \frac{Z_{0M}}{3 \cdot Z_L}$$

$$Z_1 = \frac{x\left(Z_L \cdot I_{R1} + Z_E \cdot I_{E1} + \frac{Z_{0M}}{3} \cdot I_{E2}\right)}{I_{R1} + \frac{Z_E}{Z_L} \cdot I_{E1} + \frac{Z_{0M}}{3 \cdot Z_L} \cdot I_{E2}}$$

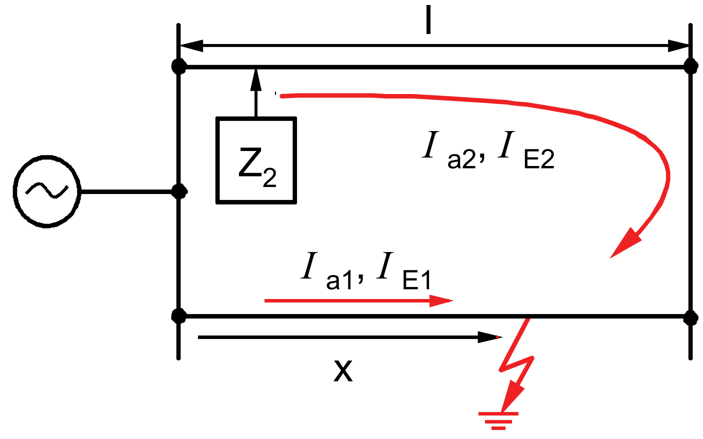


$Z_1 = x \cdot Z_L$ (correct fault impedance)

Influence of the zero sequence coupling of the parallel line (Relay on the healthy line **with** compensation)

SIEMENS

$$Z_2 = \frac{U_{R2}}{I_{R2} + \frac{Z_E}{Z_L} \cdot I_{E2} + \underbrace{\frac{Z_{0M}}{3 \cdot Z_L} \cdot I_{E1}}_{\text{compensation}}}$$



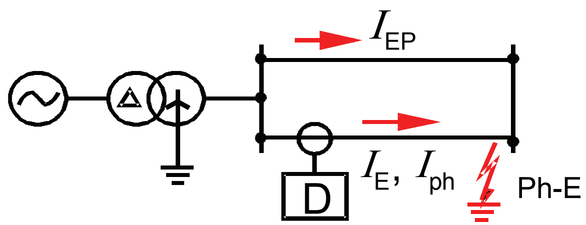
with $I_{R2} = I_{E2}$ and $I_{E1} = \frac{2 \cdot l - x}{x} \cdot I_{E2}$

$$U_{a2} = (2 \cdot l - x)(Z_L \cdot I_{a2} + Z_E \cdot I_{E2}) + x \cdot I_{E1} \cdot \frac{Z_{0M}}{3} - 2(l - x)\frac{Z_{0M}}{3} \cdot I_{E2}$$

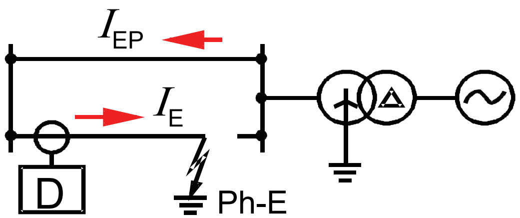
$$Z_2 = Z_L \cdot \frac{(2l-x)(1+\frac{Z_E}{Z_L}) + x \cdot \frac{Z_{0M}}{3 \cdot Z_L}}{1+\frac{Z_E}{Z_L} + \frac{2l-x}{x} \cdot \frac{Z_{0M}}{3 \cdot Z_L}}$$

$$Z_2 = Z_L \cdot (2 \cdot l - x) + \underbrace{\frac{(\frac{x}{2 \cdot l - x} - \frac{2l - x}{x}) \cdot \frac{Z_{0M}}{3 \cdot Z_L}}{1 + \frac{Z_E}{Z_L} + \frac{Z_{0M}}{3 \cdot Z_L} \cdot \frac{2l - x}{x}}}_{\text{Measuring error}} \cdot Z_L \cdot (2 \cdot l - x)$$

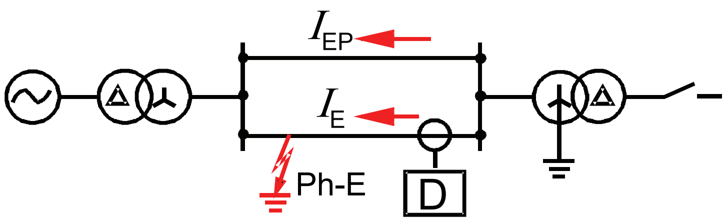
Distance protection on parallel lines
impedance measuring error dependent on switching condition



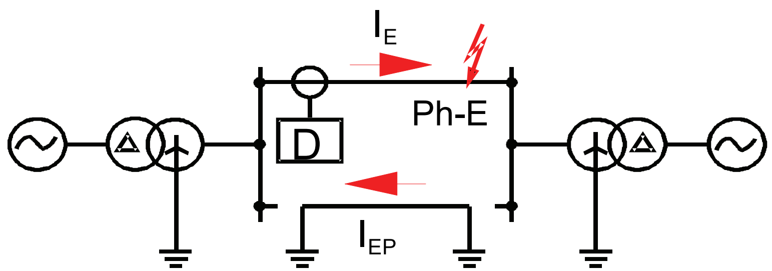
$$\Delta Z = \frac{k_{0M}}{1+k_0} \cdot Z_L = +39\,\%\,Z_L$$



$$\Delta Z = -\frac{k_{0M}}{1+k_0} \cdot Z_L = -39\,\%\,Z_L$$



$$\Delta Z = \frac{3 \cdot k_{0M}}{1+3 \cdot k_0} \cdot Z_L = \frac{Z_{0M}}{Z_{0L}} = +65\,\%\,Z_L$$

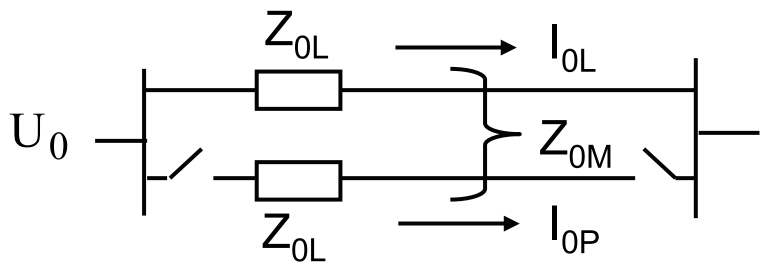


$$\Delta Z = -\frac{k_{0M} \cdot \frac{Z_{0M}}{Z_{0L}}}{1+k_0} \cdot Z_L = -\frac{Z_{0M}}{Z_{0L}} = -25\,\%\,Z_L$$

(k_0=0.71, k_{0M}=0.67 and Z_{0M}/Z_{0L}= 0.65)

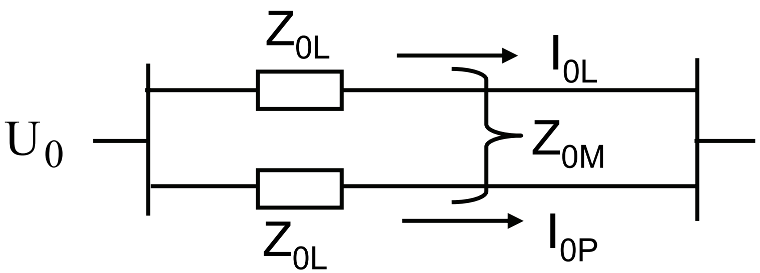
Parallel line
Earth current compensation factor k_0 dependent on switching state

Example: $K_0 = 0.71$, $K_{0M} = 0.67$, $Z_{0M}/Z_{0L} = 0.65$



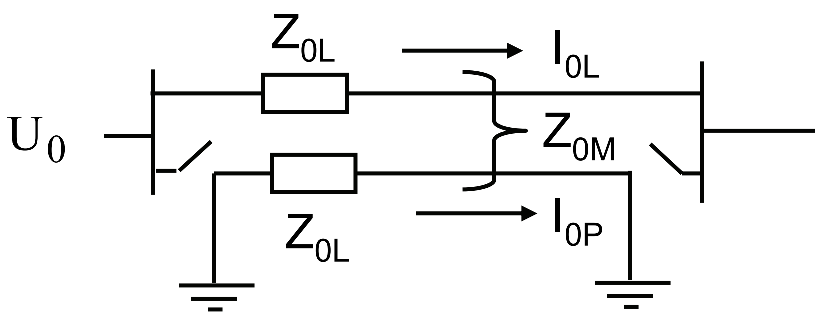
$$I_{0P} = 0 \qquad Z_{0*} = \frac{U_{0L}}{I_{0L}} = Z_{0L}$$

$$k_0 = \frac{Z_E}{Z_L} = \frac{(Z_{0L} - Z_{1L})/3}{Z_{1L}} = 0.71$$



$$I_{0P} = I_{0L} \qquad Z_0^* = \frac{U_{0L}}{I_{0L}} = Z_{0L} + Z_{0M}$$

$$k_0^* = \frac{(Z_0 - Z_{1L})/3}{Z_{1L}} + \frac{Z_{0M}/3}{Z_{L1}} = k_0 + k_{0M} = 1.38$$

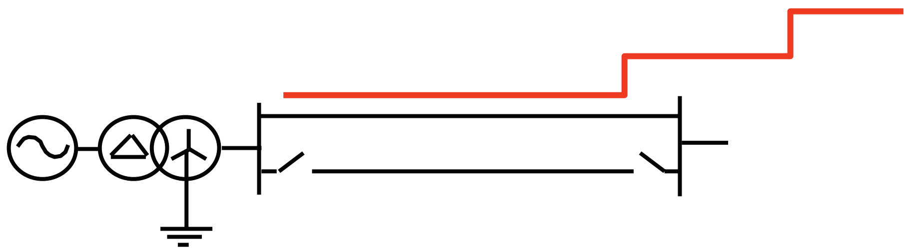


$$I_{0P} = -\frac{Z_{0M}}{Z_{0P}} \cdot I_{0L} \qquad Z_0^{**} = \frac{U_{0L}}{I_{0L}} = Z_{0L} - \frac{Z_{0M}^2}{Z_{0L}}$$

$$k_0^{**} = \frac{Z_{0L} - Z_{1L}}{3 \cdot Z_{1L}} - \frac{Z_{0M}}{Z_{0L}} \cdot \frac{Z_{0M}}{3 \cdot Z_{1L}} = k0 - \frac{Z_{0M}}{Z_{0L}} \cdot k_{0M} = 0.27$$

Parallel line
Problem of backup zone reach for Ph-E-faults

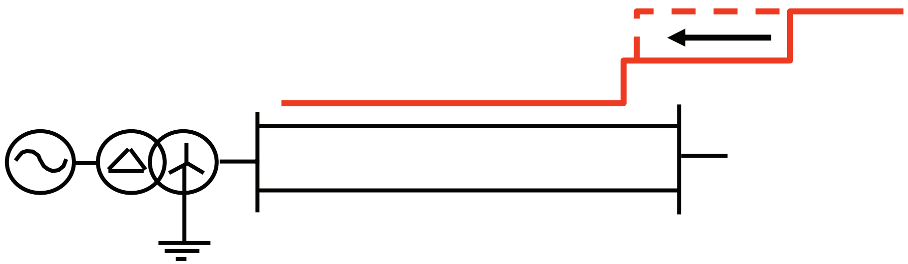
SIEMENS



Zone setting based on Ph-Ph-Faults:

$$Z_2 = 1.2 \cdot Z_L$$

$$k_0 = Z_E / Z_L \text{ of single line}$$



Zone reach for Ph-E faults:

$$Z_2 = 1.2 \cdot Z_L \cdot \frac{1 + k_0}{1 + k_0 + k_{0M}}$$

$$= \frac{1 + 0.71}{1 + 0.71 + 0.67} \cdot 1.2 \cdot Z_L = 0.86 \cdot Z_L$$

120% Overreach of 2nd zone for earth faults would require a zone setting of

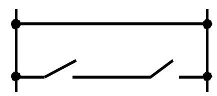
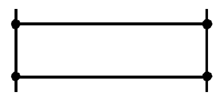
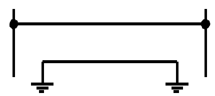
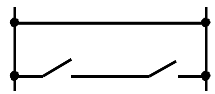
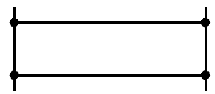
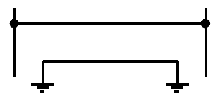
$$Z_2 = 1.2 \cdot Z_L \cdot \frac{1 + k_0 + k_{0M}}{1 + k_0} = 1.2 \cdot Z_L \cdot \frac{1 + 0.71 + 0.67}{1 + 0.71} = 1.67 \cdot Z_L$$

Use → separate k_0 factor for overreaching zones

→ or parallel line compensation

Distance measurement on parallel lines

Zone reach dependent on switching state and relay k_o-setting

		Zone reach in % line length dependent on switching state		
				
Setting to 85% line length for switching state:	 K_0 = 0.71(0.5)	**85%** (75%)	**71%** (64%)	**108%** (98%)
	 K_0 = 1.59	**108%**	**85%**	**132%**
	 K_0 = 0.27	**65%**	**56%**	**85%**

Example: 400kV-line: $K_0 = 0.71$, $K_{0M} = 0.67$, $Z_{0M}/Z_{0L} = 0.65$

Ph-to-E fault on a double circuit line with double-sided in-feed, measuring error due to parallel line coupling

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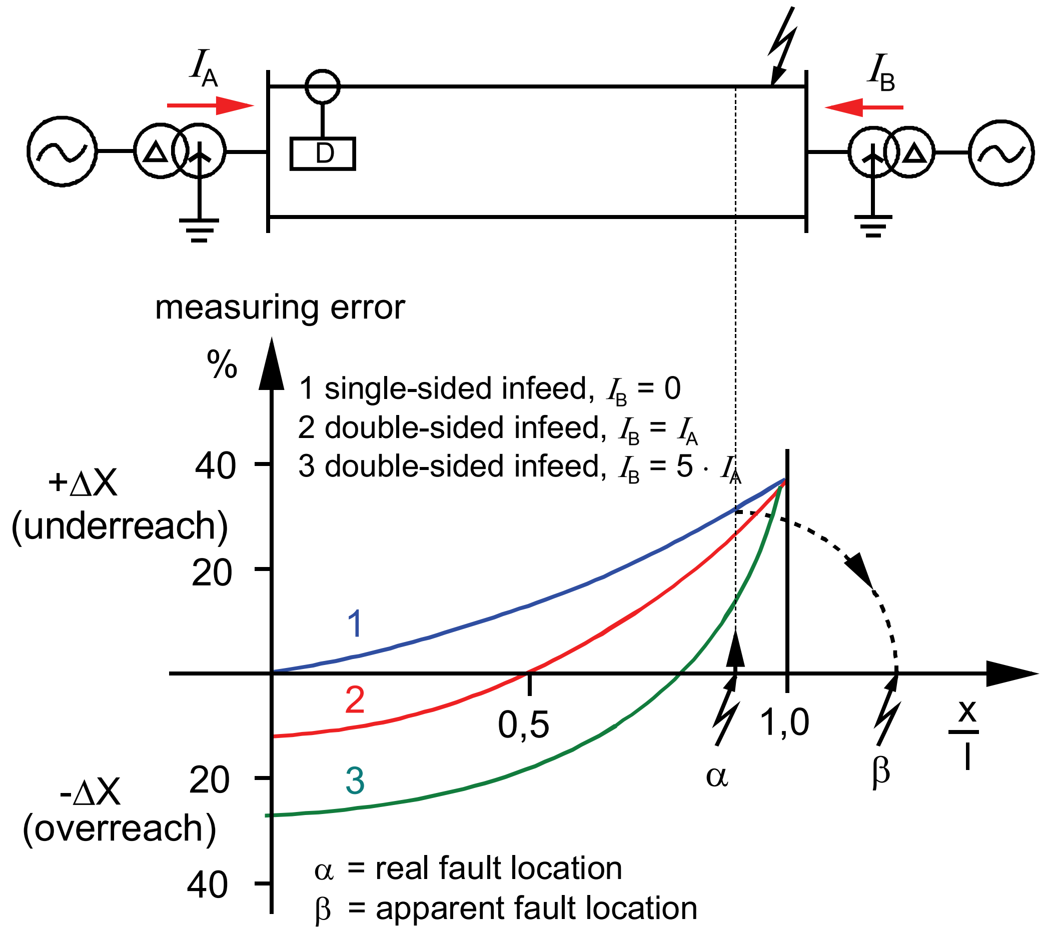
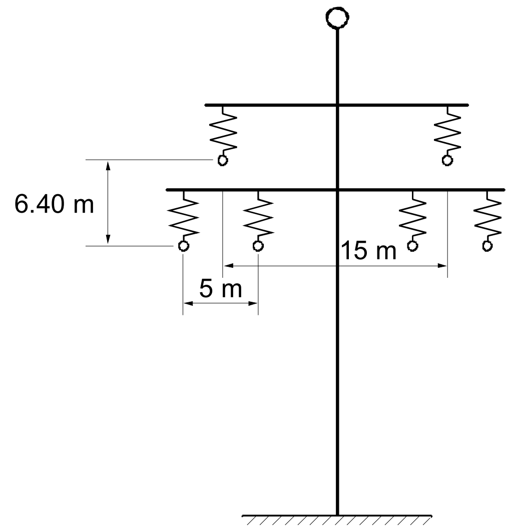


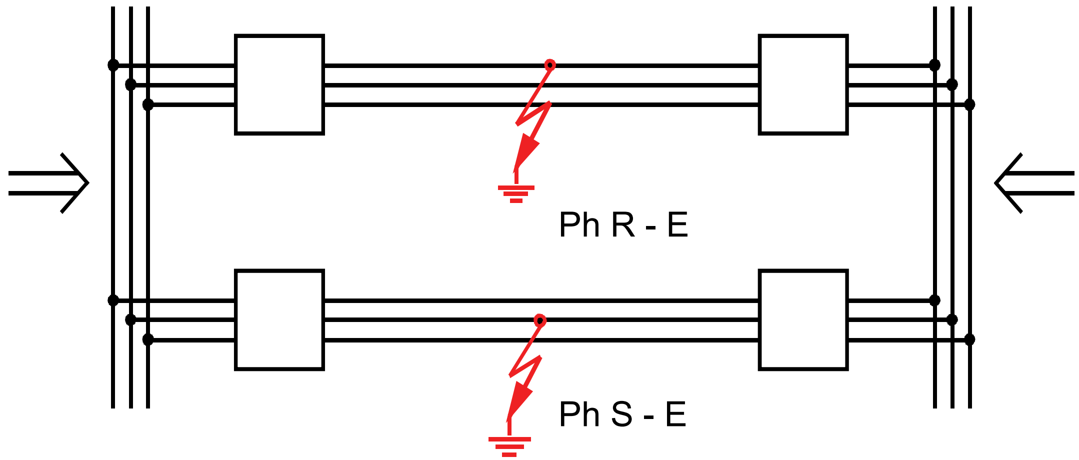


phase conductors: St Al 340/110 mm²
earth-wire: St 70 mm²

$$\frac{Z_E}{Z_L} = 0,84$$

$$\frac{Z_{0M}}{3 \cdot Z_L} = 0,68$$

Protection in case of cross country faults



Selective fault clearance in combination with single-pole auto-reclosure requires phase segregated protection:

- Differential **- Phase comparison**	**per phase**
- distance relaying using communication	**Directional comparison per phase or permissive intertripping per phase phase**

Double-circuit line, distance protection using zone extension with single-phase faults only and single-pole ARC (1)

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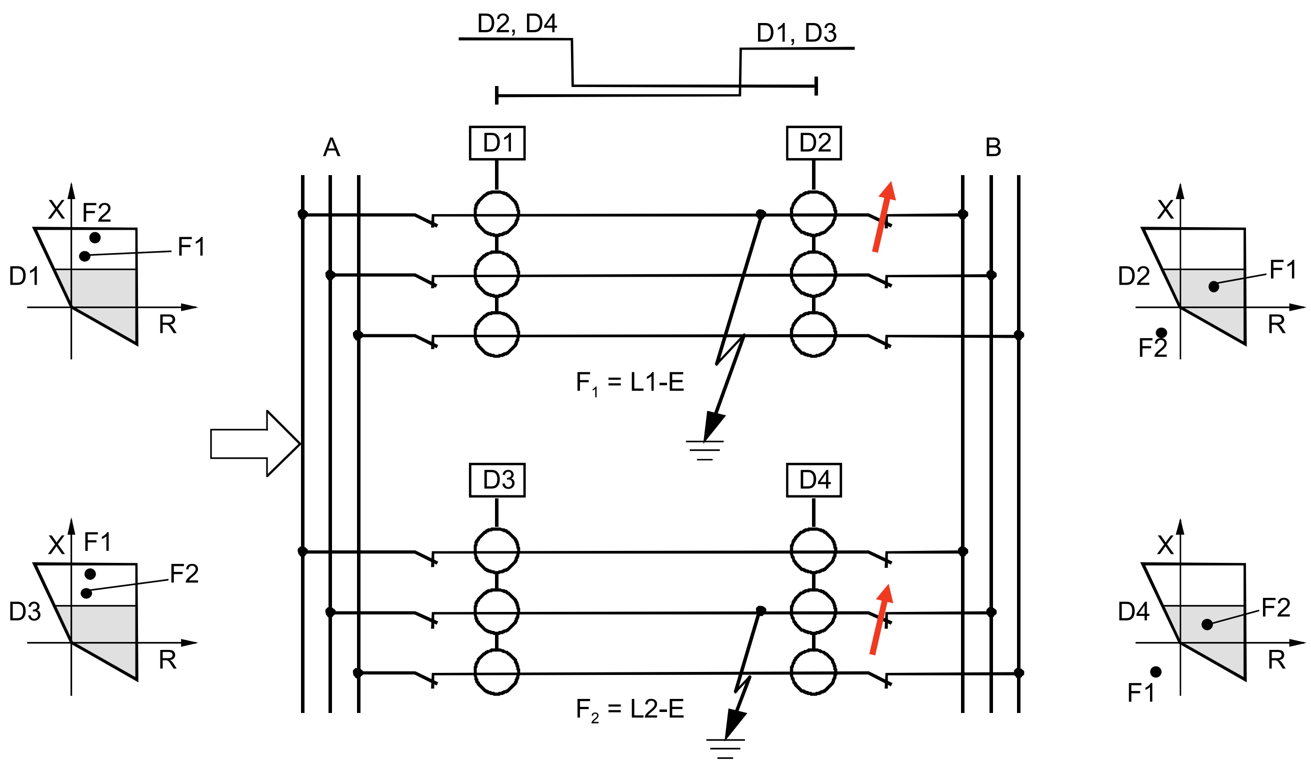
At fault inception: Multiple-phase fault detection, underreaching zones active
D2 und D4 detect single phase faults and trip single-phase each at their side.



Double-circuit line, distance protection using zone extension with single-phase faults only and single-pole ARC (2)

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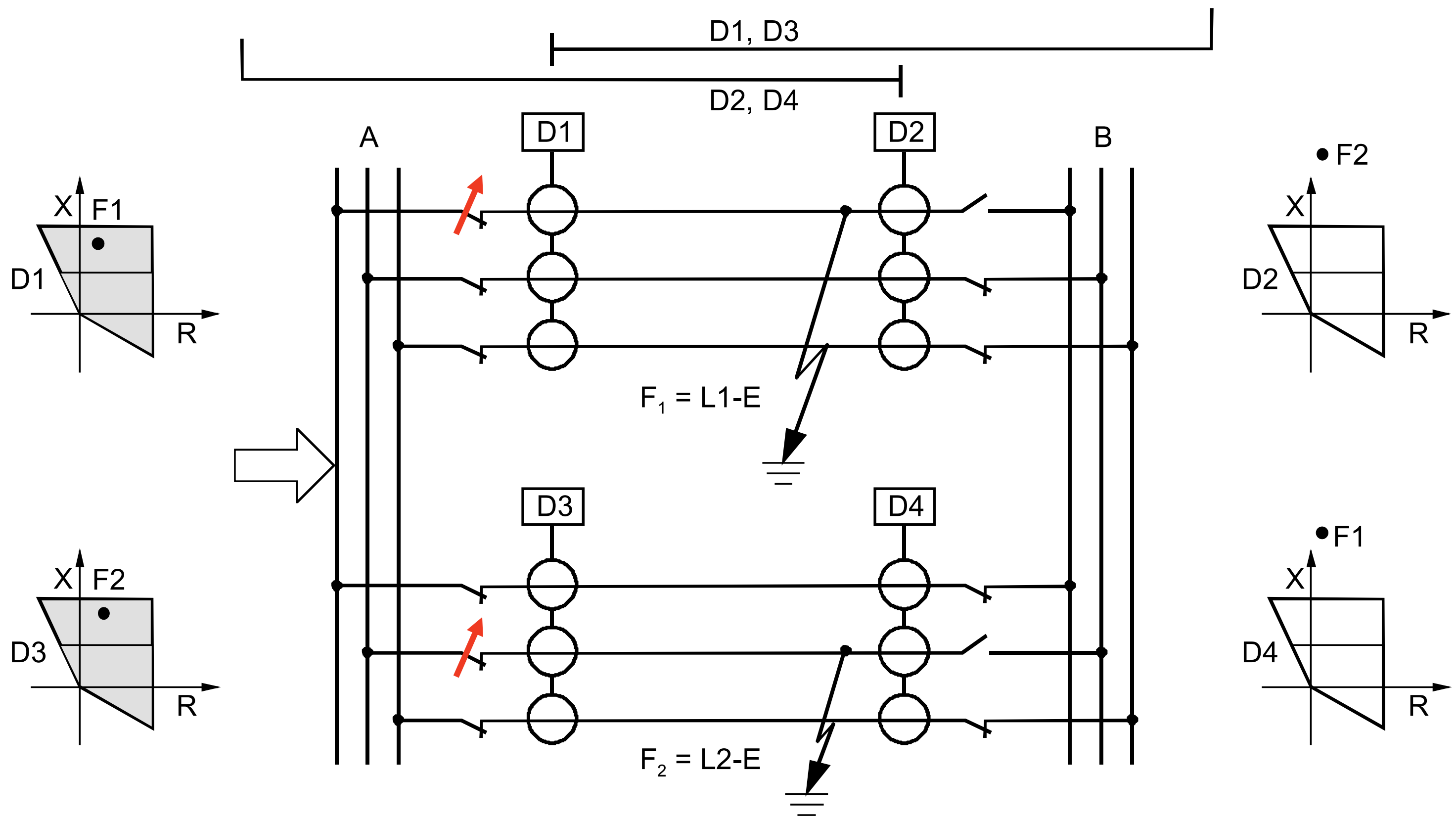
After single-pole tripping in B: Relays D1 und D3 in A change to single phase fault detection, extend zones to overreach and also trip single phase (cascaded tripping).



Double-circuit line, distance protection using zone extension with single-phase faults only and single-pole ARC (3)

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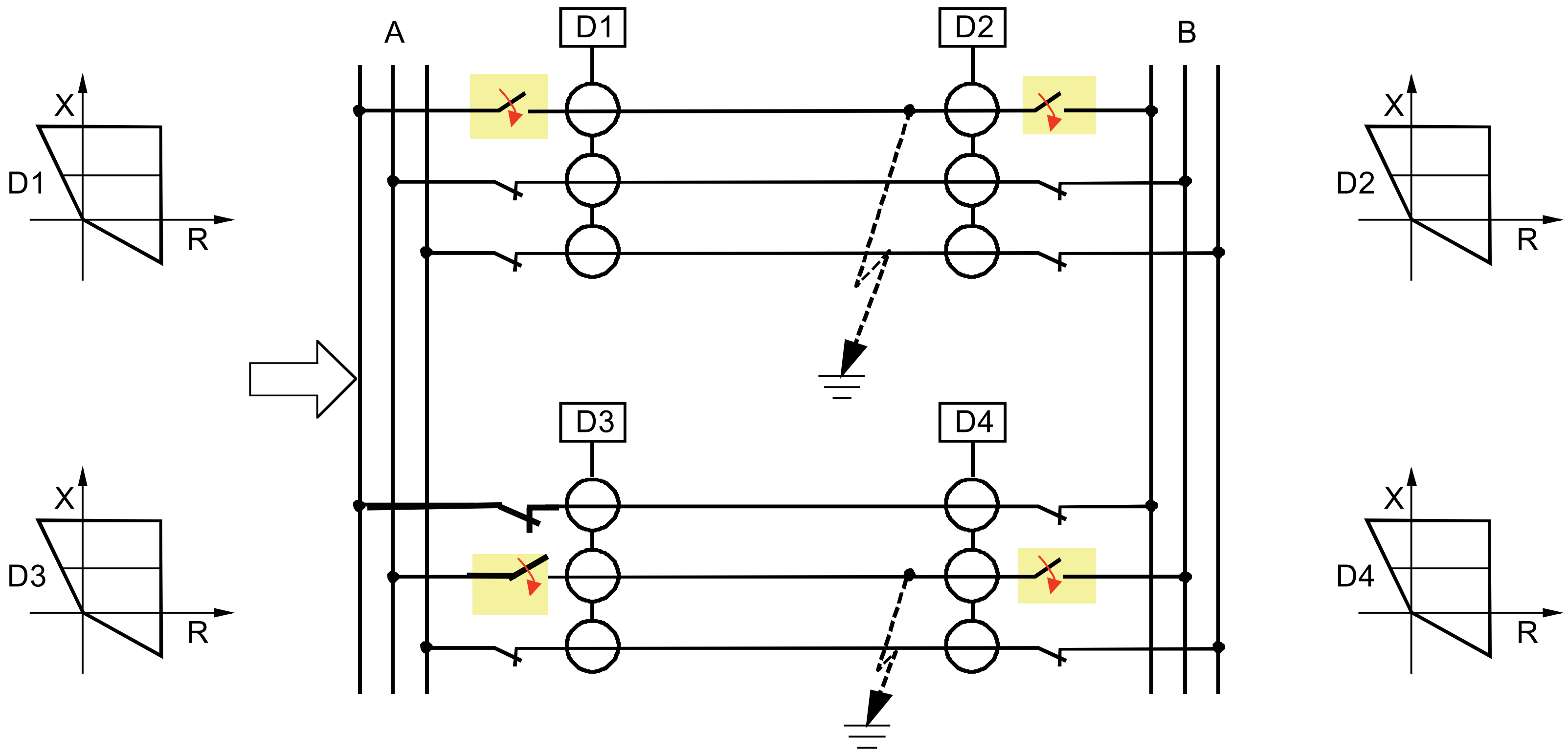
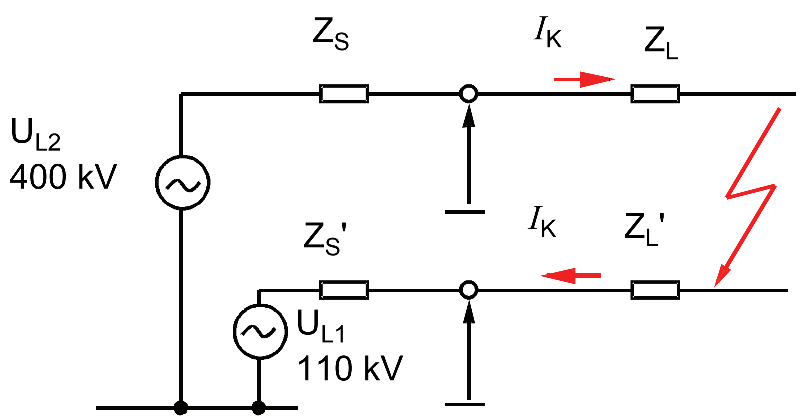
Fault now selectively cleared, one complete three-phase system remains in service
Auto-reclosure at all 4 line ends and full system recovery after single-pole dead time.

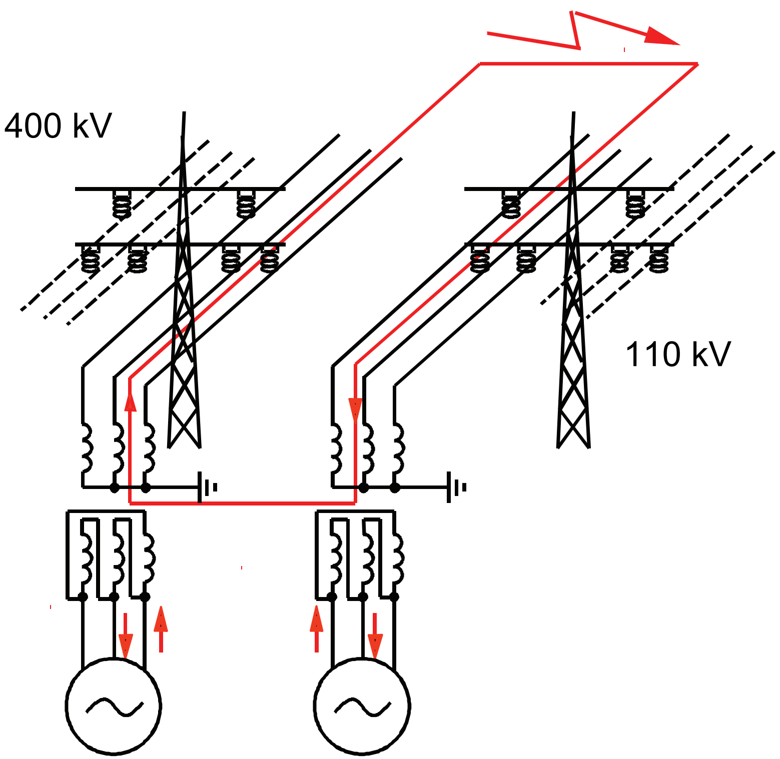


Inter-circuit faults, z.B. 400/110kV



equivalent circuit (principle)

$$Z_L + Z_L' = \frac{U_{L2\ 400\ kV} - U_{L1\ 110\ kV}}{I_K}$$



Power swing

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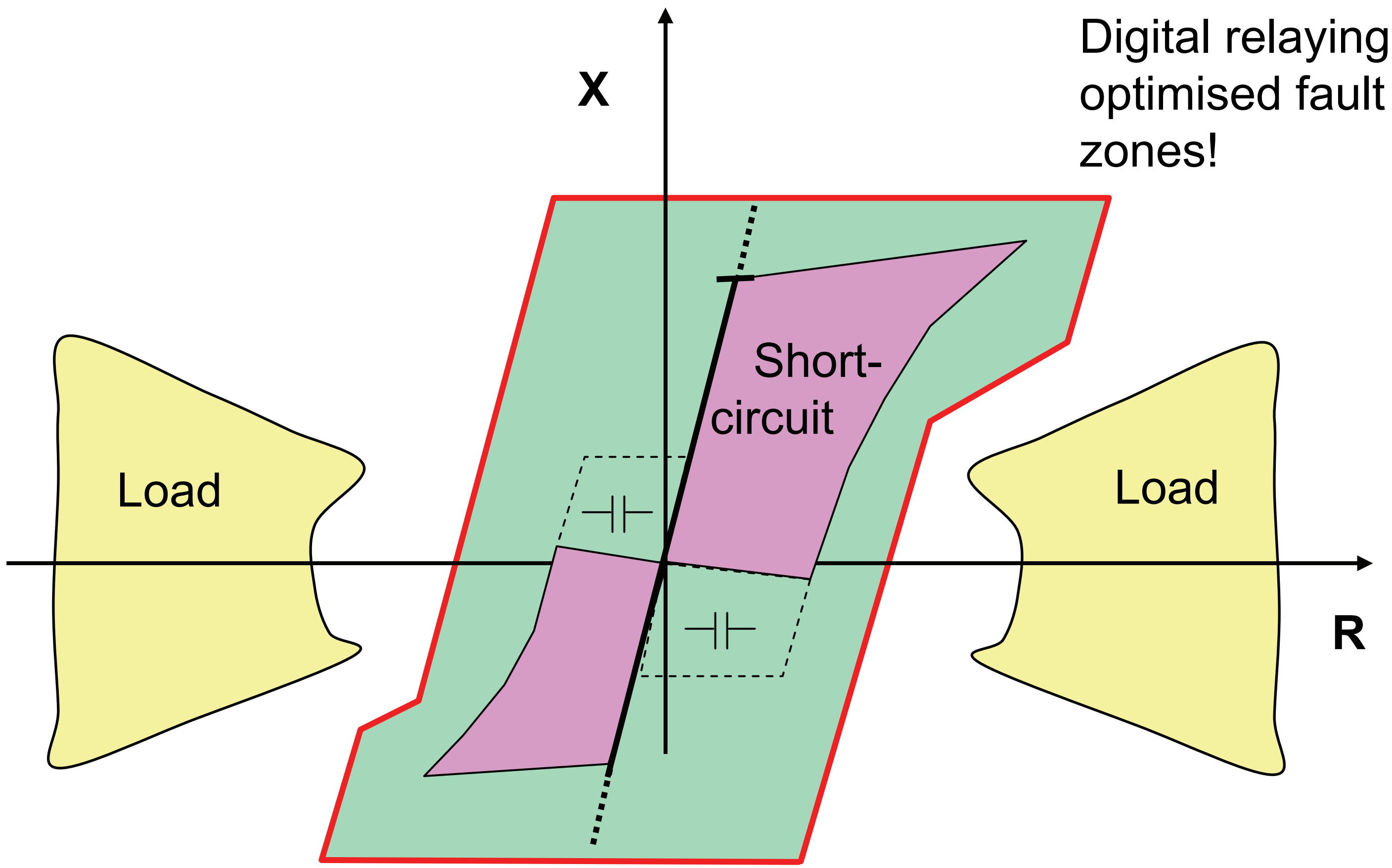
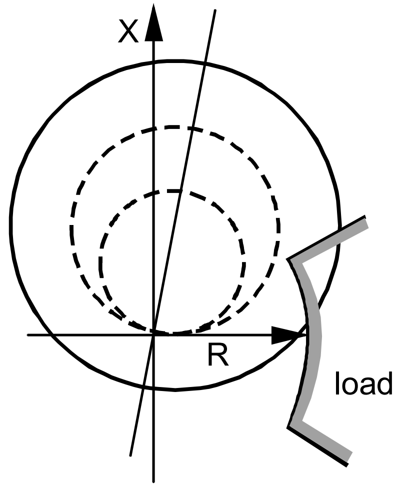
Fault versus load discrimination

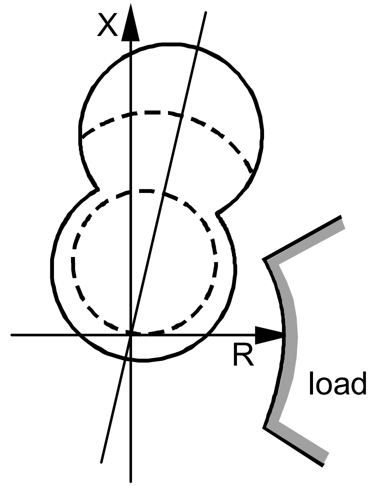
Digital relaying allows optimised fault detection zones!



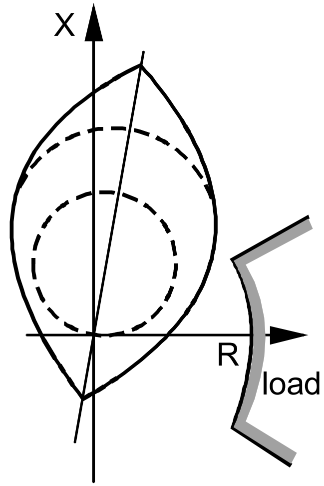
Traditional shape of fault detector zones



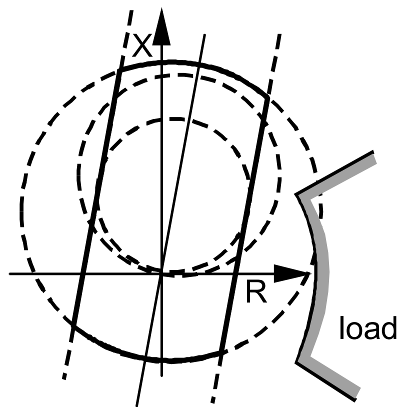
offset MHO-circle



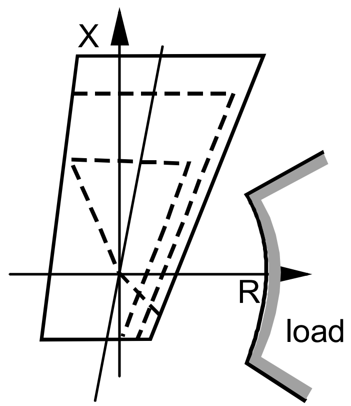
eight ("Peanut")



lense



offset MHO-circle with blinders



quadrilateral

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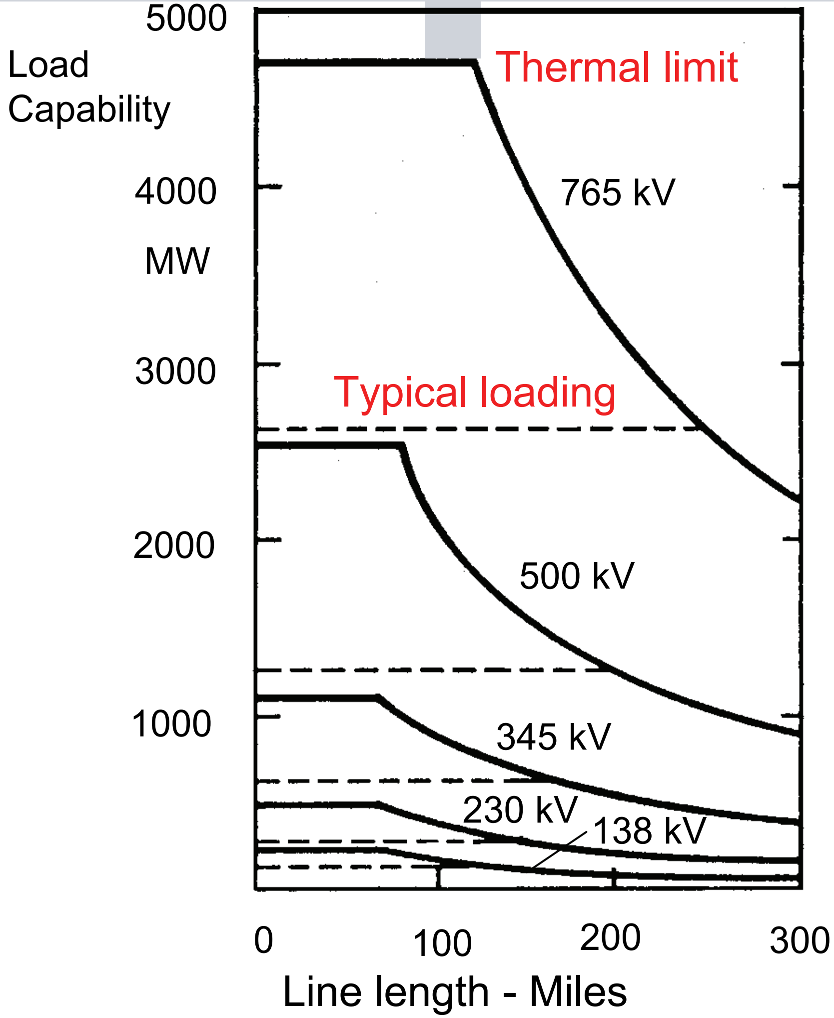
Transmission line load capabilitiy



Typical Line Capabilities (about natural load):

Voltage	Load Capability	Load Impedance
138 kV	100 MW	190 Ohm
230 kV	250 MW	212 Ohm
345 kV	600 MW	198 Ohm
500 kV	1200 MW	208 Ohm
765 kV	2500 MW	234 Ohm

Digital operating charateristics with load blocking area (selectable with relays 7SA522 and 7SA6)

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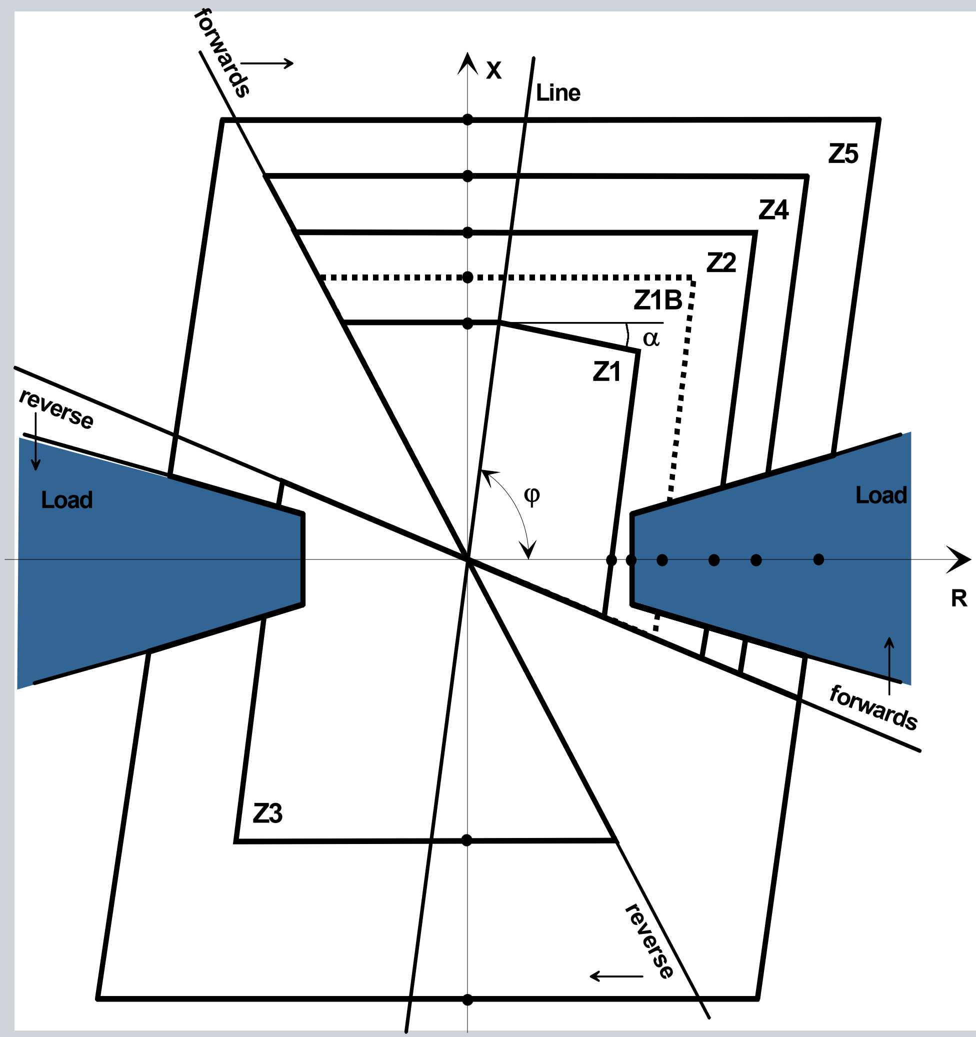

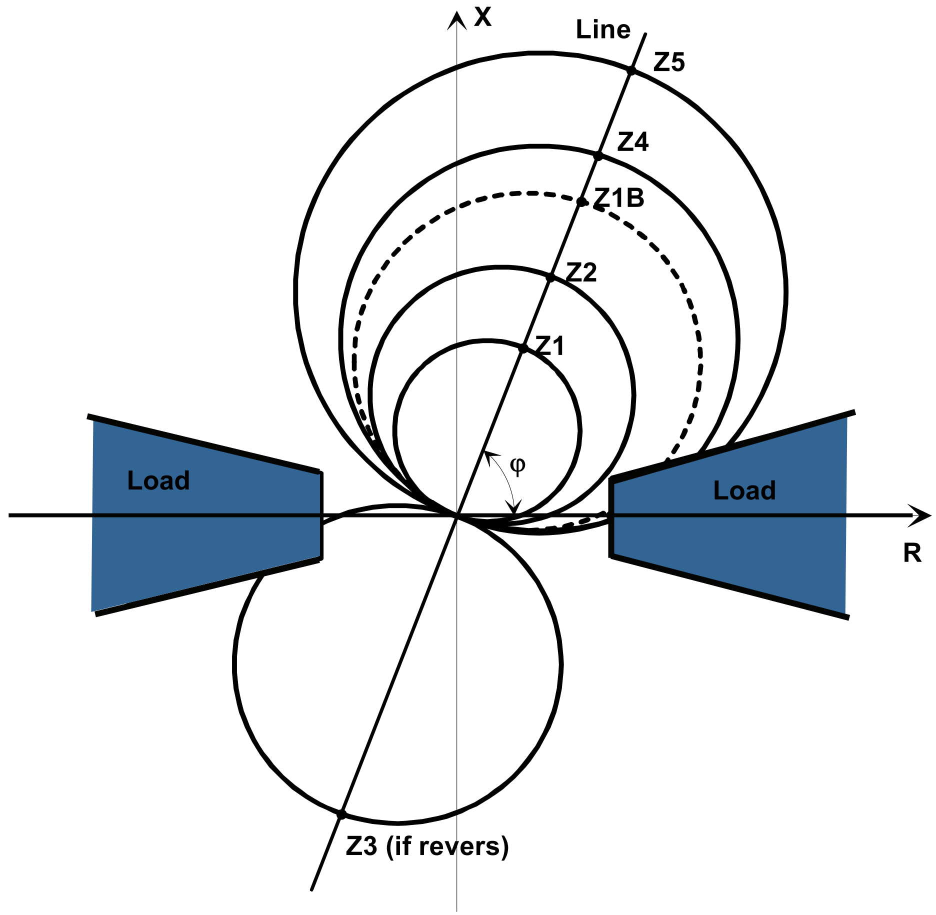

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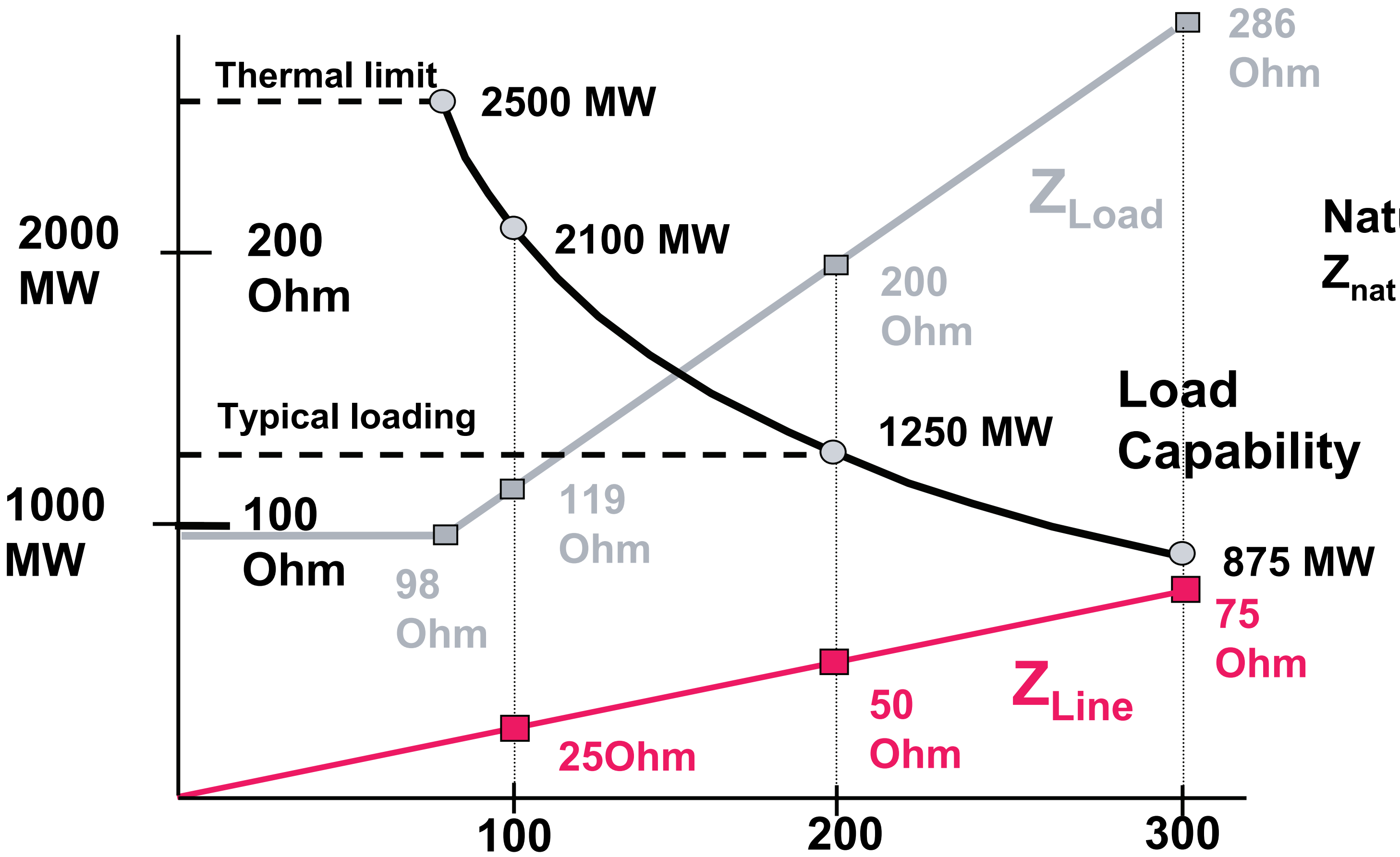
Transmission lines, Load and fault data



Natural Load:
Z_{nat} ca. 1000 MW

Load Capability

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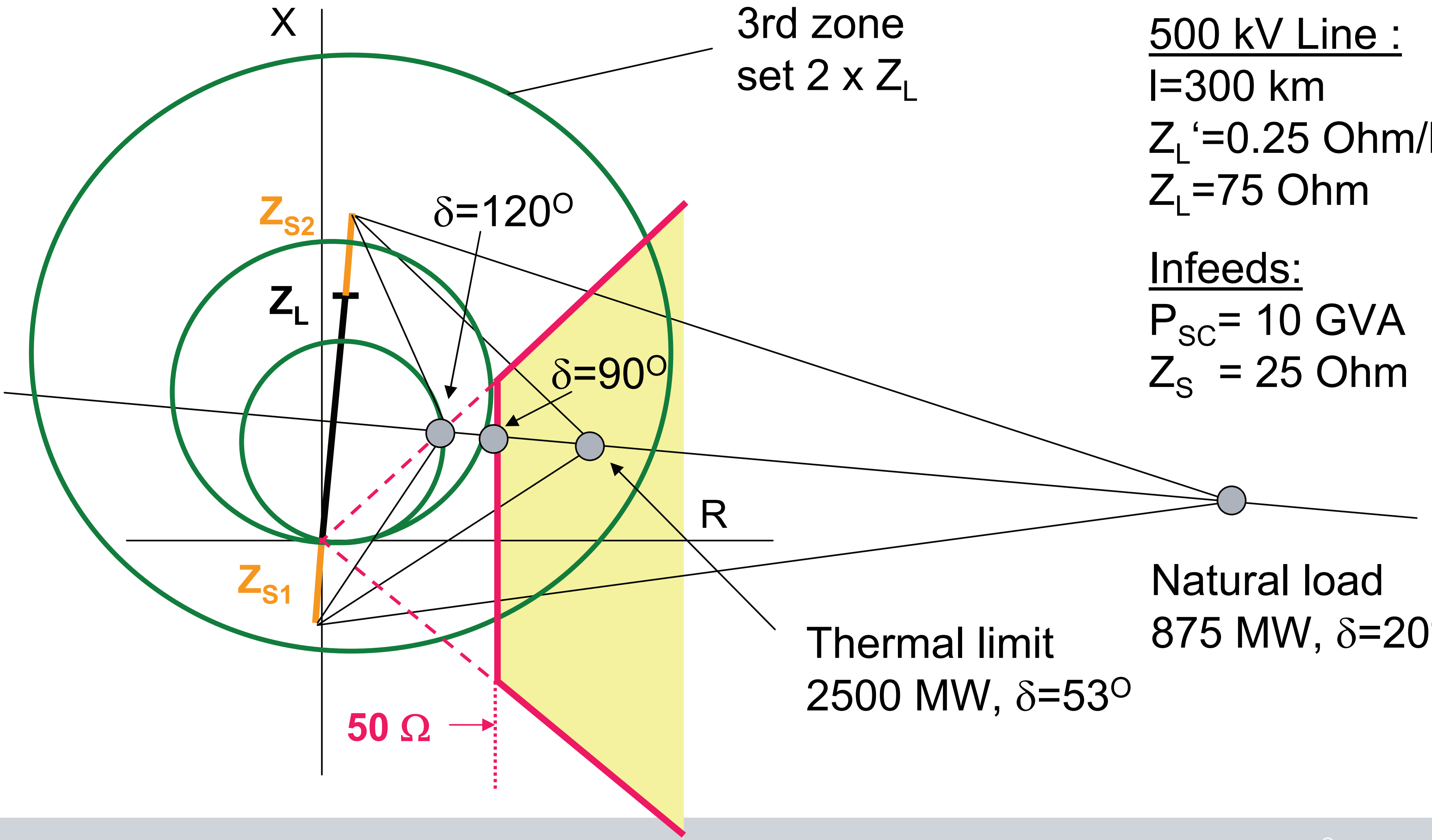
Setting of load blocking area



500 kV Line :

l=300 km

Z_L'=0.25 Ohm/km

Z_L=75 Ohm

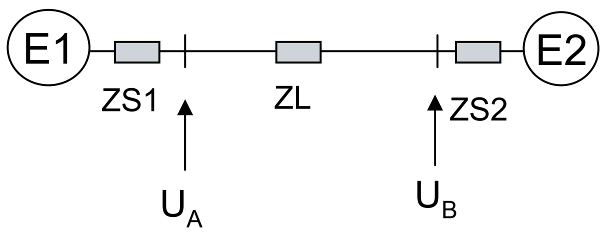
Infeeds:

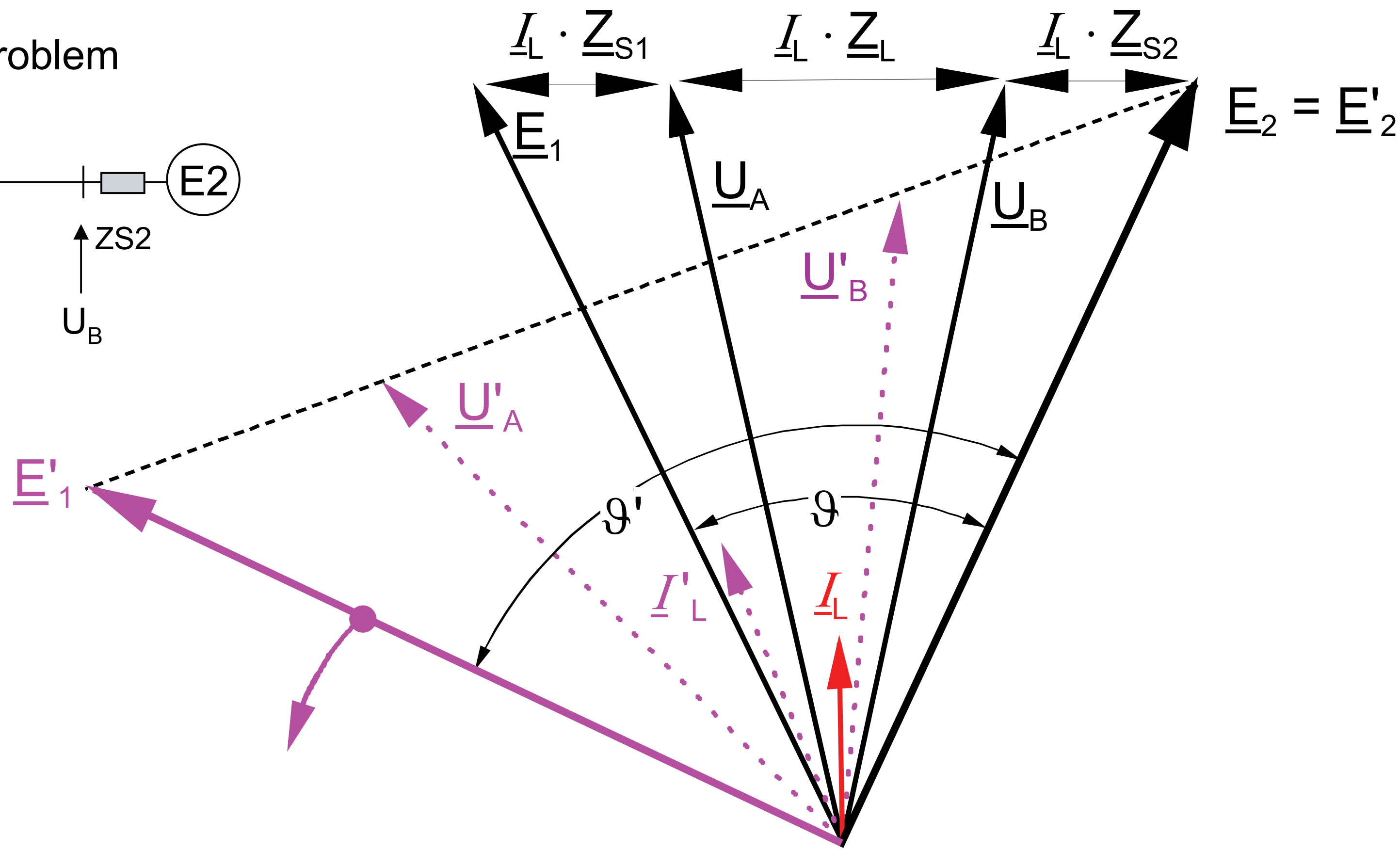
P_{SC}= 10 GVA

Z_S = 25 Ohm

Power swing: Voltage diagram

Two Machine Problem





If the angle becomes too large, the system stability can be lost

Power swing locus and relay characteristic in the impedance diagram

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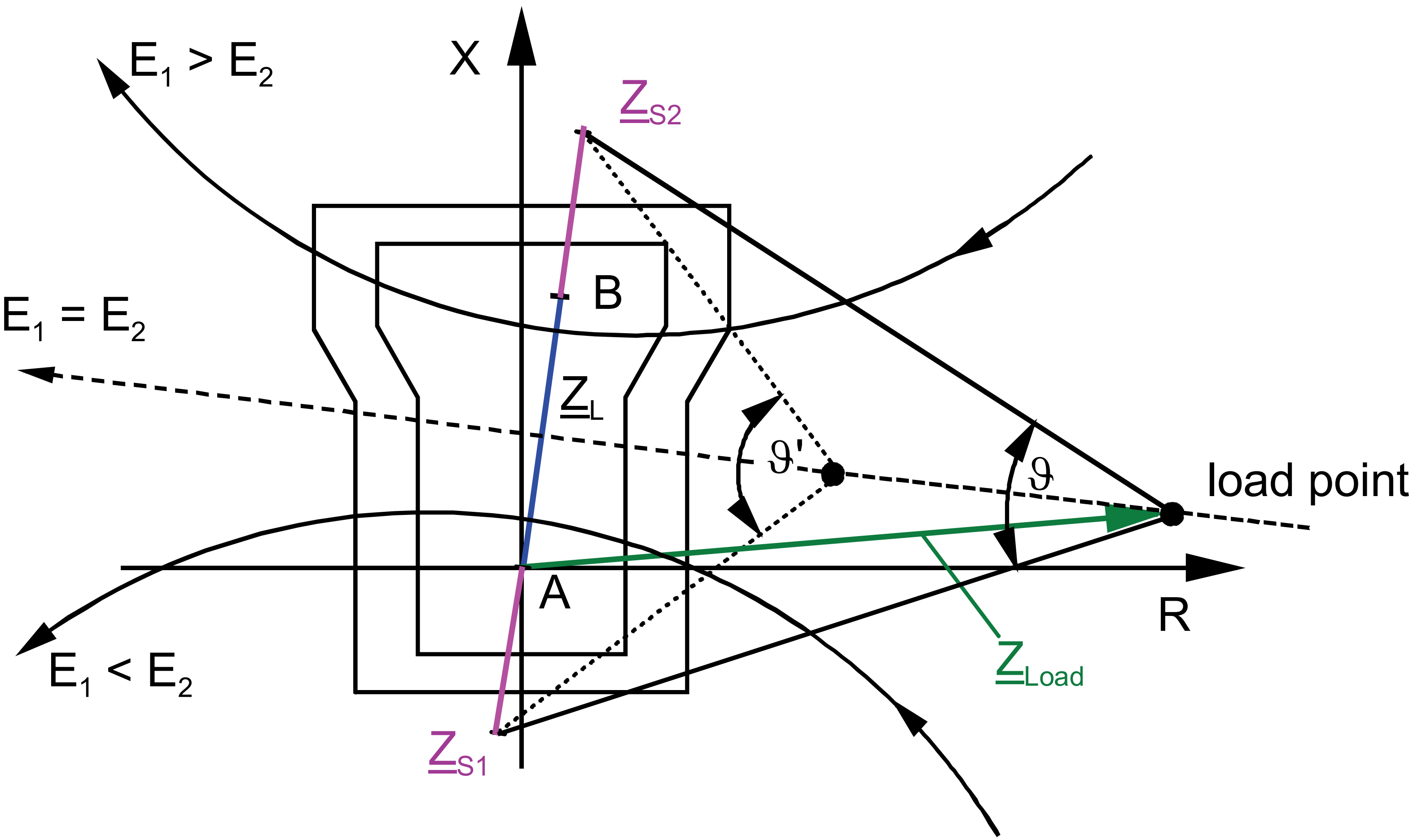
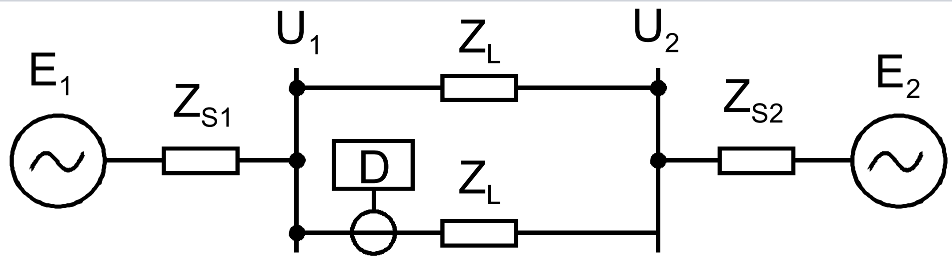
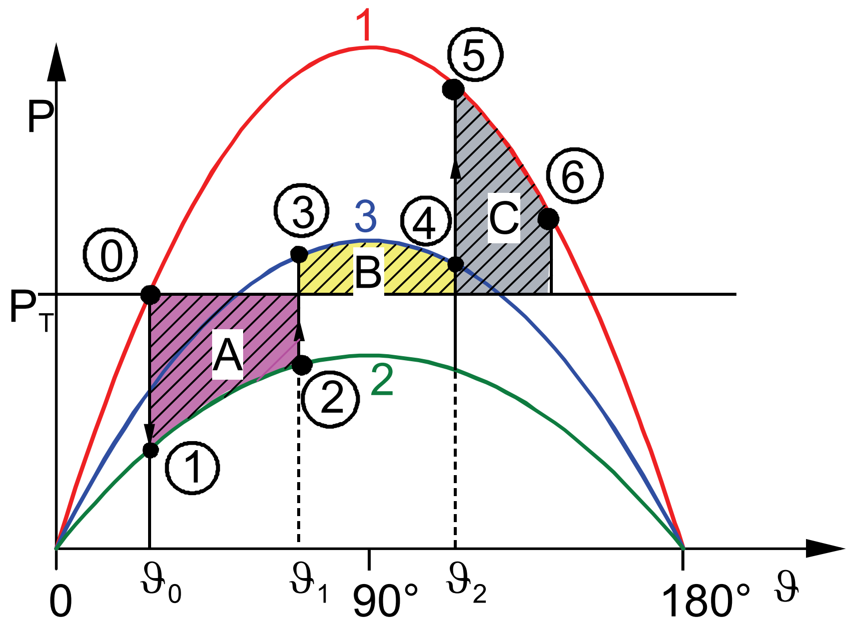
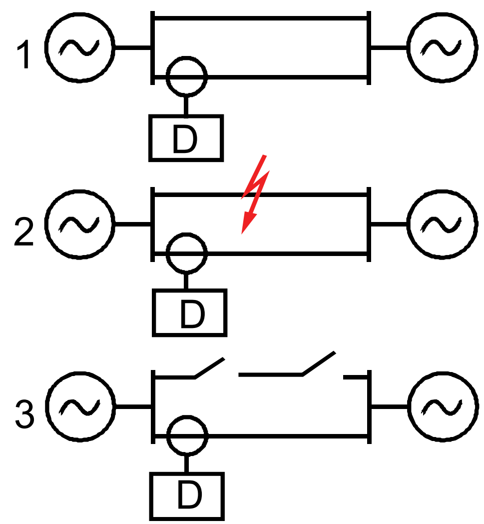


Dynamic system stability, equal area criterion



$$P_{TP} = \frac{E_1 \cdot E_2}{X_T} \cdot \sin \vartheta$$





Power swing locus in the impedance plane

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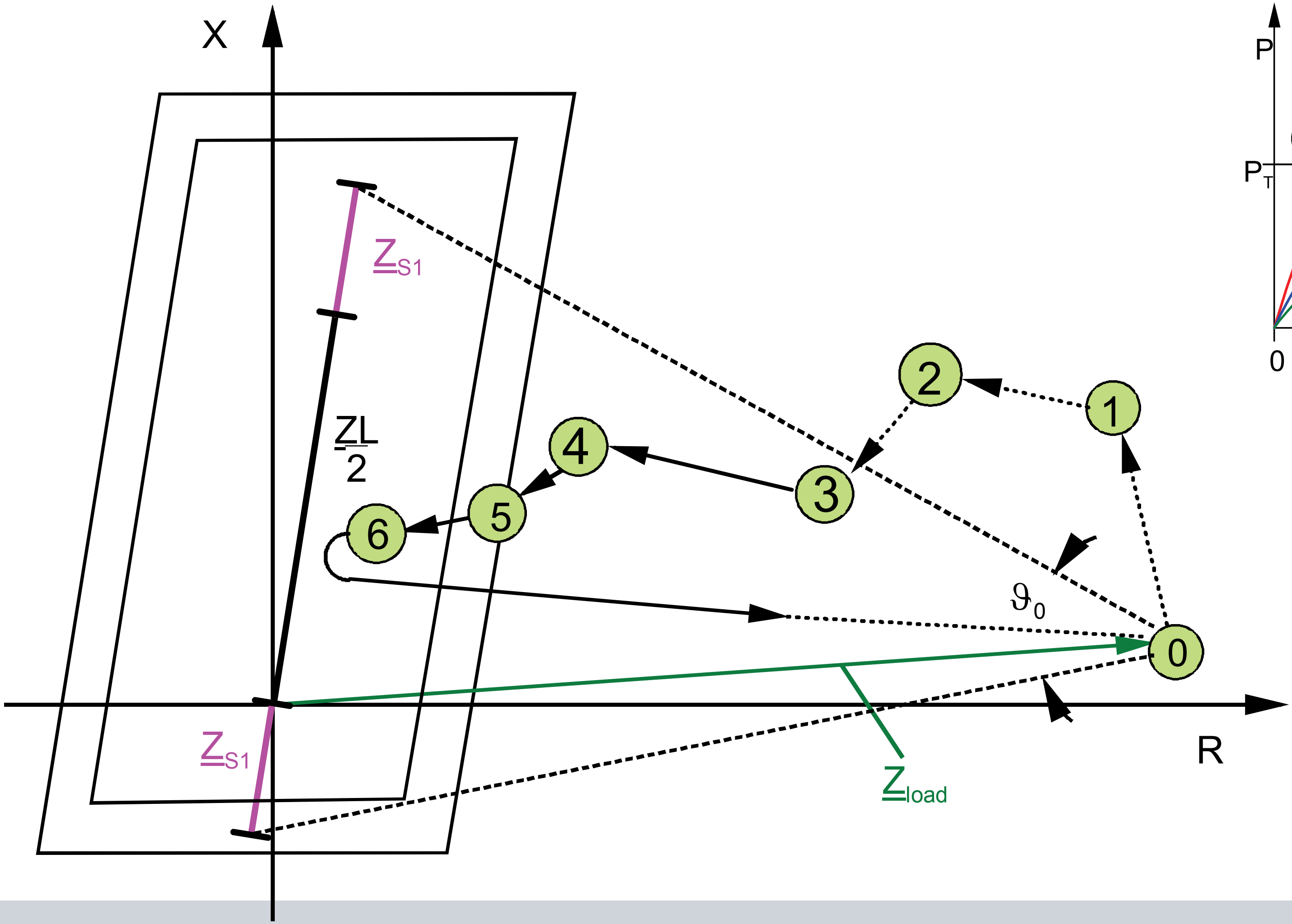

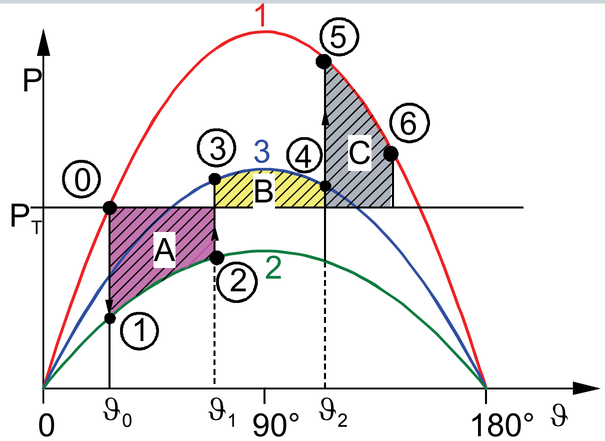

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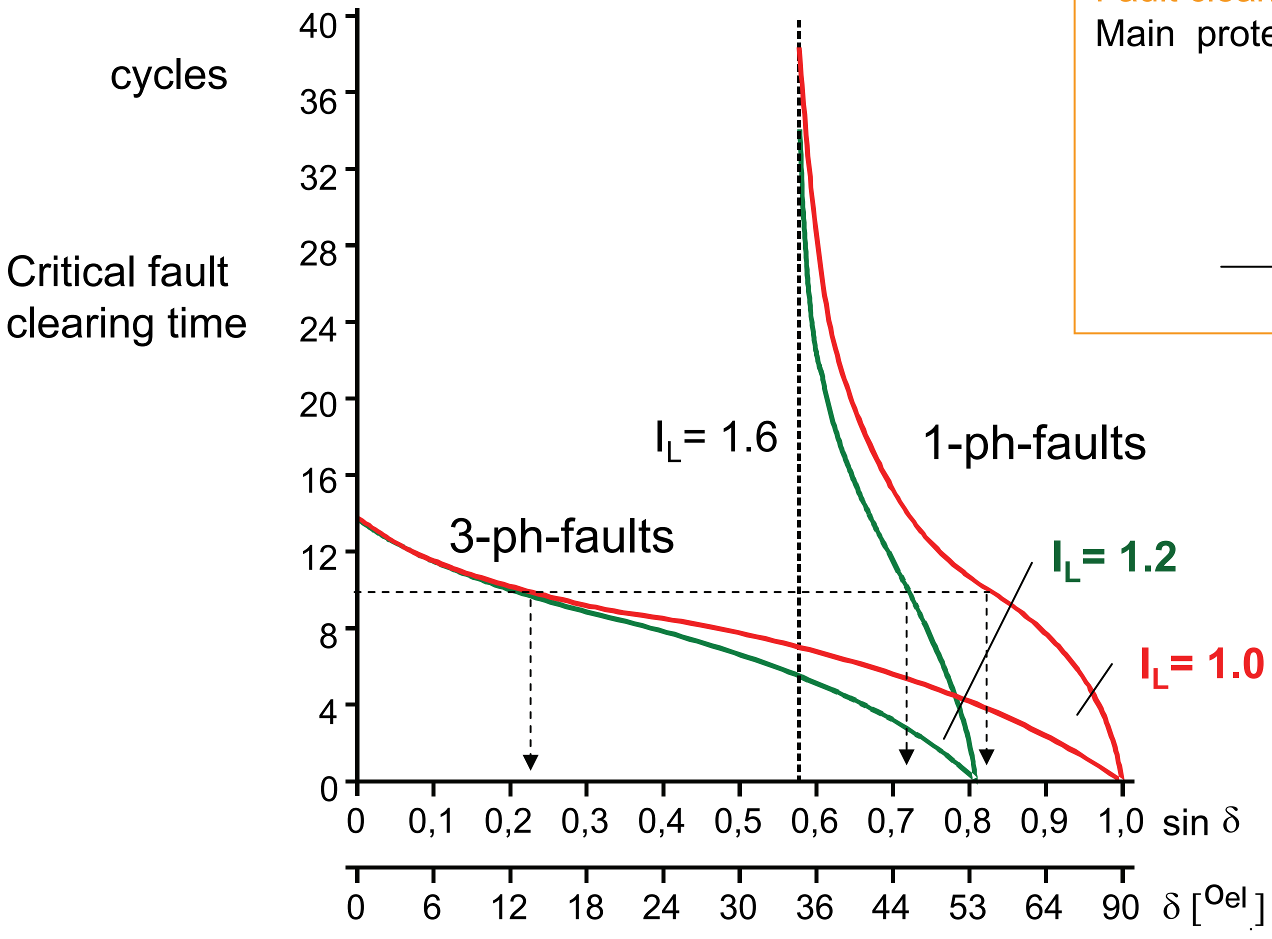
Critical fault clearing time



Fault clearing times:

Main protection (85% of line):		1 cycle
	CB:	2 cycles
	BF:	4 cycles
	CB:	2 cycles
	Total:	9 cycles

Independent tripping of CB poles required!

δ = transmission angle before fault inception

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Requirements on power swing protection

- Must prevent overfunction of distance protection during power swing up to high slip frequencies where necessary, say at least 5 Hz
- Shall maintain function also during single-pole open condition (auto-reclosusure dead time)
- Must trip on all kind of internal faults (also 3-phase) occuring during power swing (release of blocking)
- Should be setting free, without complex setting calculations
- Shall need minimum ΔZ distance, to allow high fault resistance coverage and at high load

Power swing detection: Classic method
(Not used in 7SA52 and 7SA6)

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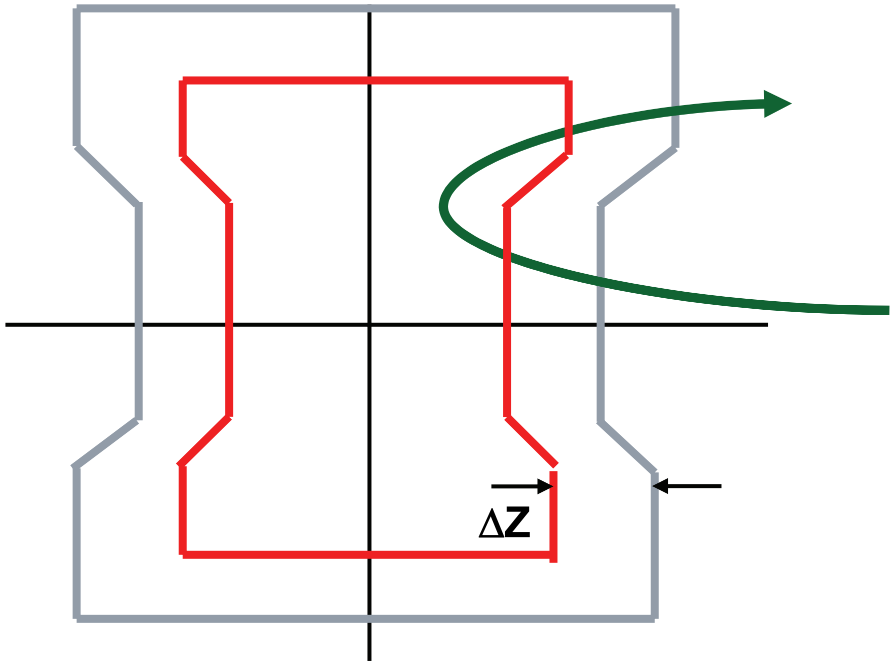


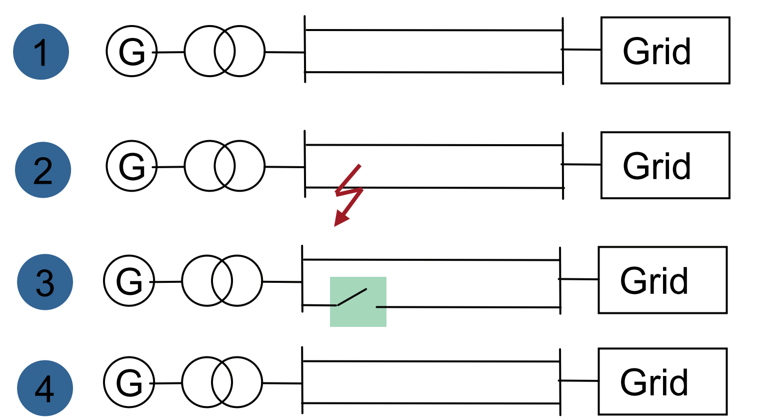
Classic power swing detection is restricted to <u>slow</u> swings

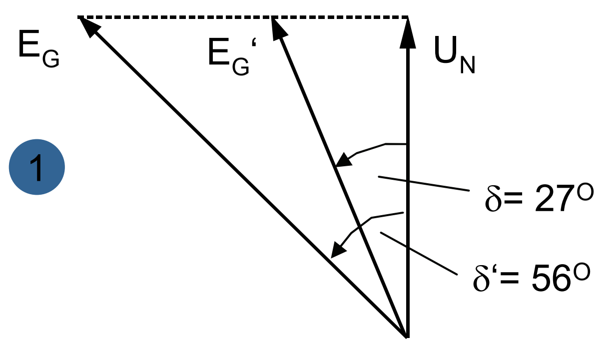
The setting of ΔZ may not be too large to avoid load encroachment (typ. 5 Ω)

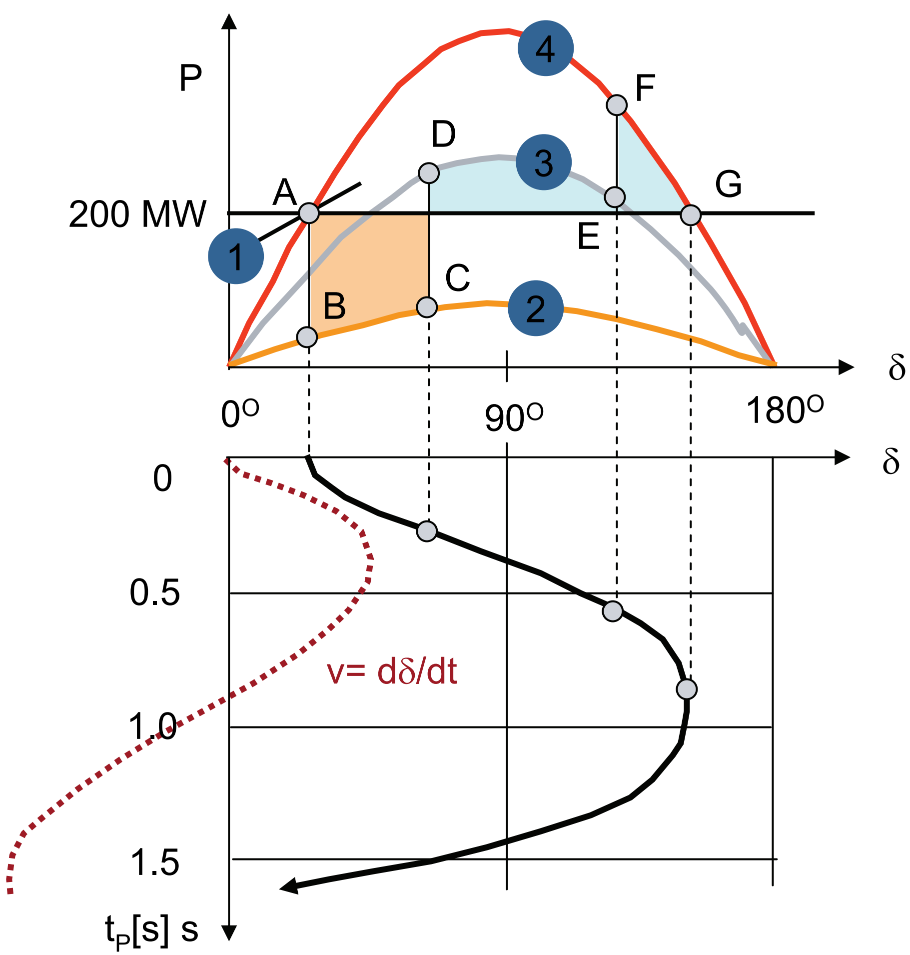
During fast swings the time available (Δt) for detection of impedance vector in the power swing zone is too short.

Δt = time for transition of Z from outer to inner zone

Power swing after 3-ph fault clearing with ARC







Steady-state condition before fault inception

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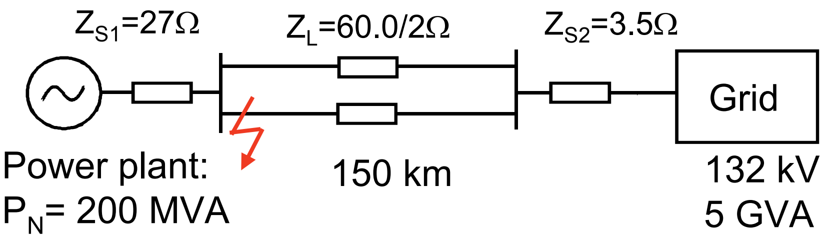
Setting of traditional power swing blocking



Maximum swing frequeny assumed: 2 Hz

Maximun Load angle: δ= 60^{Oel} (emergency case)

Outer blinder set to δ= 70^{Oel} (10^{O} security margin)

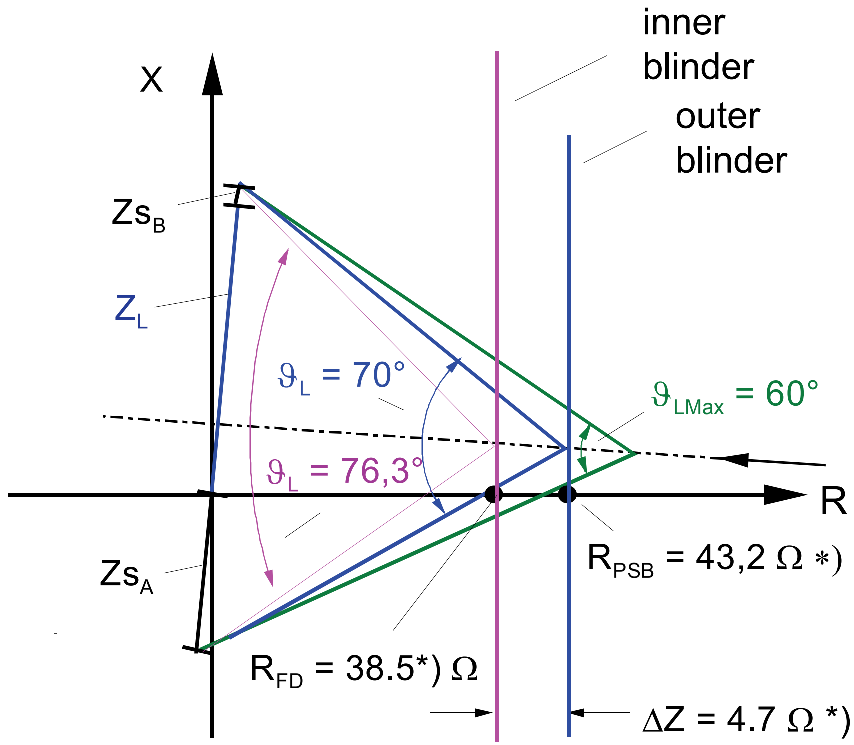
$$R_{PSB} \approx \frac{Z_\Sigma}{2} \cdot \cot\left(\frac{\delta}{2}\right) = \frac{60.5}{2} \cot\left(\frac{70}{2}\right) = 43.2\ \Omega\text{prim.}$$

$$\frac{dR_{PSB}}{dt} \approx \frac{\pi}{2} \cdot Z_\Sigma \cdot f_P \cdot tg\left(\frac{\vartheta}{2}\right)$$

$$= \frac{\pi}{2} \cdot 60.5\Omega \cdot 2.0 \frac{1}{s} \cdot \tan\left(\frac{70}{2}\right) = 133 \left[\frac{\Omega\ \text{prim.}}{s}\right]$$

Relay requirement for PSB detection: ΔT≥ 35 ms

$$\Delta Z \ge 0.035 \cdot \frac{dR}{dt} = 0.035 \cdot 133 = 4.7\ \Omega\text{prim.}$$



*) primary

Advanced Power swing blocking techniques (7SA522, 7SA6..)

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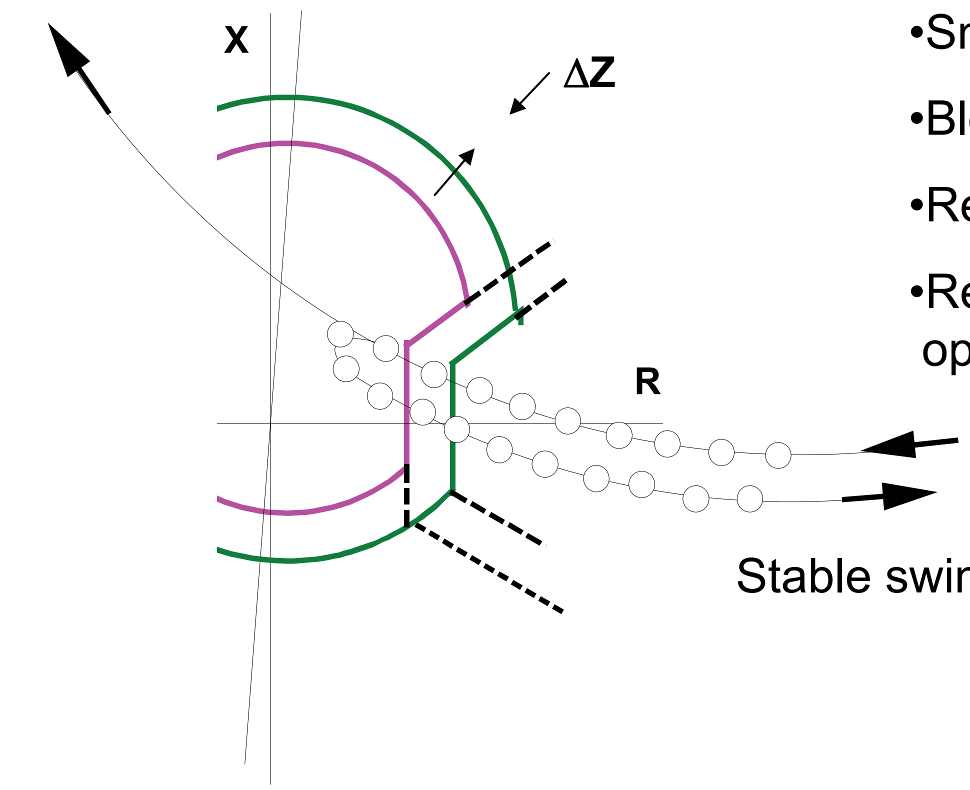

- Novel space vector based principle
- Self-setting
- Small ΔZ (5 Ohm at In= 1 A) , fixed setting
- Blocking up to high slip frequencies (7 Hz)
- Recognition of <u>all</u> fault types during swing
- Remains effective during single pole ARC open time (3-phase set-up)

- dZ/dt measurement
- Calculation of swing centre and plausibility check ($+90^{O} < \delta < -90^{O}$)

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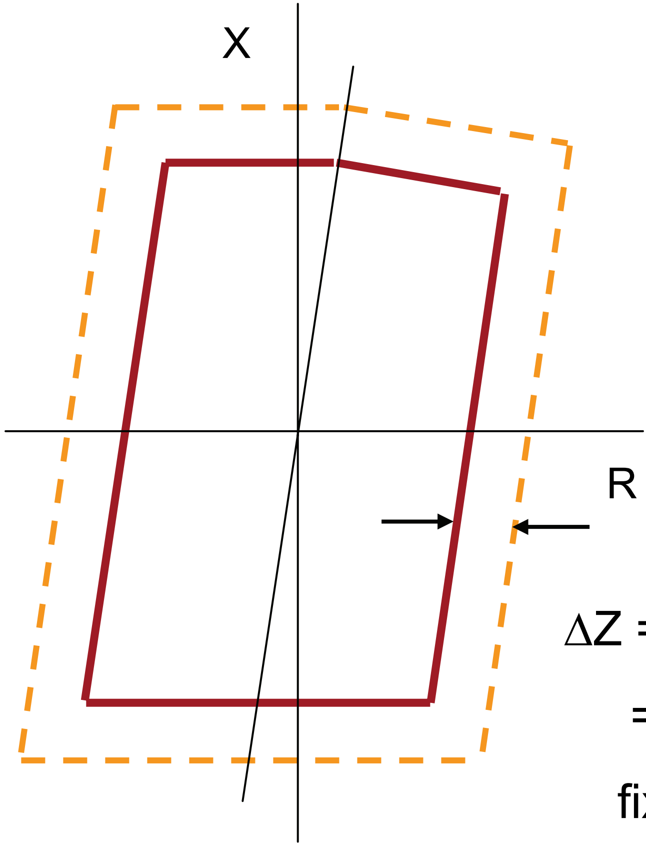
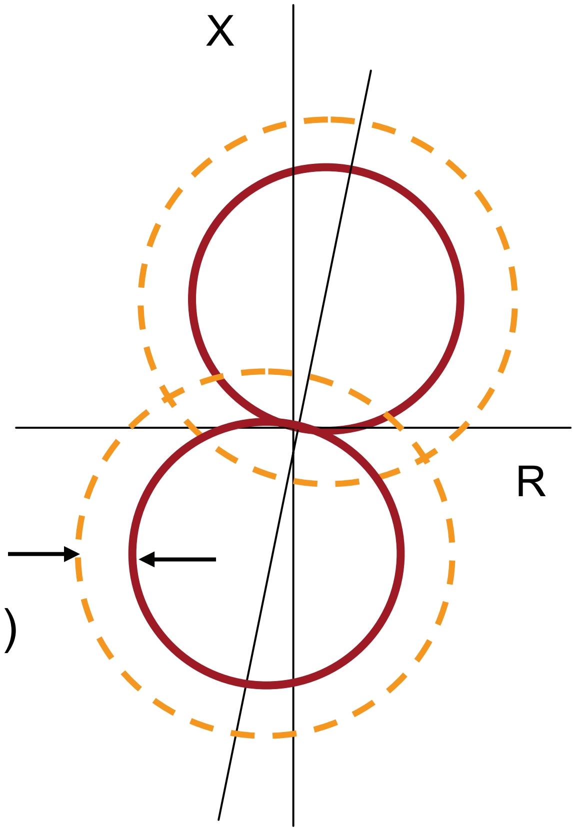
Self-adaptation of outer power swing characteristic



$\Delta Z = 5\ \Omega\ (1\ A)$

$= 1\ \Omega\ (5\ A)$

fixed value



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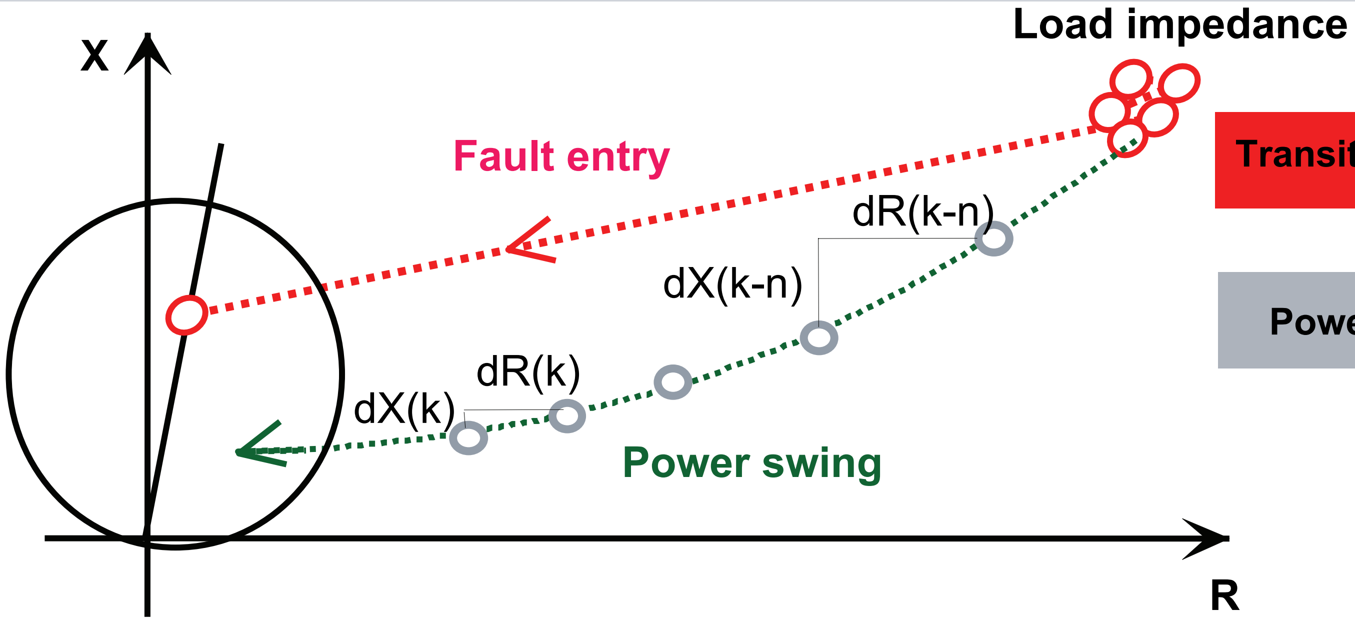
Power Swing detection: New method



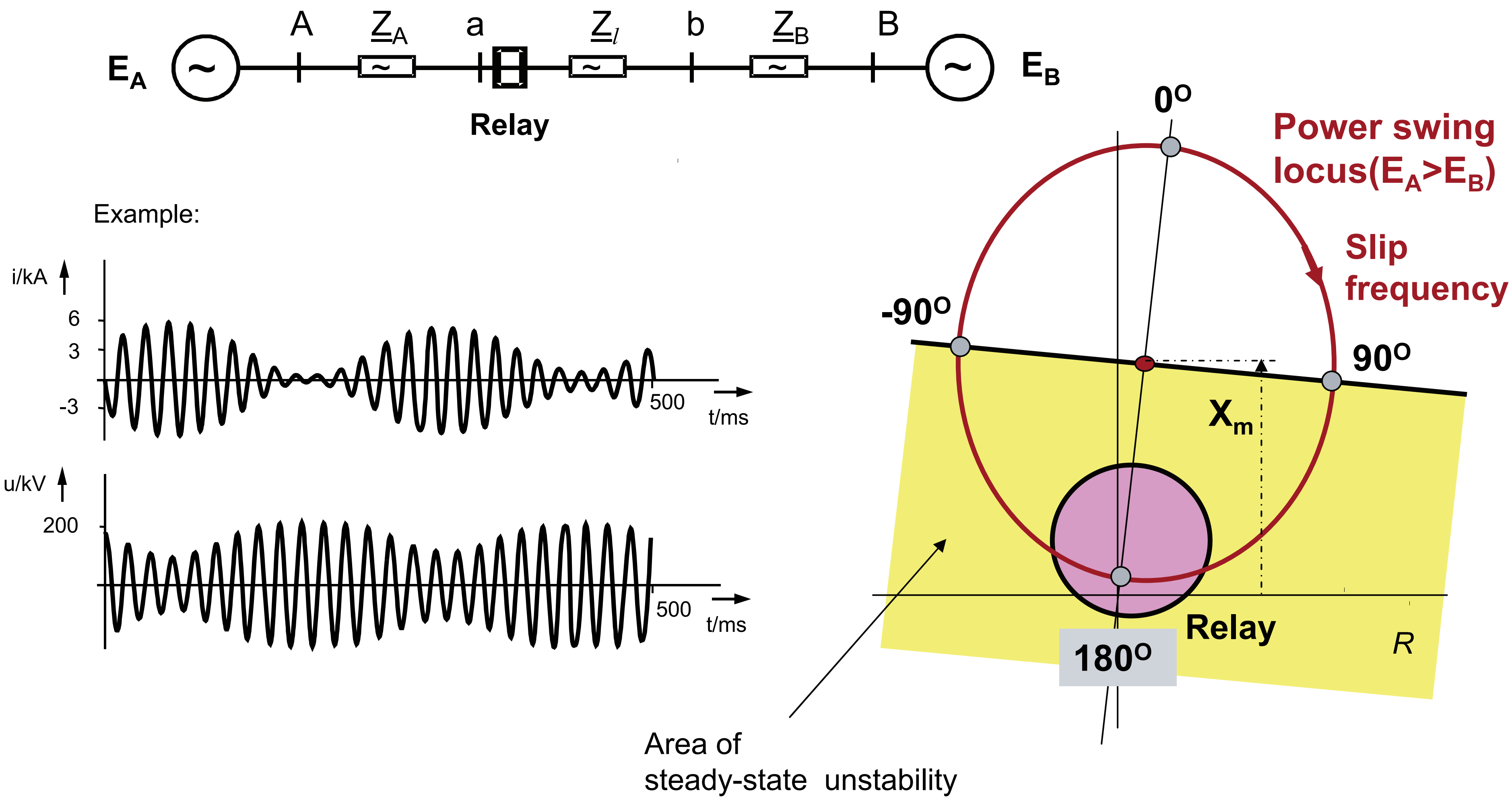
Transition from load to fault is fast

Power swing transition is slow

Continuos monitoring of the impedance trajectory

- Monitoring of trajectory continuity: R(n)-R(n-1) < 300%, Z(n)-Z(n-1) < 15%
- Monitoring of trajectory velocity (> 10 Ω/s)
- Evaluation of trajectory ellipse: unstable area: $-90^{O} < \delta < +90^{O}$)

Evaluation of the power swing process



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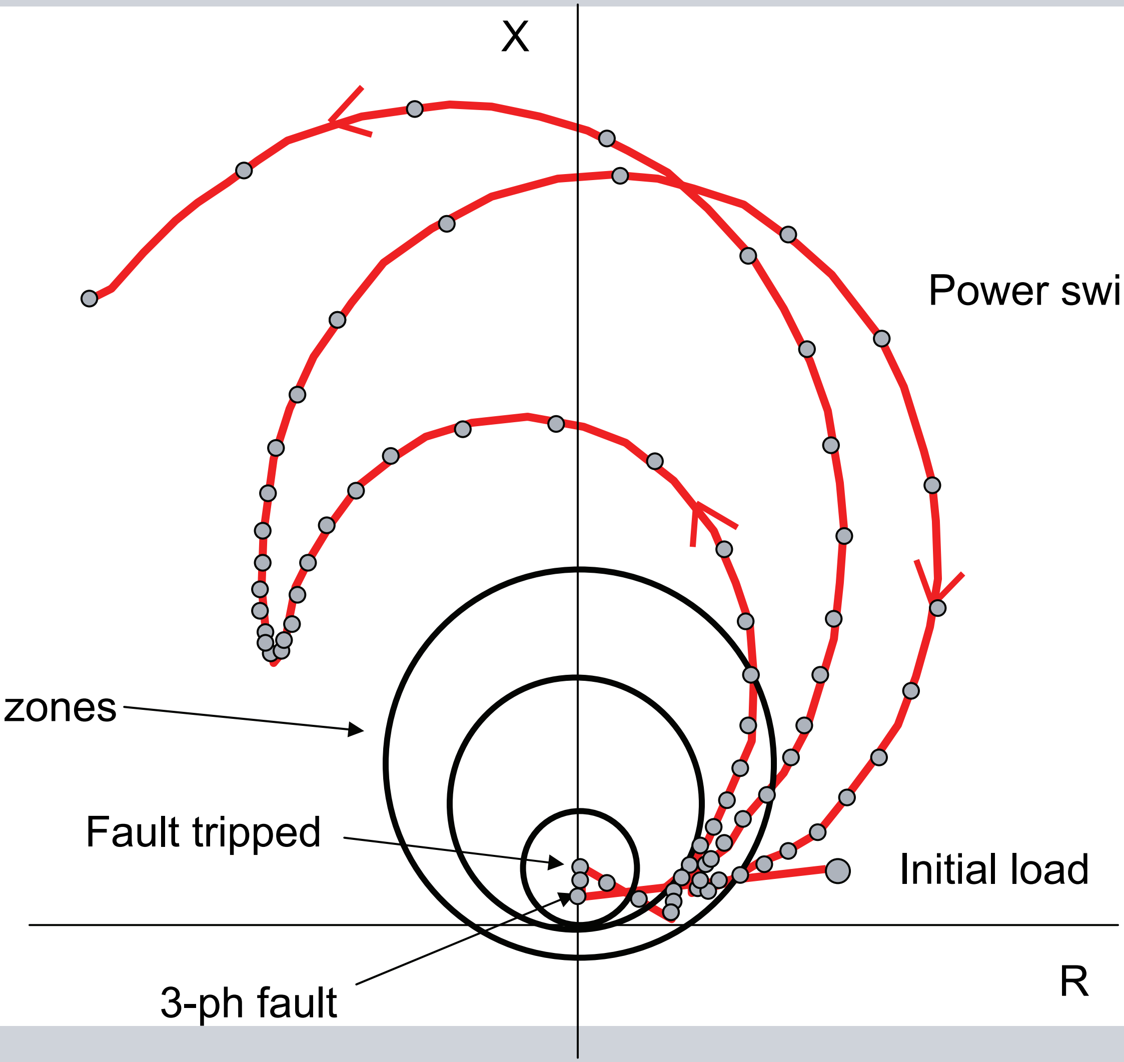
Power swing (simulation)

- Relay Impedances measured at equal time distances



Novel power swing detection provides secure operation with swing frequencies of up to 7 Hz

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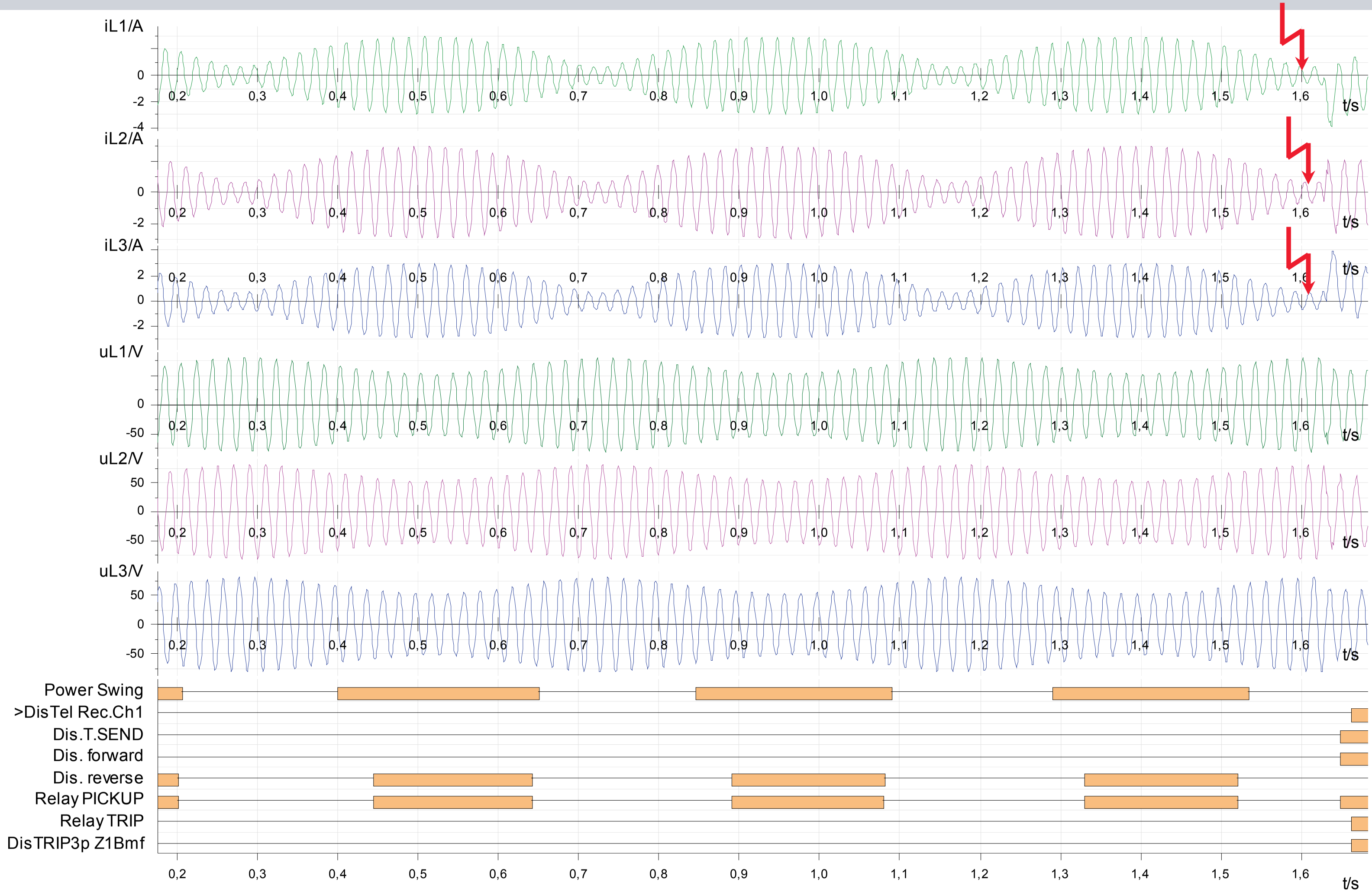
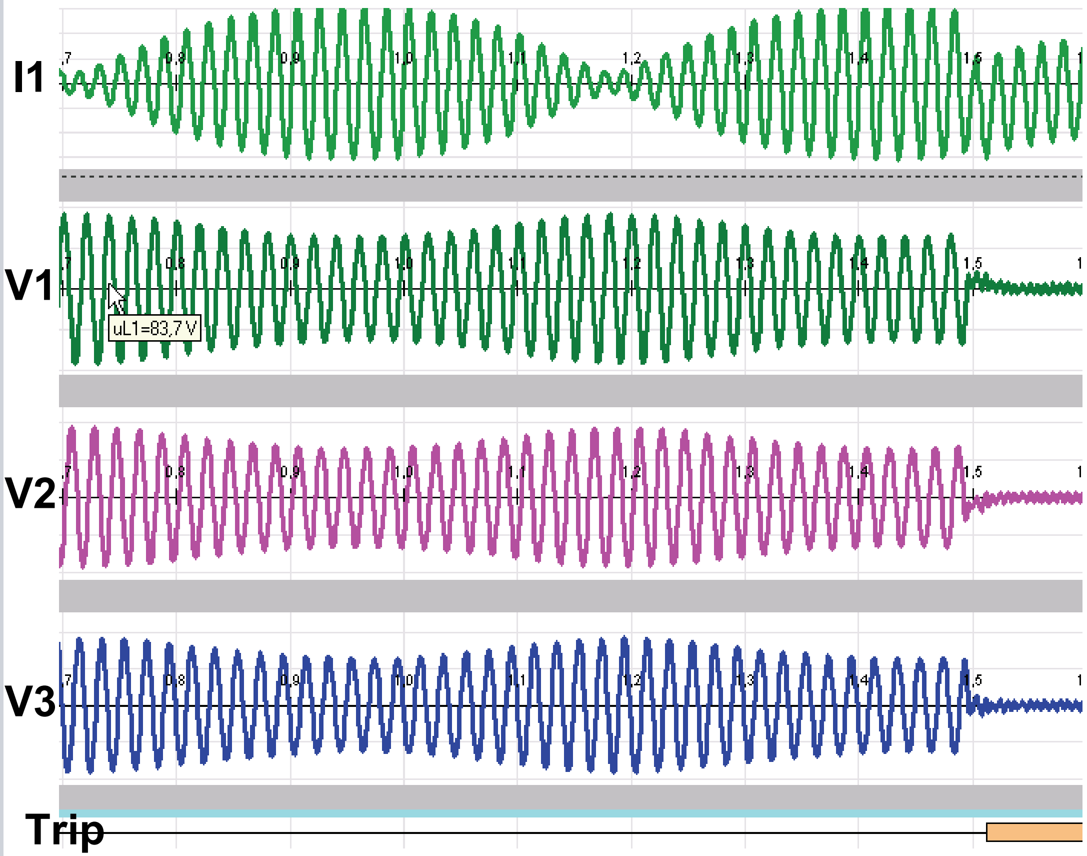
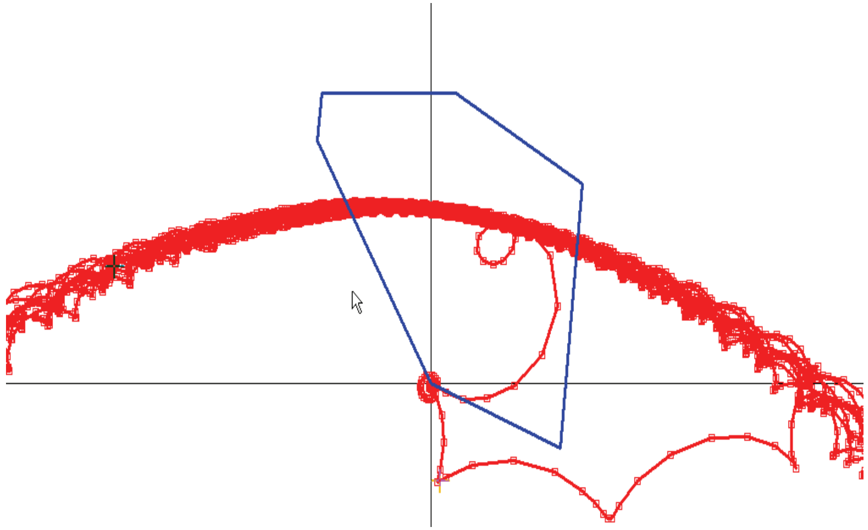


Example:
400 kV
400 km
$f_{PS} \approx 2$ Hz
3-pole fault

Three-phase fault during Power Swing





Three phase fault during power swing is detected and cleared

Fault inception while swing is inside trip characteristic

Special functions to maintain power swing blocking during one pole open condition

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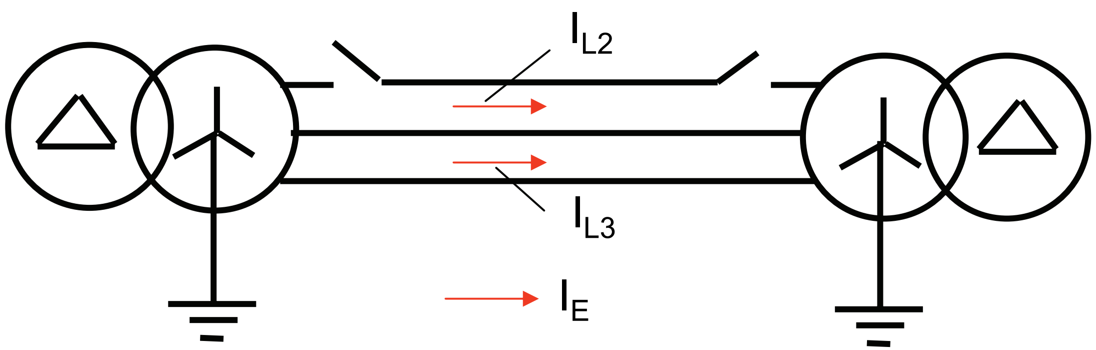
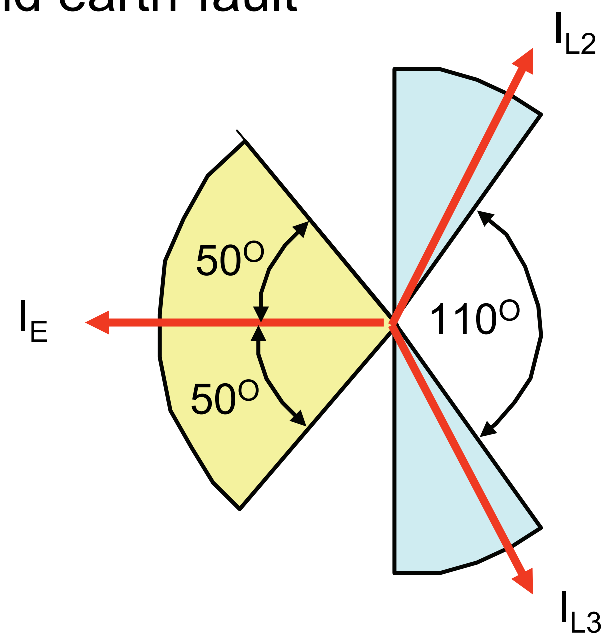
- Phase segregated measurement
- Changed criteria for symmetry monitoring and earth-fault detection





Single-phase fault detection during power swing 1-pole open condition (auto-reclosure dead time)

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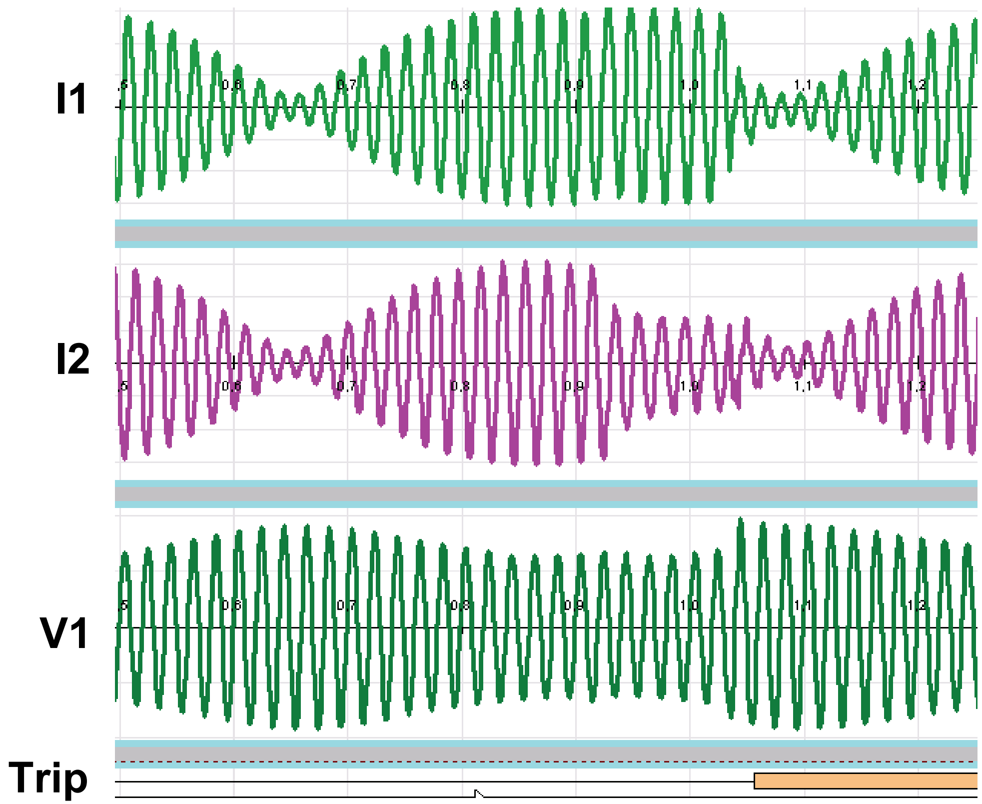

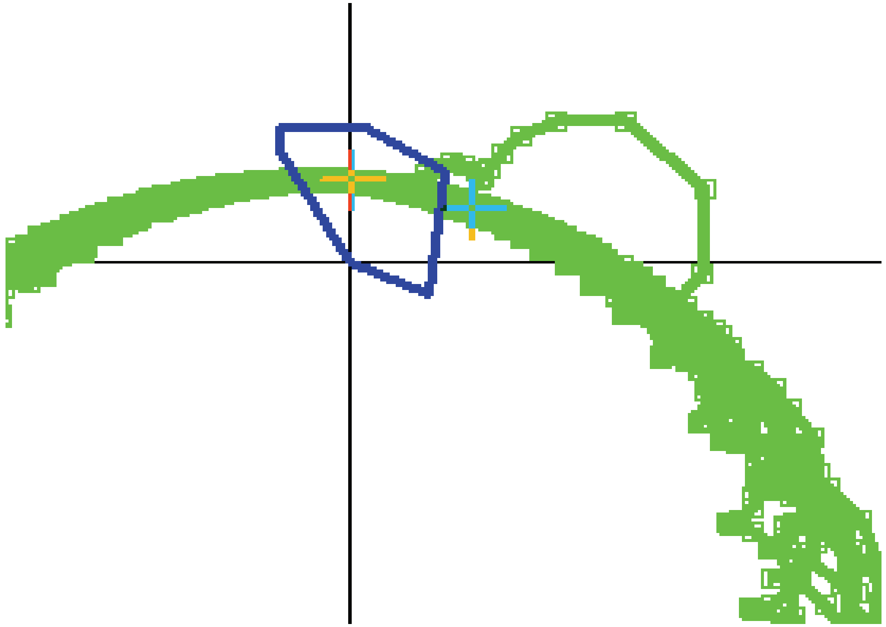

The Power swing passes through the trip characteristic several times.

Single phase fault is detected and cleared.

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Selectable actions of power swing protection

Power swing blocking

◆ Block all zones	➢ normal
◆ Block 1st zone only	➢ fast swings only
◆ Block all but 1st zone	➢ 1st zone short, electrical centre far outside

Power swing tripping

➢ controlled separation of swinging areas (tie-lines)

Conclusions

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- Shaped quadrilateral and mho type characteristics with load cut-out allow high line loading.
- Reliable power swing protection prevents overfunction under transient conditions:
  - Blocking up to high slip frequencies (7 Hz)
  - Automatic setting adaptation (no need for special analyses and calculations)
  - All kinds of fault during power swing are detected and distance protection is released to operate and trip if required
  - Power swing tripping can be selected where appropriate

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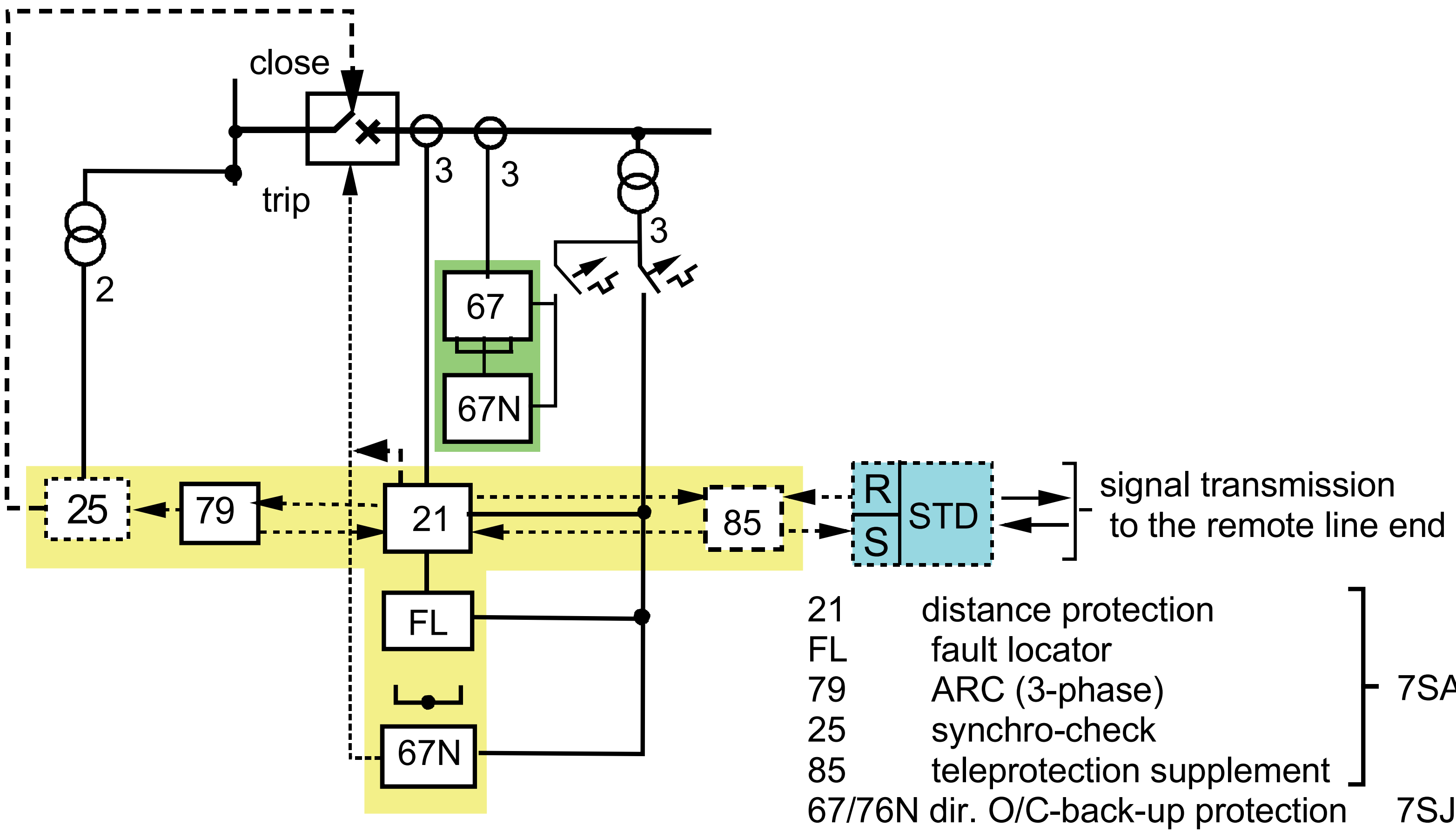
Distance Protection in the Transmission System

Protection concept for sub-transmission lines



21	distance protection	7SA6
FL	fault locator	
79	ARC (3-phase)	
25	synchro-check	
85	teleprotection supplement	
67/76N	dir. O/C-back-up protection	7SJ6
STD	signal transmission device	

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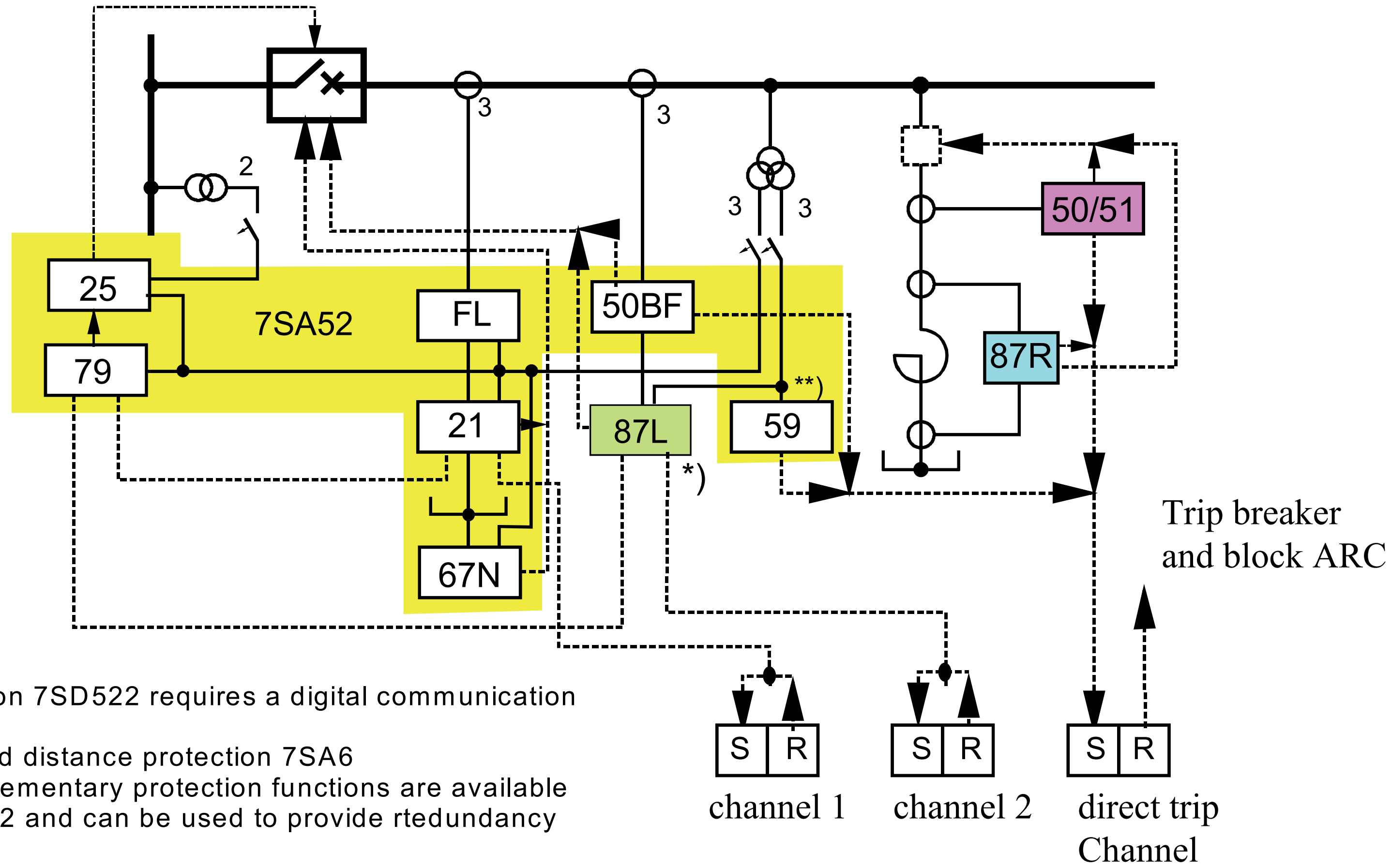
Protection Concept for EHV-lines



*) - differential protection 7SD522 requires a digital communication channel (64 kBit/s)
- alternatively second distance protection 7SA6
- In each case supplementary protection functions are available similar to the 7SA52 and can be used to provide rtedundancy

**)only on very long lines > approx. 150 km

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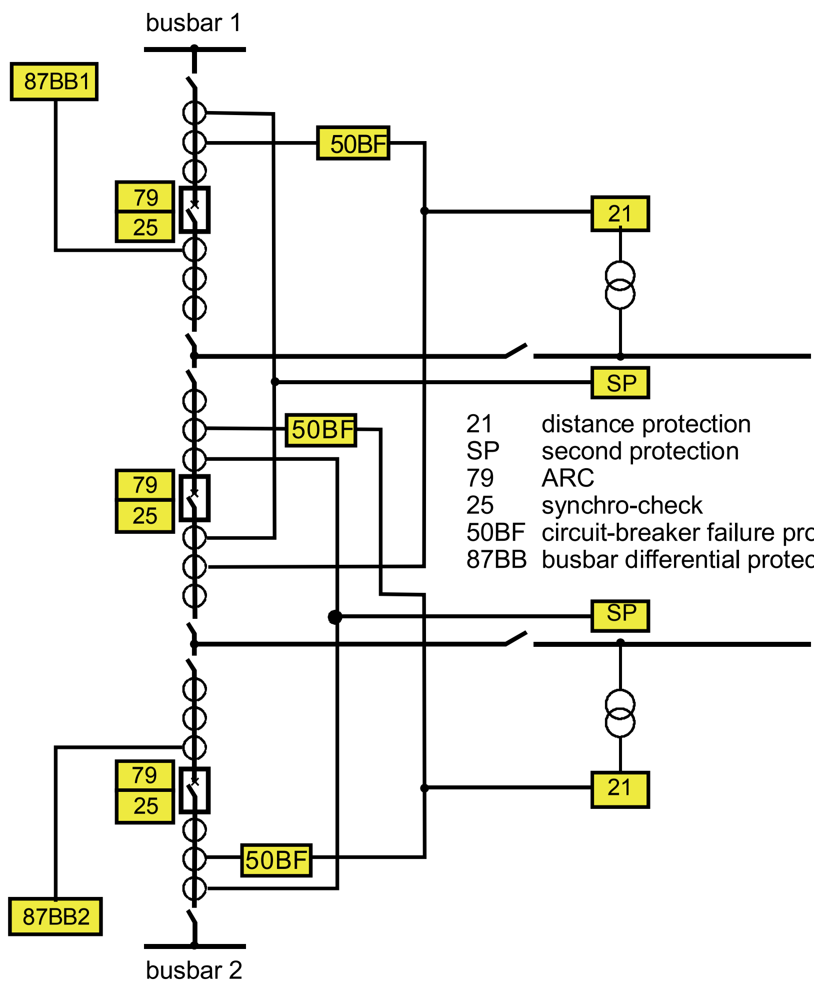
Protection concept for a 1-and-½ circuit-breaker bay



21	distance protection
SP	second protection
79	ARC
25	synchro-check
50BF	circuit-breaker failure protection
87BB	busbar differential protection

Protection concept for a ring busbar (only one protection system shown)

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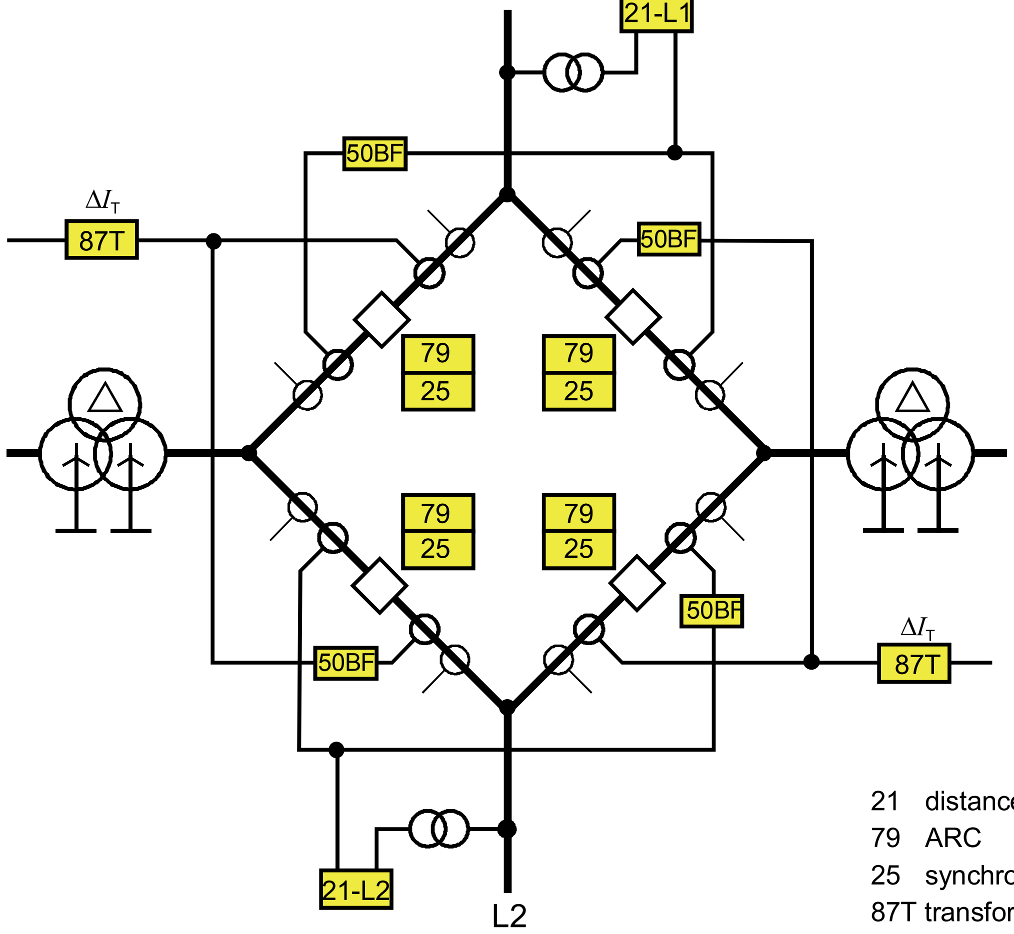

21 distance protection
79 ARC
25 synchro-check
87T transformer differential protection

Distance protection at generating units

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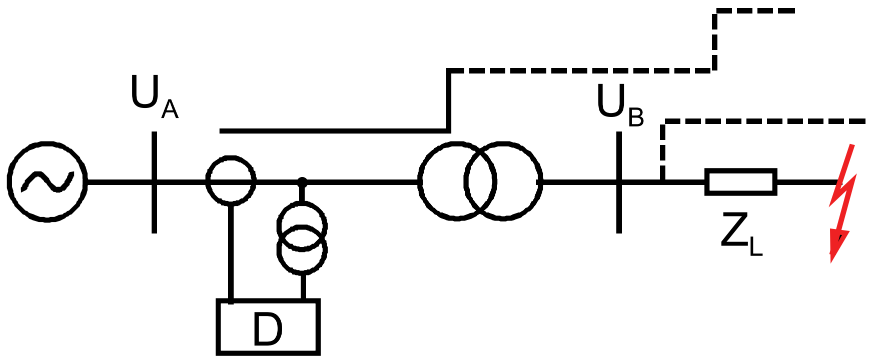
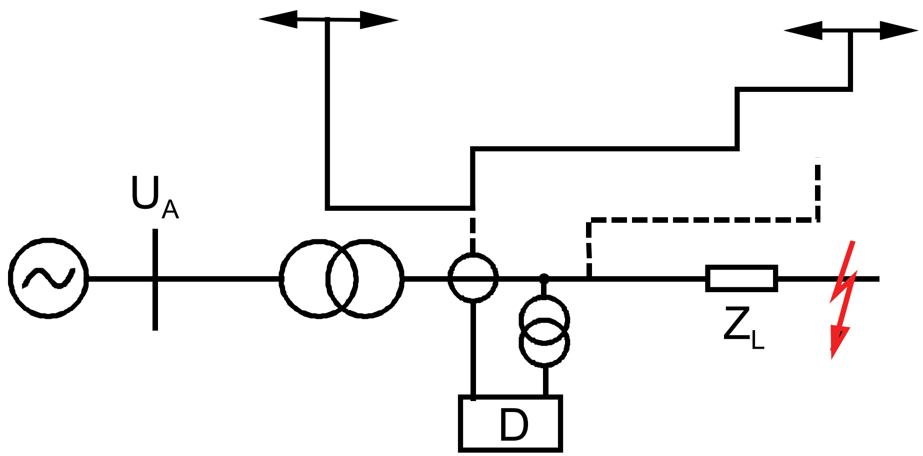


$$Z_F = Z_T + Z_L \cdot \left(\frac{U_{AN}}{U_{BN}}\right)^2$$



$$Z_F = Z_L$$

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Fundamentals of Distance Protection

Protection criterion "Impedance"

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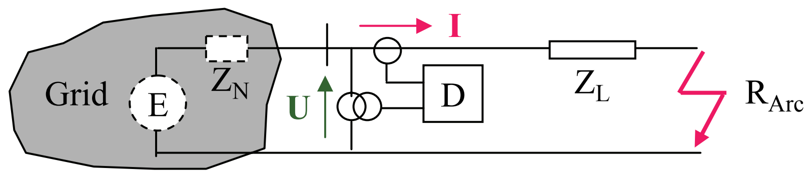
- **The fault impedance is calculated from voltage and current at the fault location: $Z = U / I$**

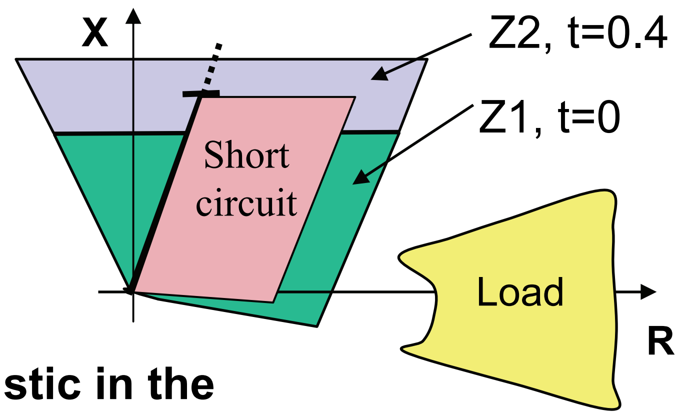
- **The fault impedance is proportional to the fault distance**



- **Add-on criterion "time" is used for selectivity and graded back-up**

Distance protection

(Impedance protection)



- **Characteristic in the impedance diagram:**

Fault loop quantities

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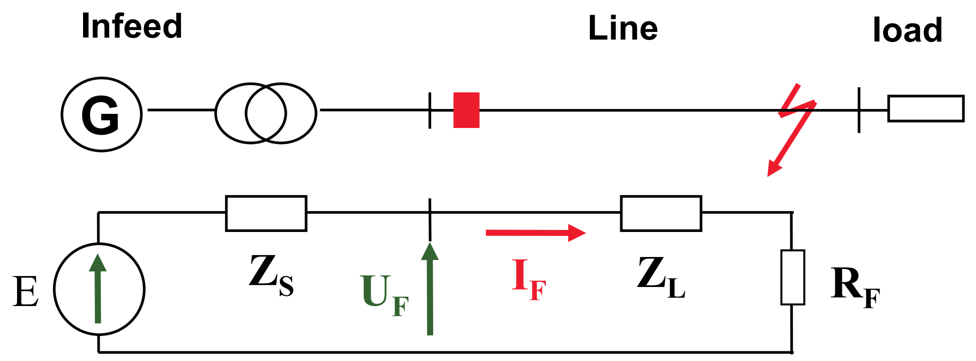

$$E = \frac{1{,}1 \times U_N}{\sqrt{3}} \qquad Z_S = \frac{U_N^{\,2}}{SSC''} \qquad Z_F = z_L'[\mathrm{Ohm/km}] \times l(\mathrm{km})$$

$$\underline{I}_{F\text{-}3ph} = \frac{\underline{E}_{Ph-N}}{\underline{Z}_S + \underline{Z}_L + R_F} \qquad \underline{U}_{F-3ph} = \frac{\underline{Z}_L + R_F}{\underline{Z}_S + \underline{Z}_L + R_F} \cdot \underline{E}_{Ph-N}$$

Influencing quantities:
- **Short circuit power of the infeed (Source impedance Z_S)**
- **Line impedance to fault location (fault impedance Z_L)**
- **Fault resistance (R_F)**
- **Star point earthing impedance (current limitation, e.g. to 2 kA)**

Example (R_F neglected):

$$E = \frac{1.1 \times 110\mathrm{kV}}{\sqrt{3}} = 70\mathrm{kV}$$

$$Z_S = \frac{110\mathrm{kV}^2}{5000\mathrm{MVA}} = 2{,}4\mathrm{Ohm}$$

$$Z_L = 0.4[\mathrm{Ohm/km}] \times 20(\mathrm{km}) = 8\mathrm{Ohm}$$

$$\underline{I}_{F\text{-}3\text{-}pol} = \frac{70\mathrm{kV}}{(2.4 + 8.0)\mathrm{Ohm}} = 6.7\mathrm{kA}$$

$$U_{F-3ph} = \frac{8\mathrm{Ohm}}{(2.4 + 8)\mathrm{Ohm}} \cdot 70\mathrm{kV} = 53.8\mathrm{kV}$$

SIR (System impedance ratio): $\frac{Z_S}{Z_L}$

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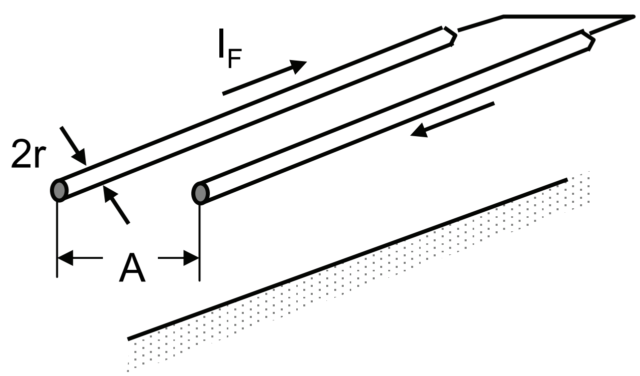
Fault loops, Impedances

Phase-Phase loop



$$\underline{Z}'_{Ph-Ph} = 2 \cdot R'_L + j\,2 \cdot \omega \cdot 10^{-4} \cdot \left(2 \cdot \ln \frac{A}{r} + 0.5 \cdot \mu_1 \right) \quad \Omega/km$$

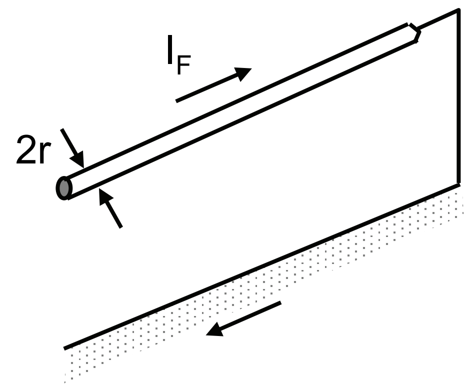
Example:

A = 3.5 m, r = 0.95 cm = $9.5 \cdot 10^{-3}$ m, ρ= 100 Ohm•m
R'_L = 0.157 Ohm/km

Z'_{Ph-Ph} = 0.314 + j0.774 Ohm/km

Z'_{Ph-E} = 0.207 + j0.737 Ohm/km

Phase-Earth loop



$$\underline{Z}'_{Ph-E} = R'_L + R'_E + j\,\omega \cdot 10^{-4} \cdot \left(2 \cdot \ln \frac{\delta}{r} + 0.5 \cdot \mu_1 \right) \quad \Omega/km$$

$$\delta = 1650 \cdot \sqrt{\frac{\rho}{\omega}} \; m \qquad und \qquad R'_E = \frac{\pi}{2} \cdot \omega \cdot 10^{-4} \quad \Omega/km$$

ρ : earth resistivity in Ωm
100 for wed soil, 500 for dry soil

μ_1 : relative permeability (1 für Cu and AL)

Calculation of the line impedances transposed line

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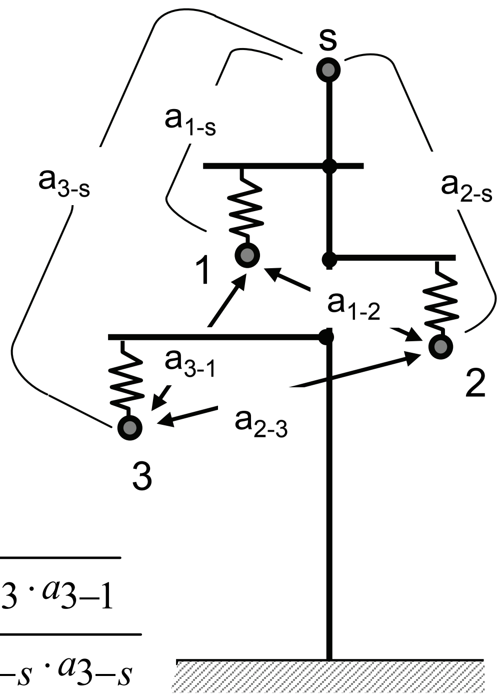

$$A = \sqrt[3]{a_{1-2} \cdot a_{2-3} \cdot a_{3-1}}$$

$$A_s = \sqrt[3]{a_{1-s} \cdot a_{2-s} \cdot a_{3-s}}$$

ρ : Earth resistivity in Ωm
100 for wed soil, 500 for dry soil

μ_1 : relative Permeability (1 for Cu and AL)

Positive-sequence impedance

$$\underline{Z}_1' = R_L' + j\omega \cdot 10^{-4} \cdot \left(2 \cdot \ln \frac{A}{r} + 0.5 \cdot \mu_1 \right) \quad \Omega/km$$

Zero-sequence impedance

Without earth wire:

$$\underline{Z}_0' = R_L' + 3 \cdot R_E' + j\omega \cdot 10^{-4} \cdot \left(6 \cdot \ln \frac{\delta}{\sqrt[3]{r \cdot A^2}} + 0.5 \cdot \mu_1 \right) \quad \Omega/\text{km}$$

With earth wire:

$$\underline{Z}_{0E}' = \underline{Z}_0' - 3 \cdot \frac{\underline{Z}_{1s}'^2}{\underline{Z}_s'} \quad \Omega/\text{km}$$

with: $\underline{Z}_{1s}' = R_E' + j\omega \cdot 10^{-4} \cdot 2 \cdot \ln \frac{\delta}{A_s} \quad \Omega/\text{km}$

$$\underline{Z}_s' = R_s' + R_E' + j\omega \cdot 10^{-4} \cdot \left(2 \cdot \ln \frac{\delta}{r_s} + 0.5 \cdot \mu_1 \right) \quad \Omega/\text{km}$$

$$\delta = 1650 \cdot \sqrt{\frac{\rho}{\omega}} \; m \qquad und \qquad R_E' = \frac{\pi}{2} \cdot \omega \cdot 10^{-4} \quad \Omega/km$$

Loop impedances (phase-phase fault)
Transposed and non-transposed line

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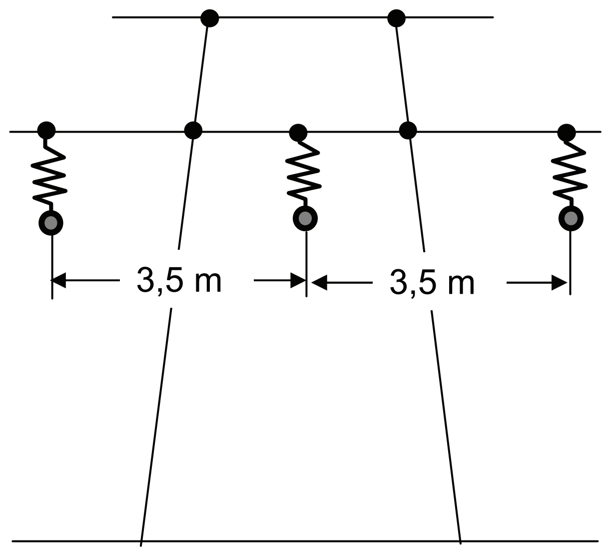
Example:

132 kV line 185/32 mm^2 Al/St

Conductor radius r= 0.95 cm = $9.5 \cdot 10^{-3}$ m
Tower configuration: see figure)
R_L'= 0.157 Ohm/km
ρ= 100 Ohm•m



Loop impedances:

Transposed line:

$\underline{Z}'_{Ph-Ph} = 2 \cdot \underline{Z}_1' = 0.314 + j0.803$ Ohm/km

Non-transposed line:

$\underline{Z}_{L1-L2} = \underline{Z}_{L2-L3} = 0.314 + j0.774$ Ohm/km (**ΔX= -3.6%** von Z_1')

$\underline{Z}_{L3-L1} = 0.314 + j0.861$ Ohm/km (**ΔX= +7.2%** von Z_1')

Estimation of positive sequence cable impedances
(Accurate data from the manufacturer)

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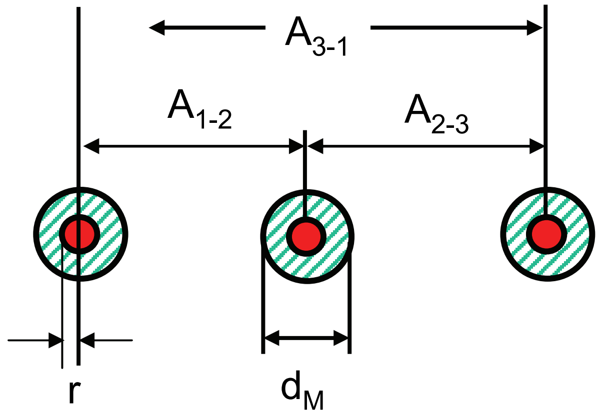

$$\underline{Z}_1' = R_L' + j\omega \cdot 10^{-4} \cdot \left(2 \cdot \ln\frac{A}{r} + 0.5 \cdot \mu_1\right) \quad \Omega/km$$

$$A = \sqrt[3]{A_{1-2} \cdot A_{2-3} \cdot A_{3-1}}$$

Example:

20 kV Plastic cable 240 mm^2

Conductor: Cu

r= 9,3 mm

d_M=39,8 mm

A= 110 mm

$$R'_L = \frac{10^3}{q[mm^2] \cdot \kappa\left[\frac{m}{\Omega \cdot mm^2}\right]} = \frac{10^3}{240 \cdot 58} = 0{,}072 \; [\Omega/km]$$

$$A = \sqrt[3]{110 \cdot 110 \cdot 2 \cdot 110} = 138{,}6$$

$$X'_L = 314 \cdot 10^{-4} \cdot (2 \cdot \ln\frac{138{,}6}{9{,}3} + 0{,}5) = 0{,}185 \quad \Omega/km$$

Cables with conductive shield:

When the conductive shield is earthed at both cable ends, X_L is reduced and R_L increased.
The coupling impedance between conductor and shield must be considered.

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Zero-sequence impedance of cables

Can hardly be calculated:

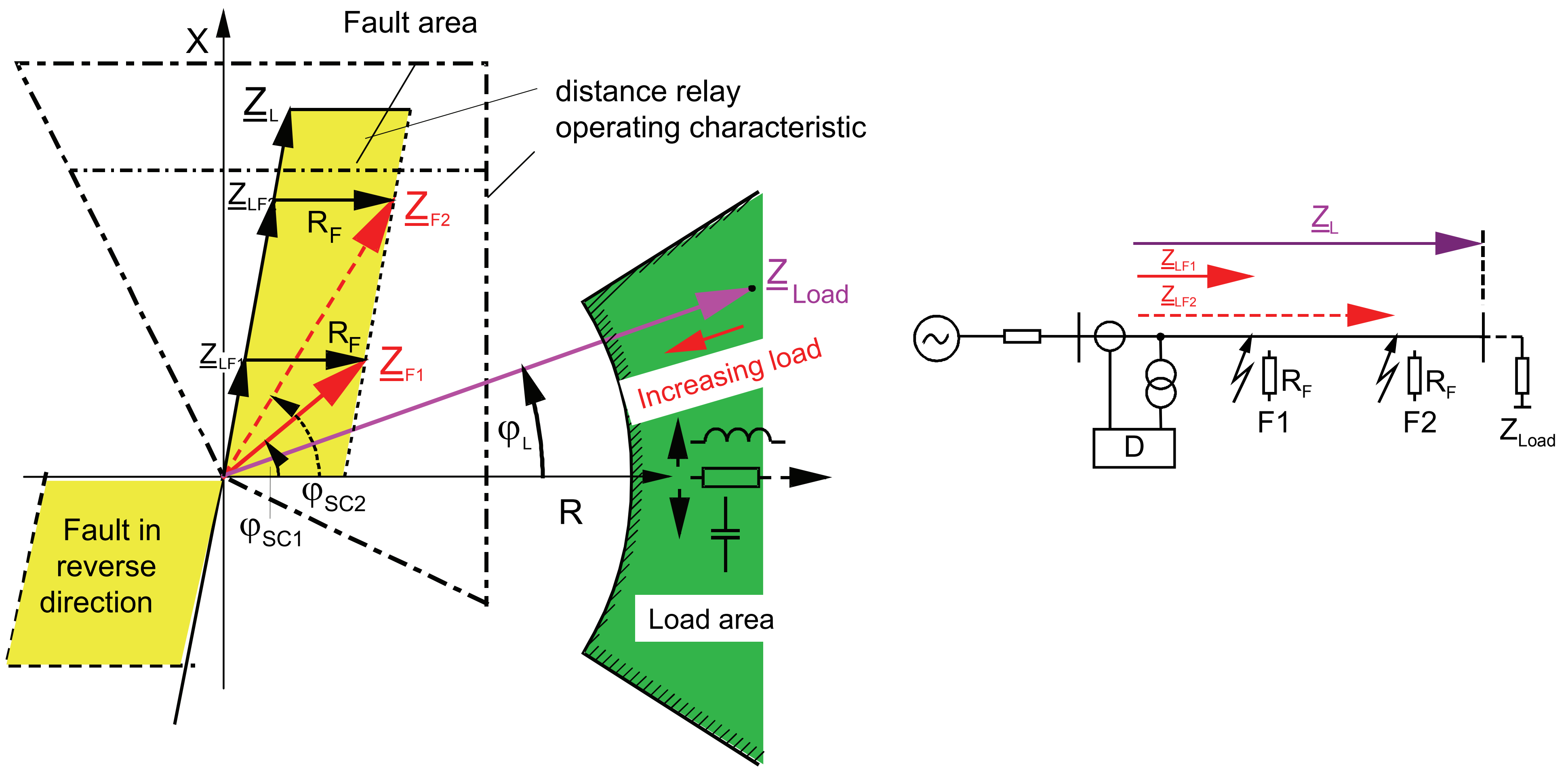
- Z_0 depends on the cable environment:
  Parallel shields of other cables, gas pipes and rails
- In case of steel armoured cables, Z_0 is also current dependent:
  Magnetising of steel bands and wires

Z_0 must be measured at the installed cable!

Measured mean values of cables in urban areas *):

400 kV	Single conductor oil cable 3x1x1200 mm² Cu 0,05 + j0,11 Ohm/km	
110 kV	Three-core separately sheathed cable 3x150 mm2 Cu 0,5 + j0,3 Ohm/km	Plastic-insulated cable 3x1x630 mm² Cu 0,45 + j0,34

Load and short-circuit impedances



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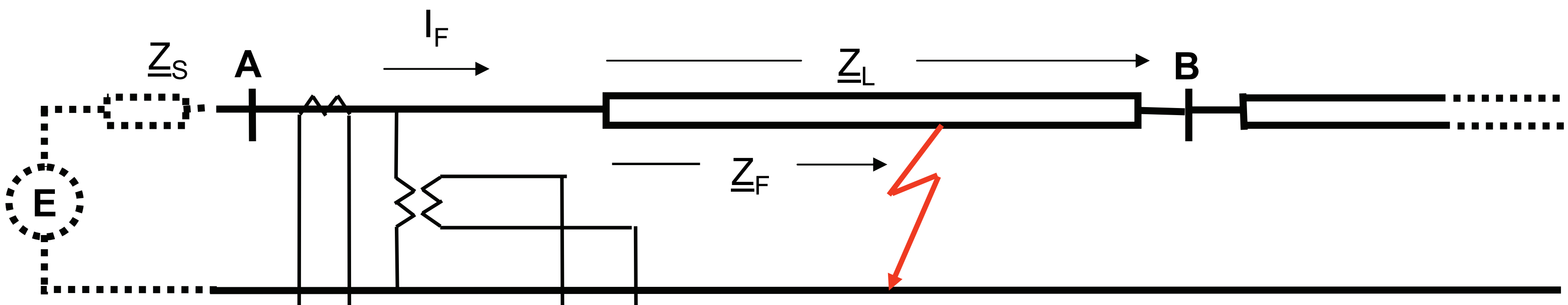
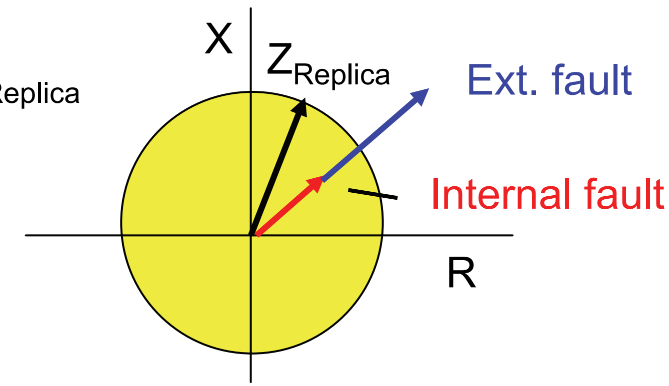
Principle of (analogue) distance relaying



Relay design:
operation if
$U_1 < U_2$
i.e. $Z_F < Z_{Replica}$



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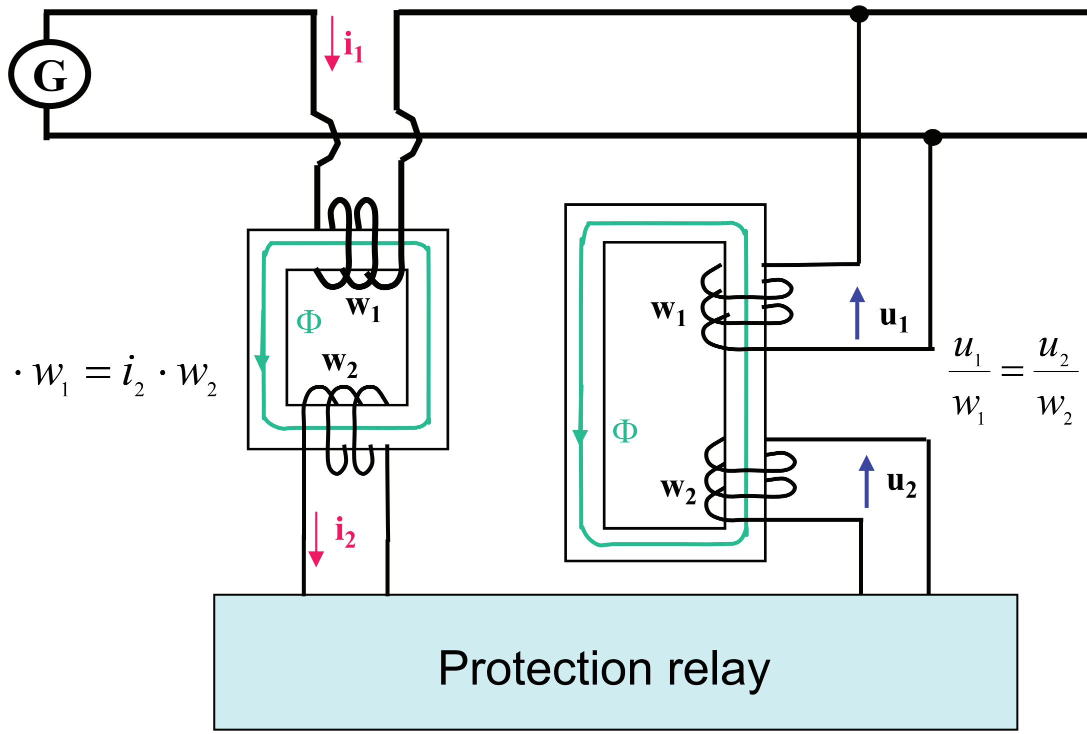
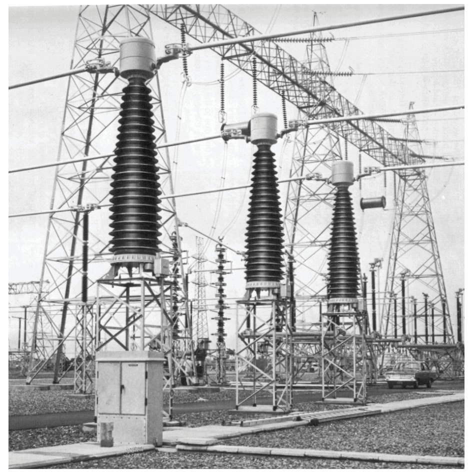
Secondary impedance



$i_1 \cdot w_1 = i_2 \cdot w_2$

$\frac{u_1}{w_1} = \frac{u_2}{w_2}$



$$I_{sec} = I_{prim} / CTR$$

$$U_{sec} = U_{prim} / VTR$$

$$Z_{sec} = \frac{CTR}{VTR} \cdot Z_{prim}$$

$$\left.\begin{array}{l} CTR = 600/1\,A \\ VTR = 110/0.1\,kV \end{array}\right\} \quad Z_{sec} = 0.55 \cdot Z_{prim}$$

Typical distance zone-characteristics

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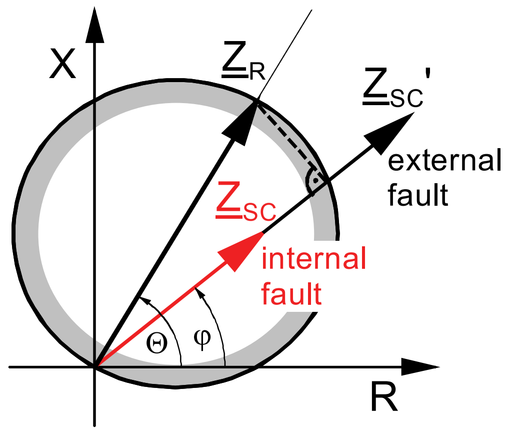
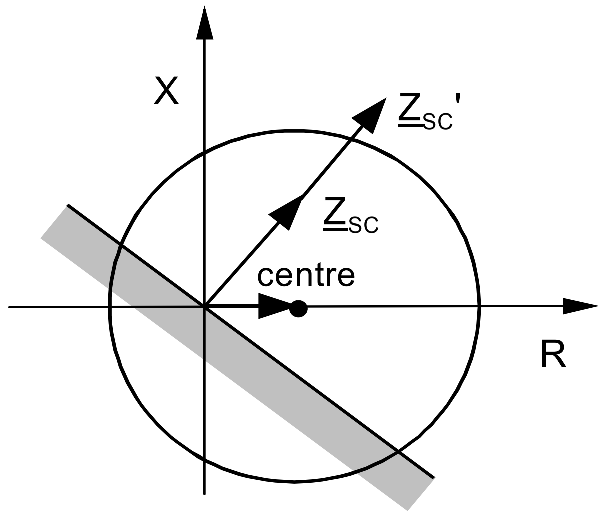
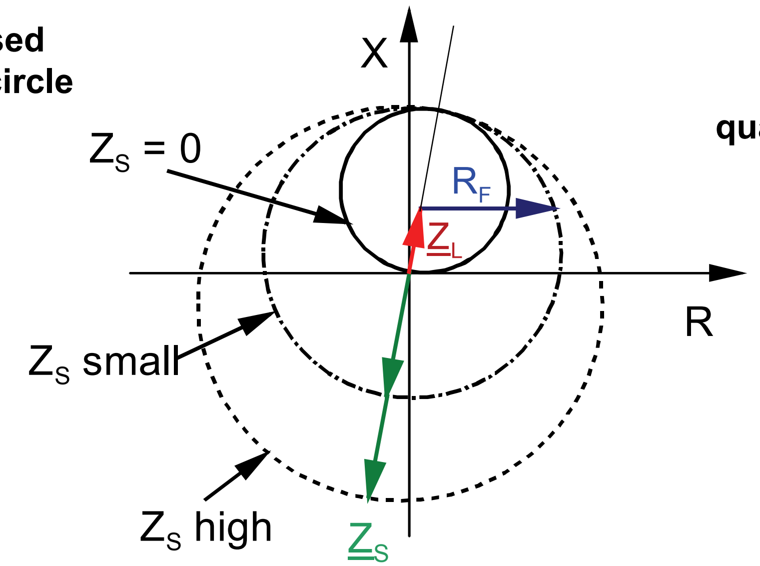
MHO-circle



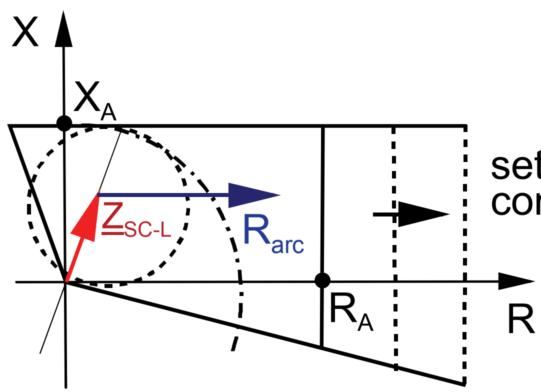
shifted circle



polarised MHO-circle



quadrilateral



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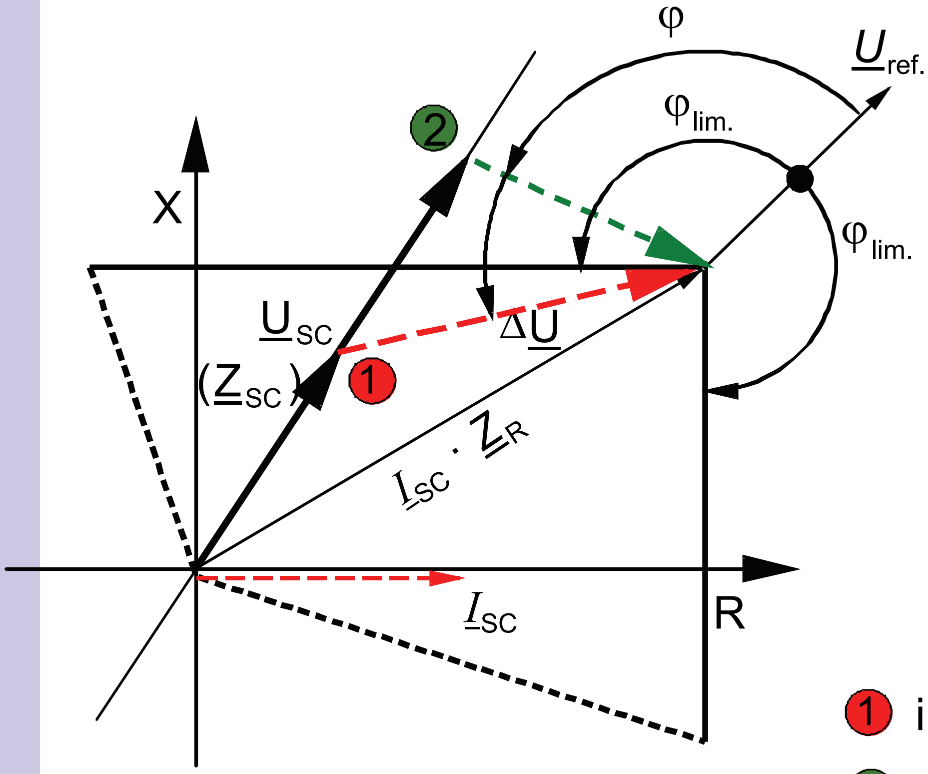
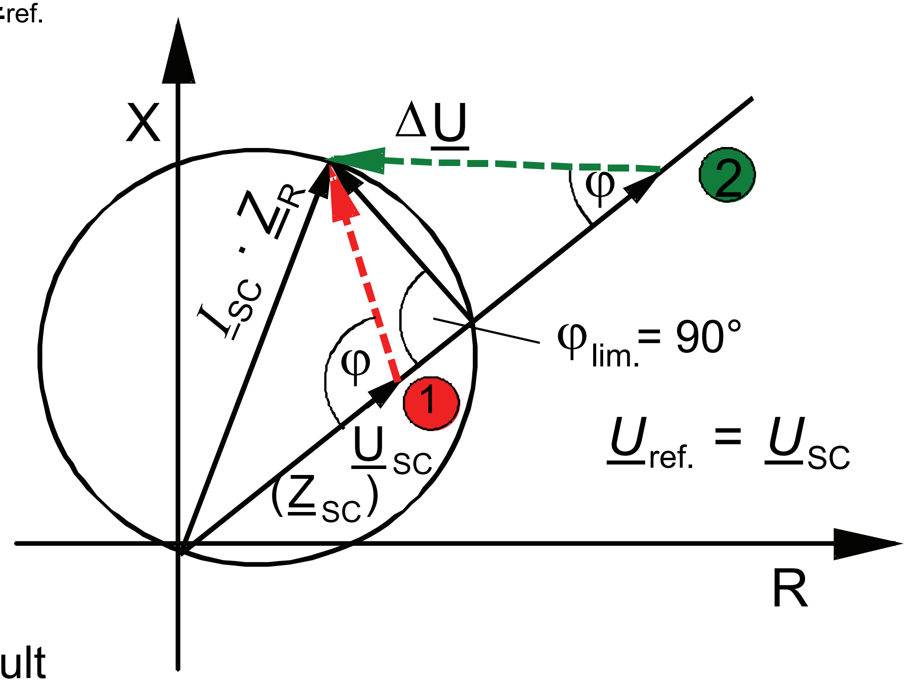
Analogue static relays: distance measurement (1)

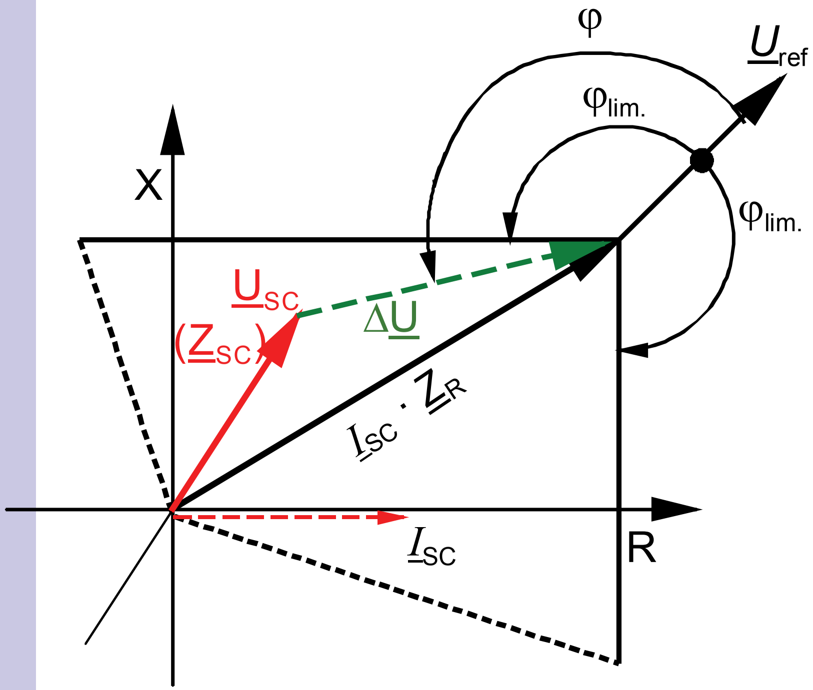


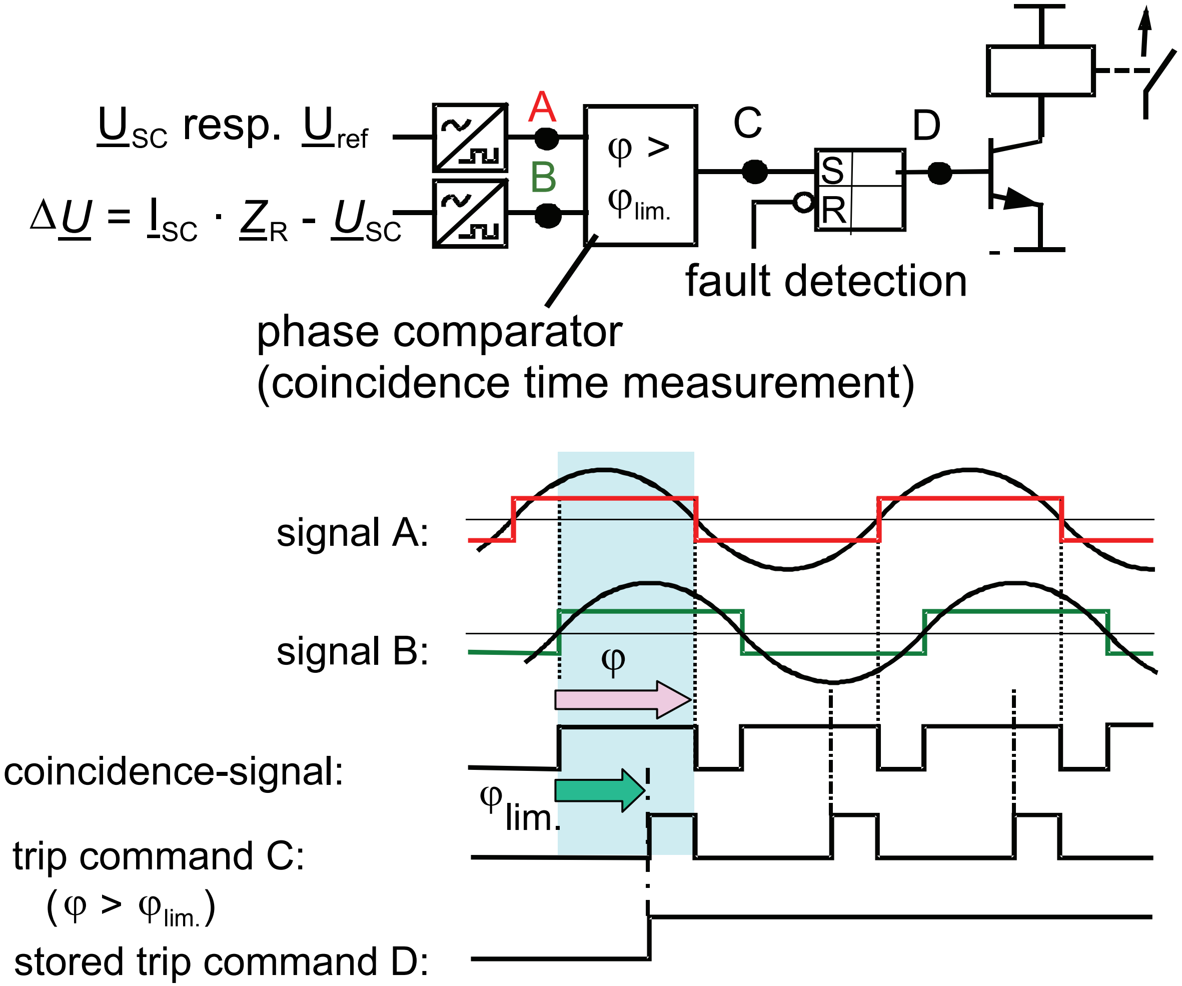


1 internal fault

2 external fault

Analogue static relays: distance measurement (2)





Traditional Impedance measurement

Phase-Phase loop

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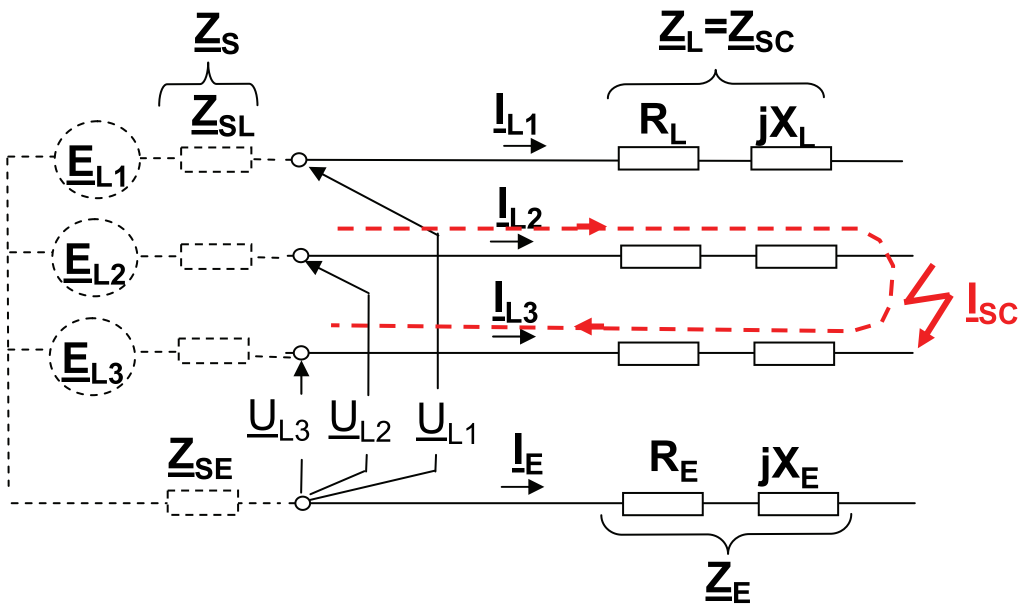
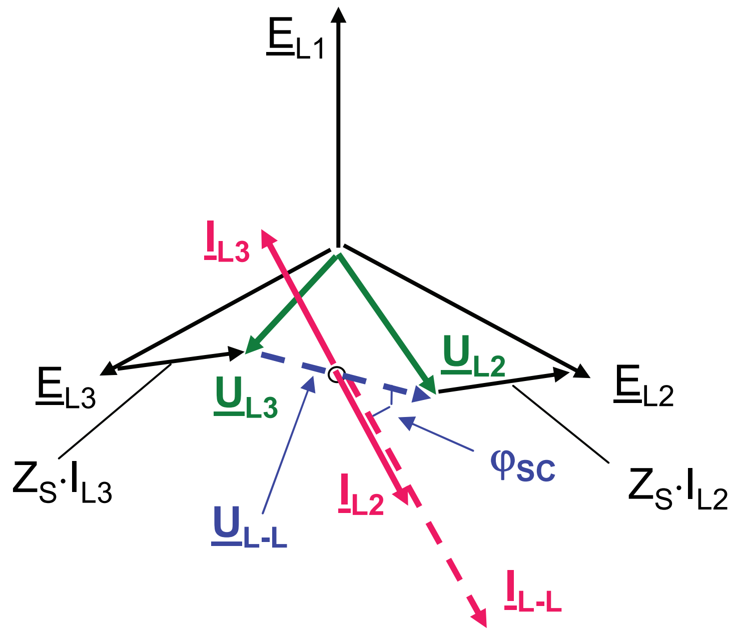
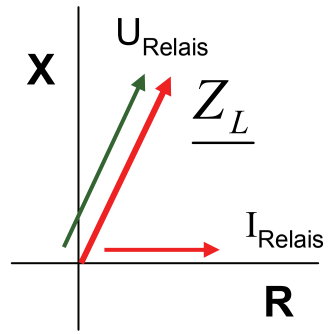




$$\underline{U}_{L2-L3} = \underline{U}_{L2} - \underline{U}_{L3} = \underline{I}_{L2} \cdot \underline{Z}_L - \underline{I}_{L3} \cdot \underline{Z}_L = 2 \cdot \underline{I}_{SC} \cdot \underline{Z}_L$$

$$\underline{I}_{L2-L3} = \underline{I}_{L2} - \underline{I}_{L3} = 2 \cdot \underline{I}_{SC}$$

$$\underline{Z}_{L2-L3} = \frac{\underline{U}_{L2} - \underline{U}_{L3}}{\underline{I}_{L2} - \underline{I}_{L3}} = \frac{\underline{U}_{L-L}}{\underline{I}_{L-L}} = \frac{2 \cdot \underline{I}_{SC} \cdot \underline{Z}_L}{2 \cdot \underline{I}_{SC}} = \underline{Z}_L$$



Traditional Impedance measurement

Phase-Earth loop

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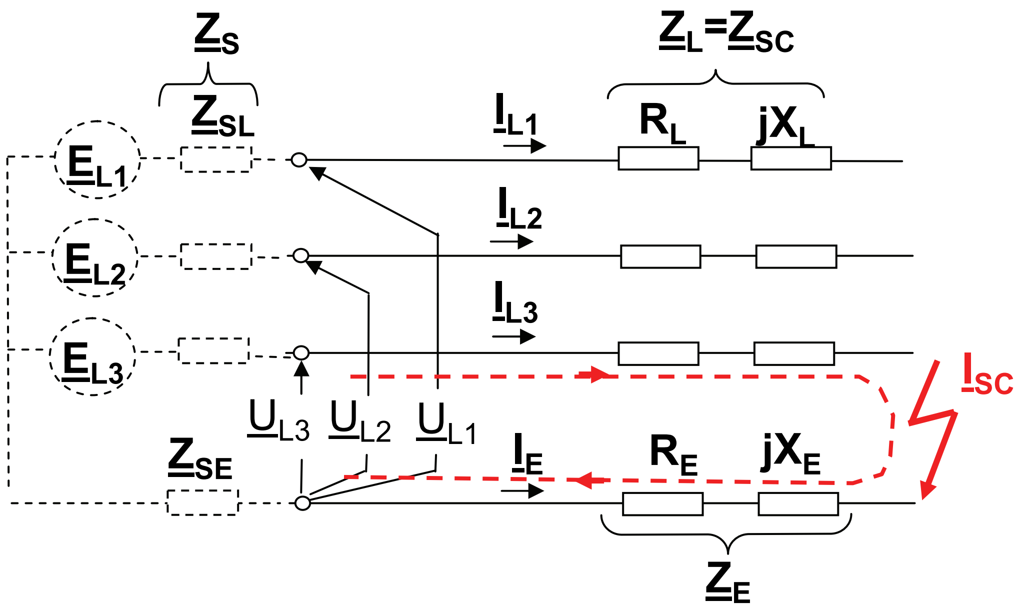

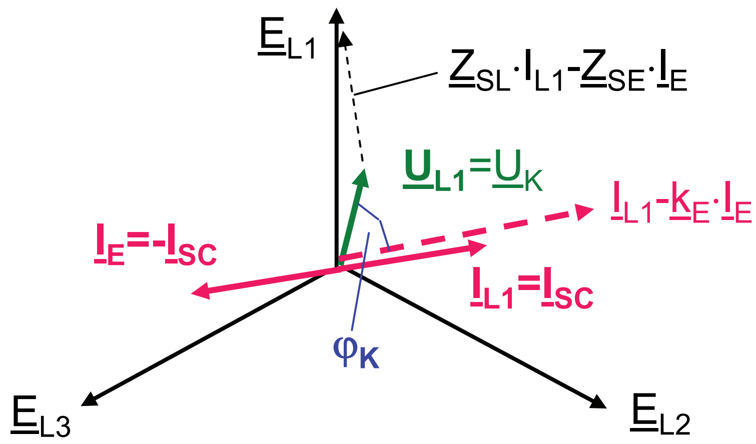

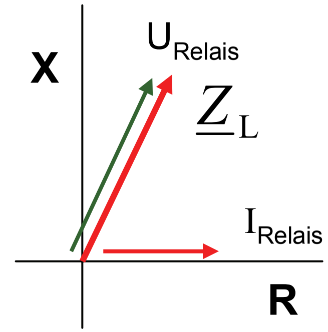

$$\underline{U}_{Relais} = \underline{U}_{L1} = \underline{I}_{L1} \cdot \underline{Z}_L - \underline{I}_E \cdot \underline{Z}_E = \underline{Z}_L \cdot \left(\underline{I}_{L1} - \frac{\underline{Z}_E}{\underline{Z}_L} \cdot \underline{I}_E \right)$$

$$\underline{I}_{Relais} = \underline{I}_{L1} - \underline{k}_{E-Relais} \cdot \underline{I}_E$$

$$\underline{Z}_{L1} = \frac{\underline{U}_{Relais}}{\underline{I}_{Relais}} = \frac{\underline{U}_{L1}}{\underline{I}_{L1} - \underline{k}_{E-Relais} \cdot \underline{I}_E} = \underline{Z}_L$$

with

$$\underline{k}_{E-Relais} = \frac{\underline{Z}_E}{\underline{Z}_L} = \left| \frac{\underline{Z}_E}{\underline{Z}_L} \right| \cdot e^{j \cdot (\varphi_E - \varphi_L)}$$

Capture of measuring data (principle)

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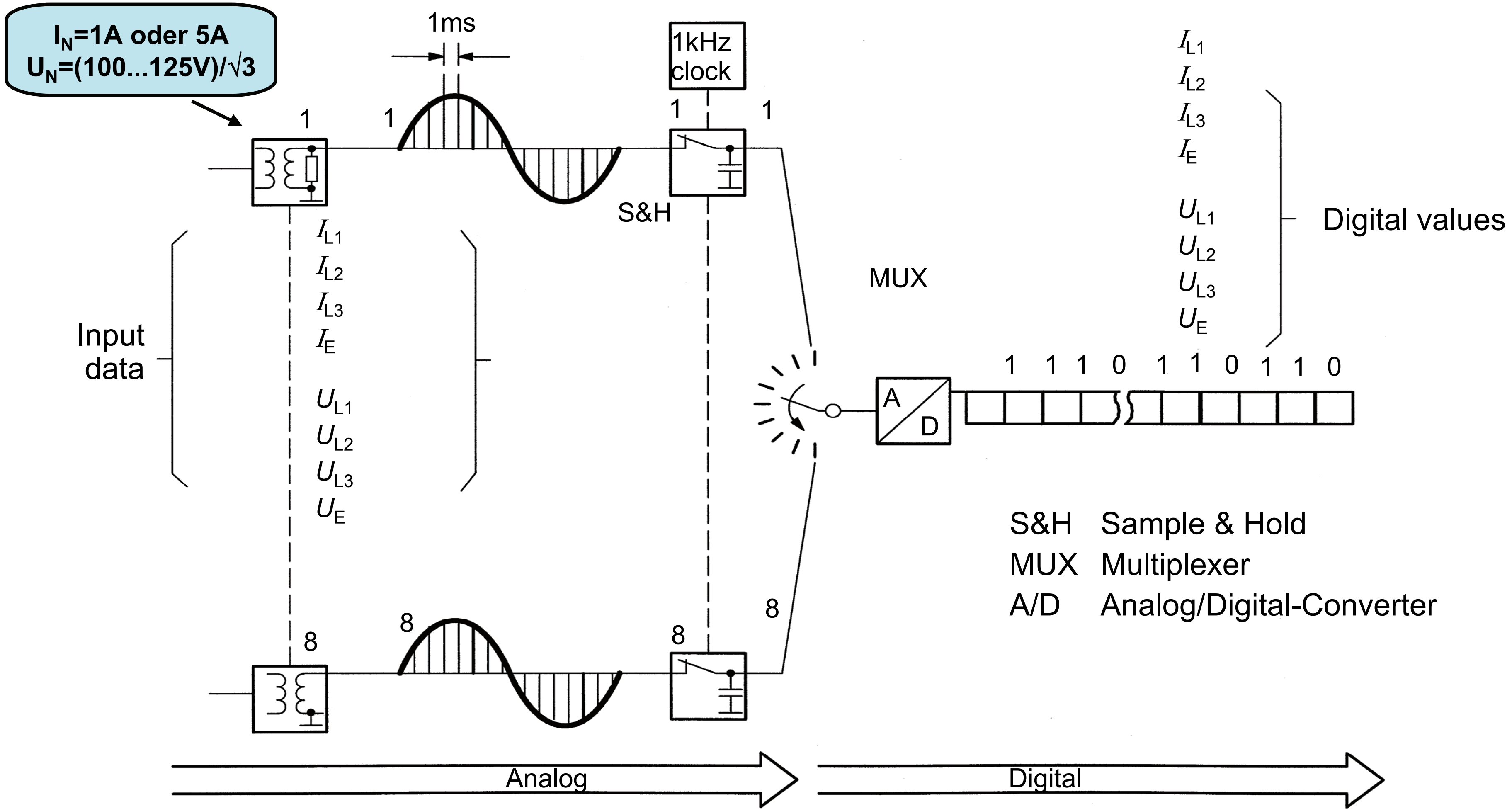

S&H Sample & Hold
MUX Multiplexer
A/D Analog/Digital-Converter

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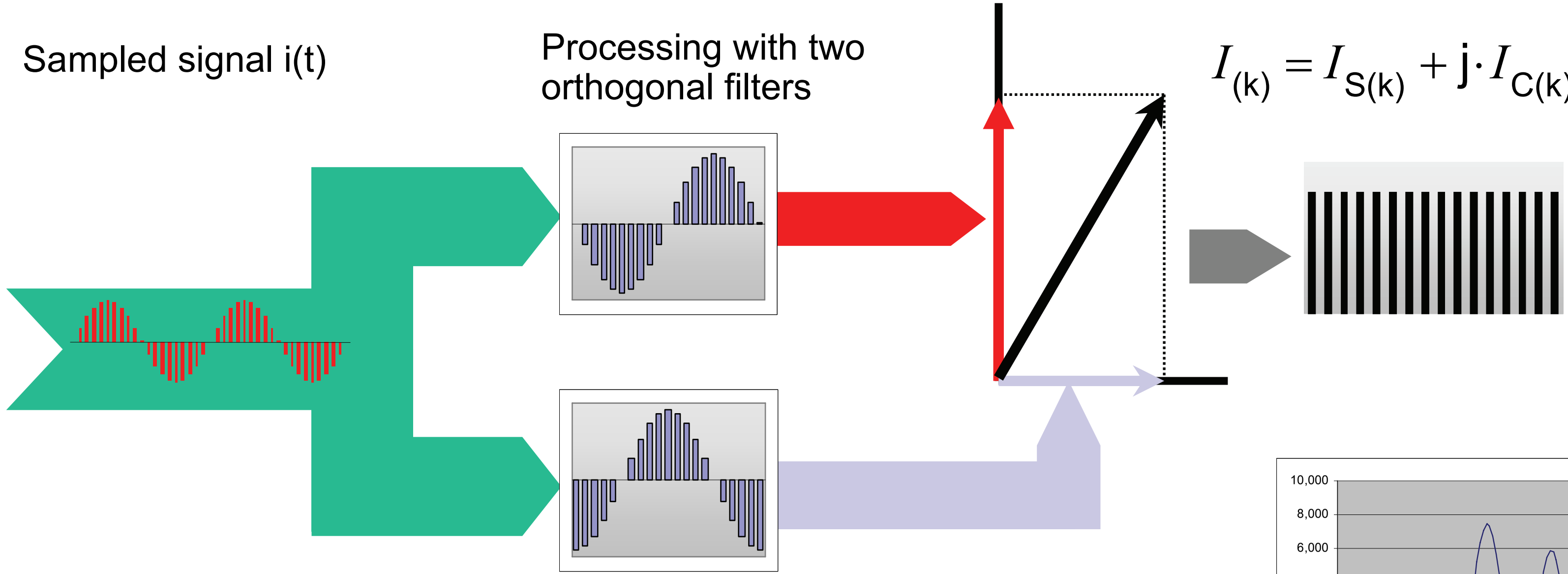
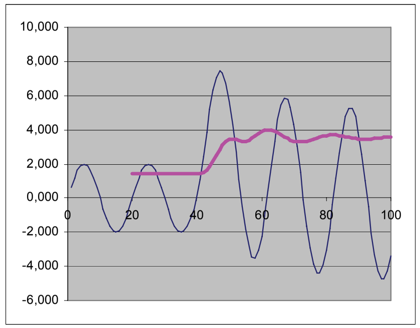
Fourier analysis of measured values

Sampled signal i(t)

Processing with two orthogonal filters

$$I_{(k)} = I_{S(k)} + j \cdot I_{C(k)}$$





$$I_S = \frac{1}{2\pi} \int_{\varnothing - 360°}^{\varnothing} I(\omega t) \cdot \sin \omega t \, dt$$

$$I_C = \frac{1}{2\pi} \int_{\varnothing - 360°}^{\varnothing} I(\omega t) \cdot \cos \omega t \, dt$$

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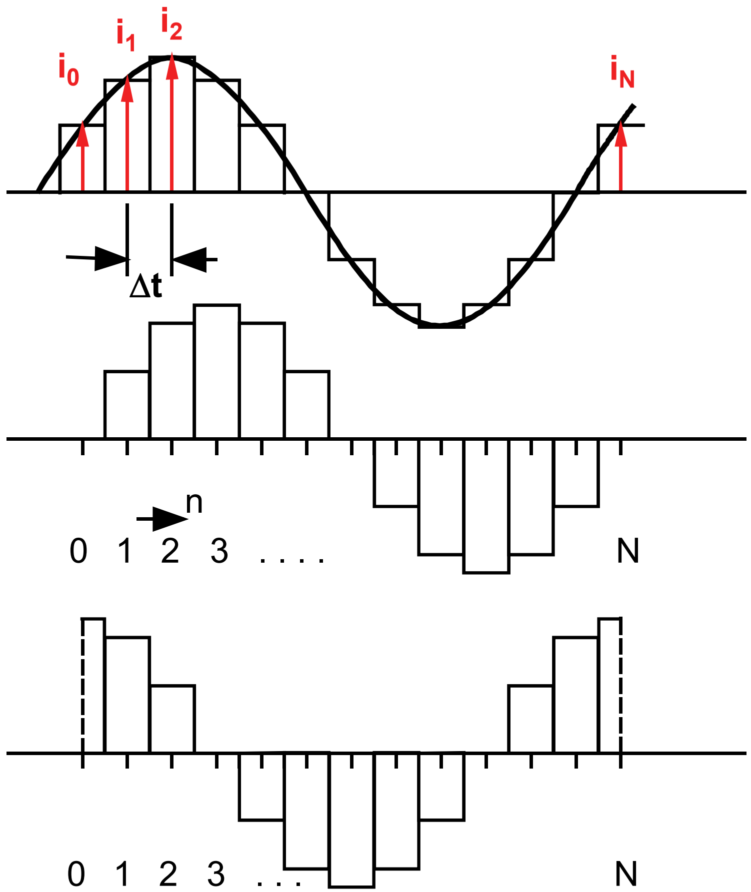
Discrete Fourier transform

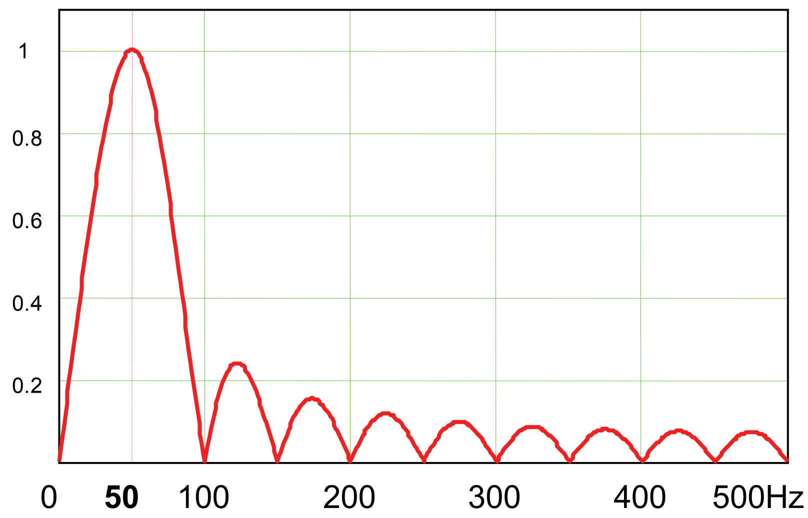


$$I_S = \frac{2}{N}\left[\sum_{n=1}^{N-1} \sin(\omega \cdot n \cdot \Delta t) \cdot i_n\right]$$

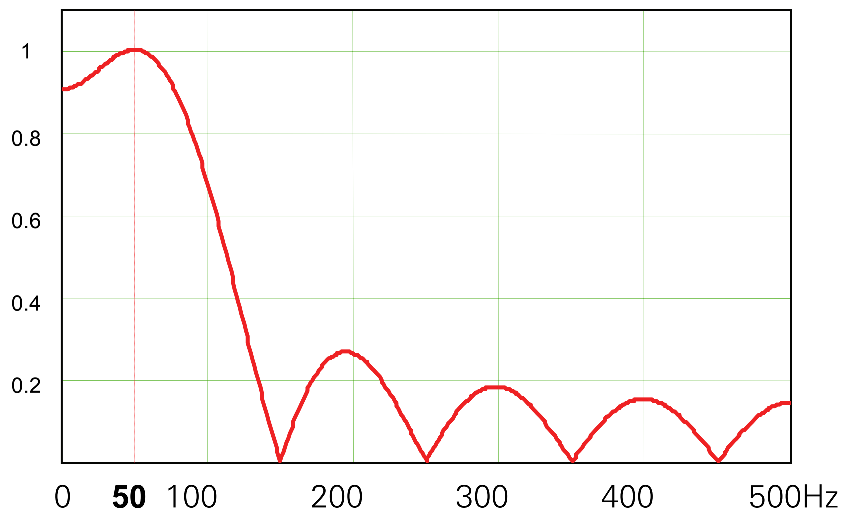
$$I_C = \frac{2}{N}\left[\frac{i_0}{2} + \frac{i_N}{2} + \sum_{n=1}^{N-1} \cos(\omega \cdot n \cdot \Delta t) \cdot i_n\right]$$

Fourier analysis: Filtering characteristics

Full cycle (20 ms at 50 Hz)



Half cycle (10 ms at 50 Hz)



Fourier transform
Determination of Voltage and current phasors

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$$u_L(t) = R_L \cdot i_L(t) + L_L \cdot \frac{di_L(t)}{dt}$$

$$Re\{\underline{U}_L\} = \frac{1}{T} \cdot \int_{-T/2}^{+T/2} u_L(t) \cdot \cos(\omega_0 \cdot t) dt$$

$$Im\{\underline{U}_L\} = \frac{1}{T} \cdot \int_{-T/2}^{+T/2} u_L(t) \cdot \sin(\omega_0 \cdot t) dt$$

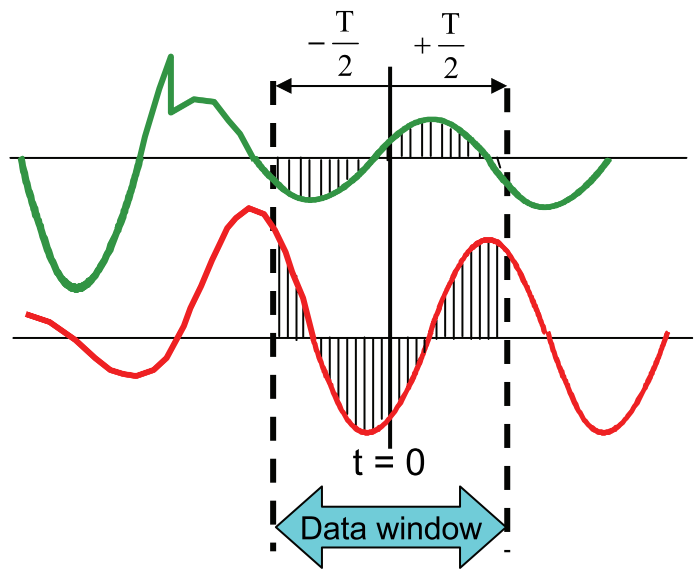
$$\underline{U}_L = Re\{\underline{U}_L\} + jIm\{\underline{U}_L\}$$

$$Re\{\underline{I}_L\} = \frac{1}{T} \cdot \int_{-T/2}^{+T/2} i_L(t) \cdot \cos(\omega_0 \cdot t) dt$$

$$Im\{\underline{I}_L\} = \frac{1}{T} \cdot \int_{-T/2}^{+T/2} i_L(t) \cdot \sin(\omega_0 \cdot t) dt$$

$$\underline{I}_L = Re\{\underline{I}_L\} + jIm\{\underline{I}_L\}$$

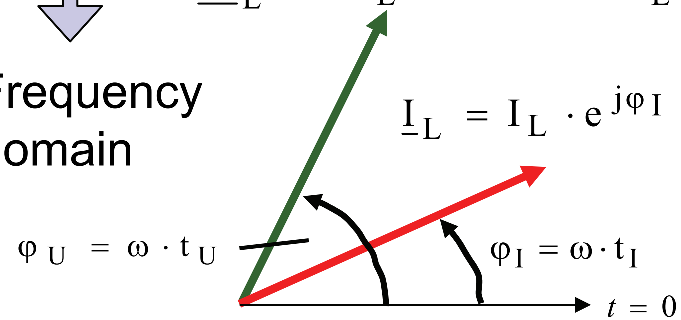
Time domain



Frequency domain

$$\underline{U}_L = U_L \cdot e^{j\varphi_U} = U_L \cdot e^{j\omega t_U}$$

$$\underline{I}_L = I_L \cdot e^{j\varphi_I} = I_L \cdot e^{j\omega t_I}$$

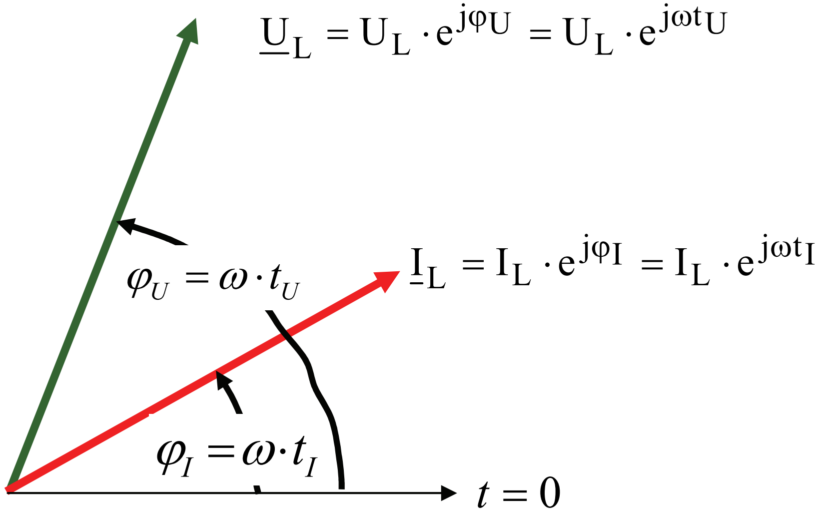


$$\underline{U}_L = U_L \cdot [\cos(\omega \cdot t + \varphi_U) + j\sin(\omega \cdot t + \varphi_U)] = U_L \cdot e^{j(\omega \cdot t + \varphi_U)}$$

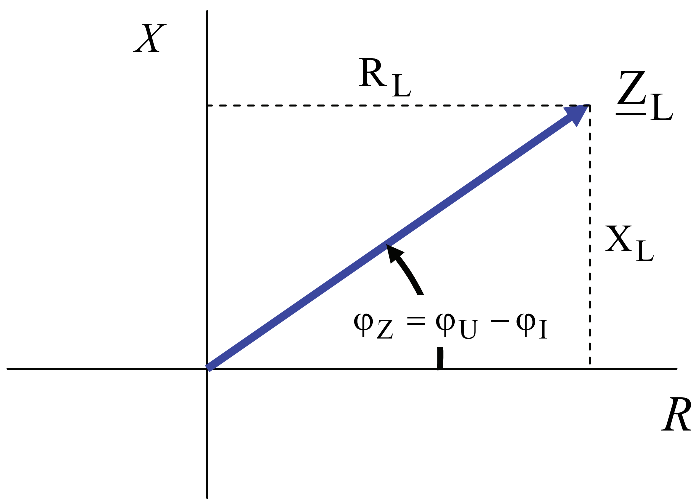
$$\underline{I}_L = I_L \cdot [\cos(\omega \cdot t + \varphi_I) + j\sin(\omega \cdot t + \varphi_I)] = I_L \cdot e^{j(\omega \cdot t + \varphi_I)}$$

Fault impedance calculation from complex U- and I-phasors

SIEMENS



Impedance plane



$$\underline{Z}_L = \frac{\underline{U}_L}{\underline{I}_L} = \frac{U_L \cdot e^{j\varphi_U}}{I_L \cdot e^{j\varphi_I}} = \frac{U_L}{I_L} \cdot e^{j(\varphi_U - \varphi_I)}$$

$$= R_L + jX_L$$

$$R_L = \mathrm{Re}\{\underline{Z}_L\} = \frac{U_L}{I_L} \cdot \cos(\varphi_U - \varphi_I)$$

$$X_L = \mathrm{Im}\{Z_L\} = \frac{U_L}{I_L} \sin(\varphi_U - \varphi_I)$$

Calculation of R_L and X_L from separate real and imaginary fault loops

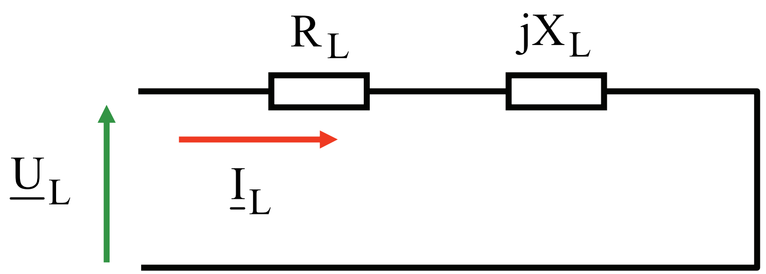
SIEMENS

$$\underline{U}_L = R_L \cdot \underline{I}_L + jX_L \cdot \underline{I}_L$$

$$Re\{\underline{U}_L\} + jIm\{\underline{U}_L\} = (R_L + jX_L) \cdot (Re\{\underline{I}_L\} + jIm\{\underline{I}_L\})$$

$$Re\{\underline{U}_L\} = R_L \cdot Re\{\underline{I}_L\} - X_L \cdot Im\{\underline{I}_L\}$$

$$Im\{\underline{U}_L\} = X_L \cdot Re\{\underline{I}_L\} + R_L \cdot Im\{\underline{I}_L\}$$



$$X_L = \frac{Im\{\underline{U}_L\} \cdot Re\{\underline{I}_L\} - Re\{\underline{U}_L\} \cdot Im\{\underline{I}_L\}}{Re\{\underline{I}_L\}^2 + Im\{\underline{I}_L\}^2}$$

$$R_L = \frac{Re\{\underline{U}_L\} \cdot Re\{\underline{I}_L\} + Im\{\underline{U}_L\} \cdot Im\{\underline{I}_L\}}{Re\{\underline{I}_L\}^2 + Im\{\underline{I}_L\}^2}$$

$$\underline{U}_L = U_L \cdot e^{j(\omega \cdot t + \varphi_U)} = U_L \cdot [\cos(\omega \cdot t + \varphi_U) + j\sin(\omega \cdot t + \varphi_U)]$$

$$\underline{I}_L = I_L \cdot e^{j(\omega \cdot t + \varphi_I)} = I_L \cdot [\cos(\omega \cdot t + \varphi_I) + j\sin(\omega \cdot t + \varphi_I)]$$

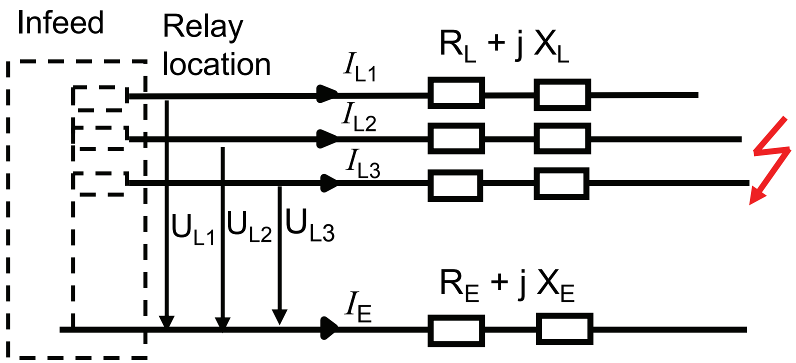
$$X_L = \frac{U_L}{I_L} \cdot \sin(\varphi_{UL} - \varphi_{IL})$$

$$R_L = \frac{U_L}{I_L} \cdot \cos(\varphi_{UL} - \varphi_{IL})$$

$$\underline{Z}_L = R_L + jX_L$$

Complex fault impedance calculation compared to real and imaginary fault loop evaluation, Single-Ph-Ph fault

SIEMENS



RL and XL calculation from real and imaginary fault loop equation:

$$X_L = \frac{Im\{\underline{U}_L\} \cdot Re\{\underline{I}_L\} - Re\{\underline{U}_L\} \cdot Im\{\underline{I}_L\}}{Re\{\underline{I}_L\}^2 + Im\{\underline{I}_L\}^2}$$

$$R_L = \frac{Re\{\underline{U}_L\} \cdot Re\{\underline{I}_L\} + Im\{\underline{U}_L\} \cdot Im\{\underline{I}_L\}}{Re\{\underline{I}_L\}^2 + Im\{\underline{I}_L\}^2}$$

$$\underline{U}_L = \underline{U}_{L2} - \underline{U}_{L3} \quad \text{and} \quad \underline{I}_L = \underline{I}_{L2} - \underline{I}_{L3}$$

Complex impedance calculation:

$$\underline{Z}_{L2-L3} = \frac{\underline{U}_{L2} - \underline{U}_{L3}}{\underline{I}_{L2} - \underline{I}_{L3}}$$

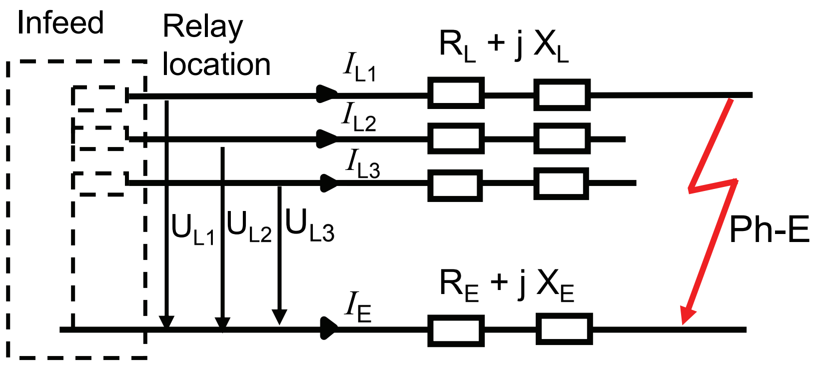
For $\underline{I}_{L3} = -\underline{I}_{L2} = \underline{I}_{SC}$:

$$R_{L2-L3} = \frac{U_{L2-L3} \cdot \cos\varphi_{SC}}{2 \cdot I_{SC}}$$

$$X_{L2-L3} = \frac{U_{L2-L3} \cdot \sin\varphi_{SC}}{2 \cdot I_{SC}}$$

Complex fault impedance calculation compared to real and imaginary fault loop evaluation, Single-Ph-E fault

SIEMENS



Complex impedance calculation:

$$\underline{Z}_L = \frac{\underline{U}_L}{\underline{I}_L - \underline{k}_0 \cdot \underline{I}_E}$$

$$\underline{k}_0 = \frac{\underline{Z}_E}{\underline{Z}_L} = \frac{\underline{Z}_0 - \underline{Z}_1}{3 \cdot \underline{Z}_1}$$

For $\underline{I}_L = -\underline{I}_E = \underline{I}_{SC}$:

$$R_{Ph-E} = \frac{U_{Ph-E} \cdot \cos\varphi_{SC}}{I_{SC} \cdot (1 + \underline{k}_0)}$$

$$X_{Ph-E} = \frac{U_{Ph-E} \cdot \sin\varphi_{SC}}{I_{SC} \cdot (1 + \underline{k}_0)}$$

RL and XL calculation from real and imaginary fault loop equation:

$$R_{ph-E} = \frac{\mathrm{Re}\{\underline{U}_{ph-E}\} \cdot \mathrm{Re}\{\underline{I}_X\} + \mathrm{Im}\{\underline{U}_{ph-E}\} \cdot \mathrm{Im}\{\underline{I}_X\}}{\mathrm{Re}\{\underline{I}_R\} \cdot \mathrm{Re}\{\underline{I}_X\} + \mathrm{Im}\{\underline{I}_R\} \cdot \mathrm{Im}\{\underline{I}_X\}}$$

$$X_{ph-E} = \frac{\mathrm{Im}\{\underline{U}_{ph-E}\} \cdot \mathrm{Re}\{\underline{I}_R\} - \mathrm{Re}\{\underline{U}_{ph-E}\} \cdot \mathrm{Im}\{\underline{I}_R\}}{\mathrm{Re}\{\underline{I}_R\} \cdot \mathrm{Re}\{\underline{I}_X\} + \mathrm{Im}\{\underline{I}_R\} \cdot \mathrm{Im}\{\underline{I}_X\}}$$

$$\underline{I}_R = \underline{I}_{ph} - \frac{R_E}{R_L} \cdot \underline{I}_E \quad \text{and} \quad \underline{I}_X = \underline{I}_{ph} - \frac{X_E}{X_L} \cdot \underline{I}_E \cdot$$

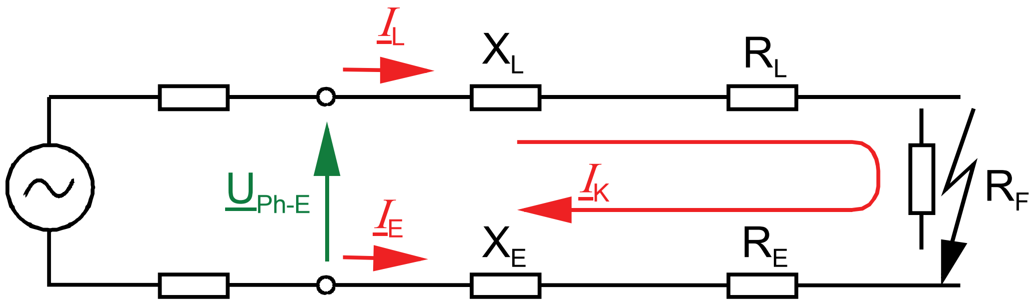
For $\underline{I}_L = -\underline{I}_E = \underline{I}_{SC}$:

$$R_{Ph-E} = \frac{U_{Ph-E} \cdot \cos\varphi_{SC}}{I_{SC}\left(1 + \frac{R_E}{R_L}\right)}$$

$$X_{Ph-E} = \frac{U_{Ph-E} \cdot \sin\varphi_{SC}}{I_{SC} \cdot \left(1 + \frac{X_E}{X_L}\right)}$$

Distance measurement (Ph-E-loop) - influence of fault resistance at separate residual compensation factors

SIEMENS

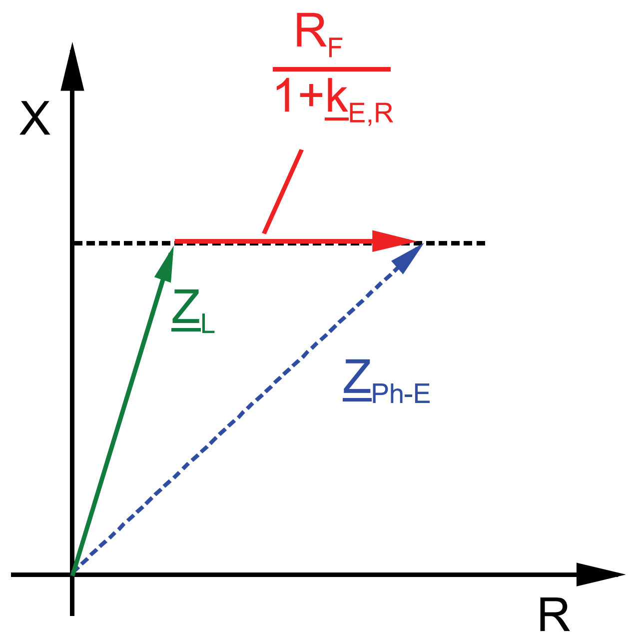


$$\underline{U}_{Ph-E} = \underline{I}_L\left(\underline{R}_L + j\,\underline{X}_L\right) - \underline{I}_E\left(\underline{R}_E + j\,\underline{X}_E\right) + R_F \cdot \underline{I}_L$$

$$X_{Ph\text{-}E} = \frac{\mathrm{Im}\left[\dfrac{\underline{U}_{Ph-E}}{\underline{I}_L}\right]}{1 + \dfrac{X_E}{X_L}} = X_L$$

$$R_{Ph\text{-}E} = \frac{\mathrm{Re}\left[\dfrac{\underline{U}_{Ph-E}}{\underline{I}_L}\right]}{1 + \dfrac{R_E}{R_L}} = R_L + \frac{R_F}{1 + k_{E,R}}$$

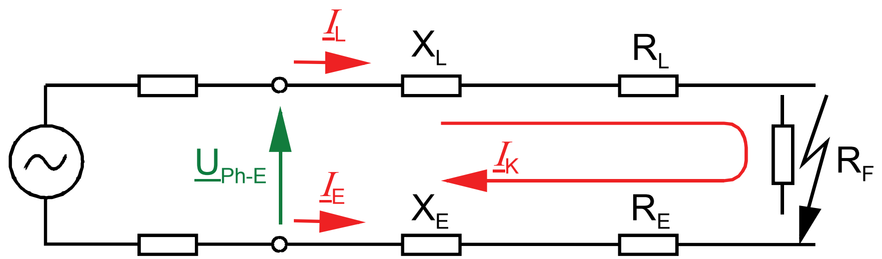
with $I_E = -I_L$



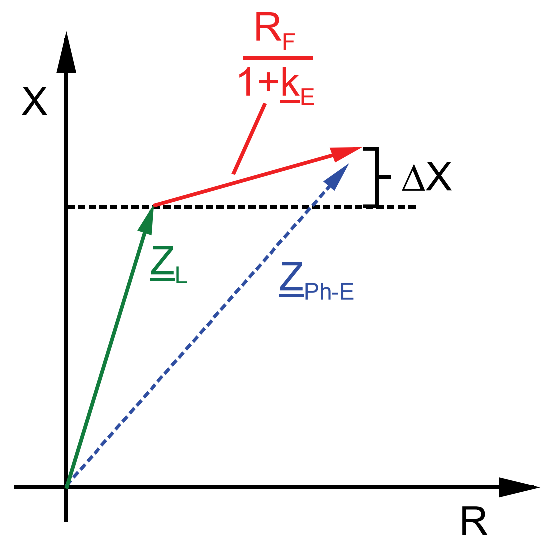
No measuring error in the X-direction

Distance measurement (Ph-E-loop) influence of fault resistance

SIEMENS



This method is not used by SIEMENS



$$\underline{U}_{Ph-E} = \underline{I}_L\left(\underline{Z}_L + \underline{Z}_E\right) + R_F \cdot \underline{I}_L \qquad \text{assume} \qquad \underline{I}_L = -\underline{I}_E$$

$$\underline{Z}_{Ph-E} = \frac{\underline{U}_{Ph-E}}{\underline{I}_L - \underline{k}_E \cdot \underline{I}_E} = \underline{Z}_L \cdot \frac{1+\frac{\underline{Z}_E}{\underline{Z}_L}}{1+\underline{k}_E} + \frac{R_F}{1+\underline{k}_E}$$

If $\underline{k}_E$ setting adapted to $\frac{\underline{Z}_E}{\underline{Z}_L}$, then $\underline{Z}_{Ph-E} = \underline{Z}_L + \frac{R_F}{1+\frac{\underline{Z}_E}{\underline{Z}_L}} = \underline{Z}_L + \frac{R_F}{1+\left|\frac{\underline{Z}_E}{\underline{Z}_L}\right| \cdot e^{j(\varphi E - \varphi L)}}$

➡ **Also an additional measuring error in the X-direction**

Numerical Impedance calculation (7SA5, 7SA6)
Evaluation of the complex Ph-Ph fault loop equation

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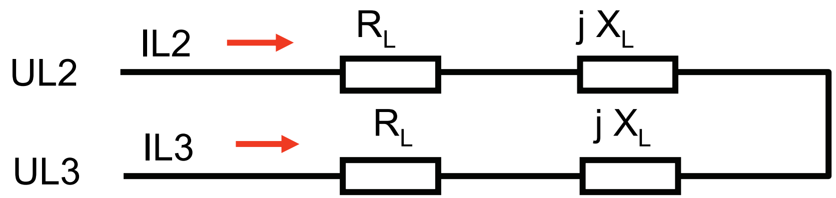
$$\underline{U}_{L1-L2} = (R_L + jX_L)\cdot(\underline{I}_{L1} - \underline{I}_{L2})$$



$$U_{L2-L3}\cdot(\cos\varphi_U + j\sin\varphi_U) = (R_L + jX_L)\cdot[I_{L2}\cdot(\cos\varphi_{I2} + j\sin\varphi_{I2}) - I_{L3}\cdot(\cos\varphi_{I3} + j\sin\varphi_{I3})]$$

$$U_{L2-L3}\cdot\cos\varphi_U = R_L\cdot(I_{L2}\cdot\cos\varphi_{IL2} - I_{L3}\cdot\cos_{IL3}) - X_L\cdot(I_{L2}\cdot\sin\varphi_{IL2} - I_{L3}\cdot\sin_{IL3})$$

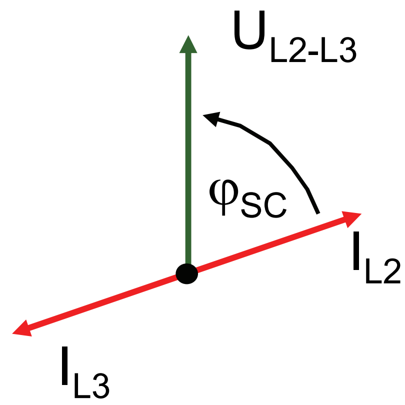
$$U_{L2-L3}\cdot\sin\varphi_U = R_L\cdot(I_{L2}\cdot\sin\varphi_{IL2} - I_{L3}\cdot\sin\varphi_{IL3}) + X_L\cdot(I_{L2}\cdot\cos\varphi_{IL2} - I_{L3}\cdot\cos_{IL3})$$

$$R_{L2\text{-}L3} = \frac{U_{L2\text{-}L3}\,[I_{L2}\cdot\cos(\varphi_{UL2\text{-}L3} - \varphi_{IL2}) - I_{L3}\cdot\cos(\varphi_{UL2\text{-}L3} - \varphi_{IL3})]}{I^2_{L2} - 2\cdot I_{L2}\cdot I_{L3}\cdot\cos(\varphi_{IL2} - \varphi_{IL3}) + I^2_{L3}}$$

$$X_{L2\text{-}L3} = \frac{U_{L2\text{-}L3}\,[I_{L2}\cdot\sin(\varphi_{UL2\text{-}L3} - \varphi_{IL2}) - I_{L3}\cdot\sin(\varphi_{UL2\text{-}L3} - \varphi_{IL3})]}{I^2_{L2} - 2\cdot I_{L2}\cdot I_{L3}\cdot\cos(\varphi_{IL2} - \varphi_{IL3}) + I^2_{L3}}$$

With $\varphi_{IL2} = 0$ *and* $\underline{I}_{L3} = -\underline{I}_{L2} : \varphi_{IL3} = -\varphi_{IL2} = 180^o$, *and* $\varphi_{UL2\text{-}UL3} = \varphi_{SC}$:

$$R_{L2-L3} = \frac{U_{L2-L3}\cdot\cos\varphi_{SC}}{I_{L2} - I_{L3}} \qquad X_{L2-L3} = \frac{U_{L2-L3}\cdot\sin\varphi_{SC}}{I_{L2} - I_{L3}}$$



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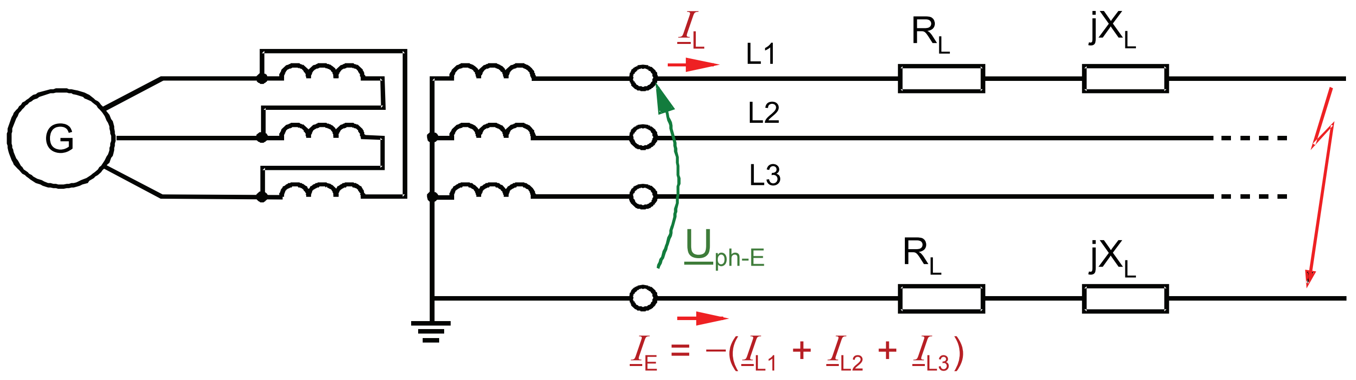
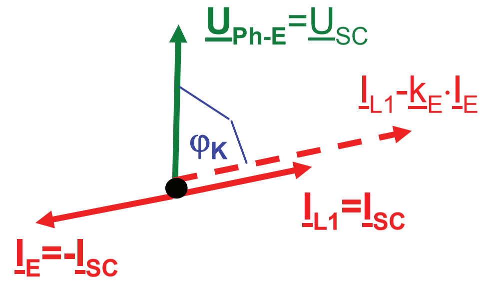
Numerical Impedance calculation (7SA5, 7SA6)
Evaluation of the complex Ph-E fault loop equation





$$X_{Ph\text{-}E} = \frac{U_{Ph\text{-}E}}{IL} \cdot \frac{\sin(\varphi_U - \varphi_{IL}) - \frac{IE}{IL} \cdot \frac{RE}{RL} \cdot \sin(\varphi_U - \varphi_{IE})}{1 - \left(\frac{XE}{XL} + \frac{RE}{RL}\right) \cdot \frac{IE}{IL} \cdot \cos(\varphi_{IE} - \varphi_{IL}) + \frac{RE}{RL} \cdot \frac{XE}{XL} \cdot \left(\frac{IE}{IL}\right)^2}$$

$$R_{Ph\text{-}E} = \frac{U_{Ph\text{-}E}}{I_L} \cdot \frac{\cos(\varphi_U - \varphi_{IL}) - \frac{IE}{IL} \cdot \frac{XE}{XL} \cdot \cos(\varphi_U - \varphi_{IE})}{1 - \left(\frac{XE}{XL} + \frac{RE}{RL}\right) \cdot \frac{IE}{IL} \cdot \cos(\varphi_{IE} - \varphi_{IL}) + \frac{RE}{RL} \cdot \frac{XE}{XL} \cdot \left(\frac{IE}{IL}\right)^2}$$

With $\varphi_{IL} = 0$, $\varphi_{IE} = -\varphi_{IL} = 180^o$ *and* $\varphi_U = \varphi_K$:

$$X_{Ph-E} = \frac{U_{Ph-E} \cdot \sin\varphi_K}{I_L + \frac{X_E}{X_L} \cdot I_E}$$

$$R_{Ph-E} = \frac{U_{Ph-E} \cdot \cos\varphi_K}{I_L + \frac{R_E}{R_L} \cdot I_E}$$

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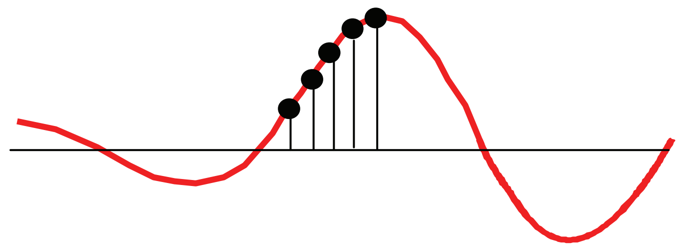
Fast impedance estimation by Least Squares approximation

$$i_{(t)} = A \cdot \sin(\omega t) + B \cdot \left(\cos(\omega t) - e^{-\frac{t}{\tau}} \right) + C \cdot \cos(\omega t)$$



Task: **Estimation of the coefficients A, B, C and τ on basis of measured current samples**

Method: **Gauß's *Minimization of error squares:***

$$\text{Delta} = \sum_{i=k-N}^{k} \left(u_{(i)} - f_{(i)} \right)^2 \Rightarrow \text{MIN}$$

$$\Downarrow$$

$$\frac{Delta}{dA\ dB\ dC d\tau} = 0$$

Delta = quality value
k = sampling number
N = length of data window
i = variable

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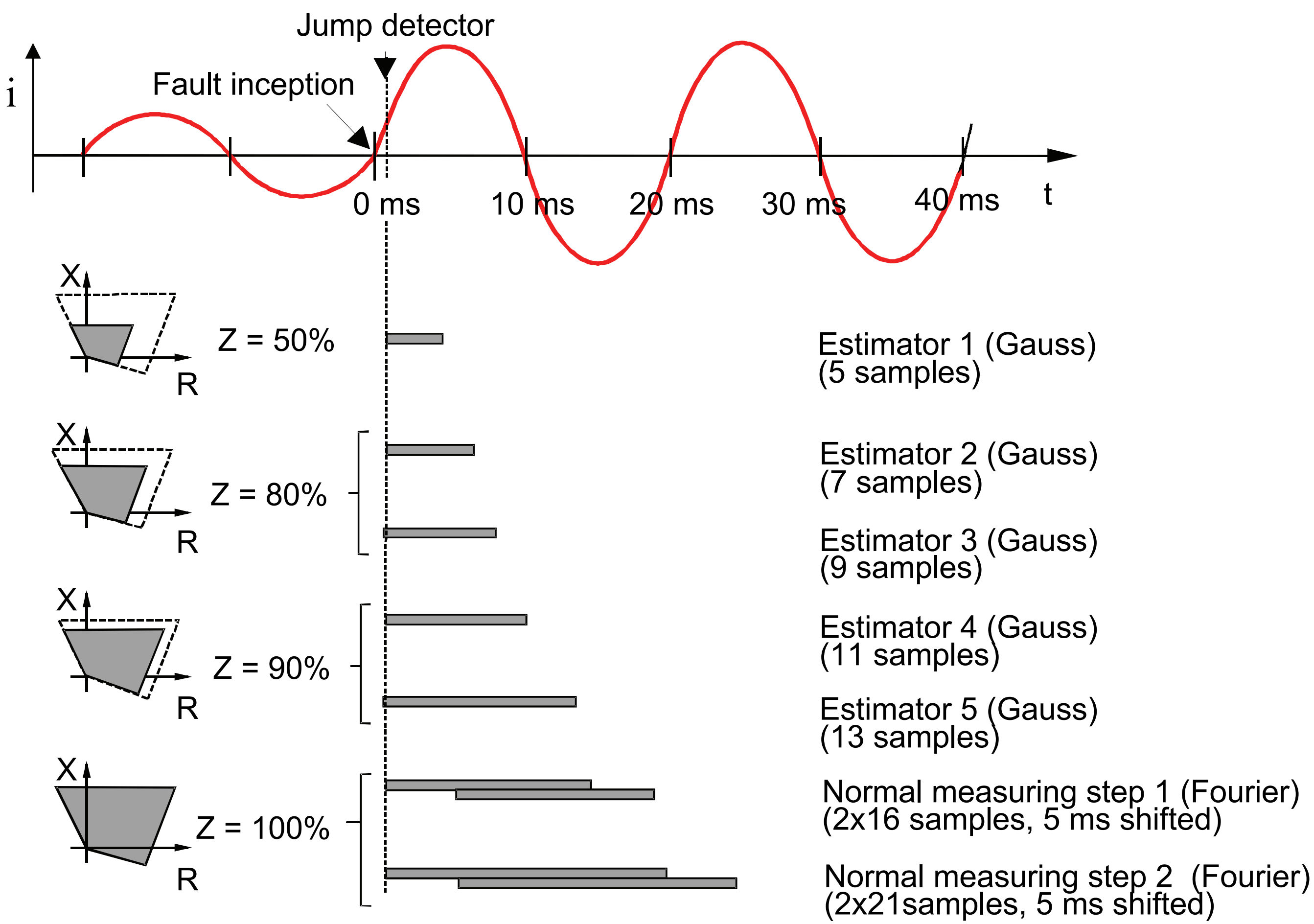
Distance protection: Adaptive measuring method



Distance protection,
Typical operating time characteristic

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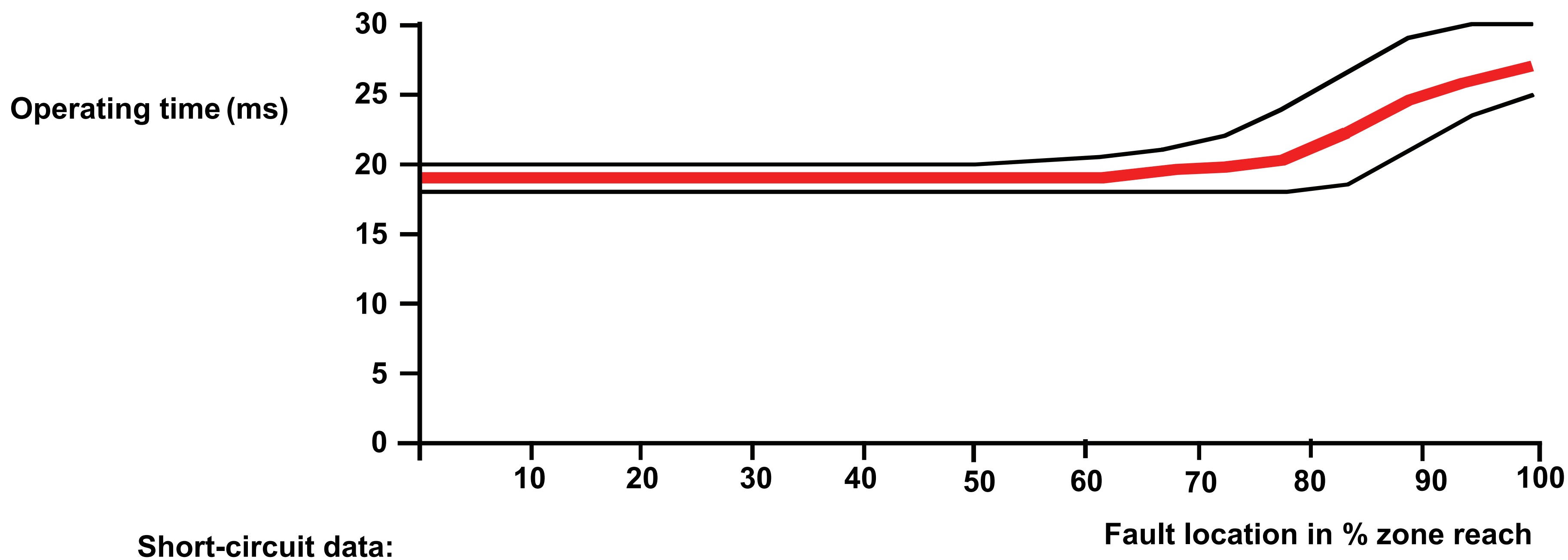

Short-circuit data:
SIR = 26
f = 50 Hz
Fault: L1-E
5 shots per fault case
Fault inception: 0° ... 90°

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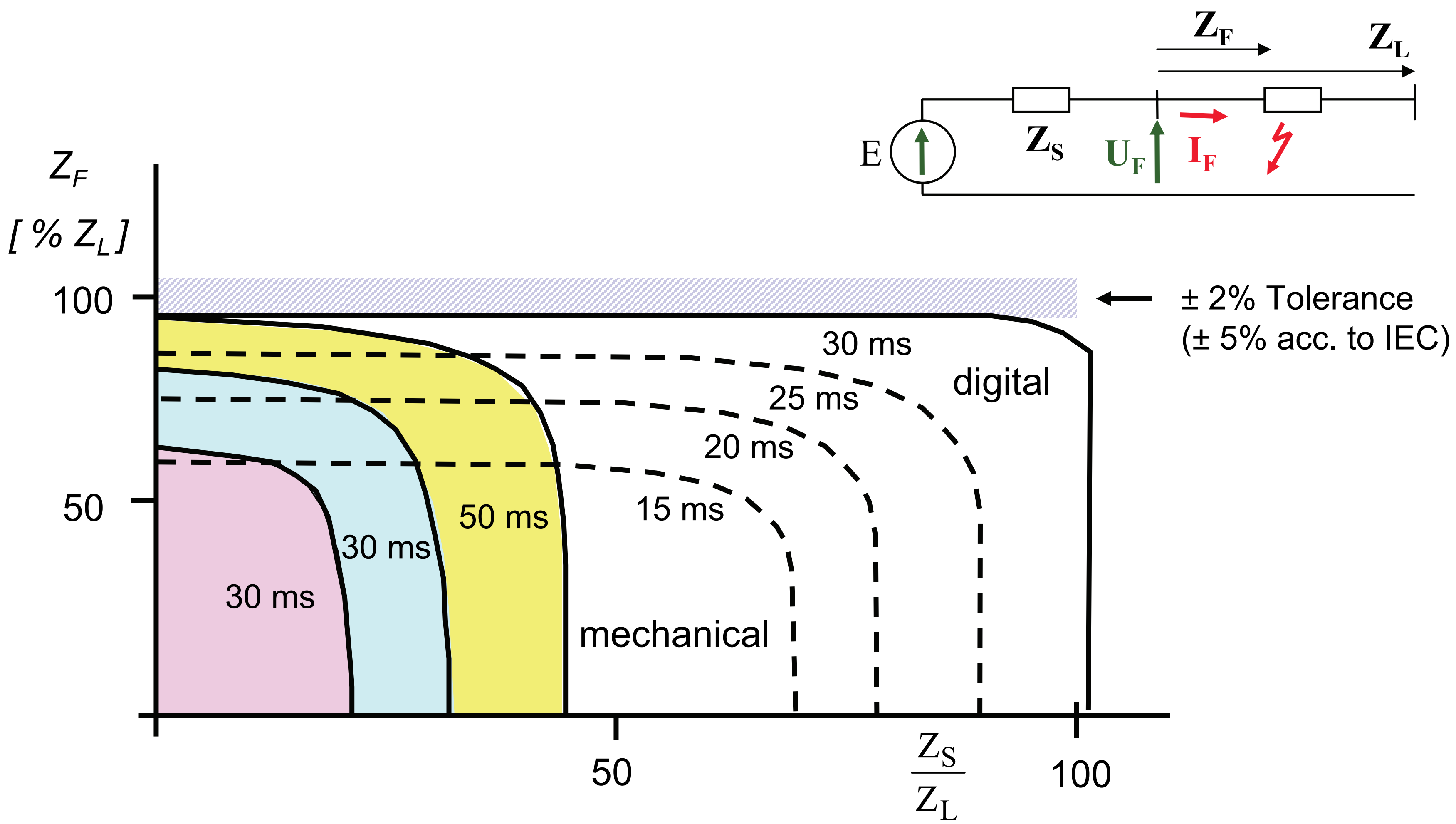
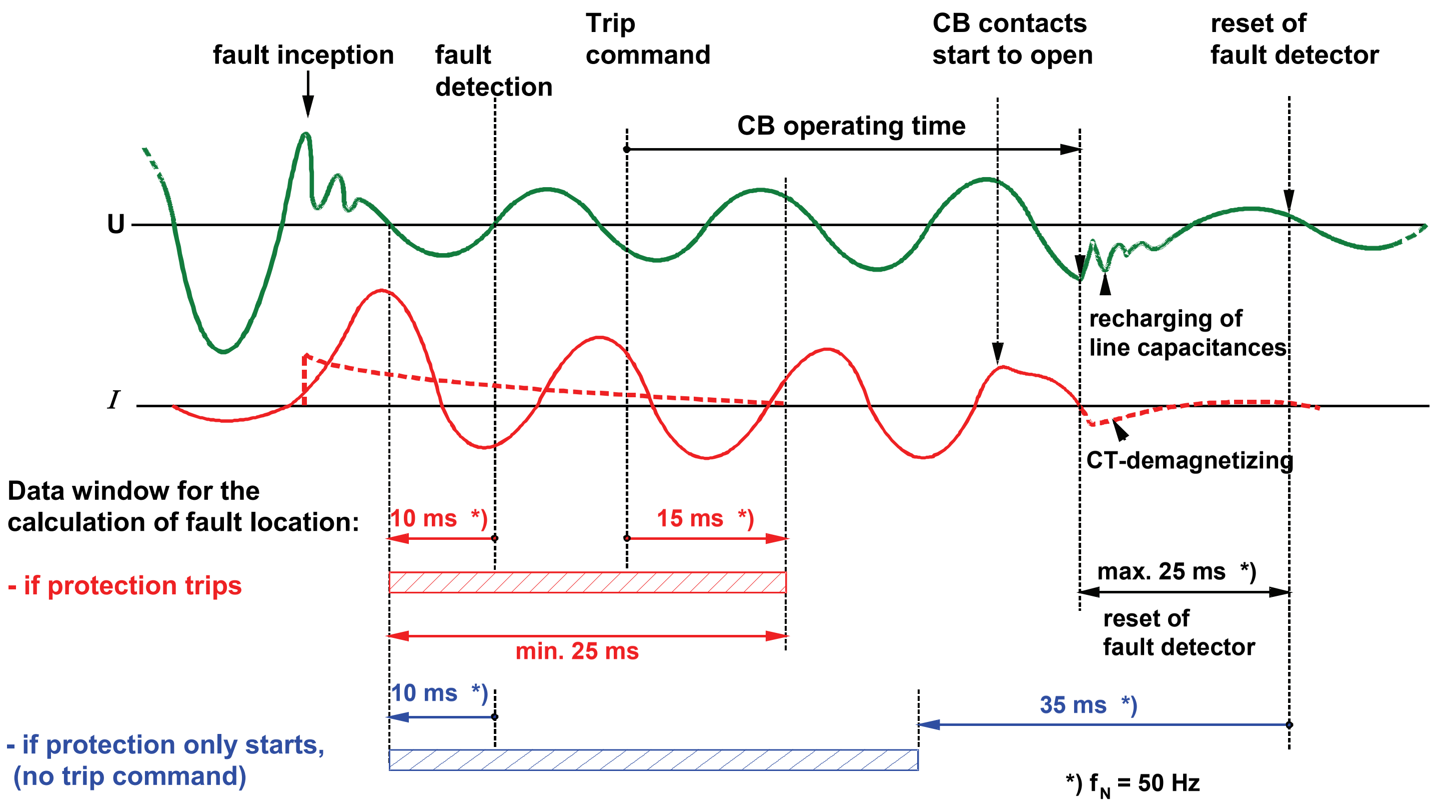
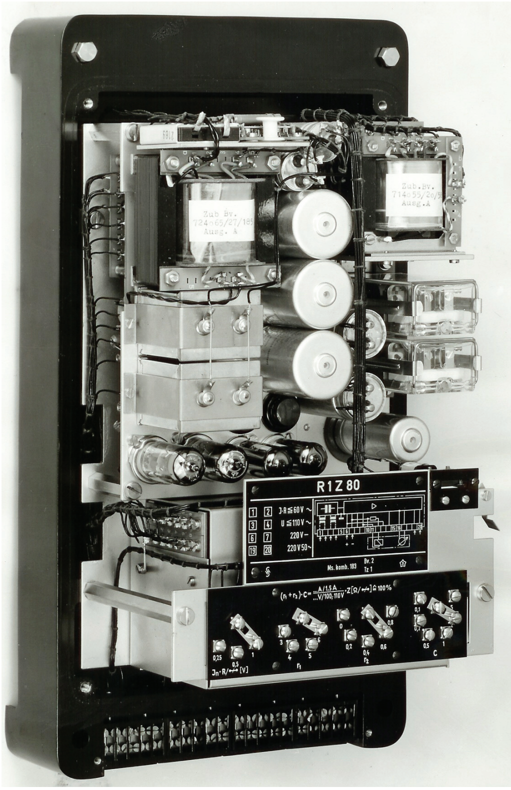
Contour diagram of distance relay performance



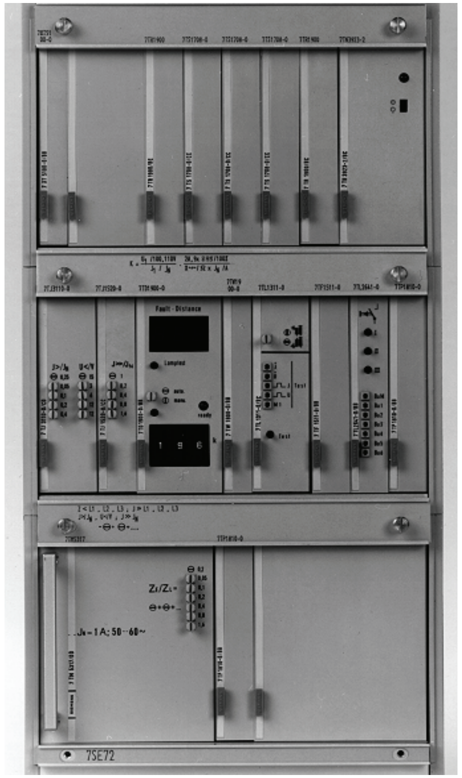
Placing of data window for distance to fault computation



Historic fault locator relays

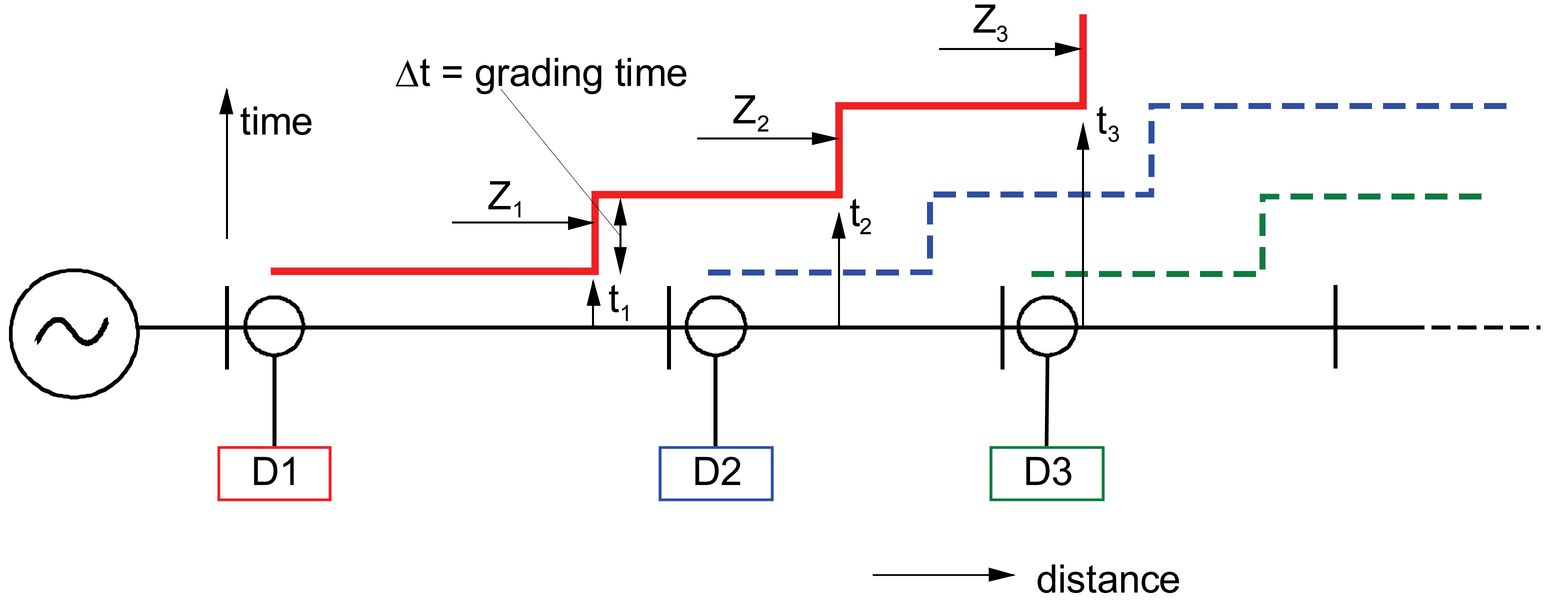


Electromechanical
(with cold cathode tubes)

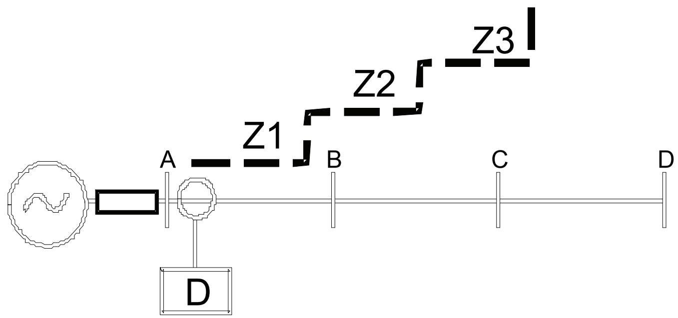


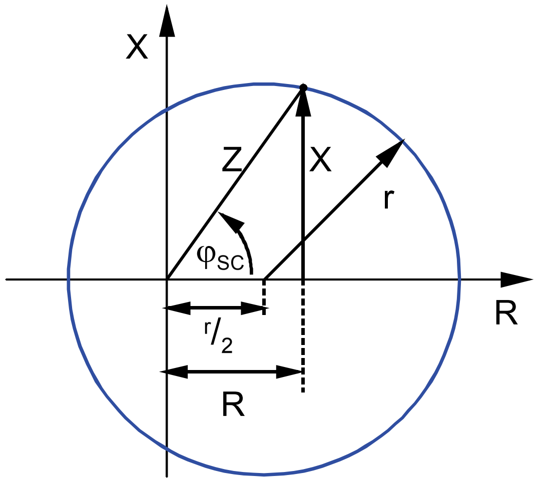
Static (electronic)

Graded distance zones



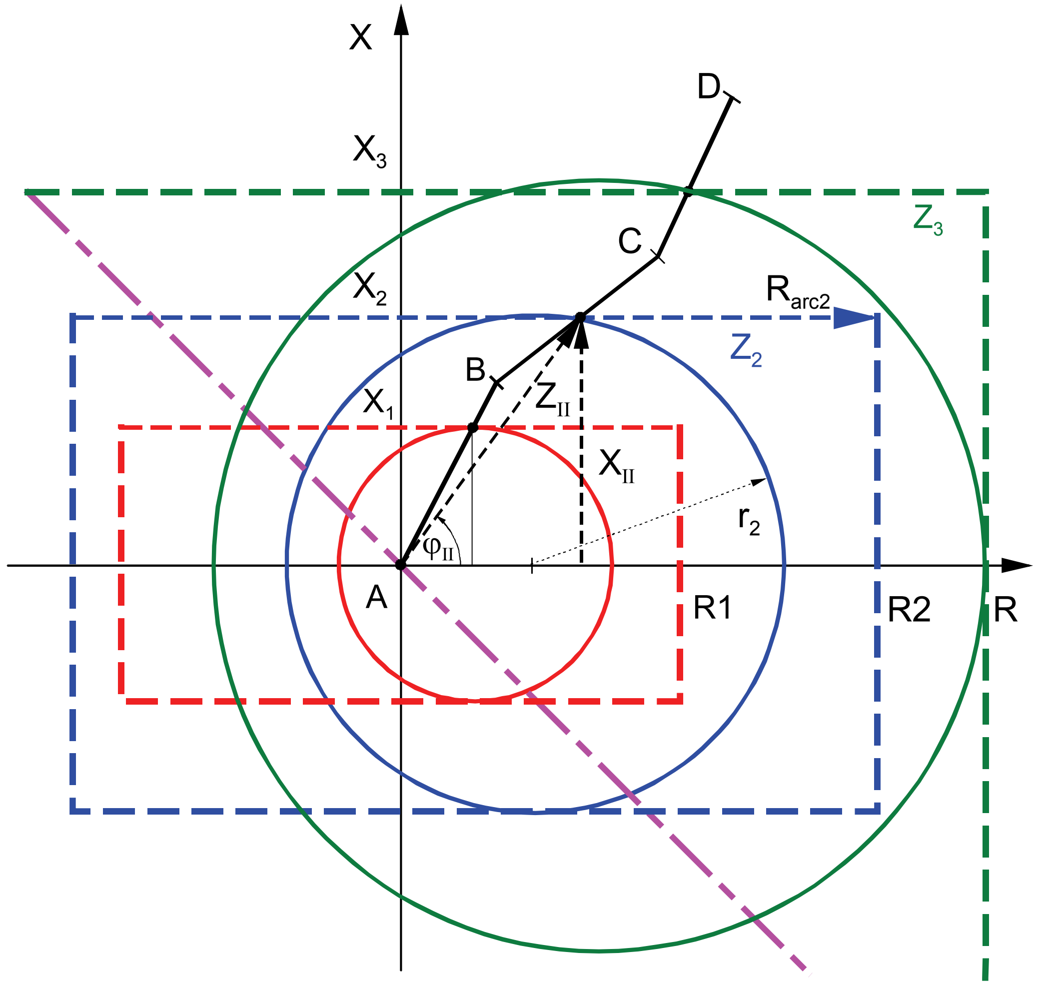
Distance zone setting - electromechanical and digital





$$r = \frac{-R \pm \sqrt{R^2 + 3 \cdot Z^2}}{3/2}$$

electro-mechanical



Determination of fault direction

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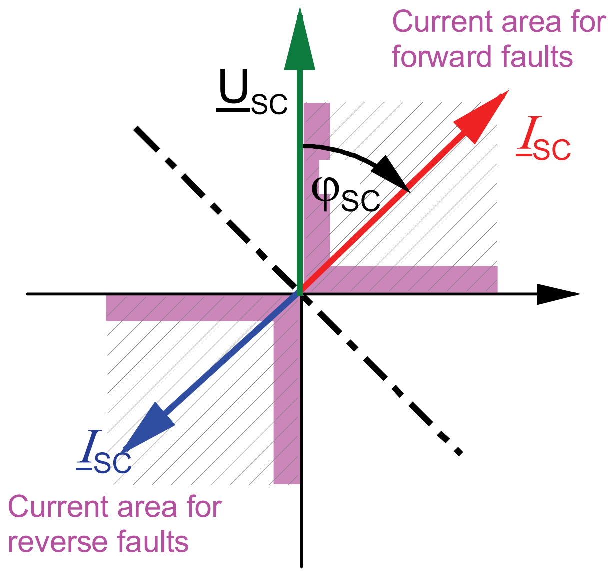
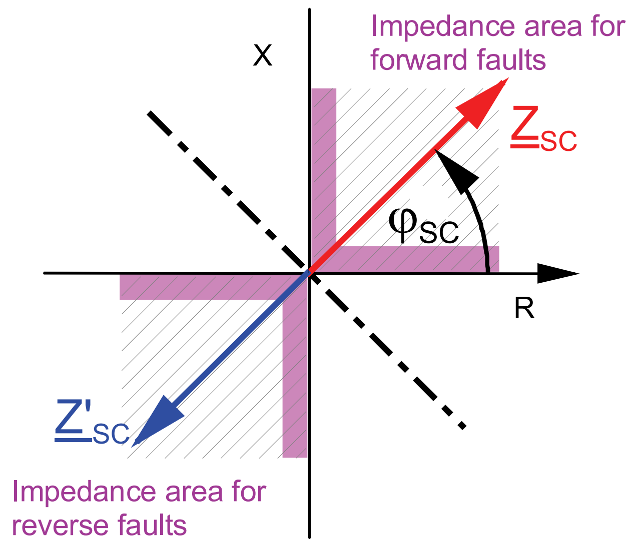


current / voltage diagram



impedance diagram

Distance protection, fault detector controlled timing

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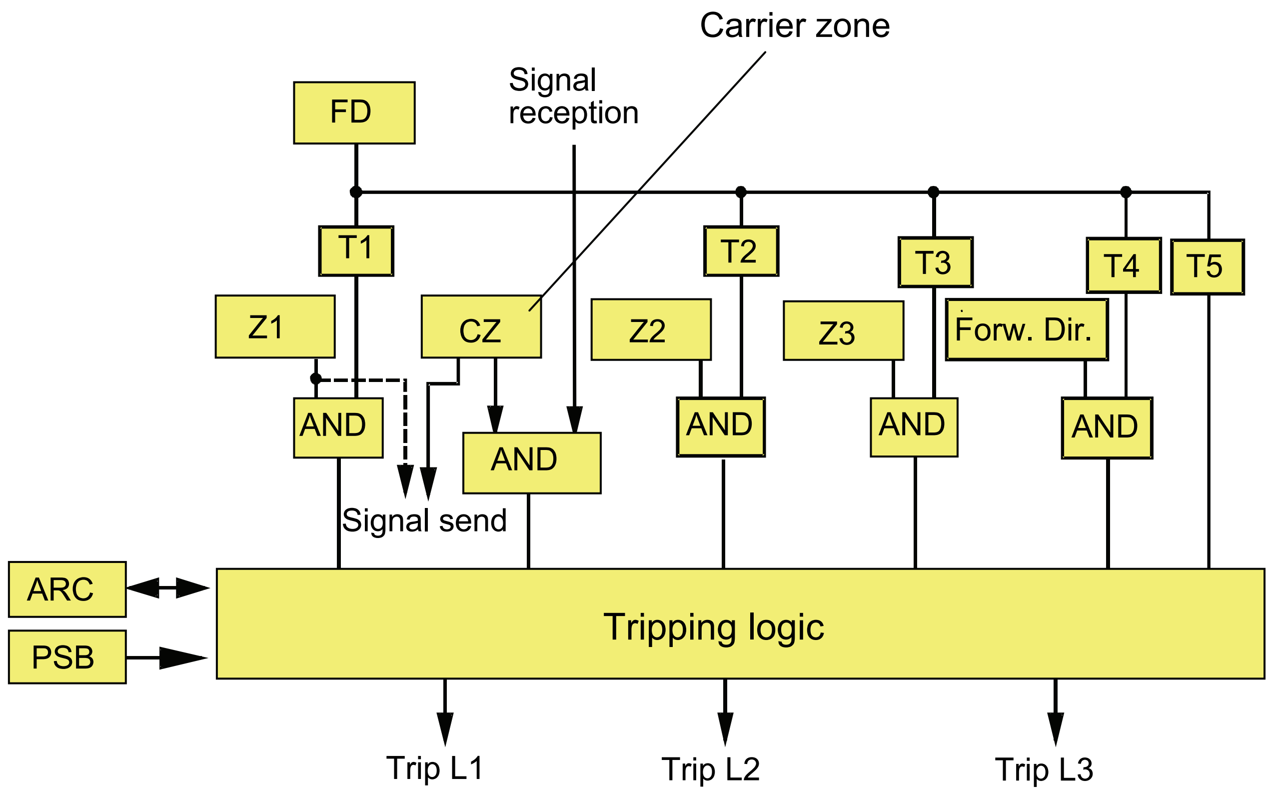
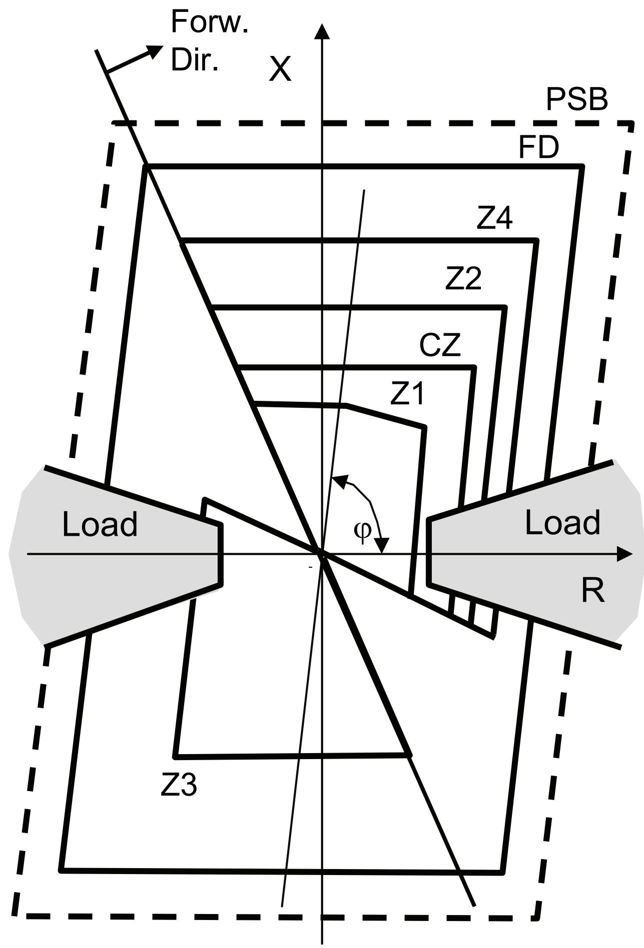
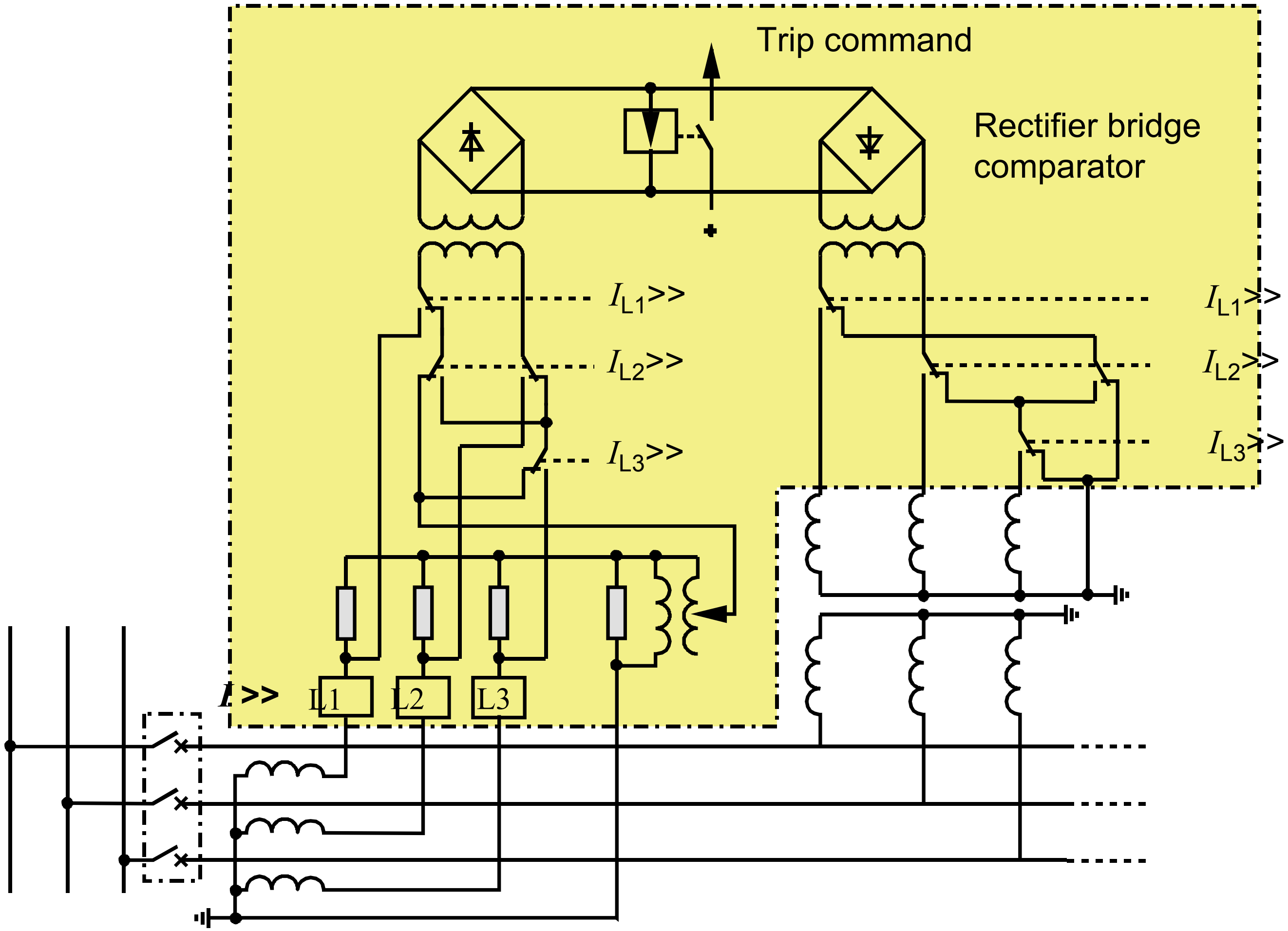




Electro-mechanical switched distance protection

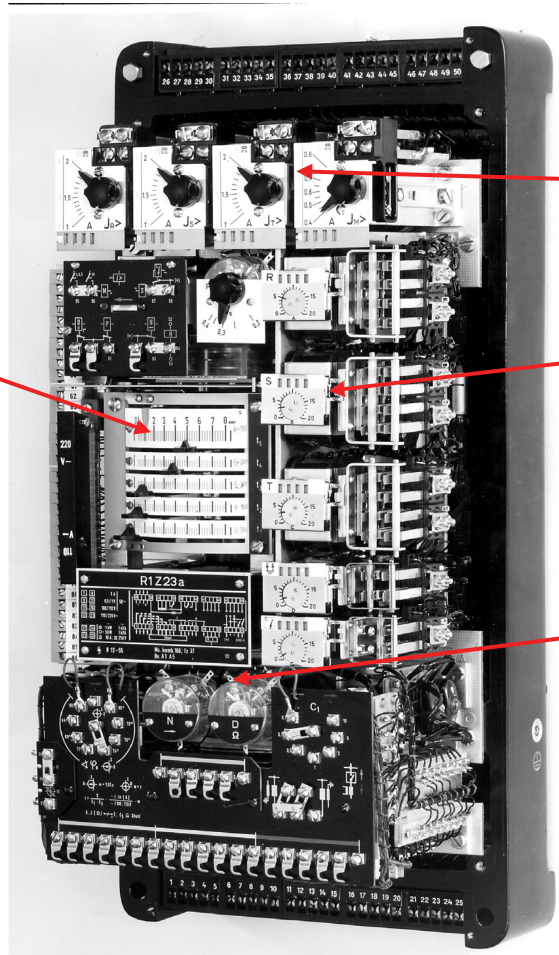
(principle of measured value switching)



Electro-mechanical switched distance protection

(Version for subtransmission networks)

SIEMENS



Timer with
slave pointer

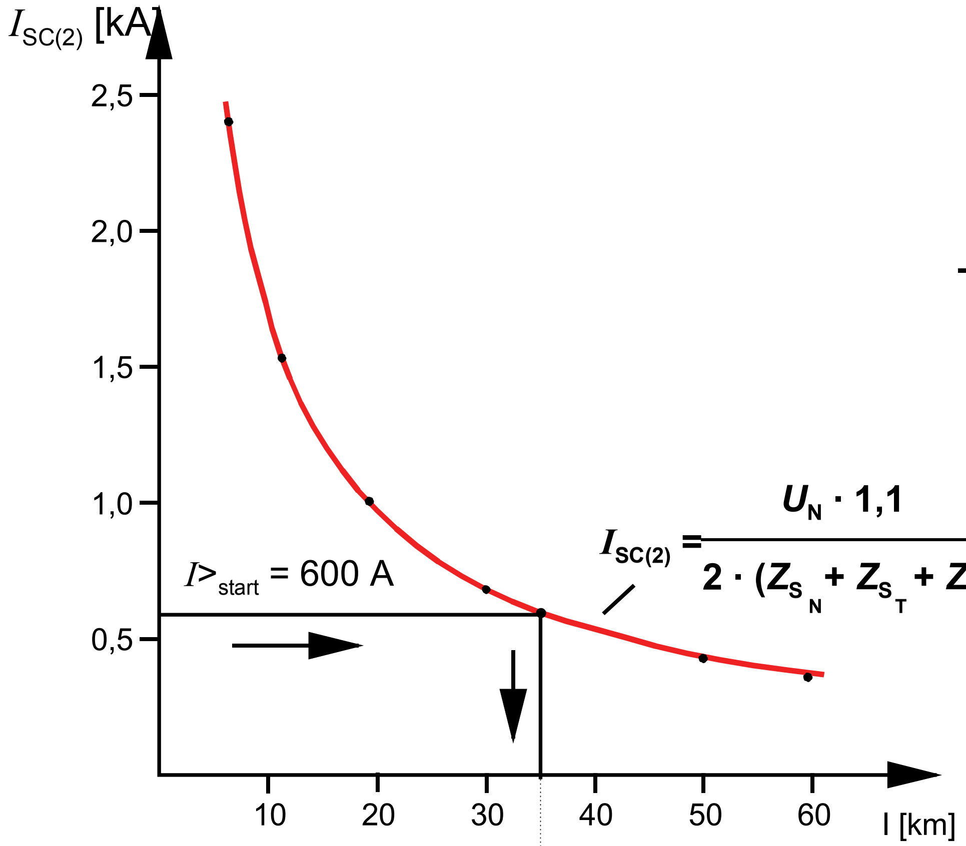
I>-starter relays
L1, L2, L3, M

Flags,
alarm relays

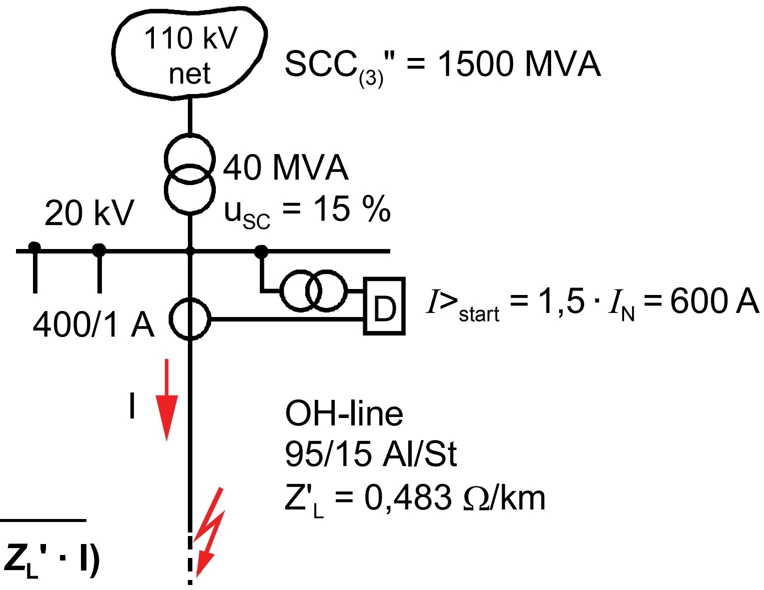
Moving coil relays
D: Distance measurement
N: Directional discrimination

Reach of overcurrent starter

ph-ph fault as an example



$$I_{SC(2)} = \frac{U_N \cdot 1{,}1}{2 \cdot (Z_{S_N} + Z_{S_T} + Z_L' \cdot l)}$$



Voltage controlled overcurrent starter

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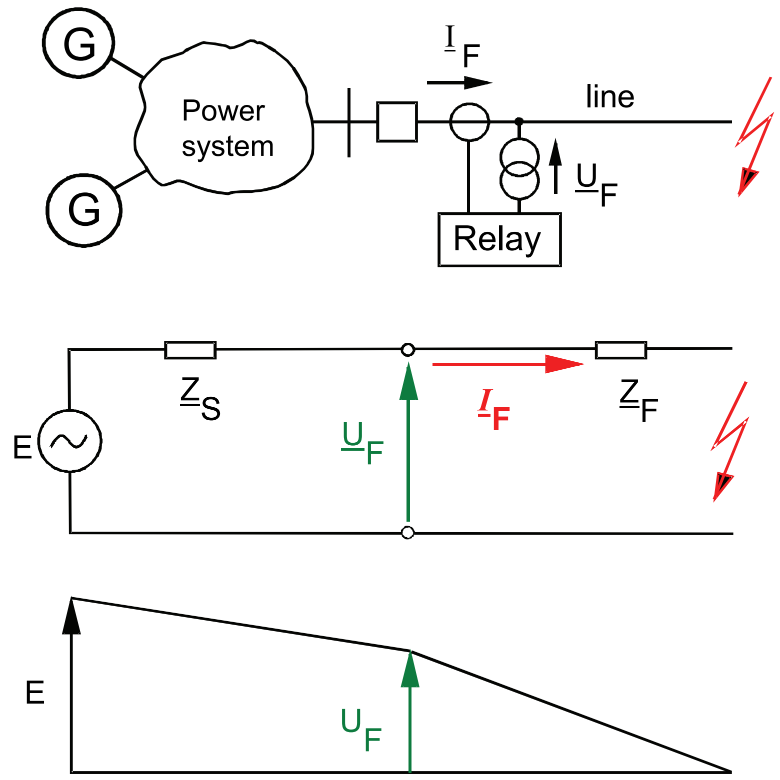

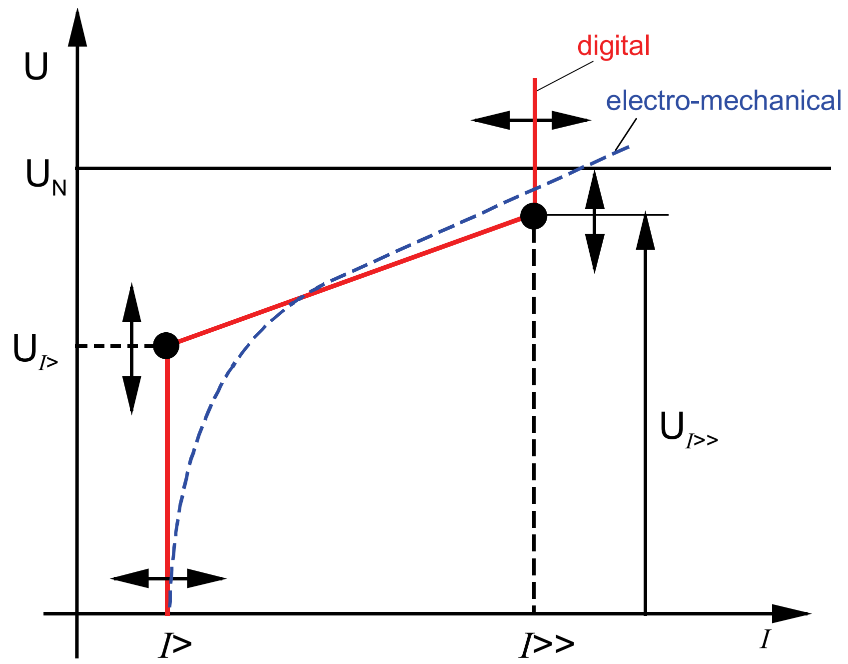

Short circuit in an effectively earthed system with unequal source and earthing conditions

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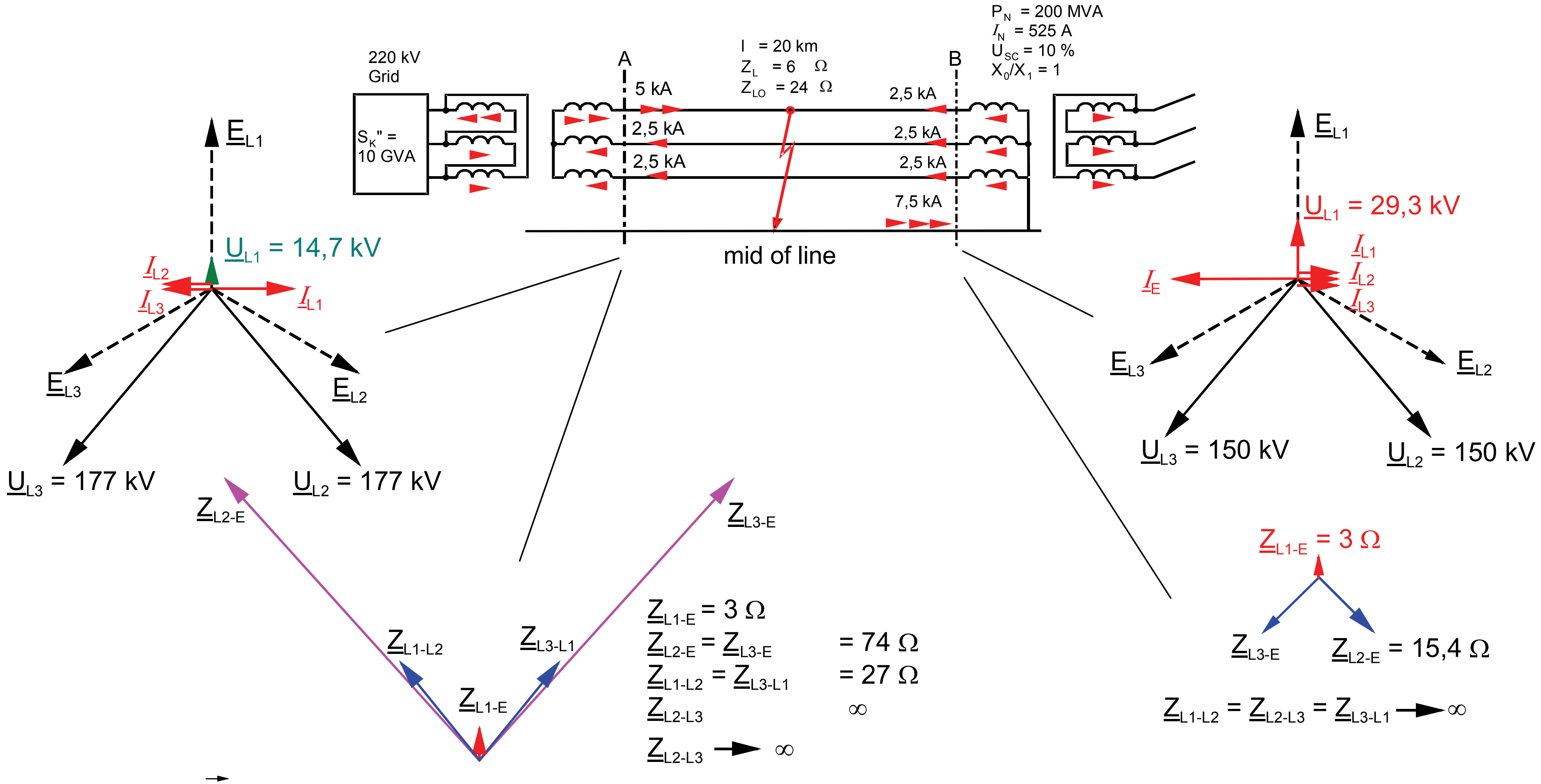
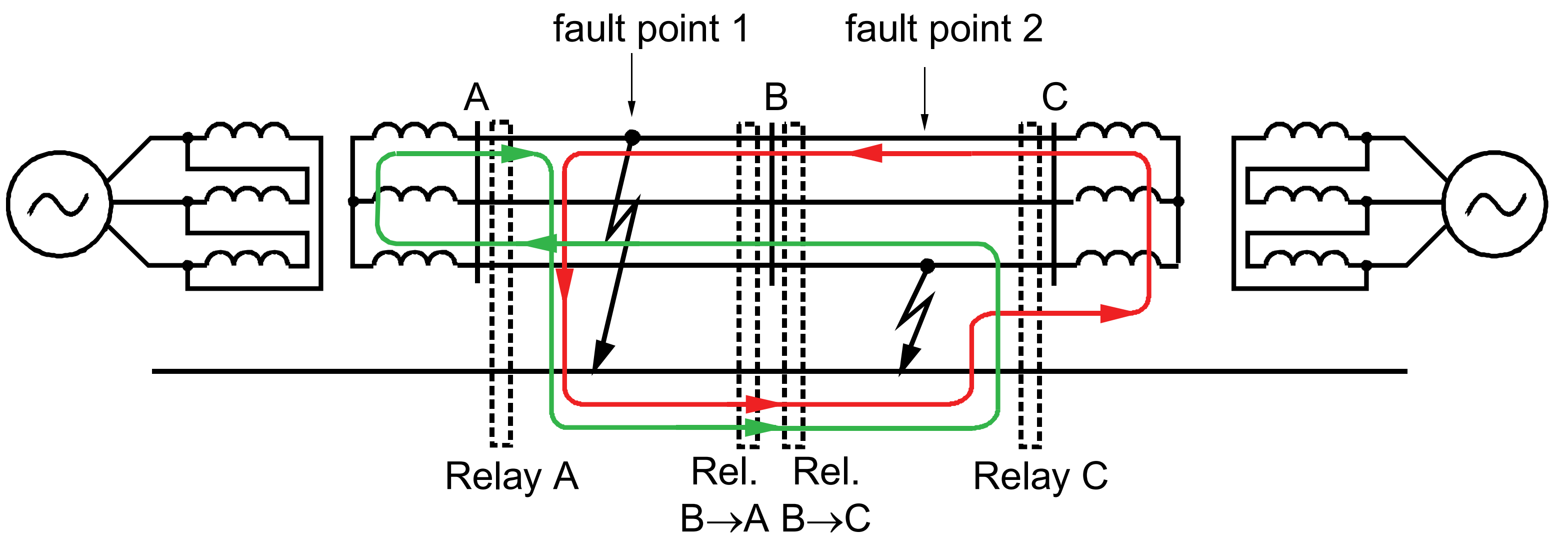
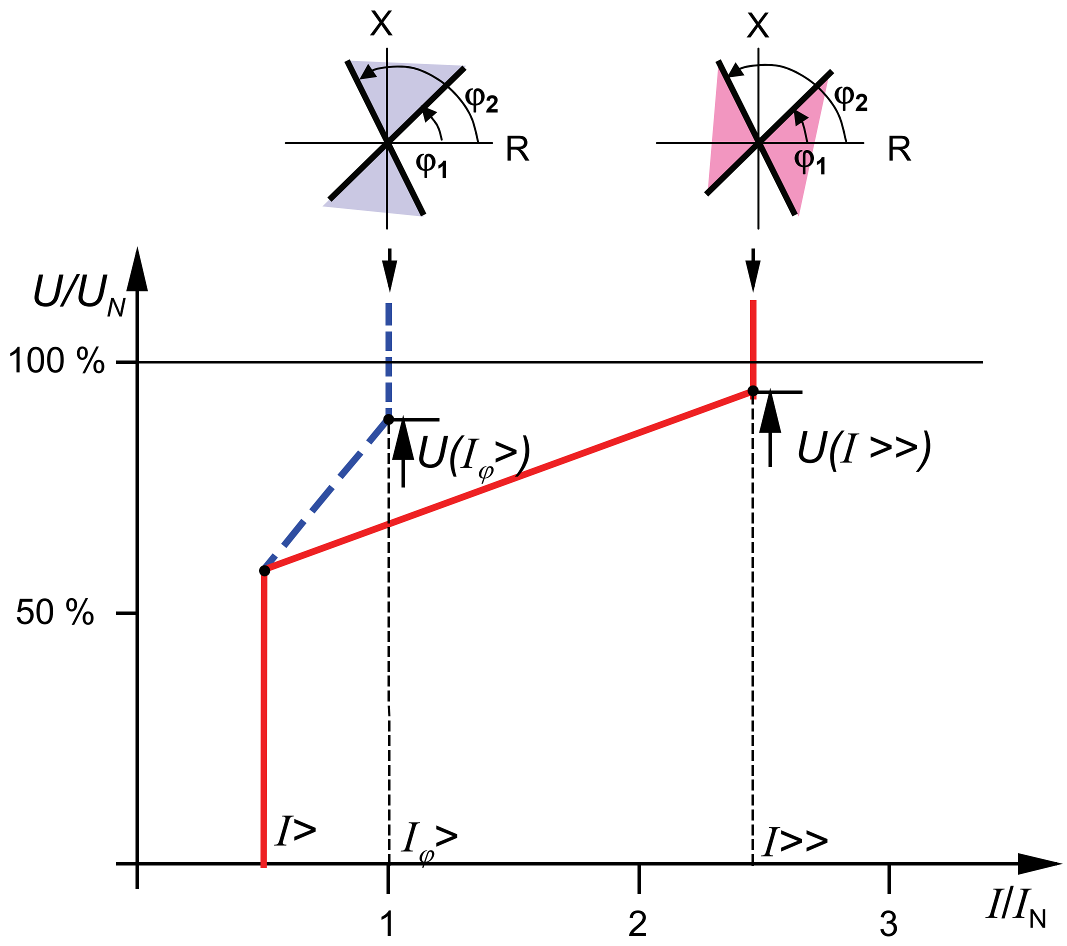


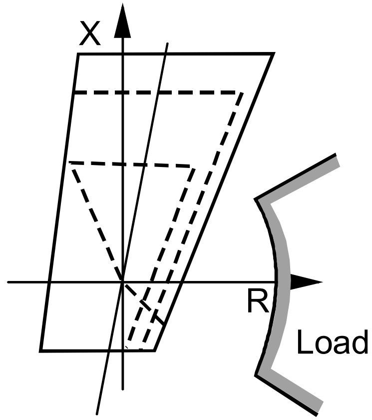
Cross country earth fault in the isolated/compensated network



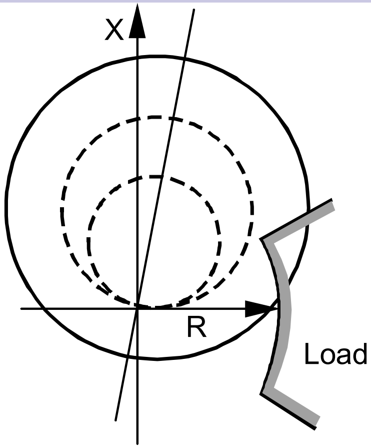
Voltage and angle controlled overcurrent starter (U-I-φ-starting)



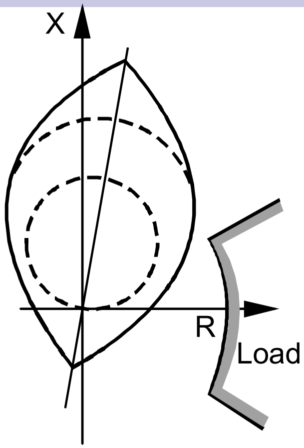
Impedance starting with conventional technology



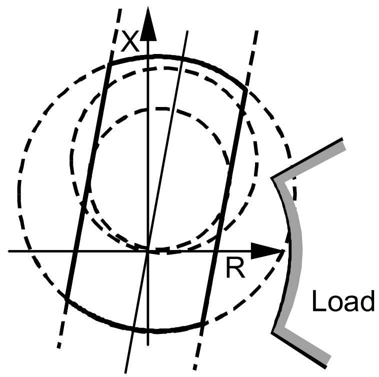
quadrilateral



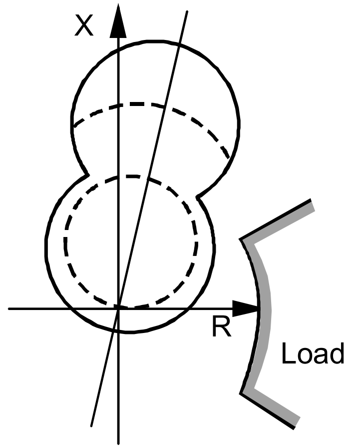
offset MHO-circle



lense



offset MHO-circle with "blinder"



eight ("peanut")

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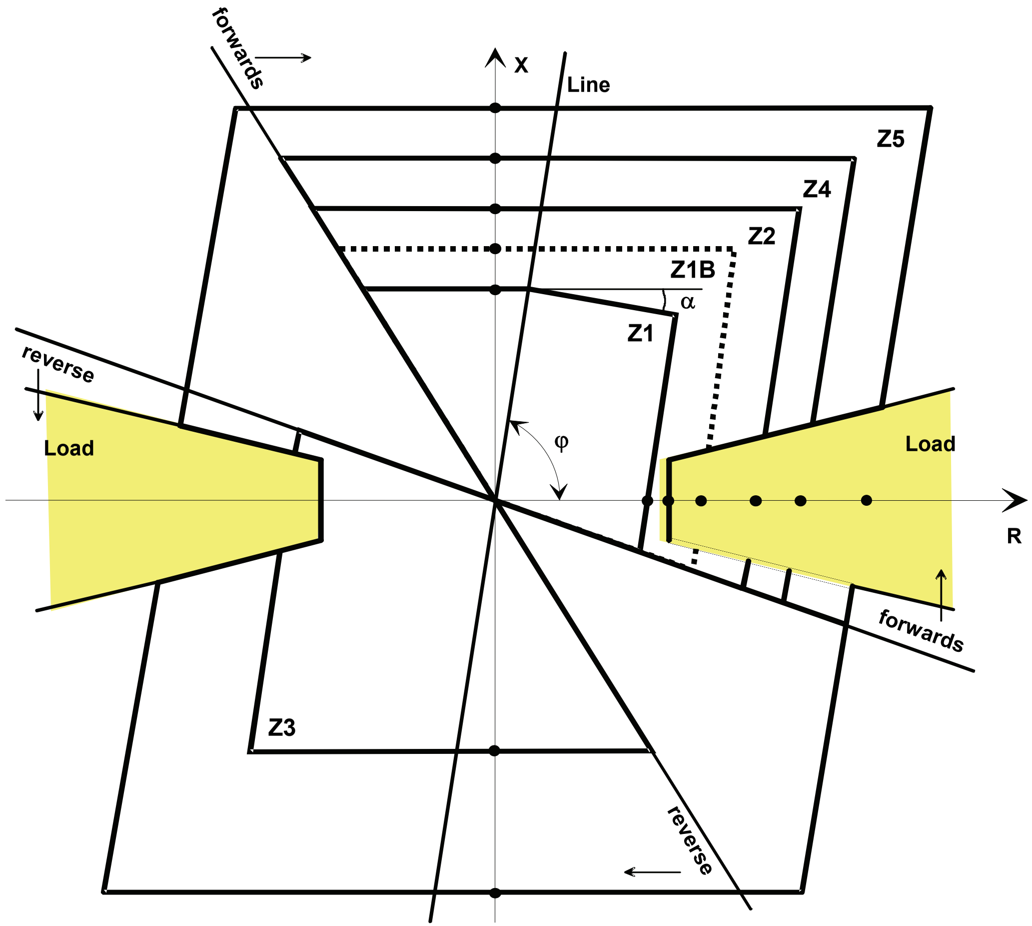
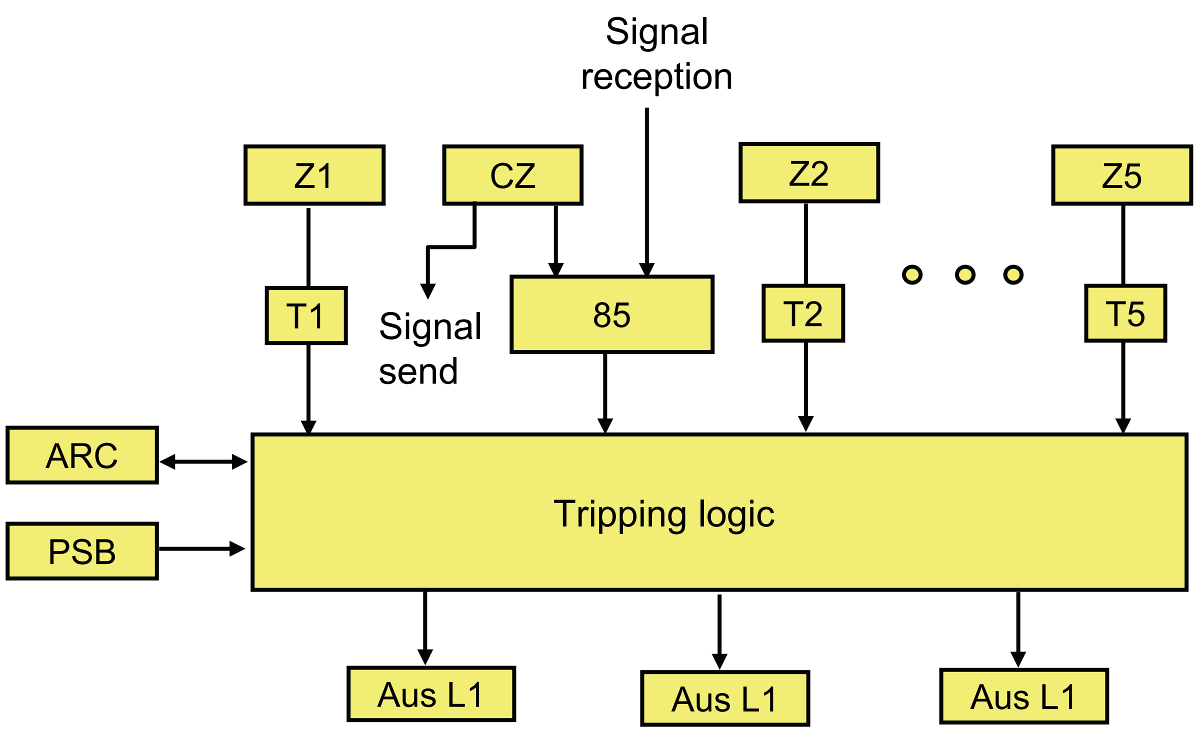
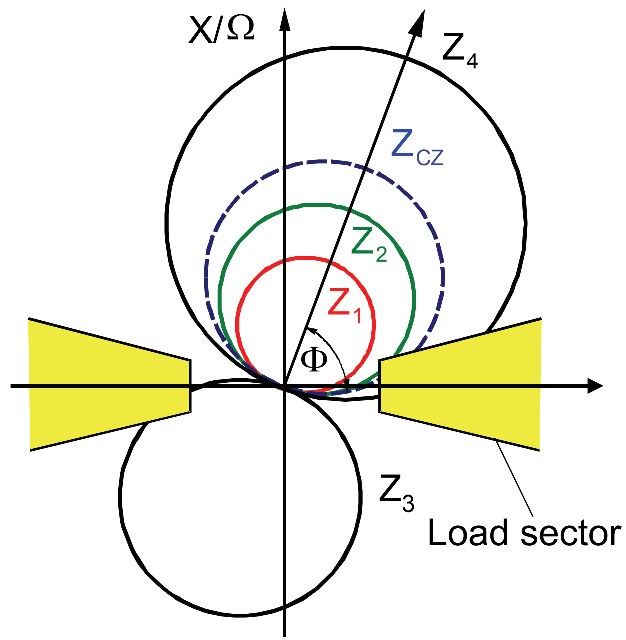
Impedance zones of modern digtital relays (7SA6 und 7SA52)



Distance protection with zone dedicated time control
“Zone Packaged“ design (7SA6 und 7SA522)

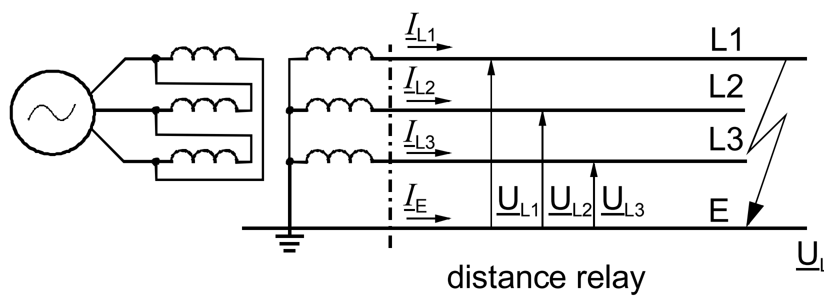
SIEMENS

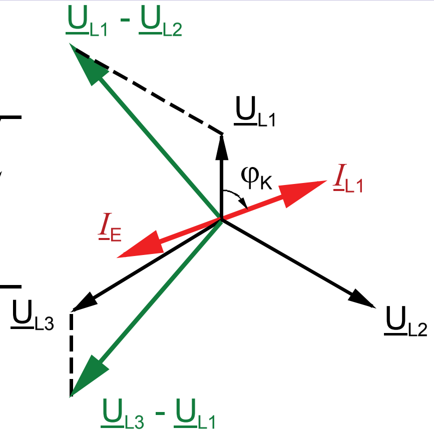


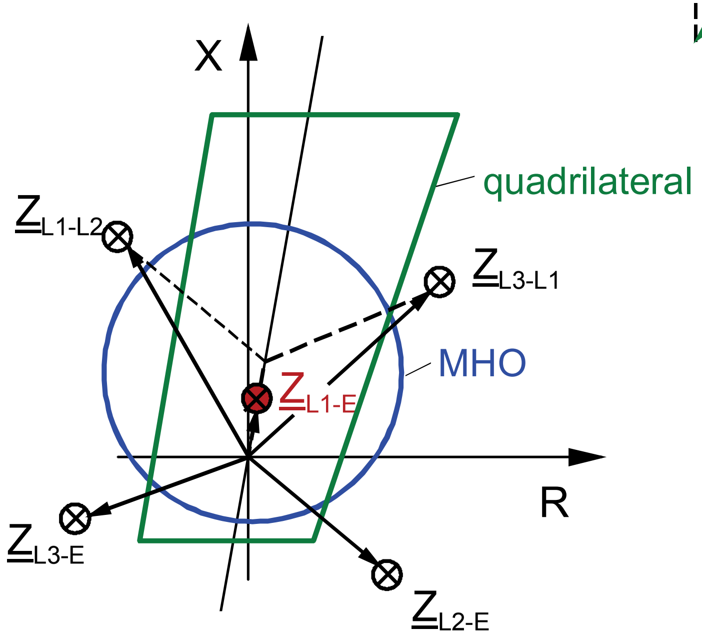


Conventional relays: limiting of the starting characteristic area for phase-selective fault detection

SIEMENS







impedance of faulted loop:

$$\underline{Z}_{L1\text{-}E} = \frac{\underline{U}_{L1}}{\underline{I}_{L1} - \underline{K}_E \cdot \underline{I}_E}$$

impedance of healthy loops:

$$\underline{Z}_{L2\text{-}E} = \frac{\underline{U}_{L2}}{\underline{I}_{L2} - \underline{K}_E \cdot \underline{I}_E}$$

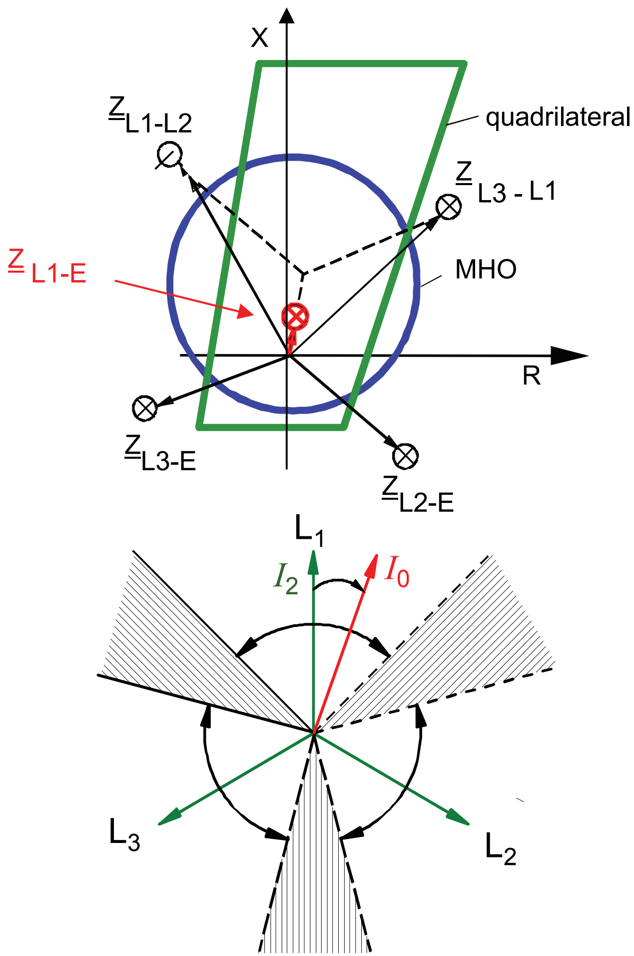
$$\underline{Z}_{L3\text{-}E} = \frac{\underline{U}_{L3}}{\underline{I}_{L3} - \underline{K}_E \cdot \underline{I}_E}$$

$$\underline{Z}_{L1\text{-}L2} = \frac{\underline{U}_{L1} - \underline{U}_{L2}}{\underline{I}_{L1} - \underline{I}_{L2}}$$

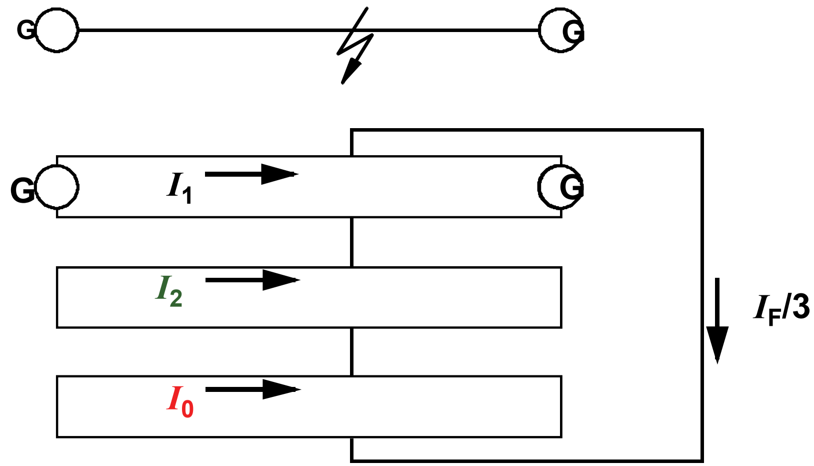
$$\underline{Z}_{L2\text{-}L3} = \frac{\underline{U}_{L2} - \underline{U}_{L3}}{\underline{I}_{L2} - \underline{I}_{L3}}$$

$$\underline{Z}_{L3\text{-}L1} = \frac{\underline{U}_{L3} - \underline{U}_{L1}}{\underline{I}_{L3} - \underline{I}_{L1}}$$

Distance protection
Modern methods of phase selection



- **Intelligent phase selection:**
  - Impedance comparison
  - Symmetrical component analysis
  - Load compensation
  - Pattern recognition



Phase selection

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Differentiating between single and double Ph-E fault

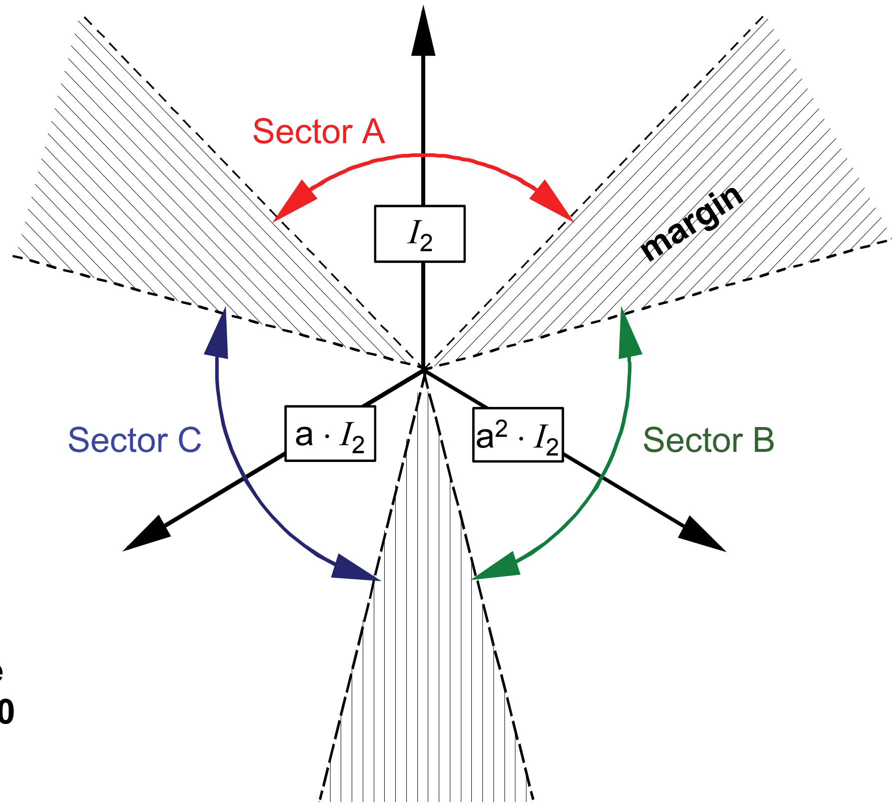
$$\underline{I}_0 = \frac{1}{3}\left(\underline{I}_{L1} + \underline{I}_{L2} + \underline{I}_{L3}\right)$$

$$\underline{I}_2 = \frac{1}{3}\left(\underline{I}_{L1} + a^2\,\underline{I}_{L2} + a\,\underline{I}_{L3}\right)$$

$\underline{I}_0 \approx \underline{I}_2$: L_1-E or L_2-L_3-E fault

$\underline{I}_0 \approx a^2\,\underline{I}_2$: L_2-E or L_3-L_1-E fault

$\underline{I}_0 \approx a\,\underline{I}_2$: L_3-E or L_1-L_2-E fault



1-Ph-E fault:
After load compensation: Currents in the healthy phases are zero or have opposite phase position

Ph-Ph-E fault:
After load compensation: Currents in faulted phases have same amplitude and show a phase difference of 120 to 180 degree dependent on earthing conditions

Distance protection
Stepped process of phase selection

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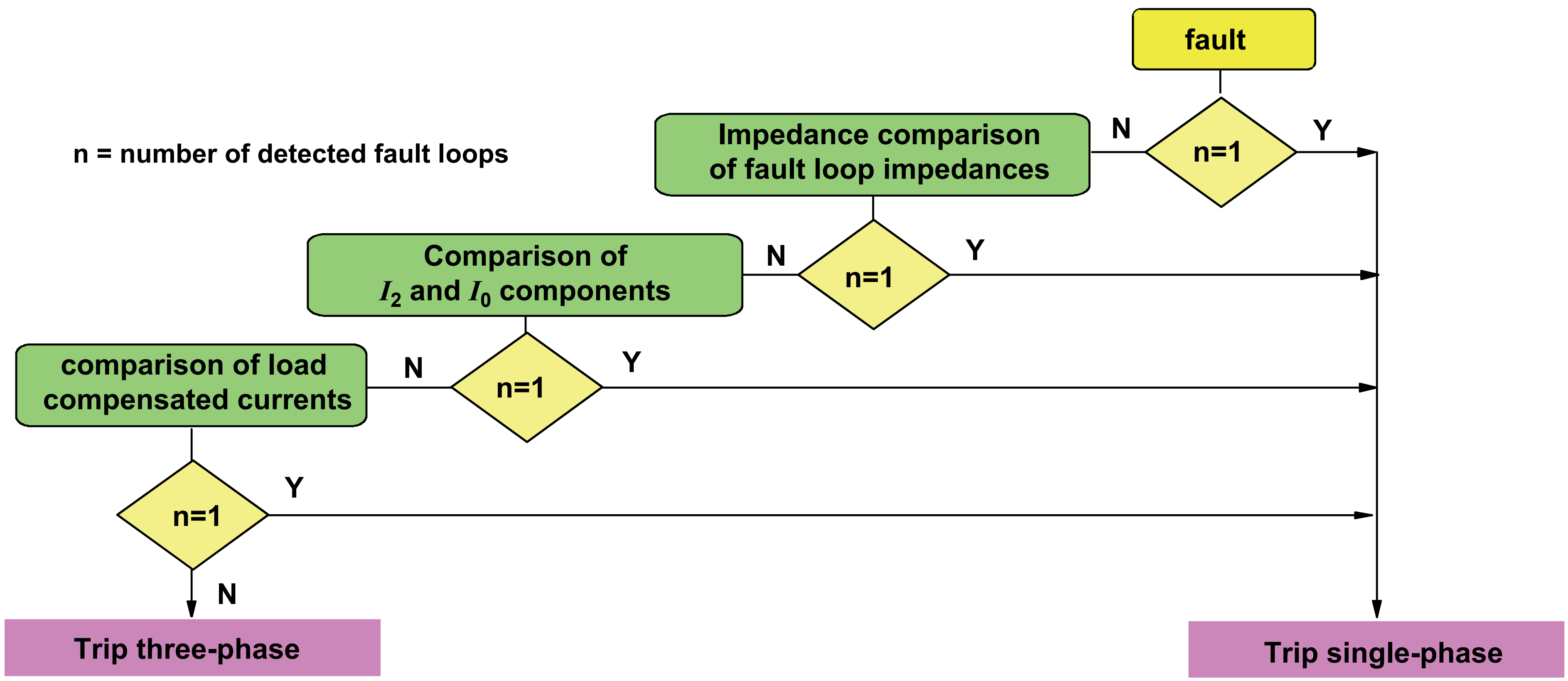

MHO-Characteristic

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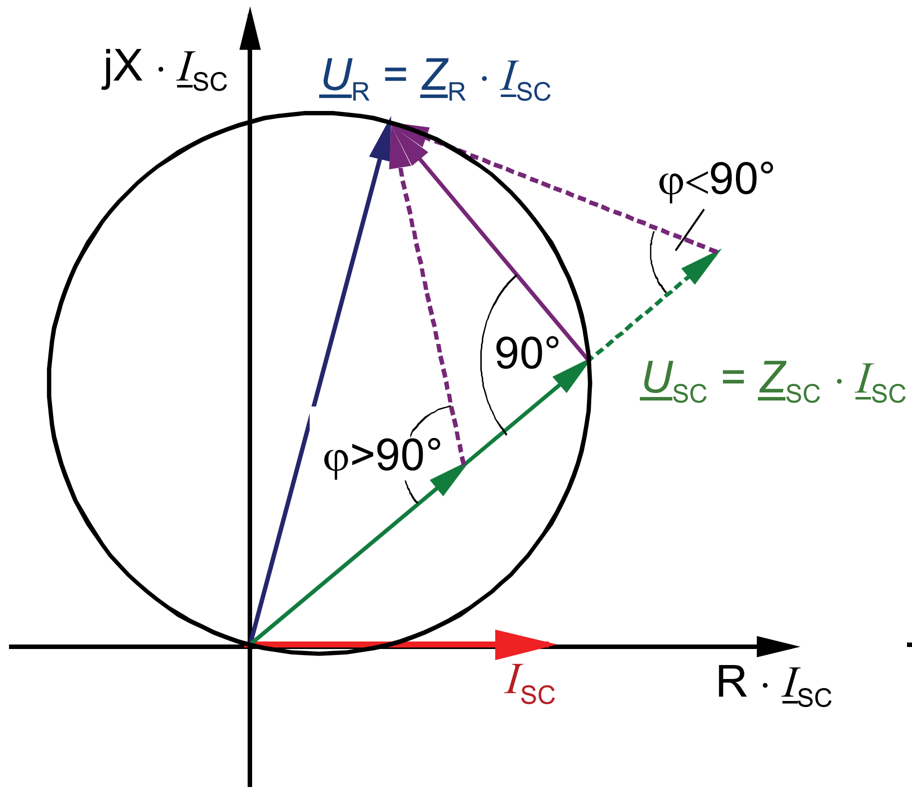
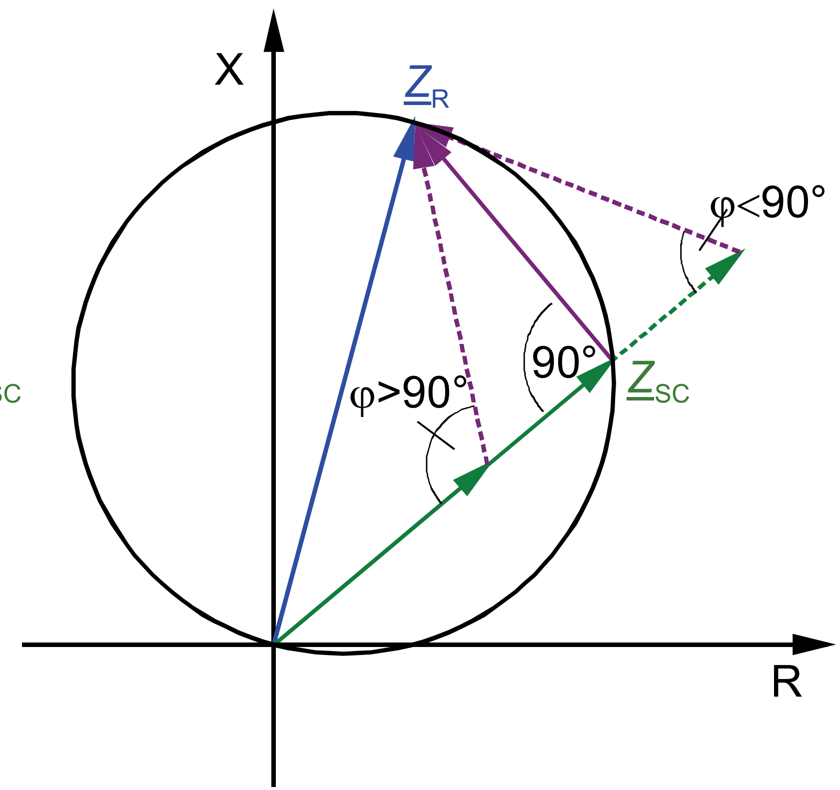


voltage diagram



impedance diagram

Directional determination, alternatives of voltage polarization

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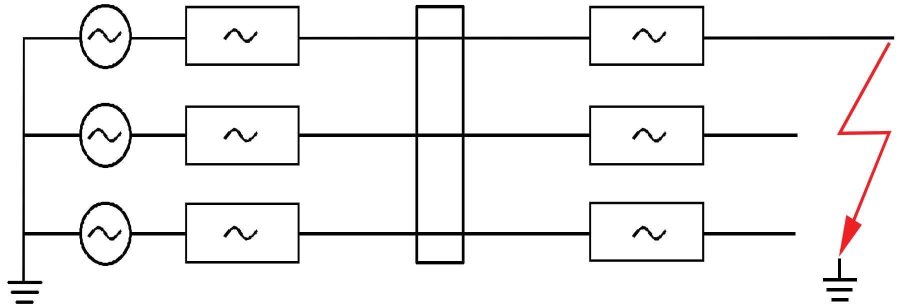
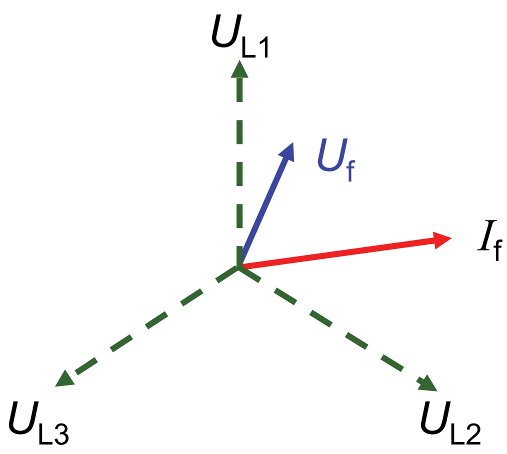
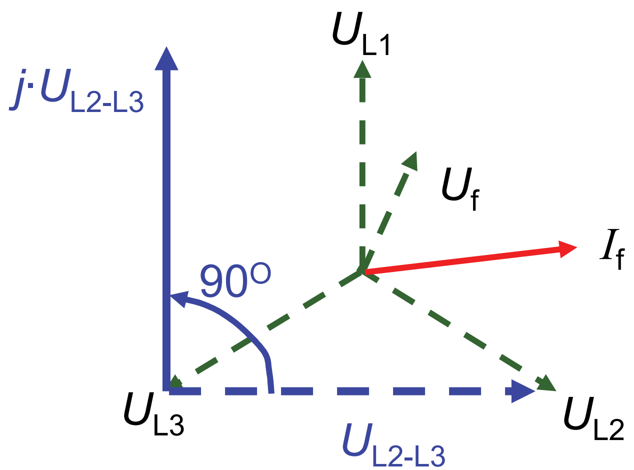
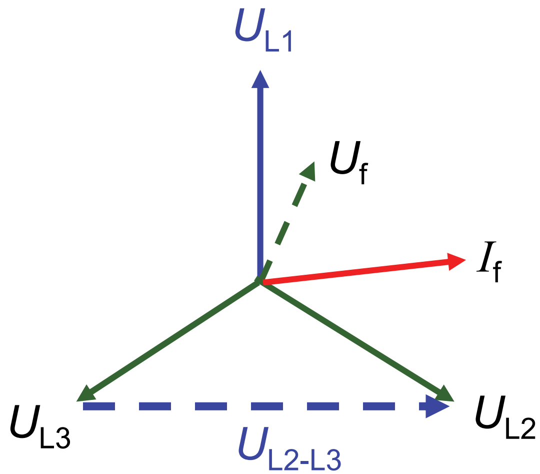




fault loop voltages



healthy phase voltages



memorised voltages

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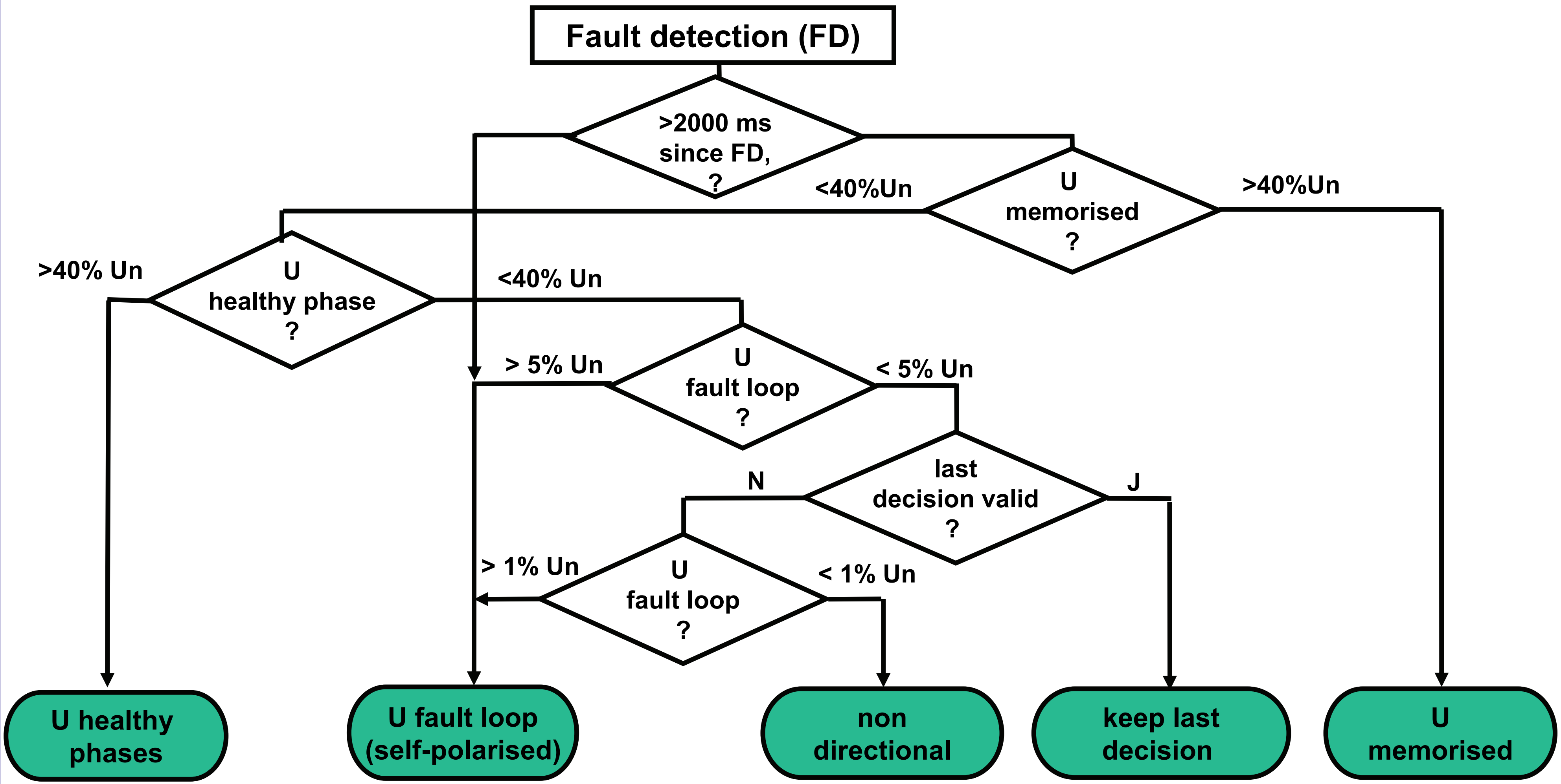
Directional determination: adaptive voltage polarisation



Determination of fault direction using healthy phase voltages

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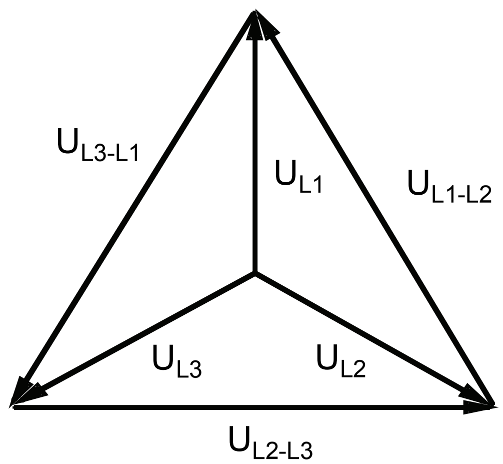

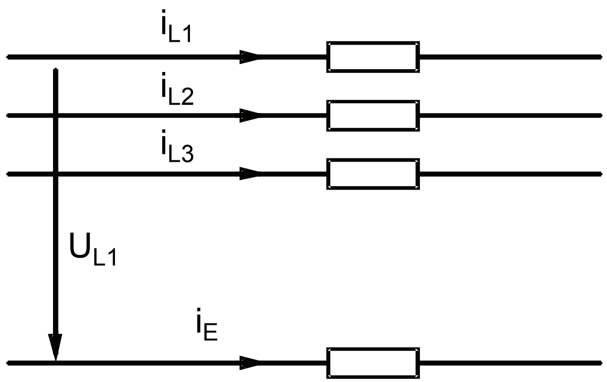

Measured values for directional decision

Fault loop	currents	voltages
L1 - E	$i_{L1} - k_E \cdot i_E$	U_{L2-L3}
L2 - E	$i_{L2} - k_E \cdot i_E$	U_{L3-L1}
L3 - E	$i_{L3} - k_E \cdot i_E$	U_{L1-L2}
L1 - L2	$i_{L1} - i_{L2}$	$U_{L2-L3} - U_{L3-L1}$
L2 - L3	$i_{L2} - i_{L3}$	$U_{L3-L1} - U_{L1-L2}$
L3 - L1	$i_{L3} - i_{L1}$	$U_{L1-L2} - U_{L2-L3}$

Directional determination using healthy phase voltages: Cross-polarisation

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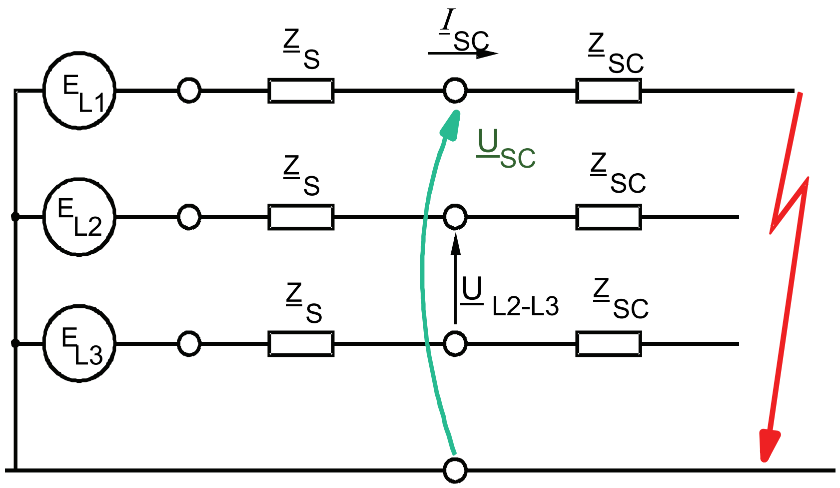
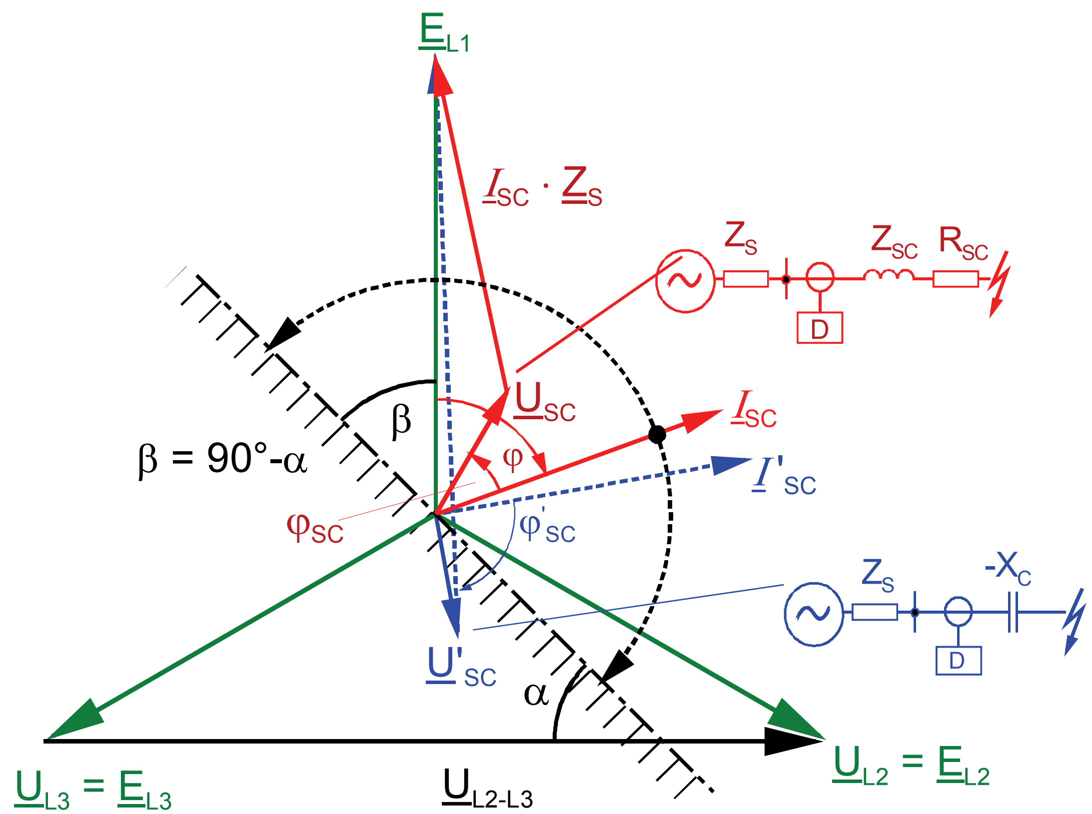


$$\underline{E}_{L1} = \underline{U}_{SC} + \underline{Z}_S \cdot \underline{I}_{SC}$$

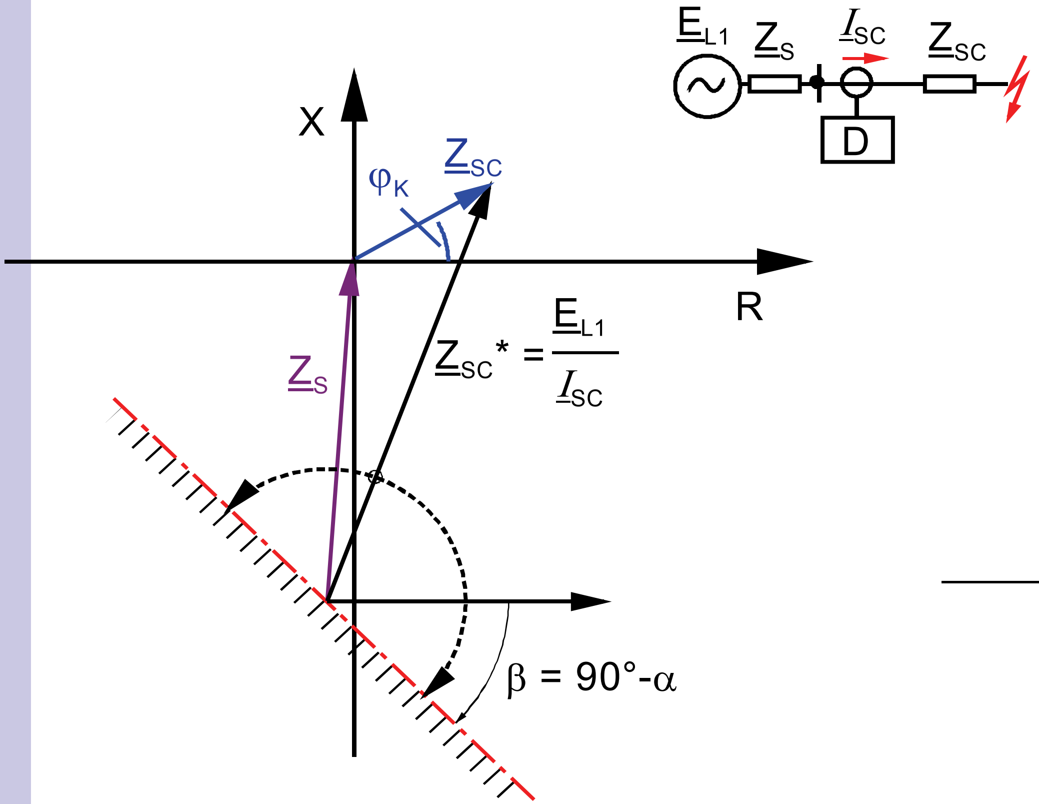
$$\underline{U}_{L2-L3} = \underline{E}_{L2-L3} = \underline{E}_{L1} \cdot \sqrt{3} \cdot e^{-j90^o}$$

Equivalent circuit

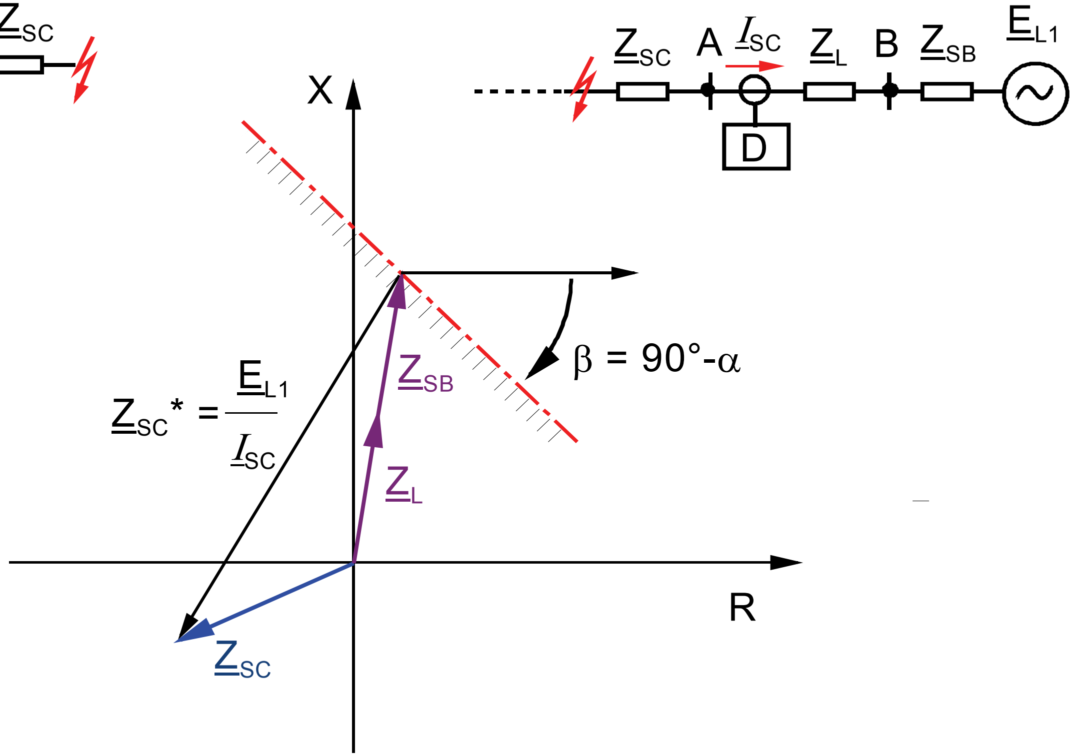


Voltage diagram

Cross-polarisation
Shift of directional characteristic with forward and reverse faults



Directional characteristic in the impedance plane for faults in the forward direction



Directional characteristic in the impedance plane for faults in the reverse direction

Quadrilateral impedance characteristic and directional determination with healthy phase voltage

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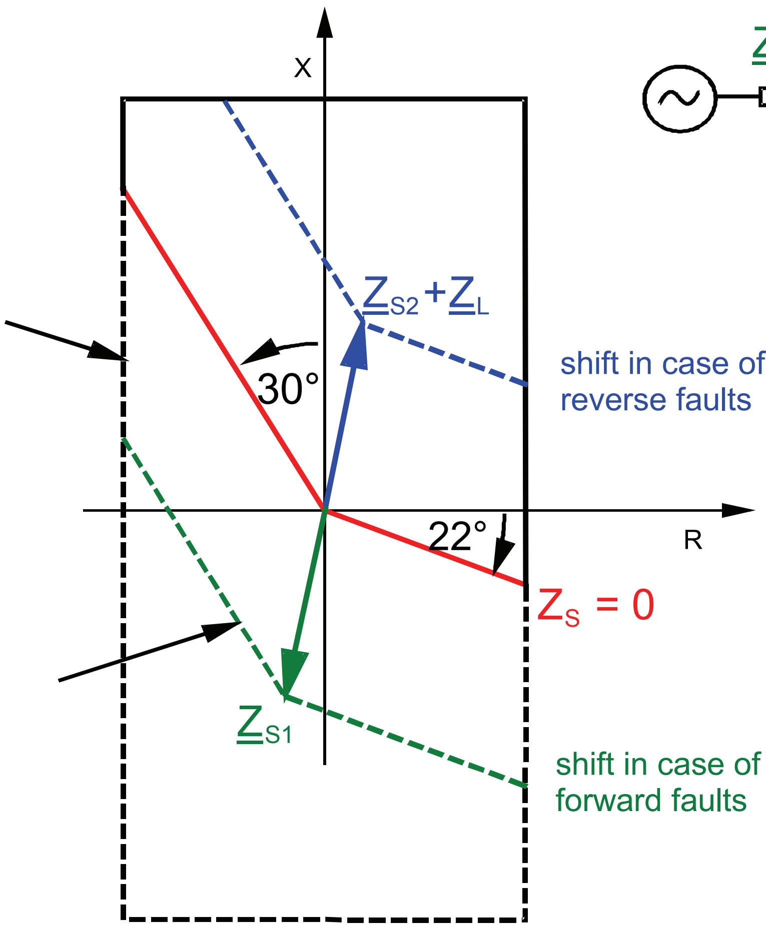
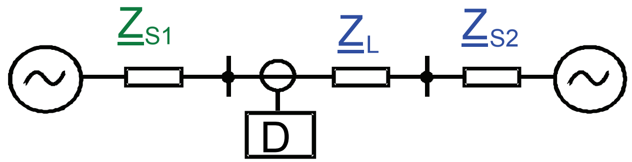
Impedance measurement:
with fault loop voltages
(fixed characteristic)

Directional determination:
with healthy phase voltages
(characteristic shifted proportional to source impedance)





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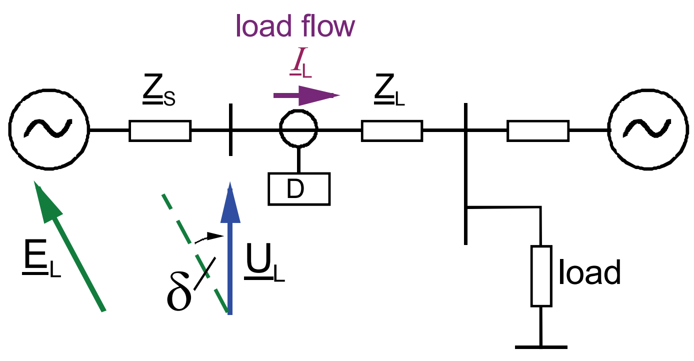
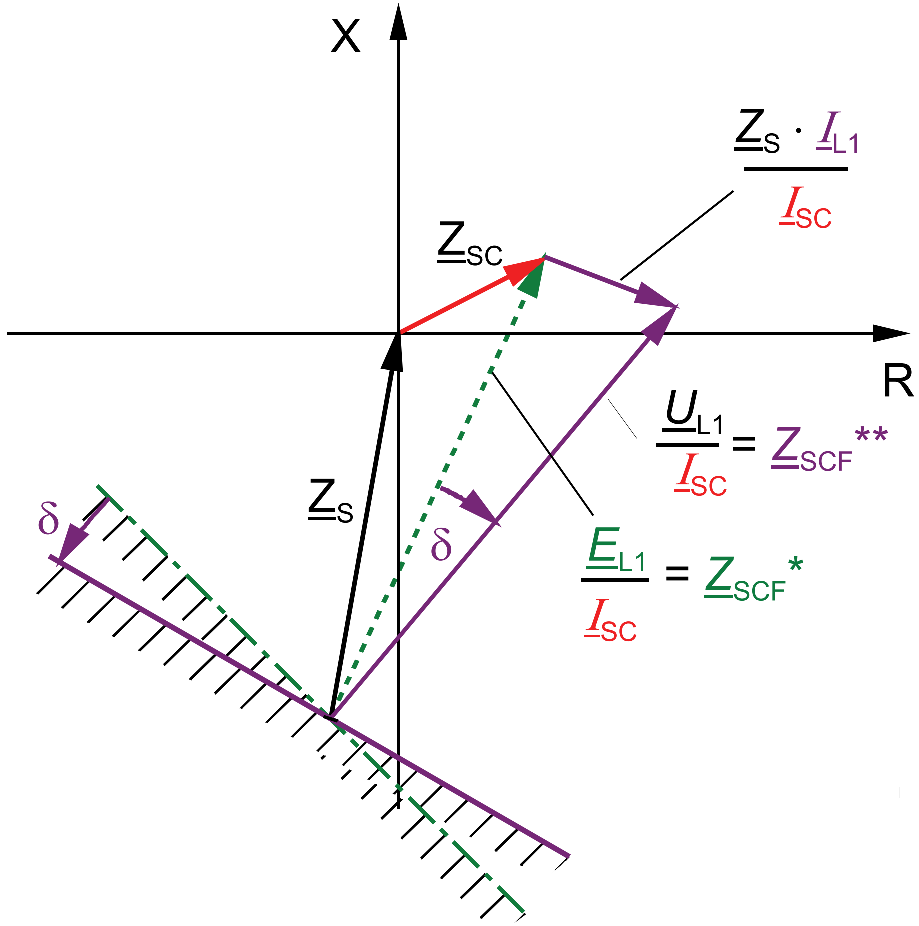
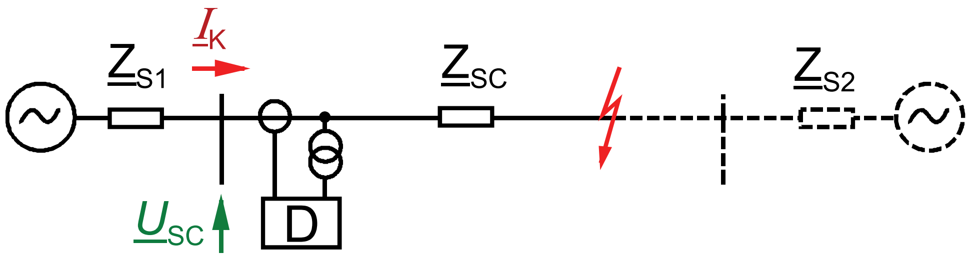
Cross polarisation:

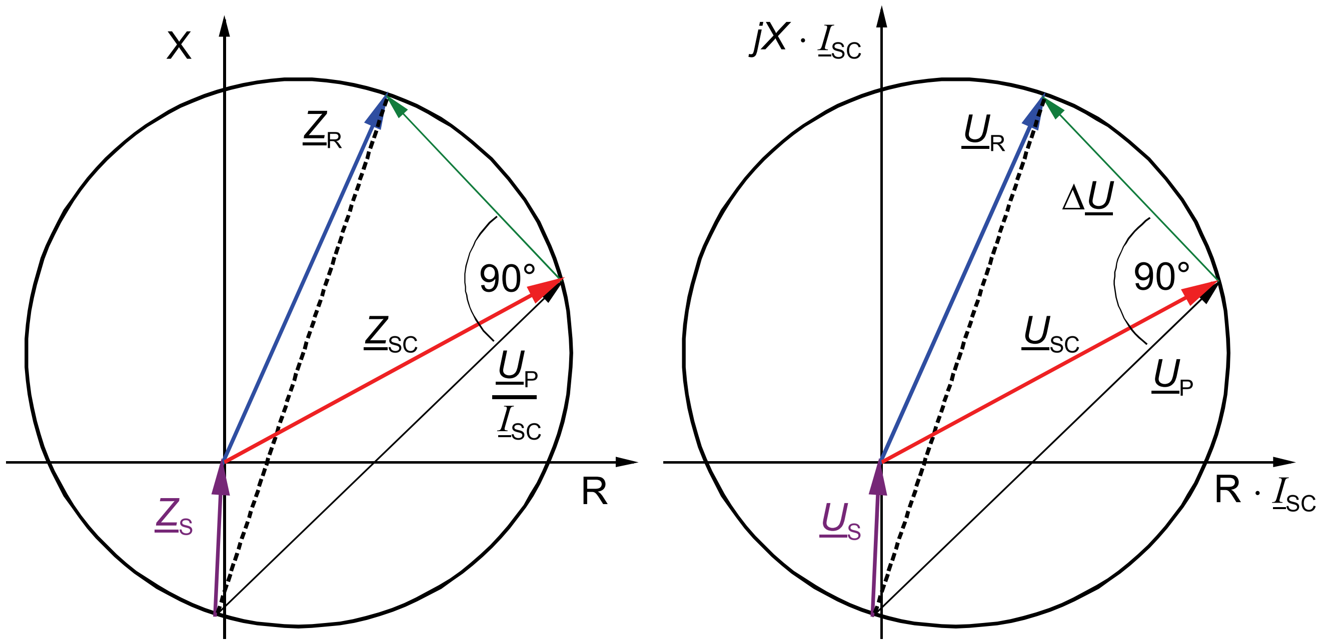
The influence of load transfer on the position of the directional characteristic





Polarised MHO-circle, fault in the forward direction





impedance diagram **Voltage diagram**

Polarised MHO-circle, fault in reverse direction

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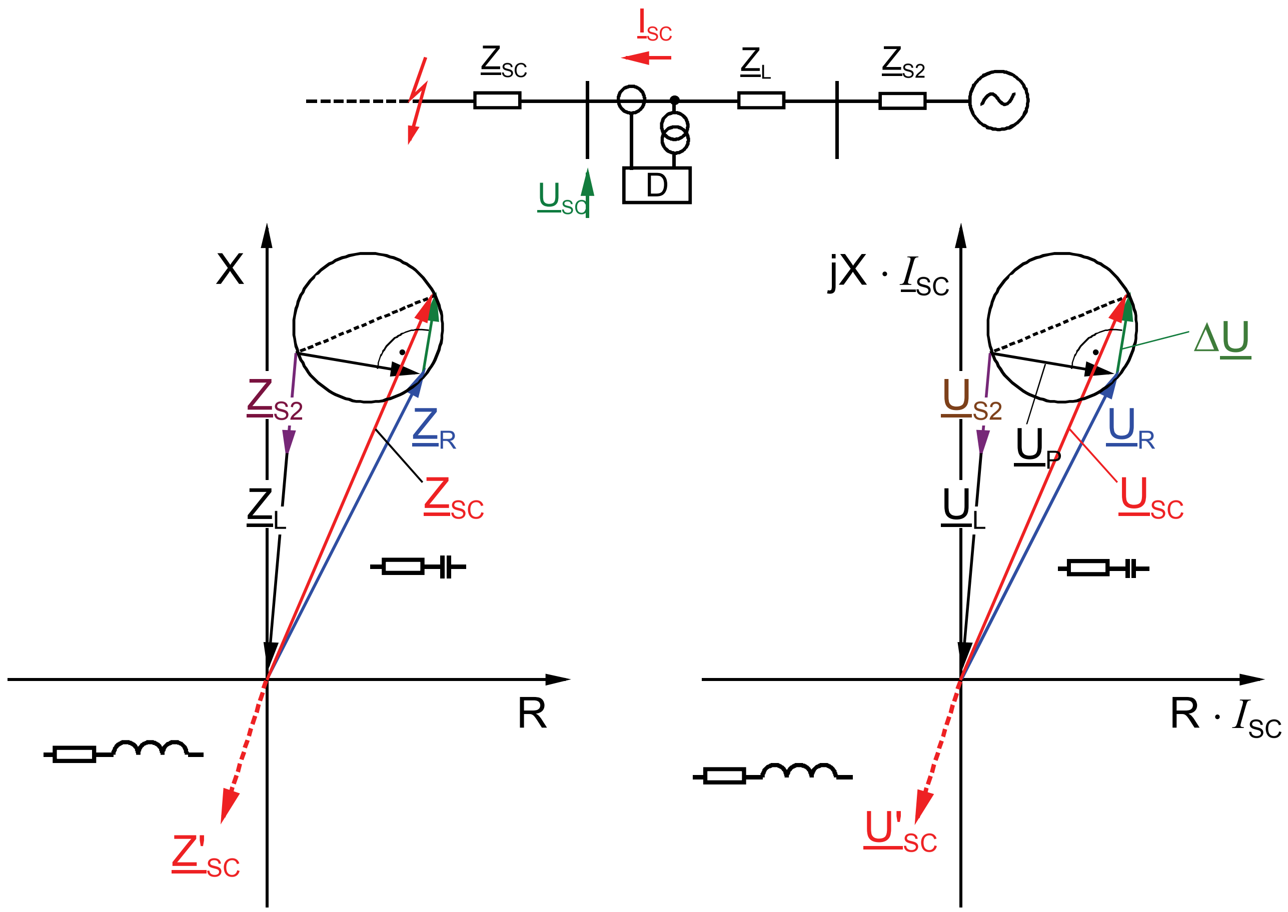

impedance diagram **voltage diagram**

Influence of load transfer on the position of the polarised MHO-circle (100% healthy phase voltage polarisation)

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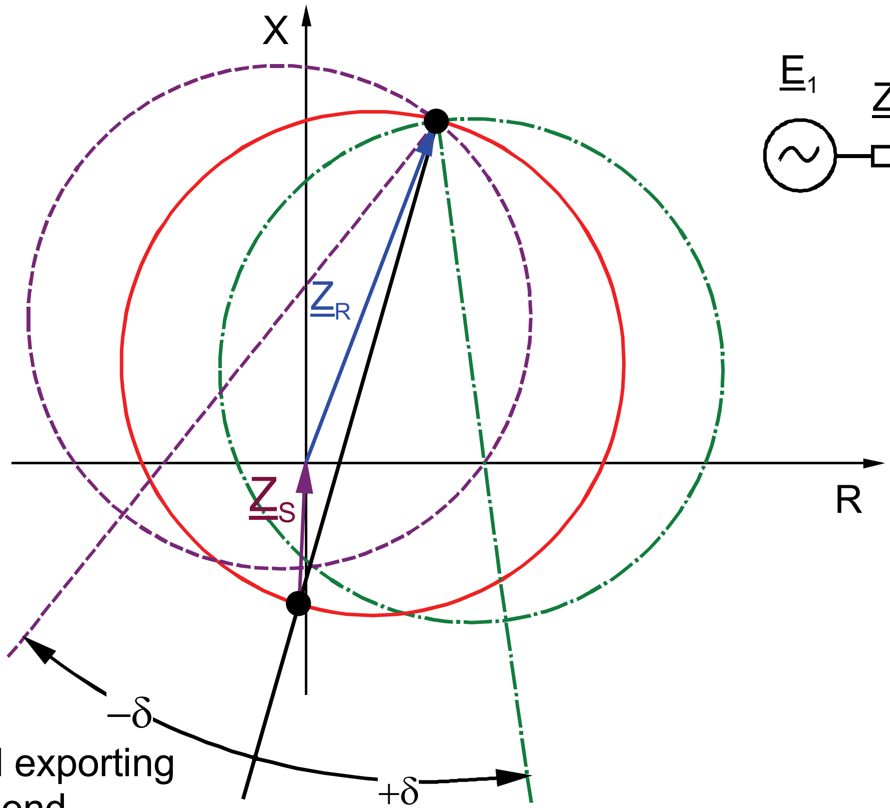

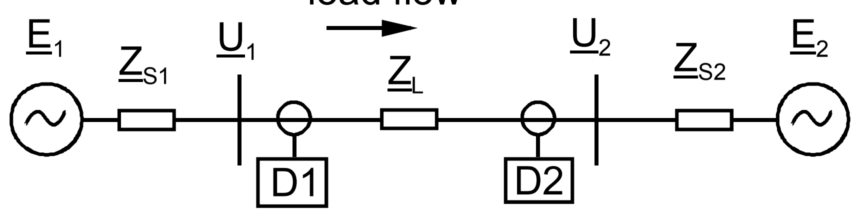

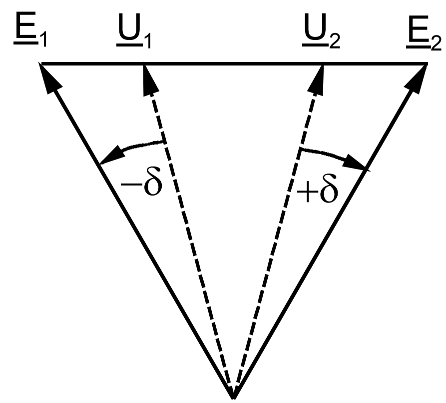

Zone grading chart, radial feeder

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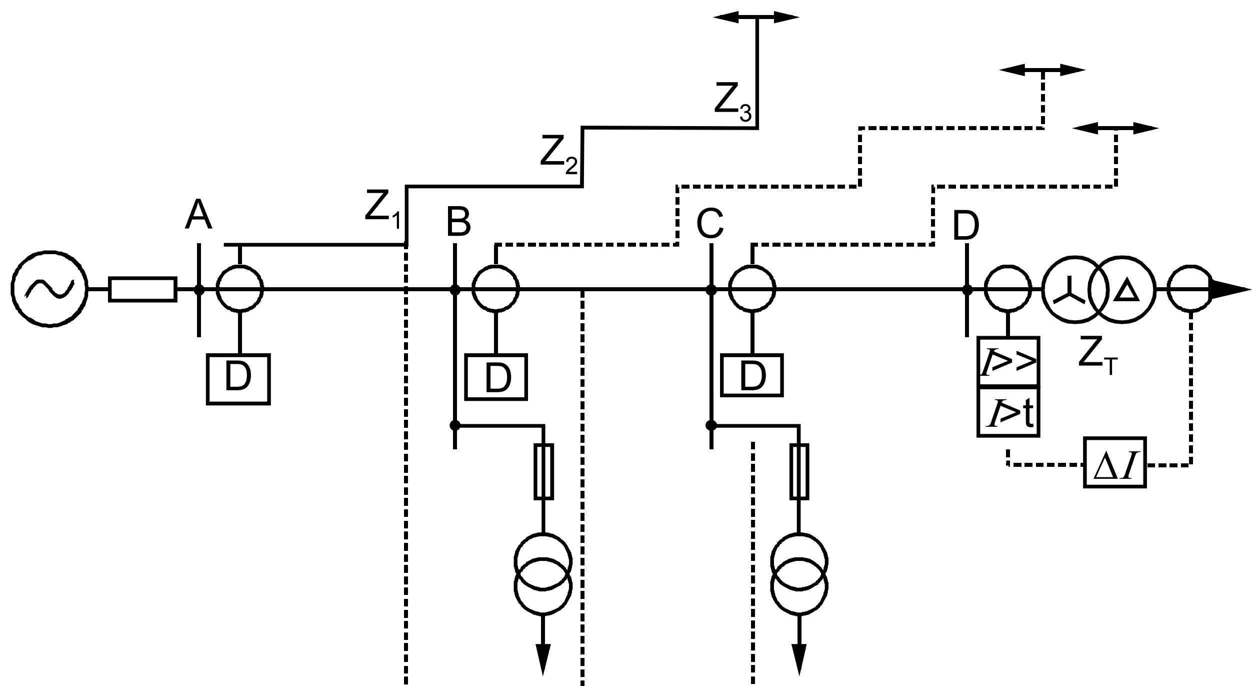
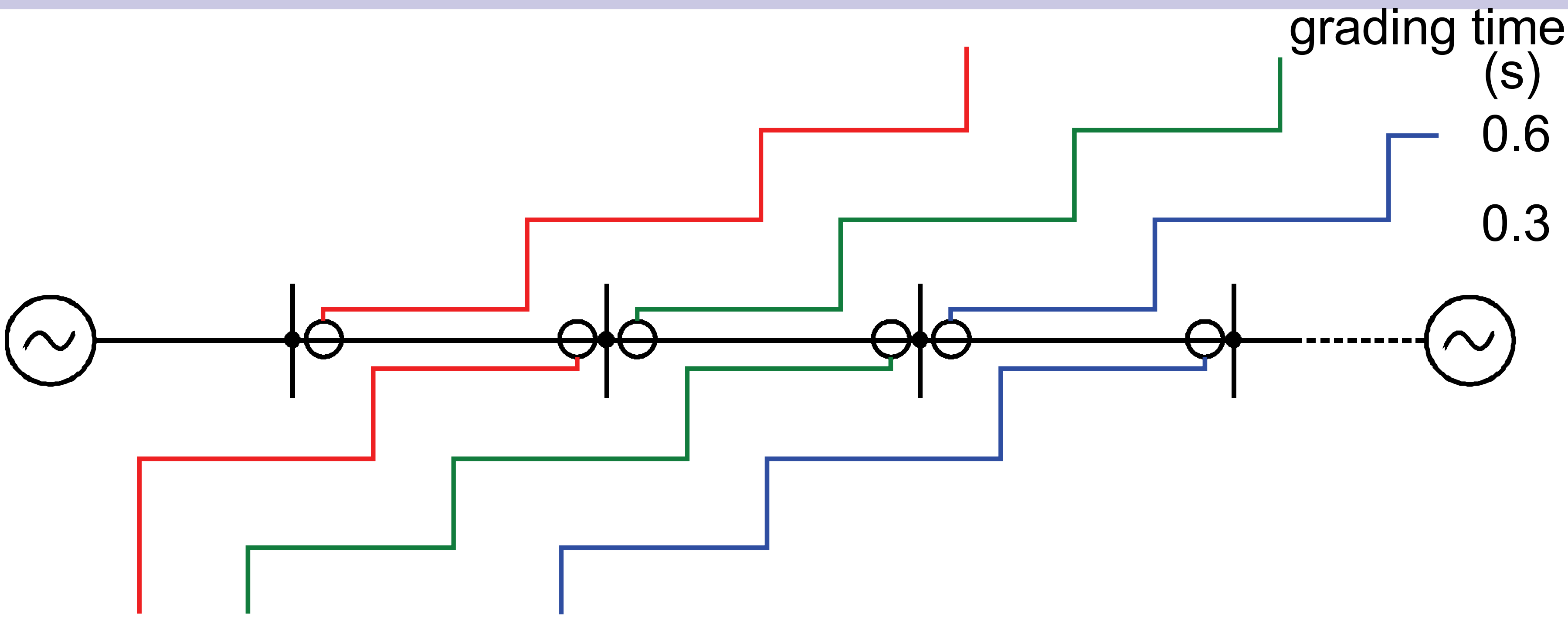


$Z_1 = 0.85\ Z_{A\text{-}B}$

$Z_2 = 0.85\ (Z_{A\text{-}B} + 0.85\ Z_{B\text{-}C})$

$Z_3 = 0.85\ [\ Z_{A\text{-}B} + 0.85\ (Z_{B\text{-}C} + 0.85\ Z_{C\text{-}D})\ ]$

Ring feeder: with grading against opposite end



Determination of grading times

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2nd Zone: It must initially allow the 1st zone on the neighbouring feeder(s) to clear the fault.
The grading time therefore results from the addition of the following times:

• **operating time of the adjacent feeder** mechanical: 25 – 80 ms
static 15 – 40 ms
digital 15 – 30 ms

\+ **circuit breaker operating time** HV / EHV: 60 ms (3 cycles) / 40 ms (2 cycles)
MV: up to about 80 ms (4 cycles)

+_**distance relay reset time** mechanical: ca. 60-100 ms (0ver-travel time)
static: ca. 30 ms
digital: ca. 20 ms.

+_**errors of the relay internal timers** mechanical: 5% of the set time, minimum 60-100 ms
static: 3% of the set time, minimum 10 ms
digital: 1% of the set time, minimum 10 ms

\+ **safety margin (ca.)** grading: mechanical-mechanical: 100 m
static/digital-mechanical or vice versa: 75 m
digital-digital or static-static 50 ms

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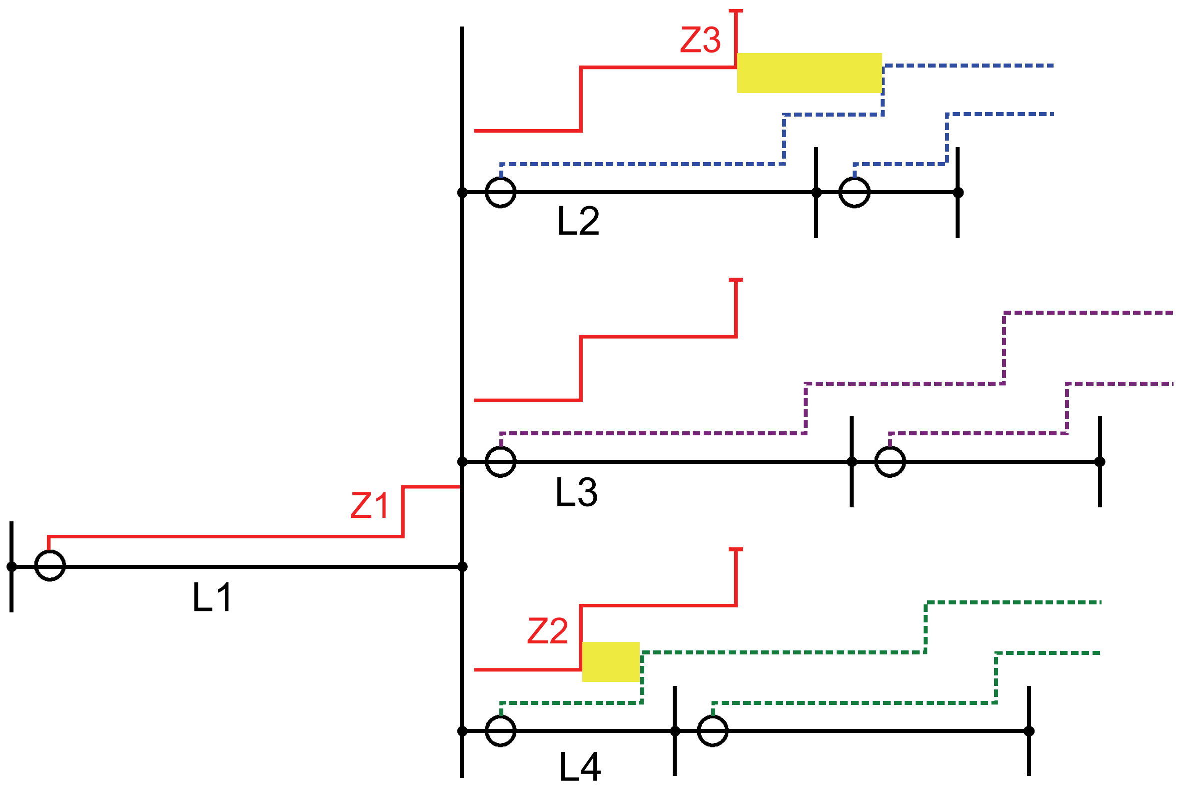
Grading in a branched radial system



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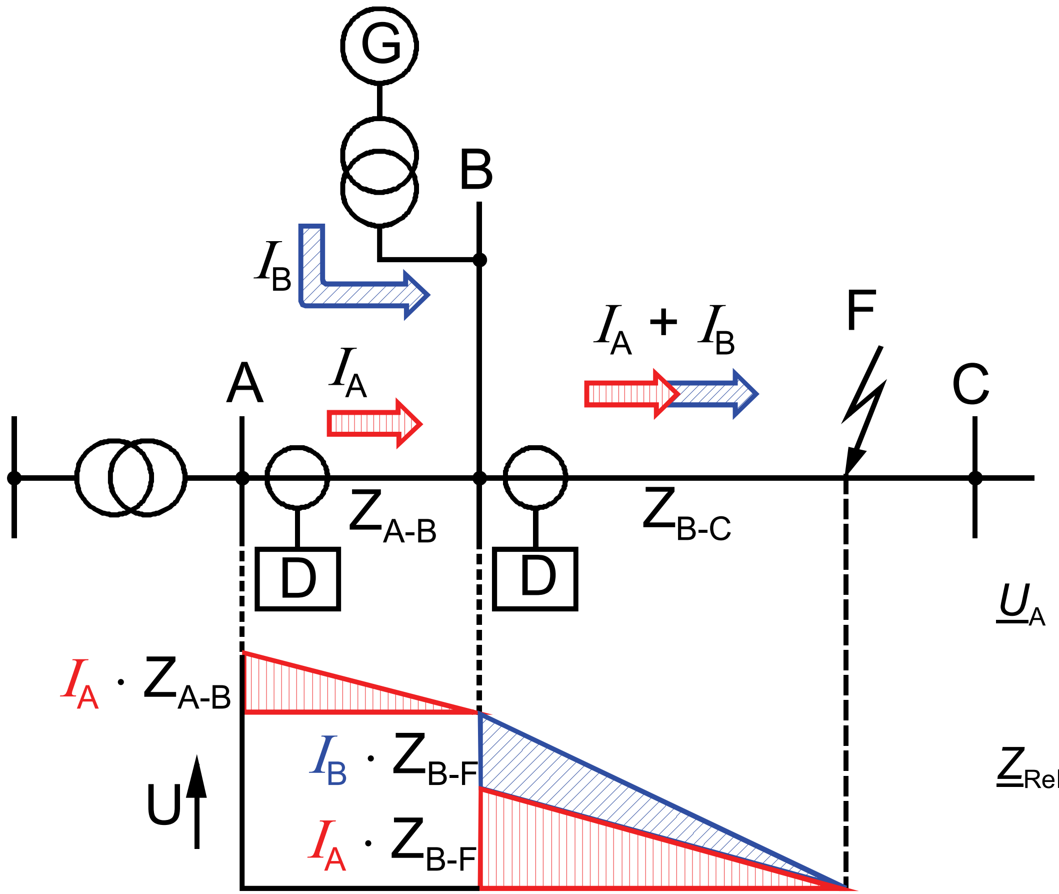
Effect of intermediate infeeds on distance measurement (1)

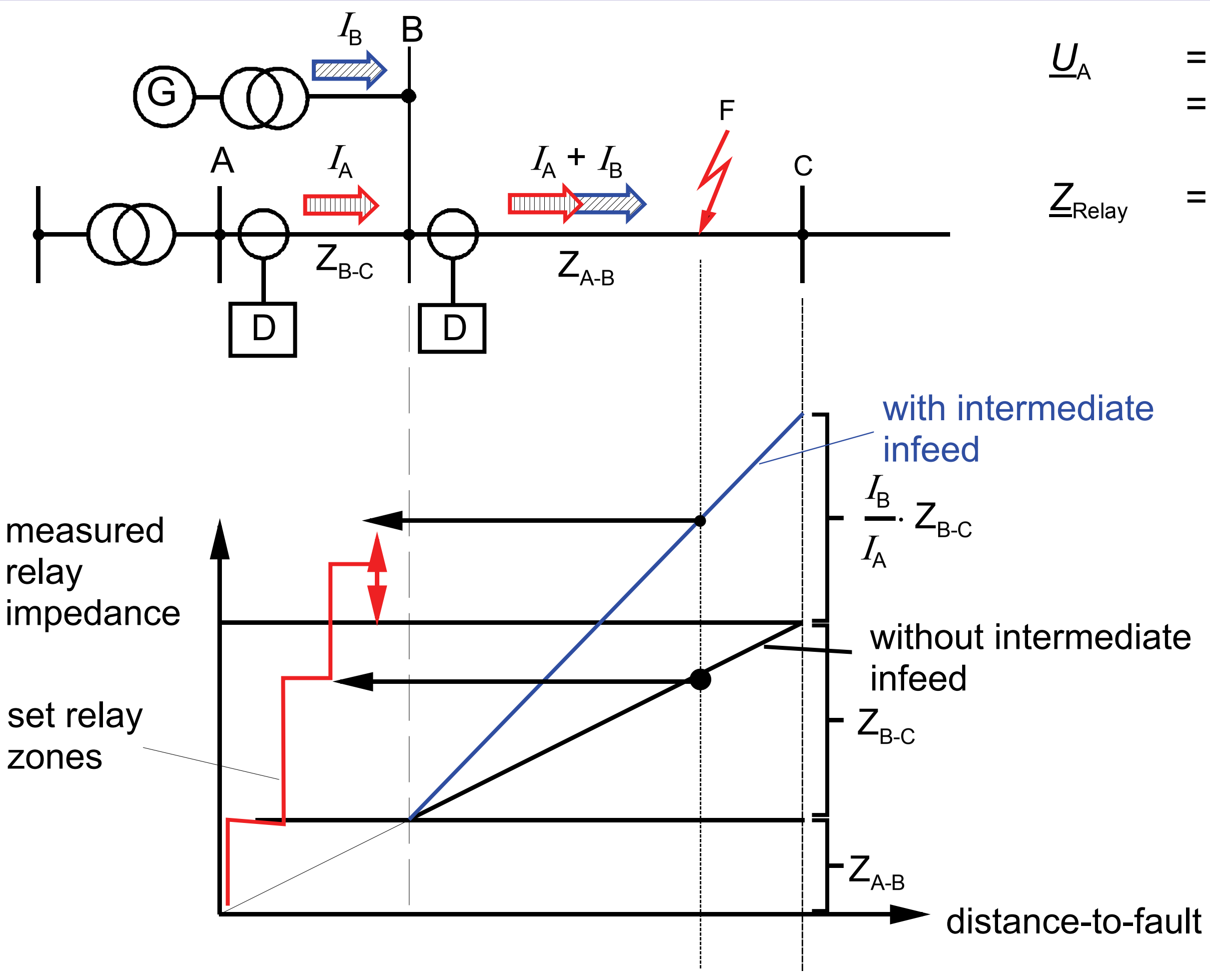


$$\underline{U}_A = \underline{I}_A \cdot \underline{Z}_{AB} + (\underline{I}_A + \underline{I}_B) \cdot \underline{Z}_{BF}$$
$$= \underline{I}_A (\underline{Z}_{AB} + \underline{Z}_{BF}) + \underline{I}_B \cdot \underline{Z}_{BF}$$

$$\underline{Z}_{Relay} = \frac{\underline{U}_A}{\underline{I}_A} = \underline{Z}_{AB} + Z_{BF} + \underbrace{\frac{\underline{I}_B}{\underline{I}_A} \cdot \underline{Z}_{BF}}_{\Delta Z \text{ (measuring error)}}$$

Effect of intermediate infeeds on distance measurement (2)

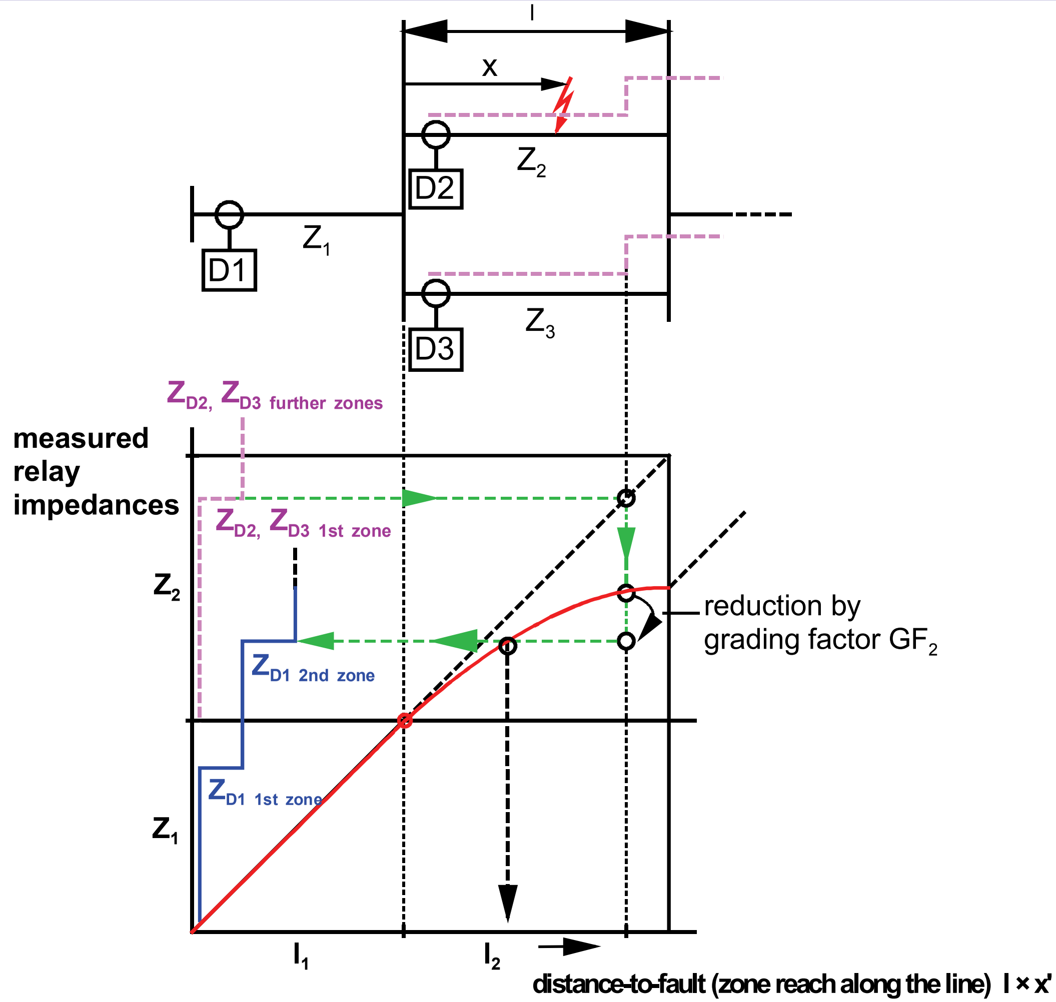
SIEMENS



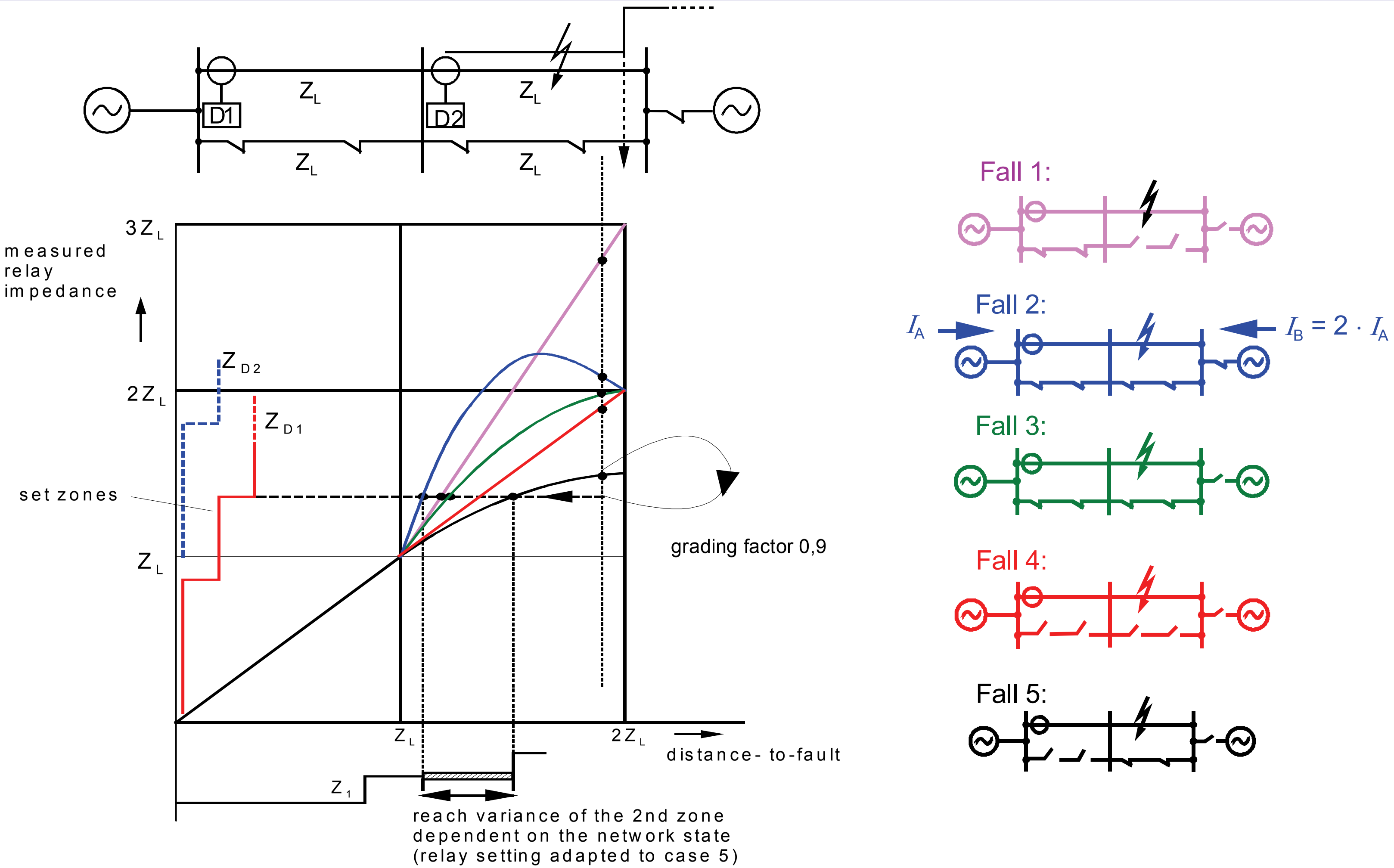
$$\underline{U}_A = \underline{I}_A \cdot \underline{Z}_{AB} + (\underline{I}_A + \underline{I}_B) \cdot \underline{Z}_{BF}$$
$$= \underline{I}_A (\underline{Z}_{AB} + \underline{Z}_{BF}) + \underline{I}_B \cdot \underline{Z}_{BF}$$

$$\underline{Z}_{Relay} = \frac{\underline{U}_A}{\underline{I}_A} = \underline{Z}_{AB} + \underline{Z}_{BF} + \underbrace{\frac{\underline{I}_B}{\underline{I}_A} \cdot \underline{Z}_{BF}}_{\Delta Z \text{ (measuring error)}}$$

Grading for parallel feeders



Zone grading for parallel lines, influence of switching conditions



 Jul-06 Author

Power Transmission and Distribution

Zone grading: Example (1)

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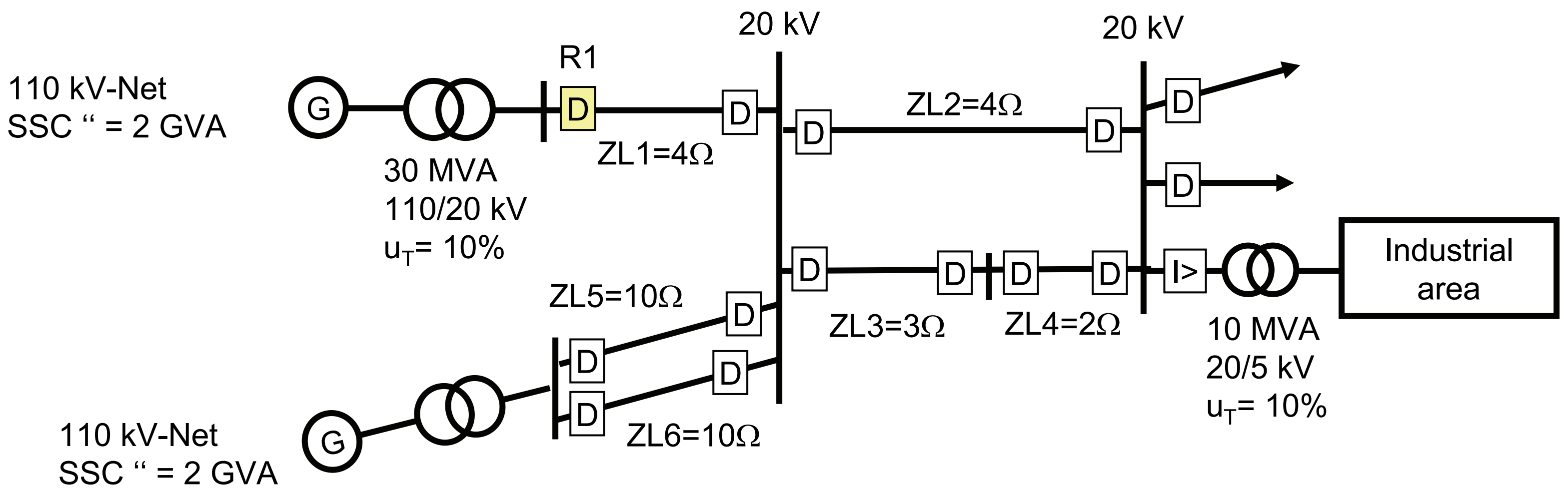

Task: Grading zones of relay 1

Zone grading: Example (2)

Calculation of equivalent impedances

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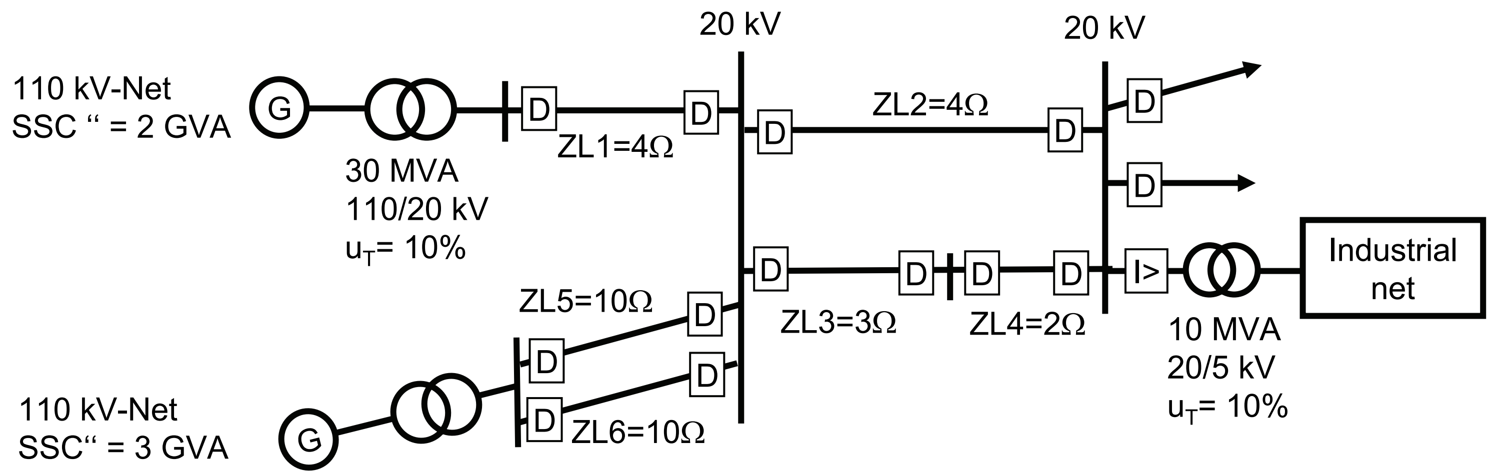

$$Z_{S\text{-}N1} = \frac{20\,kV^2}{2000\,MVA} = 0.2\,\Omega \qquad Z_{T1} = \frac{10\%}{100} \cdot \frac{20^2}{30} = 1.33\,\Omega \qquad Z_{S1} = Z_{S-N1} + Z_{T1} = 0.2 + 1.33 = 1.53\,\Omega$$

$$Z_{S\text{-}N2} = \frac{20\,kV^2}{3000\,MVA} = 0.13\,\Omega \qquad Z_{T2} = \frac{10\%}{100} \cdot \frac{20^2}{40} = 1.0\,\Omega \qquad Z_{S2} = Z_{S-N2} + Z_2 = 0.13 + 1.0 = 1.13\,\Omega$$

Zone grading: Example (3)

Adopted grading philosophy

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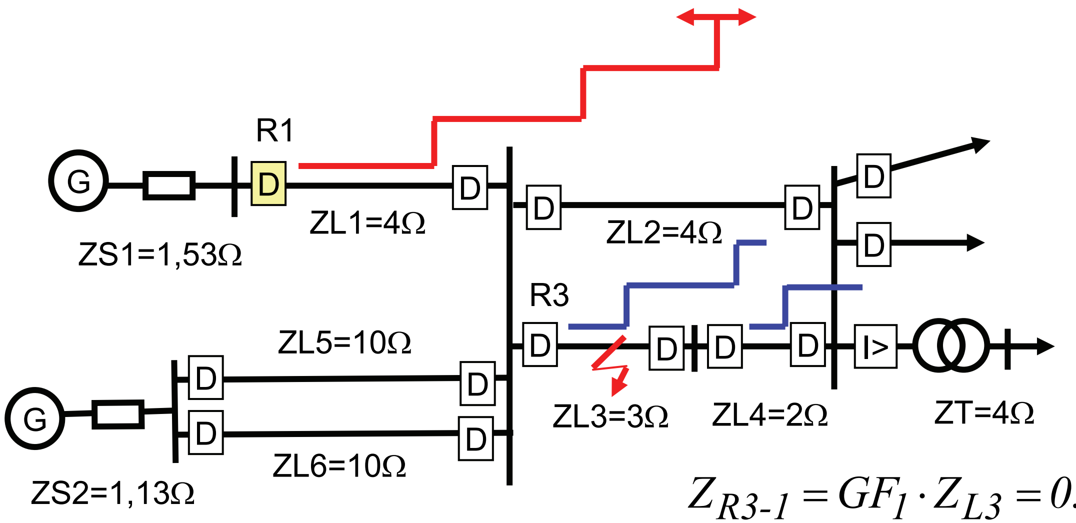

$$Z_{R3\text{-}1} = GF_1 \cdot Z_{L3} = 0.9 \cdot 3.0 = 2.7\ \Omega$$

$$Z_{R3\text{-}2} = GF_2 \cdot (Z_{L3} + 0.9 \cdot Z_{L4}) = 0.9 \cdot (3 + 0.9 \cdot 2) = 4.32$$

Zone 1: $Z_{R1\text{-}1} = GF_1 \cdot Z_{L1} = 0.9 \cdot 4.0 = 3.6\ \Omega$

Zone 2 of relay 1 must be graded to the end of 1st Zone of relay 3 (shortest impedance). The parallel way via ZL2 +ZL4 and the intermediate infeed through ZL5 und ZL6 (only one line in service) have to be considered.

Zone 3 can be graded to the end of zone 2 of relay 3 (same procedure as with the grading of zone 2), or simply 10% beyond the longest following line.

Zone grading: Example (4)

Calculation of Zone 2

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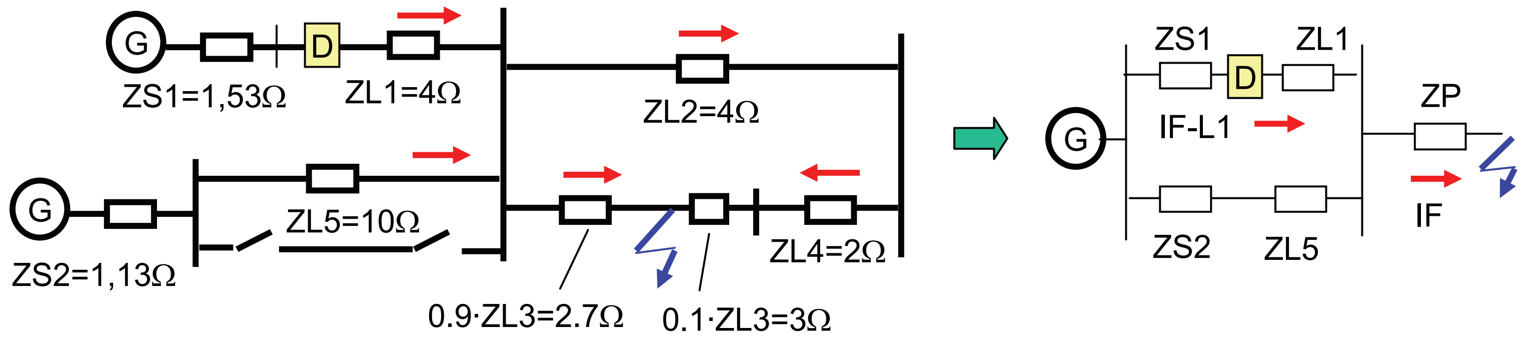


$$I_F = I_{F-L1} + I_{F-L5} = \frac{1.1 \cdot 20/\sqrt{3}}{(Z_{S1}+Z_{S1})//(Z_{S2}+Z_{L5}) + (Z_{L2}+ZL4+0.1\cdot Z_{L3})//0.9\cdot Z_{L3}} = 2.276\ kA$$

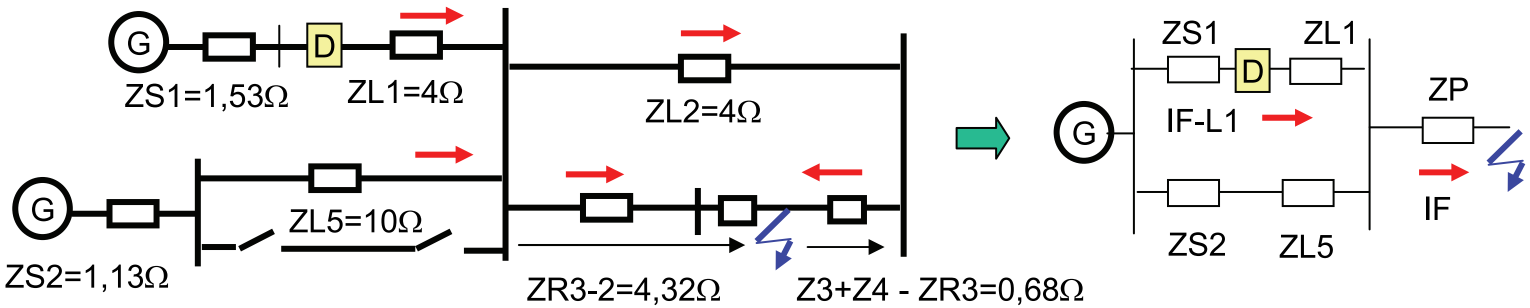
$$I_{F-L1} = \frac{Z_{S2}+Z_{L5}}{Z_{S1}+Z_{L1}+Z_{V2}+Z_{L5}} \cdot I_F = 1.520\,kA \quad and \quad I_{F-L5} = \frac{Z_{S1}+Z_{L1}}{Z_{S1}+Z_{L1}+Z_{V2}+Z_{L5}} \cdot I_F = 0.756\,kA$$

$$Z_P = (Z_{L2}+Z_{L4}+0.1\cdot Z_{L3})//0.9\cdot Z_{L3} = 1.89\,\Omega$$

$$Z_{R1-2} = \mathrm{GF}_2 \cdot (Z_{L1} + Z_P \cdot \frac{I_F}{I_{F\text{-}L1}}) = 0.9 \cdot (4.0 + 1.89 \cdot \frac{2.276}{1.520}) = 6.14\ \Omega = 1.535 \cdot Z_{L1}$$

Zone grading: Example (5)

Calculation of Zone 3



$$I_F = I_{F-L1} + I_{F-L5} = \frac{1.1 \cdot 20/\sqrt{3}}{(Z_{S1}+Z_{L1})//(Z_{S2}+Z_{L5}) + Z_{R3}//(Z_{L2}+Z_{L3}+Z_{L4}-Z_{R3})} = 2.14\,kA$$

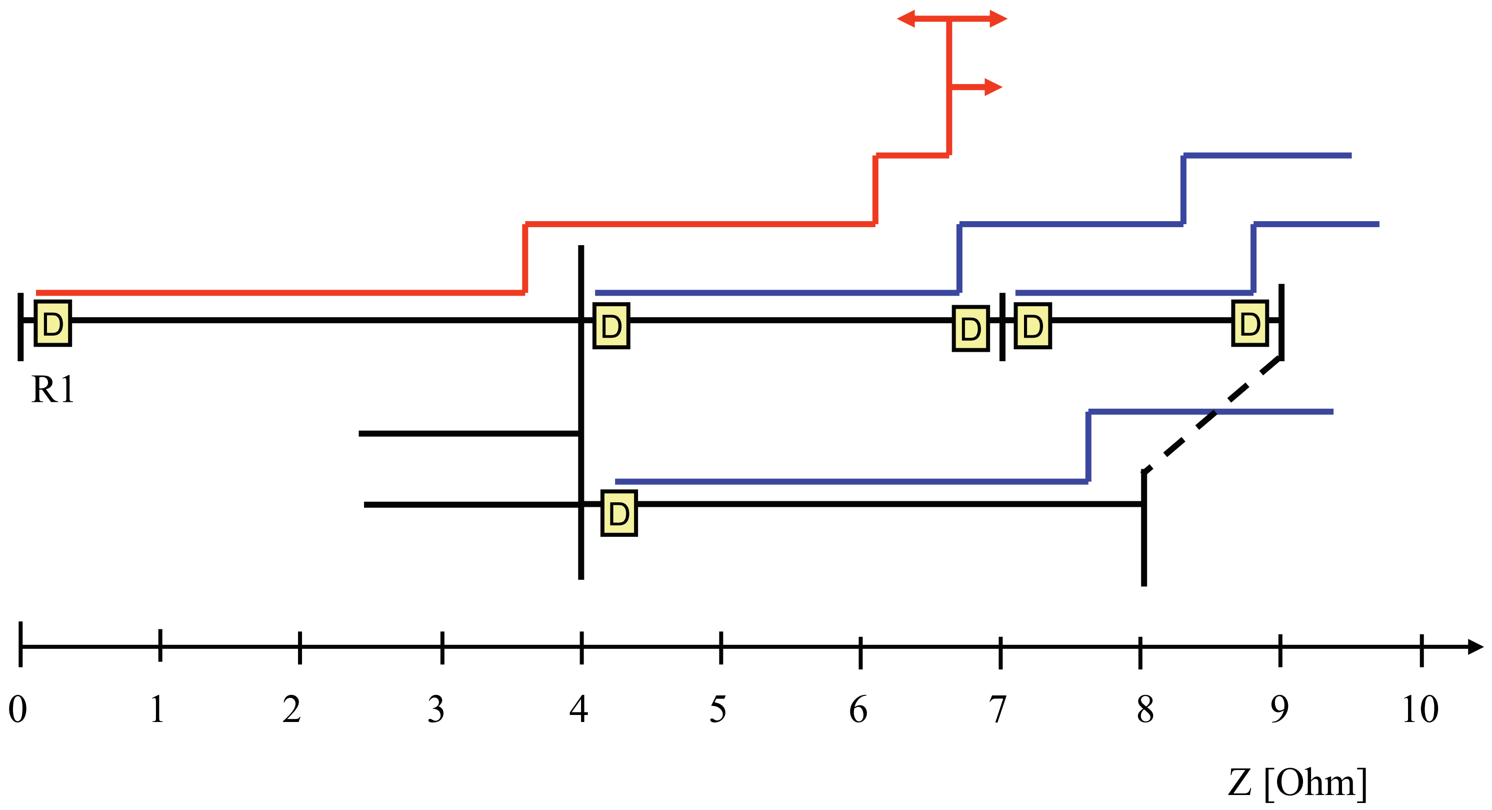
$$I_{F-L1} = \frac{Z_{S2}+Z_{L5}}{Z_{S1}+Z_{L1}+Z_{S2}+Z_{L5}} = 1.43\,kA \quad \text{and} \quad I_{F-L5} = \frac{Z_{S1}+Z_{L1}}{Z_{S1}+Z_{L1}+Z_{S2}+Z_{L5}} = 0.71\,kA$$

$$Z_P = Z_{R3}//(Z_{L2}+Z_{L3}+Z_{L4}-Z_{R3}) = 2.246\,\Omega$$

$$Z_{R1-3} = GF_3 \cdot (Z_{L1} + Z_P \cdot \frac{I_F}{I_{F-L1}}) = 0.9 \cdot (4.0 + 2.246 \cdot \frac{2.14}{1.43}) = 6.63\,\Omega = 1.66 \cdot Z_{L1}$$

Optional ohne Endzeitstaffelung: $Z_{R1-3} = 1.1 \cdot (Z_{L1} + Z_{L5}) = 1.1 \cdot (4+10) = 15.4\,\Omega$

Zone grading: Example (6)
Grading plan for relay 1



Short-circuit with fault resistance and infeed from both sides: equivalent circuit

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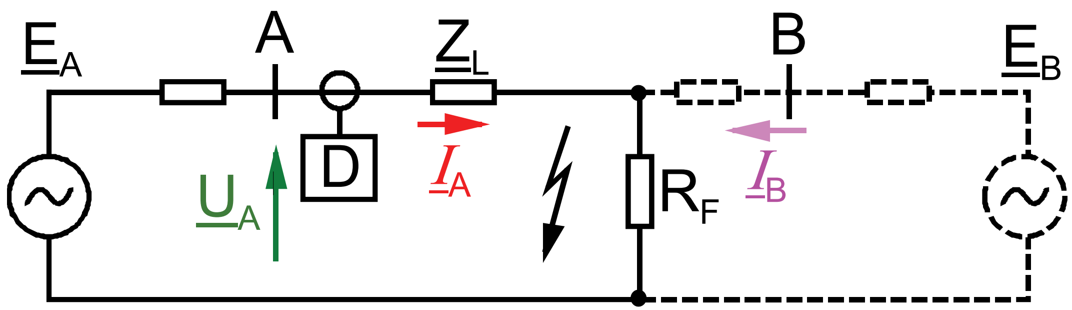
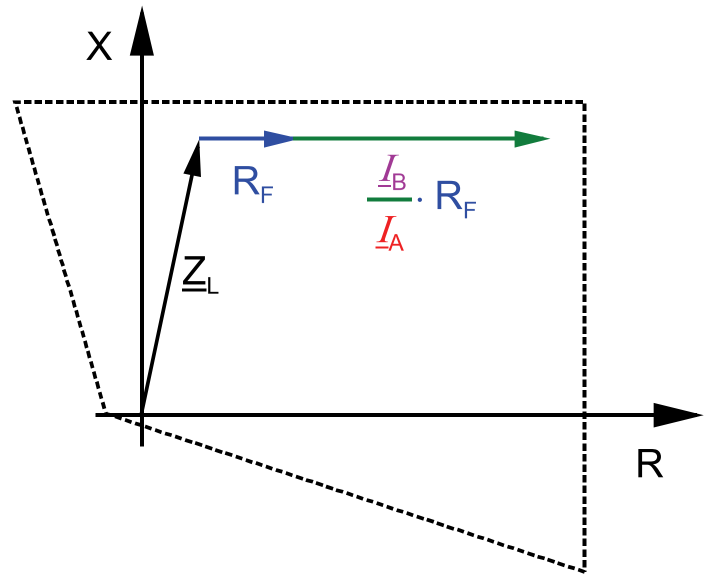


$$\underline{U}_A = \underline{I}_A \cdot \underline{Z}_L + (\underline{I}_A + \underline{I}_B) \cdot R_F$$

$$\underline{U}_A = \underline{I}_A \cdot (\underline{Z}_L + R_F) + \underline{I}_B \cdot R_F$$

$$\underline{Z}_A = \frac{\underline{U}_A}{\underline{I}_A} = \underline{Z}_L + R_F + \frac{\underline{I}_B}{\underline{I}_A} \cdot R_F$$



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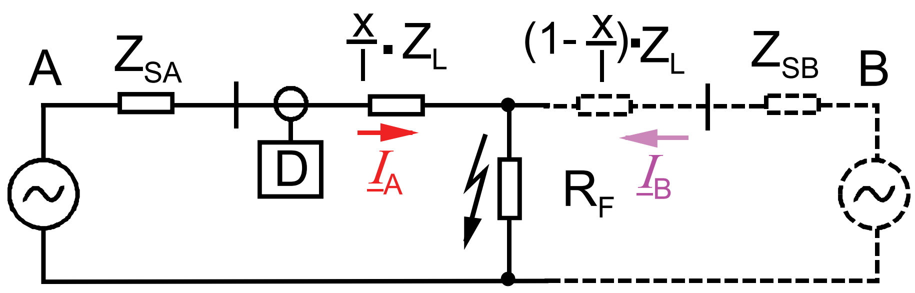
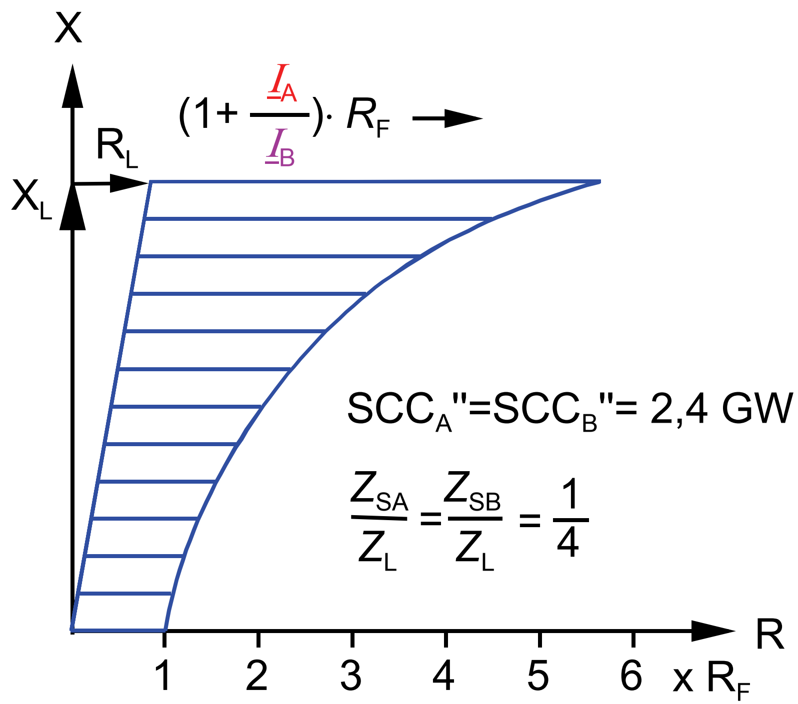
Apparent fault resistance dependent on fault location

(influence of R_F on short-circuit currents neglected)



$$\frac{\underline{I}_A}{\underline{I}_B} = \frac{\frac{Z_{SA}}{Z_L} + \frac{x}{l}}{\frac{Z_{SB}}{Z_L} + 1 - \frac{x}{l}}$$

$$Z_D = x \cdot Z_L + (1 + \frac{I_B}{I_A}) \cdot R_F$$

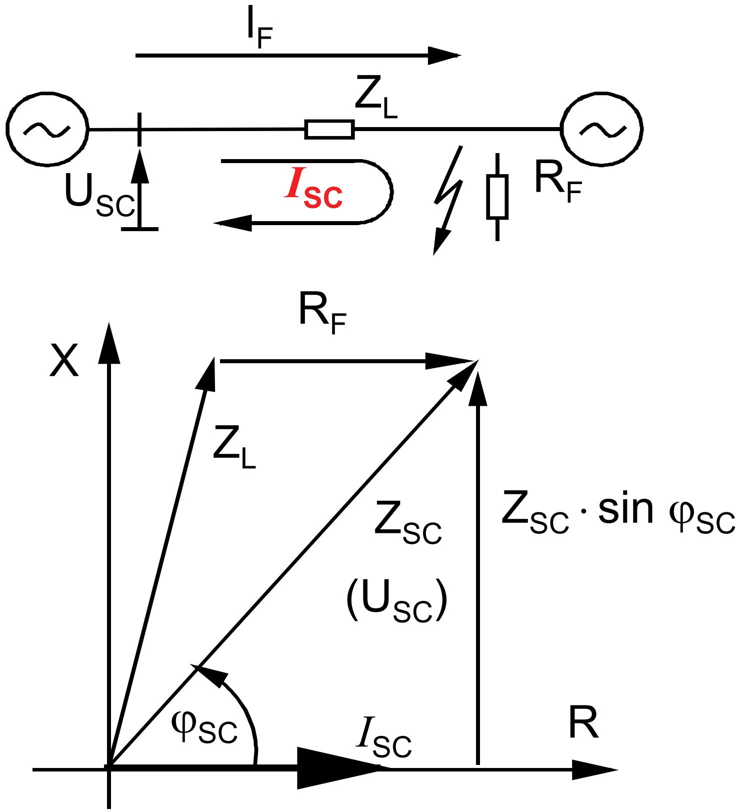


SCC_A"$=SCC_B$"$= 2,4$ GW

$\frac{Z_{SA}}{Z_L} = \frac{Z_{SB}}{Z_L} = \frac{1}{4}$

Example: 110 kV OH-line (l = 50 km)

Fault locating:
distance-to-fault measurement with arc compensation



I_F prop. $X_{SC} = K \cdot \frac{U_{SC}}{I_{SC}} \cdot \sin \varphi_{SC} = Z_{SC} \cdot \sin \varphi_{SC}$

Short-circuit with arc resistance and double-sided in-feed, influence on distance measurement

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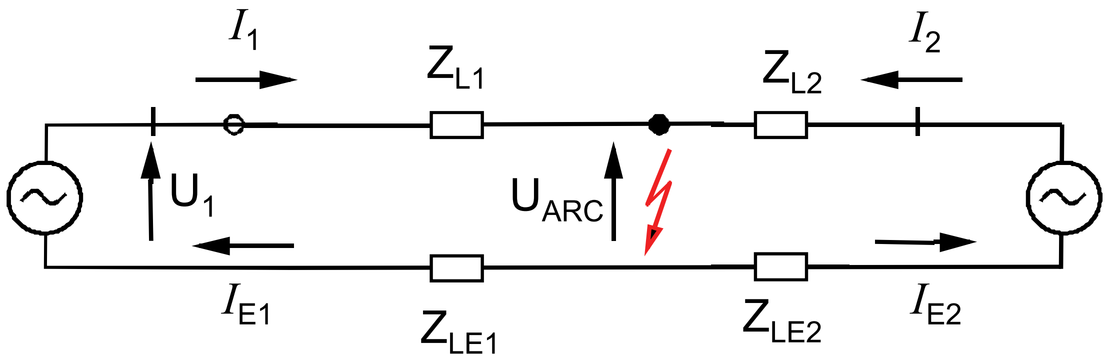

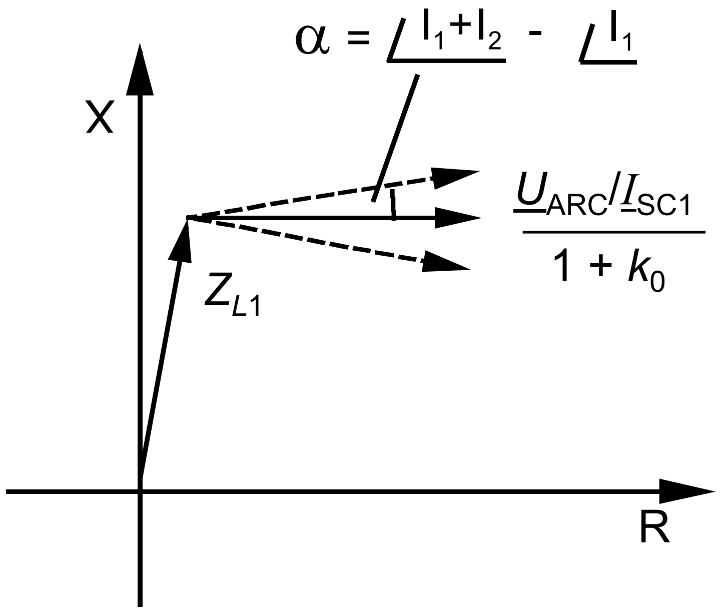

$$U_1 = I_1 \cdot Z_{L1} + I_{E1} \cdot Z_{E1} + U_{ARC}$$

$$Z_{Rel} = \frac{U_1}{I_1 + k_0 \cdot I_{E1}} = \frac{I_1 \cdot Z_{L1} + I_{E1} \cdot Z_{E1}}{I_1 + k_0 \cdot I_{E1}} + \frac{U_{ARC}}{I_1 + k_0 \cdot I_{E1}}$$

for : $I_1 = I_{E1} = I_{SC1}$ and $k_0 = \frac{Z_{LE}}{Z_L} = \frac{Z_{L0} - Z_L}{3 \cdot Z_L}$

$$Z_{Rel} = Z_{L1} + \frac{U_{ARC}}{(1 + k_0) \cdot I_{SC1}}$$

Estimation of arc resistance

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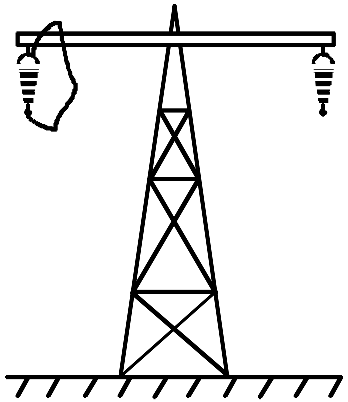

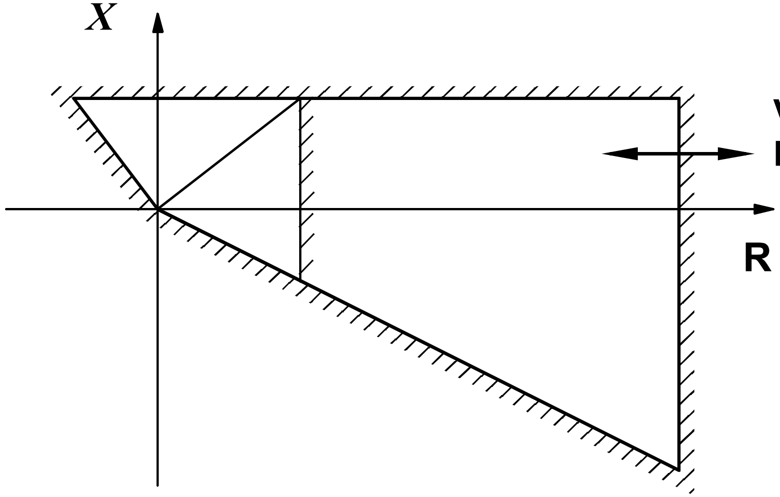

Worrington formula:

$$R_{ARC} = \frac{28700}{I[A]^{1,4}} \cdot l[m] \text{ Ohm}$$

Rough estimation:
U_{ARC} = 2500 V/m

$$R_{ARC} = \frac{2500\,[V/m] \cdot d[m]}{I_F[A]} \text{ Ohm}$$

Phase-to-phase clearances

d =	3,5 m	(110 kV)
d =	7 m	(220 kV)
d =	11 m	(380 kV)

Insulator lengths (long-rod insulator)

l =	1x1,3 = 1,3 m	(110 kV
l =	2x1,3 = 2,6 m	(220 kV)
l =	3x1,3 = 3,9 m	(380 kV)

Ph-PH-E short-circuit with fault resistances, Measured loop impedances depending on fault location

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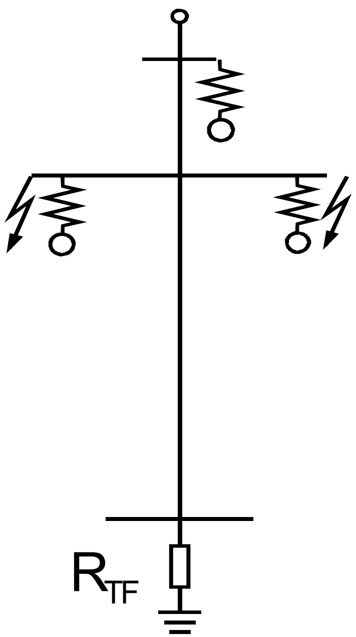

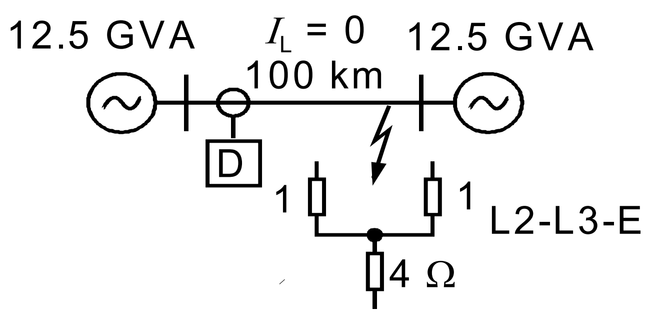

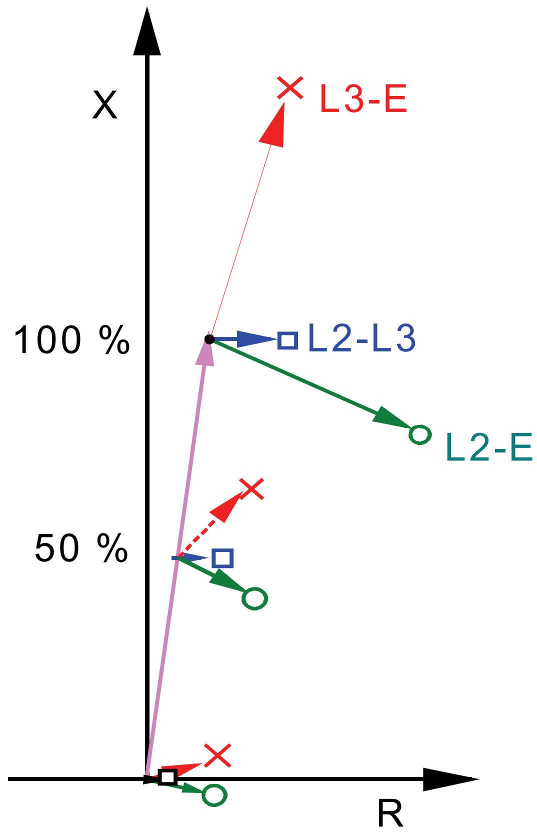

Loop impedances during Ph-Ph-E short-circuit, depending on fault resistance to earth and load conditions

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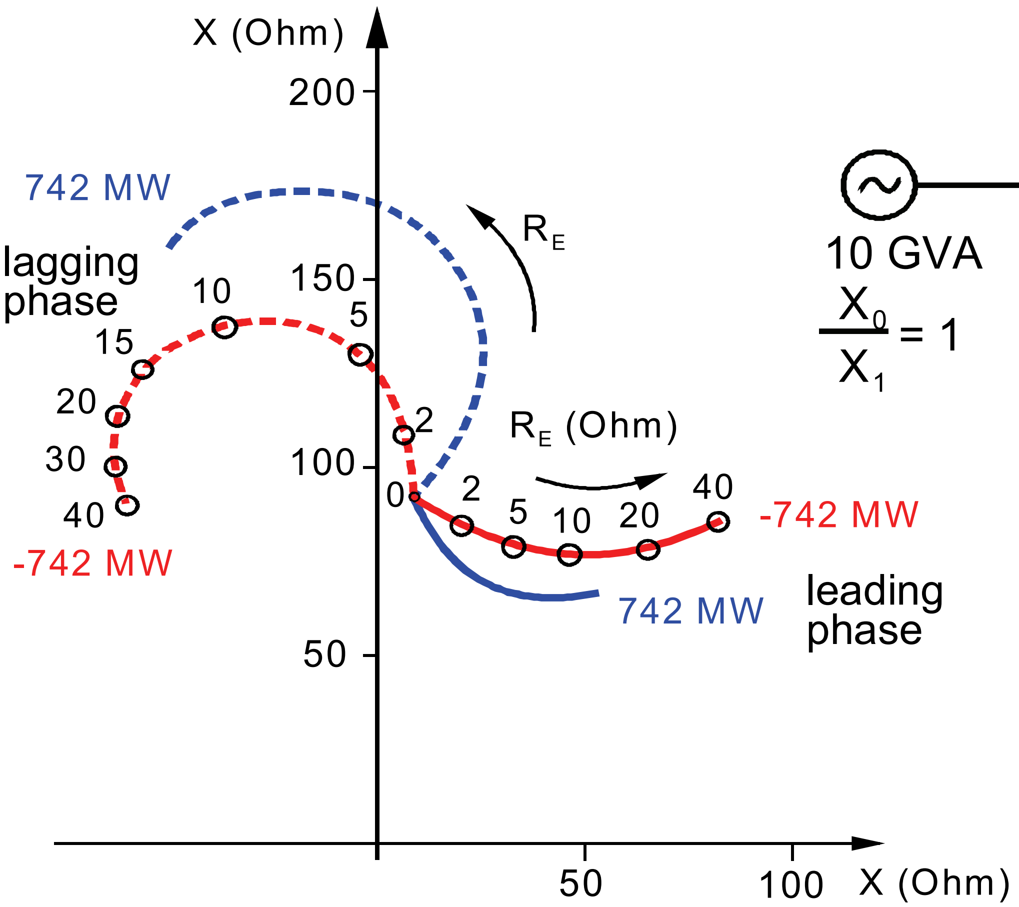

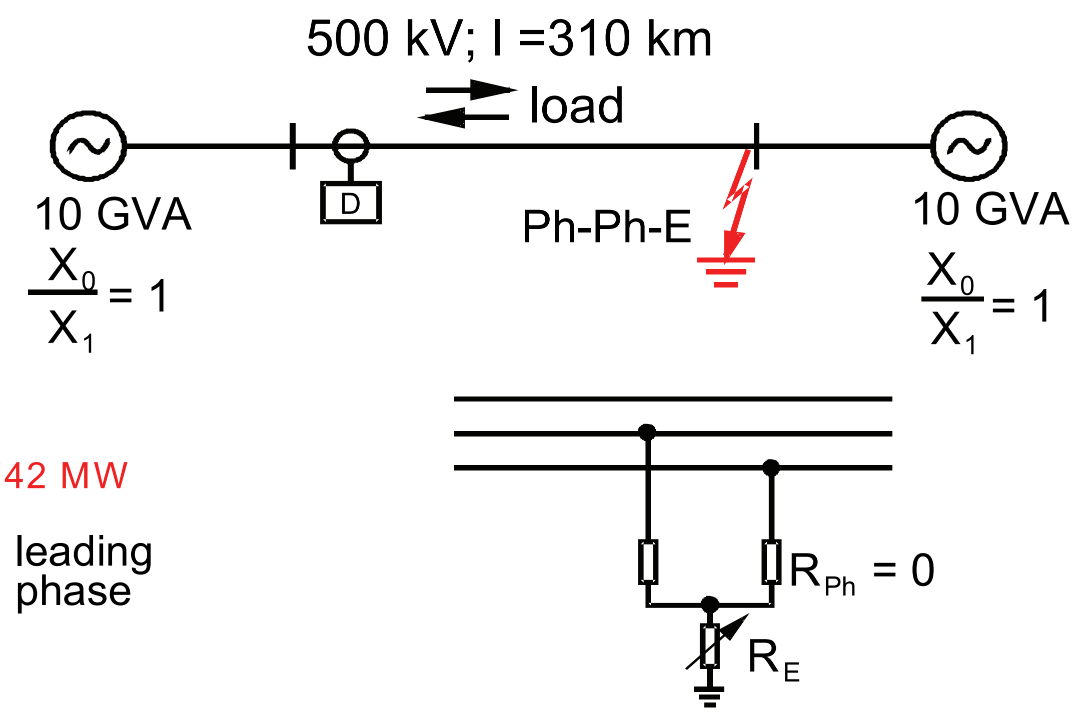

Effective arc resistance „seen“ by the distance relay with double-sided in-feed (example)

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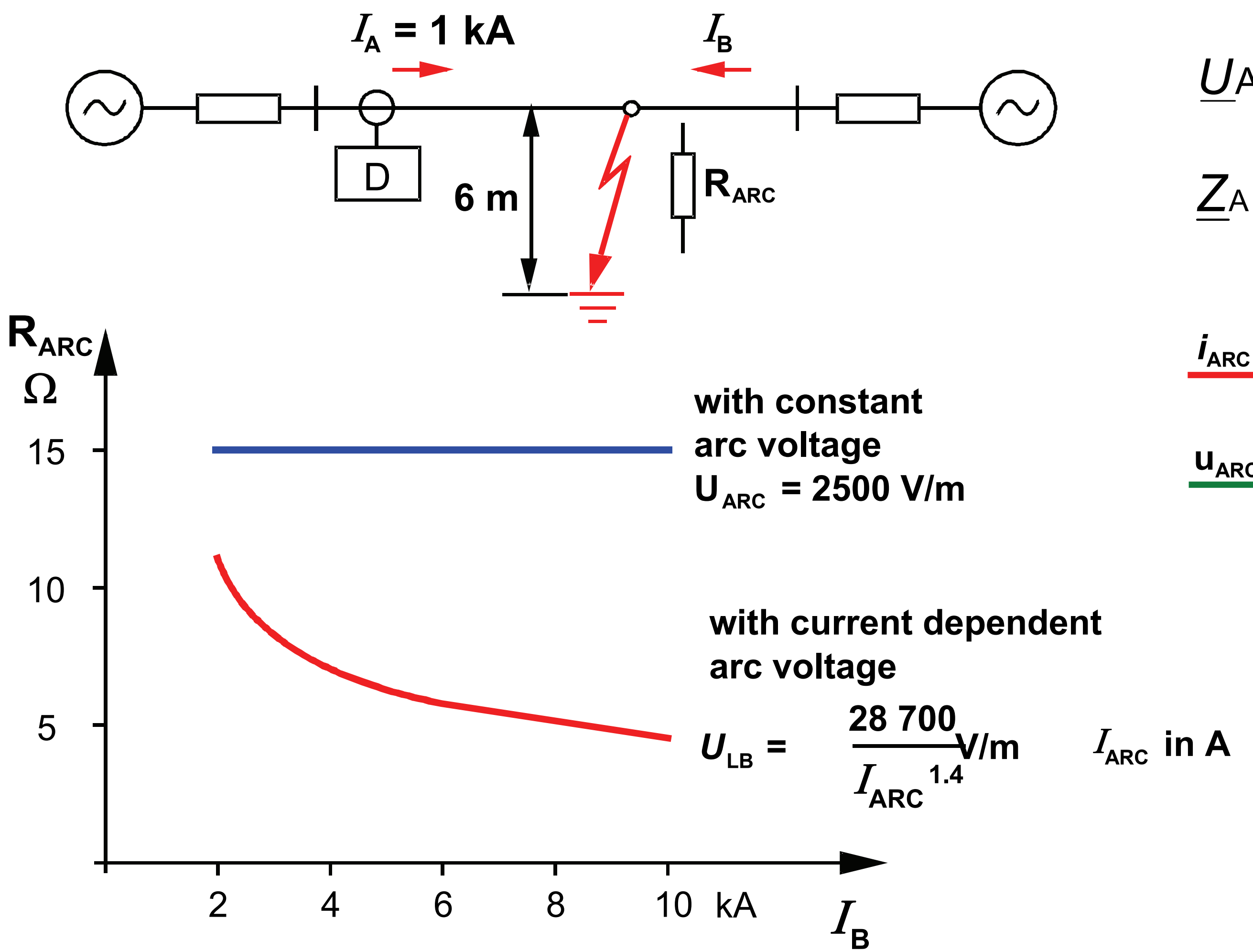
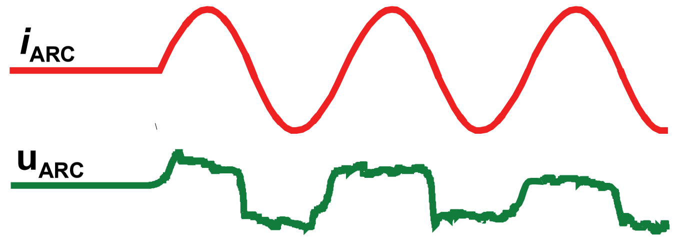


$$\underline{U}_A = \underline{I}_A \cdot \underline{Z}_L + \underline{U}_{ARC}$$

$$\underline{Z}_A = \frac{\underline{U}_A}{\underline{I}_A} = \underline{Z}_L + \frac{\underline{U}_{ARC}}{\underline{I}_A}$$



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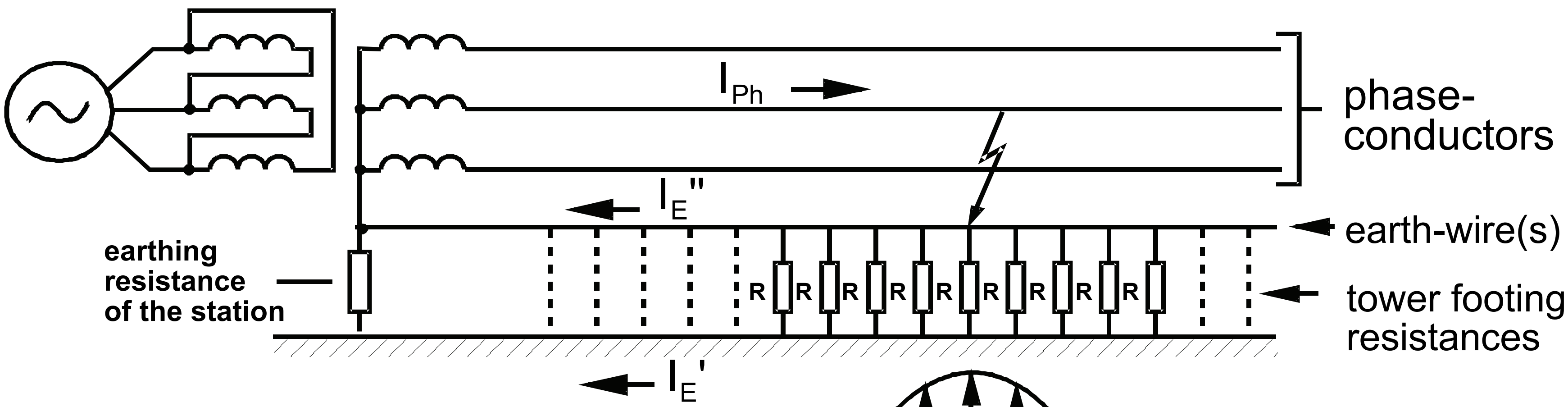
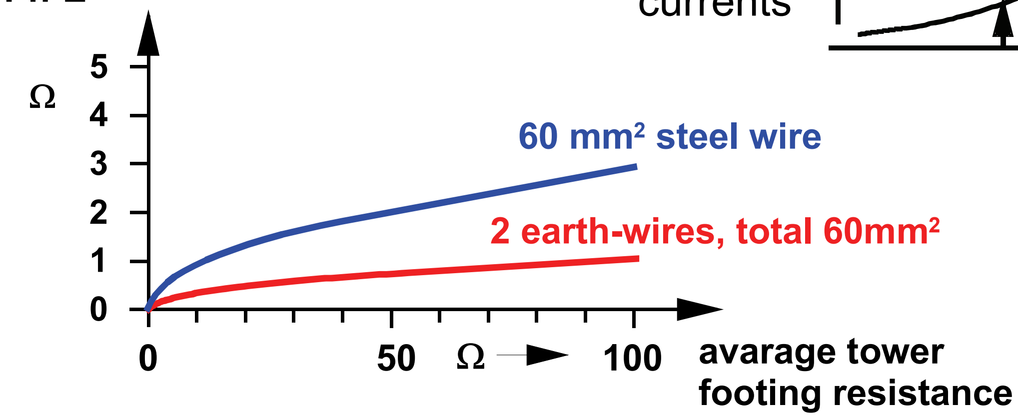
Resultant fault resistance on overhead lines with earth-wire





Quadrilateral characteristic with load cut-out for high line loadability

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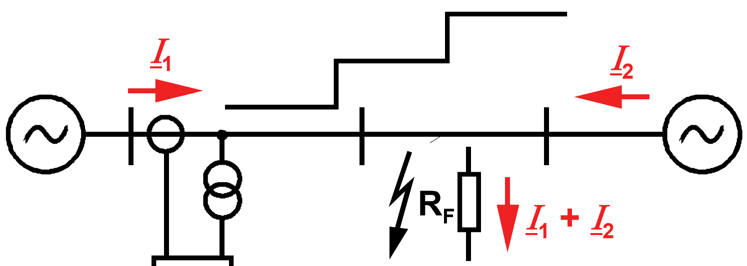
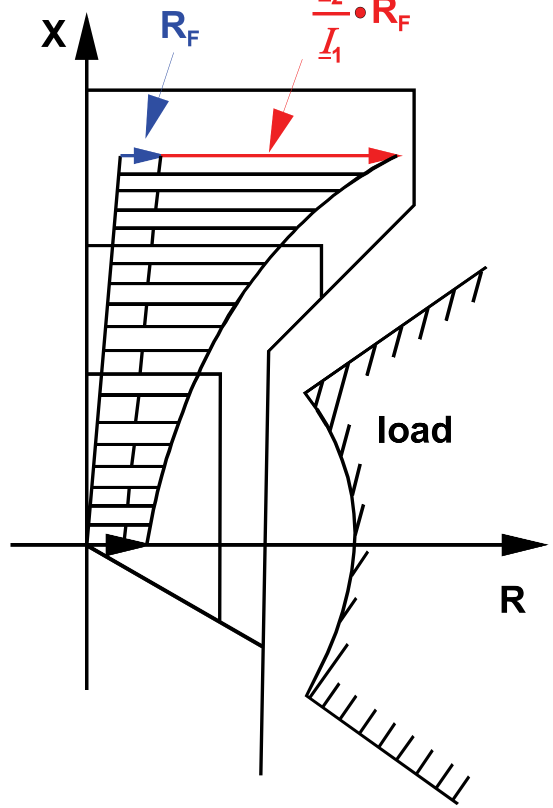
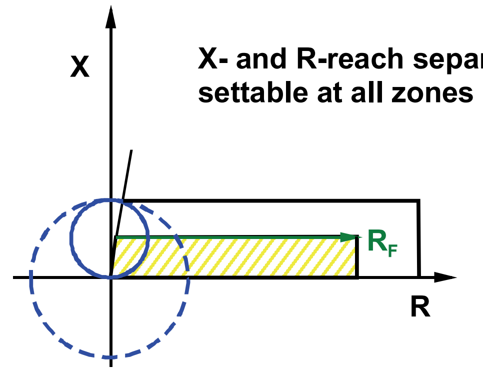


$$\underline{Z}_F = \underline{Z}_L + R_F + \frac{\underline{I}_2}{\underline{I}_1} \cdot R_F$$

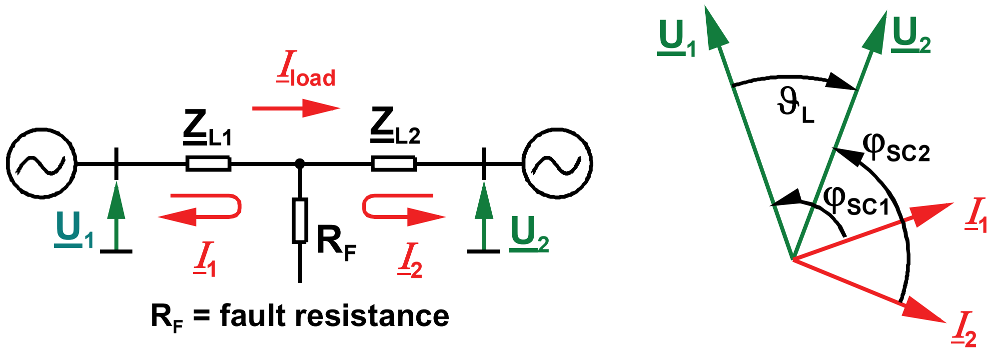
- High reach for remote back-up and adapted arc tolerance (good fault-load discrimination)



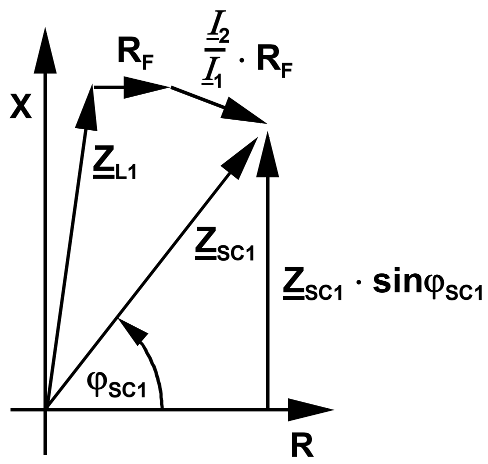
- High arc compensation even with short lines

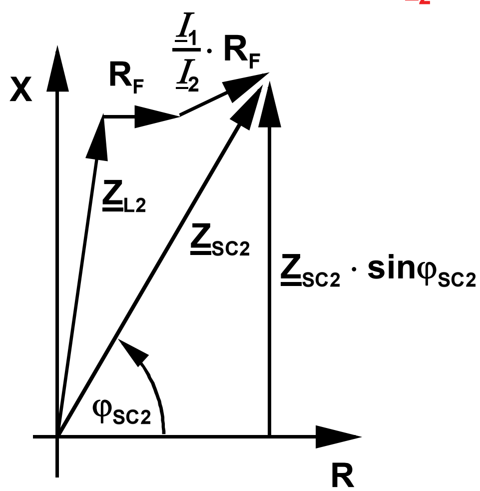


Influence of load flow on the distance measurement for faults with fault resistance



R_F = fault resistance





$$\underline{Z}_{K1} = \underline{Z}_{L1} + R_F + \frac{\underline{I}_2}{\underline{I}_1} \cdot R_F \qquad \underline{Z}_{K2} = \underline{Z}_{L1} + R_F + \frac{\underline{I}_1}{\underline{I}_2} \cdot R_F$$

Distance measuring error for faults with fault resistance in conjunction with load transfer

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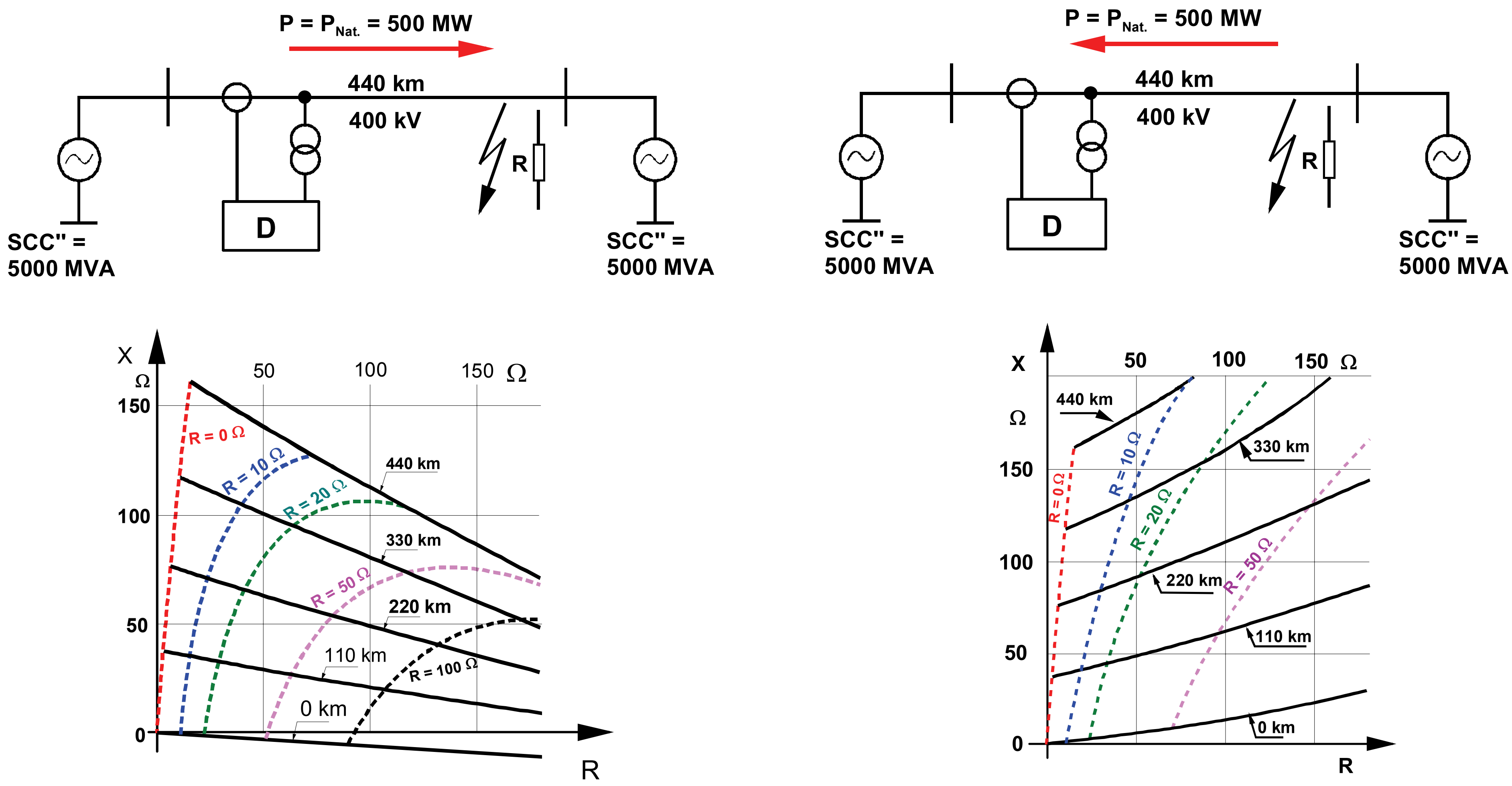

Distance measurement during resistance faults, principle of load compensation for 1-Ph-E faults

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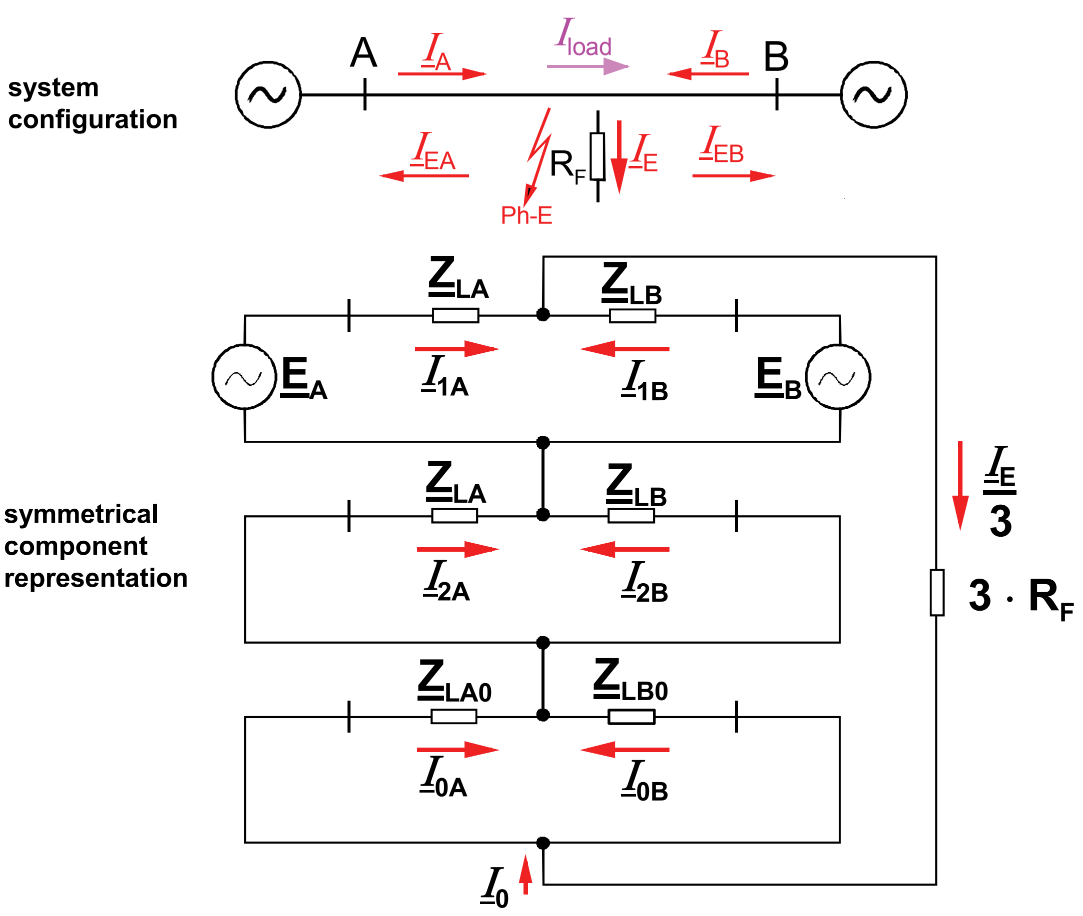

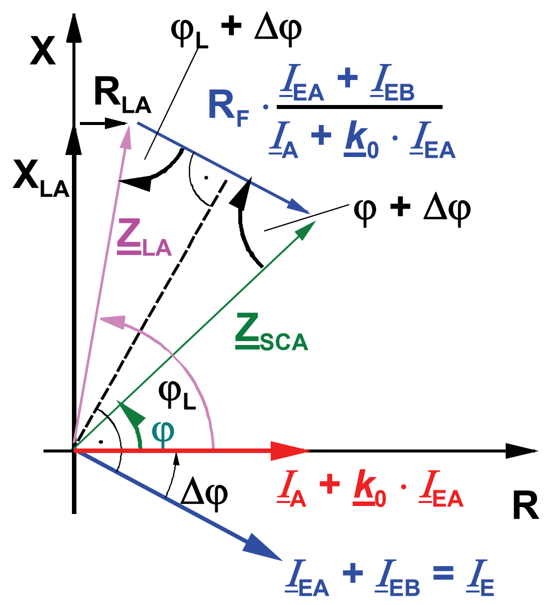

$$Z_{SCA} = \frac{U_{A\,(Ph-E)}}{(I_A + k_O \cdot I_{EA})} \qquad K_O = \frac{1}{3} \cdot \frac{(Z_{LO} - Z_{L1})}{Z_{L1}}$$

$$X_{LA} = |Z_{SC-A}| \frac{\sin(\varphi + \Delta\varphi)}{\sin(\varphi_L + \Delta\varphi)} \sin \varphi_L$$

Adaptation of the polarised MHO-circle to the rotation of the fault resistance in the case of faults with load prior to fault inception

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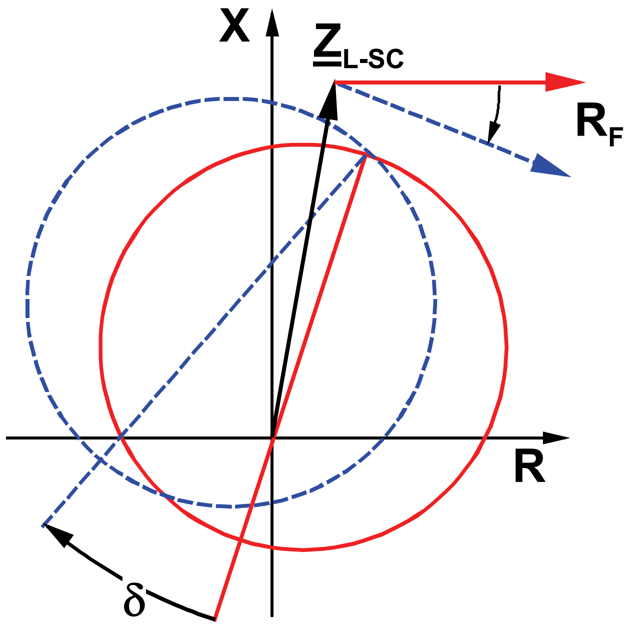
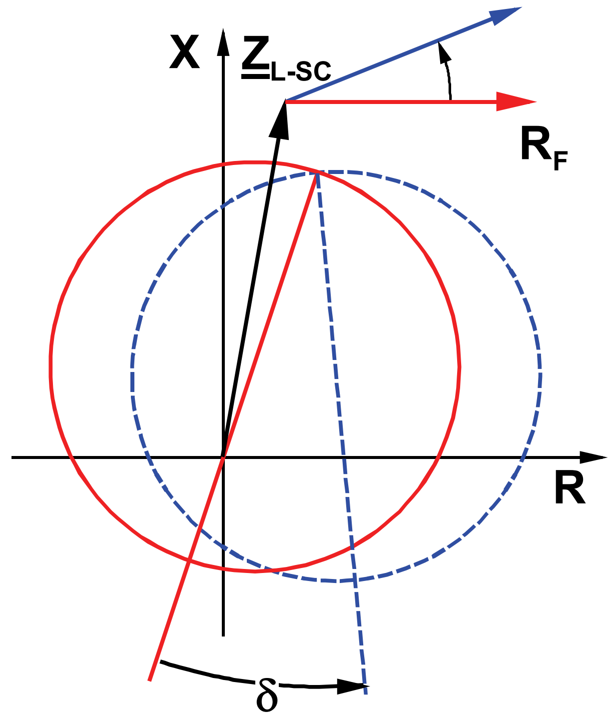


load sending line end



load receiving line end