Relays and Terminals

O242 MV Protection Relay Applications

ABB Oy Distribution Automation

NAME	RESP.DEPT.	PREPARED
MV Protection Relay Applications	FISUB/RAE	20.4.2008 E.L.
COURSE ID	**LANGUAGE**	**CHECKED**
O242	En	25.4.2008 L.N.
	REVISION	**APPROVED**
	B	25.4.2008 M.M.

MV Protection Relay Applications

Content:

Contents of chapter 1

O242 Medium Voltage Protection Relay Applications
Week 14 (31.3. -4.4. 2008)

Place: Hotel Silveria and Technobotnia

<u>Time schedule</u>

Monday 31.3.2008 (Hotel Silveria)

9:00-12:00	Introduction to various protection applications in the distribution network	Erkki Lehtonen
12:00-13:00	Lunch	
13:00-16:00	Overcurrent protection	Juha Keisala.

Tuesday 1.4.2008 (Hotel Silveria)

09:00-12:00	Earth-fault protection	Erkki Lehtonen.
12:00-13:00	Lunch	
13:00-16:00	Transformer differential protection	Juha Keisala

Wednesday 2.4.2008 (Hotel Silveria)

9:00-10:30	Generator protection	Stefan Sundfors
10:30-12:00	Motor protection	Erkki Lehtonen
12:00-13:00	Lunch	
13:00-15:30	Motor protection continues	Erkki Lehtonen
15:30-16:00	Disturbance recording	Mats Cainberg

Thursday 3.4.2008 Technobotnia

Practical training with protection models (hands-on training)
Vaasa Polytechnic / Technobothnia lab

Friday 4.4.2008 Technobotnia

Practical training with protection models (hands-on training)
Vaasa Polytechnic / Technobothnia lab

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ABB Oy Distribution Automation
Training Team

Chapter 2

Introduction

Introduction

MV Protection Relay Applications



ABB

Introduction

Topics:

- ***History***
- ***Basic Terminology***
- ***Current Transormer***
- ***Voltage Transformer***
- ***Sensors***
- ***Relay inputs***
- ***Settings***
- ***Protection Solutions***
- ***SA-D Supportline***

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Introduction

- **Brief History**
  - **Start in the Strömberg Research Center in the mid 1960´s**
    - **1965** ***First static protective relay (J3 series)***
    - **1970's** ***Digital technique and wider product range***
    - **1982** ***First microprocessor relay***
    - **1985** ***SPACOM product line introduced***
    - **1985** ***MicroSCADA programs for Substation Automation and SCADA***
    - **1987** ***Customer installations of fully integrated Substation Automation and SCADA systems***
    - **1995** ***REF 54_ series introduced***
    - **2003 RE_ 600 protection relay family introduced**
  - **Powerful growth in the 1990´s**
  - **ABB Substation Automation Oy since April 1,1999**
  - **PRU Substation Automation since January 1 2002**
  - **PG Distribution Automation since 2004**

Introduction

- Electromechanical relays
  - 1st generation, primary connected measurement
  - 2nd generation, power supplied from the instrument transformers

- Relay forms a high burden to the instrument trafos
- High risk of saturation of CTs, especially when there is a DC component in the fault current
- A lot of mechanical parts, requires regular maintenance
- Unaccurate and unsensitive settings

Introduction

- Static relays
  - *Power supplied by an external auxiliary voltage*

    - *Electronics based, analogue or digital*
    - *Relay forms a low burden to the instrument trafos*
    - *More accurate settings*
    - *Wider setting ranges*
    - *Small dimensions*

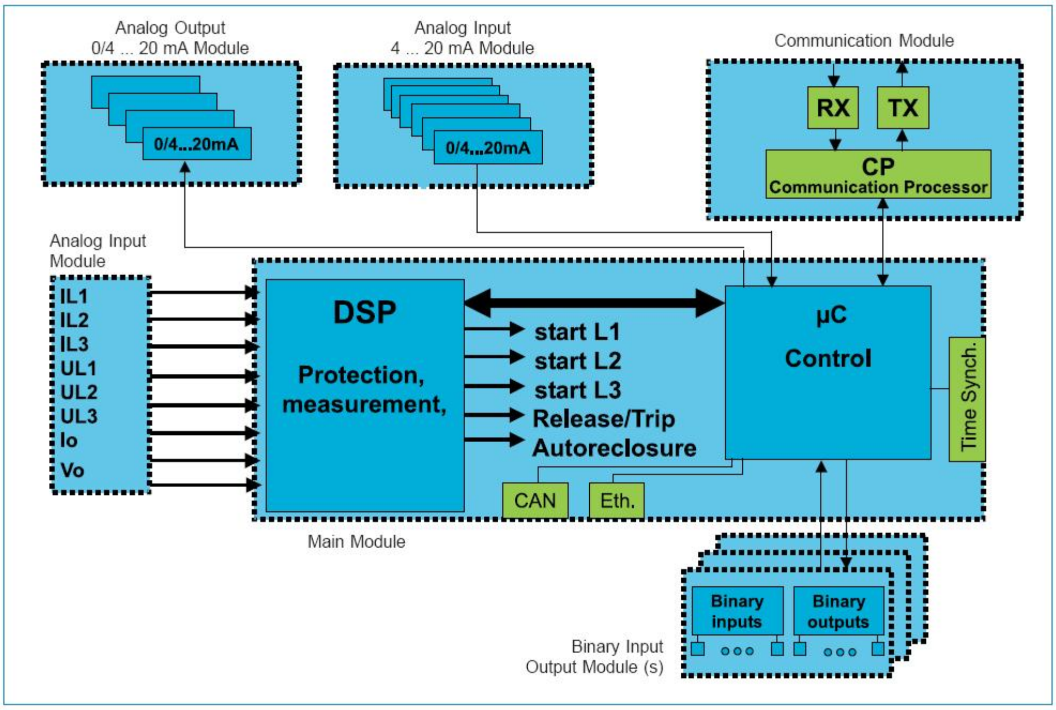
Introduction

- Numerical Relays
  - Microprosessor technology provides features as in statical relays and more…

    - Many protection functions integrated in one relay
    - Self supervision of hardware and software
    - Extensive information handling, due to communication
    - Integrated protection, measurement, control, condition monitoring, communication etc, in so called feeder terminals

Introduction

- Numerical Relays - Working principle (REF542plus)

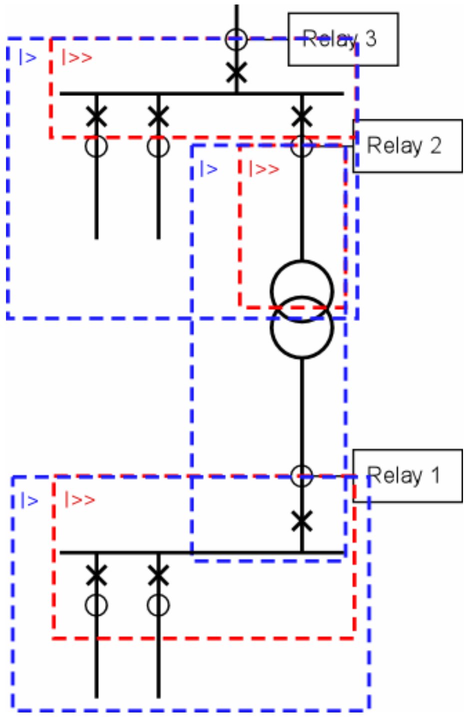


Introduction

- Purpose of Protection
  - Detect all electrical faults and some abnormal operating conditions
  - Protect human beings and properties around the power network
  - The operation must be selective
    - disconnect minimum possible part of the power network
  - The operation must be fast and sensitive
    - danger of life, damages and disturbances have to be minimized
    - the stability of the network has to be ensured in all conditions
  - Protection must cover 100% of the protected network
  - Protection should be reliable and simple
  - Commissioning tests of the protection should be possible to perform in a place of installation

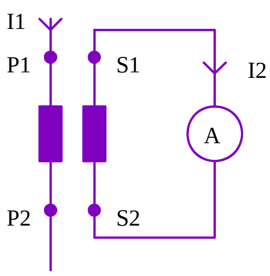
Introduction

- Protection must cover 100% of the protected network

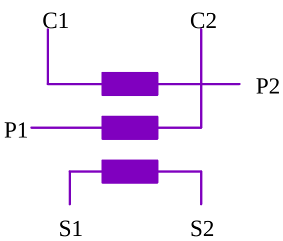


Introduction

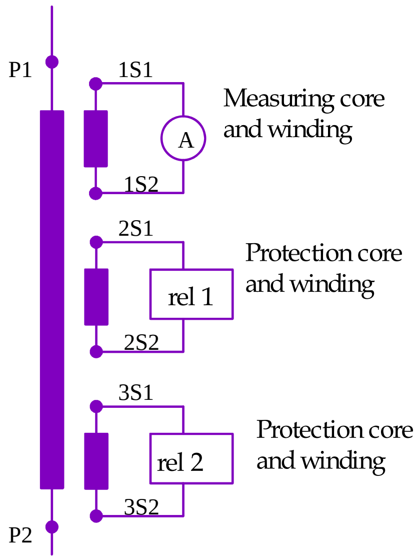
- Current Transformers (CT)



One core current transformer



Two primary windings



Three core current transformer

Introduction

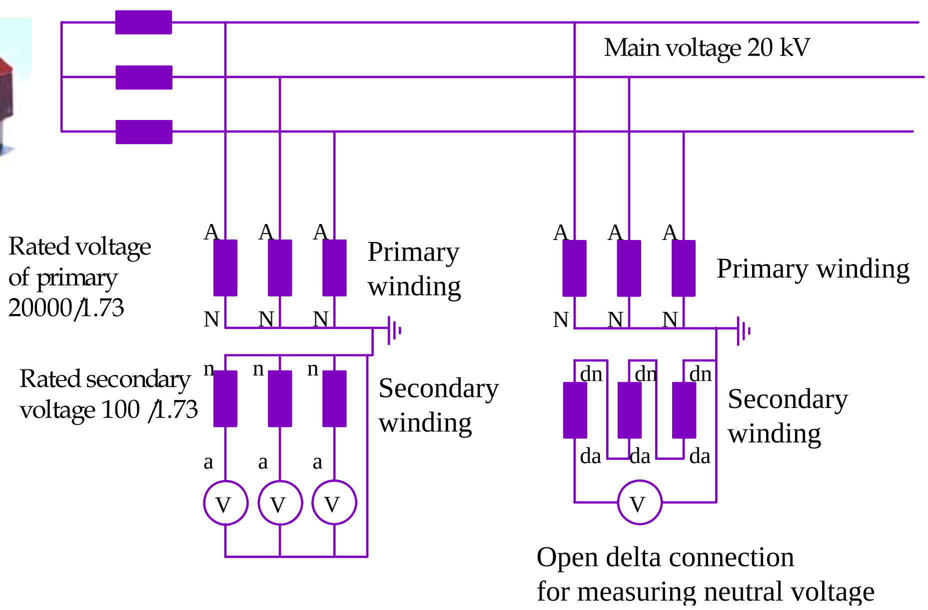
- Current Transformers (CT)

Main functions of current transformers:

- Step down primary system currents to the level, which the instruments and protection can handle
- Make it possible to use standardized secondary meters and relays
- To protect sensitive secondary devices from overloading
- Make possible centralized measuring and protection system

Introduction

- Voltage Transformers (VT) or Potential Transformers (PT)



Introduction

- Voltage Transformers (VT) or Potential Transformers (PT)

Main functions of voltage transformers:

- Step down primary system voltages to the level, which the instruments and protection can handle
- Make it possible to use standardized secondary meters and relays
- Make possible centralized measuring and protection system

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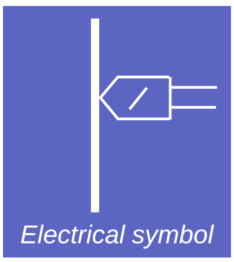
Introduction

Current sensor



Rogowski coil

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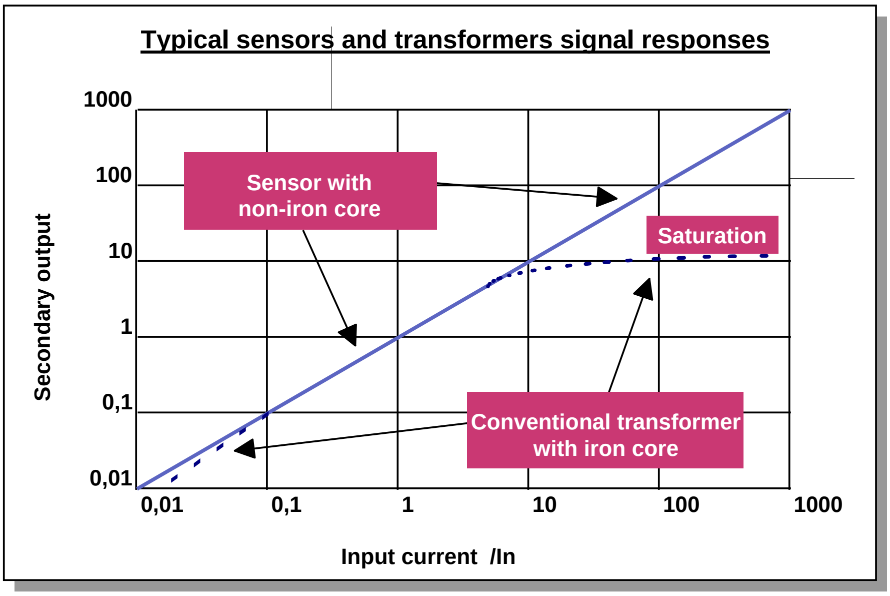
Introduction

- Current sensors
  - The current sensor is based on the principle of the Rogowski coil
  - The Rogowski coil has no iron core

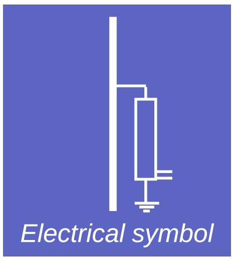


Introduction

- Current sensors
  - Linear response on all the measurement range
  - No saturation
  - No hysteresis
  - Single instrument for protection and measurement functions
  - High accuracy rating
  - High degree of immunity to electromagnetic disturbances
  - The output signal is a voltage (150 mV) function of the time/current ratio
  - A single coil covers the range 0-3200A
  - The winding can stay open while the MV switchboard is in service

Introduction

Voltage sensor



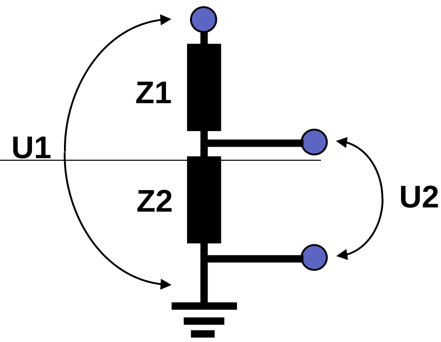
Resistive divider

Introduction

- It is based on the action of the resistive divider at the given values resistance

Z1 = 250 MΩ
Z2 = 25 kΩ

$$U2 = \frac{Z2}{Z1 + Z2} * U1$$

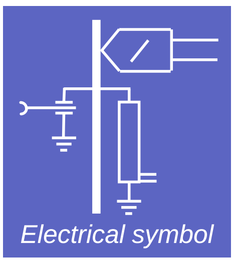


Introduction

- Voltage sensors
  - Linear response on all the measurement range
  - No saturation
  - No iron-resonance
  - Single instrument for protection and measurement functions
  - High accuracy rating
  - High degree of immunity to electromagnetic disturbances
  - The output signal is a voltage proportional to the primary voltage
  - The partition ratio is 10000 / 1
  - A single divider is used for the whole range 0 to 24 kV rated voltage

Introduction

Current and voltage sensor



Combined sensor

Introduction

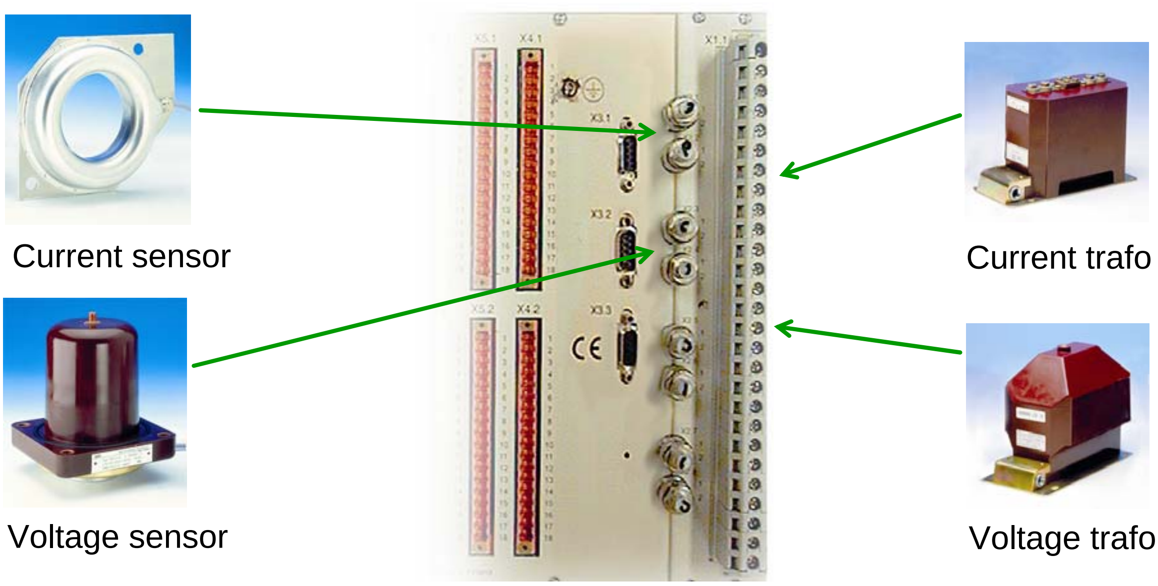
- Combined sensors
  - Integrated instrument for both current and voltage sensors
  - Same features as those of sensors separately considered
  - Capacitive indicators for the signalling lamps are integrated too
  - Two configurations with the same dimensions for all the switchboard applications:

    1) Rogowski coil + resistive divider + capacitive indicator

    2) Rogowski coil + capacitive indicator

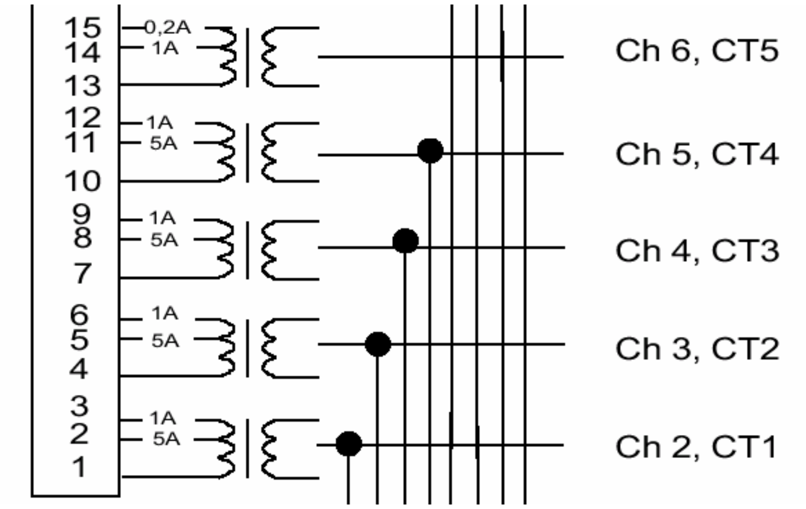
Introduction

- Measurement by the relays



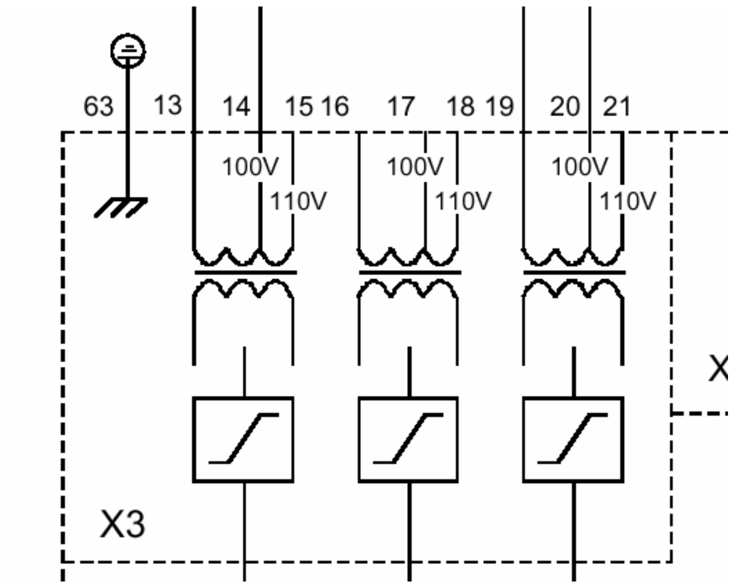
Introduction

- CT connections



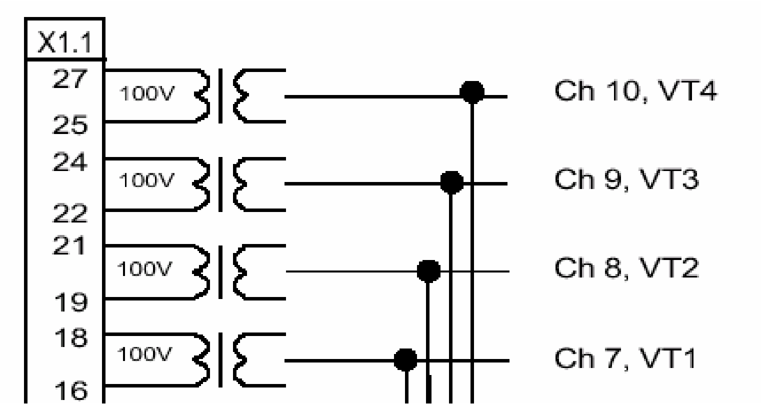
Introduction

- VT connections in SPACOM



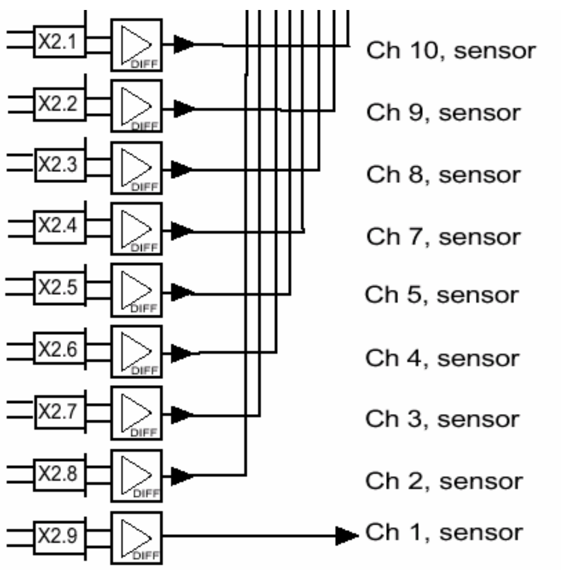
Introduction

- VT connections in REF54_
  - Nominal voltage setting by parameter
  - Parameter alternatives: 100V / 110V / 115V / 120V



Introduction

- Sensor connections



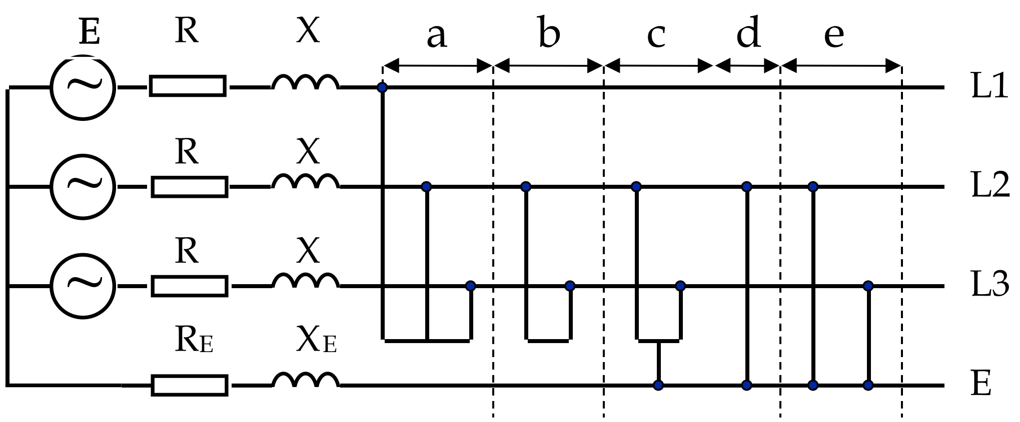
Introduction

- Technical details

Rated frequency		50.0/60.0 Hz	
Current inputs	rated current		0.2 A/1 A/5 A
	thermal withstand capability	continuously	1.5 A/4 A/20 A
		for 1 s	20 A/100 A/500 A
	dynamic current withstand, half-wave value		50 A/250 A/1250 A
	input impedance		<750 mΩ/<100mΩ/ <20 mΩ
Voltage inputs	rated voltage		100 V/110 V/115 V/120 V (parameterization)
	voltage withstand, continuous		2 x U_n (240 V)
	burden at rated voltage		<0.5 VA
Sensor inputs, max 9	voltage range RMS		9.4 V RMS
	voltage range peak		±12 V
	input impedance		>4.7 MΩ
	input capacitance		<1 nF

Introduction

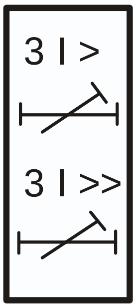
- Different types of faults in power systems

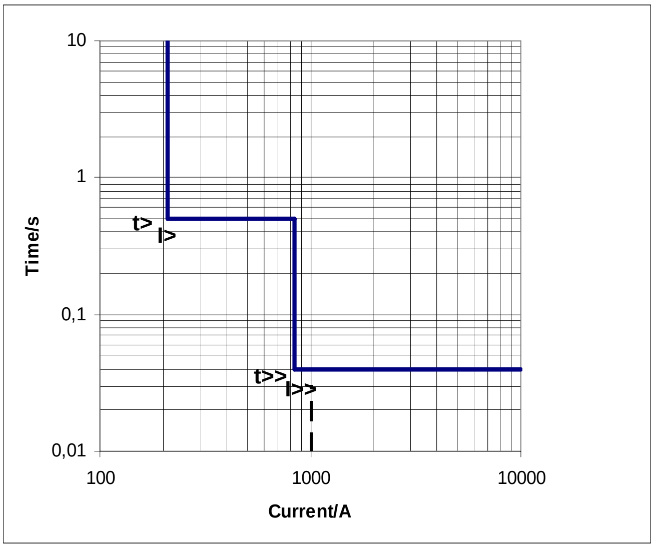


a) three-phase
b) phase-to-phase
c) phase-to-phase-to-earth
d) earth fault
e) cross-country fault

Introduction

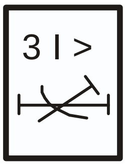
- Definite time characteristic

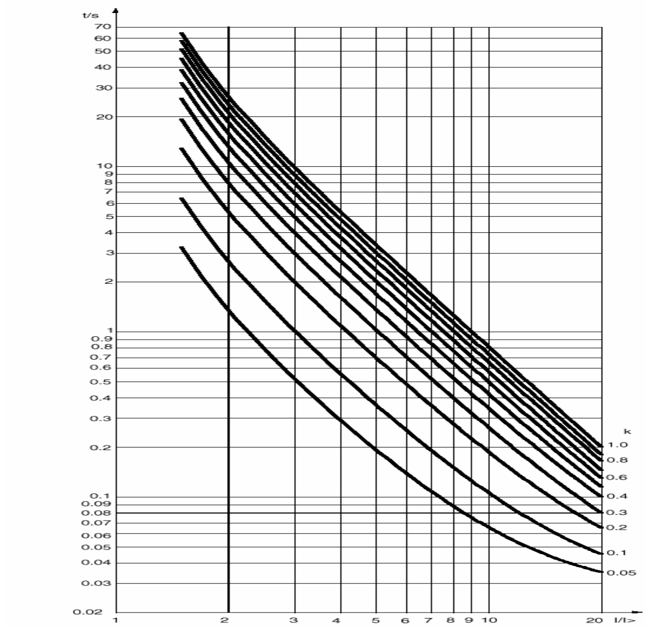




Introduction

- Inverse time characteristic





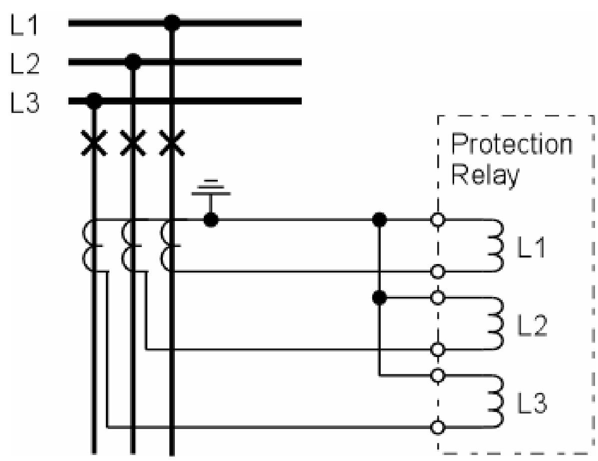
Introduction

- Relay symbols and device numbers

IEC 617-series	IEEE C37.2-1991
3I> 3-phase overcurrent relay with settable time delay	51 AC time overcurrent relay
3I>> 3-phase overcurrent relay with settable time delay, high set stage	50 Instantaneous overcurrent relay
I⏚> Earth fault current relay with settable time delay	51N See 51 above, suffix letter N = Neutral (or network)
Id> Differential current relay	87 Differential protective relay

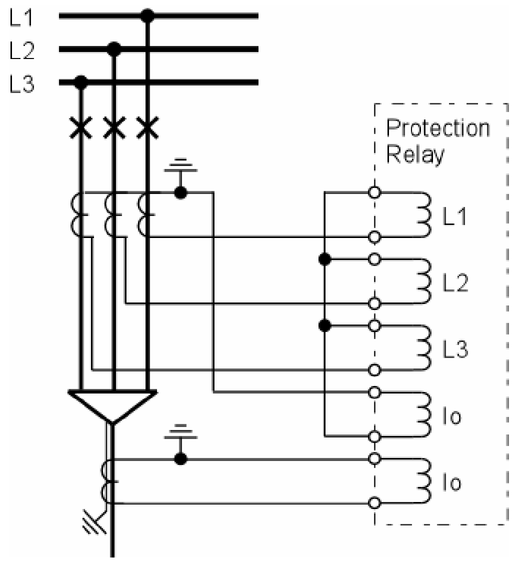
Introduction

- Measuring principles
  - Non-directional overcurrent (short-circuit protection)
  - Overload protection
  - Unbalance protection
  - Phase discontinuity protection
  - Undercurrent protection or loss of load protection



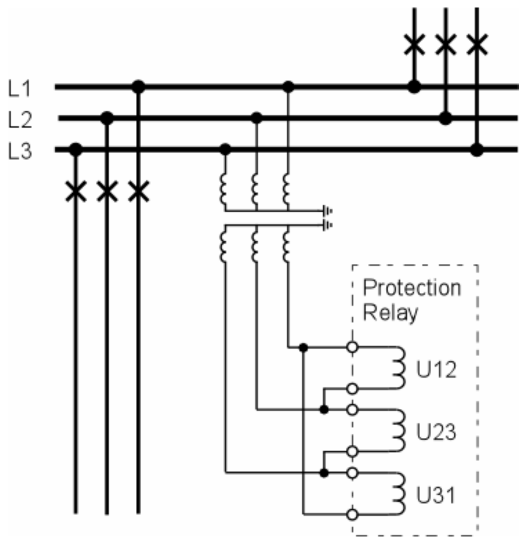
Introduction

- Measuring principles
  - Non-directional earth-fault protection
    - Sum connection
    - Ring core CT



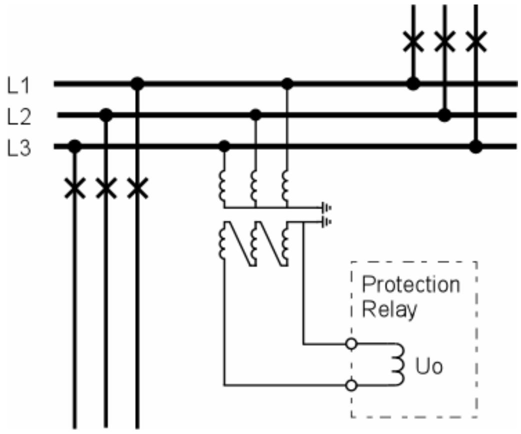
Introduction

- Measuring principles
  - Over- / Undervoltage protection
  - Frequency protection



Introduction

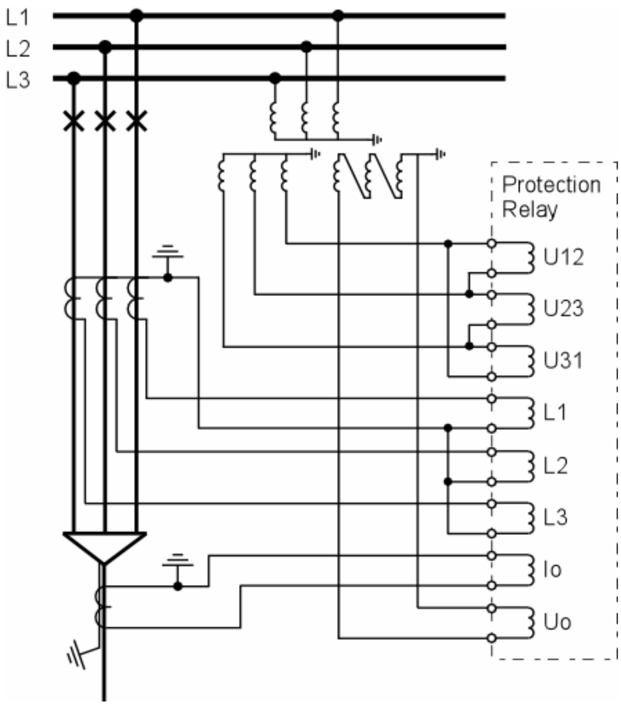
- Measuring principles
  - Earth-fault protection
    - Residual voltage protection



ABB

Introduction

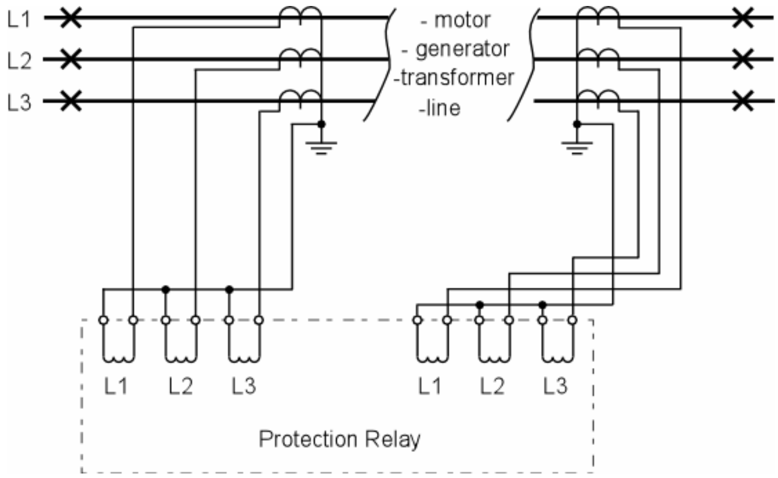
- Measuring principles
  - Directional overcurrent protection
  - Directional earth-fault protection
  - Voltage dependent overcurrent protection
  - Distance protection
  - Over-/Under magnetizing protection
  - Over / Under / Reverse power protection



ABB

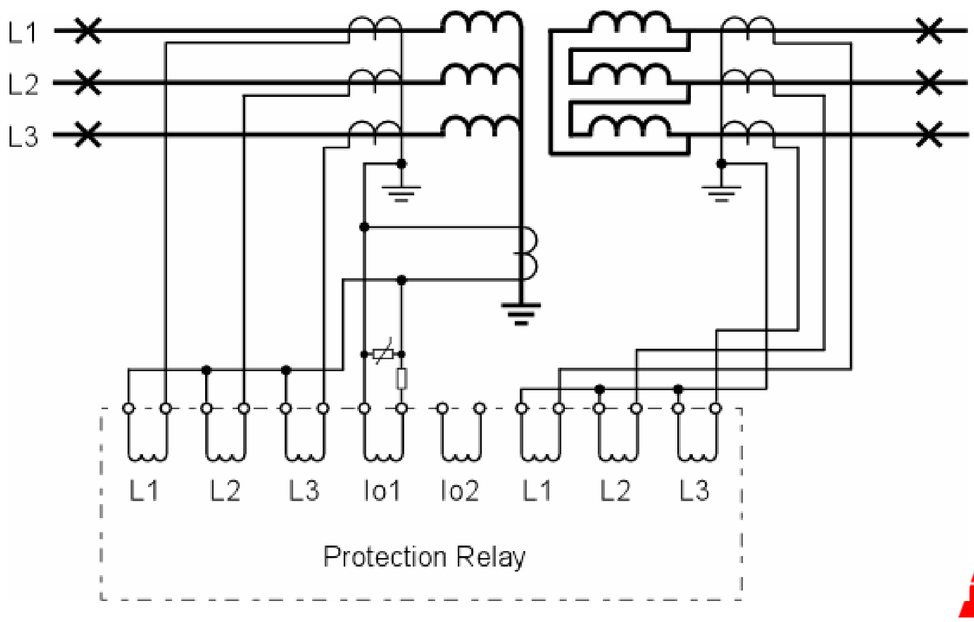
Introduction

- Measuring principles
  - Differential protection



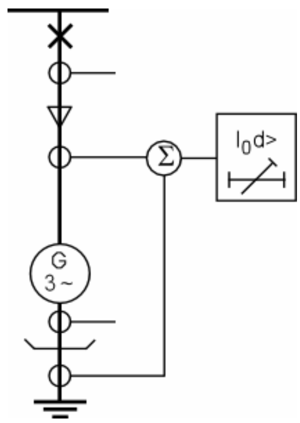
Introduction

- Measuring principles
  - Differential protection
  - Restricted earth-fault protection



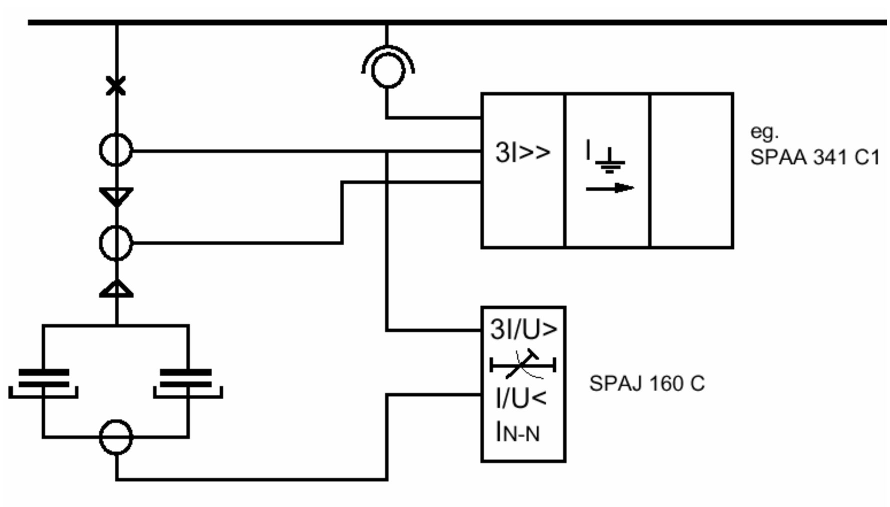
Introduction

- Measuring principles
  - Residual current protection
    - Differential current principle
    - Operates also when generator circuit breaker is open
    - SPACOM module SPCJ 2C30
    - Setting range typically: 0.5 - 5.0%



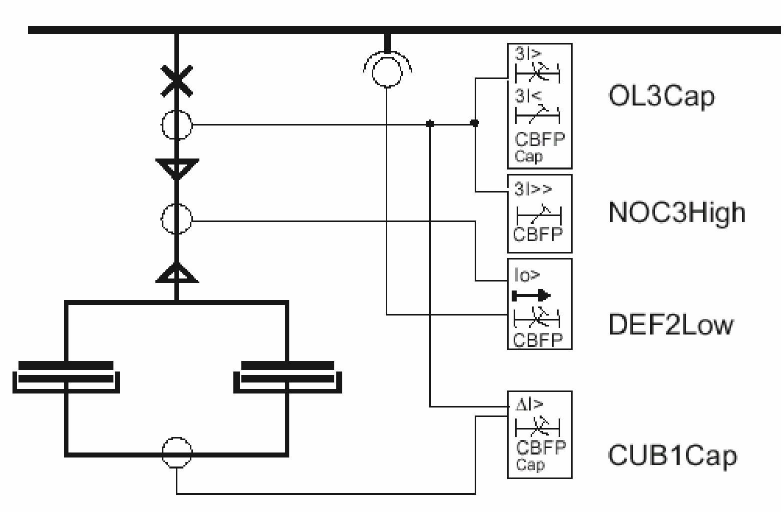
Introduction

- Measuring principles
  - Capacitor bank protection by SPACOM relays



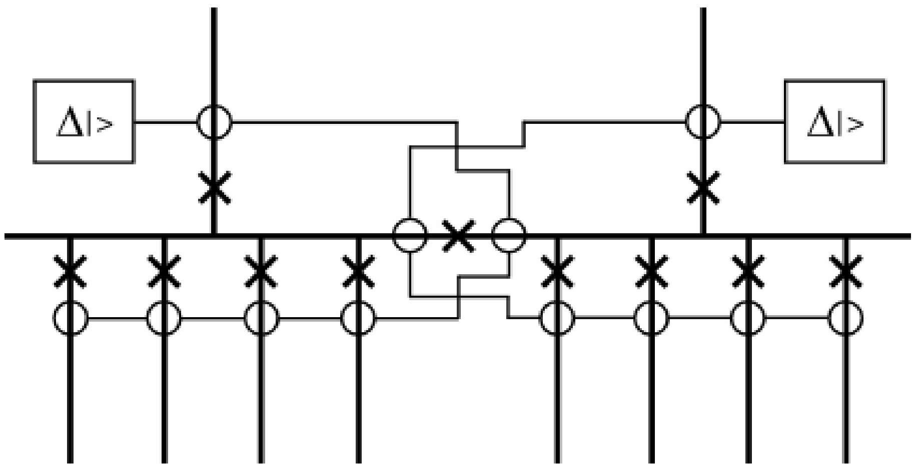
Introduction

- Measuring principles
  - Capacitor bank protection by REF54_ relays



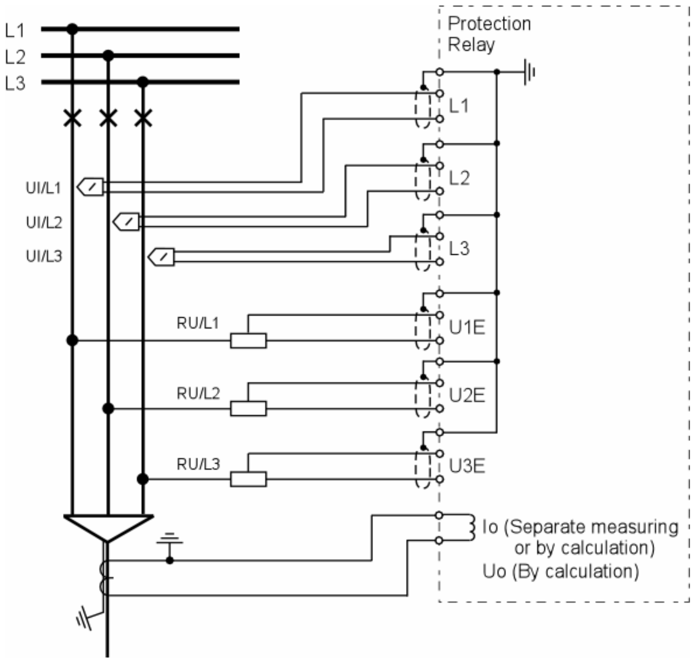
Introduction

- Measuring principles
  - Bus-differential protection e.g. by SPAE010



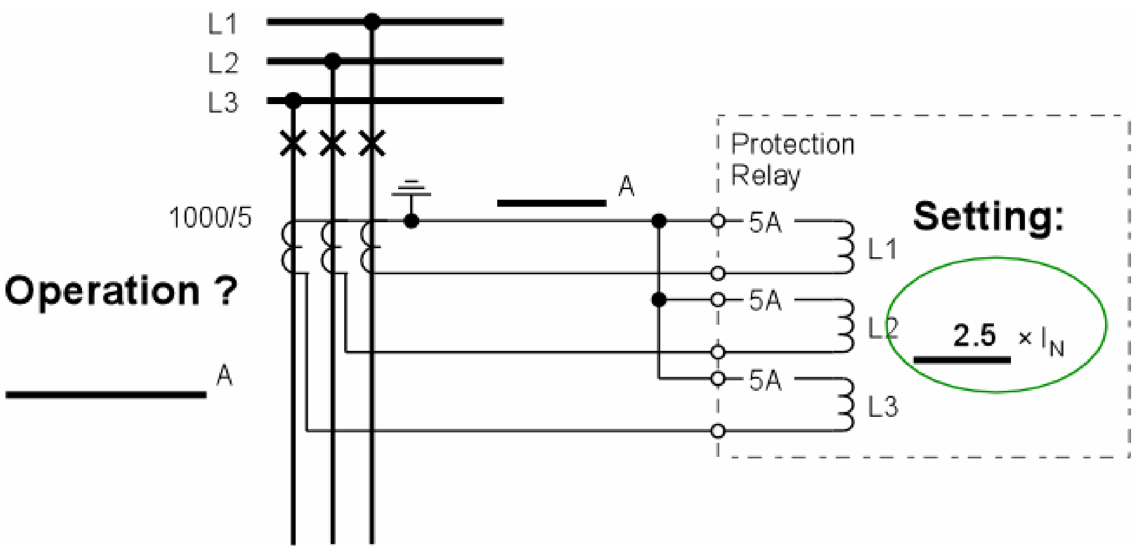
Introduction

- Measuring principles
  - Current and voltage sensors



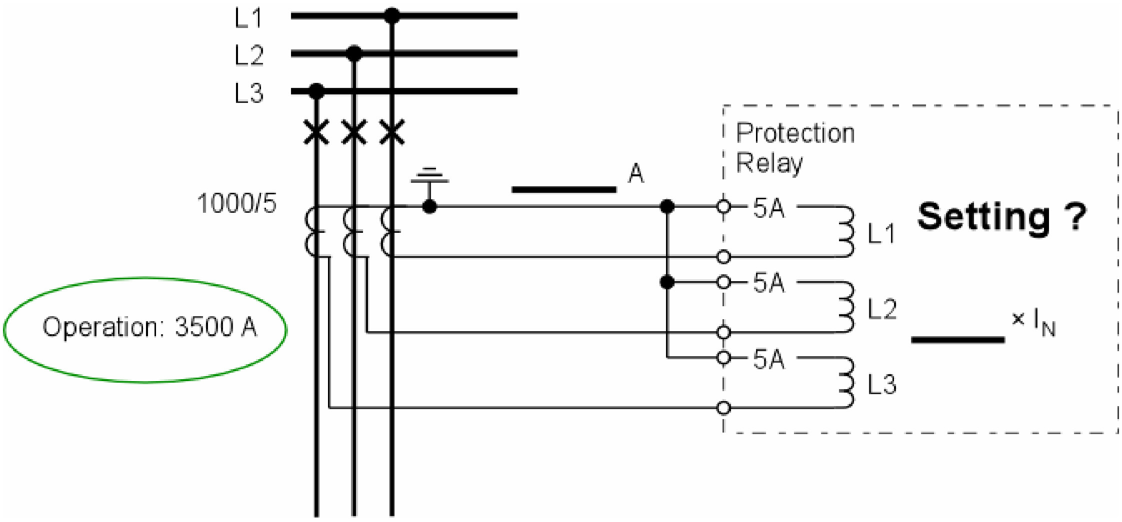
Introduction

- Effect of CT and setting



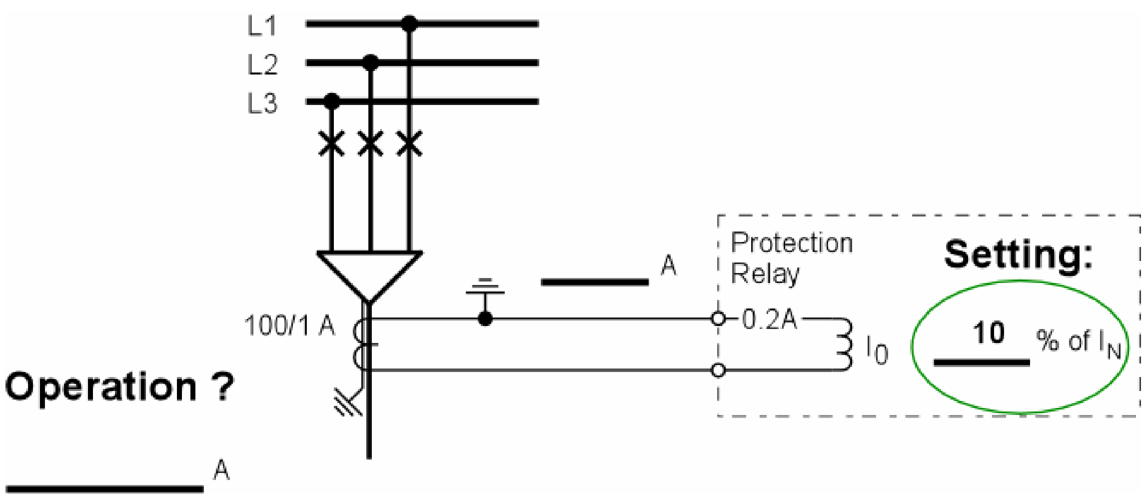
Introduction

- Effect of CT and setting



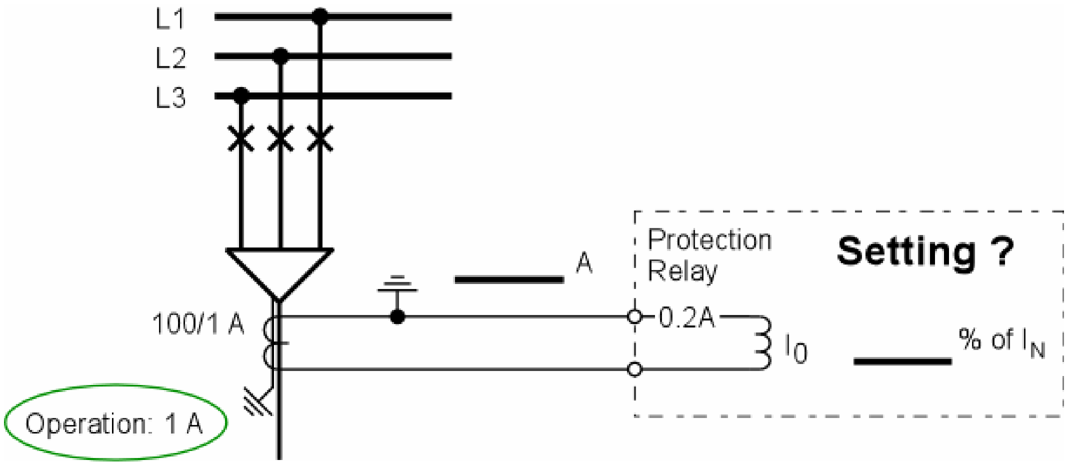
Introduction

- Effect of CT and setting



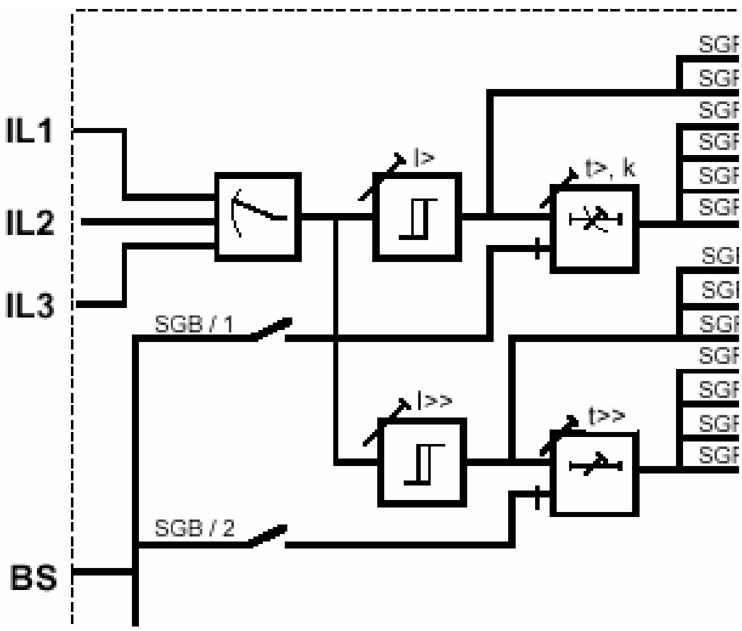
Introduction

- Effect of CT and setting



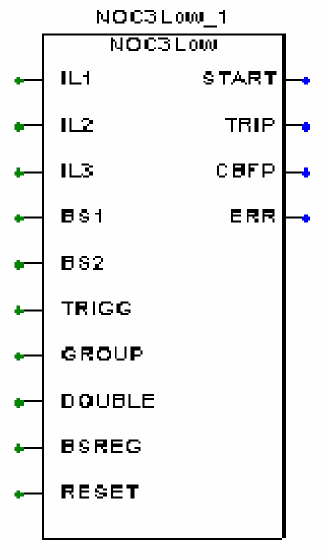
Introduction

- Blocking signals with SPACOM relays



Introduction

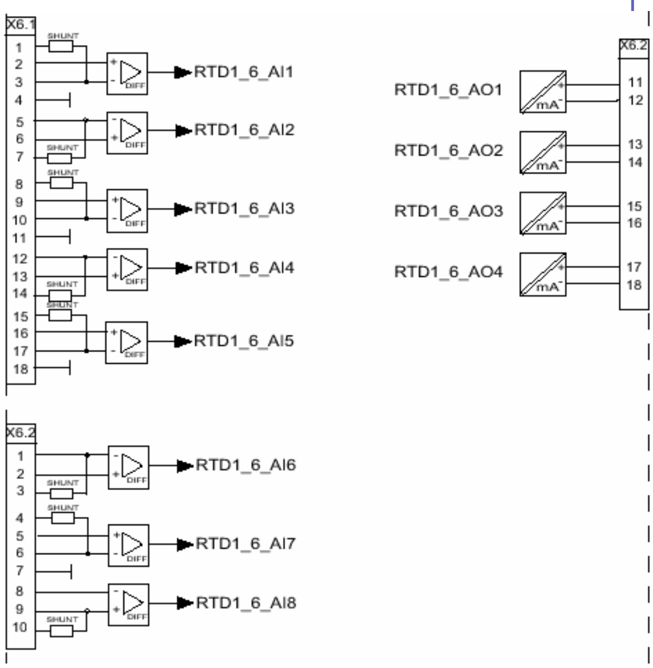
- Blocking signals with RED500 relays
  - <u>The DT ot IDMT timer is allowed to run only if the blocking signal BS1 is inactive</u>, i.e. its value is FALSE. When the signal becomes active, i.e. its value turns to TRUE, the timer will be stopped (frozen).
  - <u>When the blocking signal BS2 is active, the TRIP signal cannot be activated</u>. The TRIP signal can be blocked by activating the signal BS2 until the function block drops off.



ABB

Introduction

- Analogue input/output card
  - Used for
    - thermal overload protection
    - external measurement
  - 4 measuring modes
    - voltage
    - mA
    - Ω
    - °C
  - 4 analogue outputs
    - 0…20mA or 4…20mA



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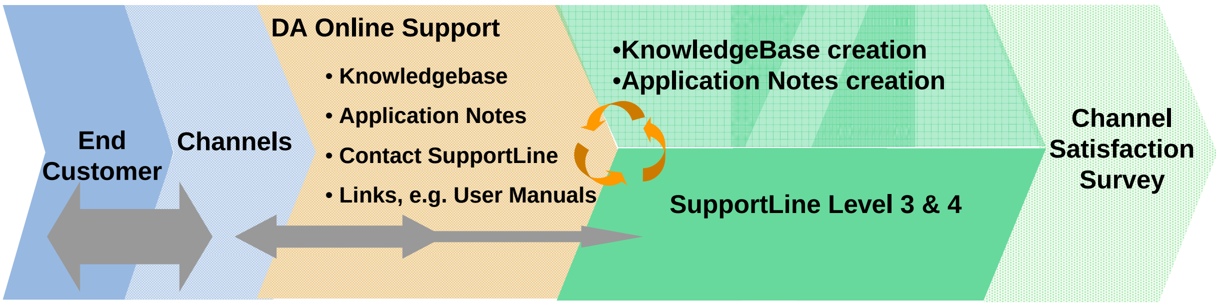
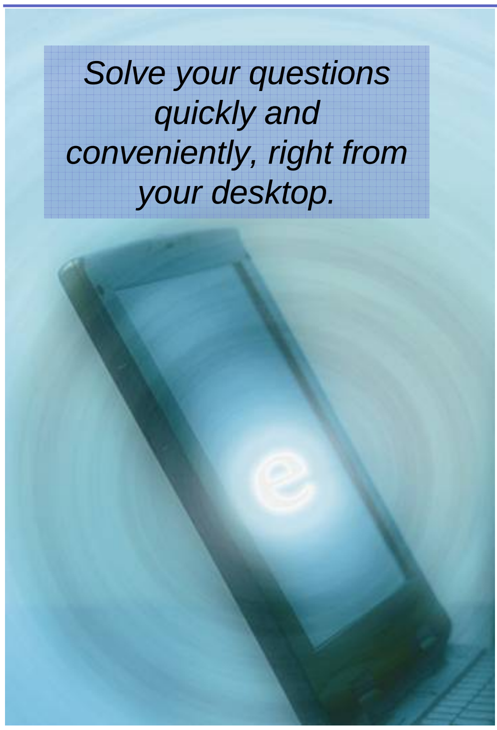
Customer Support process

- Online Support is a customer support service portal for the channels.
- SupportLine is a customer support service that gives answers to the unique questions which can not be solved in Online Support.



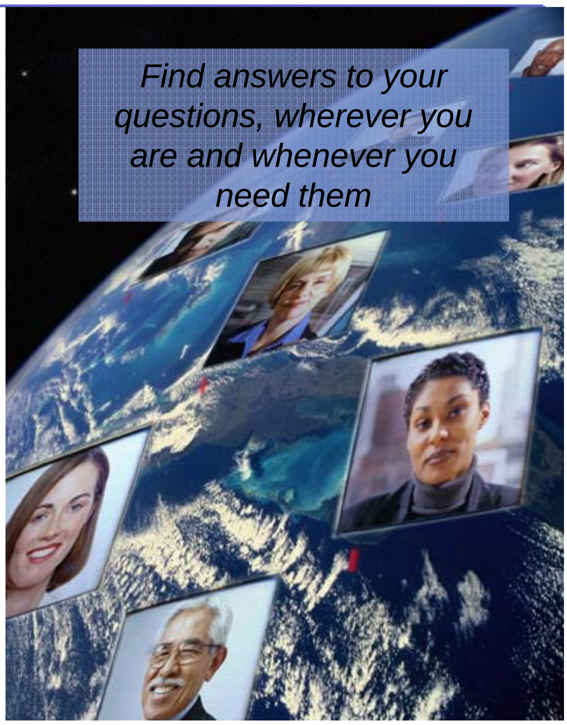
Online Support - Easy access to information



- Support portal of choice for ABB people who need fast answers to technical questions
- Online self-service including capability to send questions to SupportLine
  - One single user interface on ABB intranet
  - Easy to use and find information
    - Questions & Answers
    - Application Notes
    - Other product related documentation
  - Includes a web-based tool to automate and speed-up the problem resolution
  - New content continuously added by SupportLine specialists

Online Support - extensive service around the clock

- Brilliant method for learning more about the distribution products and their applications
- You can gain experiences from others, since answers are based on SupportLine case content
- The obtained knowledge can be utilized in different activities
  - Engineering
  - Commissioning
  - Support & Services
  - but also in Marketing & Sales
- Online Support available 24/7/365

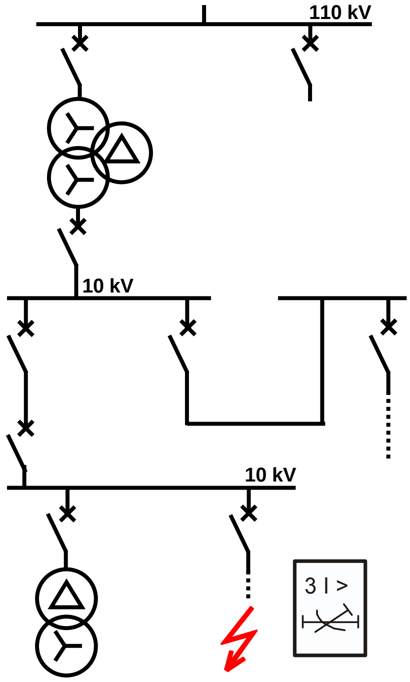


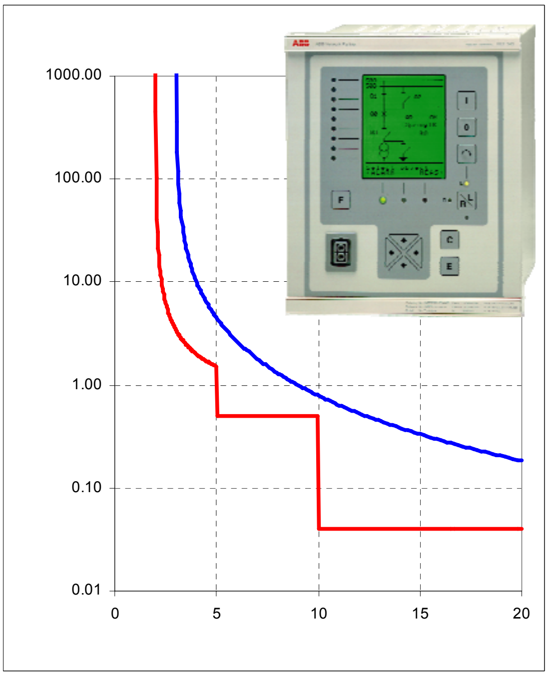
http://inside.abb.com/sa-dsupportline

Chapter 3

Overcurrent protection

Short Circuit Protection





Contents

Contents

- Time and current selective protection
- Blocking based protection
- Time and direcionally selective
- Others
  - Differential protection
  - Distance protection
- Backup protection
- Relay setting
- Excercise

Introduction

Causes of a short circuit

- Ageing of an isolation and mechanical damages due to overload or environmental stress
- Temporary earth equipment has been forgotten in position
- Arc over the healthy isolation due to over voltage
- Mechanical deliberate or non deliberate damage, which bypass or destroy the isolation
- Wrongly usage i.e. connection of power supply to the temporary earthed station, using of the disconnector to the live network or connections during incorrect synchronization

Introduction

Damage to a plant due to fault current

- Direct effects:
  - Damages between charged components due to mechanical forces
  - Damages to charged components due to thermal effects of the current
  - Mechanical damages and danger of life due to arc
  - Dangerous voltages between earthed components
  - Disturbance voltages near the fault
- Indirect effects:
  - Under voltage in the undamaged part of the network
  - Temporary load peaks after the fault situation
  - Loss of system stability

Introduction

Purpose of protection

- Detect all electrical faults and some abnormal operating conditions
- Protect human beings and properties around the power network
- Protection must be sensitive and fast
  - danger of life, damages and disturbances have to be minimized
  - the stability of the network has to be ensured in all conditions
- Operation must be selective (discriminating)
  - disconnect minimum possible part of the power network
- Protection must cover 100% of the protected network
- Protection should be reliable and simple
- Commissioning tests of the protection should be possible to perform in a place of installation

Introduction

Purpose of protection

- **Danger of life, mechanical damages and the risk of failure propagation have to be minimized:**

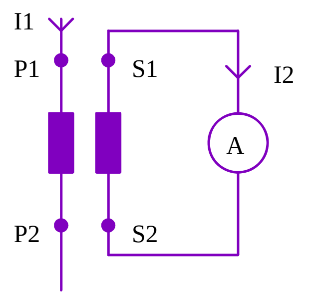
The Operation time of the protection have to be considered specially !!

Example: Effect of trip time on damages caused by arc, “Rule of thumb”:

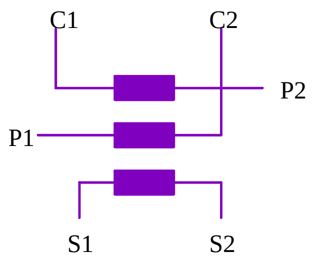
35 ms	**Practically no damages to people and switchgear, which can be taken in use after insulation level metering**
100 ms	**Small damages, minor repairs and cleaning required before the switchgear is ready to use**
500 ms	**Heavy damages to people and switchgear, which must be replaced almost totally**

Current measuring

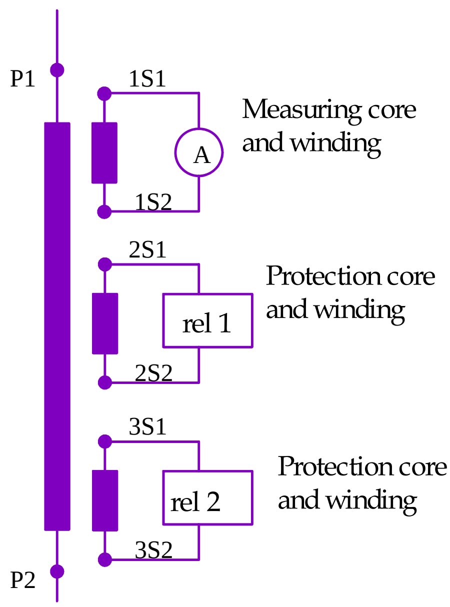
Current transformer (CT)



One core current transformer



Two primary windings

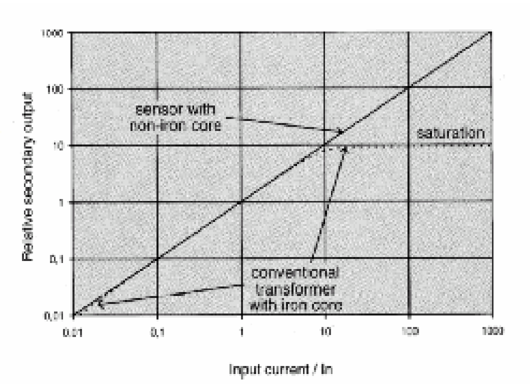


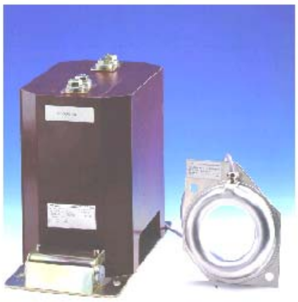
Three core current transformer

Current measuring

Current sensor (Rogowski coil)

- Extensive dynamic range
- Non-saturable
- High degree of accuracy
- Small in volume and weight
- High degree of safety





Rated current	80 – 300 – 800 A
Primary current	10....1600 A
Output Voltage	150 mV (50 Hz)
Rated Frequency	50, 60 Hz
Temperature Range	–40....+70 C
Accuracy	Class 1
Short Circuit Withstand Current	31,5 / 80 kA
Weight	1,0 kg

Current measuring

Main functions of CT / sensor:

- Step down primary system currents to the level, which the measurement and protection circuits can handle
- Make it possible to use standardized secondary meters and relays
- To protect sensitive secondary devices from overloading
- Make possible centralized measuring and protection system

Current measuring

Current transformer (CT)

600/5/5 5P10 15VA

P=Protection

Rated burden
- the sum of the burdens of all devices connected to the load of the current transformer plus the load of the conductors must not be greater than the rated burden

Rated primary current

Rated secondary current
- one protection winding
- one instrumentation winding

Accuracy limit factor F_n
- it is the multiple of the primary rated current at which the total error at rated CT burden does not exceed 5% for a class 5P CT, respectively 10% for a class 10P CT

Accuracy class
- typical values for current transformers 5P (5%) and 10P (10%)

When dimensioning the CT´s and when making the relay settings the possible saturation has to be taken into account

Current measuring

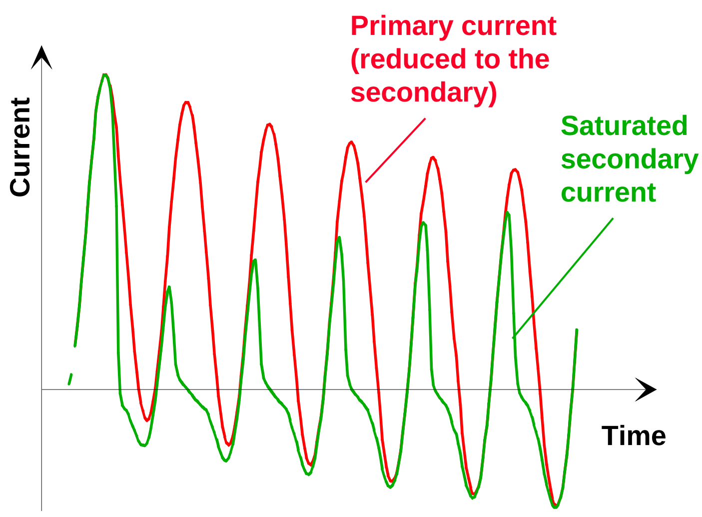
Saturation of CT

- CT will saturate, when the magnetic flux density reaches the saturation limit for the magnetic flux:

Sinusoidal current with rated burden $\geq$ accuracy limit factor x rated nominal current

$$I_{Saturate} \geq F_a \times I_N$$

(=total error exceeds 5% at class 5P, respectively 10% at 10P)



Current measuring

Saturation of CT

- DC component, remanence flux or large burden may cause CT's to saturate even with minor currents
- When the CT is saturated the magnetizing current of the CT will grow rapidly and therefore the secondary current will reduced
- Current transformer saturation may cause false operations of relays or prolong the operation time

Current measuring

Calculating the accuracy limit factor ALF

- The approximate value of the effective accuracy limit factor F_a corresponding to the actual CT burden can be calculated on the basis of the next equation:

600/5/5 5P10 15VA

$$F_a = F_n \times \frac{S_{in} + S_n}{S_{in} + S_a}$$

Where,

F_n = nominal accuracy limit factor

S_{in} = internal burden of the CT

S_n = nominal burden of the CT

S_a = actual burden of the CT

$S = I^2 \times R$

Current measuring

Calculating the accuracy current limit factor ALF

- Burden caused by the conductor between CT and relay

$$S_{Cu} = k \times \frac{l[m]}{A[mm^2]}[VA]$$

k, when the CT is only in one phase and return conductor included

I_{2n}/A	k
1A	0.0352
2A	0.1408
5A	0.88

(k = δ x 2 x I^2)
ρ =resistivity for copper

k, when the CT´s are in three phase and common return conductor.

I_{2n}/A	k
1A	0.0192
2A	0.0768
5A	0.48

(k = δ x 1.1 x I^2)
ρ =resistivity for copper

Current measuring

Exercise, calculate ALF

CT data:	300 / 5 5P20 10VA R_{in} = 0.07 Ω
Relay measuring transformer resistance:	0.02 Ω
Length of wire between CT and relay:	40m
Area of wire:	4mm²

Calculate the actual over current limit factor ALF (F_a) for a three phase connection with common return conductor.

Current measuring

Correct answer to exercise

300 / **5** 5P**20** **10VA**

Nominal current	In = 5 A
Nominal accuracy limit factor	Fn = 20
Nominal burden of the CT	Sn = 10 VA
Internal burden of the CT	Sin = In² x R_{in} = (5A)² x 0.07 Ω = 1.75 VA
Actuall burden of the CT	Sa = (5A)² x 0.02 Ω + 0.48 x 40m / 4mm² = 0.5 VA + 4.8 VA = 5.3 VA
Result	Fa = 20 x (1.75 + 10) / (1.75 + 5.3) = 33.3

Setting of the high-set current stage

Why the F_a factor is important ?

The maximum current setting (high-set) for the protection relay (rule of thumb)

$$= 0.7 \times \frac{I_{K\min}}{I_{1n}} \quad or \quad 0.7 \times F_a \quad whichever\ is\ smaller$$

Where I_{kmin} is the minimum primary current, at which protection must operate

I_{1n} is primary rated current of CT

F_a is the accuracy limit factor

I.e. when selecting CT for protection

$$F_a \geq \frac{High-set\ current}{0.7}$$

Protection methods

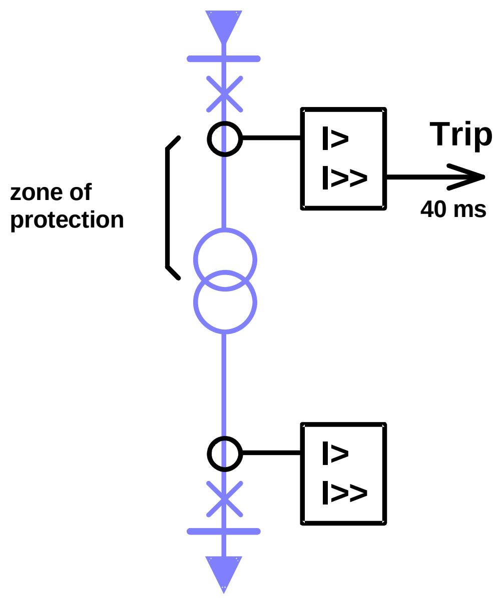
Introduction

- The operation time of the relay is depending on the protection method
- Differences between different methods are in the operation time, the amount of protective stages and in the implementation of selectivity
- "FAST" methods:
  - current selective protection
  - differential protection
  - distance protection
  - blocking based protection
  - directional comparison protection
  - arc protection
- "SLOW" methods:
  - time selective protection
  - time- and directionally selective protection

Current selective protection

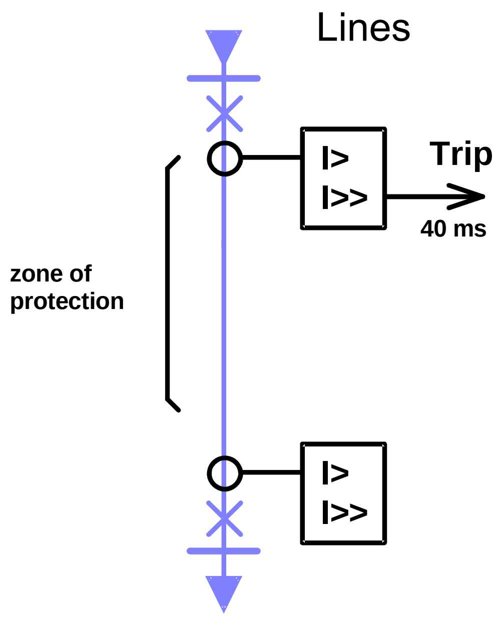
- Fault is discriminated by current
- Suitable only when current varies with the position of the fault because of the difference in impedance.

- Typical application 1
  - Fault-current in LV-side does not exceed setting in HV- side => LV trip
  - Fault-current in HV side => HV trip



Current selective protection

- Typical application 2



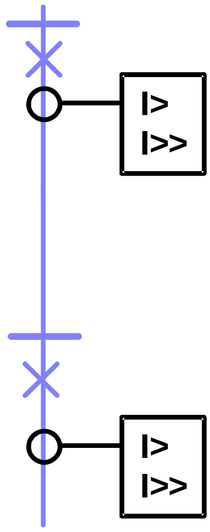
Current selective protection

- Advantages
  - Operation time in relay ~40 ms
  - Simple and reliable
  - Low-priced
- Disadvantages
  - Coarse operation (setting ~10 - 20*In)
  - Applications restricted: specially in line protection
  - Separate backup protection necessary

Time selective protection

Basis

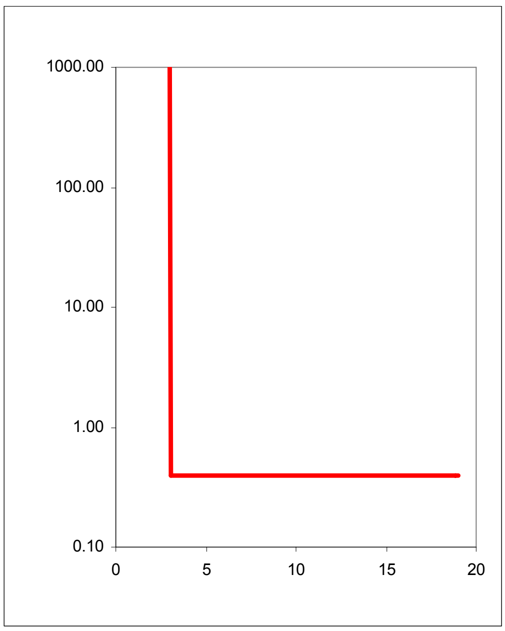
- Fault is discriminated by the operation time
- I.e. the operation times are graded
- Relay closest to the fault operates first
- No back-up needed
- Simple solution
- Suitable for radial network



Time selective protection

Two type of time delays

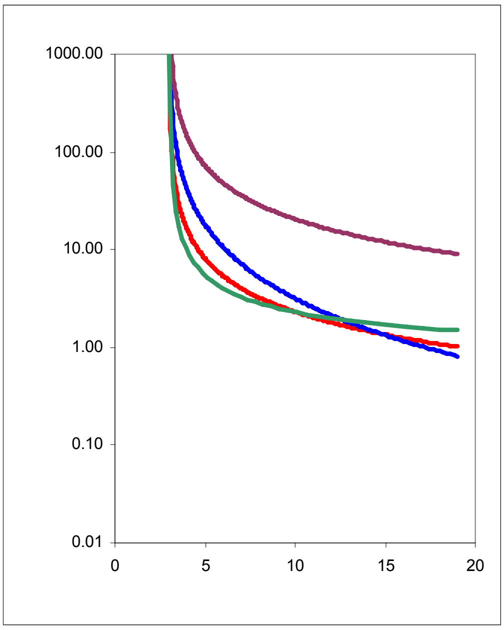
- Definite time operation
    - Operate time is independent of current
    - Two settings:
        - current
        - time delay in secs.



Time selective protection

Two type of time delays

- Inverse time operation (IDMT)
  - Operation time depends on the current
  - Shorter operation time with higher current
  - 4 curve (standard) types
    - normal inverse (NI)
    - very inverse (VI)
    - extremely inverse (EI)
    - long time inverse
  - special types (etc. RI and RD types)
  - Two settings:
    - current
    - time multiplier (k = 0.05..1)



Time selective protection

Two type of time delays

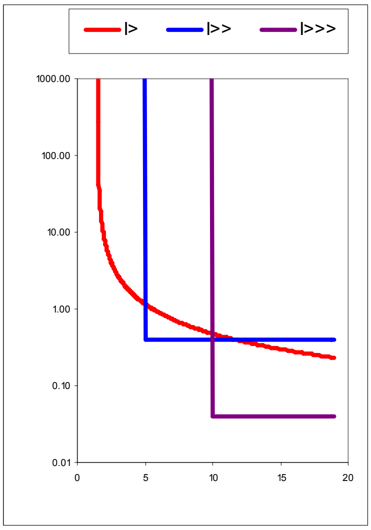
NI curve is known as the 3/10 characteristic because 10 x setting gives 3 secs (k=1)

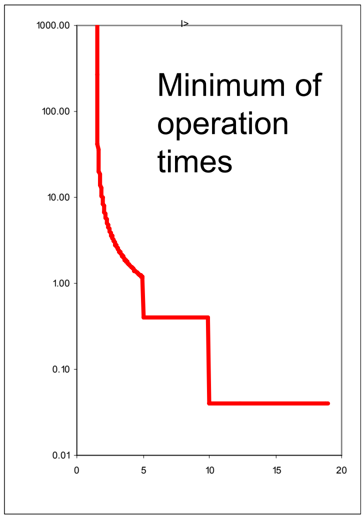
- NI is suitable in networks where:
  - changes in the networks connection situation can cause considerable changes in the short circuit currents
  - the difference in the amplitude of short circuit currents between the cable ends is large
- VI is suitable in networks where:
  - changes in the networks connection situations do not affect the short circuit currents to any greater extent.
  - the difference in the short circuit currents amplitude between the cable ends are not big enough to make use of the NI-curve.
- EI is mainly used when selectivity to fuses is required.
  - Typical application: protection of a line for a distribution transformer.
- LI is used for protection of neutral earthing resistors.

Time selective protection

Co-operative action of multiple overcurrent stages

- Overcurrent relay has normally two or three over current stages
  I>, I>> and I>>>, each having individual settings

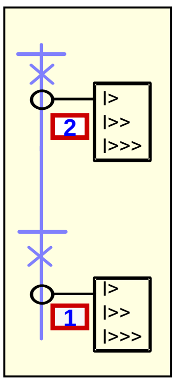


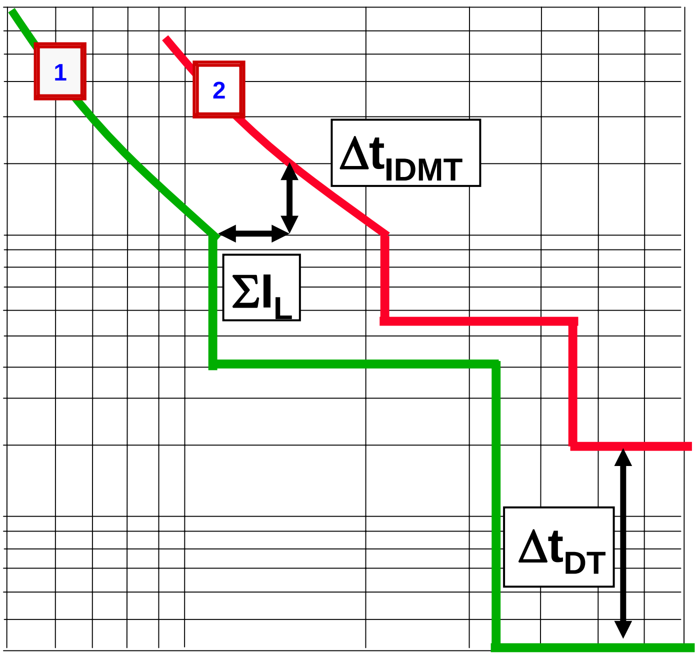


Time selective protection

Discrimination of operation times

- Time grading = operation time difference between adjecent protection stages
- We have ΣI_L because the load currents at levels 1 and 2 are not same.





Time selective protection

Time grading - definite time

$$\Delta t_{DT} = 2 \times t_E + t_R + t_{CB} + t_M$$

where t_E = tolerance of the relay op.time

t_R = retardation time of the relay

t_{CB} = operation time of CB

t_M = marginal time

t_R = Retardation time (Overshoot time) = time needed to cancel the trip.

t_M = Delay of an auxiliary relay (if used)
+ Possible delay of operation due saturation of CT. In theory this could be same as the time constant of DC-component. In practice 20 ms is enough because all protection stages will be delayed.

Time selective protection

Time grading - definite time - example

$$\Delta t_{DT} = 2 \times t_E + t_R + t_{CB} + t_M$$

tolerance (2x25 ms)	50 ms
op.time of CB	50 ms
retardation time	30 ms
marginal	20 ms
	150 ms

Time selective protection

Time grading - inverse time

- Rule of thumb for numerical relays
  - NI, VI, LI: 0.20 x t_1 + 150ms
  - EI: 0.35 x t_1 + 150ms

Time selective protection

Time grading - inverse time

$$\Delta t_{IDMT} = t_1 \times \left(\frac{1 + \frac{E_1}{100}}{1 - \frac{E_2}{100}} - 1 \right) + t_R + t_{CB} + t_M$$

where t_1 = op.time of the relay of the closest location

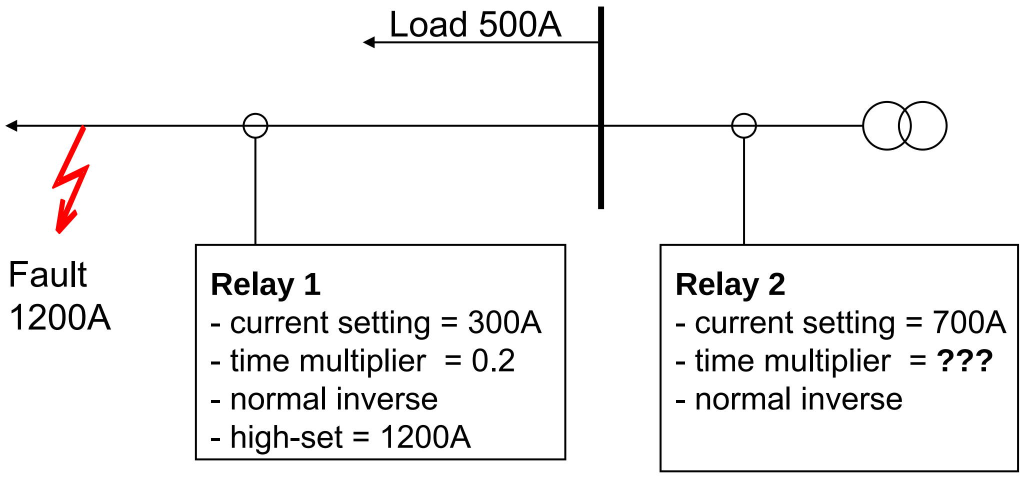
E_1 = error of the relay of the closest location

E_2 = error of the relay of the next location

Time selective protection

Time grading - inverse time - example step by step

0. Data from the fault calculation

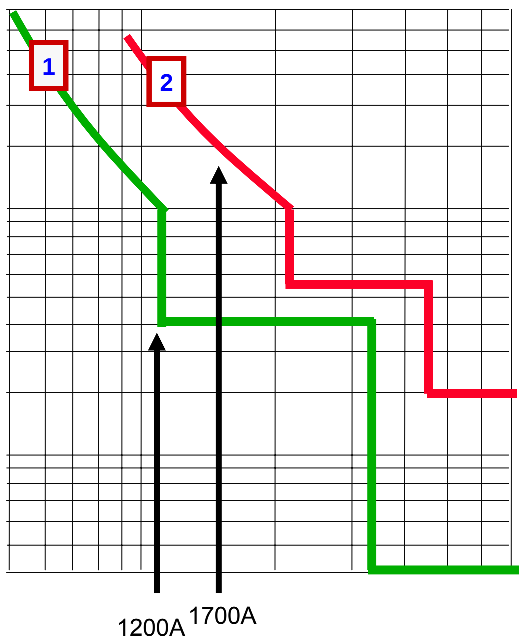


Time selective protection

Time grading - inverse time - example step by step

1. Find the current values
   - Use the high-set of relay 1 for grading
   - When no high-set, use the fault current at location 1

I_1 = 1200A ≈ 4.0 x setting (relay 1)
I_2 = 1700A ≈ 2.4 x setting (relay 2)



Time selective protection

Time grading - inverse time - example step by step

2. Look time-tolerances from the table

   Here we have Normal inverse, E=5%

   => relay 1: 1.13xE ≈ 6%

   => relay 2: 2.22xE ≈ 11%

This information can be found from the standards BS 142 and IEC 255-4 (expressed in the relay manuals)

I/I>	Normal	Very	Extremely	Long time
2	2,22E	2,34E	2,44E	2,34E
5	1,13E	1,26E	1,48E	1,26E
7	-	-	-	1,00E
10	1,01E	1,01E	1,02E	-
20	1,00E	1,00E	1,00E	-

Time selective protection

Time grading - inverse time - example

3. Calculate effect of measuring accuracy (+ CT errors)

   Here we use ±3%

   ⇒ Calculate the change in operating time when using -3% and +3%

   ⇒ Calculate the per cent errors. Take the highest value.

4. Sum erros 2) and 3) and we have E_1 and E_2

   E1 = 6% + 2% = 8% (relay 1)

   E2 = 11% + 3% = 14% (relay 2)

Time selective protection

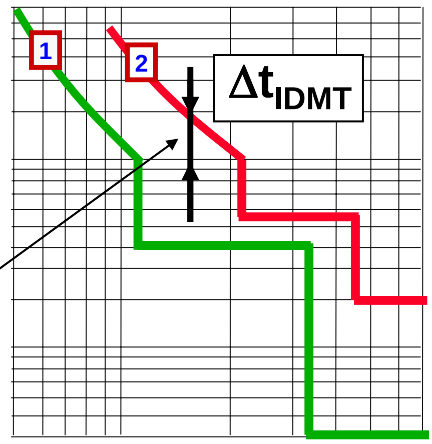
Time grading - inverse time - example

5. Use equation

   t1 = time of relay 1 (at 1200A) ≈ 1000 ms

$$\Delta t_{IDMT} = t_1 \times \left(\frac{1+\frac{E_1}{100}}{1-\frac{E_2}{100}} - 1 \right) + t_R + t_{CB} + t_M$$

t1x(1-E1/100)/(1-E2/100)-1)	256 ms
op.time of CB	50 ms
retardation time	30 ms
marginal	20 ms
	356 ms



Time selective protection

Time grading - inverse time - example

6. Find time multiplier *k* for relay 2

   time of relay 1 + grading = 1000 ms + 356 ms = 1356ms

   Using
   - Normal Inverse curve
   - current 2.4 x setting
   - operation time 1.356 s

   => the time multiplier *k* ≈ 0.18

$$k = \frac{\left(\left(\frac{I}{I>} \right)^{\alpha} - 1 \right) \times t}{\beta}$$

Time and current selective protection

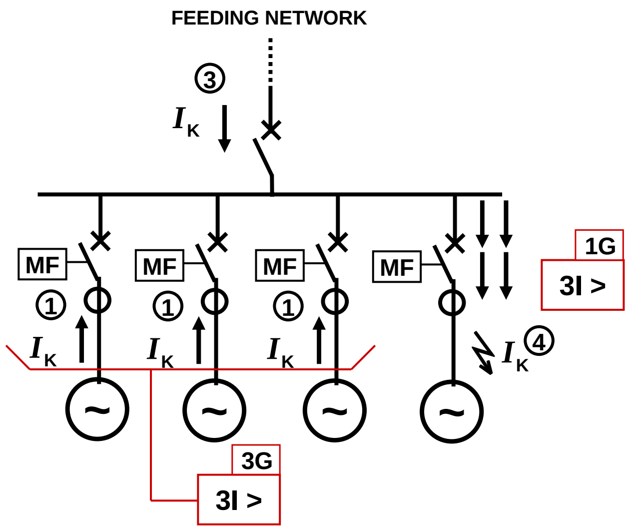
Principle

- Fault current magnitude depends on which side of the relay the fault is located
- Different operation times for both directions
- Relays with inverse time characteristics

Time and current selective protection

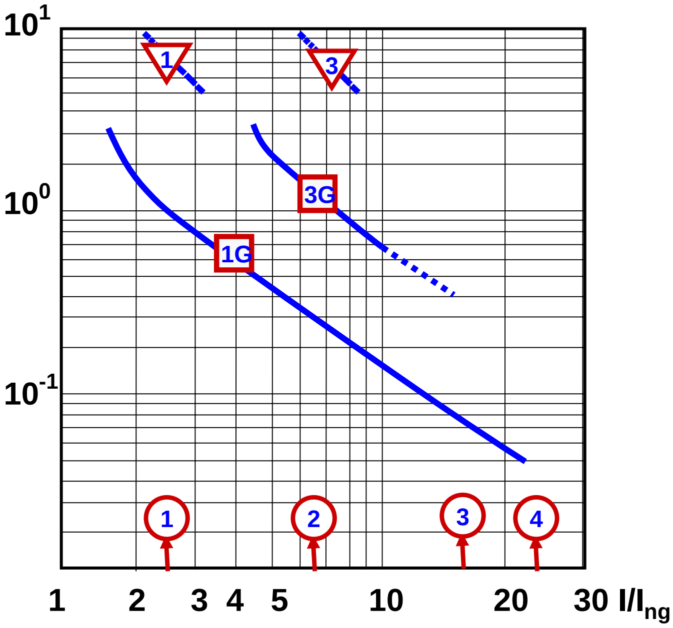
Example

- 4 generator system
- Fault in generator 4
- Other 3 generators and network feeds the short circuit current
- => Current of each individual healthy generator is less than 1/3 of the gen. 4 short circuit current



Time and current selective protection

Example



1G SHORT-CIRCUIT CURRENT FOR 1 GENERATOR

1 GENERATOR THERMAL WITHSTAND

3G EQUIVALENT SHORT-CIRCUIT CURRENT FOR 3 GEN.

3 EQUIVALENT THERMAL WITHSTAND OF 3 GEN.

1 SHORT-CIRCUIT CURRENT FOR 1 GENERATOR

2 EQUIVALENT S-C CURRENT FOR 3 GEN.

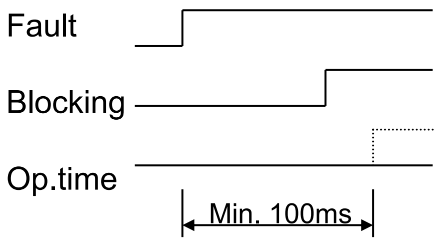
3 SHORT-CIRCUIT CURRENT FOR SUPPLY NETWORK

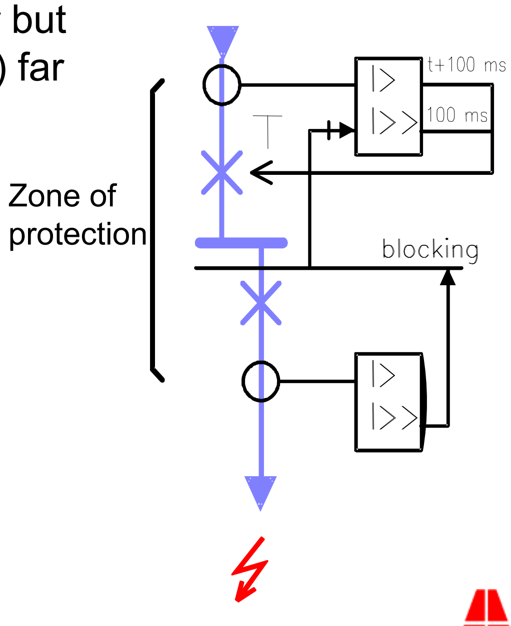
4 TOTAL SHORT-CIRCUIT CURRENT

Blocking based protection

Introduction

- In purpose of faster protection
- Both relays detects the fault in feeder but the relay near the fault blocks relay(s) far from the fault
- Note time needed for blocking

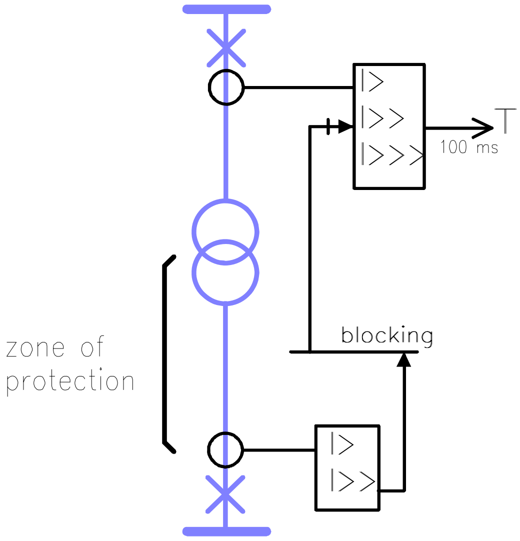




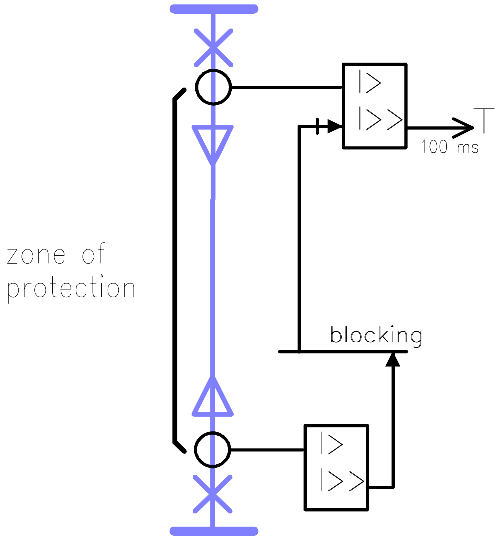
Blocking based protection

Typical applications

- LV side of a transformer



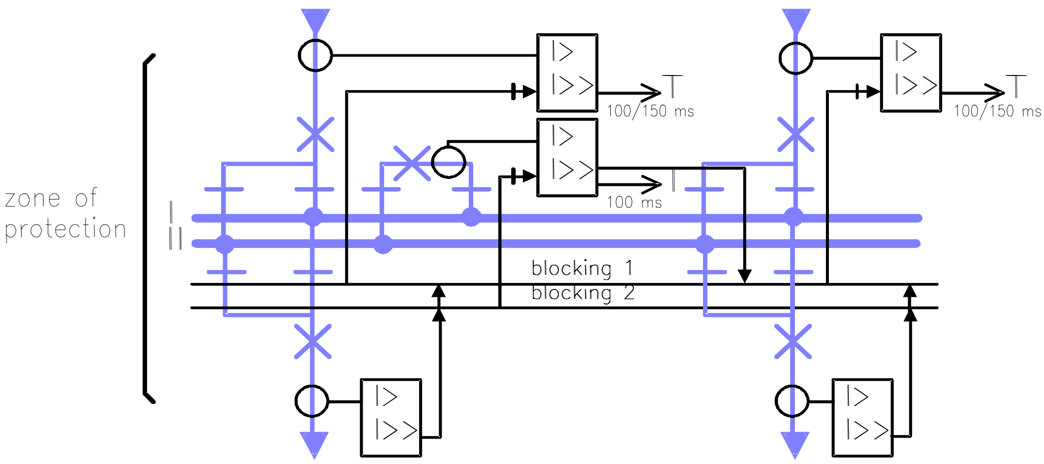
- Line



Blocking based protection

Typical applications

- Busbars (1- and 2-bus systems)



Blocking based protection

Advantages and disadvantages

- Advantages
- Technical solution is simple
- Rather fast operation, operation time is 100 ms
- Includes a backup protection (time delay)
- Low-priced

- Disadvantages
- Auxiliary connection is needed in Line protection applications

Blocking based protection

Time needed for blocking - example

0 ms

Starting time of the relay

40 ms

Input delay on the relay to be blocked

50 ms

Retardation time

80 ms

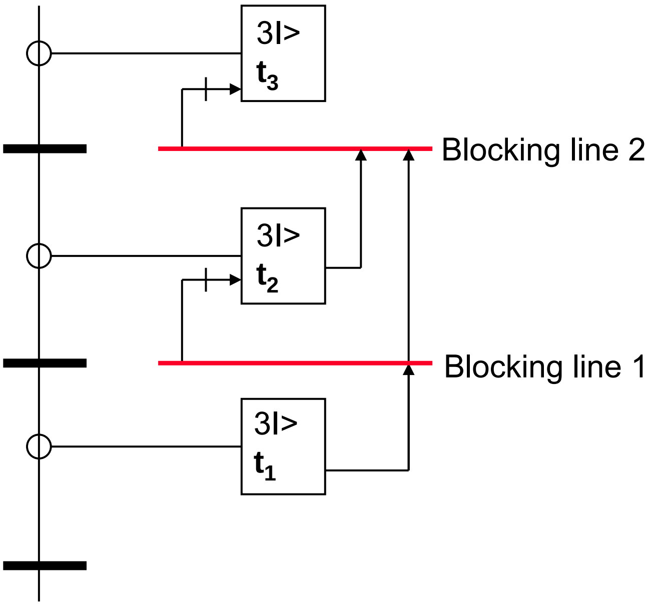
Marginal

100 ms

Typically 100ms when no aux.relay is used.

Blocking based protection

Time needed for blocking - exercise

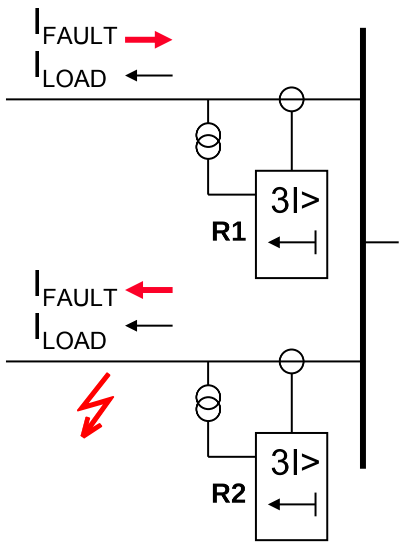


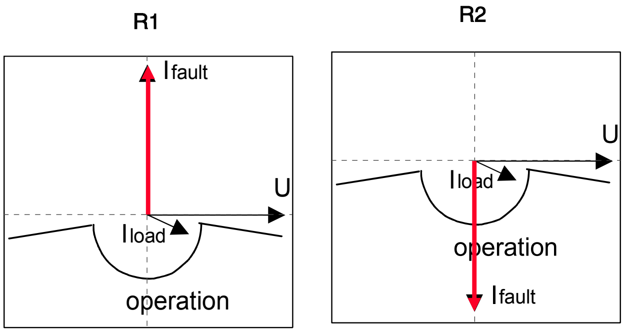
Let t_1 = 40ms, find the minimum operation times t_2 and t_3

Time and directionally selective

Introduction

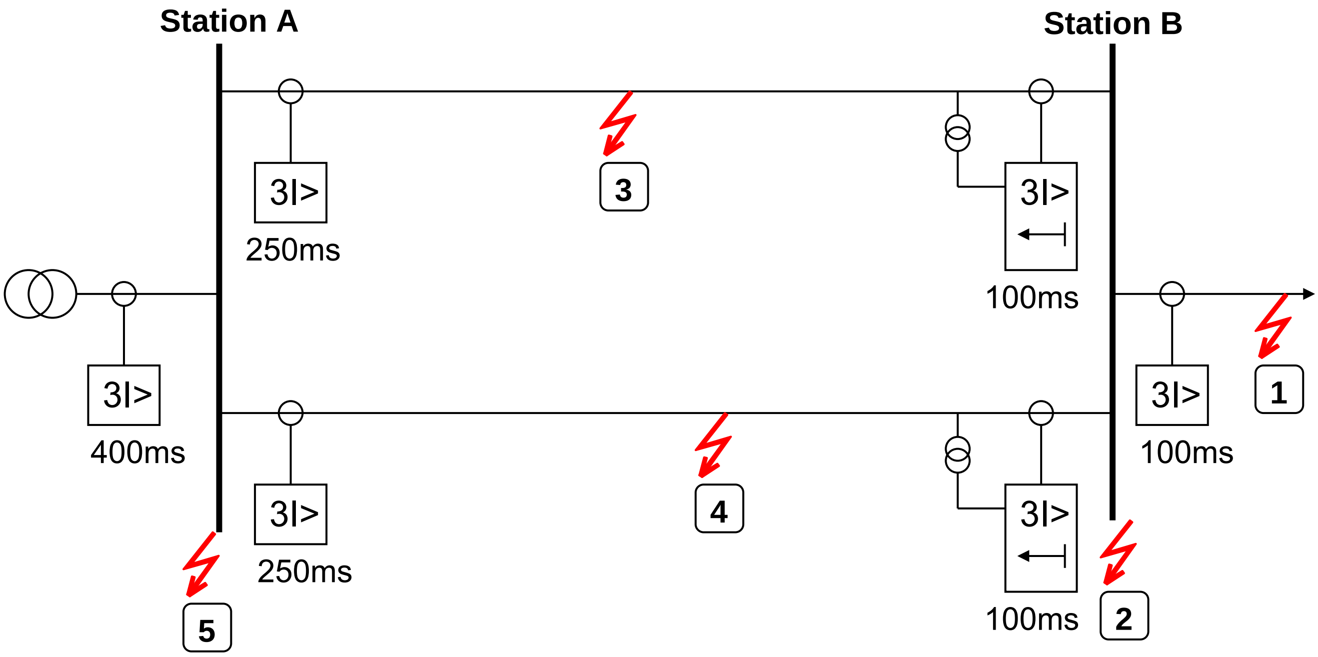
- Directionally selecitive over current protection operates when both
  - current exceeds the setting value
  - direction of fault current agrees the setting of operation area (base angle)





Time and directionally selective

Exercise



Time and directionally selective

Correct answer to the exercise

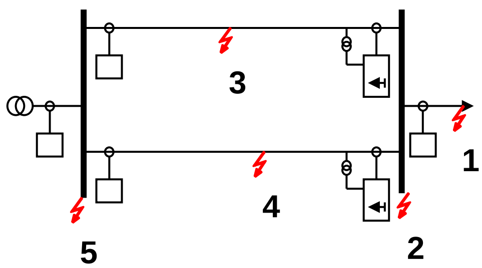
1. 100 ms The nearest relay

2. 250ms Station A, both feeders
(Direction opposite in Station B relays)

3. 100 ms Station B, upper feeder, directed relay
(Lower feeder have opposite direction)
=> no fault current at lower feeder
250 ms Station A, upper feeder

4. 100 ms Station B, lower feeder, directed relay
250 ms Station A, lower feeder

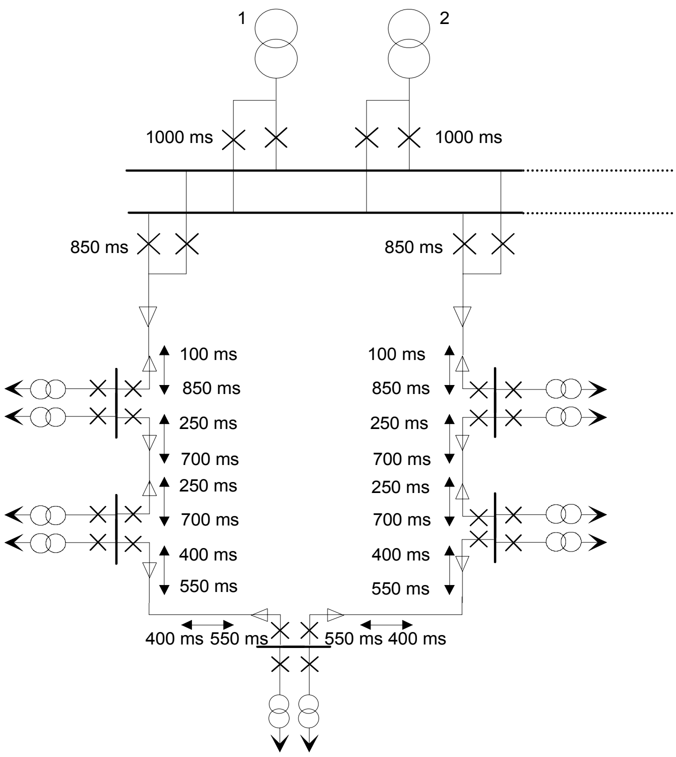
5. 400 ms Station A, relay behind the transformer



Time and directionally selective

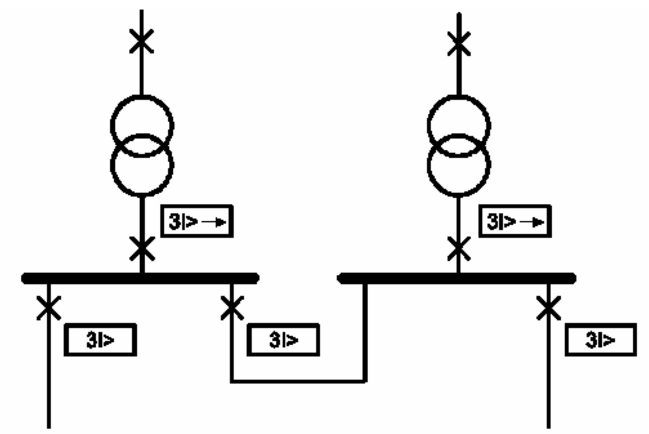
Advantages/disadvantages

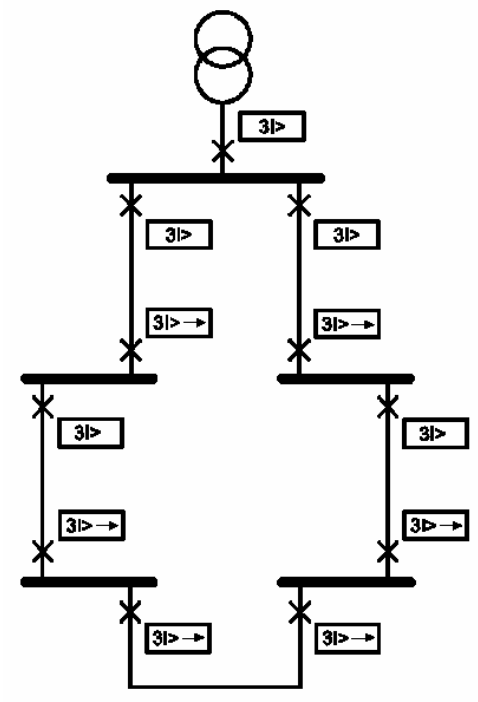
- Advantages:
  - Selective protection to meshed networks
  - Solution with normal directional relays
  - No auxiliary connections
  - Cheapest way to protect the meshed networks
- Disadvantages:
  - Operation times are rather long near the supply



Time and directionally selective

Typical applications





Time and directionally selective

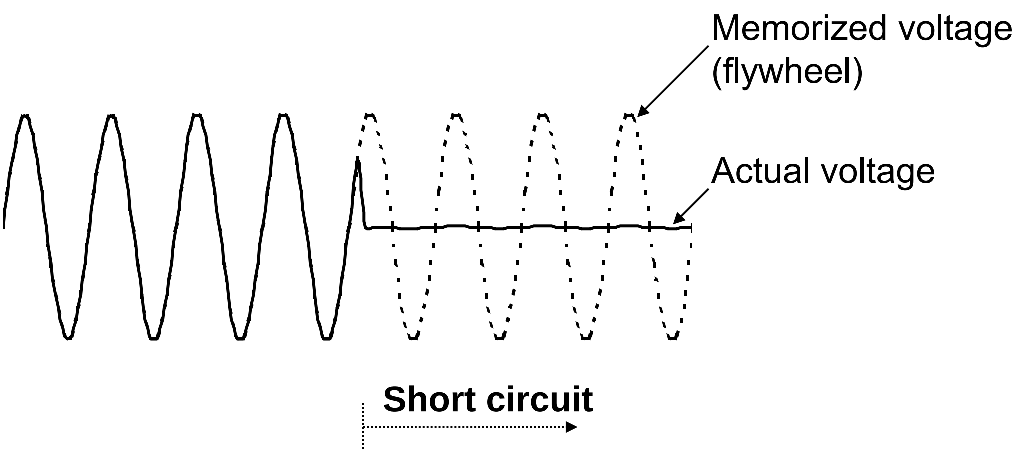
Principles of direction criteria

- Current phasor is compared to phase-to-phase voltage phasor
  - All phases individually: I1 - U23, I2 - U13, I3 - U12
  - Relay will operate is any of phases fullfill the operation criterias
- Two phase currents and two phase-to-phase voltages
  - Only the phases having the fault is considered
  - Example (two phase fault) I1 - I2 phasor is compared with U23 - U31 phasor
- Two phase currents and one phase-to-phase voltage
  - Only the phases having the fault is considered
  - Example (two phase fault) I1 - I2 phasor is compared with U12 phasor

Time and directionally selective

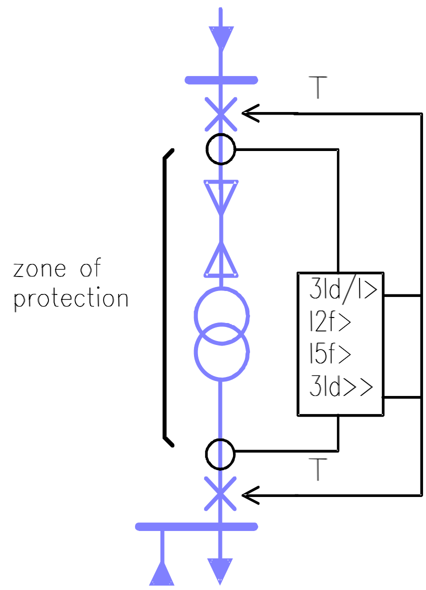
Voltage memory

- Phase-to-phase voltages can drop to (near) zero in short circuit
- The voltage phasors must be stored prior the fault



Differential protection

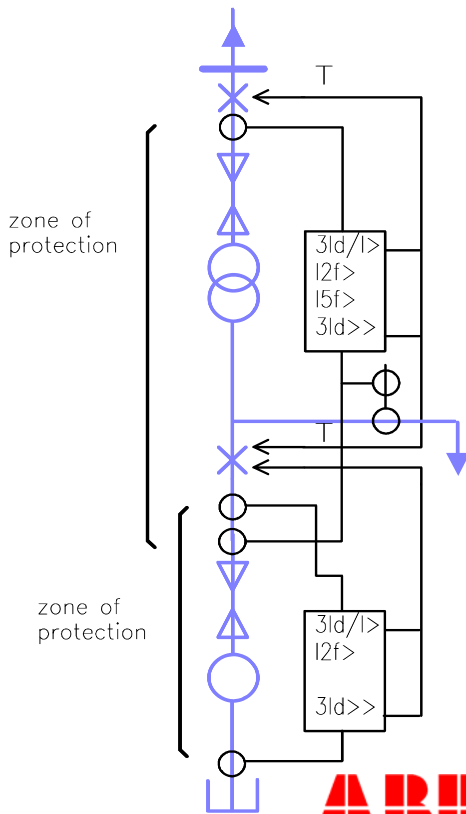
- Phase currents are measured on both sides of protection zone (I.e. protected component) = unit protection
- Phase current differential (magnitude and/or phase) causes the operation.
- Fast
- Applications
  - Transformers
  - Rotating machines



Differential protection

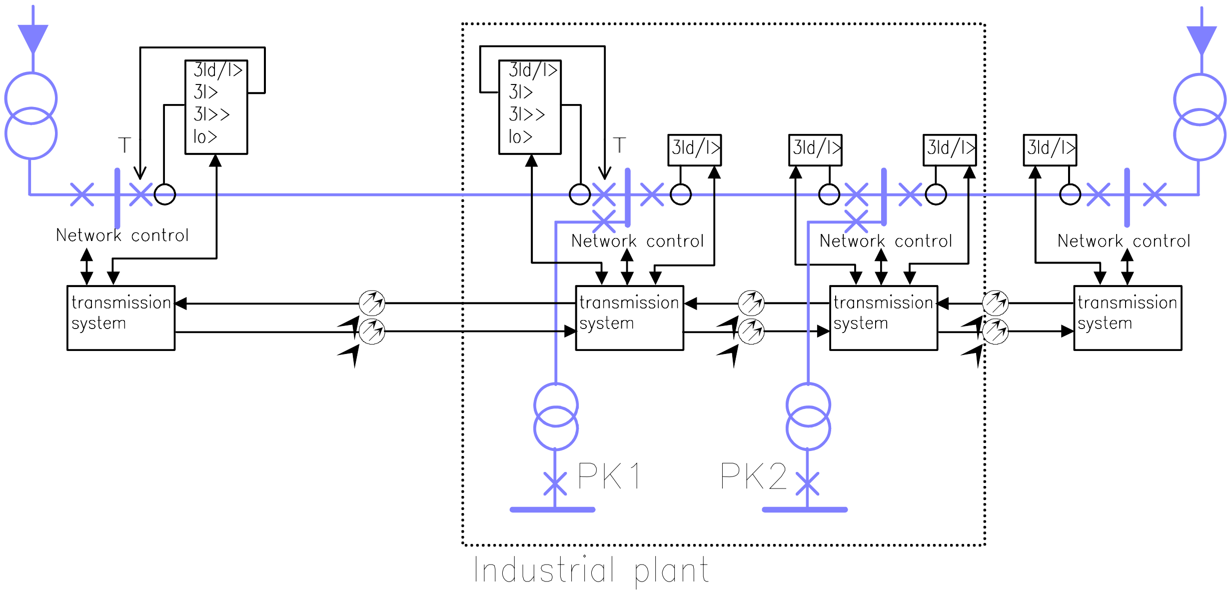
Advantages:
- Operation time in stabilized stage ~ 50 ms, operation time in instantaneous stage ~10 ms
- Sensitivity (basic setting P > 20 % *In for transformers, P > 5 % *In for generators)
- Usable for many different applications
- Exactly defined protected zones (absolutely selective)

Disadvantages:
- Separate backup protection necessary
- High accuracy of current transformers (Fa>40)
- High-priced



Line differential protection

Basic diagram of modern line differential protection system



Line differential protection

Advantages:

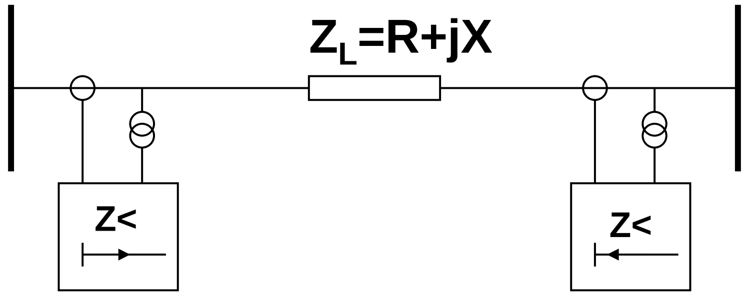
- Selective protection to meshed networks
- Operation time in relay ~30 ms
- High sensitivity
- Exactly defined protected zones (absolutely selective)
- May include a backup protection
- Fiber optics connection can be used also in substation control systems and that will provide a chance to make absolutely selective earth-fault protection
- Unaffected by power variation
- Zone of protection could be over a serial capacitor

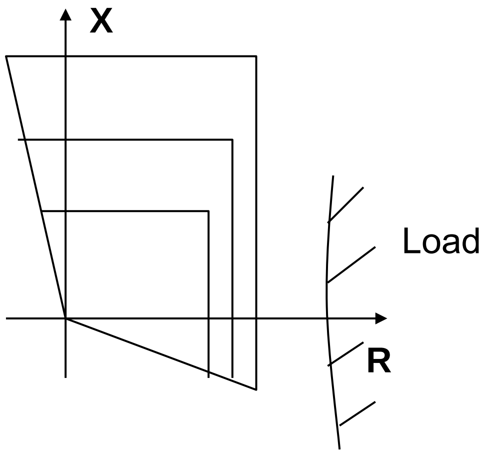
Disadvantages:

- Fiber optics connection is expensive
- Busbar protection not included
- Difficult to perform in branch line applications

Distance protection

- Distance protection relay is a directional underimpedance relay
- Relay measures U/I and trip if the measured value is less than the value set
- Application: Transmission lines





Distance protection

Advantages:

- Selective line protection to meshed networks
- Operation time is typically ~30 ms in relay
- Backup protection for other relays because of many protection zones
- 1st zones are establishing fast and almost absolutely selective protection, which will cover about 85 % of protected zone
- Auxiliary connection is not necessary
- Unaffected by connecting and loading variation
- Versatile operation (short circuits, earth-faults, network and load variations)

- If fibre optics auxiliary connection is used, then we can use:
  - rapid autoreclosure for entire line (optional)
  - straight transfer tripping to make tripping faster
  - protection for short lines by using interlockings and 1. zone overreaching
  - separate absolutely selective protection against high resistance earth-faults (compare to directional comparison method)

Distance protection

Disadvantages:

- Sensitivity is depending on load impedance
- Next reasons are impeding the operation
  - weak background network + short line (operation accuracy, selectivity)
  - fluctuating power (latching is optional)
  - effect of a fault resistance (accuracy, sensitivity)
- High-priced, optional functions are increasing a price of relay
- Difficult to calculate the settings

Backup protection

- Protection should be active even when one device is damaged

=> each protection unit must have a backup and the operation of each breaker must be secured.

Methods:

Remote back-up protection

- Is formed naturally from successive protection stages upstream in the network (time selective protection)
- Sometimes these stages do not overlap totally, when local back-up protection and circuit-breaker failure protection are called for

Local backup

- Separate relay is used, main and back-up protection trip the same CB, e.g. O/C relay is used as back-up protection for differential relay

Circuit-breaker failure protection

- The trip command is transferred to the next CB upstream in the network

Relay setting

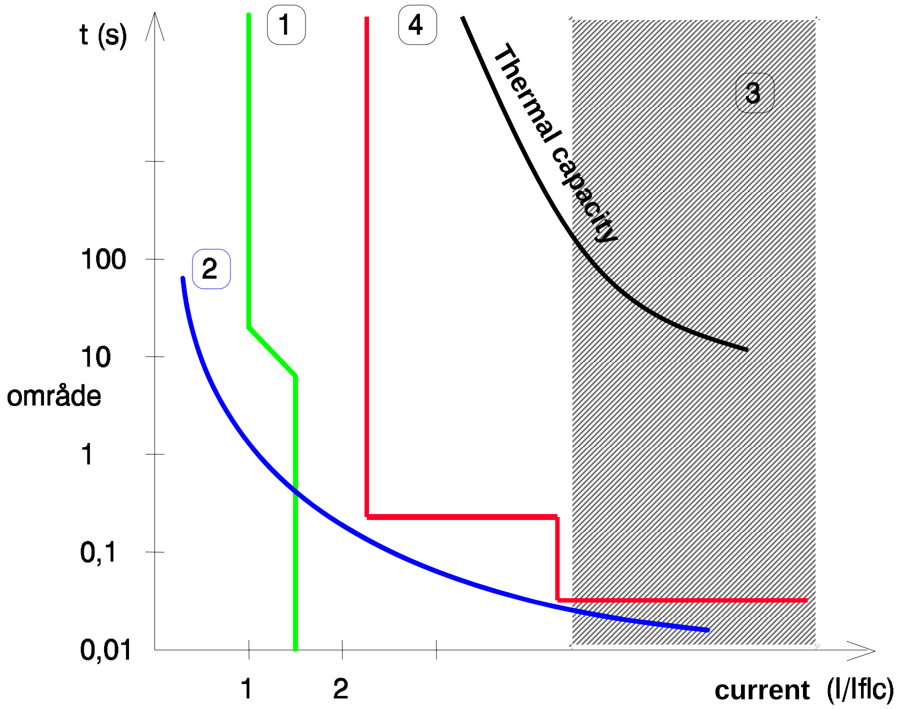
Example: Over current relay setting

1 normal load current

2 inrush current

3 minimum fault current

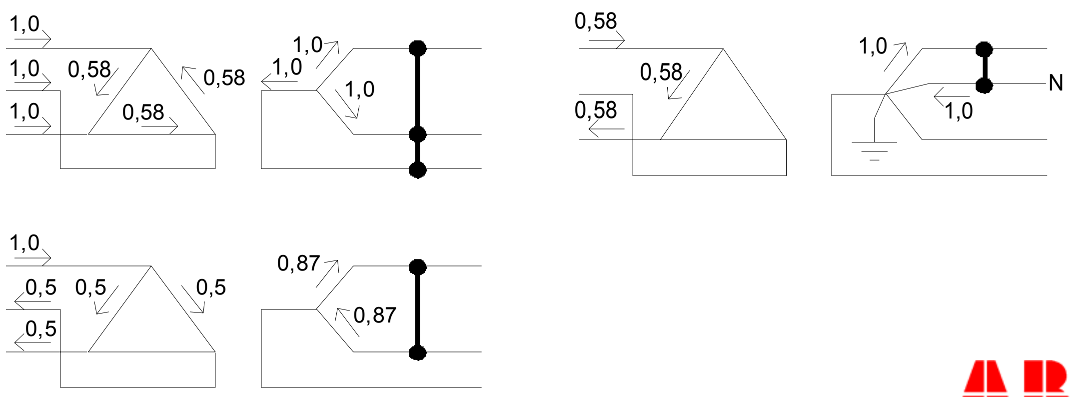
4 setting of the relay



Relay setting

Take into account in fault calculation

- Different connections of the network
- Voltage level
- Fault type
- Fault resistance (arc)
- Effect of Dyn-connected transformer to the fault currents in primary side if fault is in the secondary side of the transformer



Relay setting

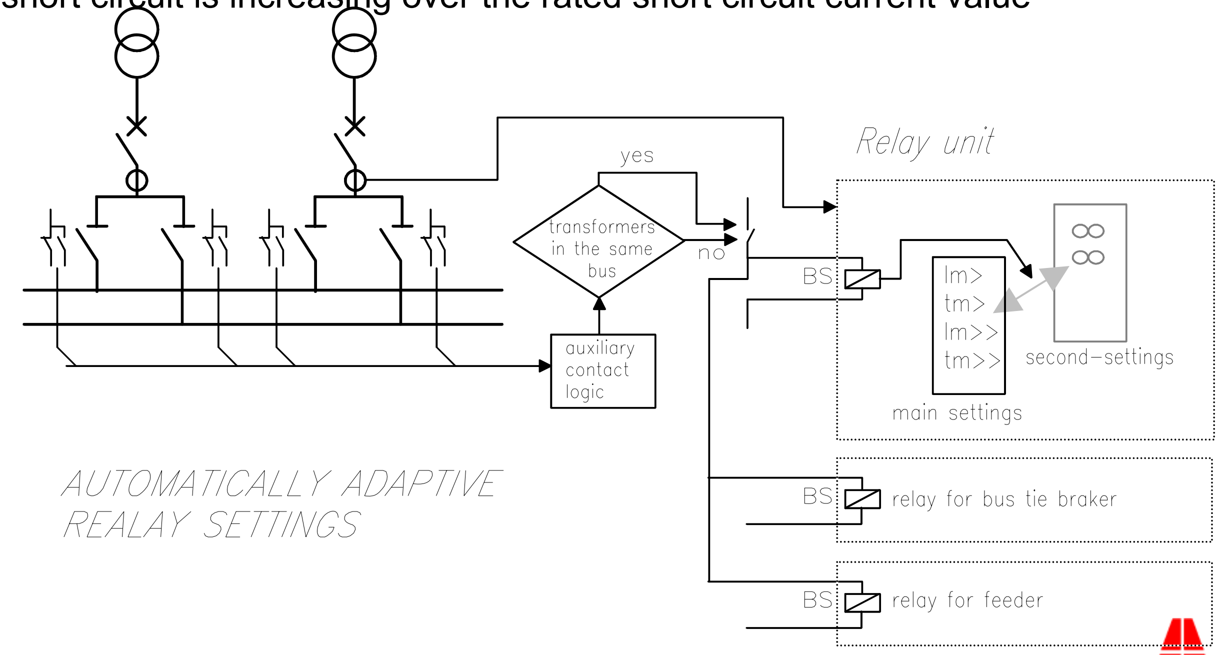
Adapting of relay settings according to feeder connections

- When connection- and load situations are shifting, relay settings have to be changed
- Example
  - Decrease of minimum fault current due to feeder connections
  - Reversal of supply: use of backup supply, changing of supply in the meshed networks
  - Connection of parallel transformer (in time when parallel connection)
- Adapting could be either Automatic or Manual

Relay setting

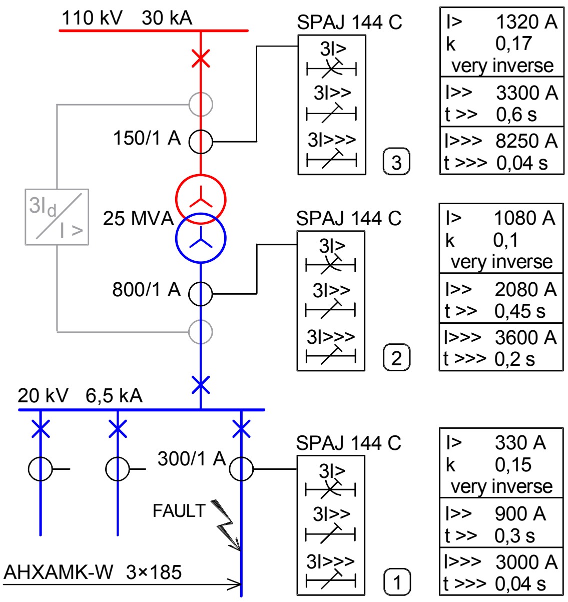
Example for adapting the relay setting

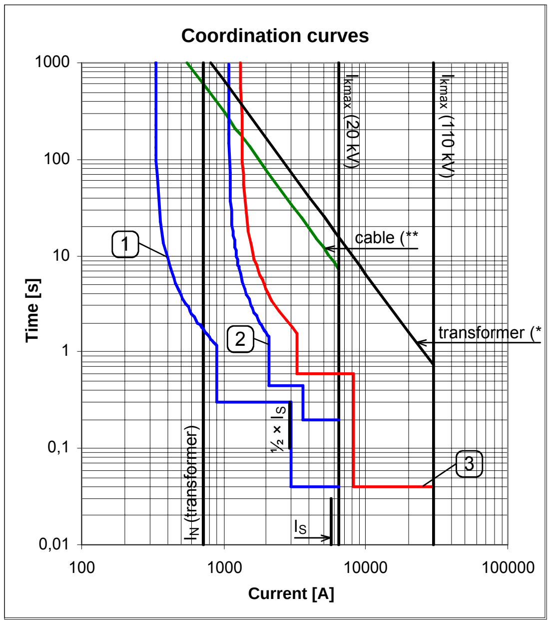
Transformers are connected temporarily to parallel connection, then short circuit is increasing over the rated short circuit current value



Relay setting examples

Time selective protection





I_S = transformer inrush current

half-time for inrush current = 0,1 - 0,3 s

I_{NMAX} for cable = 330 A

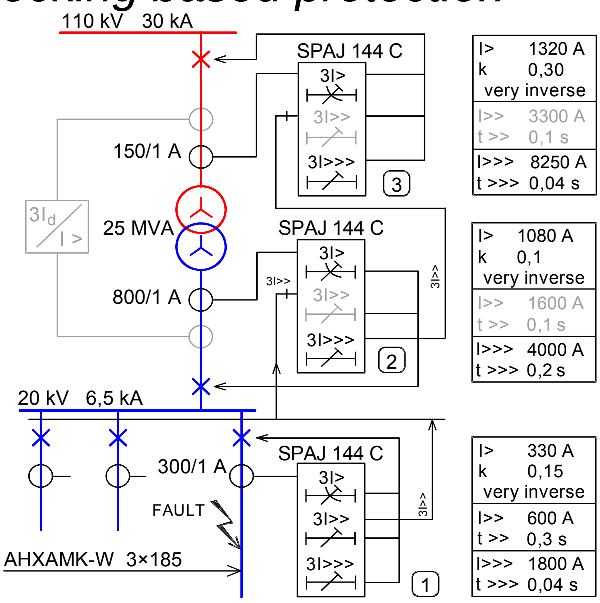
I_{kmax} for cable = 17,5 kA / 1 s

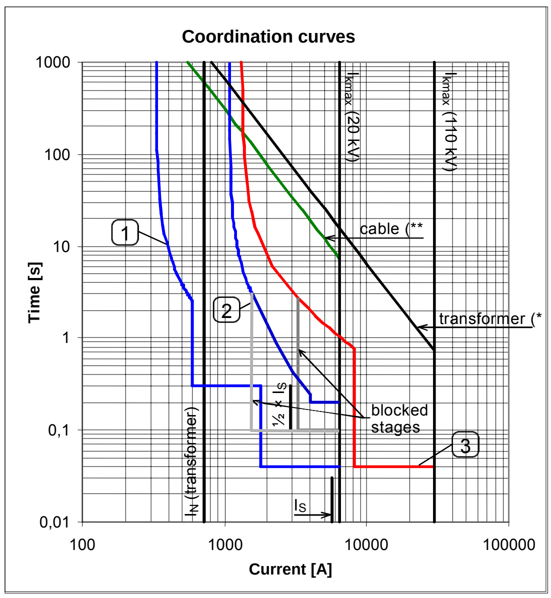
(* the Transformer through-fault current duration curve

(** the Cable current duration curve

Relay setting examples

Blocking based protection





3I>> stage of relay 1 sends a blocking signal to relay 2 and 3I>> stage of relay 2 sends a blocking signal to relay 3. Now, 3I>> stages of the relay 2 and relay 3 are blocked.

I_S = transformer inrush current

half-time for inrush current = 0,1 - 0,3 s

I_{NMAX} for cable = 330 A

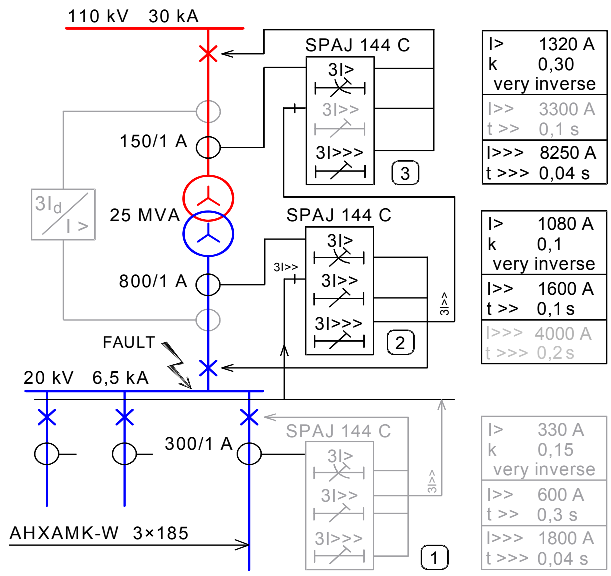
I_{kmax} for cable = 17,5 kA / 1 s

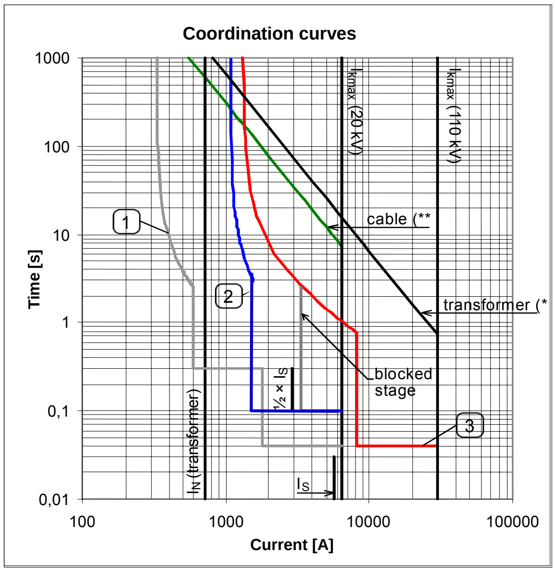
(* the Transformer through-fault current duration curve)

(** the Cable current duration curve)

Relay setting examples

Blocking based protection





No blocking signal from relay 1. So, 3I>> stage of relay 2 is not blocked. Now, the relay 2 trips in 0,1 s.

3I>>> stage of relay 2 sends a blocking signal to relay 3. 3I>> stage of relay 3 is blocked.

I_S = transformer inrush current

half-time for inrush current = 0,1 - 0,3 s

I_{NMAX} for cable = 330 A

I_{kmax} for cable = 17,5 kA / 1 s

(* the Transformer through-fault current duration curve)

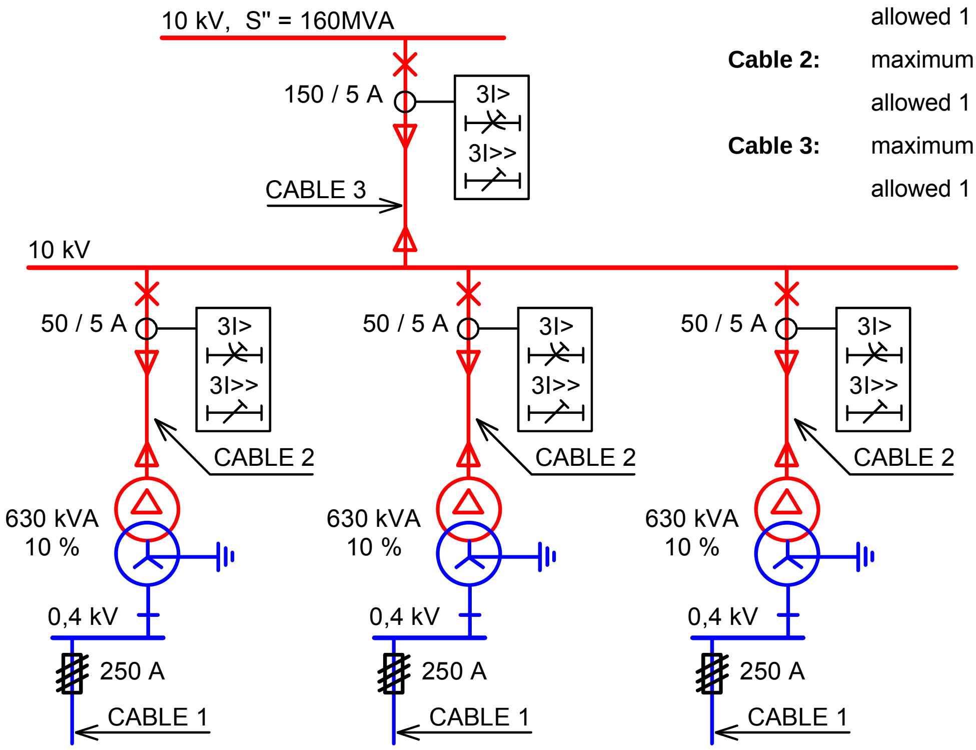
(** the Cable current duration curve)

Exercise

Cable 1: maximum nominal current = 260 A (0,4 kV)
allowed 1 second short circuit current = 10kA

Cable 2: maximum nominal current = 94 A (10 kV)
allowed 1 second short circuit current = 3 kA

Cable 3: maximum nominal current = 170 A (10 kV)
allowed 1 second short circuit current = 8 kA



Formulas:

$$S_T'' = S_n / Z_k$$

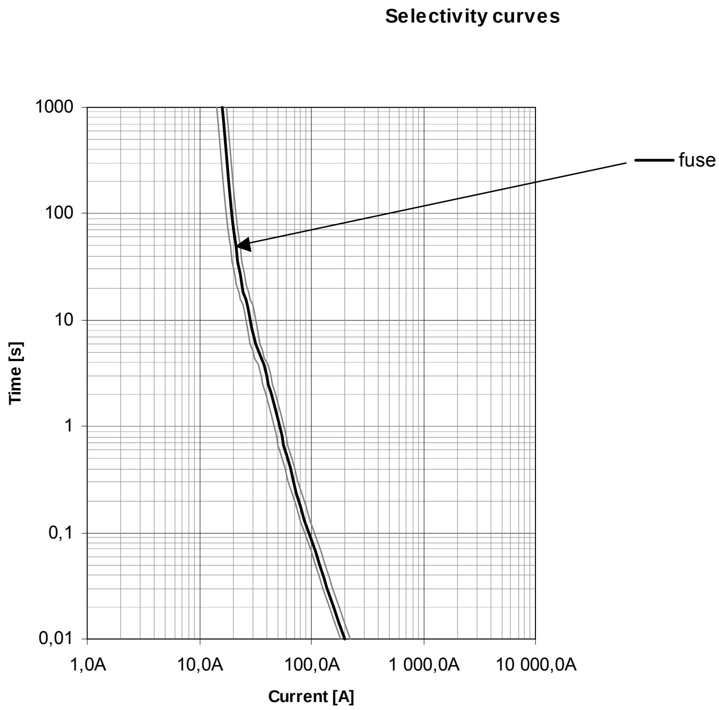
$$I_k'' = \frac{1.1 \times S_k''}{\sqrt{3} \times U_n}$$

$$I_{kt} = \frac{I_{k1}}{\sqrt{t}}$$

Exercise

Selectivity graph

Logarithmic scales on the both axes.
The ready made curve is for the fuse on 400V side.



Exercise

Cable thermal curve

Cable 1 I_{nmax} = 260A (0.4kV)
I_{k1sec} = 10kA (0.4kV) (=400A in 10kV)

if the current is 5000A then the time is (=200A in 10kV)

$$t_{max} \times I^2_{kmax} = t_{1s} \times I^2_{k1s}$$

$$t_{max} = \left(\frac{I_{k1s}}{I_{kmax}}\right)^2 \times t_{1s} = \left(\frac{400}{200}\right)^2 \times 1\sec =$$

Exercise

Cable thermal curve

Cable 2 I_{nmax} = 94 A (10 kV)
I_{k1sec} = 3 kA (10 kV)

if the current is 1000A then the time is:

$$t = \left(\frac{3000}{1000}\right)^2 \times 1\text{sec.} = 9\text{sec.}$$

Cable 3 I_{nmax} = 170 A

I_{k1sec} = 8 kA

if the current is 4000A then the time is:

$$t = \left(\frac{8000}{4000}\right)^2 \times 1\text{sec} = 4\text{sec.}$$

Exercise

Relay 1

IEC 354, short time energ. loading of distr. transformers is 2.0 p.u.

I > = 2 x transformer nominal current = _____ A

t > = _____ (=selectivity with fuse)

S'' (Network) = 160MVA S'' = short circuit power

$$S'' \text{ (Transformer)} = \frac{630\text{kVA}}{10\%} = 6.3\text{MVA}$$

$$\Sigma S'' = \frac{S_1 \times S_2}{S_1 + S_2} = \frac{160 \times 6.3}{160 + 6.3} = 6.06\text{MVA}$$ (Short circuit power after transformer)

$$I_k'' = \frac{1.1 \times 6.06\text{MVA}}{\sqrt{3} \times 0.4\text{kV}} = 9.62\text{kA}$$ (Short circuit current in 400V side)

Exercise

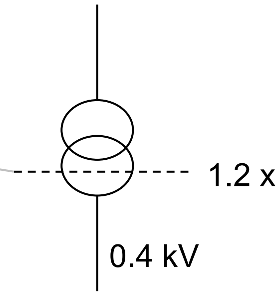
Relay 1 continues

Current in 10kV side:

$$I = \frac{0.4kV}{10kV} \times 9.62kA = 385A$$

I>> = 1.2 x $I_{k(0.4kV)}$ = 1.2 x ______ = ______ A

t>> = 0.04s (minimum setting)



Max. fault current in 10kV side:
(Before transformer)

$$I_k'' = \frac{1.1 \times 160MVA}{\sqrt{3} \times 10kV} = 10.2kA$$

Exercise

Relay 2

I > should be between stage one of relay 1 and I_{nmax} of cable 3. 150A is a good estimate.

Nominal current of transformer:

$$I_n = \frac{630kVA}{\sqrt{3} \times 10kV} = 36A$$

Max. total load = 1.1 x 3 x 36A = 119 A. Therefore I> = 150A is OK!

t > = ______+ 0.15 s = ______

Exercise

Relay 2

I >> should be at least 1.2 x half life value of inrush current. Inrush current is normally about 10 times the nominal current.

Inrush current for one transformer:

$$I_s = 10 \times I_n = 10 \times 36 = 360A$$

Typical duration of inrush peak value: 10 ms - 30 ms

Half life typically: 0.1 - 0.3s (**I**= 0.5 x 360 = **180 A**)

Exercise

Relay 2 continues

If all transformers are connected to the network at the same time:

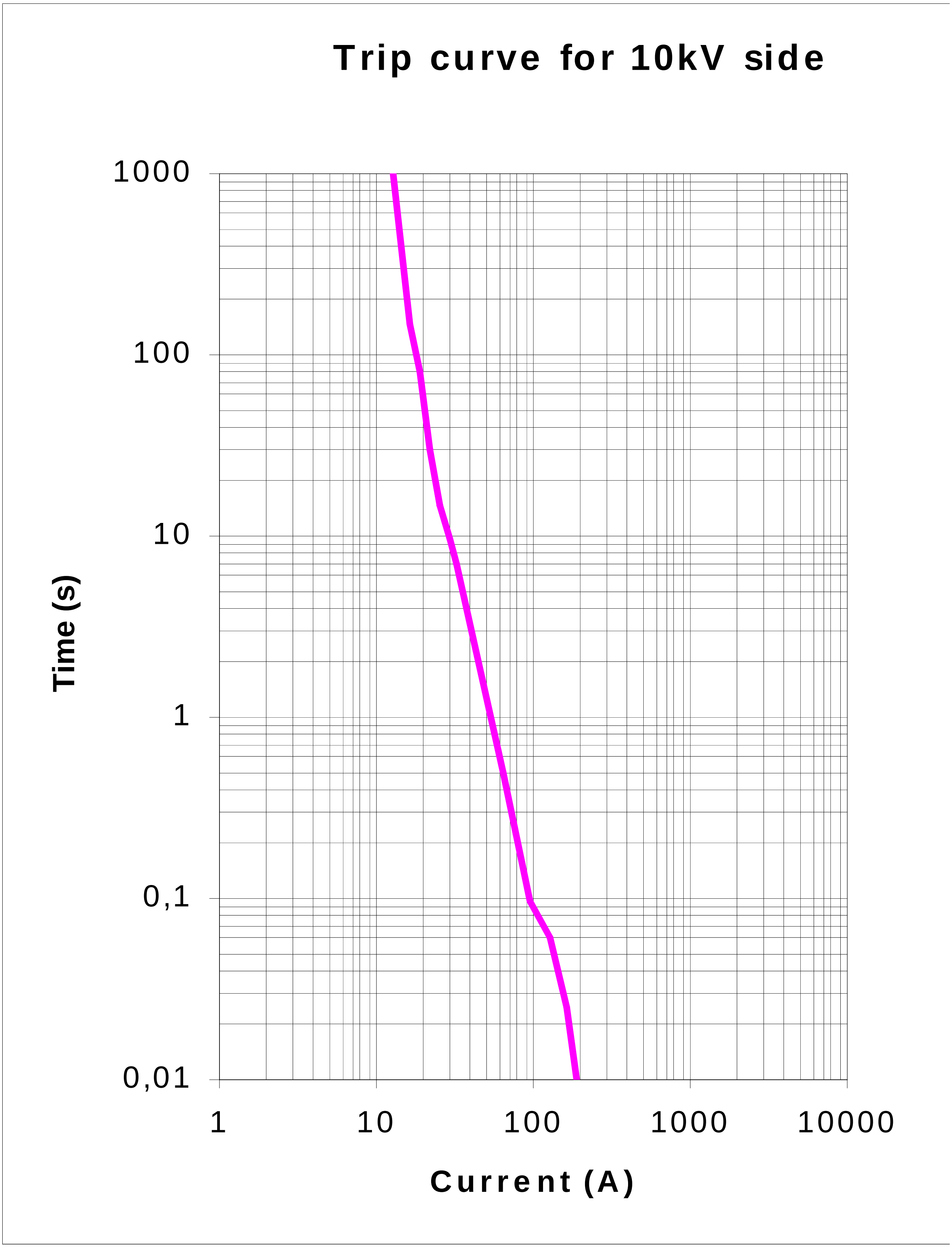
I_s = 3 x (10X36) = 1080A

0.5 x I_s = 540 A

540A x 1.2 = **648 A**

I >> = 650 A is a good estimate

t >> = 0.04s + 0.15s = 0.2s


Trip curve for 10kV side
Time (s)
1000
100
10
1
0,1
0,01
1
10
100
1000
10000
Current (A)

Chapter 4

Earth-fault protection

Earth-Fault Protection

MV Protection Relay Applications

ABB

Earth-Fault Protection

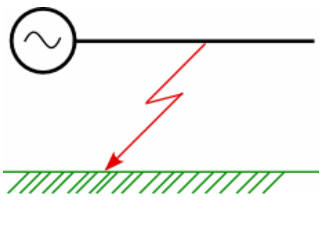
Topics:

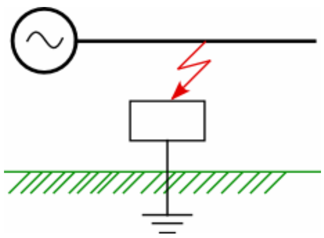
- ***Earth-fault***
- ***Isolated neutral***
- ***Compensated neutral***
- ***Resistance earthed***
- ***Solidly earthed***
- ***E/F Protection of Power Transformer***
- ***Measurements***
- ***Setting of E/F relay***

ABB

Earth-Fault Protection

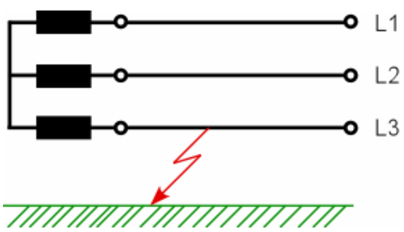
- What is earth-fault?
  - Fault in the isolation between live part and earth
  - Fault in the isolation between live part and part that has contact to earth



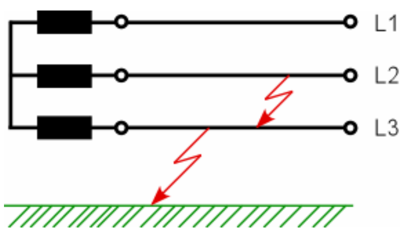


Earth-Fault Protection

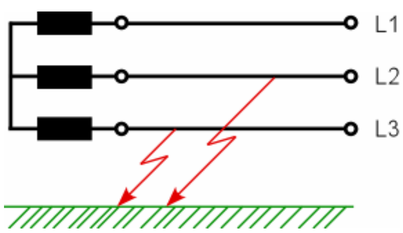
- Earth-fault in 3-phase system



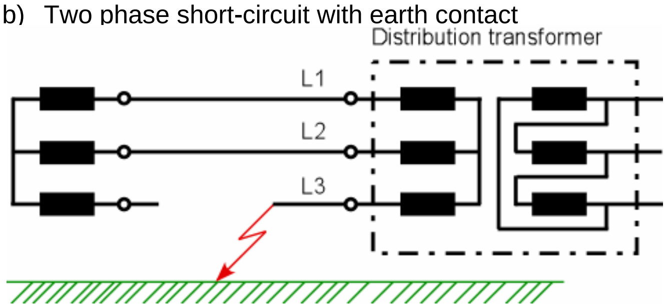
a) Single phase fault



b) Two phase short-circuit with earth contact



c) Double earth-fault



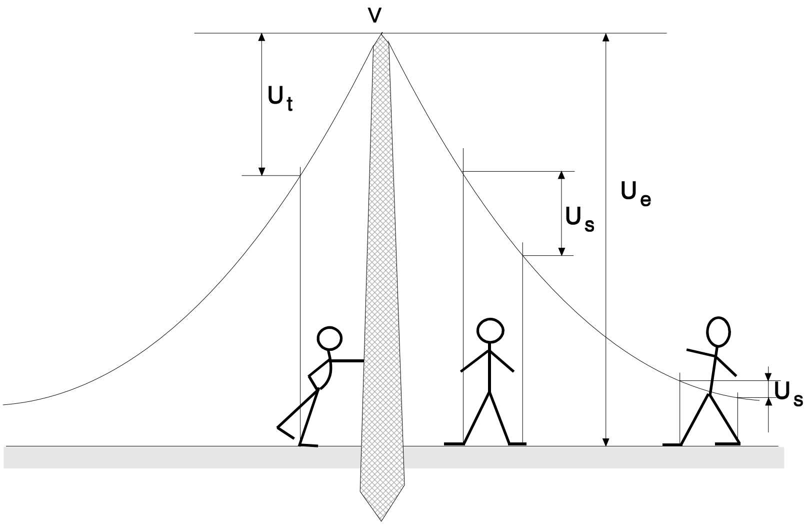
d) Line break down and one phase earth-fault on the load side

Earth-Fault Protection

- Earth-fault situations
  - Flashover to earthed parts or parts with contact to ground
  - Trees touching overhead lines
  - Vehicles touching overhead lines
  - Isolators with weak insulation
  - Cable insulation faults caused by aging or physical damage
  - Overhead line fallen to ground
  - etc...

Earth-Fault Protection

- Hazard voltages



Earth-Fault Protection

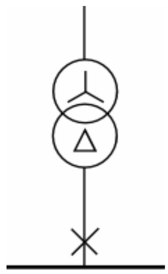
- Why to protect at earth-faults

  - Limit the hazard for the public
  - Minimize the degree of damage of electrical equipment
  - Disconnect the faulty part of the network to avoid any enlargement in other parts, due to overvoltage
  - Stated by national electricity safety regulations

Earth-Fault Protection

- *Isolated neutral*

The earth fault current is depending of the size of the galvanically connected network (cables/overhead lines)



\+ Low earth fault currents

\+ Faults allowed to stay on for a longer time

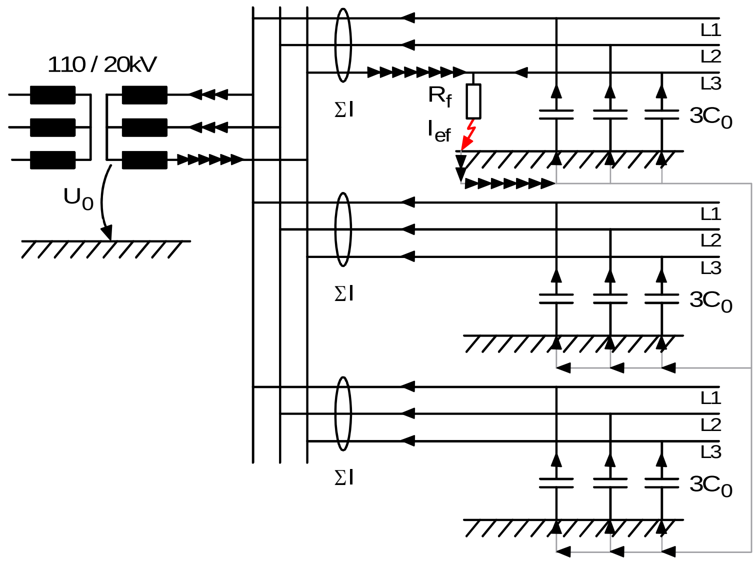
\+ Some faults cleared by themselves

\- High overvoltages during earth faults

\- Large number of temporary faults -> many reclosing activities

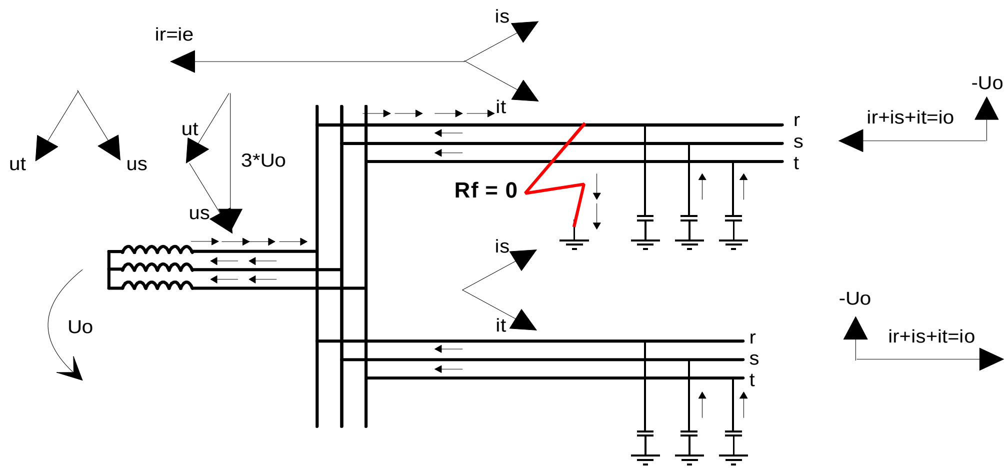
Earth-Fault Protection

- *Isolated neutral*
  - One phase earth-fault



Earth-Fault Protection

- *Isolated neutral*
  - Unsymmetrical system



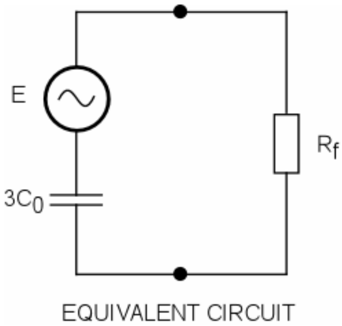
Earth-Fault Protection

- *Isolated neutral*

Calculation of earth fault current

In the case where the fault resistance Rf is zero (0), the fault current can be calculated as follows:

Ie = $3\omega C_0 E$



Co = earth capacitance per phase
E = phase voltage

For overhead lines the earth fault current (Rf=0) can roughly be calculated as follows:

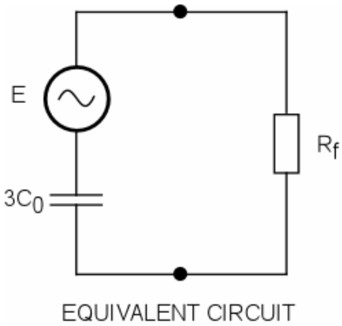
$$I_e = \frac{U \times l}{300}\ [A]$$

U = phase-phase voltage [kV]
l = length of the galvanically connected OH-lines [km]

Earth-Fault Protection

- *Isolated neutral*

Calculation of earth fault current



In earth faults there is usually some fault resistance R_f involved, which reduces the earth fault current I_{ef}

$$I_{ef} = \frac{I_e}{\sqrt{1 + \left(\frac{I_e}{E} R_f\right)^2}}$$

Earth-Fault Protection

- *Isolated neutral*

The measurable neutral current ΣI_{ef}

• The residual current measurement of the faulty feeder will not measure the whole earth fault current I_{ef}

• The earth fault current fed by the faulty feeder is not measured by the zero sequence measurement of the faulty feeder

$$\Sigma I_{ef} = \frac{(I_e - I_{e\,feeder})}{I_e} \times I_{ef}$$

ΣI_{ef} = residual current measurement of the faulty feeder

I_e = earth fault of the network, when $R_f = 0$

I_{ef} = calculated earth fault current at a certain fault resistance R_f

Ie_{feeder} = earth fault current of the faulty feeder, when $R_f = 0$

Earth-Fault Protection

- *Isolated neutral*

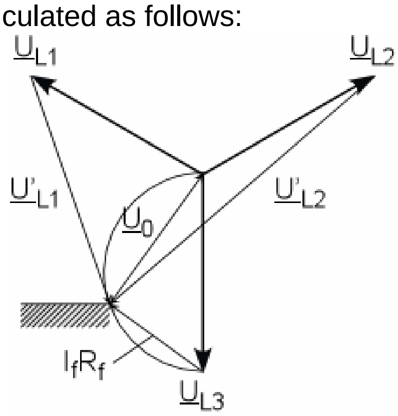
Calculation of zero sequence voltage (U_0)

- Zero sequence voltage indicates that there is an earth fault in the network
- If the fault resistance Rf = 0, the zero sequence voltage level is the same as the phase voltage (E)

The zero sequence voltage can be calculated as follows:

$$U_0 = \frac{I_{ef}}{3\omega C_0} \quad ,\text{or}$$

$$U_0 = \frac{E}{\sqrt{1 + \left(\frac{I_e}{E} R_f\right)^2}}$$

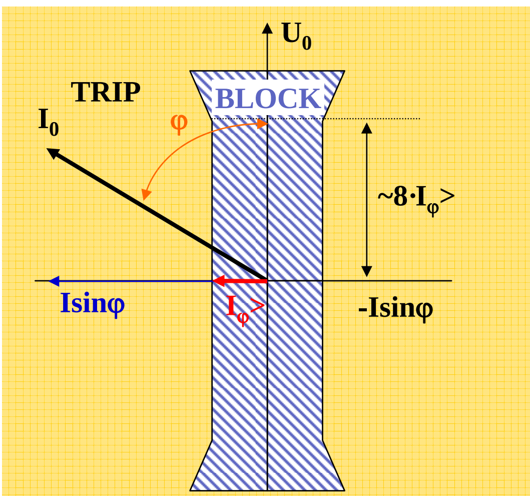


Earth-Fault Protection

- *Isolated neutral*
  - Protection relays in isolated network
    - Non-directional or directional earth-fault relays can be used
      - Relay can operate by Io or Isinφ principle
      - Isinφ principle requires also Uo measuring

Earth-Fault Protection

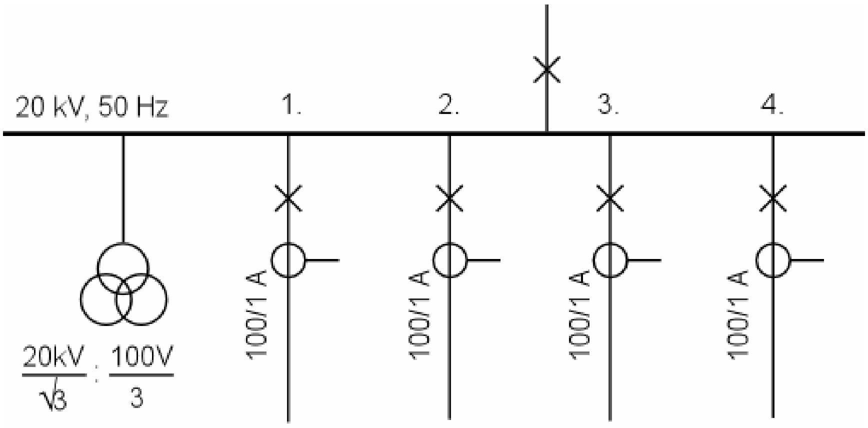
- *Isolated neutral*
  - Isinφ principle



Relay characteristics for directional earth fault protection, Isinφ measurement

Earth-Fault Protection

- *Isolated neutral* / Exercise



C_0/phase [µF/km]	0.32	0.32	0.32	0.32
lenght [km]	2.00	6.00	4.00	1.00

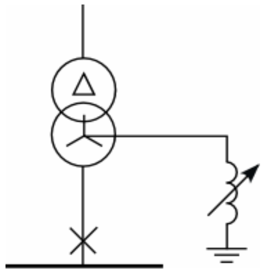
Earth-Fault Protection

- *Isolated neutral* / Exercise

- Calculate E/F current (I_e) when $R_f = 0\Omega$
- Calculate E/F current (I_{ef}) and residual voltage (Uo) when $R_f=500\Omega$
- Calculate measurable neutral current (ΣI_{ef}) for feeders 1, 2, 3 and 4

Earth-Fault Protection

Compensated neutral



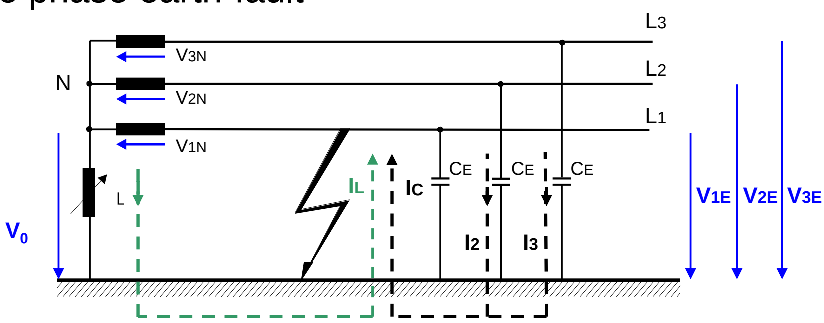
The earth fault current is depending of the size of the galvanically connected network and the degree of compensation

+ Low earth fault currents
+ Faults can stay on for a longer time
+ Most of the arcing earth faults cleared by themselves, less autoreclosings
- High overvoltages during earth faults
- Relay protection more complicated

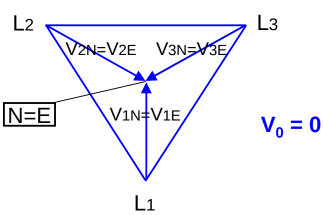
Earth-Fault Protection

Compensated neutral

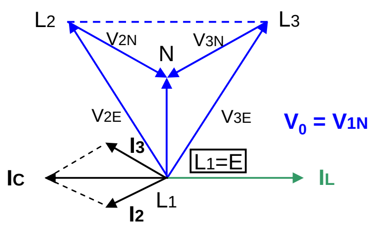
- One phase earth-fault



Voltages in healthy nework

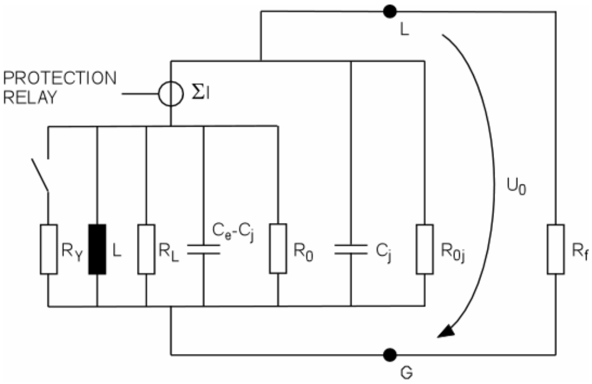


Voltages during an earth-fault



Earth-Fault Protection

- *Compensated neutral*



U_0 = Residual voltage
R_Y = Parallel resistance
R_f = Fault resistance
R_L = coil leakage resistance
R_0 = system leakage resistance
L = coil inductance
C_e = network earth capacitances
C_j = earth capacitance of an faulty feeder

E/F current :

$$I_{ef} = \frac{\sqrt{1 + R_r^2\left(3\omega C_0 - \frac{1}{\omega L}\right)^2}}{\sqrt{(R_f + R_r)^2 + R_f^2 R_r^2\left(3\omega C_0 - \frac{1}{\omega L}\right)^2}} \times E$$

Resistive component of E/F current:

$$I_{efp} = \frac{1}{\sqrt{(R_f + R_r)^2 + R_f^2 R_r^2\left(3\omega C_0 - \frac{1}{\omega L}\right)^2}} \times E$$

Residual voltage:

$$U_0 = \frac{R_r}{\sqrt{(R_f + R_r)^2 + R_f^2 R_r^2\left(3\omega C_0 - \frac{1}{\omega L}\right)^2}} \times E$$

Earth-Fault Protection

- *Compensated neutral*
  - Degree of compensation
    - The amount of compensation is called for compensation degree, K
    - If value of K is one or near it, the network is completely compensated
    - Over compensated, if K > 1
    - Under compesated, if K < 1

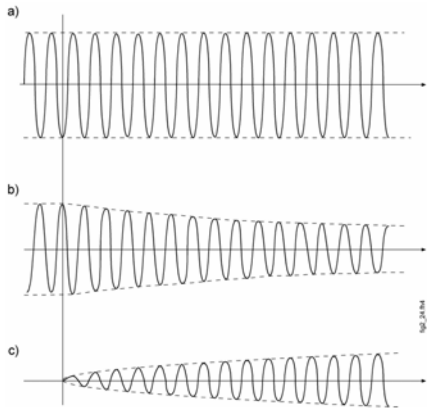
$$K = \frac{I_L}{I_C}$$

I_L = current of compensation coil during an earth-fault

I_C = capasitive earth-fault current during an earth-fault when fault resistance is zero

Earth-Fault Protection

- *Compensated neutral*
  - Principle of operation
    - low earth-fault current
    - recovery voltage is increasing slowly up to phase voltage level because of compesation coil
    - improbability of new arc ignition



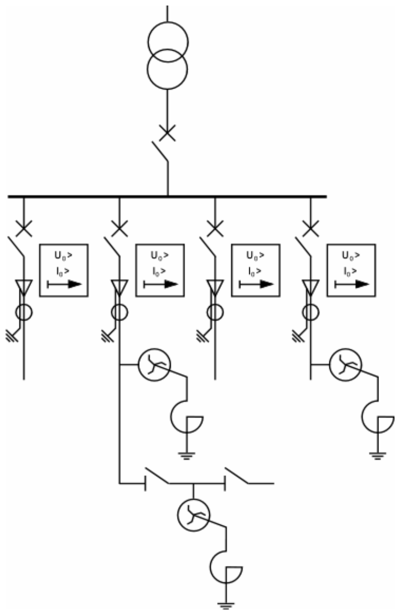
a) the steady state phase voltage
b) the residual voltage
c) the phase voltage of faulty phase

ABB

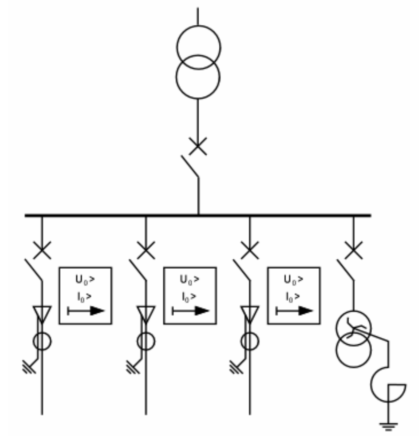
Earth-Fault Protection

- *Compensated neutral*
  - Principle of compensation

DECENTRALIZED COMPENSATION



CENTRALIZED COMPENSATION

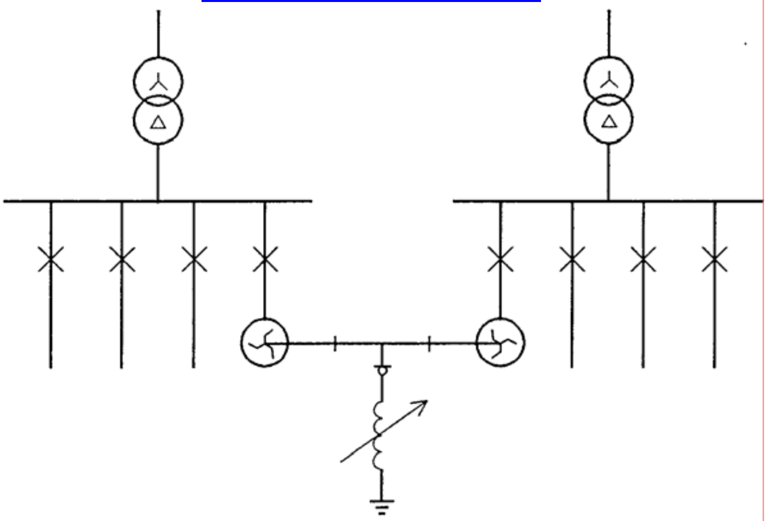


ABB

Earth-Fault Protection

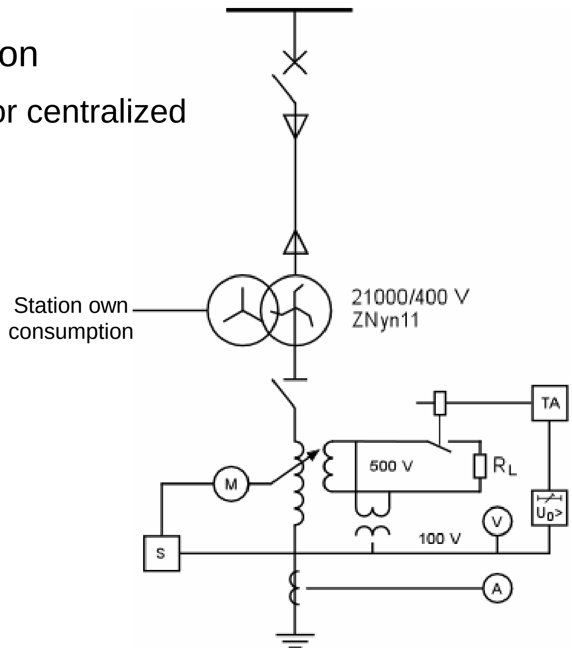
- *Compensated neutral*
  - Principle of compensation

CENTRALIZED COMPENSATION FOR TWO SEPARATE NETWORKS



Earth-Fault Protection

- *Compensated neutral*
  - Centralized compensation
    - Example connection for centralized compensation



Earth-Fault Protection

- *Compensated neutral*
  - Typical operation for parallel resistor
    - Resistor will be connected with short delay after the fault detection
    - Resistor is continuously in use
    - Resistor is continuously in use but will be unconnected after fault detection - if the earth-fault will not be self extinguished within short time delay the parallel resistor will be connected again

ABB

Earth-Fault Protection

- *Compensated neutral*
  - Protection relays in compensated network
    - Directional earth-fault relays must be always used
      - Directional E/F protection requires Uo and Io measuring
      - Relay direction must be possible to set by basic angle or by changing the operation characteristics in Isinφ or Icosφ
      - The protection should have back-up protection in case of service or repair for primary system, meanwhile the network is in isolated position

        - separate protection relay

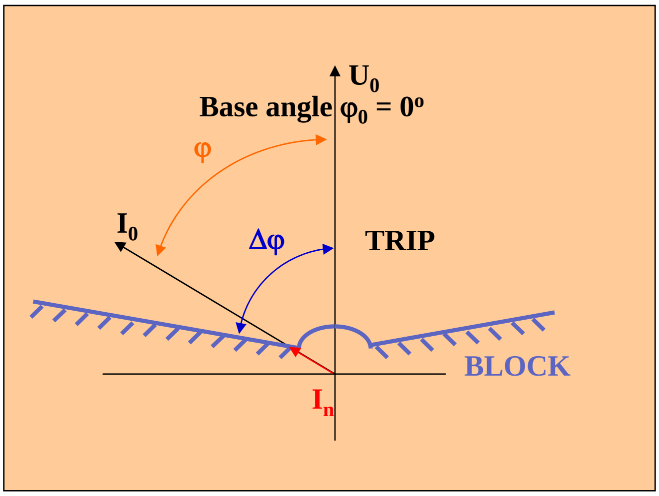
        - using of second settings

        - by setting the relay according to new network connection

ABB

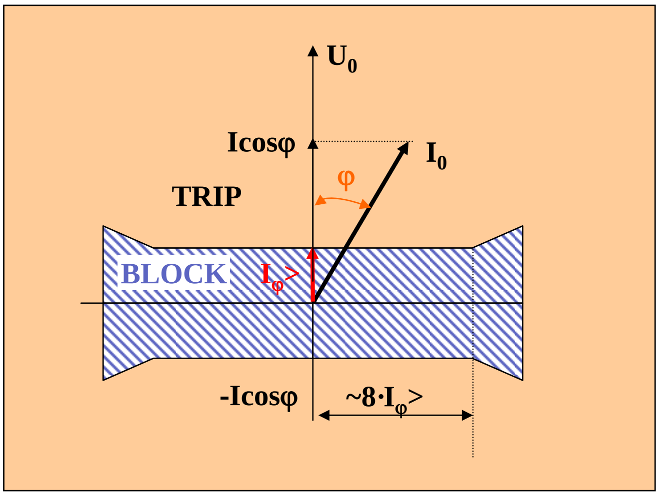
Earth-Fault Protection

- *Compensated neutral*
  - Basic angle operation



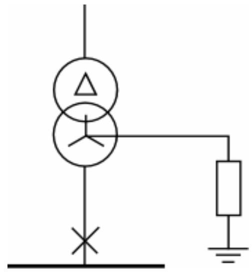
Earth-Fault Protection

- *Compensated neutral*
  - Icosφ operation



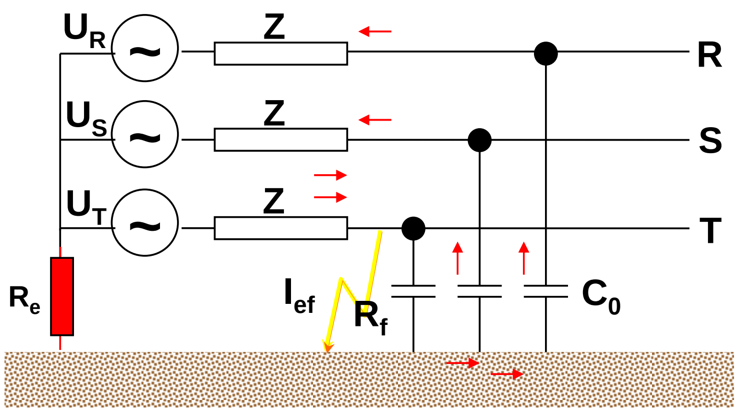
Earth-Fault Protection

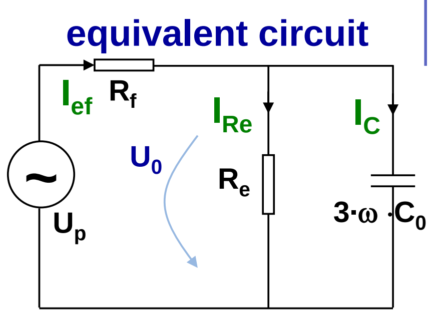
- *Resistance earthed neutral*
  - **Earthing current is depending of the earthing resistor**
  - High resistance earthed (Ief < 25 A typ.)
  - Low resistance earthed (Ief >25 A typ.)



Earth-Fault Protection

- *Resistance earthed neutral*



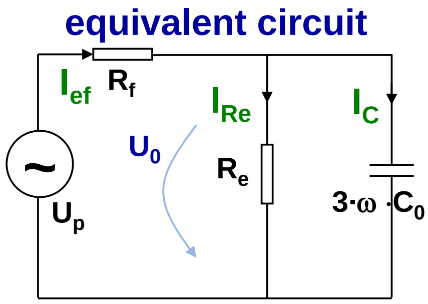


Earth-Fault Protection

- *Resistance earthed neutral*
  - Calculation of earth fault current

The earth fault current I_{ef}:

$$I_{ef} = \frac{E\sqrt{1+(R_e 3\omega C_0)^2}}{\sqrt{(R_f + R_e)^2 + (R_f R_e 3\omega C_0)^2}}$$



In the case that $Xc_0 >> R_e$, the Ief calculation can be simplified:

$$I_{ef} = \frac{E}{R_e + R_f}$$

Earth-Fault Protection

- *Resistance earthed neutral*
  - Calculation of zero sequence voltage (U_0)
    - Zero sequence voltage indicates that there is an earth fault in the network
    - The highest zero sequence voltage level is the same as the phase voltage (E)

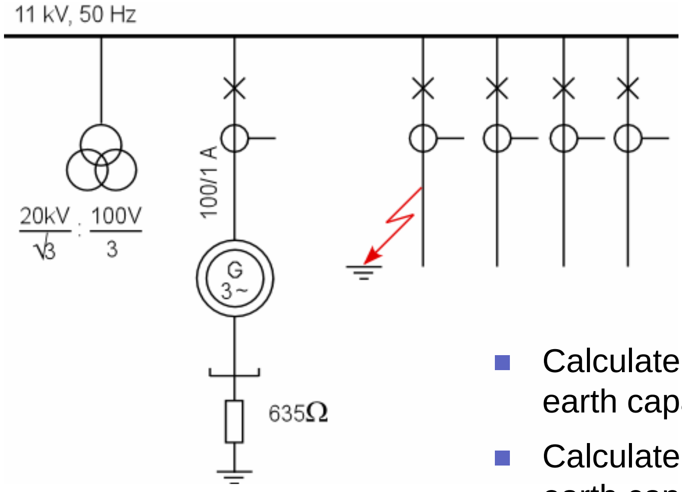
$$U_0 = \frac{I_{ef}}{\sqrt{\left(\frac{1}{R_e}\right)^2 + (3\omega C_0)^2}}$$

or when $Xc_0 >> R$:

$$\frac{U_0}{E} = \frac{R_e}{R_e + R_f}$$

Earth-Fault Protection

- *Resistance earthed neutral* / Exercise

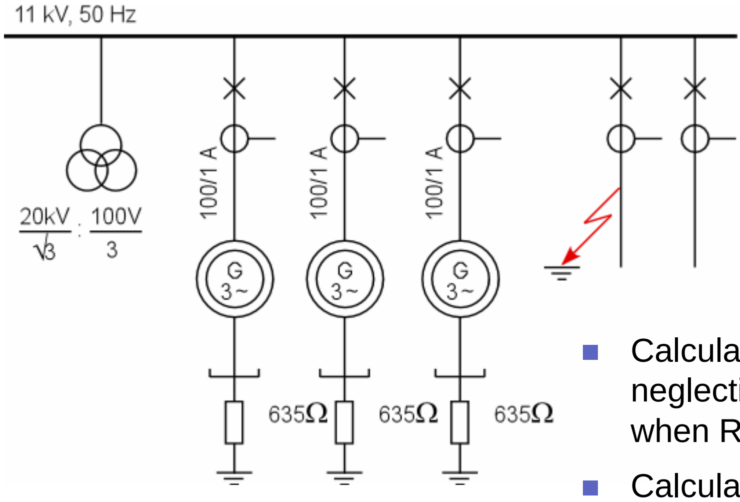


- Calculate earth-fault current neglecting earth capacitances, when $R_f = 0\Omega$
- Calculate earth-fault current neglecting earth capacitances, when $R_f = 500\Omega$

ABB

Earth-Fault Protection

- *Resistance earthed neutral* / Exercise



- Calculate earth-fault current neglecting earth capacitances, when $R_f = 0\Omega$
- Calculate earth-fault current neglecting earth capacitances, when $R_f = 500\Omega$

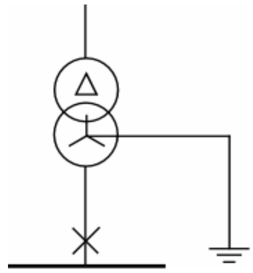
ABB

Earth-Fault Protection

- *Solidly earthed neutral*

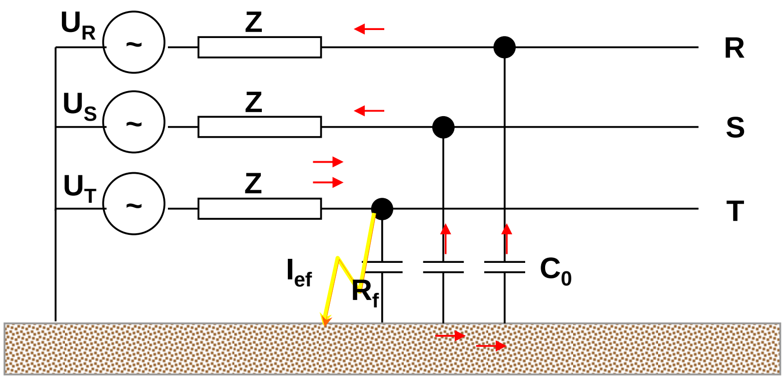
Earth fault currents as big as short circuit current

+ Low overvoltages during earth fault
+ Easy to protect
- Earth faults have to be immediately disconnected
- High earth fault current (at the highest appr. equal to the three phase short circuit)
- Requires good earthing circumstances



Earth-Fault Protection

- *Solidly earthed neutral*



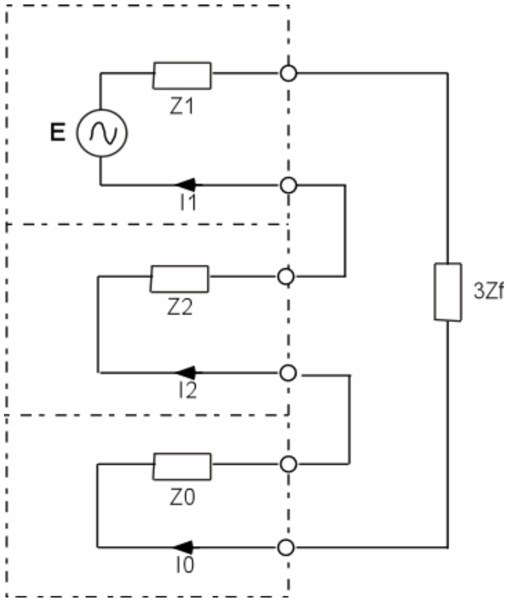
- Max. current is equal to the three phase short-circuit currents, thus requiring immediate clearing
- For systems fed from a solidly grounded generator, the availabe earth-fault current is greater than Ik3, because X0 << X1
- The single phase earth fault current vary largely with location and fault resistance

Earth-Fault Protection

- *Solidly earthed neutral*

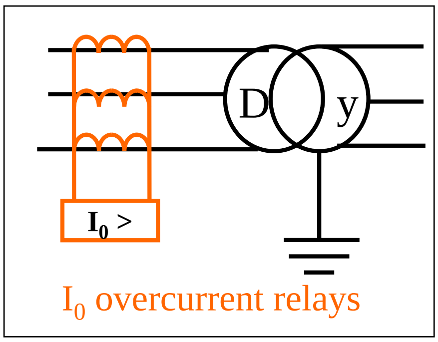
Calculation of earth fault current, using symmetrical components

$$I_f = \frac{3E}{Z_0+Z_1+Z_2+3Z_f}$$



Earth-Fault Protection

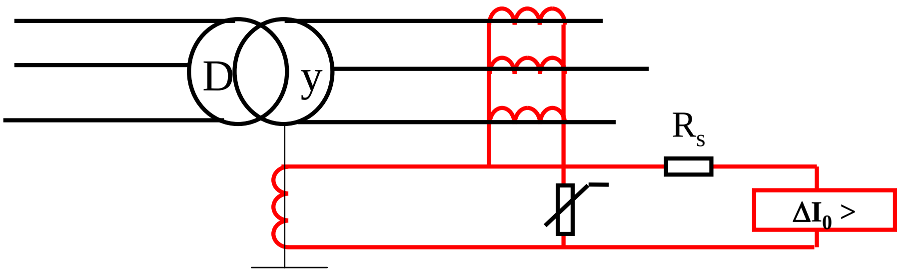
- E/F protection of power transformer
  - Delta windings and unearthed star windings of power transformers can be protected by I_0 overcurrent relays
    - relay operate only for earth faults in the transformer, since it has no earth connection through which to supply an external fault



  - Relay is usually instantaeous...
    - **high impedance type if supplied by a residual connection of three parallel CTs (prevents false operation due to unequal saturation of CTs during heavy external faults)**
    - **an ordinary overcurrent relay, if core balance CTs are used**

Earth-Fault Protection

- <u>E/F protection of power transformer</u>
  - <u>For star windings with earthed neutral</u>, the restricted earth fault connection is usally used
    - differential connection, which provides relay current only for single phase faults of the windings
    - with instantaeous relays, relays must be high impedance type
    - in order to avoid problems caused by magnetic unbalance and 3rd harmonics in the excitation current of CTs, the relays must be tuned to the fundamental frequency or 3rd harmonic filter must be used

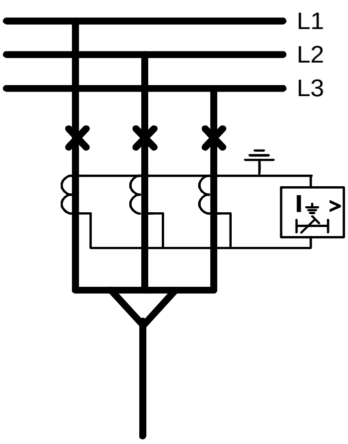


restricted earth fault relay

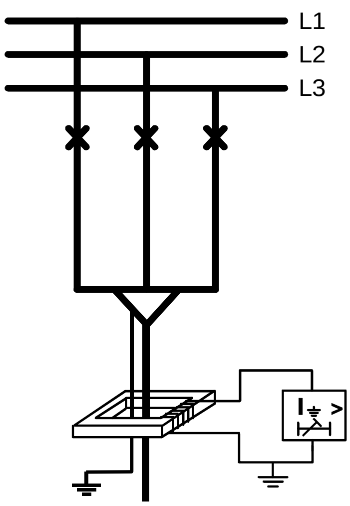
Earth-Fault Protection

- *<u>Measurements</u>*

Residual connection



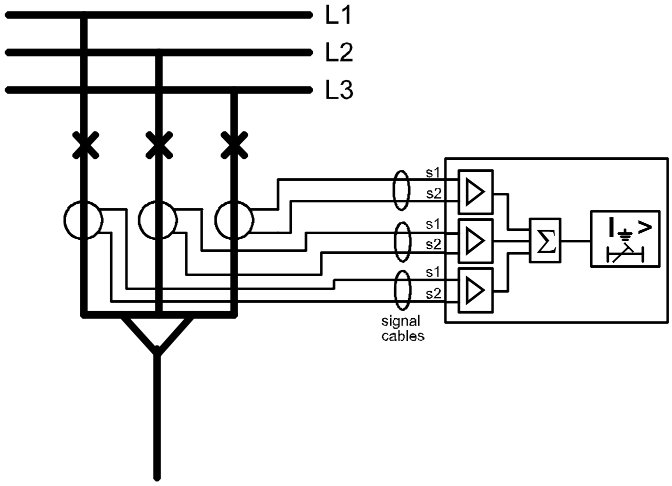
Cable core transformer



Earth-Fault Protection

- *Measurements*
  - Rogowski current sensors

Ipn : 80, 300, 800 A
Ip : 10...1600 A
Usn : 0.150 V
accuracy: Class 1



ABB

Earth-Fault Protection

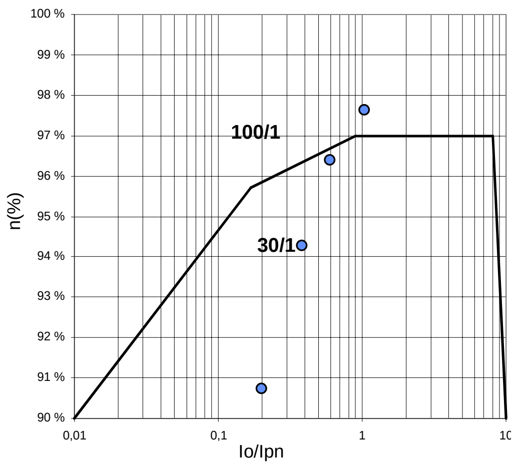
- *Measurements*
  - Cable core transformer

The efficiency factor n should be considered when calculating the relay setting:

$$Io_{relay} = \frac{n}{100} * \frac{I_{sn}}{I_{pn}} * I_0$$

Io_{relay} = relay setting (A)
n = Efficiency of the CT (%)
Isn = Rated secondary current of the CT
Ipn = Rated primary current of the CT
I_0 = Primary earth fault current (A)

Efficency factor n for a 100/1 transformer as a function of the networks earth fault current (solid line). Within the mentioned current range is the phase angle error less than 5 degrees.

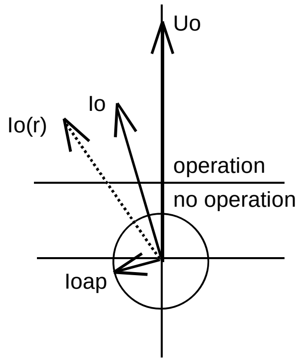


continued...

ABB

Earth-Fault Protection

- *Measurements*
  - Residual connection of current transformers
    - The accuracy is defined by the max. apparent residual current
    - The apparent residual current is a result of the inaccuracy of each CT
    - Worst case apparent residual current: Class 5P, 2 % and Class 10P, 6%
    - Practical values are 1% and 3%
    - The angle, between the apparent residual current and the residual current can be rather arbitrary



Earth-Fault Protection

- *Measurements*
  - Residual connection of current transformers

The apparent residual current should be considered when calculating the relay setting:

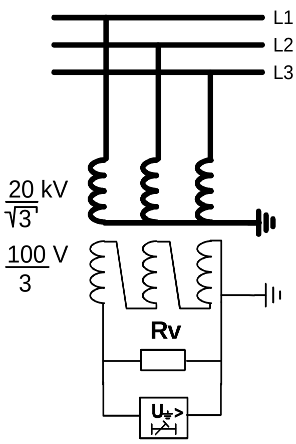
$$Io_{relay} = \frac{(I_0 - I_{0ap})I_{sn}}{I_{pn}}$$

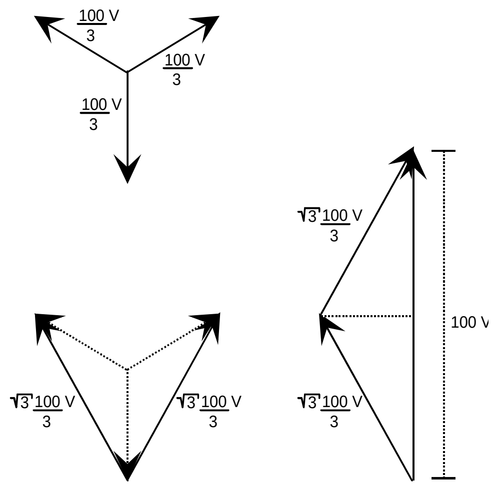
Io_{relay} = relay setting (A)
Isn = Rated secondary current of the CT
Ipn = Rated primary current of the CT
I_0 = Primary earth fault current
I_{0ap} = Max apparent residual current (primary value)

Earth-Fault Protection

- *Measurements*
  - Residual voltage

Open Delta connection of voltage trans-formers



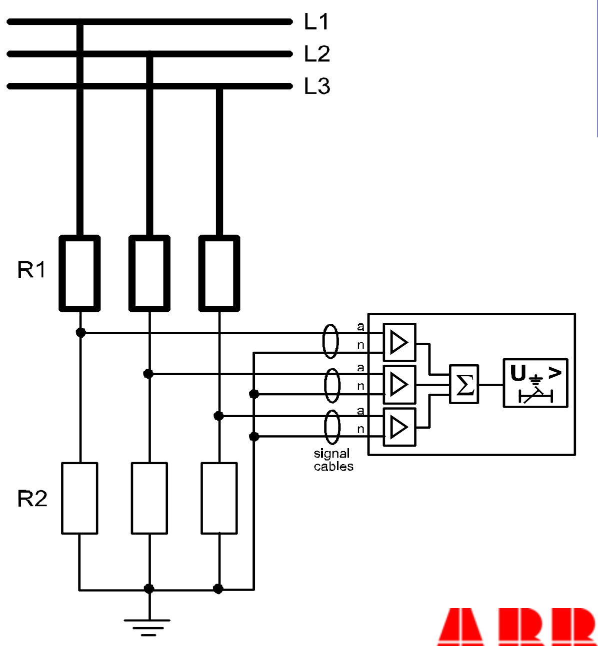


Earth-Fault Protection

- *Measurements*
  - Residual voltage

Resistive voltage dividers

Upr : 20/sqrt(3) kV
Usr : 2/sqrt(3) V
accuracy: Class 1 / 3P



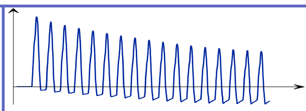
ABB

Chapter 5

Transformer protection

ABB Oy, Distribution Automation
Vaasa, Finland

Power Transformer Differential Protection



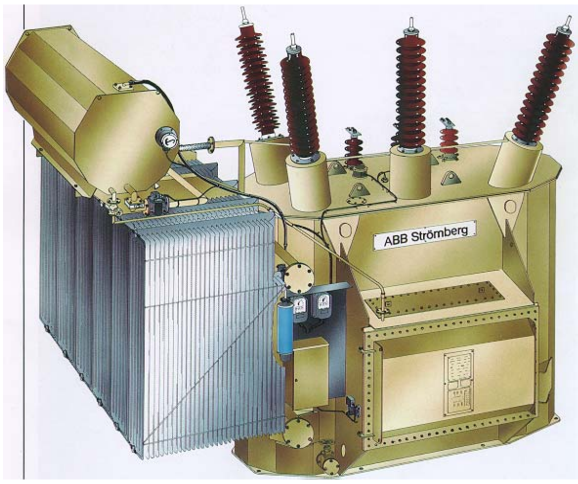
Transformer Protection

Contents

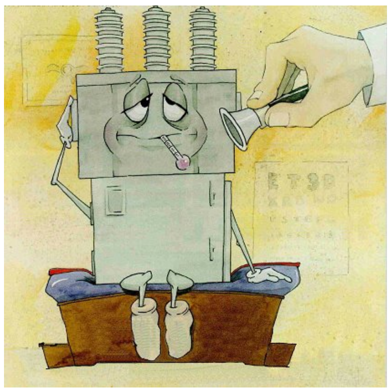
Transformer Protection

Part 1

Introduction



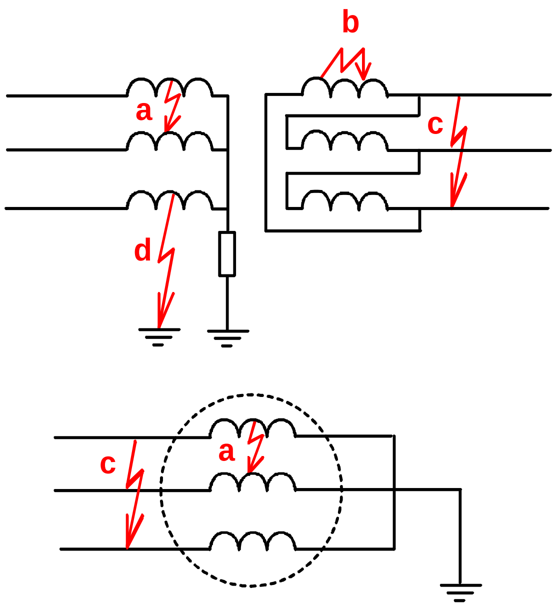
Faults



- Transformer faults are caused by
  - Long time overheat causes ageing of the insulation
  - Dirty or bad quality oil
  - Partial discharge at the insulation
  - Climatic and connecting overvoltages
  - Short circuit forces at windings caused by external fault
- Transformer failures needs expensive and long time repairing. Good protection against fault is needed.

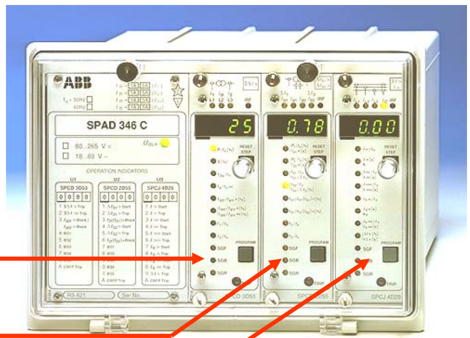
Faults

- Electrical type of faults
  - Winding short circuits(a)
  - Inter-turn faults (b)
  - Short circuits (c)
  - Earth faults (d)



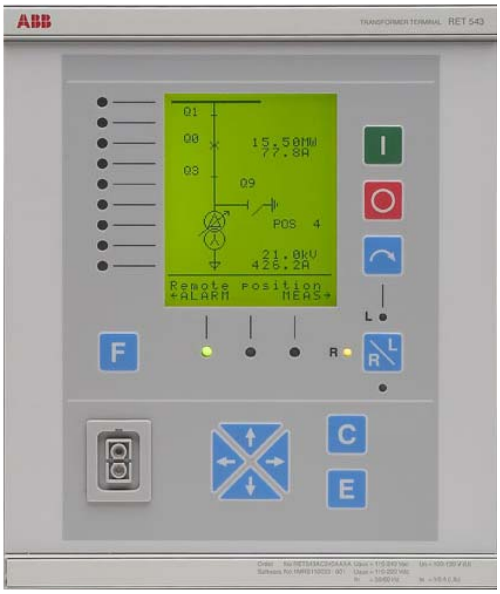
Overall Power Transformer Protection

- SPAD 346C
  - Grouping of the Transformer Protection
    - Winding short circuit and interturn protection: differential relay
    - Earth-fault protection
    - Overcurrent protection



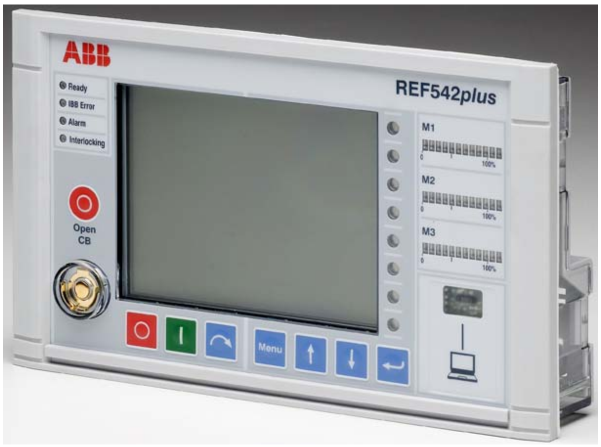
Overall Power Transformer Protection

- RET 54x
  - Basic version
    - All protection functions that uses only current measurements
    - DIFF, OC, EF, Thermal, NPS
    - Optionally automatic voltage regulator
  - Multi version
    - Basic plus functions using voltage
    - Directional protection, Voltage protection, Frequency protection, Overexcitation, underimpedance
  - Control version
    - No protection, automatic voltage regulator



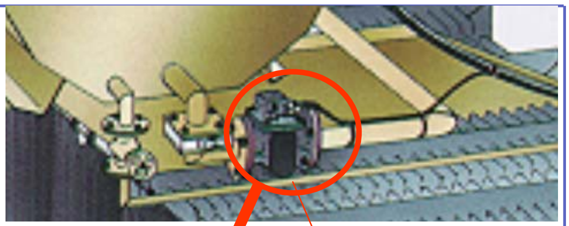
Overall Power Transformer Protection

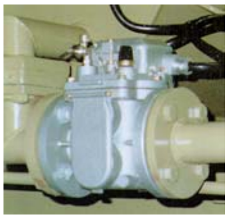
- REF 542*plus*



Overall Power Transformer Protection

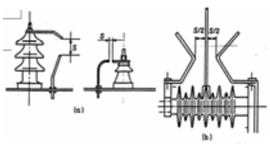
- Transformer Protection
  - Gas relay (Buchholz)
    - Installed in the tube between the coil conservator and the transformer tank
    - Partial discharge etc. => bubbles in the oil are trapped into the relay => alarm
    - Heavy fault => oil impulse wave => trip in about 100 - 300 ms
  - Pressure relay of the on-load tap changer.

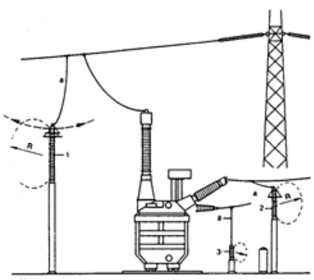




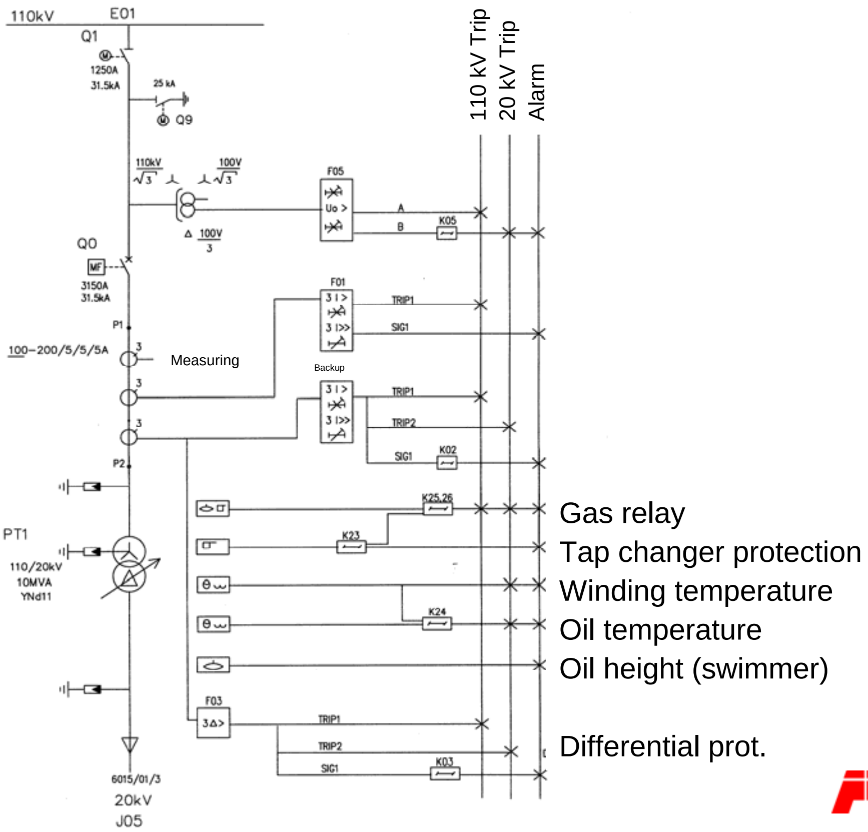
Overall Power Transformer Protection

- Transformer Protection
  - Over load protection: Oil thermometer, winding temperature inductor system, thermal overload relay
  - Over voltage protection: Spark-gaps, surge arresters
  - Oil quality analysis, partial discharge monitoring etc





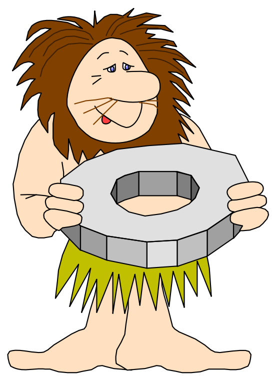
Protection scheme, example



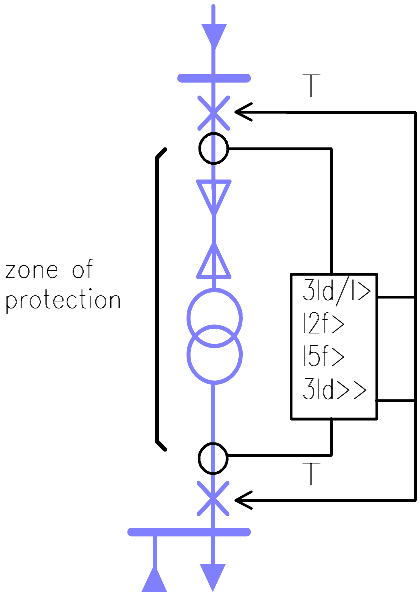
Part 2

Differential Protection

Applications, Theory and Settings



Principle, pros and cons



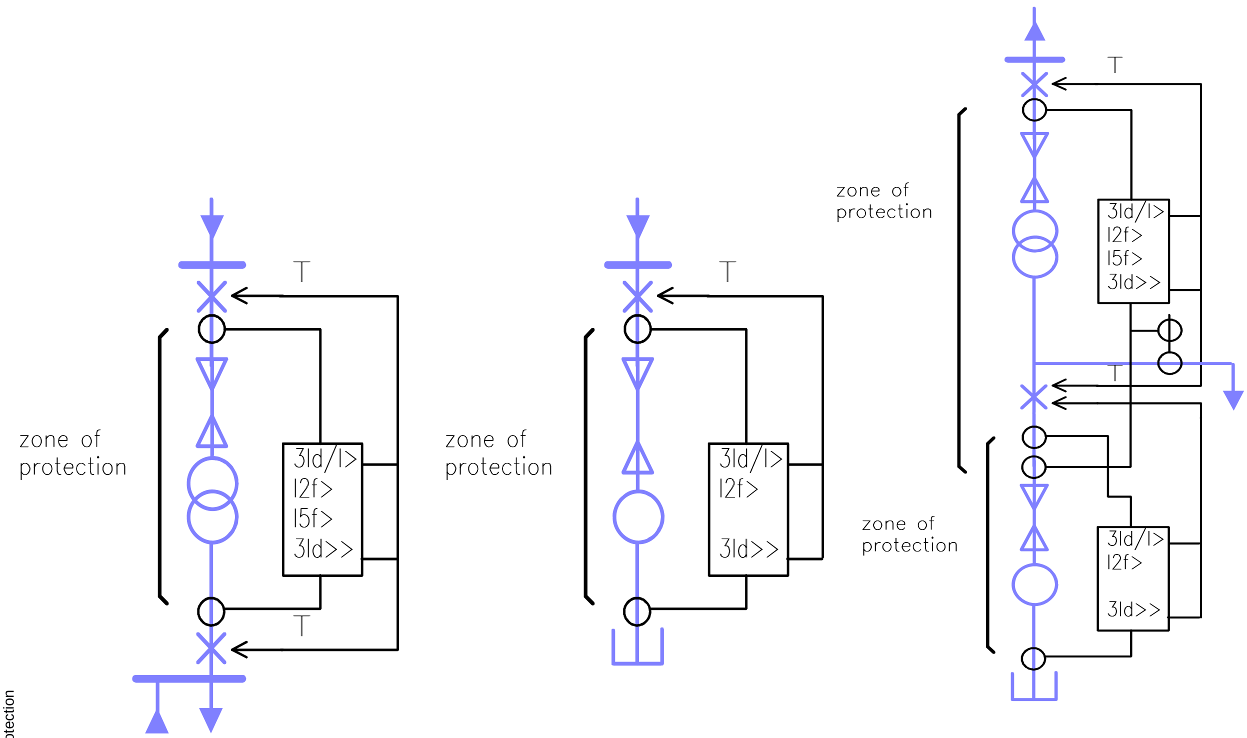
Advantages:

- Operation time in stabilized stage ~ 50 ms, operation time in instantaneous stage ~10 ms
- Sensitivity (basic setting P > 20 % *In for transformers, P > 5 % *In for generators)
- Usable for many different applications
- Exactly defined protected zones (absolutely selective)

Disadvantages:

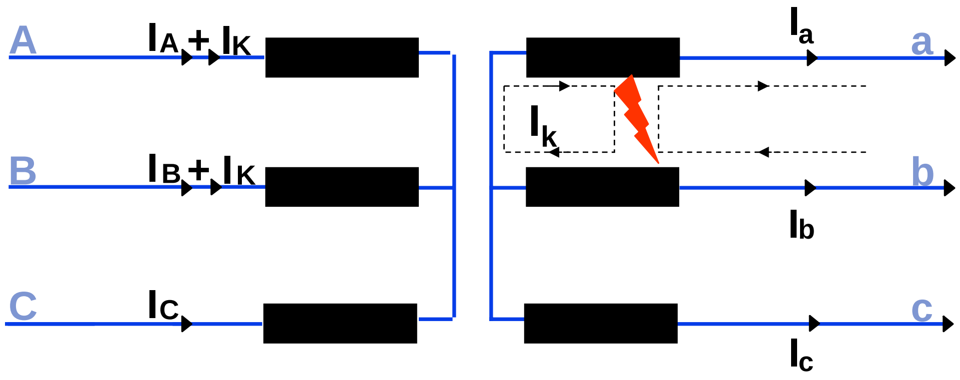
- Separate backup protection necessary
- High accuracy of current transformers (Fa>40)
- High-priced

Applications: Transformers & Rotating Machines



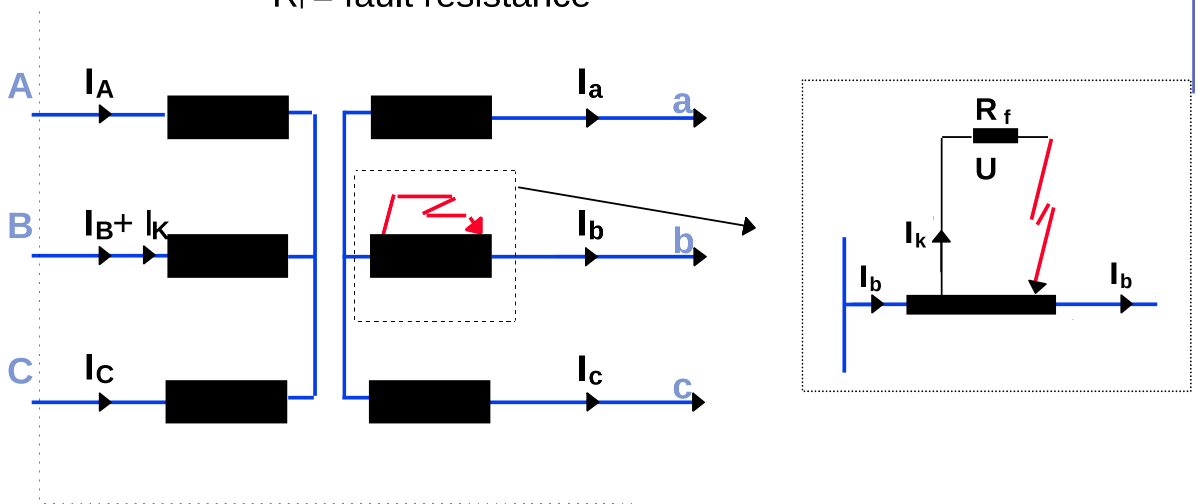
How can it see winding short circuit?

I_K = extra current in primary
I_k = extra current in secondary

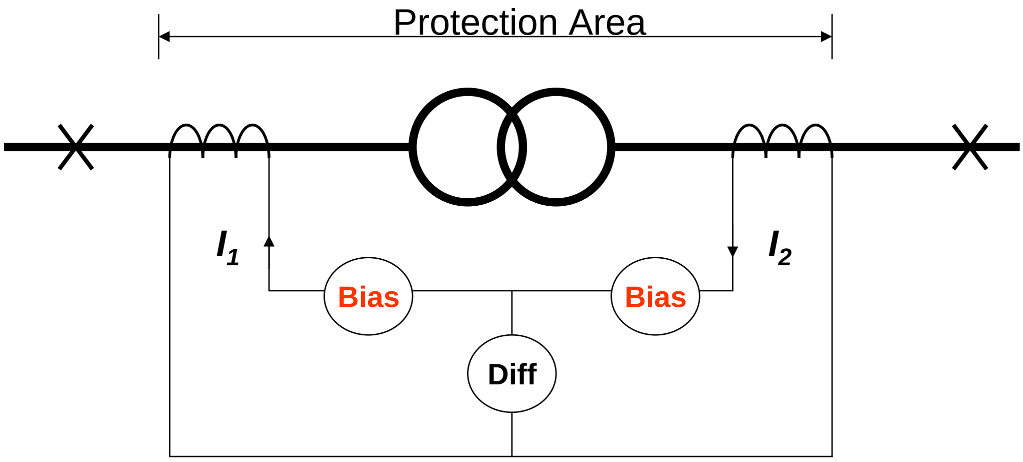


How can it see interturn fault?

I_K = extra current in primary
I_k = extra current in secondary
R_f = fault resistance



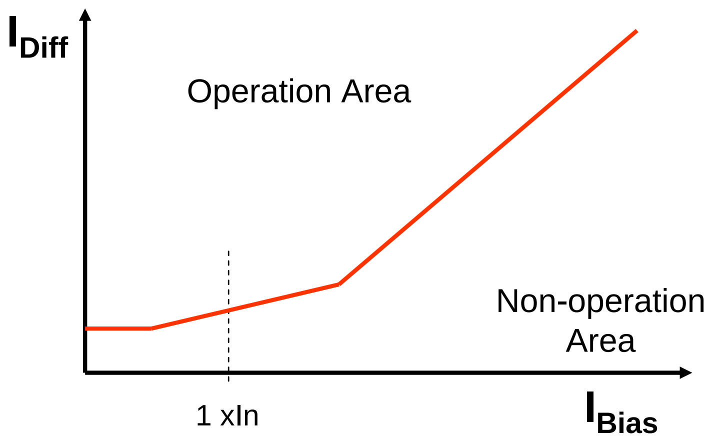
Principle of Differential Protection Relay



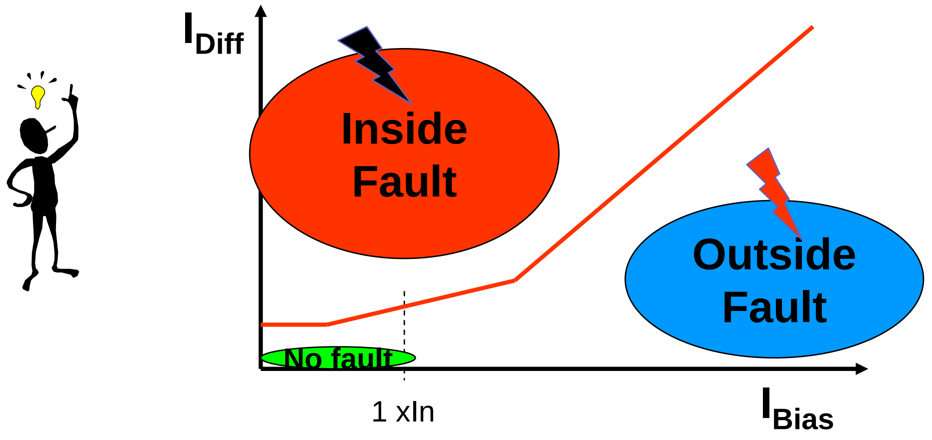
Biased Differential protection

$$I_{Diff} = \left| \overline{I_1} - \overline{I_2} \right| \qquad I_{Bias} = \frac{\left| \overline{I_1} + \overline{I_2} \right|}{2}$$

Operation characteristics



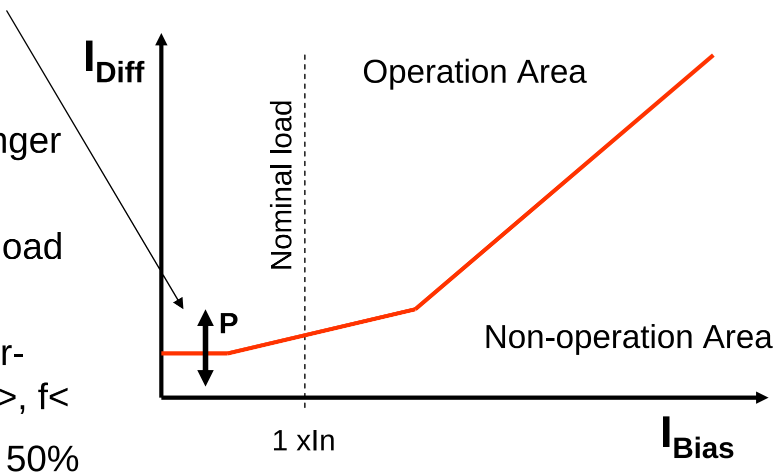
Operation characteristics



Stabilized Differential Protection = Sensitivity & Stability

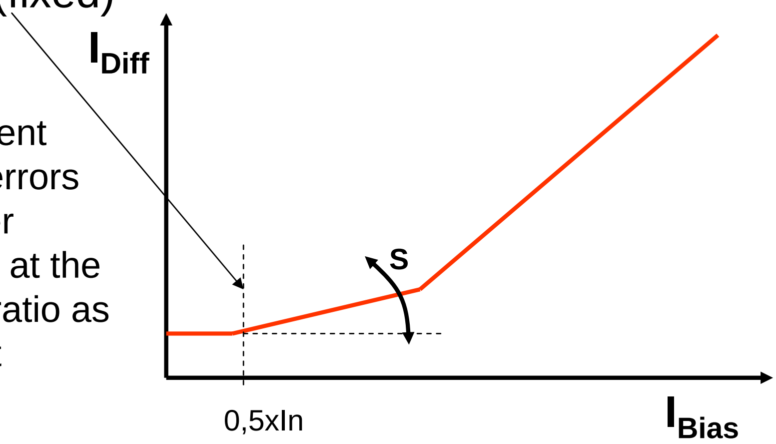
Operation characteristics, settings (SPAD/RET)

- Basic Setting (P)
  - CT errors
  - Varying tap-changer positions
  - Transformer no-load current
  - Transformer over-magnetisation U>, f<
  - setting range 5 - 50%
    - ≥ 20% for transformers
    - ≥ 5% for generators



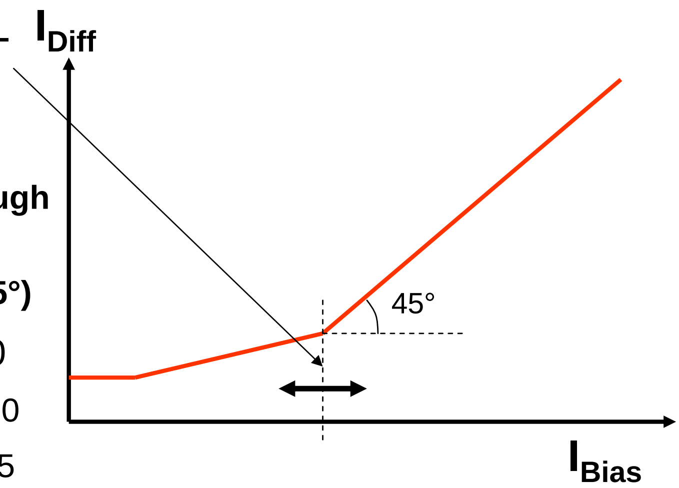
Operation characteristics, settings (SPAD/RET)

- 1st turning point (fixed)
- Starting ratio (S)
  - Differential current caused by CT errors and tap-changer positions grows at the same per sent ratio as the load current increases
  - setting range 10 - 50%

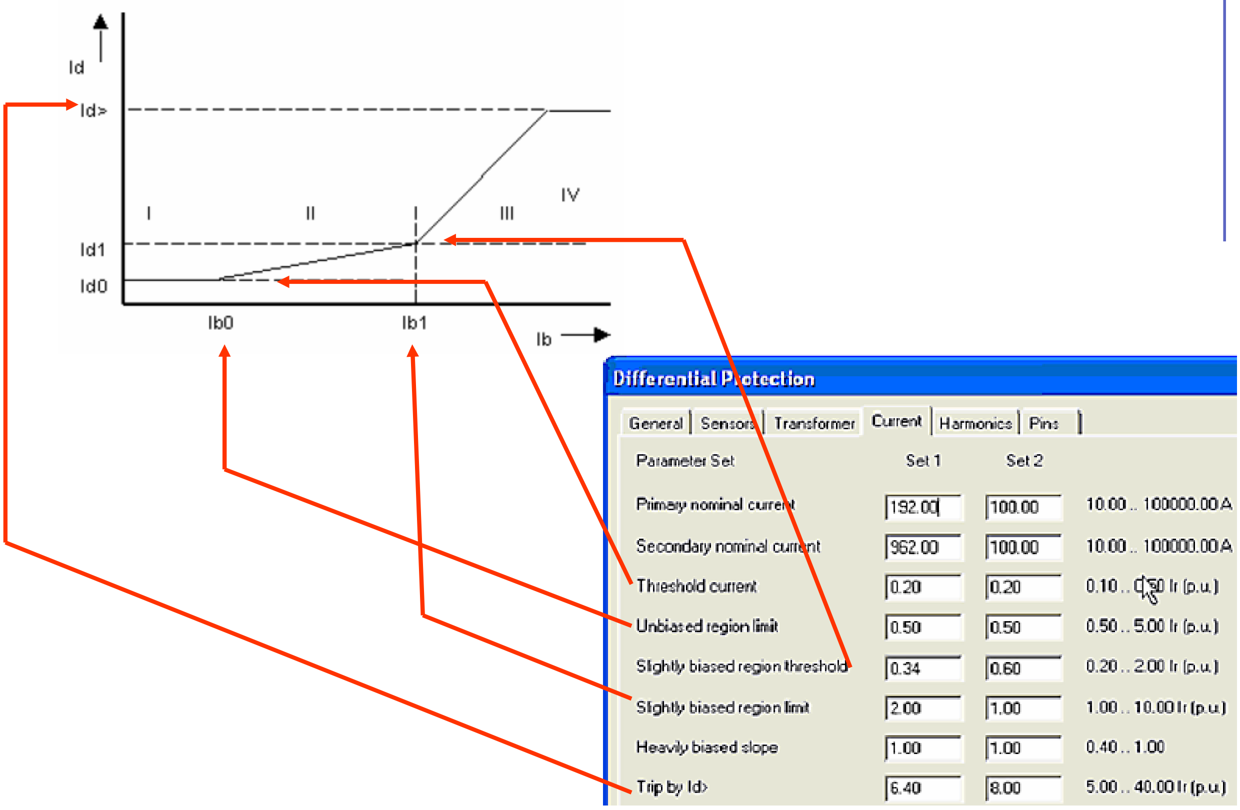


Operation characteristics, settings (SPAD/RET)

- 2nd turning point (turn-point 2)
  - CT saturation at **high currents passing through the transformer**
  - **Slope always 100% (45°)**
  - setting range 1.0 - 3.0
    - Trafo: <u>1.5</u> - 2.0
    - Generators: 1.0 - 1.5
    - Motors: 1.0



Operation characteristics, settings (REF 542*plus*)



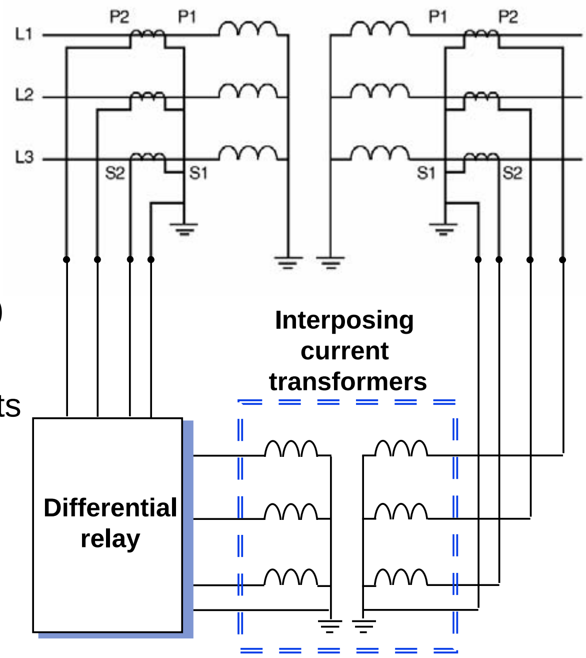
Part 3

Differential Protection

Advantages of Numerical Relay

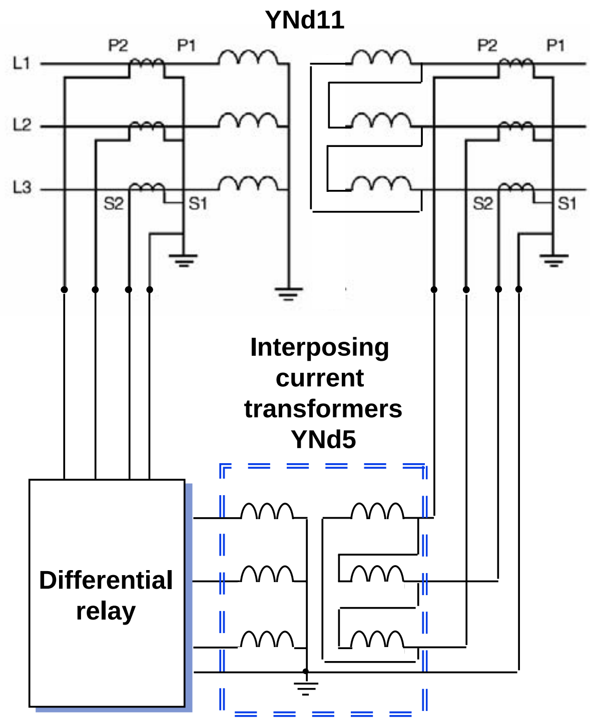
Need for interposing CTs (old relays)

- Matching the secondary currents
  - Example: 115/20 kV, 75 MVA, CTs are 400/5 and 2500/5
    - HV: In = 376A (relay has 4.7A)
    - LV: In = 2165A (relay has 4.3A)
    - ⇒ Interposing CT required for matching the secondary currents



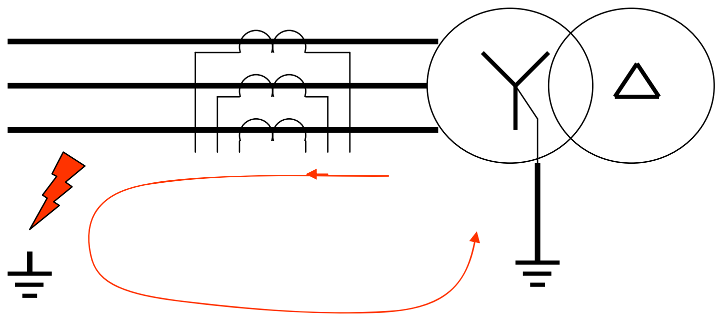
Need for interposing CTs (old relays)

- Matching Vector Groups
  - Example: YNd11
    - 30 degree phase difference
    - ⇒ Interposing CT required for D/Y transformation



Need for interposing CTs (old relays)

- **Elimination of the zero-sequence components**
  - **Neutral connected Y-windings**
  - **Earthing transformers**

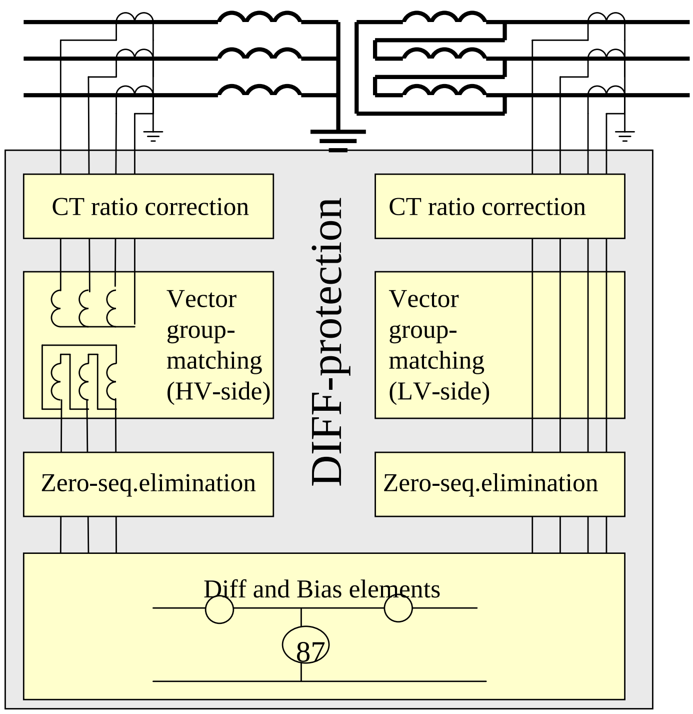


E/F current flows in the HV-side only. Without elimination the relay will see this as a differential current!

ABB

Advantages of Numerical Relay

- Numerical computation of
  - Vector group matching
  - CT ratio corrections
  - Zero sequence elimination
- Eliminates the need of interposing CTs (for two-winding transformers).

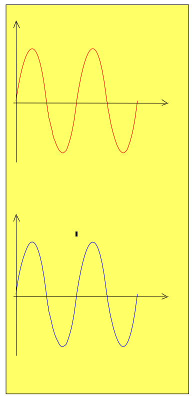


ABB

Advantages of Numerical Relay

- Phase current and differential current display
  - Values are after CT ratio correction
    - HV and LV currents should be equal
    - Differential currents should be about zero

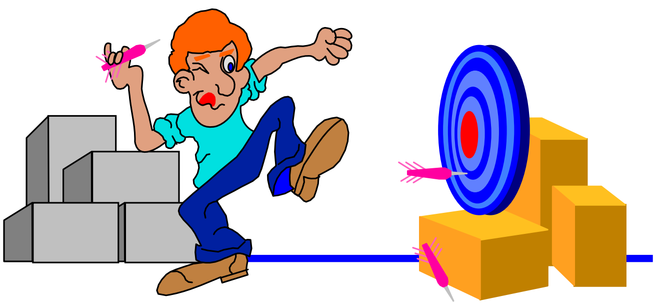
- Phase angles
  - Values are after Vector Group Matching
    - 120 degree between phases
    - 0 degree between HV and LV
- Disturbance recording function for fault analysis
- Plus more



Part 4

Differential Protection

Setting calculations



CT ratio correction, SPAD 346C

- Power Transformer Rated current

$$I_N = \frac{S_N}{\sqrt{3} \times U_N}$$

- CT ratio correction

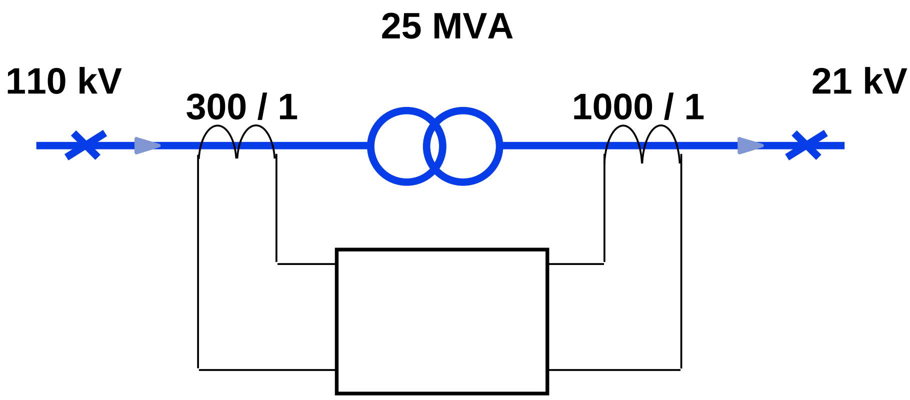
$$I_1/I_N = \frac{I_N}{I_{CT-\text{primary}}}$$

The exact equation:

$$\left(I_1/I_N = \frac{I_N}{I_{CT-\text{primary}}} \times \frac{I_{CT-\text{secondary}}}{I_{relay}} \right)$$

CT ratio correction, SPAD 346C

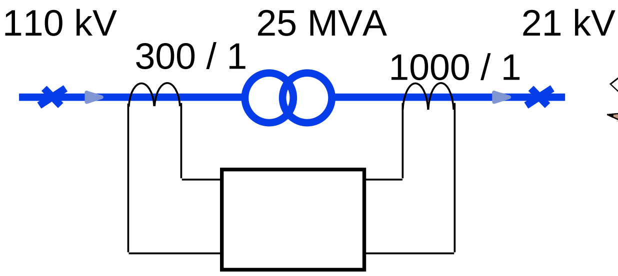
- Exercise: calculate the CT ratio correction settings for both HV and LV sides

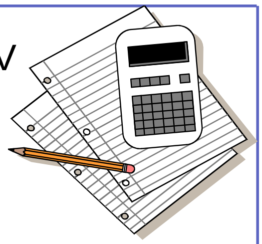


CT ratio correction, SPAD 346C

$$I_N = \frac{S_N}{\sqrt{3} \times U_N}$$

$$I_1/I_N = \frac{I_N}{I_{CT-primary}}$$





HV-side I_N =

I_1/I_N =

LV-side I_N =

I_2/I_N =


Operation characteristics

- S – setting (starting ratio) =
  - Rated accuracy of the CTs +
  - On Load Tap Changer range (RET 54x can have autom.adaptation) +
  - Relay operation accuracy (4%) +
  - Margin
- P – setting (basic setting) =
  - S/2 + 10% (No-load losses + over-excitation)
- I_{2tp} - setting (turn-point 2)=
  - 1.5 (typically)

Operation characteristics

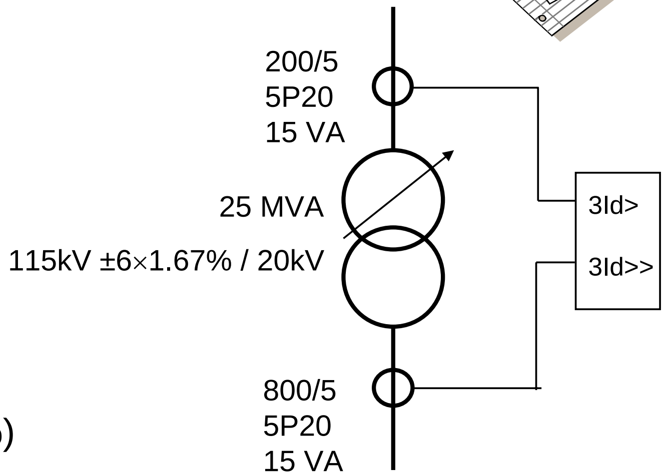
- Exercise: calculate the S and P settings and select the I_{2tp} setting

S - setting

(HV ct)
(LV ct)
(Tap changer)
(Relay accuracy)
(Margin)
_____ **%**

P - Setting = **%** (S/2+10%)

$\mathbf{I_{2tp}}$ =

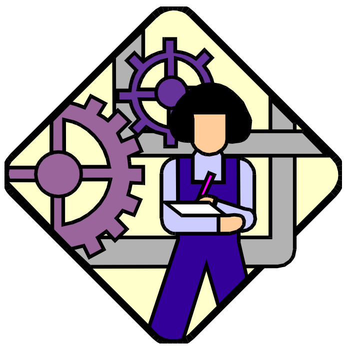


But what if… SPAD 346C

- "CT ratio correction" setting range is not enough?
  - Example: Calculated settings are I_1/I_n = 0.35 and I_2/I_n = 0.45
    - smallest possible setting is 0.40 => we use I_1/I_n = 0.40
    - because I_1/I_n was rised, also I_2/I_n must be rised (same per cent)
    - => I_2/I_n = 0.45 x 0.40/0.35 = 0.51
  - It is also possible to use 1A input instead of 5A input, but check the thermal and dynamic withstand of the input!

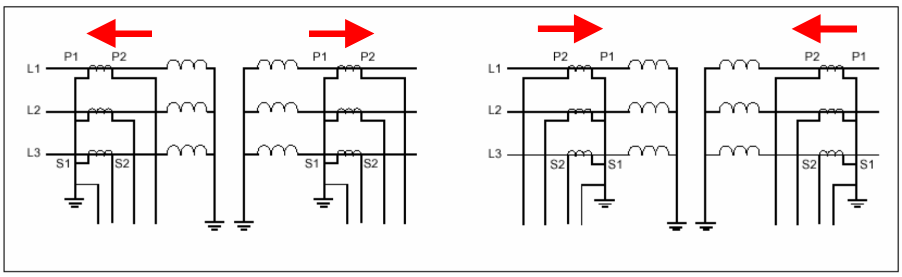
Part 4

Differential Protection
Vector Groups and Blocking

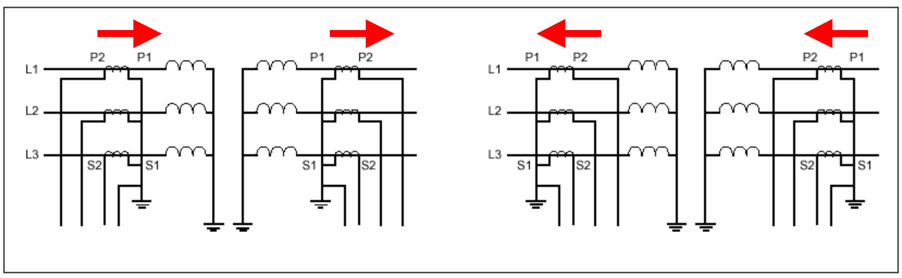


CT connections

- The difference between Type I and II is 180 degrees



Type II

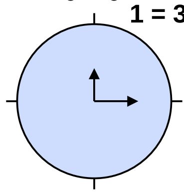


Type I

Vector Groups

Power transformer vector group I	II	Switches SGF1/1...8 1	2	3	4	5	6	7	8	Checksum
Yy6	Yy0	0	0	0	0	0	0	0	0	0
YNyn8	YNyn2	0	0	1	0	1	1	0	0	52
YNyn10	YNyn4	0	0	1	0	0	0	1	0	68
YNyn6	YNyn0	1	1	0	0	0	0	0	0	3
Yy0	Yy6	0	0	1	1	0	0	0	0	12
YNyn2	YNyn8	0	0	1	0	1	0	0	1	148
YNyn4	YNyn10	0	0	1	0	0	1	0	1	164
YNyn0	YNyn6	1	1	1	1	0	0	0	0	15
Yd1	Yd7	0	0	0	1	0	0	0	0	8
YNd1	YNd7	0	0	0	0	0	0	0	1	128
Yd5	Yd11	0	0	1	0	0	0	0	0	4
YNd5	YNd11	0	0	0	0	0	1	0	1	160
Yd7	Yd1	0	0	1	0	1	0	0	0	20
YNd7	YNd1	0	0	0	0	0	1	0	0	32

Phase angles

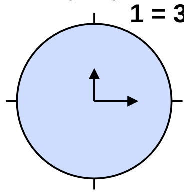


Vector Groups

Table 1 Vector group of the transformer

Vector group of the transformer	HV connection	LV connection	Clock number	Io elimination
Yy0	Y	y	0	Not needed
YNy0	YN	y	0	HV side
YNyn0	YN	yn	0	HV & LV side
Yyn0	Y	yn	0	LV side
Yy2	Y	y	2	Not needed
YNy2	YN	y	2	Not needed
YNyn2	YN	yn	2	Not needed
Yyn2	Y	yn	2	Not needed
Yy4	Y	y	4	Not needed
YNy4	YN	y	4	Not needed
YNyn4	YN	yn	4	Not needed
Yyn4	Y	yn	4	Not needed
Yy6	Y	y	6	Not needed
YNy6	YN	y	6	HV side
YNyn6	YN	yn	6	HV & LV side
Yyn6	Y	yn	6	LV side
Yy8	Y	y	8	Not needed
YNy8	YN	y	8	Not needed
YNyn8	YN	yn	8	Not needed
Yyn8	Y	yn	8	Not needed
Yy10	Y	y	10	Not needed
YNy10	YN	y	10	Not needed

Phase angles



Transformer Protection

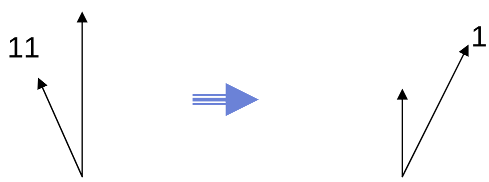
Do I need zero-sequence elimination?

- No, if
  - D -winding
  - Y -winding, with unearthed neutral
  - Y/D -transformation is done in vector-group matching
- Otherwise
  - activate elimination

But what if…

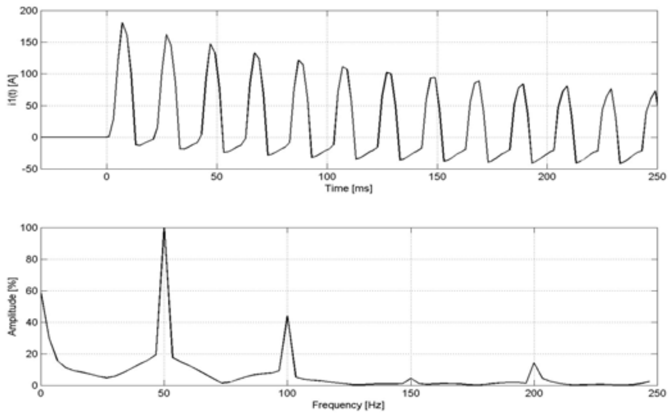
- HV and LV connections are swapped?
  - Example: YNd11
    - Swap HV/LV letters: YNd => Dyn
    - Calculate 12 - “old clock position”: 12 - 11 = 1

    ⇒ Dyn1

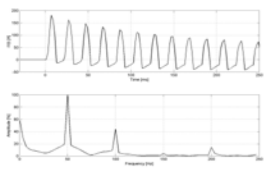


Inrush current at transformer energising

- May be many times the rated current
- Halving time may be up to several seconds (big transformers)
- Represents differential current => causes the relay to operate if nothing is done
- Contains a large amount of second harmonics



2nd harmonic blocking



⇒ In an inrush situation the operation of the stabilized stage is inhibited by a blocking function based on the second harmonic of the differential current.

- The amount of 2nd harmonic is calculated and compared to the fundamental component at each phase individually.
- Each phase is blocked if it's weighted value exceeds the setting
- Default setting 15%

$$I_{A,B,C} = \frac{I_{2f}}{I_{1f}}$$

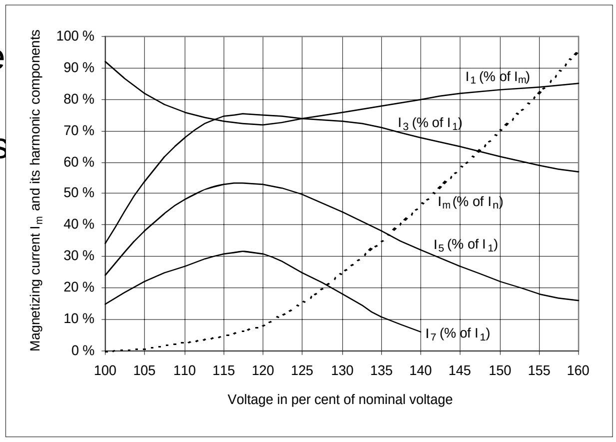
Weighing in phase A

$$\frac{4 \times I_A + I_B + I_C}{6}$$

- Id>> stage is not blocked

Over-excitation

- U> or f< causes saturation of the transformer core
  ⇒ magnetizing current increases
  ⇒ relay sees this as diff.current
  ⇒ relay might trip
- But small and temporary over-magnetization is not dangerous
  ⇒ the fifth harmonic component of the magnetizing current can be used to detect and block low-stage at over-magnetization.
- If the voltage goes very high there is a risk of breaking down the insulation of the transformer
  ⇒ de-blocking



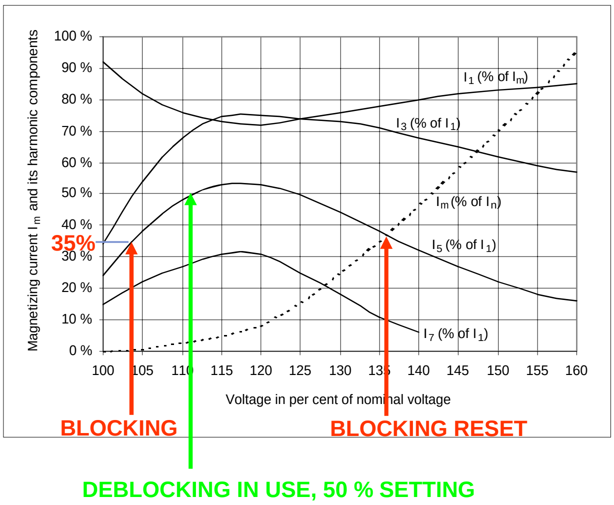
Magnetizing current and its harmonic components in the primary current of an overexcited power transformer

Over-excitation

Fifth harmonic settings:

Blocking in use, 35 % setting:
Relay is blocked when the line voltage reaches a value of 104%. If the voltage continues to rise, then the blocking will be reset when the voltage reaches 137%.

Deblocking in use, 50 % setting:
When deblocking is used the blocking will be deblocked at approx. 111 %.



Part 5

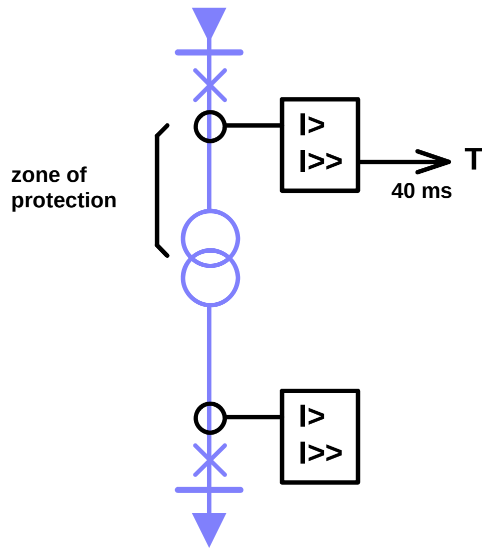
Overcurrent

and

Earth-Fault Protection

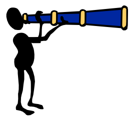
Overcurrent protection

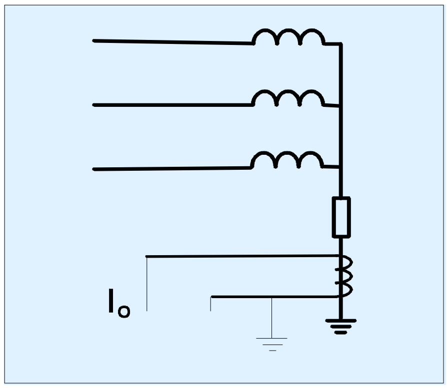
- Back-up for differential protection
- I> stage time selective with down stream relay => "slow" protection
- I>> stage current selective => fast protection but covers typically only 80 % of the transformer



E/F protection, Neutral current Principle

- Neutral or residual current is connected to Io input
- Does not know where the fault is => backup protection

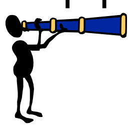


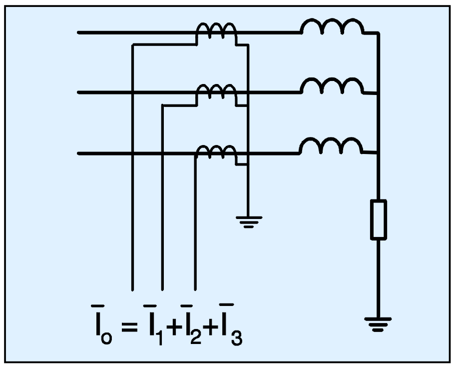


- Can also be directional in the RET 54x Multi-version

E/F protection, Calculated Residual O/C Principle

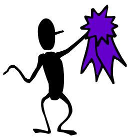
- Calculated sum of phase currents (Io input not used)
- Does not know where the fault is => backup protection

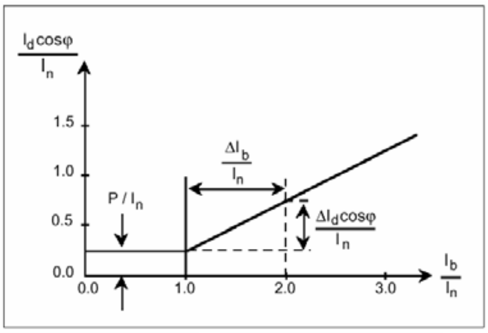




E/F protection, Stabilized Differential Principle

- Compares fundamental components of the measured Io and calculated sum of phase currents
- Trips only if the fault is inside the operation area

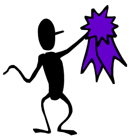


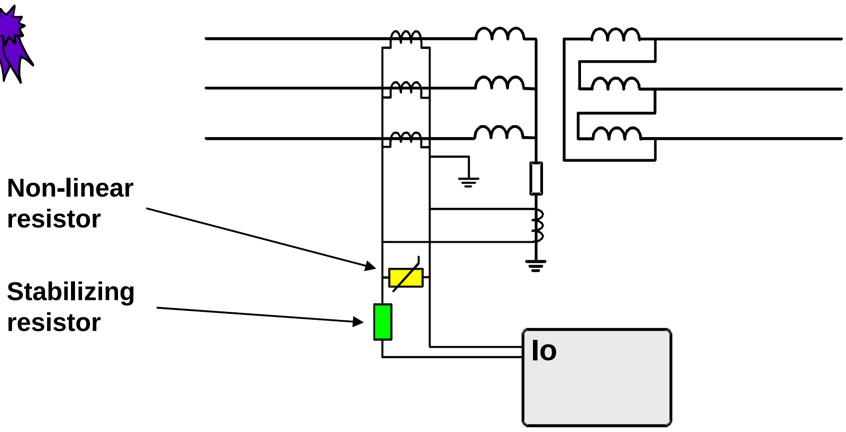


$I_d = |\Sigma I - I_0|$ $\quad I_b = \frac{|I_{L1}|+|I_{L2}|+|I_{L3}|}{3}$

E/F protection, High-Impedance Principle

- Known also as Restricted Earth Fault (REF) Principle
- Traditional and reliable protection
- High stability, even with partially saturated CTs
- External stabilizing and often non-linear resistor needed
- Trips only if the fault is inside the operation area

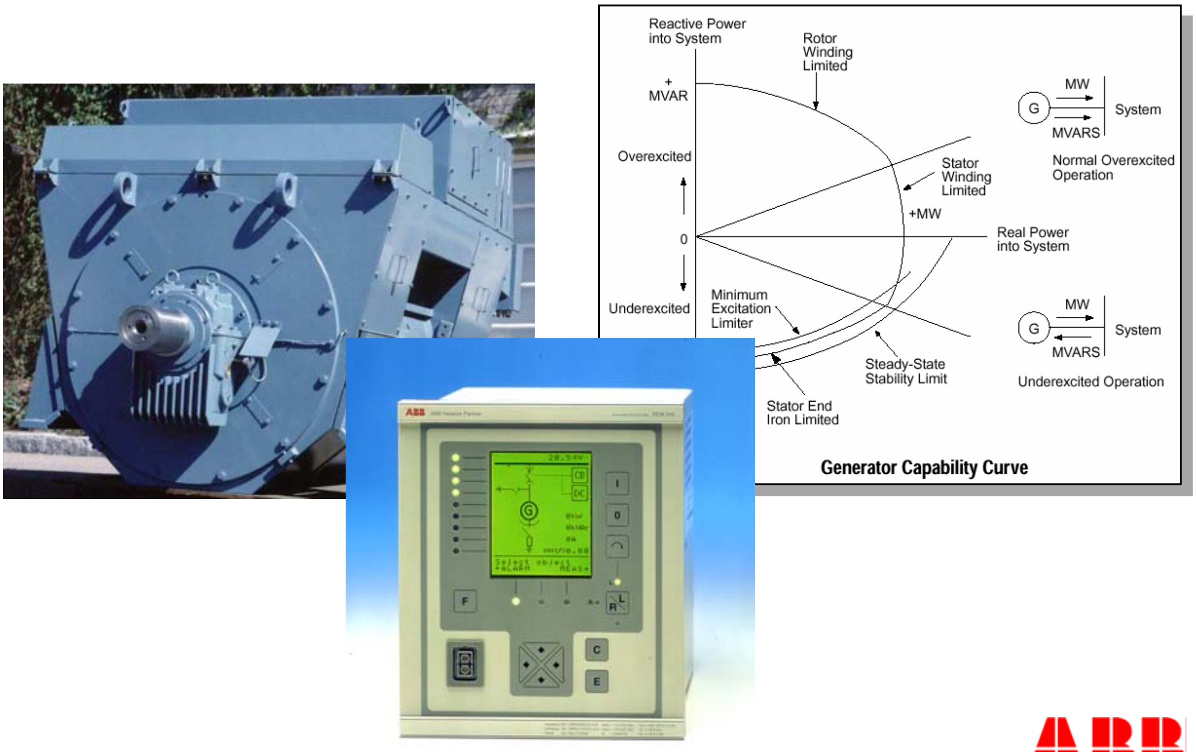




ABB

Contents of chapter 6

Generator protection



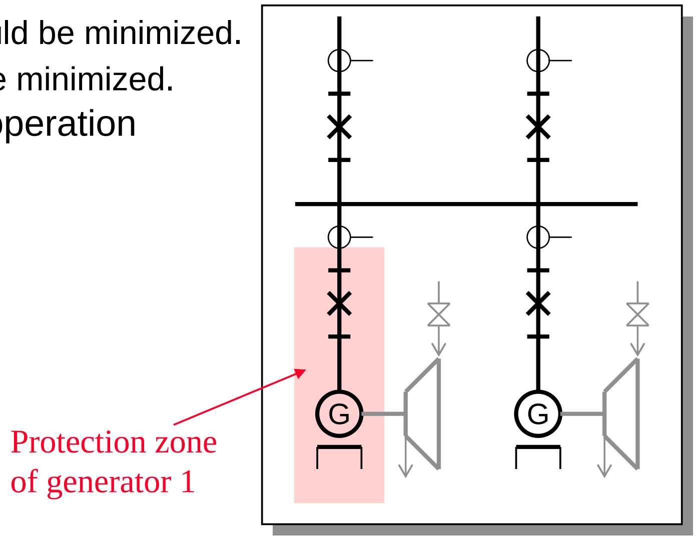
Part I

- Protection objectives
- Faults and failures

Objectives (1/2)

- Protection against faults inside of the protection zone
  - Effects in the fault location should be minimized.
  - Effects to the network should be minimized.

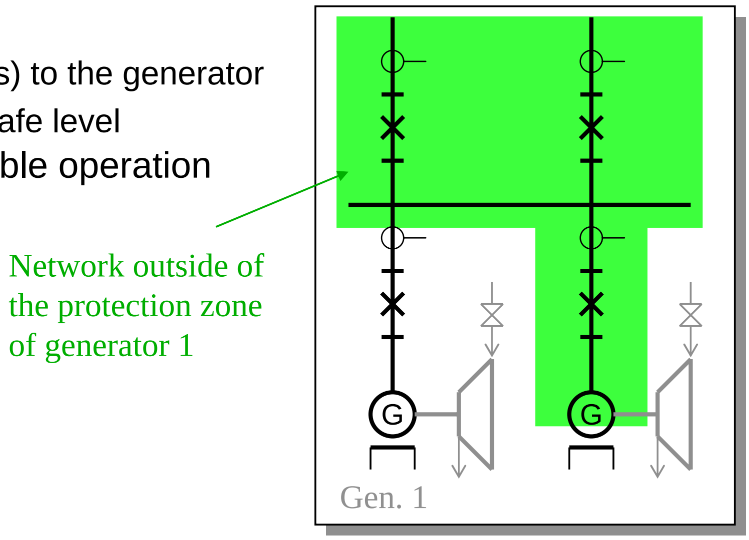
⇒ Fast, reliable and sensitive operation



Objectives (2/2)

- Protection against faults outside of the protection zone and against network disturbances
  - Limiting the effects (damages) to the generator and to the prime move to a safe level

⇒ Selective, stable and reliable operation



Faults and failures (1/5)

Inside faults and failures (1)

I Stator

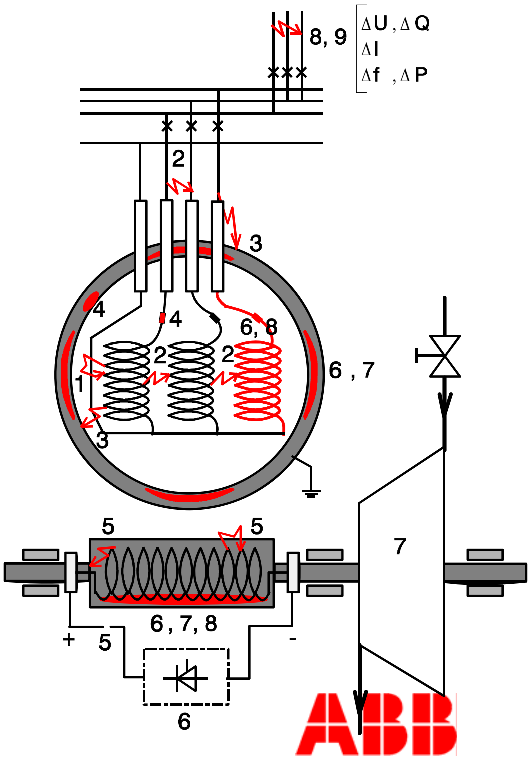
1. Interturn faults
2. Windings, short-circuits
3. Earth-faults
4. Local ‘hot spots’

II Rotor & excitation

5. Earth-faults, interturn faults, short-circuits, breaks

Objectives

- Minimized effects in fault location
- Disturbances to the network minimized
- **Fast and sensible operation**



Faults and failures (2/5)

Inside faults and failures (continued)

II Rotor & excitation

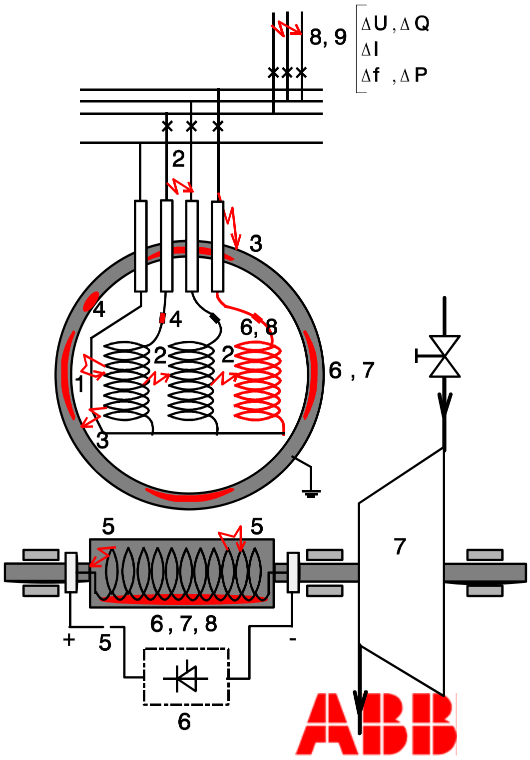
6. Over/under-excitation (causes over/under-voltage, thermal stress, loss-of-synchronism)

III Prime mover

7. Over/under-frequency, reverse power, out of step (causes mechanical and thermal stress to the generator and mover

Objectives

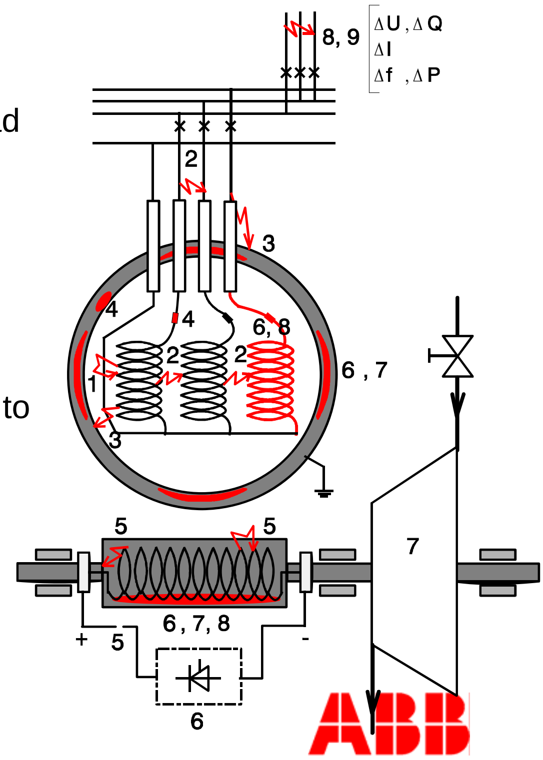
- Limiting the effects to the generator and network to a safe level.
- **Sensible and accurate operation**



Faults and failures (3/5)

Outside faults and failures

8. Short-circuits, earth-faults, unbalance, overload (causes thermal stress, out of step)
9. Disconnection of loads, generators or feeders from the network (causes over/under-frequency, over/under-voltage)



Objective

- Limiting the effects to the generator and network to a safe level.
- **Selective and stable operation**
- **Sensible and accurate operation**

Faults and failures (4/5)

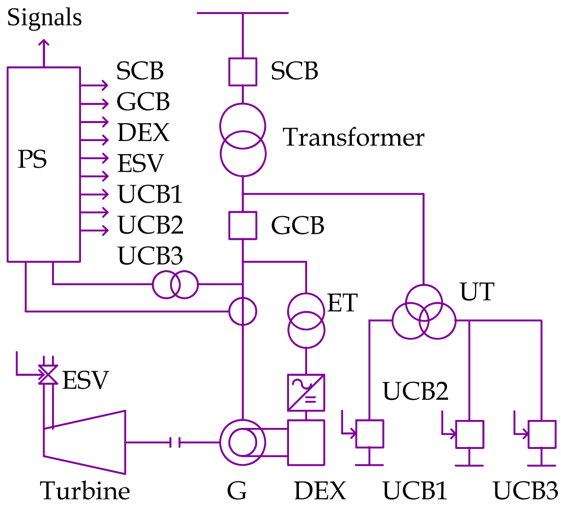
The trip of the circuit breaker is not enough in generator faults

- The prime mover (turbine) must be shut down
- Magnetization must be removed
- Other measures (CO_2 quenching gas, alarming etc.)

Faults and failures (5/5)

Allocation of tripping signals of generator / transformer unit

PS = Protection system
SCB = Power system circuit breaker
GCB = Generator circuit-breaker
DEX = De-excitation switch
ESV = Turbine emergency stop valve
UCB = Unit auxiliaries circuit breakers



Part II

- Operation principles and typical settings
  - Fault situations
  - Effects
  - Protection and typical settings

Short-circuit protection

Fault situations:

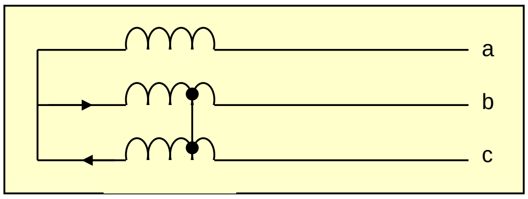
- Stator internal fault
- Stator external fault (for example in the machine terminals)
- Backup for the network short-circuit

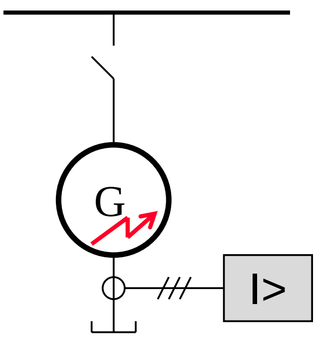
Effects:

- Runaway (especially in close-up short-circuits, the voltage collapses, generator cannot generate power to the network => speed increases rapidly)
- Loss of stability/mechanical stress when short-circuit is tripped => fast operation needed

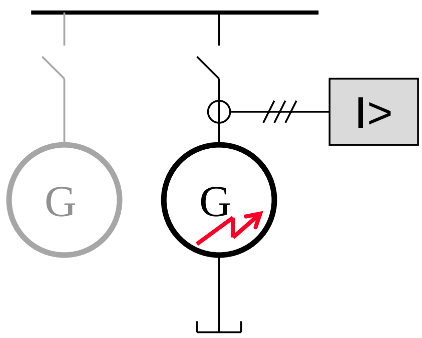
Short-circuit protection

Stator internal fault, does it matter where the CTs are located?





Protects at internal stator faults



Protects only if CB is closed and other generators or network feed fault current

Short-circuit protection

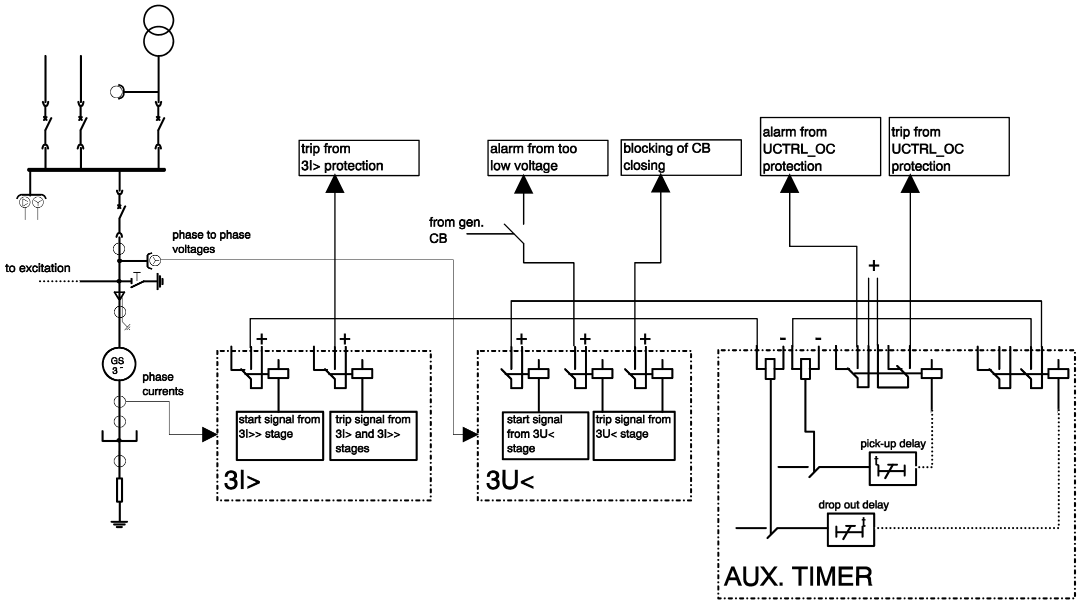
Terminal short-circuit protection, voltage controlled overcurrent protection:

- In the generator has high synchronous reactance (turbogen.) the short-circuit current can be less than the rated current.
- If the short-circuit occurs at or near machine terminals, the generator voltage and magnetization (rectifier magnetized) can also drop so much that the actual fault current can be less than the rated load current

- => Voltage controlled overcurrent protection:
  - normal voltage: relative high overcurrent setting
  - low voltage: low overcurrent setting

Short-circuit protection

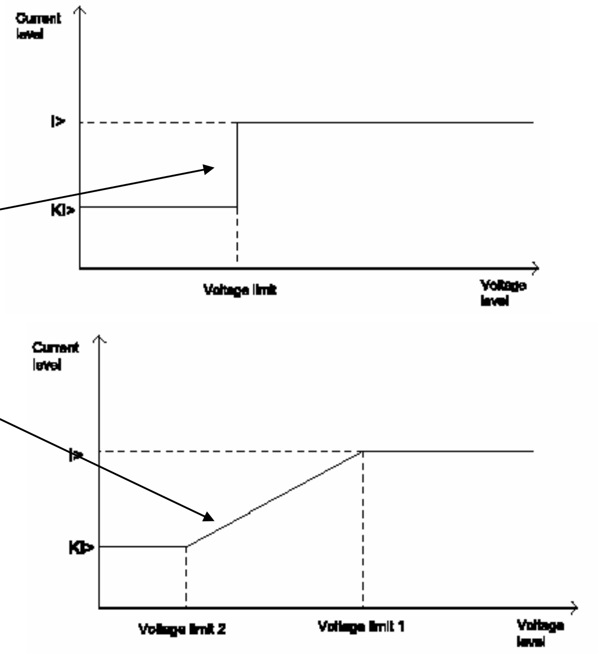
Terminal short-circuit protection, voltage controlled overcurrent protection, **old way**:

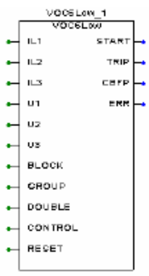


Short-circuit protection

Terminal short-circuit protection, voltage controlled overcurrent protection:

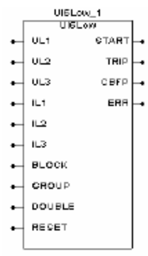
- VOC6Low/High function block
  - voltage step mode
  - voltage slope mode

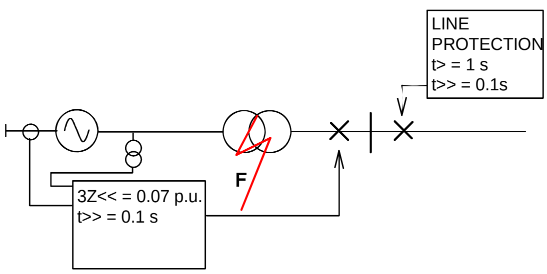


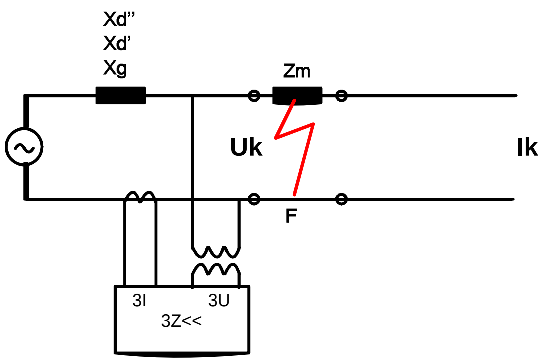


Short-circuit protection

Terminal short-circuit protection, under-impedance protection:







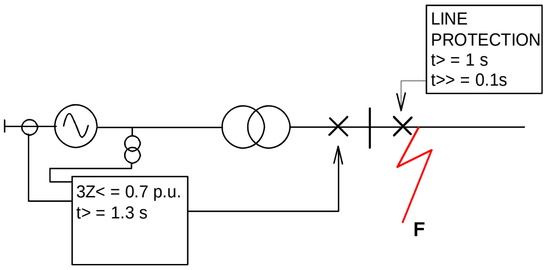
FAULT DATA

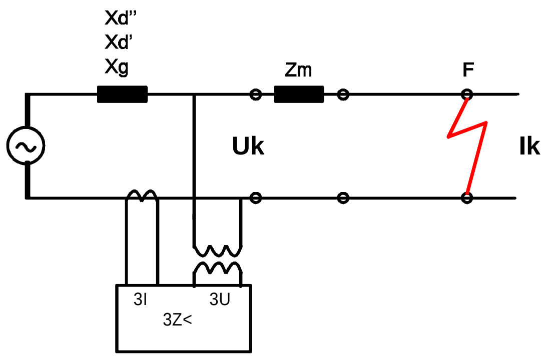
Z_{source} / Z_{load}	I_k / I_n	U_k / U_n	Z_{relay} / Z_{load}
0.19 (x_d'')	≈ 5.3	≈ 0.3	≈ 0.05
0.25 (x_d')	≈ 4.0	≈ 0.2	≈ 0.05
2.25 (x_g)	≈ 0.4	≈ 0.02	≈ 0.05 (*)
2.25 (x_g)	≈ 1.2	≈ 0.06	≈ 0.05 (**)

(*) without AVR
(**) with AVR

Short-circuit protection

Back-up protection for network, under-impedance protection:





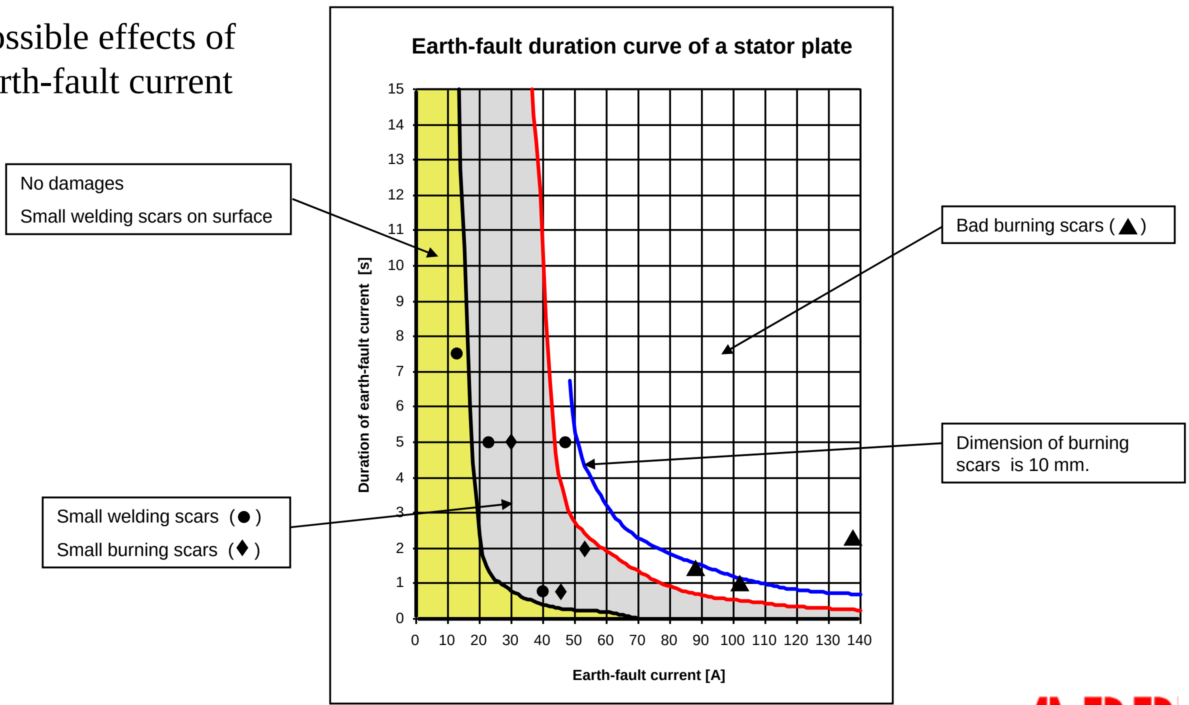
FAULT DATA

Z_{source} / Z_{load}	I_k / I_n	U_k / U_n	Z_{relay} / Z_{load}
0.24 (x_d'')	≈ 4.2	≈ 0.4	≈ 0.1
0.30 (x_d')	≈ 3.3	≈ 0.3	≈ 0.1
2.30 (x_g)	≈ 0.4	≈ 0.04	≈ 0.1 (*)
2.30 (x_g)	≈ 1.1	≈ 0.1	≈ 0.1 (**)

(*) without AVR
(**) with AVR

Stator earth-fault protection

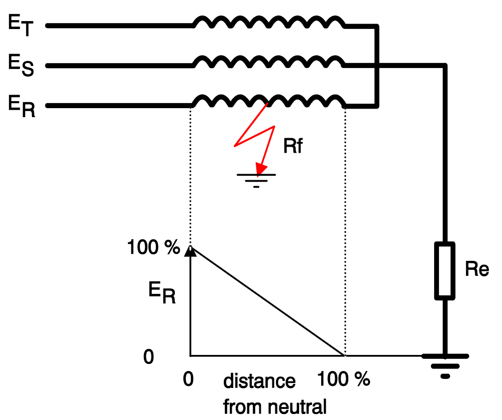
Possible effects of earth-fault current



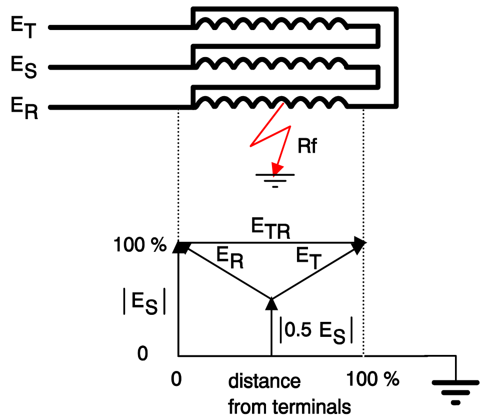
Stator earth-fault protection

Winding voltage against earth:

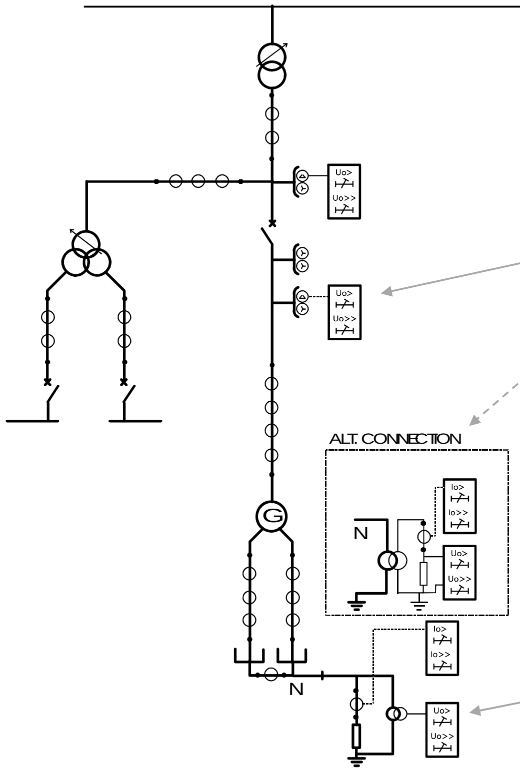
Y-winding:



D-winding:



90 % Stator earth-fault protection



Protection for a generator - transformer block:

- 2-stage residual voltage (Uo) protection

- Point of measuring the residual voltage:
  - Open delta of VT and/or start point VT
  - Alternatively from the secondary of aux.transformer

- For back-up a 2-stage Uo or Io protection

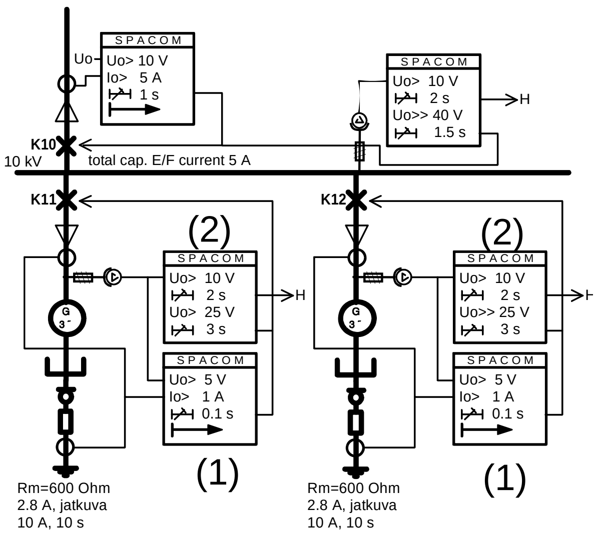
- Protection must operate also when gen.breaker is open → Uo protection at block-transformer side.

- ***Protection covers 90-95 % of stator winding***

90% Stator earth-fault protection

Protection for a bus bar coupled generator:

• Start points earthing with high resistance (Ief < 50 A)



- 2-stage Io differential protection with direction information **(1)**
- Io measured with core balanced CTs
- Protection operates also when the breaker is open or the (machines own) earthing resistor is out of use
- Back-up protection with 2-stage Uo protection **(2)** or Io protection (Io measured form the start point)
- Protection must operate also when the fault is on the bus bar → Uo-protection **(2)**

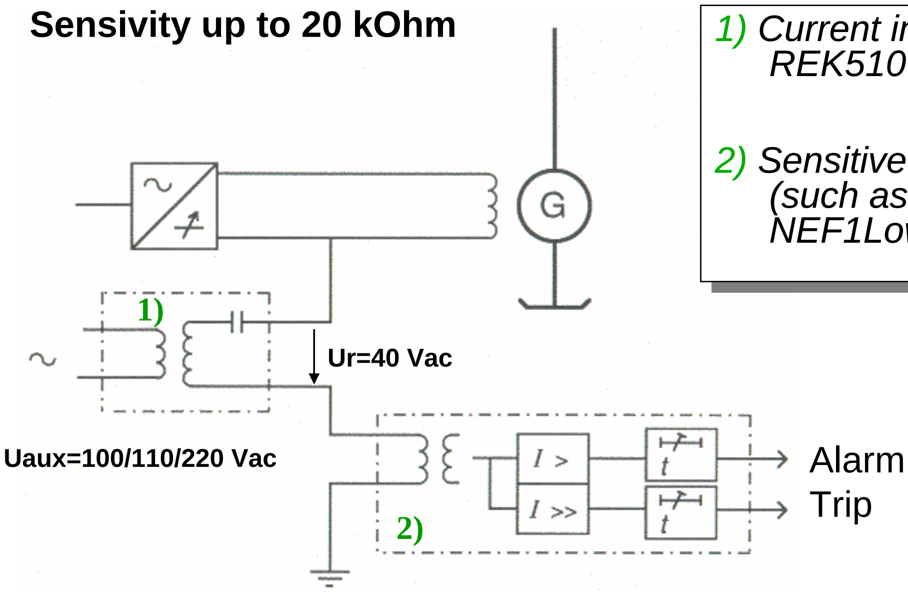
- ***Protection covers 90-95 % of stator winding***

Solution for rotor E/F protection (ansi code 64F)

Sensivity up to 20 kOhm

1) Current injection device REK510 or equivalent

2) Sensitive earth-fault protection (such as REJ 517 or NEF1Low&High function block



Reverse power

Fault situation: Generator takes active power from the network

- Fault of prime mover power-output (ex. fuel feed, steam flow, regulator fault etc.)
- Stopping of prime mover without of opening the main-breaker (I.e. the reverse power relay can be used and is used in normal shut-down to open the breaker.)
- Out of synchronism

Effects:

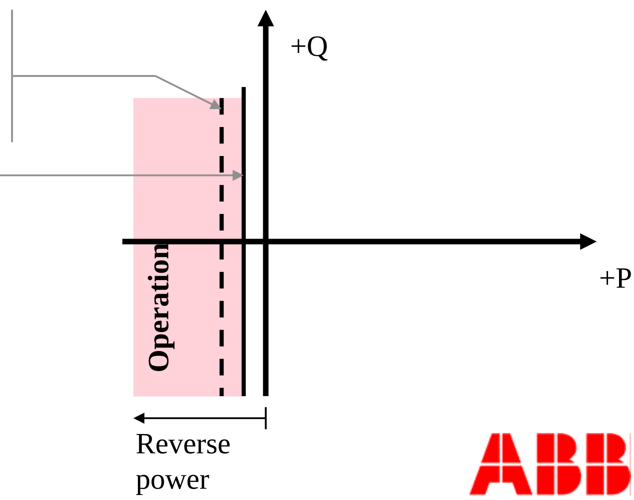
- Mechanical and thermal stress to the <u>prime mover</u>
- In case of out-of-synchronism: strong swinging of active and reactive power and terminal voltages => mechanical and thermal stress to the generator and to the prime mover.

Protection: to prevent damage mainly on the prime mover (turbine or engine)

Reverse power

Protection: (reserve power)

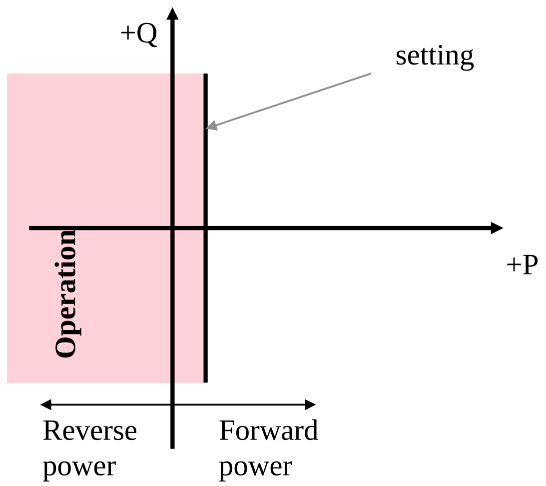
- The setting value depends on the losses of the primemover-gen. -unit
- Typical values of a primemover-gen. -unit running at rated speed (all power taken from the network).
    - Steam turbine 1-3 %
    - Diesel engine 25 %
    - Hydraulic turbine 3 %
    - Gas turbine 5 %
- For reliable operation the setting should be half of the presented value.



Reverse power

Protection: (minimum power)

- For the largest turbo-generators, where the reserve power may be substantially less than 1% a minimum power relay is obtained to trip the machine when the active power output is less than 1% of rated value.



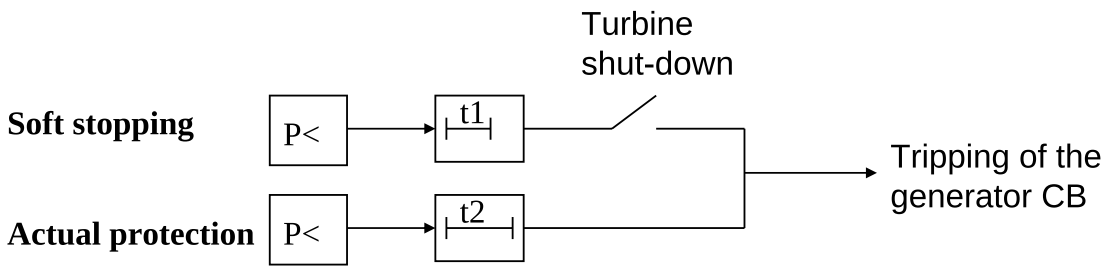
Reverse power

Protection:

- Reverse power protection with 2 (or 3) stages:
  - 1. stage: controlled “soft” stopping, the stage operates and opens the main and field breakers (prevents over-speeding)
    - Short operation time
  - 2. stage: is the actual protection(trip)
    - Operation time several seconds (depending on the prime mover)
  - 3. stage can use integrating time-relay that ensure the operation in case of asynchronous operation.
  - Short time reverse power situations occurs at synchronisation and network power swings => protection should not be too fast

Reverse power

- Controlled “soft” stopping: Turbine is shut-down, the kinetic energy is fed to the network, where after the breaker is tripped (t1) without danger of speeding the generator.



- If no shut-down has been carried out, the second stage (t2) trips the generator in a reverse power situation

Under-excitation

Fault situation: under-excitation or loss-of-excitation

- Short-circuited or broken excitation circuit (e.g. fault in slip rings)
- Opening of field-breaker, exciter fault
- High capacitive load

Effects:

- Rotor-iron heating by the eddy currents in rotor iron and dampers
- Under-voltage at the terminals because of increased reactive power
- Stator heating by the increased reactive current and magnetic flux
- Moving from synchronous to asynchronous operation (out-of-sync.):
  - Strong swinging of active and reactive power and terminal voltages
  - Disturbs the network and consumers
  - Thermal and mechanic stress

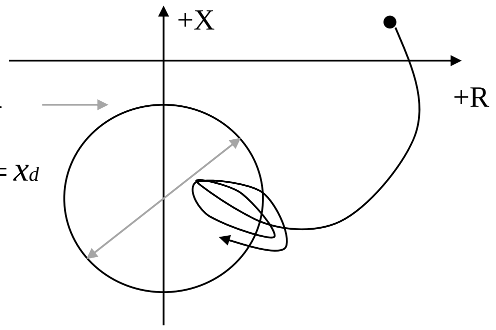
Under-excitation

Protection:

- 1- or 2-stage (alarm + trip) under-reactance protection (mho-relay)

$$Offset = \frac{x_d'}{2}$$

$$Diameter = x_d$$



x_d' = transient reactance
x_d = synchronous reactance

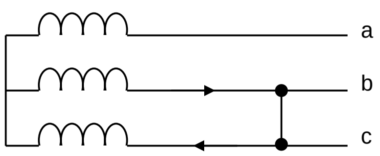
- 1- or 2-stage over-current protection based on the magnitude and direction of reactive current (alarm + trip).

Unbalance / Negative phase-seq. current

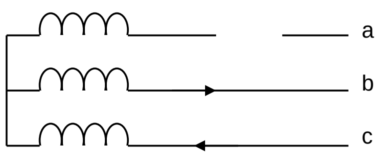
Fault situation: asymmetric load in stator

- Asymmetric fault (2-phase short-circuit or earth-fault)
- Incomplete (1 or 2-phase) operation of circuit breaker or disconnecting switch
- Asymmetric loads (1-phase loads, 3-phase asymmetric loads)

line-to-line fault



broken phase condition



Unbalance / Negative phase-seq. current

Effects :

- Negative phase sequence (NPS) in stator current (I_2)
- Eddy currents in rotor iron and dampers → dangerous rotor heating (additional losses by negative phase sequence current $(I_2)^2$ x t
- Vibration, mechanical stress

Protection:

- 1 or 2-stage negative phase-sequence current protection (alarm + trip)
- Allowed continuous NPS tolerance must be known (Typically 8..12% with turbogenerator and 20..30% with salient pole machine)
- Typical short time tolerance $(I_2)^2$ x t
    - Turbine-generator 30 sec.
    - Hydraulic generator 40 sec.
    - Diesel generator 40 sec.
    - Rotating compensator 30 sec.

Over- and under-voltage

Fault situation: Stator over- or under-voltage

- Fault in voltage regulator
- Under-excitation or loss-of-excitation → under-voltage
- Too high inductive or capacitive load because of a trip of load / generator / transmission network
- Trip of main breaker with full load and possible over-speeding (over-voltage)

Effects:

- Stress caused to the insulator material by over-voltage
- Thermal stress of iron core by over-magnetising (over-voltage)
    - Increasing of magnetic flux density: $B = k * (E/f)$
    - Saturation of iron core
    - Increasing of leakage flux and spreading of flux to unlaminated parts
- Stator overload because of sudden diminution of the network (inductive overload → under-voltage)

Over- and under-voltage

Protection:

- Over-voltage protection with two stages:
  - 1. Stage: definite time, setting according the voltage tolerance of the machine
  - 2. Stage: definite time (fast operation), prevents instant damages to the insulator material and damaging over-magnetising of iron core

  - Typical settings:

1. stage:	1.10 x Un, tolerance of the machine ± 5 %
	1.13 x Un, tolerance of the machine ± 7.5 %
	1.15 x Un, tolerance of the machine ± 10 %
	operation time 5 - 10 s
2. stage:	1.3-1.4 x Un
	operation time 0.1 s

Over- or under-frequency

Fault situation:

- Sudden changes of load. E.g. loosing the connection to main grid (infinite system) → underfreq. or sudden tripping of large load → overfreq.
- Fault if power control or prime mover while operating in island
- During starting and stopping the generator

Effects:

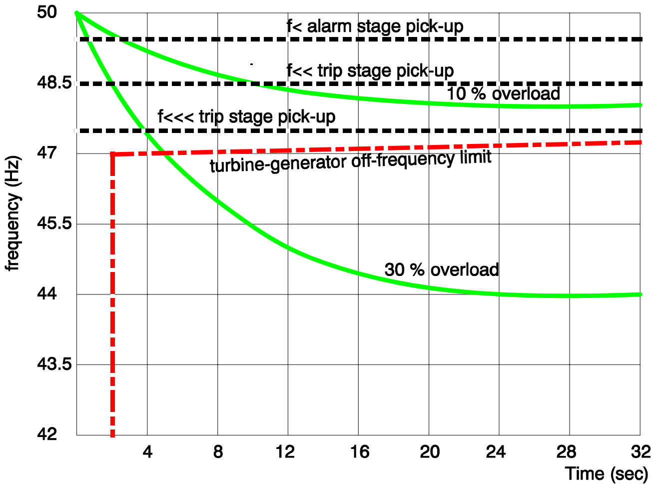
- Mechanical and thermal stress to the prime mover (over/under-freq.)
- Thermal stress to the iron core by the over-magnetising (undrefreq.)
  - Increasing of magnetic flux density: **B = k * (E/f)**
  - Saturation of iron core
  - Increasing of leakage flux and spreading of flux to unlaminated parts

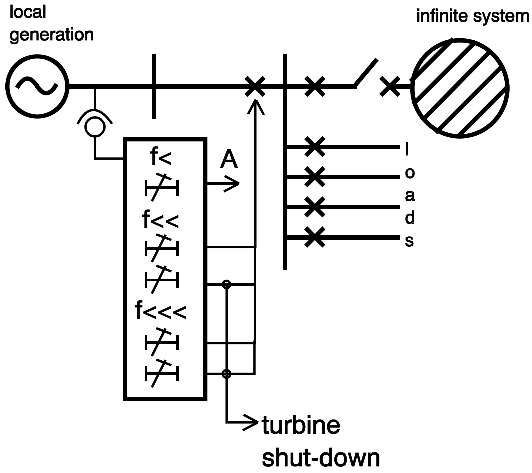
Protection:

- 2-stage over-frequency protection (alarm + trip)
- 2- or 3-stage under-frequency protection (alarm + 2 x trip)

Over- or under-frequency

Example of under-frequency protection: df/dt when connection to main grid is lost.
Supposition is 10-30 % power loss in the worst case:





Over-magnetising

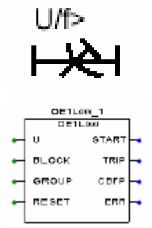
Fault situation: increased U/f -ratio

- Increasing of voltages and / or decreasing of frequency

Effects:

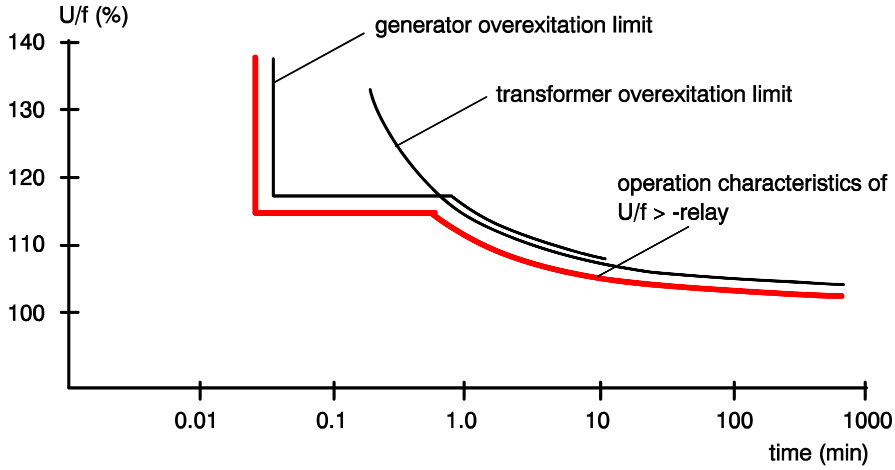
- Thermal stress to the iron core by the over-magnetising (overvoltage.)
  - Increasing of magnetic flux density: **B = k * (E/f)**
  - Saturation of iron core
  - Increasing of leakage flux and spreading of flux to unlaminated parts

Over-magnetising



•Protection:

- 2-stage protection based on U/f -ratio.



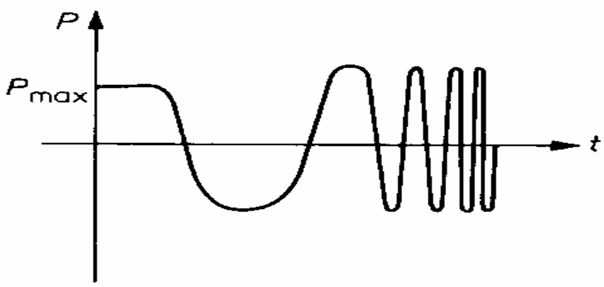
Asynchronous operation

Fault situation: Generator set out of synchronous operation

- Under-excitation
- Fault in the network
- Incorrect phase order when switching in

Effects:

- Strong swinging of active- and reactive power and terminal voltages
  - Rotor-iron heating by the eddy currents in rotor iron and dampers
  - Stator heating because of the increased current and magnetic flux
  - Mechanical and thermal stress to the generator and prime mover



Asynchronous operation

•**Protection:**

- A completion of reverse power and under-excitation protections with integrating time relay
- An out-of-synchronism protection for big machines

Voltage-unbalance = Fuse-fail function

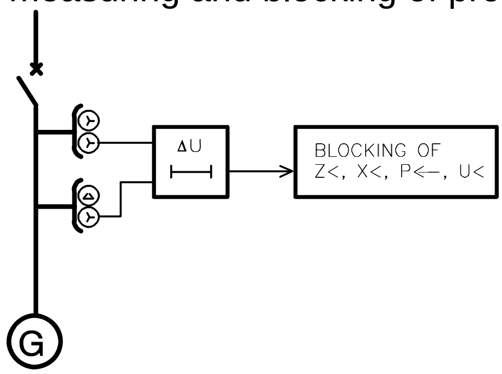
Fault situation: Meas.voltage for the protection disappears (Z<, X<, P<-, U<)

- Fuse blow or opening of MCB in the measuring circuit
- VT fault

Effect: Protection functions can operate (without real primary fault)

Protection: fuse failure protection

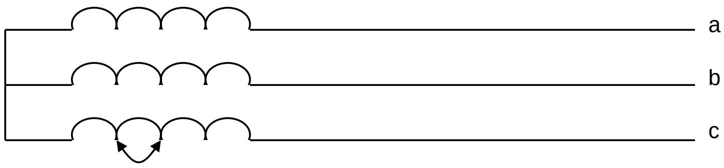
- Voltage-unbalance measuring and blocking of protection functions



Stator interturn protection

Fault situation:

- An insulation injury between different turns of the same phase



Effects:

- Local overheating of the winding, which may result in severe damage

Protection:

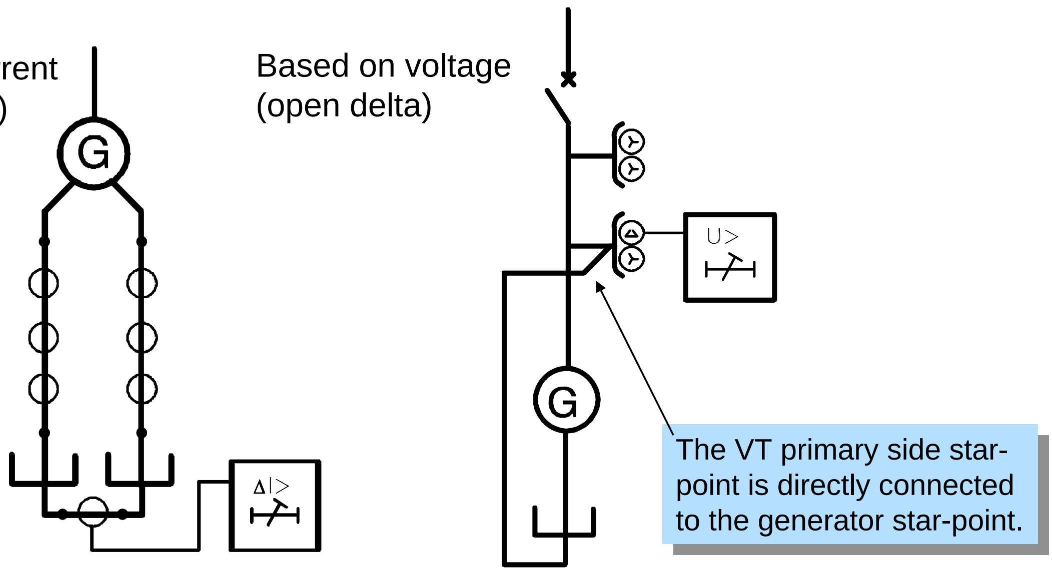
- Protection is required if two or more turns of the same phase winding are located in the same winding slot.

Stator interturn protection

Protection:

Based on current
(split winding)

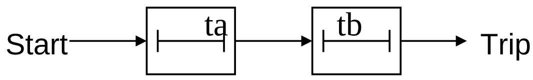
Based on voltage
(open delta)



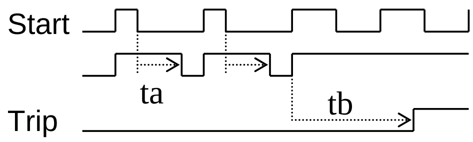
Integrating time relay

In cases where the measured variable (e.g. reactance, reverse power) swing in to and out from the operation area (i.e. the protection starts and resets periodically) the relay might not trip.

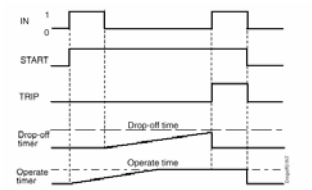
- Solution 1: Time relays



ta = drop-out delay
tb = pick-up delay



- Solution 2: Drop-off time (e.g. REM -relay)

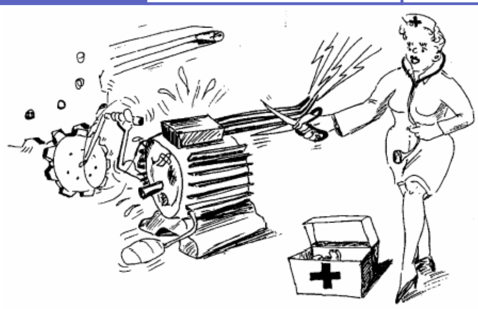


Chapter 7

Motor protection

ABB Oy, Distribution Automation
Vaasa, Finland

AC Motor Protection
(3-phase induction and synchronous motors)



ABB

Contents

ABB

Part 0

AC Motors

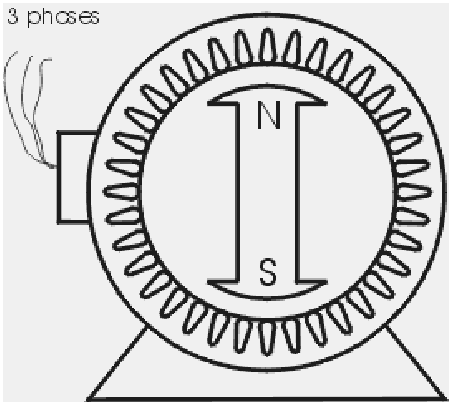
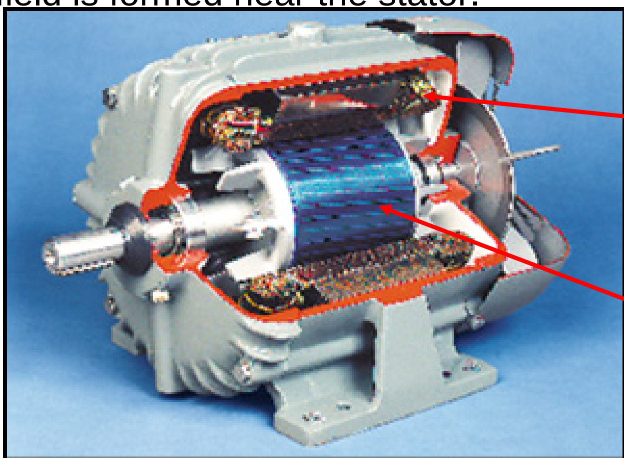


Image from Machine Elements in Mechanical Design, Robert L. Mott

Induction AC motor

There are only two main components: the *stator* and the *rotor*. The stator contains a pattern of copper coils arranged in windings. As alternating current is passed through the windings, a moving magnetic field is formed near the stator.



AC induction motors incorporate a myriad of design details. Among these are the rotor assembly (center) precisely balanced against vibration, special coatings to protect the windings, precision ball bearings, and cooling fan (far right), depending on the model. (Photo courtesy of Lincoln Motors, Cleveland, O.)

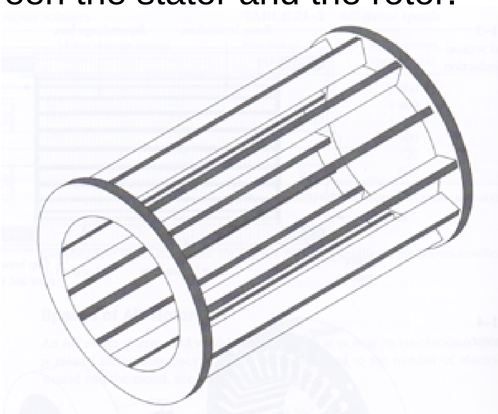
Stator
(stationary part)

Rotor
(rotating part)

Induction AC motor

The rotor is constructed of a number of conducting bars running parallel to the axis of the motor and two conducting rings on the ends. The assembly resembles a squirrel cage, thus this type of motor is often called a squirrel-cage motor.

Magnetic field formed by the stator induces a current in the rotor, creating its own magnetic field. The interaction of these fields produces a torque on the rotor. Note that there is no direct electrical connection between the stator and the rotor.



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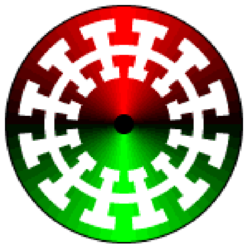
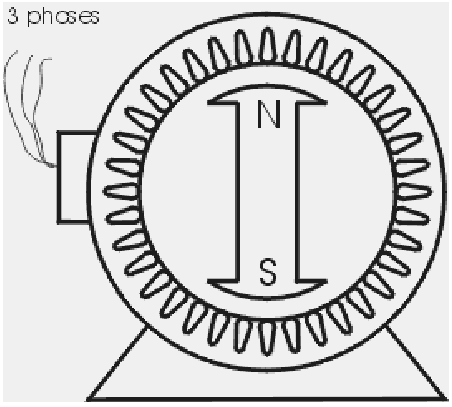


Animation © Motorola, Inc.

Synchronous AC motor

The synchronous motor operates at exactly synchronous speed with no slip. The rotor is of a constant polarity (either a permanent magnet or an energized electromagnet) and the windings of the stator are wrapped in such a way as to produce a rotating magnetic field. Such motors provide very little torque at zero speed, and thus need some kind of separate starting apparatus. Often a squirrel-cage rotor is built into the main rotor. When the motor reaches a few percent of synchronous speed, the rotor is energized and the squirrel cage becomes ineffective.



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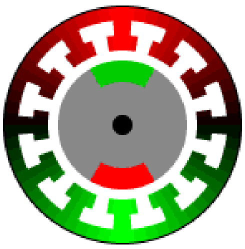
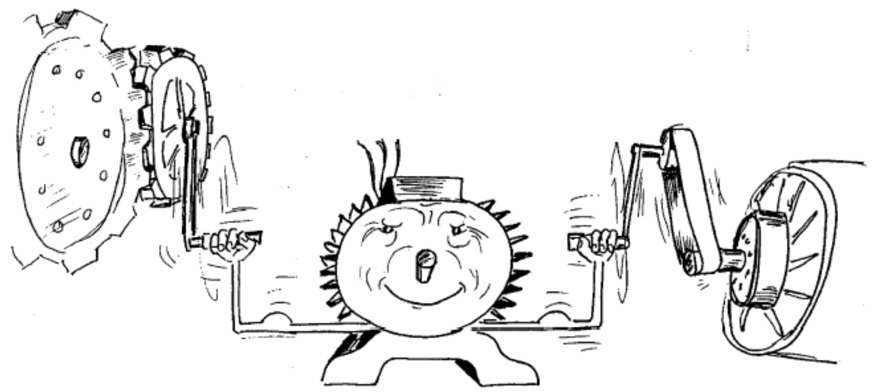


Animation © Motorola, Inc.

Part 1

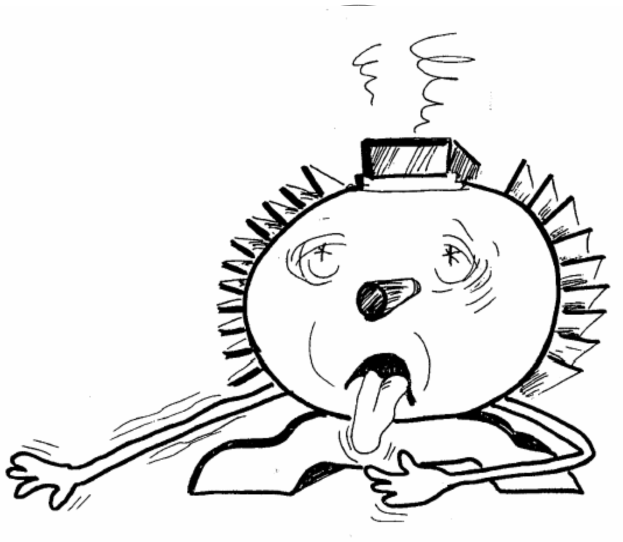
Introduction



Protection objectives

- Protection must be able to operate for abnormal conditions
  - Internal faults
    - Insulation failure (e.g. winding short-circuits, earth-faults)
    - Bearing failure
    - Under-magnetisation (synchronous motors)
  - Externally imposed faults
    - Overload, insufficient cooling
    - Start-up stress, reversed sequence starting
    - Supply voltage unbalance or single phasing
    - Over- and undervoltage
    - Vibration
    - Etc.

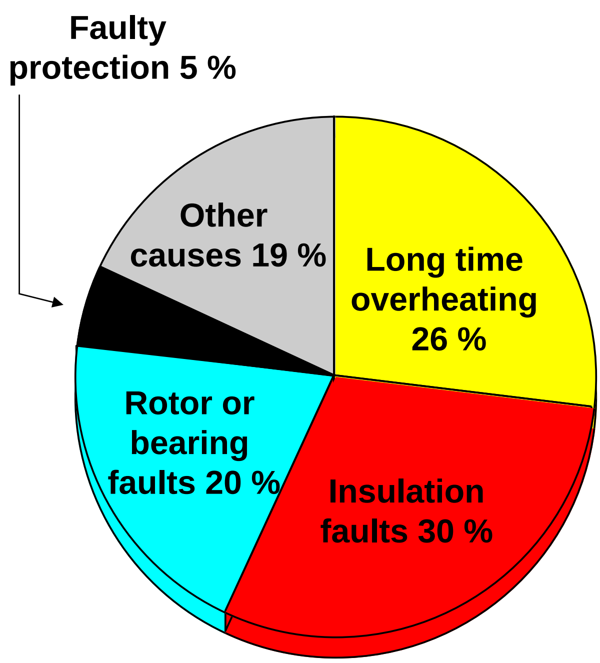
Causes for motor damages in industrial drives



- Long time overheating 26 %
- Insulation faults 30 %
- Rotor or bearing faults 20 %
- Faulty protection 5 %
- Other causes 19 %

ABB

Protective functions needed



- Thermal overload protection
- Short-circuit and earth-fault protection
- Start-up supervision and thermal sensor (RTD) unit
- Continuous self-testing of the protection relay
- Other protective functions

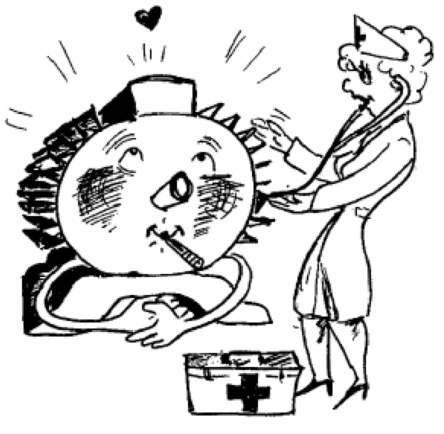
ABB

Motor Protection Relays

REM 610

REF/REM 54x

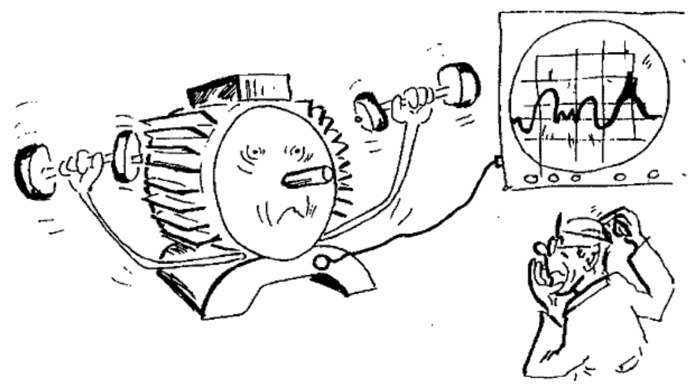
SPAM 150C



REX 521- H07

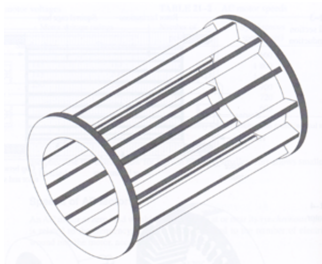
Definitions

- Cold motor ⇔ rated ambient temperature (40°C)
- Hot (warm) motor ⇔ rated operating temperature



Definitions

- Hot spots ⇔ at high current levels (during start-up and overload) the rate of temperature rise is high and in a short time only part of the heat is transmitted from the winding and rotor rods to the stator/rotor iron
  - End of stator windings
  - Joints of the rotor rods and conducting rings

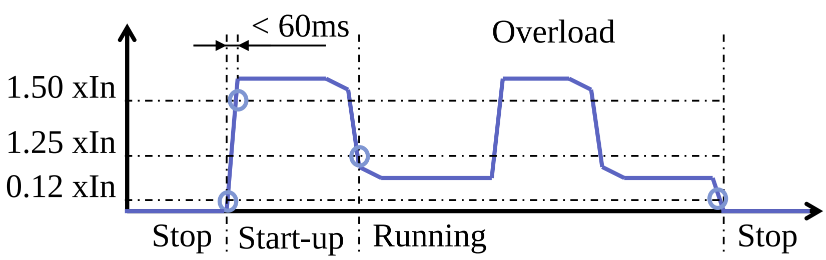


How Stop/Start-up/Run conditions are defined

Stop = All phase currents are below 0.12 x I_N.

Start-up = The phase currents rise from a value below 0.12 x I_N to a value exceeding 1.5 x I_N in less than 60 ms. The starting situation ends when the currents fall below 1.25 x I_N (more than 100 ms).

Run = The phase currents are over 0.12 x I_N and the start condition is not active.



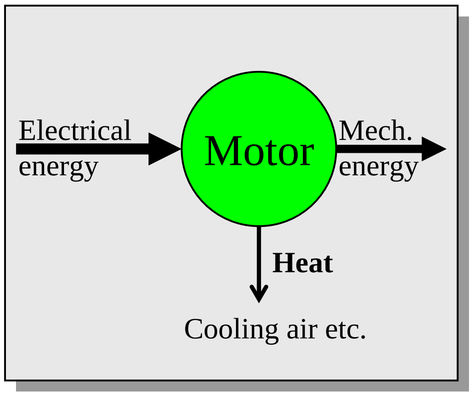
Check the exact values from the relay manual

Part 2

Thermal Protection

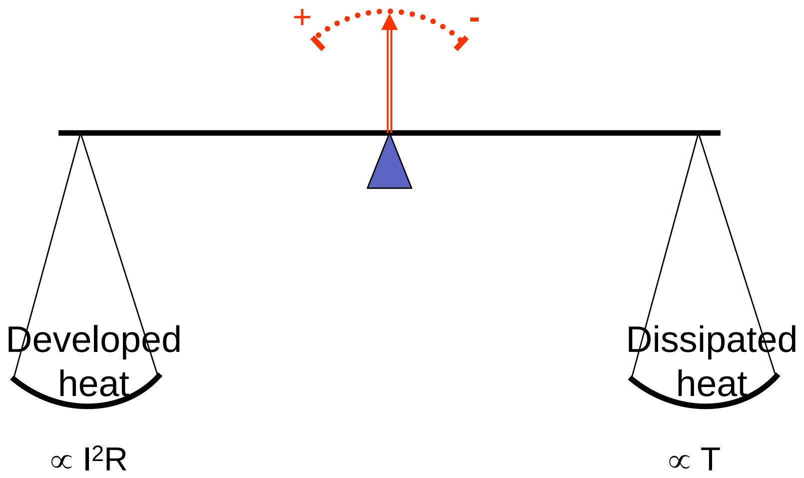
Motor Thermal Behaviour

- Heat is developed at a constant rate due to the current flow
  - Light load => low current => small heat development
  - Rated => rated current => adequate heat development
  - Overload => high current => high heat development



Motor Thermal Behaviour

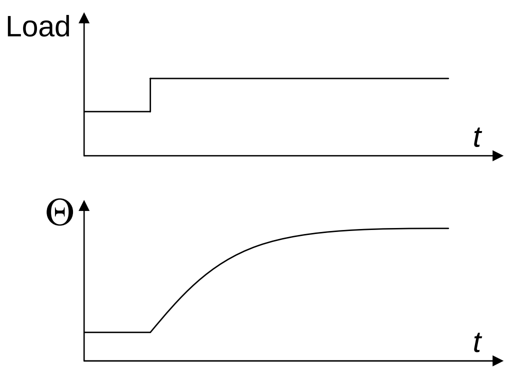
- Heat dissipation rate is proportional to the motor temperature
  - The higher the motor temperature is the faster heat is dissipated
- Motor temperature will increase or decrease until the developed heat and the dissipated heat are in balance



Motor Thermal Behaviour

- Heating follows an exponential curve
  - Rate of temperature rise depends on motor thermal time constant τ and is proportional to square of current

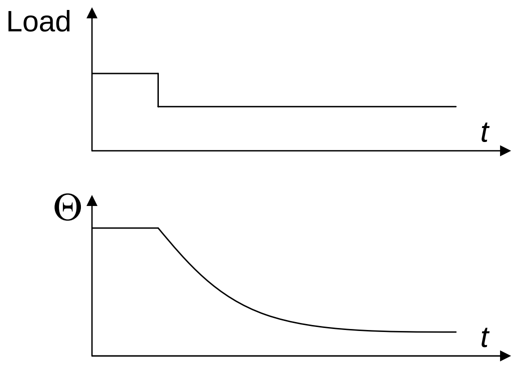
$$\Theta \approx K \times \left(\frac{I}{I_{FLC}}\right)^2 \times \left(1 - e^{-t/\tau}\right)$$



K	= constant
e	= 2.7183 (Neper)
t	= time
τ	= time constant
I	= highest phase current
I_{FLC}	= Full Load Current

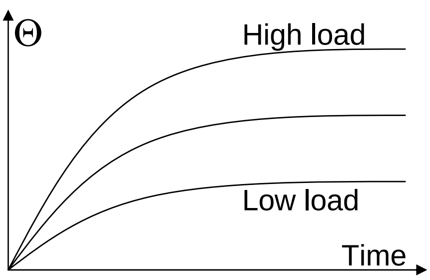
Motor Thermal Behaviour

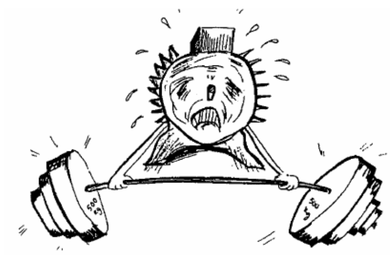
- Cooling also follows an exponential curve
  - Rate of temperature drop depends on cooling time constant. (Can be different when the motor is stopped.)



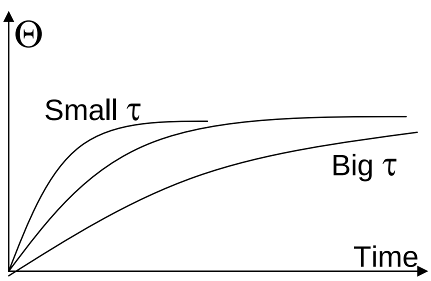
Motor Thermal Behaviour

- Heating with different loads





- Heating with different time constants

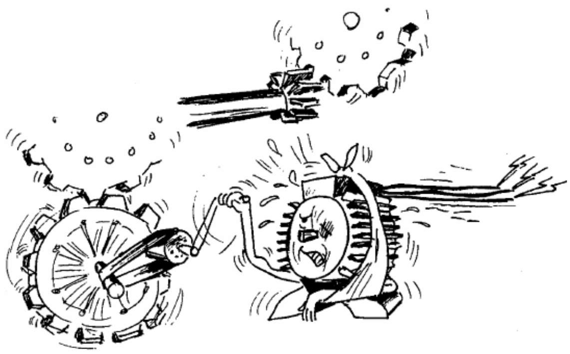


"Thermal" Protections

- Thermal overload protection
  - Keeps track of the thermal load
  - Settings are often based on the number of allowed **hot starts**
- Cumulative start-up counter
  - Limits the number of consecutive (**cold**) **starts**
- Start-up supervision
  - Protection against locked rotor & prolonged start-up time
  - Settings based on a **single start-up**, no memory from the history
- Temperature protection with RTD sensors
  - Direct temperature measurement from the stator, bearings etc.

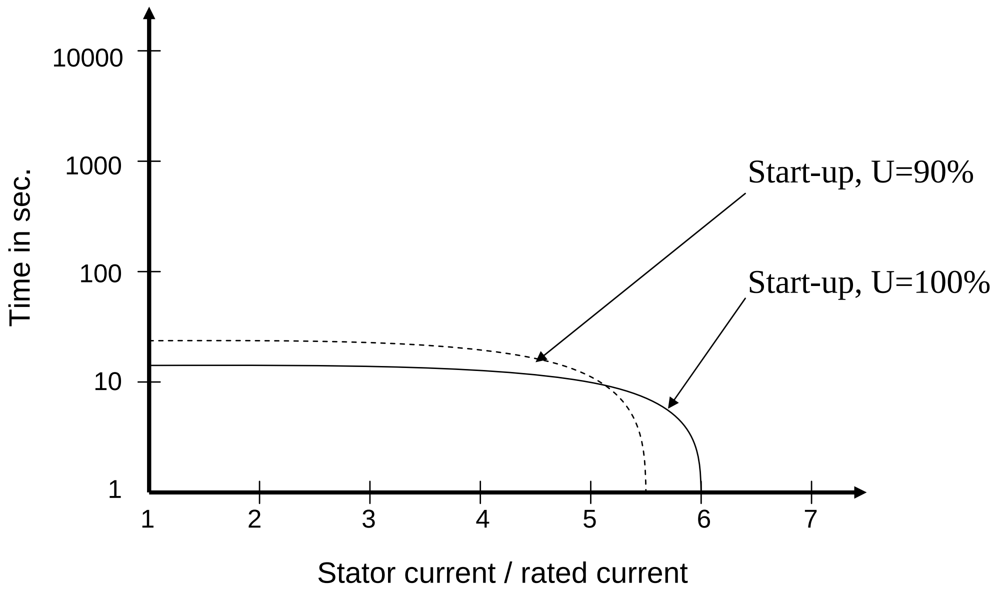
Part 3.0

Thermal Overload Protection



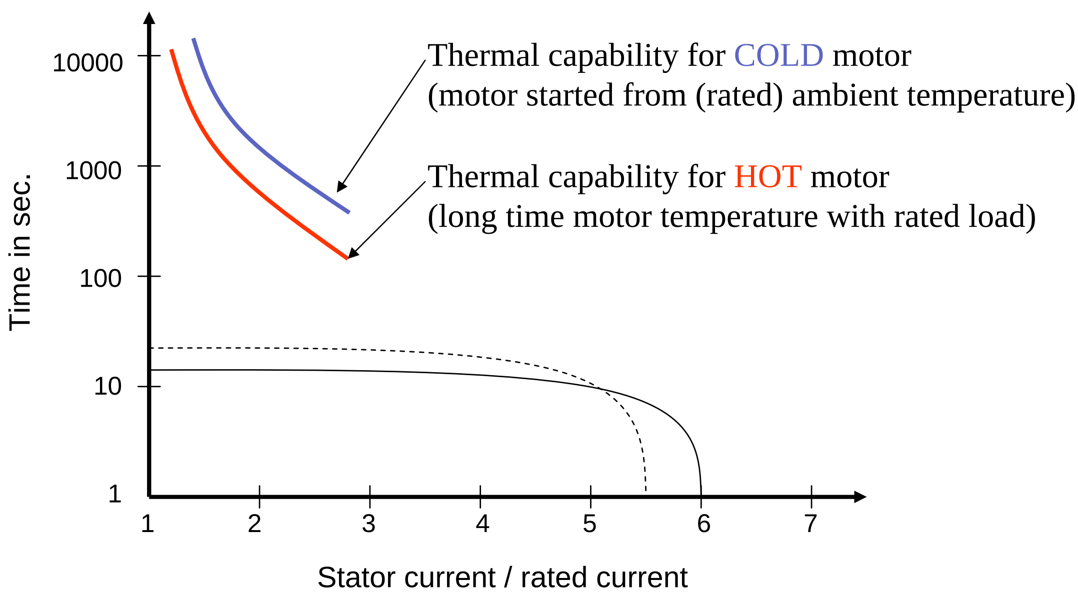
Time - current curves

- Motor start-up curves



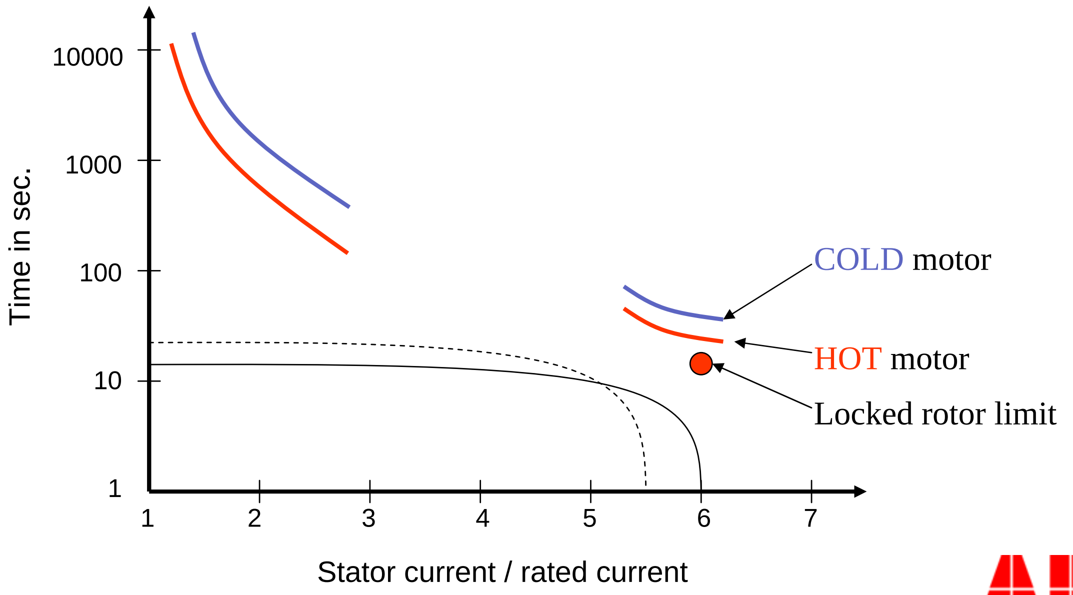
Thermal withstand curves

- Thermal capability, running

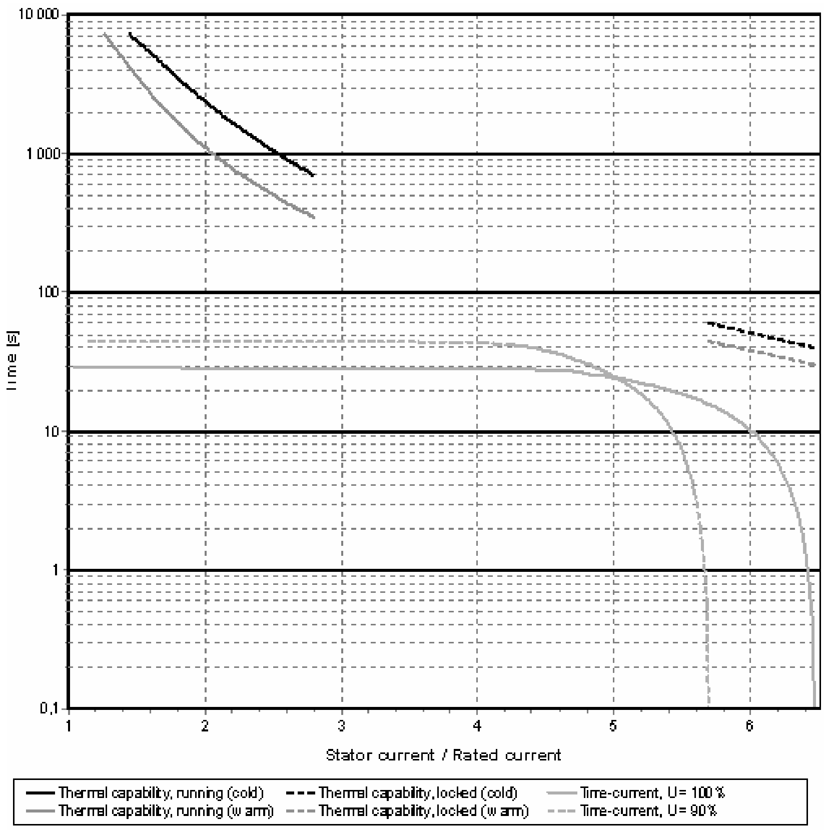


Thermal withstand curves

- Thermal capability, accelerating/locked rotor
- Permissible locked rotor time



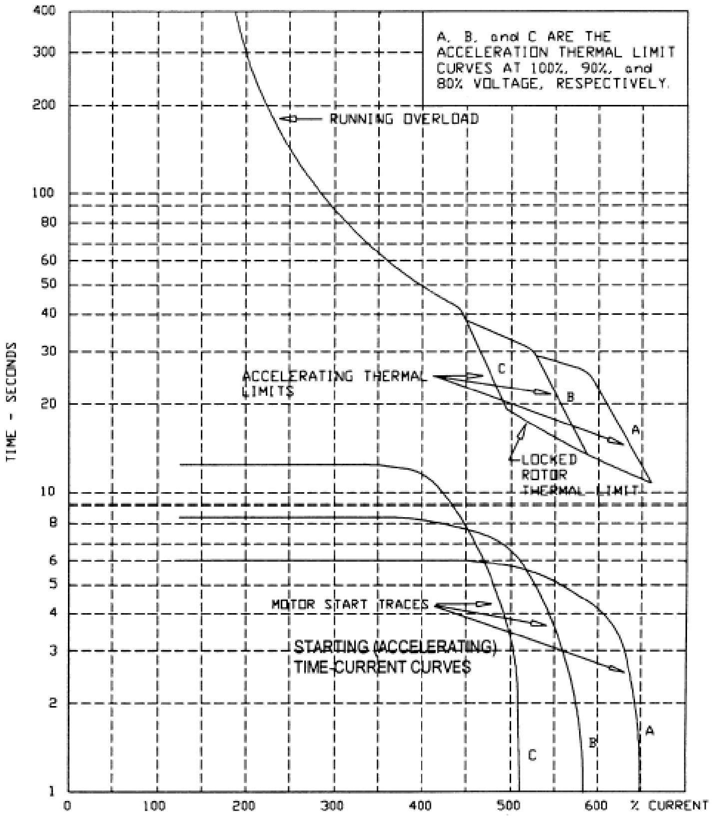
Example 1



Squirrel cage motor HXR 500

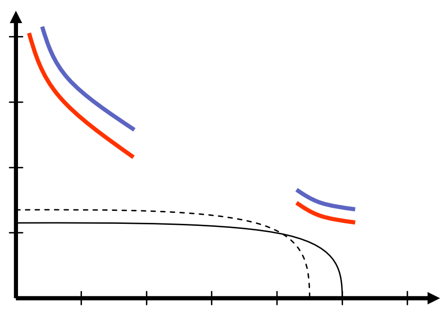
- 900 kW
- 3 kV
- 200 A
- 1492 rpm

Example 2



Protection consideration

- Relay should operate
  - Before the thermal capability limits are exceeded
  - Before the permissible locked rotor time (if motor is not rotating)
- Relay should not operate
  - At normal start-up conditions

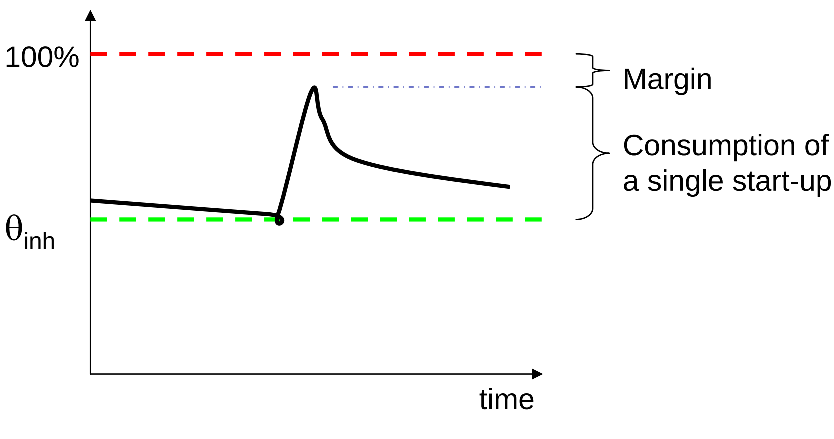


Protection consideration

- However, the setting is often calculated to
  - Allow certain number of consequent starts
- Cooling factor
  - At motor standstill the fan in the motor shaft is not rotating
  - Typically cooling is 4 - 6 x slower
  - With external cooling (like water cooling) the factor can be 1 - 2.

Restart Inhibition level

- Prevents restart if the temperature is too high
  - without inhibition the relay would trip at next start-up
- Setting (θ_{inh})
  - 100% - “consumption of one start-up” - margin



Restart Inhibition level

- Consumption of a single start can can be calculated, if the operation time for a cold motor with start-up current is known

$$consumption = \frac{\textbf{start} - \textbf{up} \;\; \textbf{time}}{\textbf{trip time}} \times \textbf{100\%}$$

Restart Inhibition level

- Exercise 1, propose a suitable setting for restart inhibition
  - Thermal level before start-up was 15% and immediately after 60%

- Exercise 2, propose a suitable setting for restart inhibition
  - Start-up time = 7.5 sec
  - Trip time = 22 sec

Prior alarm level

- Setting considerations
  - Should be higher than the thermal level of the motor which has been running for a long time with full load
  - Should give enough time to reduce the load
  - Generally, prior alarm level is set to 80 .. 95 % of the trip level
- Undesirable alarms?
  - At motor restart (compare alarm level to restart-inhibit margin)
  - At relay power-on
    - Relay has no memory of the situation before power-off, therefore a hot (warm) motor condition is assumed. For example SPAM 150C begins from 74% after power-on.

Part 3.1

Thermal Overload Protection

REM 610 & SPAM 150

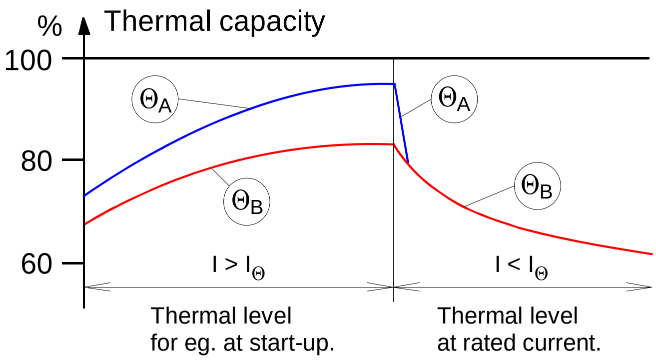
Thermal Overload Protection

- Thermal model of one time constant (t_{6x})
- Conventional operation mode (p = 100%)
  - Transformers, soft-starters
  - At a nominal load (FLC) the temperature will eventually rise up to 95% of the trip temperature

  ⇒ Restart is possible only if
    - start-up current (I.e. thermal stress at start-up) is small
    - after sufficient (long) cooling time

Thermal Overload Protection

- “Hot-spot” operation mode (p=50%)
  - Motors with Direct-On-Line (DOL) starts
  - At start-up or any overload situation the relay follows the temperature of the “hot spots”.
  - After start-up or overload the temperatures inside the motor will level out. Relay simulates this by “remembering only 50% of the thermal rise during the start-up/overload”

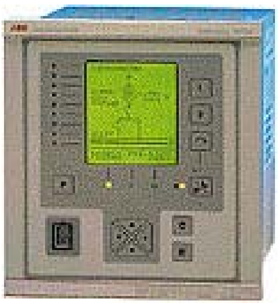


Part 3.2

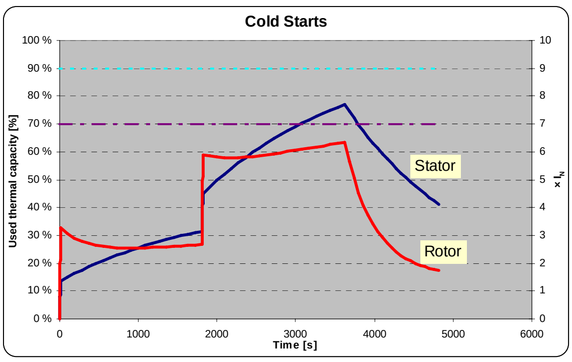
Thermal Overload Protection

REM 54_ & REX

(TOL3Dev function block)



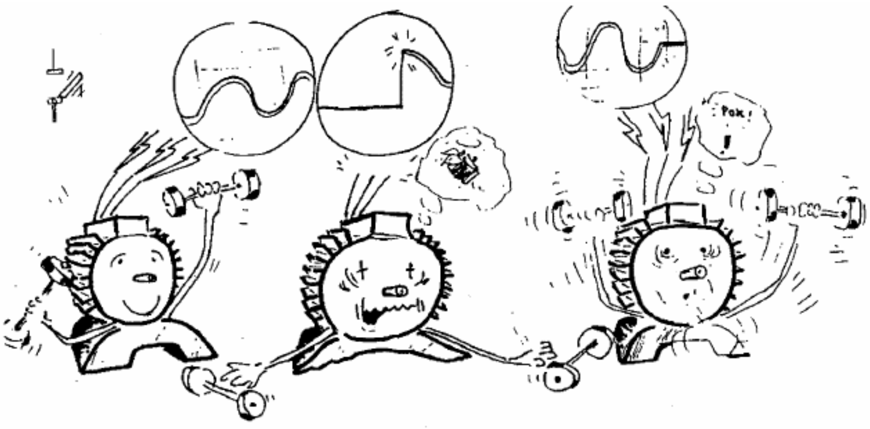
Thermal Overload Protection



- Thermal model of two time constant for both stator and rotor
- Thermal curves ready for 4 type of motors, 2 type of generators and one transformer
- Current in p.u. values (scaling factor must be set correctly!)
- Basic (“motor data”) and Advanced settings (“real settings”)
  - Advanced settings is automatically re-calculated by the relay whenever Basic settings has been changed

Part 4

Consecutive Starts



Cumulative start-up counter

- General
  - Supplementary & Backup protection to the thermal overload
  - Limits the number of consecutive starts ⇒ protection against cumulative thermal stress caused by the starts

  - Does not Trip but inhibits restarting!

Cumulative start-up counter

- Number of consecutive starts?
  - Typically 2 cold / 1hot (or 3 cold / 2 hot) starts within an hour
  - Typically 10 min cooling time after previous start/running before restarting.
    - Check the motor manufacturer data, there can be surprises

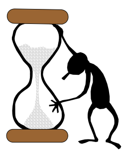
NUMBER CONSECUTIVE STARTS (Cold / Hot) *Numero de arranques consecutivos (Frio / Caliente)*	No.	2 / 1
MAX. STARTING FREQUENCY // warm condition *Frecuencia máxima de arranques // condición caliente*	No. / h	max. 1,5 (every 40 min. after restart and running) Max. 1,5 (cada 40 min. despues rearranque y servicio)

  - Sometimes the process / devices connected to the motor limits the number of starts or set requirements for the minimum standstill-time
    - speed reduction gear
    - etc

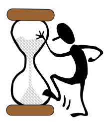
Cumulative start-up counter

- Operation of a Cumulative Start-Up Counter

  - The motor start-up time is added to the counter
  - If the counter value exceeds the set inhibit-limit the motor is not allowed to be restarted

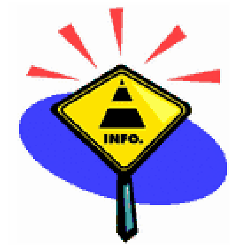


    - Inhibition is activated at the begin of the last start-up. This does not abort starting!
  - The counter value is decreased with a fixed countdown rate



  - Only after the counter value falls below inhibit-limit the motor is allowed to be restarted

Cumulative start-up counter



- Settings
  - The inhibit level

    $\Sigma t_{si} = (n-1) \times ts + 10\%$

    where n = number of allowed start-ups

    ts = starting time (in seconds)
  - Countdown rate

    $\Delta\Sigma t_s = ts / \Delta t$

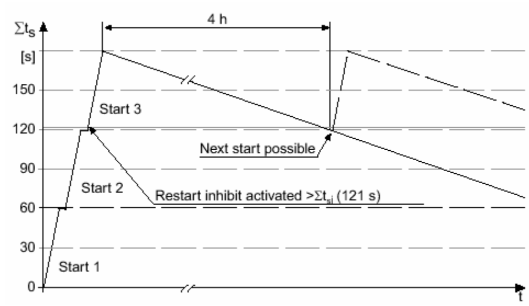
    where ts = starting time (in seconds)

    Δt = count time for one start-up (in hours)

  - Compromising number of starts at nominal and under-voltage
    - If calculated with nominal start-up time, fewer starts will be allowed at under-voltage situation

Cumulative start-up counter

- Exercise: calculate the settings
  - Starting time = 60 sec.
  - 3 cold start-up is allowed in 4 hours

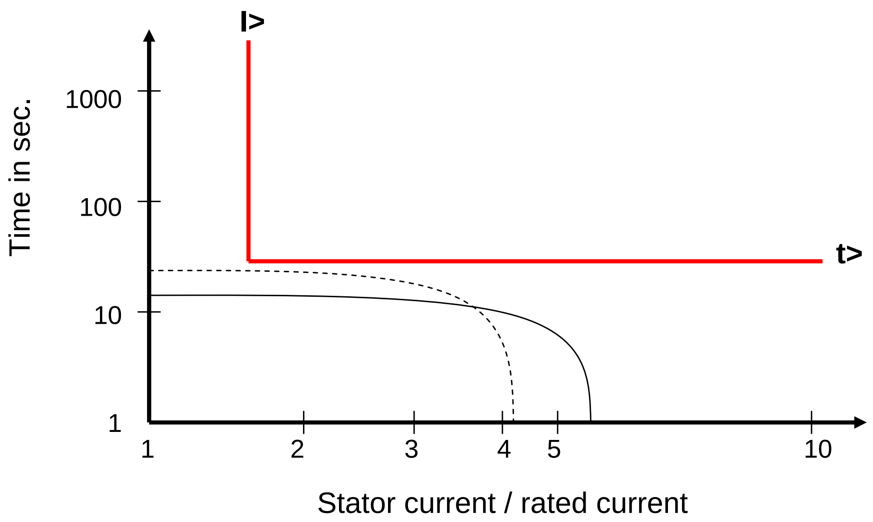


Part 5

Start-Up Supervision
= Locked Rotor Protection

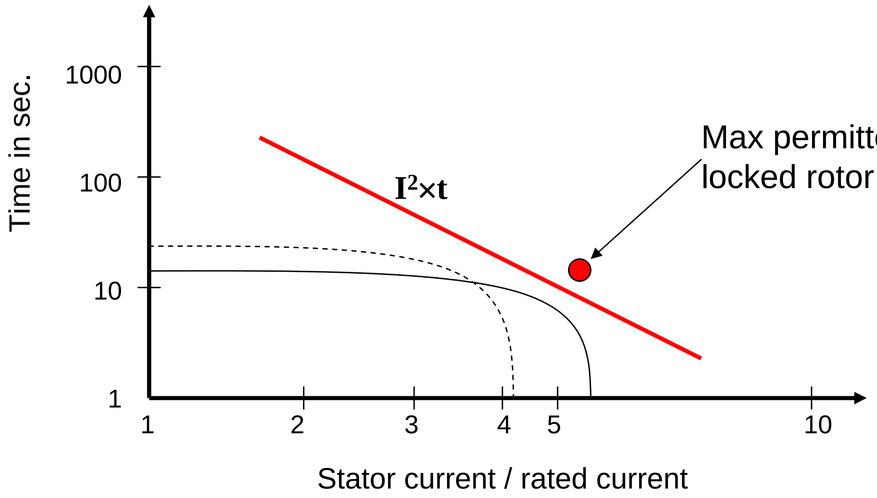
Start-up supervision with O/C protection

- Protection against prolonged start-up
  - Definite time O/C protection ⇒ time setting must be long enough to allow starting at undervoltage



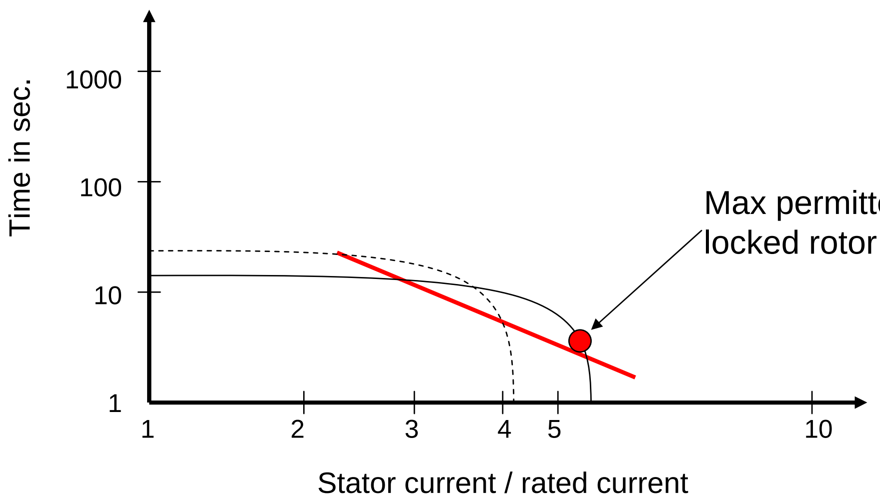
Start-up supervision, thermal stress principle

- Thermal stress is proportional to $I^2 \times t$
  - Represents energy needed to get the rotor to run full speed
  - Represents thermal stress in case of stall

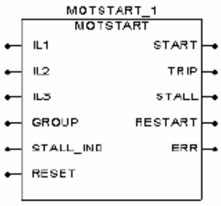


Safe stall time less than start-up time

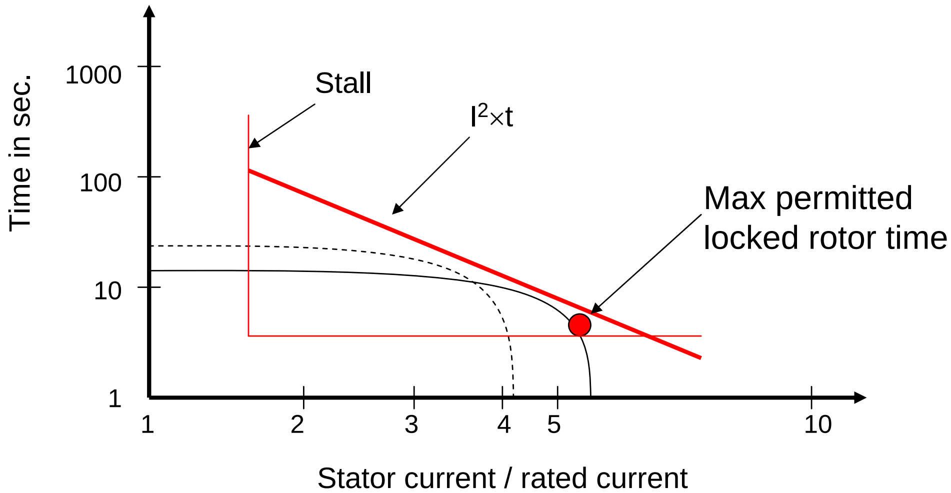
- Typically Exe -type of motor
- Protection operation time set below the start-up time
- Protection must be blocked by a speed switch when the rotor is speeding up



Safe stall time less than start-up time



- "IIt & Stall"operation mode
  - Stall = definite time operation, blocked by the speed switch

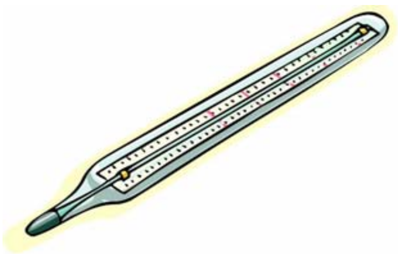


Thermal stress principle

- Can be set to operate only at start-up or whenever the start value Is is exceeded

Part 6

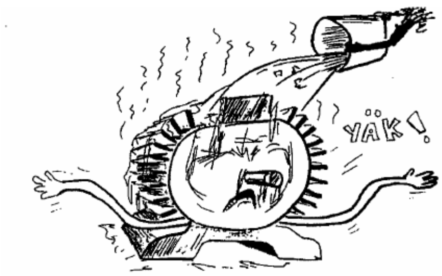
Temperature Protection with RTD or Thermistor Sensors



ABB

Temperature Protection

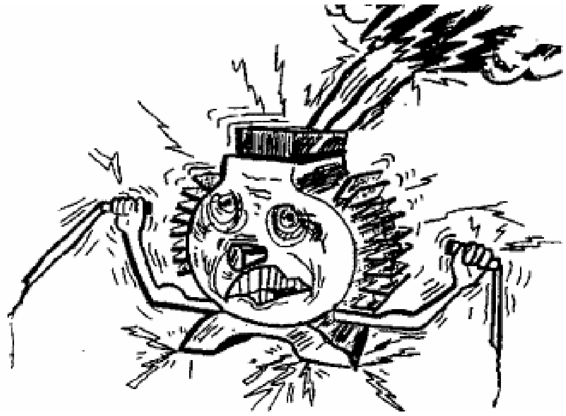
- Does not detect rapid change
  - start-up, heavy overload
- Supplements the thermal overload protection, which does not detect reduced cooling
  - Dirt
  - Cooling system failures
- Bearings etc.



ABB

Part 7

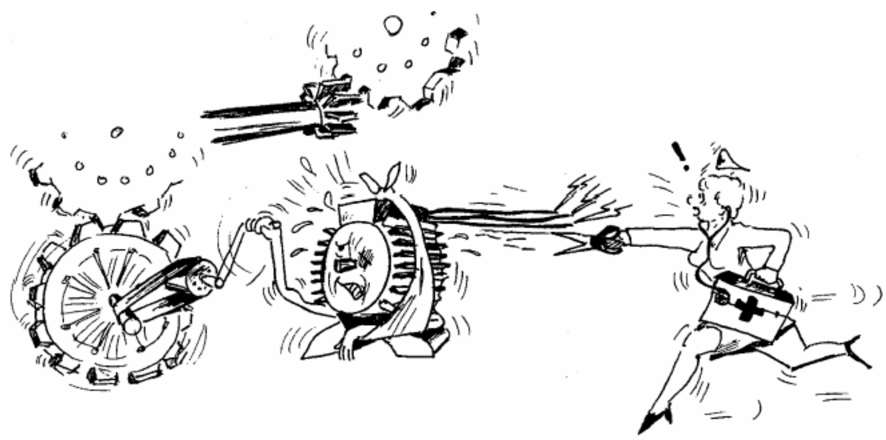
Short-Circuit Protection



ABB

High-set Overcurrent Protection

- Interwinding short-circuit protection for the motor
- Phase-to-phase short-circuit protection for the feeder cable
- Typical setting 1.5 x start-up current
- Fast operation!

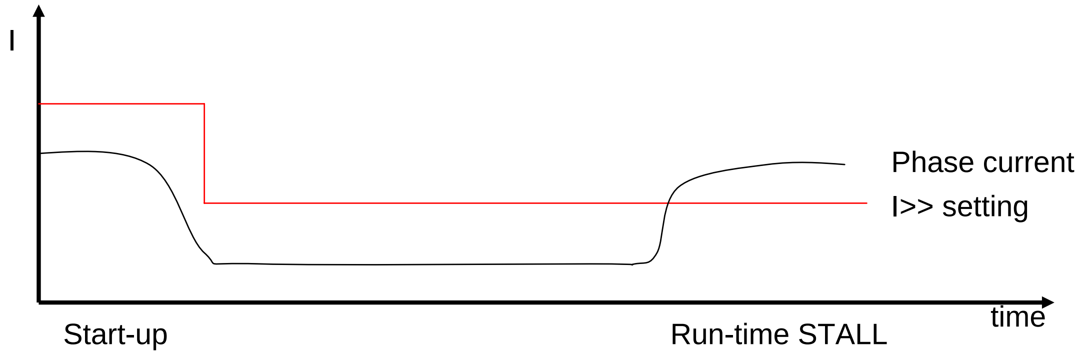


ABB

High-set Overcurrent Protection

- Doubling effect
  - I>> setting can be set for automatic doubling during a motor start-up. Setting is selected 75% - 90% of start-up current

⇒ High-set Overcurrent functions as a fast run-time stall protection



Part 8

Unbalance Protection

Unbalance protection

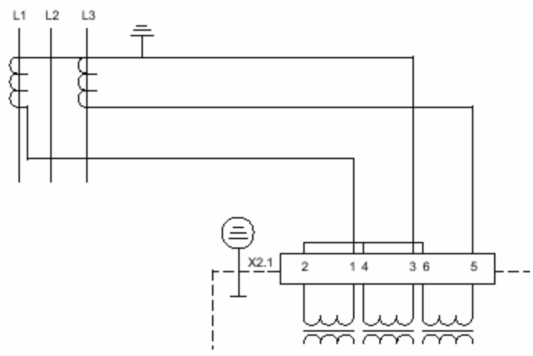
- Unbalance causes negative sequence component of phase current => causes a $2 \times f_N$ rotating flux to the rotor-circuit => the rotor temperature starts to rise.
- Squirrel-cage induction motors can withstand unbalance pretty good, but a full broken phase condition is not allowed (about as severe situation as locked rotor)

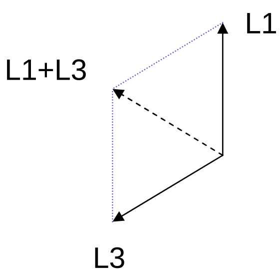
- Two principles are used: NPS and Min-Max
- Inverse time characteristics gives selective operation when multible motorfeaders.

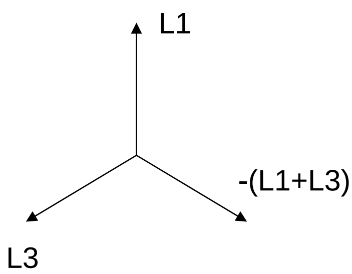
ABB

Unbalance Protection

- 3 phase currents are required
- In case of 2 x CT
  - The sum of two phase currents is connected to the relay
  - NPS3Low/High function block (REM 54_, REX) can be set to two-phase operation mode
  - E/F current will cause errors







ABB

Unbalance Protection

- Small voltage unbalance can cause high current unbalance

$$\Delta I \approx \Delta U \times \frac{I_{\text{Start-up}}}{I_{\text{FLC}}}$$

  - If, for example, the start-up current is 5 x FLC, a 2% voltage unbalance causes 2% x 5 = 10% current unbalance

$$\frac{\text{Positive Phase Sequence Reactance}}{\text{Negative Phase Sequence Reactance}} \approx \frac{I_{\text{Start-up}}}{I_{\text{FLC}}} \approx \frac{\Delta I}{\Delta U}$$

Unbalance protection, NPS principle

- Negative Phase Sequence Current (NPS, I_2) is calculated from the phase currents vectors
  - Inverse operation, a good estimation of the time constant K is

$$K = \frac{175}{(Istart)^2}$$

where I_{start} = start-up current of the motor x FLC

Unbalance protection, Min-Max Principle

- Phase discontinuity protection (SPAM 150C)
  - The unbalance ΔI is calculated

$$\Delta I = \frac{I_{L\,\max} - I_{L\,\min}}{I_{L\,\max}} \times 100\%$$

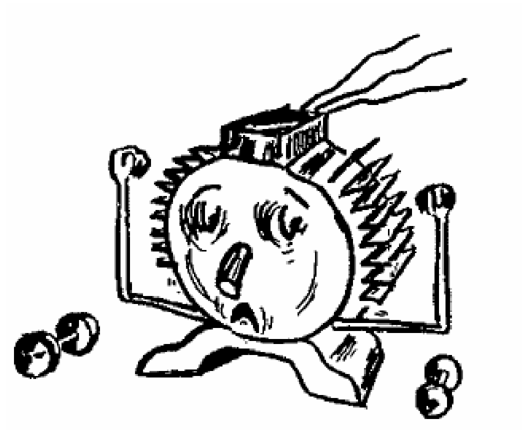
  - If the phase currents are less than the FLC

$$\Delta I = \frac{I_{L\,\max} - I_{L\,\min}}{I_{FLC}} \times 100\%$$

  - ΔI and negative phase sequence (NPS) are not the same!
    - For example 12% NPS sensitivity requires a setting of $12\% \times \sqrt{3} = 20.7\%$

Part 9

Loss of Load



Undercurrent Protection

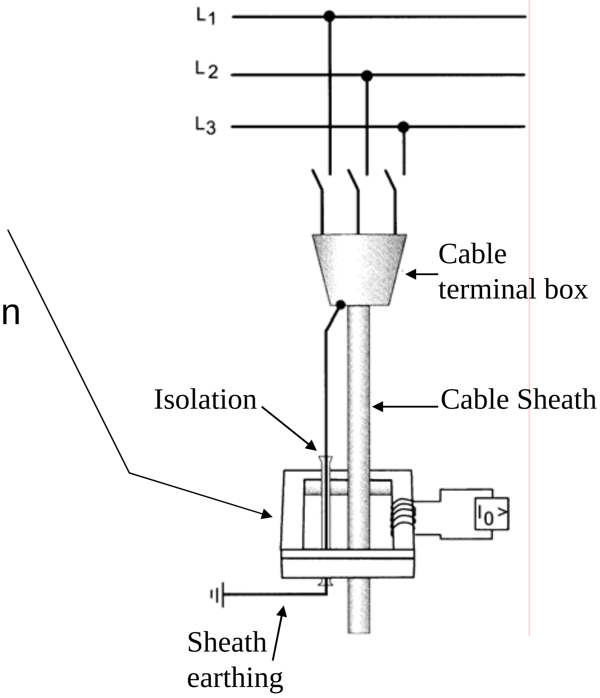
- Operates upon a sudden loss of load
- Can be used in applications where the loss of load indicates a fault condition
  - submersible pumps, when cooling is based on the constant flow of liquid
  - conveyor motors, broken belt
- Automatically blocked when the phase currents falls below blocking level (8..12%)

Part 10

Earth Fault Protection

Earth Fault Protection

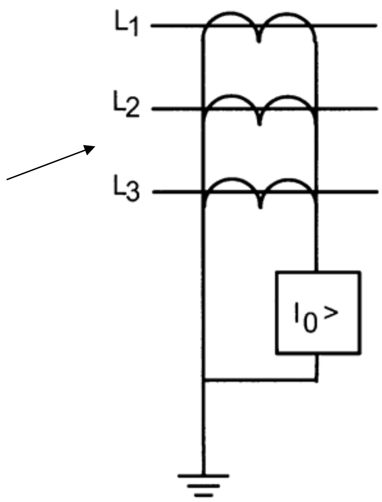
- Protection typically non-directional, definite time
- Core Balanced CT (ring CT, toroidal CT)
  - a must for sensitive protection
  - recommended CT ratio 50/1 or higher
    - CT construction
    - Secondary side voltage
    - Efficiency



ABB

Earth Fault Protection

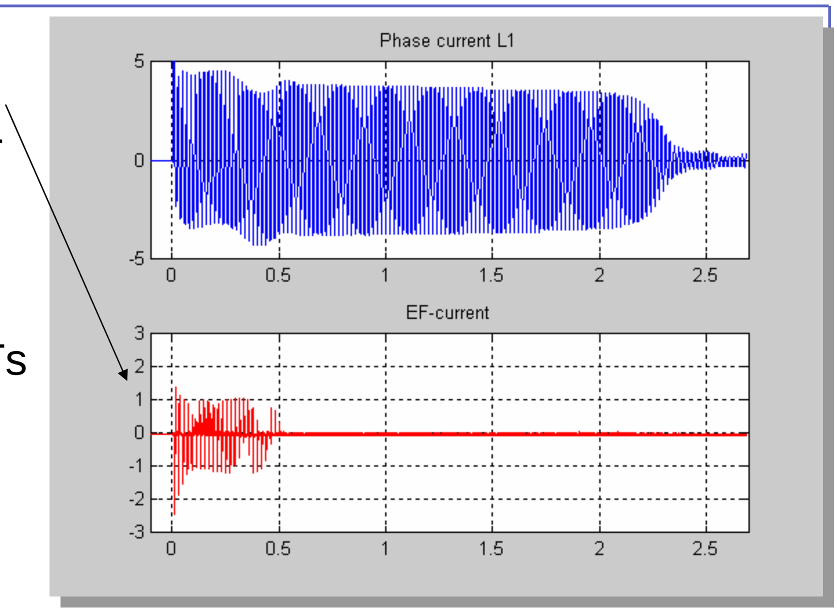
- When using *sum connection* of CTs (known as Holmgren circuit) an apparent EF-current will occur
  - differencies of CTs
  - saturation of CTs mainly at start-up because of the DC-component
  - Minimum recommended setting 10% of the CT rated primary current



ABB

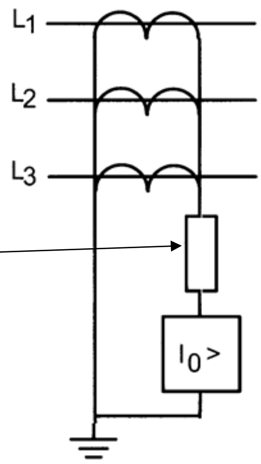
Earth Fault Protection

- Apparent E/F current will occur at startup due to the saturation of CT when sum connection of CTs is used.



Earth Fault Protection

- Avoiding problems of apparent E/F current
  - Long operation time, or
  - Temporary blocking of operation at start-up, or
  - Stabilising resistor

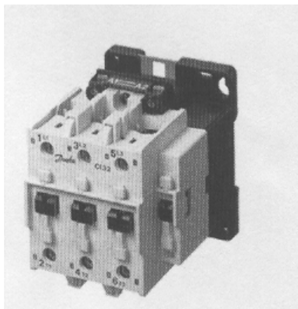


Part 11

Miscellaneous

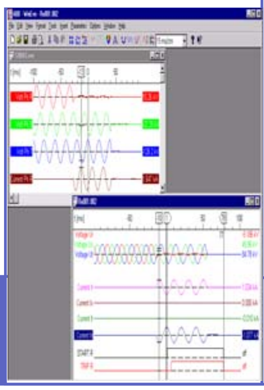
Contactor controlled drives

- Relay must have normally closed trip contact
- Contactor cannot break high currents
  - High-set O/C protection should be set out-of-use
  - E/F protection should be inhibited on high overcurrents

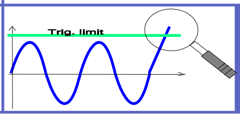


ABB

Contents of chapter 8



Disturbance Recording



- The object is to give basic understanding of
  - Different kind of recording possibilities
  - Measuring technology
  - Terminology
- Contents
  - Application
  - Internal or external recorder
  - Basics of measuring technology
  - Triggering
  - Operation modes
  - Miscellaneous

Application

- Tool for analyzing network behavior and protection problems in electrical power systems.
- Helps to verify the proper operation of protective relays and circuit breakers.
- Helps to locate disturbances.
- Makes it easier to find correct settings for protective devices.
- Gives information about normal phenomena of network (inrush currents, motor start current etc.).

ABB

Internal or external recorder?

- Internal disturbance recorders
  - SPCR 8C27 - recorder module for SPACOM series
  - MEDREC16 - function block for REF, REM, REX
  - Relays with built-in recorders: SPAD 346C, REJ/U, RE_610…
  - Advantages
    - Build in, no need for additional wiring
    - Triggered from the relay operation or when exceeding trigger value (overcurrent, over/undervoltage etc)
    - Communication for setting and downloading recorders via relay
    - Tools for downloading and analyzing
  - Disadvantages
    - Typically fixed sampling frequency
    - Typically limited memory capacity

ABB

Internal or external recorder?

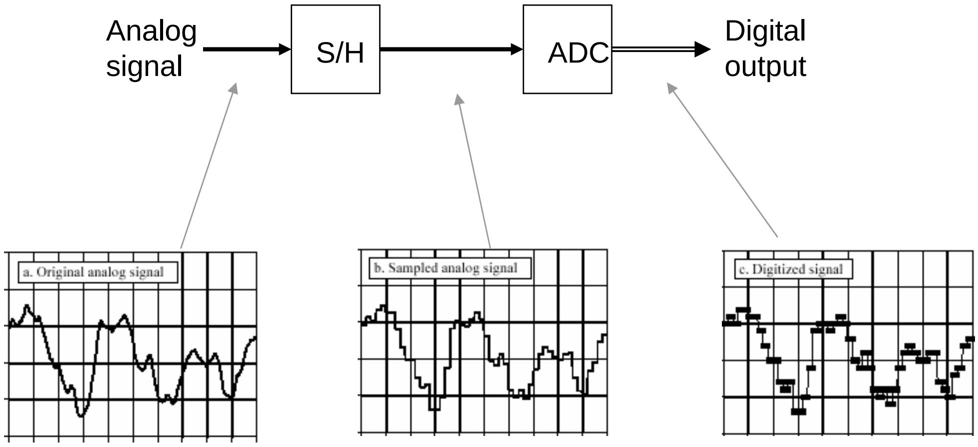
- External disturbance recorders
  - Oscilloscopes, power analyzers etc
  - Advantages
    - Higher memory capacity (when recording one shot only)
    - Higher sampling frequency
    - Paper print-out?
  - Disadvantages
    - Connections to secondary circuit, current/voltage probes needed
    - File format?
    - Saving/upload ? (manually/automat., floppy, HD, communication)
    - Analyzing software, compatibility?
    - Price? (depends on number of channels, memory and speed)

Basics of measuring technology

- Signal = physical (usually analogue) quantity that is connected to the recorder and what the recorder converts to a digital format for recording
- Measuring error = the difference between measured and true value, either a systematical or random error.
- In everyday language we say ex. 1% accuracy when we mean 1% inaccuracy, i.e. measuring error is 1%.

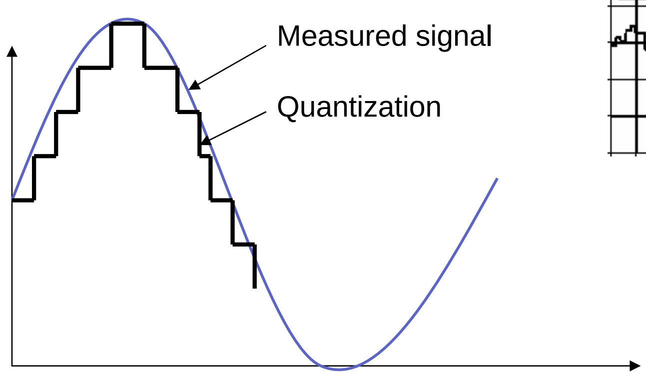
Basics of measuring technology

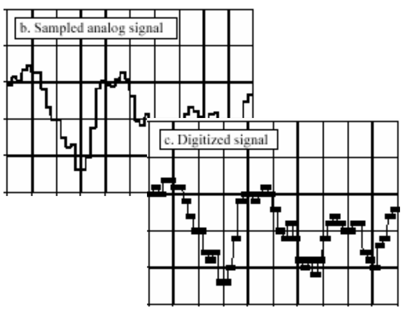
- <u>Analog to digital conversion</u>. A sample and hold (S/H) circuit is used to keep the signal constant while the conversion to digital value (ADC) is taking place.



Basics of measuring technology

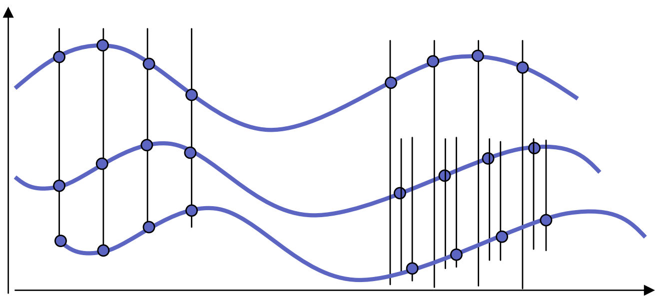
- <u>Resolution</u> = The capability of the measuring device to record small changes. When an analog values are converted to digital (discrete) values it is also rounded to nearest possible output value. This is called <u>quantization</u>. In practice the resolution tells the worst rounding.





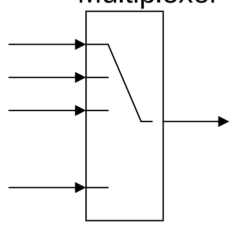
Basics of measuring technology

- Simultaneous sampling = All channels are typically sampled and held simultaneously.
- Multiplexed sampling = A common technique for measuring several signals with a single S/H and ADC is multiplexing where channels are scanned with a one by one. I.e. channels are not samples simultaneously.



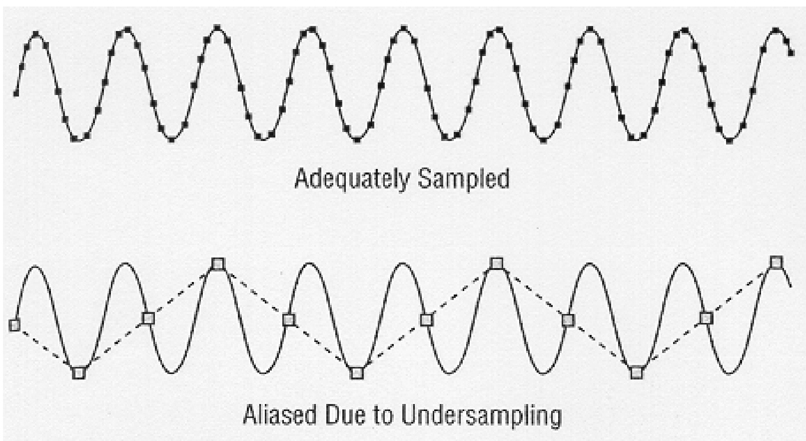
Simultaneously sampling

Multiplexed sampling



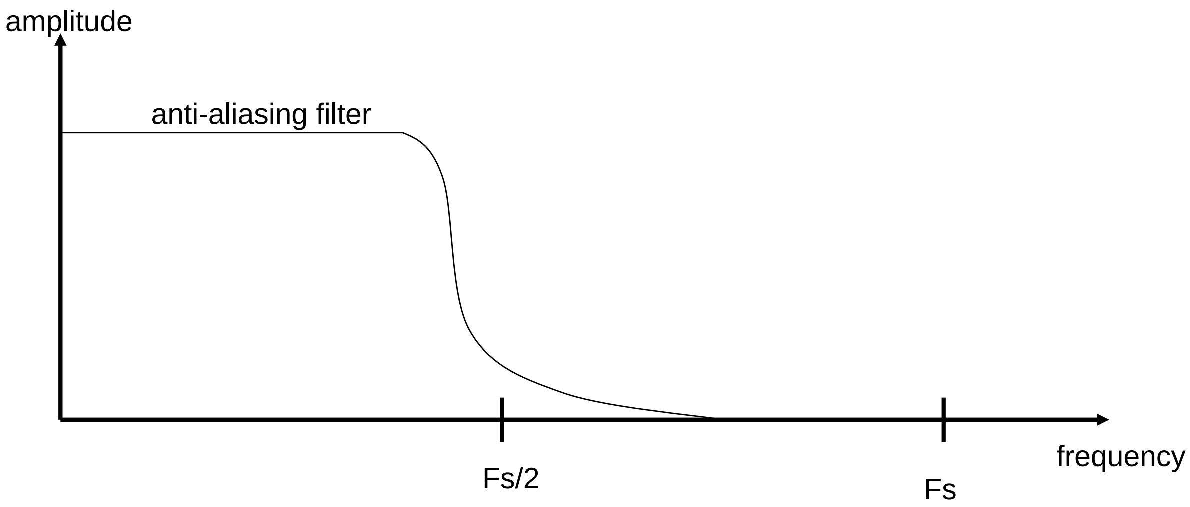
Basics of measuring technology

- Aliasing is an effect of too low sampling rage. According Nyquist theorem the sampling rate must be more than 2 x the highest measured frequency.



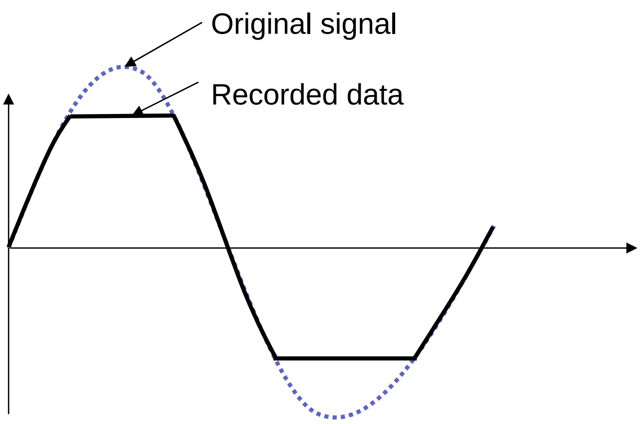
Basics of measuring technology

- Anti-aliasing filter = an analog filter cutting off frequencies from the signal that might be aliased.



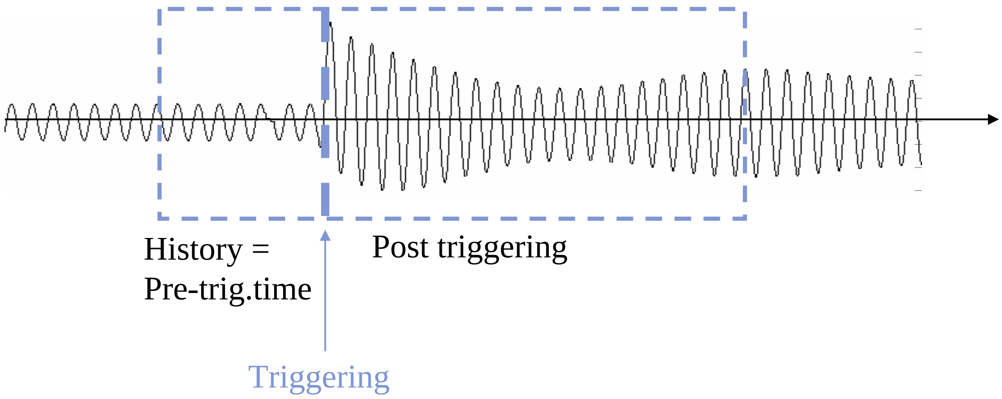
Basics of measuring technology

- Cutting = The signal amplitude exceeds the measuring range.



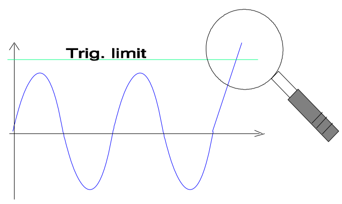
Basics of measuring technology

- Pre/post trig.time. The recorder has a capability to record data before the triggering as well. I.e. the whole recording consist data before and after fault (triggering).

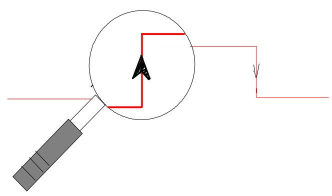


Triggering

- Measured analog signal exceeds a adjustable limit
  - Overcurrent, over/undervoltage, ...
  - Filter time = how short/long time limit must be exceeded

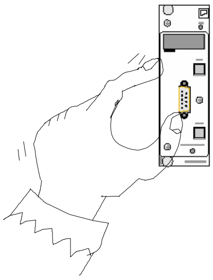


- Digital signal changes
  - Rising or falling edge

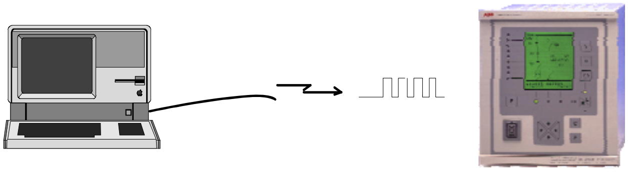


Triggering

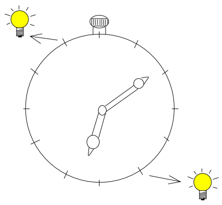
- Manual triggering



- Remote triggering via communication bus



- Periodic triggering



Operation modes (when memory fills up)

- Saturation = when memory becomes full the waveform capturing is stopped and no new recordings can be made unless old recordings are downloaded/destroyed.
- Overwrite = the oldest recording is automatically destroyed when memory capacity is needed for new recordings
- Extension = a new triggering during an on-going recording interrupts the current recording and start a new one.

Miscellaneous

- Exclusion time or dead time is the time after triggering, when all new trigs from the same reason is rejected.