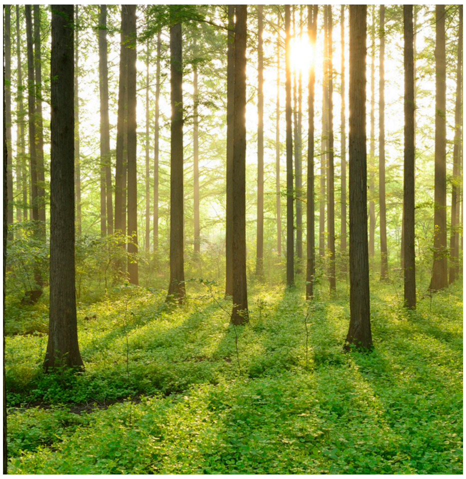
PROTECTION INTERACTION BETWEEN NUCLEAR POWER PLANT AND EXTERNAL POWER SYSTEM

REPORT 2019:611



NUCLEAR

GRID INTERFERENCE ON NUCLEAR
POWER PLANT OPERATIONS

Energiforsk

Protection Interaction Between Nuclear Power Plant and External Power System

LARS MESSING

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Foreword

Faults and other incidents in the transmission system and in the nuclear power plants interact with the function of the fault clearance systems. With a smarter design of fault clearance systems, a high dependability and probability of disconnecting when needed can be achieved, at the same time as the probability of unwanted disconnection is low.

Lars Messing, senior consultant at DNV GL, describes the existing fault clearance system and events that can challenge the system. Furthermore, suggestions on design changes and measures that can be taken to strengthen the fault clearance system are provided. The project is part of the Grid Interference on Nuclear power plant Operations, GINO, program that is financed by The Swedish Radiation Safety Authority, Vattenfall, Uniper/Sydkraft Nuclear, Fortum, Skellefteå Kraft and Karlstads Energi.

These are the results and conclusions of a project, which is part of a research programme run by Energiforsk. The author/authors are responsible for the content.

Sammanfattning

Olika typer av händelser och fel i transmissionsnätet och i kärnkraftverken påverkar felbortkopplingssystems funktion. Kraven är att felbortkopplingssystemen skall vara pålitliga, dvs. sannolikheten att bortkoppla fel skall vara hög, och säkra, dvs. sannolikheten för oönskad bortkoppling av anläggning skall vara låg. Dessa krav är i viss mån motstridiga.

I denna rapport beskrivs olika typer av fel och händelser i transmissionssystemet som påverkar skyddssystemet. Nuvarande uppbyggnad av felbortkopplingssystemen beskrivs och utvärderas. Vidare presenteras förslag till ändringar av felbortkopplingssystemen, som skulle kunna stärka systemets pålitlighet och säkerhet:

- Kan redundansen för transmissionsledningarnas skyddssystem förändras för att öka säkerheten (minska risken för oönskad bortkoppling)?
- Kan redundansprincipen för aggregatskydden förändras för att öka säkerheten (minska risken för oönskad bortkoppling) med bibehållen pålitlighet? En princip enligt ”dual 2 out of 2” beskrivs.
- Utveckling av system för att minimera risken för personfel ”human errors”. Detta gäller t.ex. beräkning och inställning av skyddsenheter.
- Byte av skyddsenheter som närmar sig slutet på livslängden.
- Förändrad princip för felbortkoppling i hjälpkraftsystemet.
- Koordinering av skydd för osymmetri.

Elsystemet utvecklas mot att innehålla mer och mer intermittent produktion som inte levererar systemdrifttjänster, främst frekvensreglering, i samma utsträckning som kärnkraftverken. Detta bedöms inte påverka felbortkopplingssystemet i kraftverken.

Summary

Faults and other incidents in the transmission system and in the nuclear power plants interact with the function of the fault clearance systems. The requirements on fault clearance system are that it shall have high dependability, i.e. the probability to disconnect faults shall be high, and high security, i.e. the probability of unwanted disconnection of non-faulted object shall be low. These requirements are to some extent contradictive and must be evaluated to reach an acceptable compromise.

This report describes different types of faults and other incidents influencing the protection system. The present design of the fault clearance systems, both in the transmission system and in the power plant, is described and evaluated. Suggestions for possible changes of the fault clearance system are presented:

- Possibility of changes of the transmission system protection system to be changed to increase security with maintained degree of dependability.
- Possibility of changes of the generating unit system protection system to be changed to increase security (reduction of the risk of unwanted trip) with maintained degree of dependability. The redundancy principle "Dual 2 out of 2" is described.
- Development of methods/systems to minimize the risk of "human errors". This can, for example, be applied to calculation and parameter setting of protection units.
- Replacing protection hardware due to end of lifetime and to enable improved functionality.
- New principle for the auxiliary system protection is described.
- Improved coordination of asymmetry protection (negative sequence voltage/current protection.

Furthermore, there might be opportunity in the future for the nuclear power plants to provide ancillary services, such as frequency control. This is not expected to have an influence on the fault clearance system.

List of content

1 Background and goals

The fault clearance systems in the Swedish transmission system and in the power plants are designed and commissioned at different periods. During the years protection systems of different technical generations have been implemented. In addition, the power system has changed:

- New types of generating units connected to the grid via power electronics
- Reduction of the inertia in the system
- Changes of power flow in the transmission system

The changed conditions, as well as protection system technical development, gives the following questions:

- Why are the fault clearance system designed as it is?
- Is improvement needed? If so: How can it be improved?
- How does the electricity system changes influence fault clearance?

In this report the following items are covered.

Chapter 2: Description and evaluation of the existing transmission system protection systems. The different primary system faults and critical operation situations are discussed. This **gives the background** giving the consideration made when the existing protection system was specified and designed.

Chapter 3: Description and evaluation of the existing NPP protection systems. The different primary system faults and critical operation situations are discussed. This **gives the background** giving the consideration made when the existing protection system was specified and designed.

Chapter 4: In this chapter ideas of improvements of the protection systems are discussed

Chapter 5: Ancillary services influence on protection is covered

2 Description and evaluation of the existing protection systems – transmission system protection

2.1 FAULTS AND OTHER INCIDENTS IN THE POWER SYSTEM WITH INFLUENCE ON THE NPP

Transmission systems normally have wide geographical spreading. Therefore, the system is exposed to different conditions that might cause different kind of disturbances.

2.1.1 Short circuits, fault ride through

Short circuits can be caused by lightning, pollution, salt storms and many other factors. The phase to phase short circuits are in almost all cases arcing faults with very low fault resistance. In case of three phase short circuits the power transfer close to the fault will be significantly reduced, giving risk for generator first swing instability. Therefore, the fault clearance time for three phase faults is essential for fault ride through. A maximum critical fault clearance time (CCT) requirement is specified by the grid code, to assure the power system security. In case of two-phase short circuits, the fault clearance time is less critical.

In case of faults in the transmission system it is required that generating units shall remain connected to the transmission system under the following conditions:

Referring to Nordel report: “Operational Performance Specifications for Thermal Power Units larger than 100 MW”, 1995

“The units shall be designed so that they can withstand the following **generator** voltage variations resulting from faults in the grid, without disconnection from the grid”

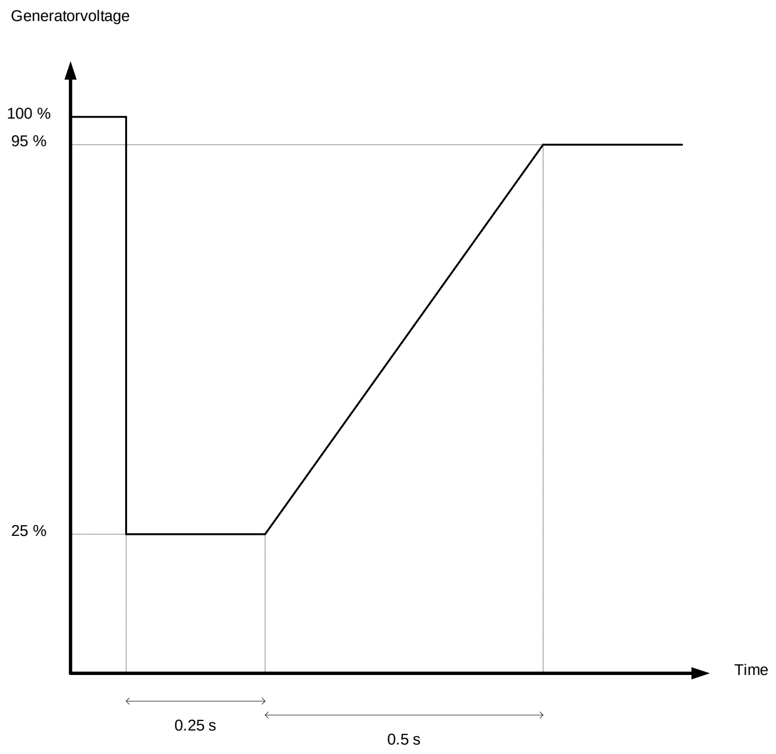

Figure 1 Fault ride through voltage profile according to Nordel 1995

Referring to SvKFS2005:2

Large power plants shall stay in operation in case of voltage variation according to the profile voltage in the meshed point transmission system, close to the studied power plant. An example is Ringhals where this refers to the voltage in Horred or Strömma.

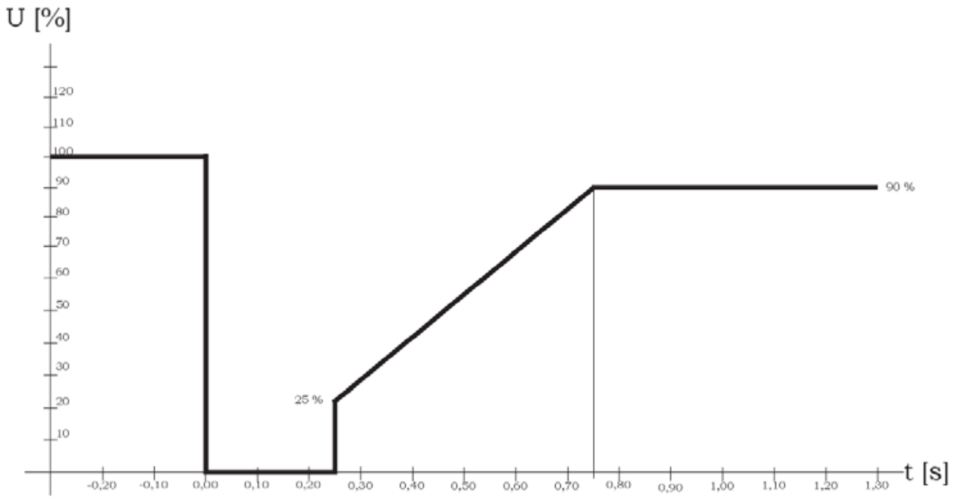

Figure 2 Fault ride through voltage profile according to SvKFS2005:2

In the new grid code, the requirements are slightly changed. Large power plants (type D) shall stay in operation in case of voltage variation according to the profile (voltage in the connection point to the meshed transmission system, i.e. at the high voltage side of the unit transformer):

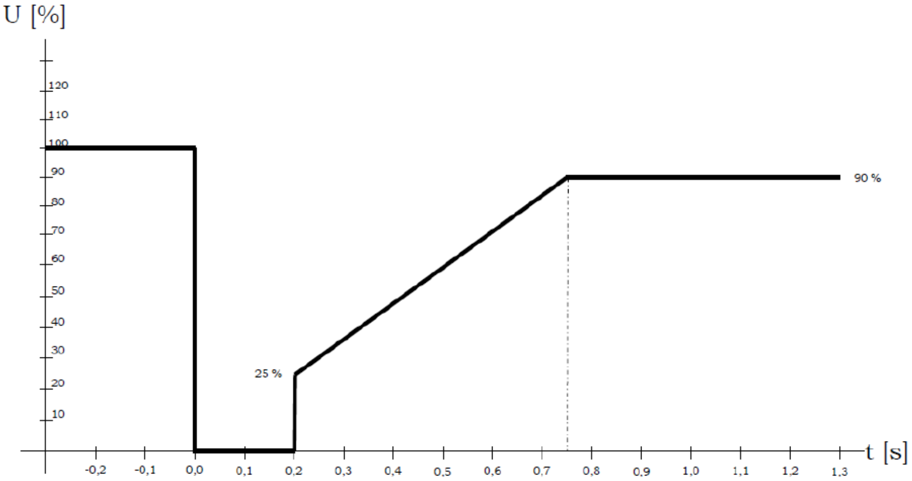

Figure 3 Fault ride through voltage profile according to RfG: COMMISSION REGULATION (EU) 2016/631

It shall be observed that the voltage before the fault is 100 % meaning 400 kV even if the transmission system is normally operated within the interval 410 – 415 kV. The reactive power interchange with the transmission system shall be close to 0.

The estimation of the critical fault clearance time (CCT) is dependent of several factors:

- Fault type: the worst case is three phase short circuit. This fault type is used in dynamic simulation studies for the purpose to estimate CCT. Phase to phase short circuit and single phase to earth faults give longer CCT. From statistics: about 60 - 80 % of all transmission line faults are single phase to earth fault[1].
- Generator excitation before the fault: low excitation gives shorter CCT.
- Distance to fault from the power plant.
- Strength of the transmission system at the point of connection, **after trip of the faulted object**. Sometimes dynamic simulations to investigate CCT are done with intact network after fault clearance. Such studies give unrealistic results.

2.1.2 Earth Faults

Phase to earth faults can be caused by lightning, pollution, salt storms and many other factors. In case of phase to earth fault, the fault resistance is the combination of an arc resistance and the resistance of the between the faulted endpoint of the arc and "real" earth.

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[1] Entso-e: Nordic and Baltic grid disturbance statistics 2016

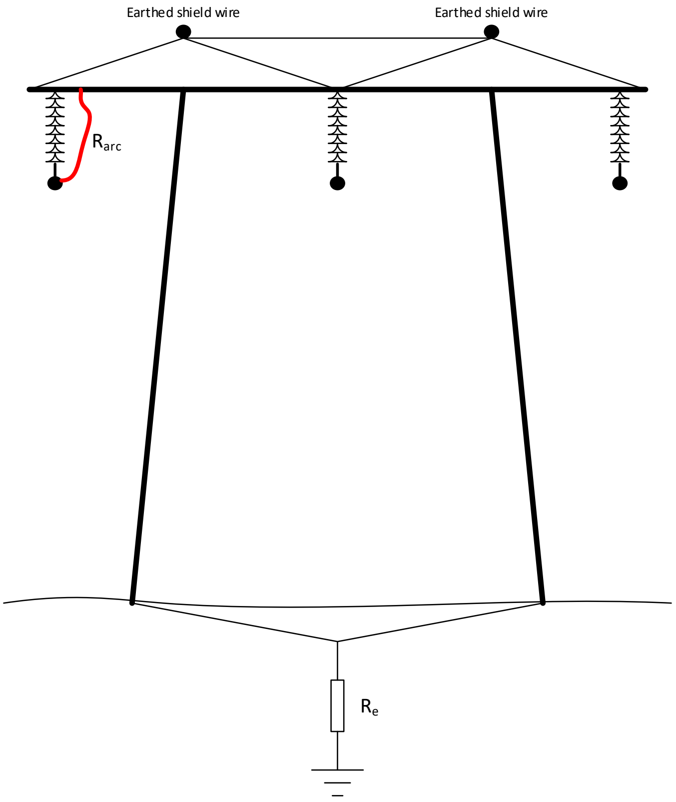
The resistance of the arc is depending on the fault current magnitude and the arc length. A commonly used way to estimate this resistance is to use the van Warrington formula[2].

$$R_{arc} = \frac{28710}{I_{arc}^{1.4}} \cdot L\ \Omega$$

I_{arc} is the arc current in amperes

L is the arc length in meters

The resistance to "real" earth is depending on several factors. Two examples giving very different conditions:



The earthed shield wires will be connected to several towers thus connecting several earting footint resitance in parallel
Resulting earth fault resistance < R_e

Figure 4 Transmission line earth fault: Low Fault resistance

In this case there will probably be relatively low resulting fault resistance. The tower footing resistance vary significantly between different areas depending on the earth resistivity.

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[2] *Protective Relays – their Theory and Practice.* A.R. van C. Warrington. Chapman and Hall, 1962.

The opposite extreme:

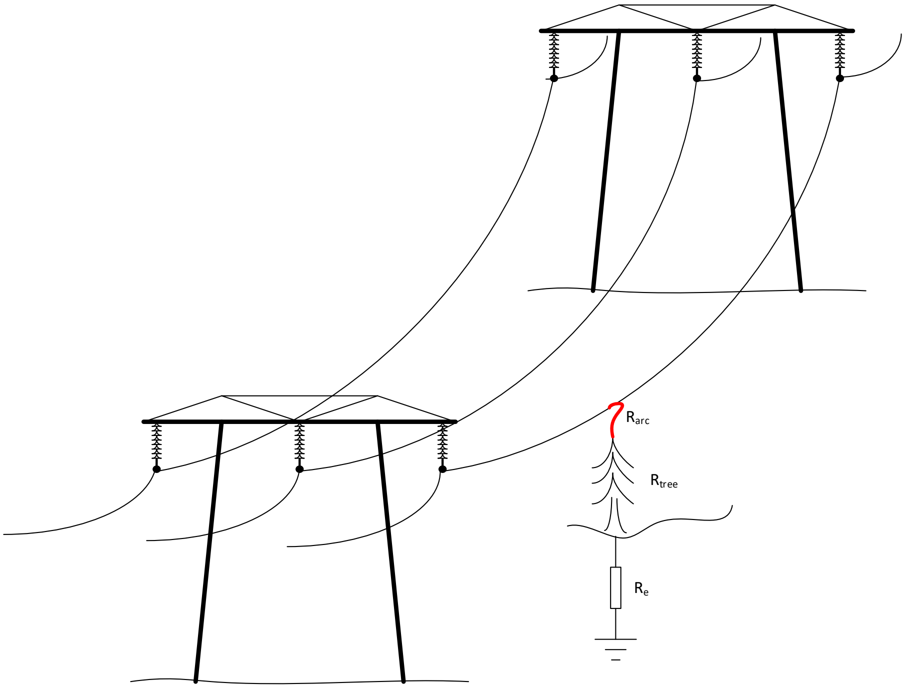

Figure 5 Example of transmission line high resistive earth fault

This fault gives very high fault resistance. Earth faults caused by growing vegetation are very rare, in transmission systems, but there are examples where transmission lines are overloaded so much that the conductor sag results in flash over to high trees.

2.1.3 Unsymmetrical conditions / series faults

Unsymmetrical conditions occur in the power system mainly due to interruption of one phase or two phases. The reason for this might be:

- Broken line conductor
- Unsymmetrical circuit breaker: “One phase open-Two phases closed” or “Two phases open-One phase closed”
- Unsymmetrical disconnector: “One phase open-Two phases closed” or “Two phases open-One phase closed”

This condition will cause negative- and zero-sequence currents and voltages in the power system. The amplitude of the negative sequence and zero sequence components of current and voltage, is dependent of the power transfer though the asymmetry. In case of low power transfer, it is difficult to detect the unsymmetrical condition as the negative sequence and zero sequence currents are proportional to the power transfer in case of unsymmetrical conditions as described.

Negative sequence current gives additional losses in rotating machines (generators and motors) and thus risk for damage.

2.1.4 Circuit breaker failure

The circuit breaker is a fundamental part of the fault clearance system. In the transmission system it is essential that disconnection of high currents faults is made very fast, normally within less than 100 ms.

There is always a risk that the circuit breaker fails to trip, due to different causes. This inability to trip is often hidden and will only be detected at a real breaker maneuver. The fault must however be cleared.

A very efficient way to enable fast circuit breaker reserve, is to have two breakers in series connection, as suggested by NERC and IEEE. This solution is however uncommon but used in some critical applications. Therefore, it is common praxis to apply breaker failure protection that detects the failure to interrupt the current and sends trip signals to back-up circuit breakers. The consequences of breaker failure protection operation are increase of the fault clearance time and extended disconnection of components compared to “normal” fault clearance. The latter is however highly dependent on the switchyard design.

2.1.5 Abnormal voltages/voltage collapse

The transmission system voltage shall during undisturbed operation be within acceptable limits. According to ENTSO-E operation grid code: “COMMISSION REGULATION (EU) 2017/1485 of 2 August 2017” the operation voltage shall be within 0.9 – 1.05 pu, referring to 400 kV base in the Nordic countries (360 – 420 kV). It should be noted that voltage down to 0,9 pu is in practice occurring during very stressed system conditions.

In case of high power-transmission this will influence the system voltage and in the worst case, voltage collapse can occur. Assume an equivalent power system:

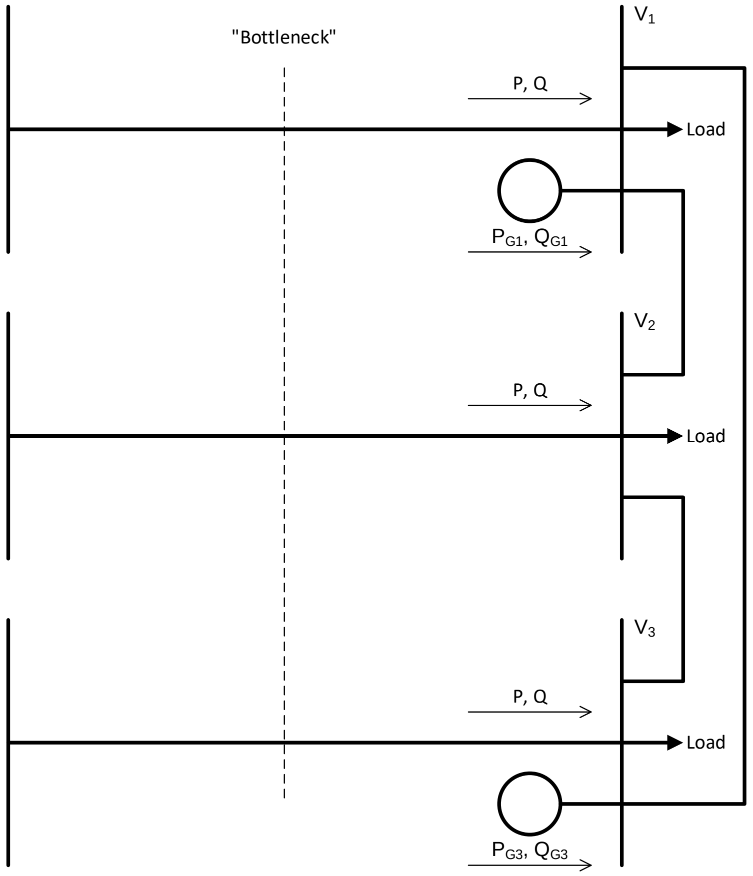

Figure 6 Simple network example showing power transfer

An equivalent receiving voltage can be shown in the “nose curve”. The “tip” of the nose curve indicates the maximum power transfer through the bottleneck. If a line is tripped this power limit for voltage stability is decreased. If the power transfer exceeds the limit the system will collapse, and we get a fast voltage collapse.

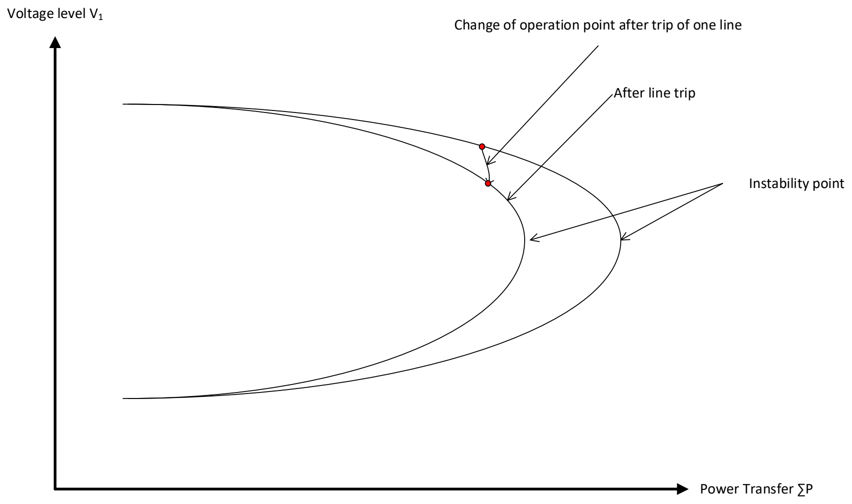

Figure 7 Voltage at receiving line end depending on power transfer

In some cases, the system will survive as a lower voltage will reduce the load power at the receiving end. The load will however recover due to transformer tap changer increase of voltage in the distribution systems fed from the transmission system. In addition, some load: electrical heating with thermostat, will recover. The consequence will be that a **delayed voltage collapse** occurs.

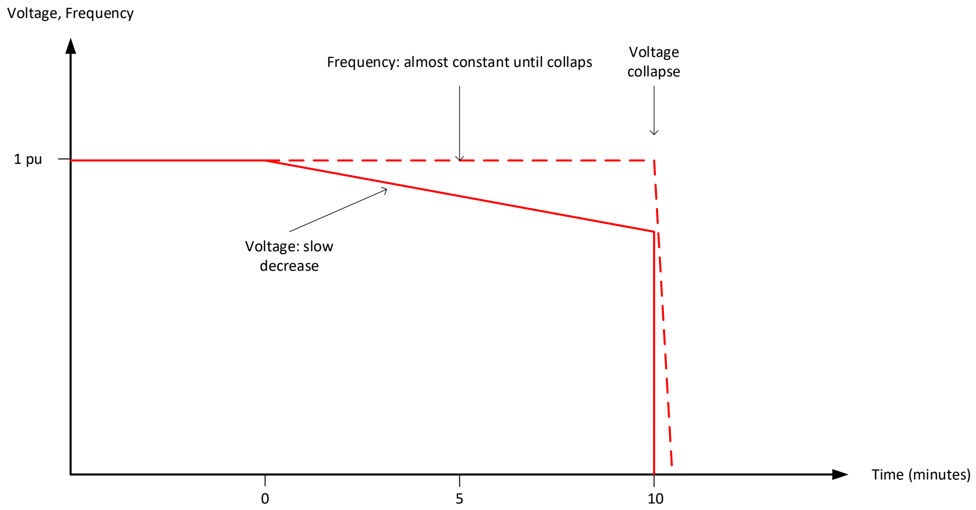

Figure 8 Voltage and frequency at slow (delayed) voltage collapse

The transmission system is normally operated within margins so that voltage stability is maintained after any "normal" disturbance (N-1) where one object (transmission line or another critical object) is disconnected. The voltage stability can however not be guaranteed in case of more severe disturbances.

The risk of voltage collapse is, in many cases, difficult to detect as the voltage before the incident is within acceptable limits.

If a voltage collapse occurs, it is essential that the NPP transfer to house-load operation. The voltage collapse can be detected by the following protection functions:

- Undervoltage protection tripping the unit breaker

The undervoltage protection must be set to assure selectivity to the short-circuit protections in the transmission system. This means that the trip delay must be set considering the fault ride through voltage profile (generator voltage side):

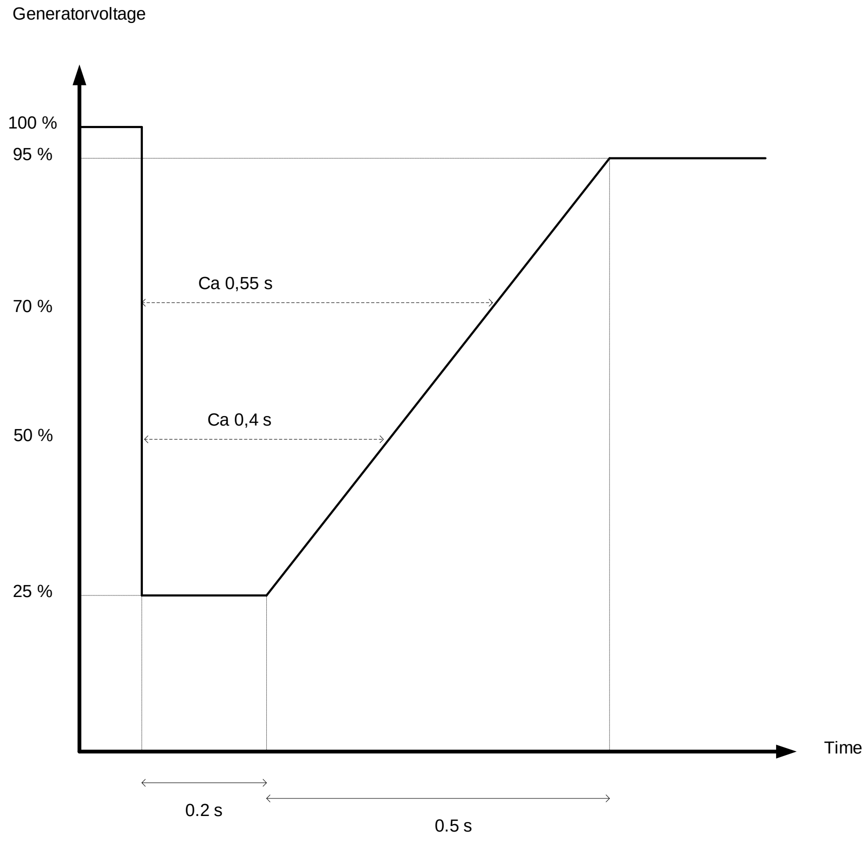

Figure 9 Generator voltage profile for undervoltage protection setting

The time delay for the undervoltage protection might be too long to guarantee transfer to house-load operation.

- Pole slip protection

The pole slip protection is often based on impedance movement seen from the generator. Also, this protection function must distinguish between the fast short-circuit movement of the impedance locus and the slower impedance movement in case of voltage collapse. The voltage collapse can however be very fast at the point of collapse.

The two protection functions are not intended to detect voltage collapse.

One option to detect voltage collapse or risk of voltage collapse, is to use synchronized wide area measurement of voltage in the power system. These measurements can primarily be used to shed load to prevent voltage collapse.

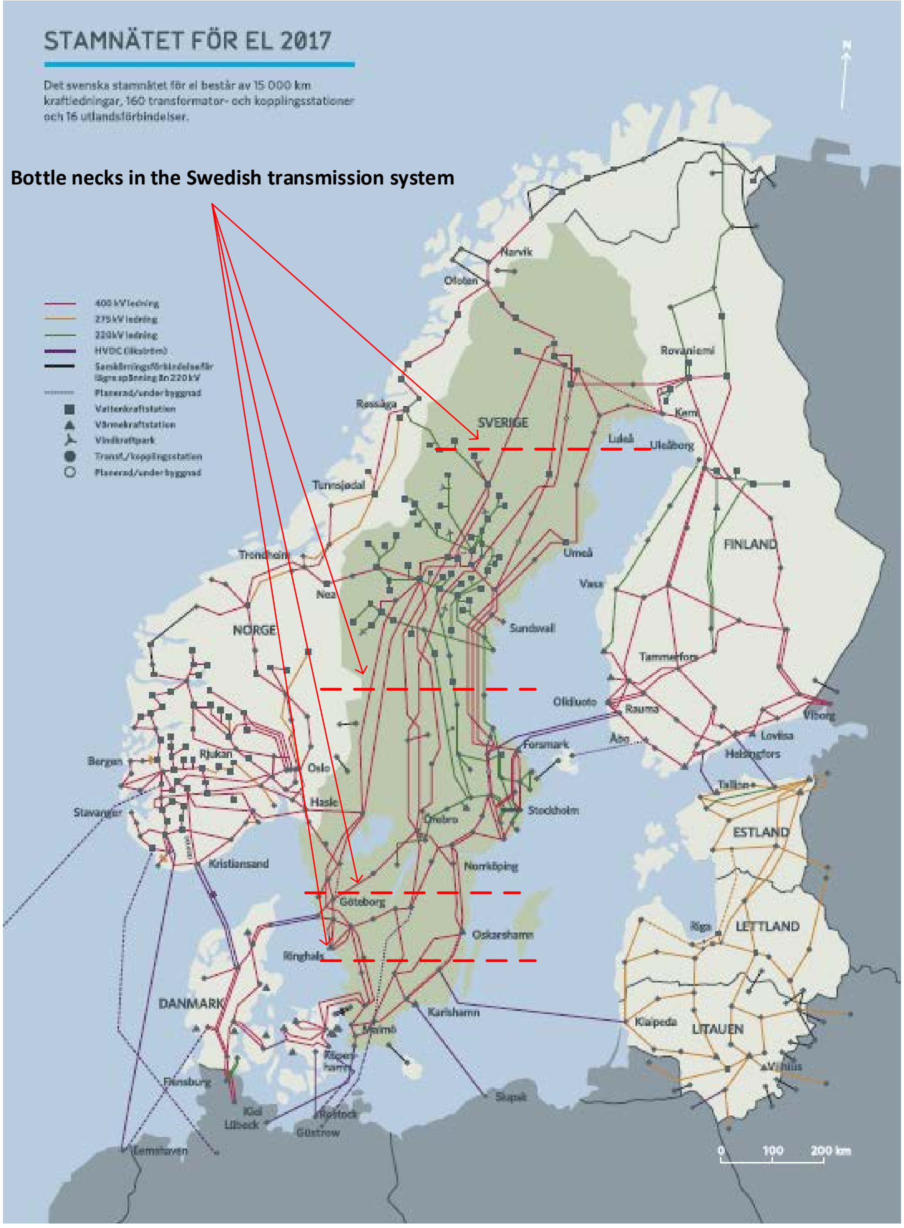

Figure 10 Bottle necks in the Swedish transmission system

It is of great value, for the transmission system, that the NPP:s can transfer to house load operation after a voltage collapse.

2.1.6 Reactive power compensation

Trend: Increased amount of cables in the power system, both in transmission, sub-transmission and distribution systems gives requirement of increased reactive power compensation to keep the voltage within acceptable level. One consequence might be requirement to operate the large generating plants, especially the NPP, with under-excitation, to keep the transmission system voltage to acceptable levels.

A consequence of operation a generator at low excitation is decreased transient stability (fault ride through). Coordination between the excitation system and the under/overexcitation protection is thus essential.

2.1.7 Abnormal frequency

The frequency in the power system is an indicator of active power balance. The frequency is in-signal to control system of generating plants regulating the power balance. Normally there is enough regulating control power available in the system to maintain frequency within the stipulated limits, both in normal operation and during disturbances. I some cases, especially at disturbances where the power unbalance gets larger than the available disturbance reserves, the frequency will be outside the limitations. It is of course important that the generators are not operating outside the required frequency limitations: 47,5 – 51,5 Hz.

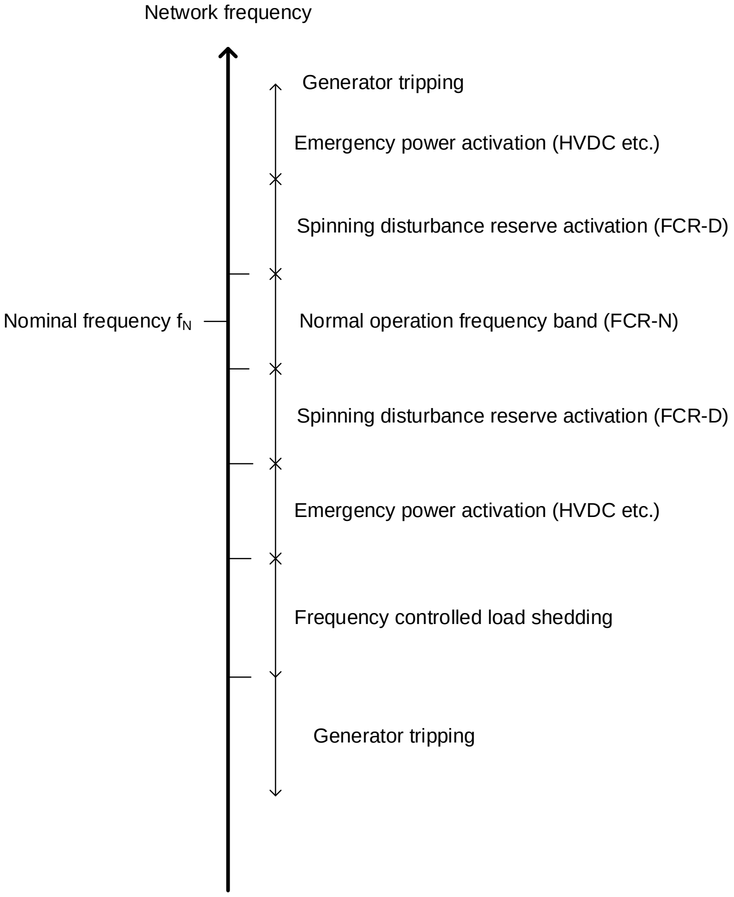

Figure 11 Overview of different frequency control measures

In case of **low frequency** other automatic actions are activated such as disturbance spinning reserves, emergency power from HVDC-links and finally frequency-controlled load shedding. It the frequency get lower than 47,5 Hz all means of restoring the power unbalance are activated without success, and blackout will occur. In this case no time coordination between underfrequency protection can help. This must be acceptable.

Trend: The increasing amount of wind and solar based power generation results in difficulties predict the system power balance and thus to keep the frequency within the acceptable range. In the present situation these generation plants do not participate in the frequency control. Especially during low load situations with a large amount of wind-based generation, there might be risk of power imbalance where all frequency controlling generators are operating at minimum active power, resulting in high frequency. In case of **high frequency**, generating units will be disconnected from the power system after trip from over frequency protection. The risk can be:

The frequency reaches a value higher than 51,5 Hz, activating many generators over-frequency protections. If the trip time delay is the same for many of these generators, they will trip at the same time and the system can suddenly transfer **from a high frequency situation** (generated power > load power) **to a low frequency situation** (generated power < load power). This might lead to system blackout.

To overcome this risk there should be time delay coordination between over-frequency protections of power generation larger than a set value. This could be compared to the coordination of frequency-controlled load shedding schemes.

2.1.8 Power oscillations

There are always some power oscillations in the power system, where groups of generators at different location in the system, oscillates against each other. Different modes of oscillation can be identified in the system. The oscillations are continuously initiated by small changes of load or other reasons. Normally these oscillations are well damped.

In the figure some modes of power oscillations between groups of generators in the Nordic power system are shown.

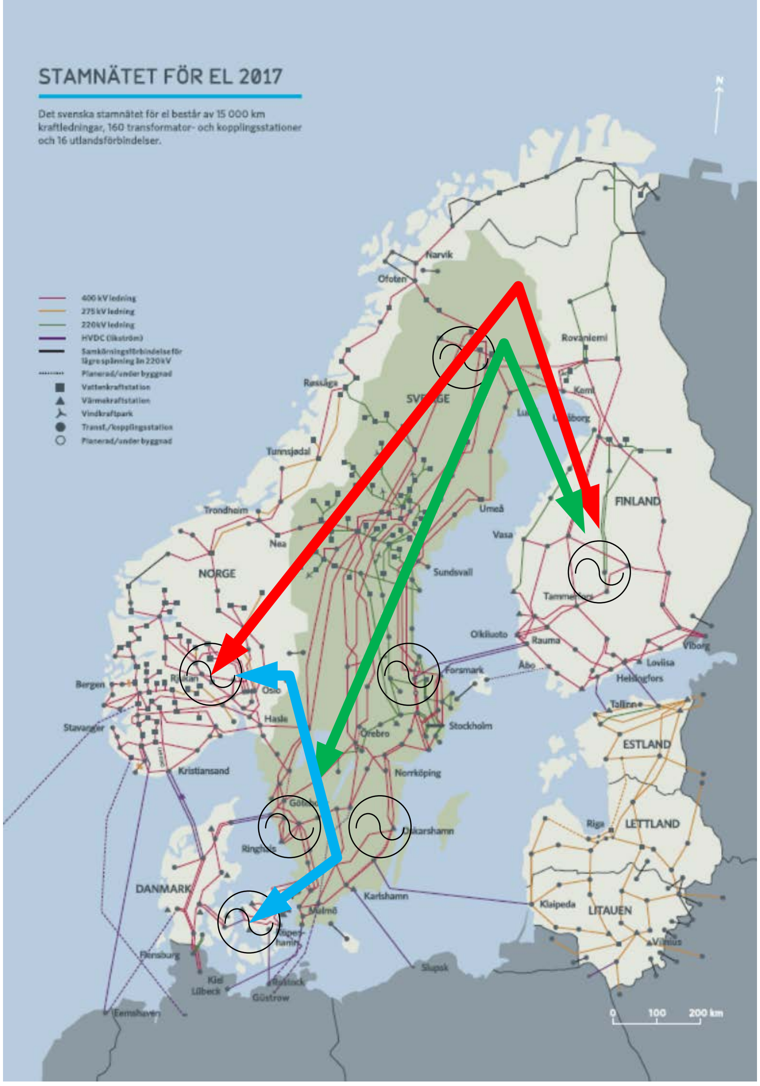

Figure 12 Some identified modes of oscillations in the Nordic transmission system

Every mode of oscillation has individual frequency and damping. If any of the oscillation modes have negative damping (increasing oscillation amplitude), there is a risk of network split and total network collapse. The collapse is equivalent to out of step conditions (phase angle opposition) in power plants or between line ends of transmission lines.

There are possibilities to detect oscillations in the power system. There are two different principles for actions in case of oscillations:

- If severe power oscillations occur there is a risk that distance protection will trip as the locus of apparent impedance reach zones for trip. The consequence will be line disconnection and probably total or partial system black-out. Therefore, the distance protection can be equipped with power oscillation detection, blocking one or more distance protection zones (power swing blocking). **This option is not used in the Swedish transmission system**.

- In some power systems, where undamped oscillations are likely to occur, it is preferred to split the system in case of undamped oscillation. The network split is made on selected bottleneck transmission lines. The aim is that the remaining two systems will recover, in some cases after load shedding.

Power oscillations have significant influence on generating plants, as the undamped oscillation can lead to pole slip (out of phase). The pole slip gives large generator current and mechanical stress on generator and turbine.

2.1.9 Geomagnetic induced currents

During periods of high solar activity plasma with protons and electrons are emitted from the sun. These has impact on the earth magnetic field. The changes in the earth magnetic field will induce geomagnetic induced currents (GIC) in the earth surface. The consequence is that low frequency (almost DC) zero sequence current will flow in the transmission system. This current will result in DC saturation of directly earthed transformers connected to the transmission system. The problems:

- The saturation of power transformer might lead to increased heating and insulation damage of the transformer
- The (close to) DC current on the transmission lines will cause partly saturation of CT and thus risk of unwanted earth fault protection trip
- Risk of trip of generation plant (Negative sequence current protection start at Oskarshamnsverket unit 3, 1986-02-08)

Unwanted operation of sensitive earth fault protection, as a consequence of GIC, is avoided as the protection function has harmonic restrain/blocking. This function is initially indented for detection of transformer inrush current.

To protect the transformer, the earthing can be adaptive so that the neutral point is connected via a resistor in situation with risk of GIC in the transmission system. The figure shows the solution in Oskarshamnsverket unit 3. Normally the resistor is by-passed via a disconnector. In case of risk for GIC the disconnector is open.

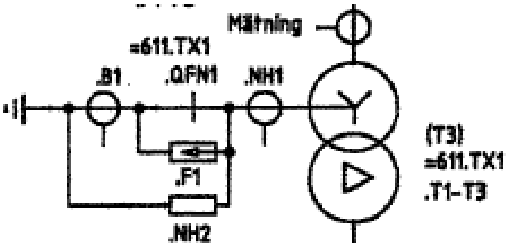

Figure 13 Application of neutral point resistor

2.1.10 Sub-synchronous resonance

Sub-synchronous resonance (SSR) is a well-known phenomenon in power systems with series compensated transmission lines together with synchronous turbo generators. The SSR phenomenon can be divided into three different types: IGE (Induction generator effect), TI (Torsional interaction) and TA (Torsional amplification).

For the NPP generators the TI and TA phenomena are of importance. In the power plant the turbine generator set are masses (different turbines) connected to each other's via shaft segments. The masses and shaft segments give torsional swing modes with different resonance frequencies. The number of modes is n-1 if the number of masses is n. These resonance frequencies are normally below 50 Hz.

In the power system with series compensated transmission lines, resonance will occur between the equivalent inductance in the system and the series capacitance. If the network resonance frequency coincides with a torsional mode of the turbine shaft generator set, small oscillations can result in large sub-synchronous currents amplifying the oscillation. In worst cases this will lead to large torsional stress and damage of the turbine shaft.

It is essential that sub-synchronous oscillations are detected so that countermeasures can be activated, for example series capacitor by-pass.

In Forsmark NPP such detection is installed. In addition, SSR protection is installed on the series compensated lines that are electrically close to Forsmark NPP

2.2 IDENTIFICATION OF SHORT CIRCUIT FAULTS IN THE POWER SYSTEM, CRITICAL FOR NPP

The nuclear power plants are heavily influenced of what happens in the external transmission system. **It is difficult to identify all possible critical fault scenarios**.

In case of short circuits or phase to earth faults in the transmission system different protection functions are activated. In modern protection units many different protection functions are available. It is therefore often preferred to use many of these protection functions to guarantee a high degree of dependability. Increased number of functions will however decrease the security (the risk of unwanted trip will increase).

Below some examples of critical faults scenarios are shown.

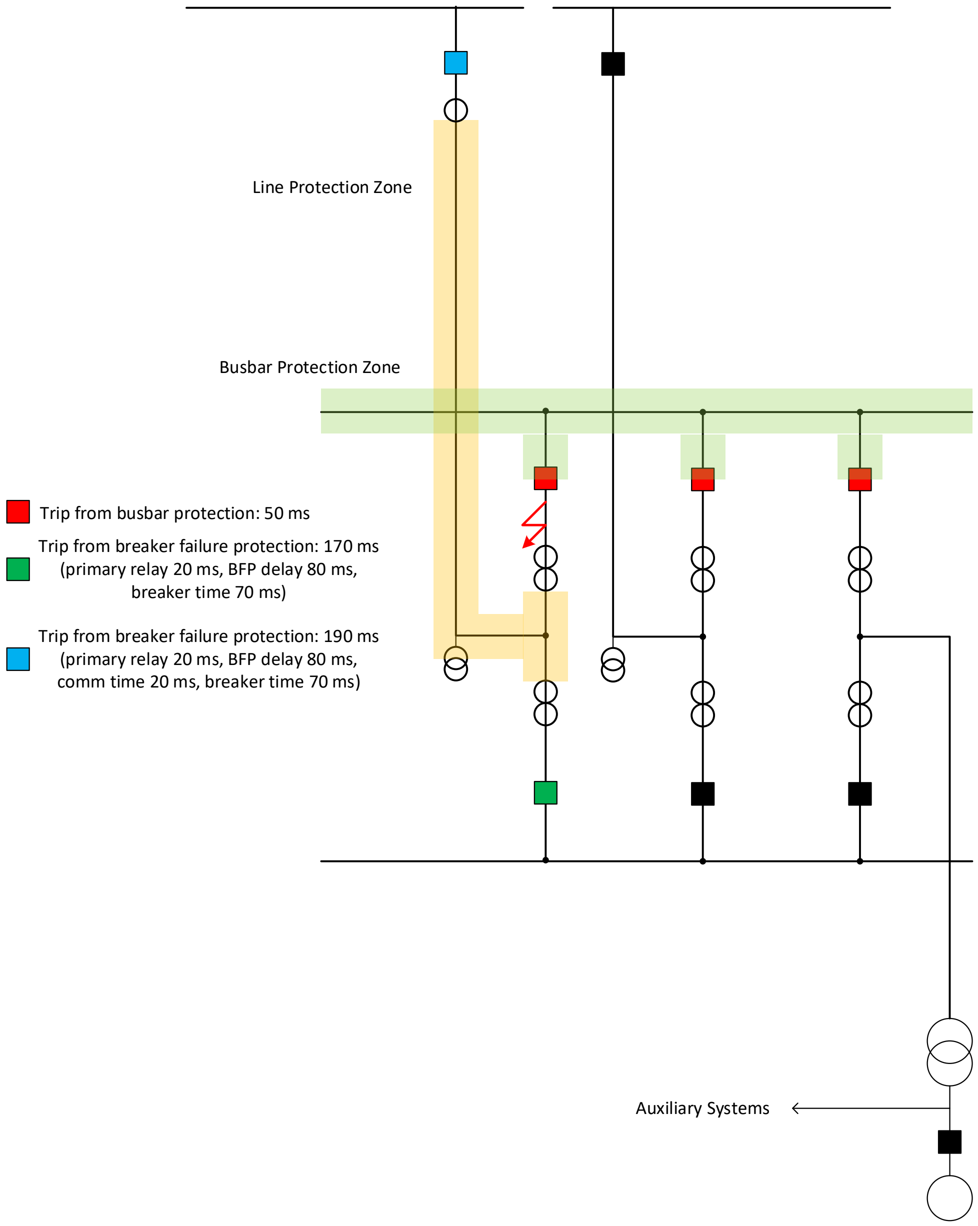

Figure 14 Example of a critical switchyard fault scenario

The consequence of the fault, shown in Figure 14, could be pole slip of the generator, as the fault clearance time is close to the critical fault clearance time (CCT). Trip of the generator and the transmission line is more severe than the criteria used in planning and operation of the power system. This is a scenario that can happen, but the **probability of the scenario** should be estimated:

1. The fault is located between the circuit breaker and the CT feeding both the busbar protection and the line protection.
2. The fault is a three-phase short circuit. In case of other fault types, the critical fault clearance time is longer, and the generator will probably remain in stability.

In this example the fault clearance system trip as the system is designed. The consequence is however very dependent of the state of the transmission system after the fault sequence.

The described scenario is considered to have low, but not negligible, probability.

Example: normal line earth fault. It is assumed that the protection of the transmission lines is as:

Sub 1:

Distance protection (Z<) with permissive communication scheme. The distance protection has 3 zones activated:

Zone 1: Set to about 85 % of the line impedance, instantaneous trip. Zone 1 is used for sending acceleration signal in **underreach** communication schemes.

Zone 2: Set to overreach the whole line (often 125 % of line impedance), 0,4 s trip delay. Zone 2 is used for sending acceleration signal in **overreach** communication schemes and to give non-delayed trip in case of received acceleration signal.

Zone 3: set, if possible, to detect fault at the objects connected adjacent busbar, 0,8 – 1,2 s trip delay.

Residual overcurrent protection ($3I_0$>) with permissive communication scheme. The distance protection has 4 steps activated:

Step 1: Forward direction. Set to about 1,25 % of earth fault current at earth fault on the adjacent busbar, instantaneous trip. Step 1 is used for sending acceleration signal in **underreach** communication schemes.

Step 2: Forward direction. Set to overreach the whole line (often 75 % of earth fault current at earth fault on the adjacent busbar, with about 20 Ω fault resistance), 0,4 s trip delay. Step 2 is used for sending acceleration signal in **overreach** communication schemes and to give non-delayed trip in case of received acceleration signal.

Step 3 (often named 23): Forward direction. Set, to detect earth faults with some degree of fault resistance (35 Ω at remote busbar)., 0,8 s trip delay.

Step 4 (often named 3): Non-directional. Set to a low pick up value (80-120 A primary residual current). Current dependent time delay with logarithmic characteristic. Used to detect high resistive earth faults and series faults.

Sub 2: In this example considered to be equal to sub 1 protection.

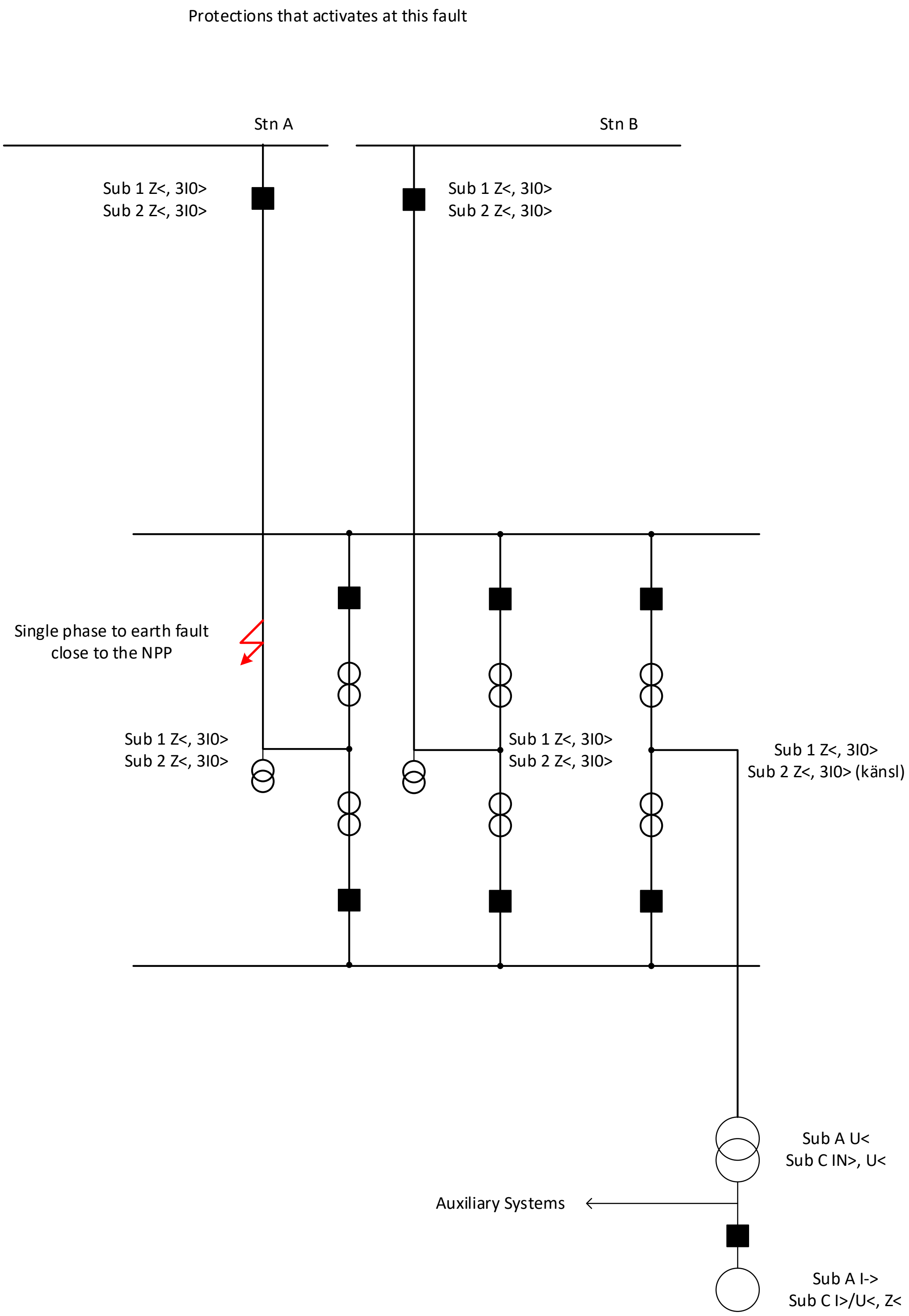

Figure 15 Example of line fault scenario

We have the following conditions:

A single phase to earth fault at the line between the power plant and station A. It is assumed that this line is 100 km long. According to statistics[3] the fault rate is 0.36 faults/100 km,year. About 70 - 85 % are single phase to earth faults. This means roughly that this line will be hit by a phase to earth fault every 3.5 years.

The following protections shall be activated and **shall trip**:

Bay	Protection function	Activation
Pow.Plant – Stn A	Z<, Sub 1	Zone 1 **Trip** Zone 2 send acc
Pow.Plant – Stn A	3I0>, Sub 1	Step 1 **Trip** Step 2 send acc
Pow.Plant – Stn A	Z<, Sub 2	Zone 1 **Trip** Zone 2 send acc
Pow.Plant – Stn A	3I0>, Sub 2	Step 1 **Trip** Step 2 send acc
Stn A – Pow.Plant	Z<, Sub 1	Zone 2 + receive acc **Trip**
Stn A – Pow.Plant	3I0>, Sub 1	Step 2 + receive acc **Trip**
Stn A – Pow.Plant	Z<, Sub 2	Zone 2 + receive acc **Trip**
Stn A – Pow.Plant	3I0>, Sub 2	Step 2 + receive acc **Trip**

It can be concluded that there are eight protection functions detecting and tripping this fault (four at each line end). The dependability is high: **very little probability of failure to trip this fault**. In case of breaker failure there will be breaker failure trip of all breakers on one busbar section (connecting the faulted breaker). The consequence will be extended fault clearance time. In transmission systems the circuit breakers have separate pole mechanics. It is therefore not likely that the breaker fails to trip all three poles. After the normal trip time to the back-up trip there is a less severe fault.

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[3] Entso-e: Nordic and Baltic Grid Disturbance Statistics 2017

The following protections might be activated and **shall not trip**:

Bay	Protection function	Activation
Pow.Plant – Stn B	Z<, Sub 1	Zone 1 reverse dir Zone 2 reverse dir Receive acc
Pow.Plant – Stn B	3I0>, Sub 1	Step 1 reverse dir Step 2 reverse dir Receive acc
Pow.Plant – Stn B	Z<, Sub 2	Zone 1 reverse dir Zone 2 reverse dir Receive acc
Pow.Plant – Stn B	3I0>, Sub 2	Step 1 reverse dir Step 2 reverse dir Receive acc
Stn B – Pow.Plant	Z<, Sub 1	Zone 2 + send acc Zone 3 start
Stn B – Pow.Plant	3I0>, Sub 1	Step 2 + send acc Step 3 start
Stn B – Pow.Plant	Z<, Sub 2	Zone 2 + send acc Zone 3 start
Stn B – Pow.Plant	3I0>, Sub 2	Step 2 + send acc Step 3 start
Pow.Plant – Gen unit	Z<, Sub 1	Zone 1 reverse dir Zone 2 reverse dir
Pow.Plant – Gen unit	3I0>, Sub 1	Step 1 reverse dir Step 2 reverse dir
Pow.Plant – Gen unit	Z<, Sub 2	Zone 1 reverse dir Zone 2 reverse dir
Pow.Plant – Gen unit	3I0>, Sub 2	Step 1 reverse dir Step 2 reverse dir
Unit transformer	U< Sub A	start
Unit transformer	IN> Sub A	start
Unit transformer	U< Sub C	start
Generator	Z<	Zone 2 start
Generator	I->	Start

Bay	Protection function	Activation
Generator	I>/U<	Start
Pow.Plant – Stn A	BFP, Sub 1	Start
Pow.Plant – Stn A	BFP, Sub 2	Start
Stn A – Pow.Plant	BFP, Sub 1	Start
Stn A – Pow.Plant	BFP, Sub 2	Start

There are at least 22 protection functions activated in this case. **The risk of unwanted trip is not negligible**. Possible reasons for unwanted trip:

- False acceleration signal in the line protection communication schemes
- Hardware fault giving false trip
- Improper parameter setting of protections
- Unexpected operational states giving unforeseen conditions for the protection system

Consideration 1: Can the number of protection functions for transmission lines be reduced without unacceptable reduction of fault clearance dependability, giving increase of fault clearance security?

Consideration 2: Shall overreaching protection functions, for example generator under impedance protection zone 3, be set to detect all faults on adjacent objects? The experience in the world is that the overreaching zone 3 of distance protection has given unwanted disconnection of non-faulted lines, resulting in power system blackouts.

2.3 EXISTING REQUIREMENTS ON PROTECTIONS IN THE TRANSMISSION SYSTEM

The requirements on protections can be divided between different factors; selectivity, speed, sensitivity and redundancy.

2.3.1 Selectivity

The definition according to IEC: “selectivity of protection: the ability of a protection to identify the faulty section and/or phase(s) of a power system”.

In transmission systems selectivity is of outmost importance as disconnection of more than the faulted object might cause system total or local blackout. Most transmission systems are designed to the n-1 criterion.

2.3.2 Speed

In transmission systems it is often stated that low resistive short circuits and earth faults shall be cleared without intentional delay There will however always be some delay from fault inception until fault clearance including:

- Protection operation time: In transmission system applications this is normally < 30 ms

Break-time of the circuit breaker: In transmission systems: 2 periods (40 ms in 50 Hz systems, Svenska kraftnät states < 45 ms)

2.3.3 Sensitivity

It is essential to have sensitive earth fault protections in the transmission system. Before about 1980 the sensitive earth fault protection was a simple residual overcurrent protection with a standard time delay, normally 1,2 s and a pick-up current in the range 60 – 120 A. This is still the principle used in the Swedish 130 kV systems. As this protection type is unselective it was found to be unacceptable in the 220 and 400 kV systems. Therefor a new principle was agreed 1981.[4]

The requirement for sensitivity is related to the ability to detect High resistive earth faults in the transmission system and the ability to detect series faults. The requirement for the sensitive and fault clearance time for earth fault protection in the Swedish transmission system is stated:

Time characteristic: $t = 5.8 + 1.35 \cdot ln\left(\frac{I}{I_a}\right)$ where I_a shall be settable: 80 – 200 A (prim) and the minimum operation value shall be settable down to 80 A (prim).

The sensitivity enables detection of high resistance earth faults, for example earth fault of overhead lines with arcing fault to growing vegetation.

The sensitivity also enables detection of series faults (example asymmetric poles of circuit breakers.

The logarithmic current depending time delay enables selective fault clearance.

2.3.4 Redundancy

In the fault clearance system, there are requirements on dependability and security. They are to some extent in contradiction to each other.

The definition of Dependability (IEC): "the probability for a protection of not having a failure to operate under given conditions for a given time interval"

The definition of Security (IEC): "the probability for a protection of not having an unwanted operation under given conditions for a given time interval"

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[4] Selektiv bortkoppling av små nollföljdsströmmar, Stamnätsnämndens Driftkommitté, Arbetsgruppen för Reläskyddsfrågor, Mars 1981.

A normal requirement for fault clearance systems is that a faulted object shall be cleared even if one component of the fault clearance system fails to operate. In practice this means that there shall always be back-up protection for each object (transmission line, power transformer, busbar, etc.).

For each object; transmission line, power transformer and other objects, the redundancy is based on two separated subsystems, sub 1 and sub 2. This principle has been standard in the transmission system for a long time. The system can schematically be described as:

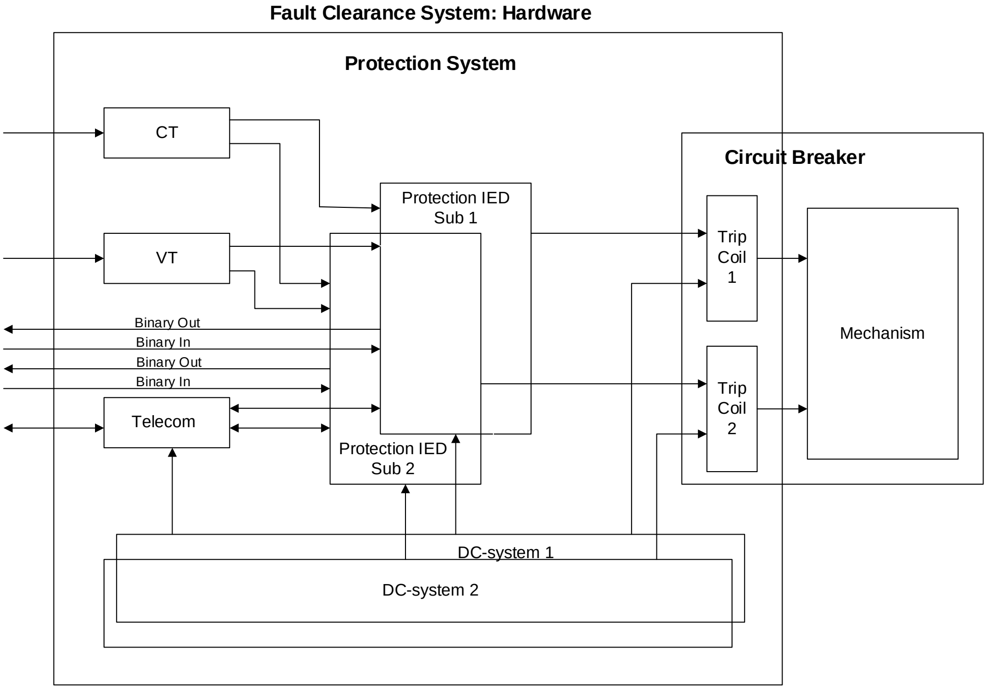


Figure 16 Principle for fault clearance system redundancy

It is essential that the two systems are separated as far as possible. The means mainly **galvanic separation** and information separation between sub 1 and sub 2. Some limitation of independence between the systems, normally accepted:

- Single current transformer with different cores feeding sub 1 and sub 2 protection units
- Single voltage transformer where sub 1 and sub 2 protection units are fed via different main fuses
- Single circuit breaker with separate trip coils for sub 1 and sub 2, where a breaker failure protection, tripping back-up breakers, is applied to each subsystem. It must be pointed out that the breaker failure protection will give additional delay of the fault clearance.

The redundancy principle is designed to assure disconnection of all faults even if one component fails to operate. This gives a high degree of dependability. However, if many protection units are applied in parallel there might be some risk of unwanted disconnection of the protected object, thus giving reduced security.

Normally the redundancy is considered only looking at the hardware. The experience is however that a non-negligible part of malfunctions of the fault clearance system, is due to “human errors”. This can be:

- Mistakes in the protection system design
- Mistakes in construction of the protection system
- Mistakes in wiring
- Mistakes in protection unit configuration
- Mistakes in protection unit parameter setting
- Mistakes during maintenance
- Mistakes in the physical setting Etc.

The risk of **“human errors”** is probably increasing as the complexity of the protection increases. To cope with this risk there should be some kind of “human redundancy”. This could be defined as “quality assurance”.

2.4 TRANSMISSION LINE PROTECTION PRINCIPLES

There are several principles to design transmission line protection. Below some of the commonly used principles are discussed.

2.4.1 Distance protection with communication scheme

The distance protection evaluates the apparent impedance from the relay point (CT and VT) to the fault point. The apparent reactance is seen as a distance to fault.

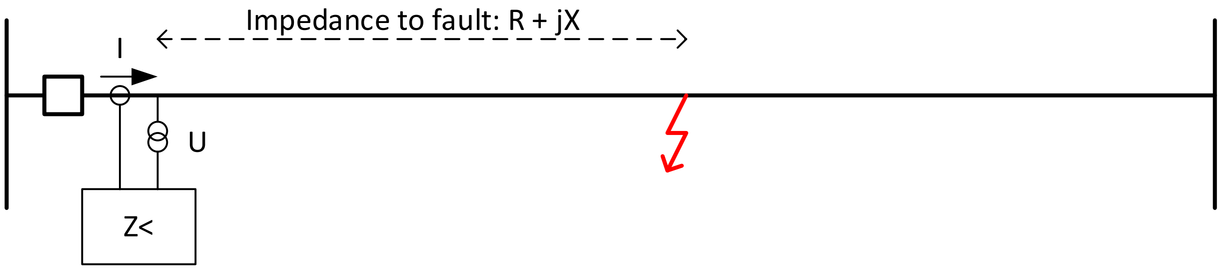


Figure 17 Distance protection application

The distance protection has several zones with different reach and operate time. One example of distance characteristic:

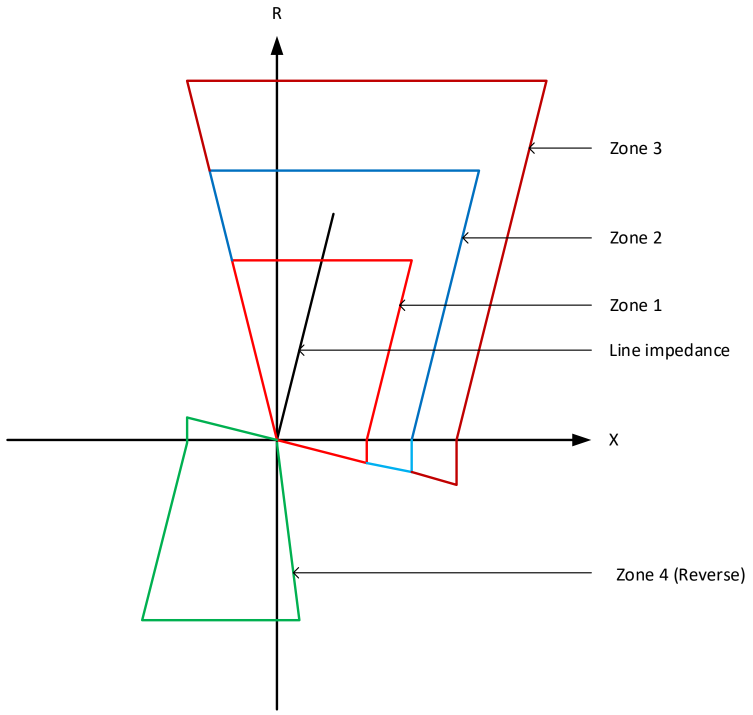


Figure 18 Distance protection impedance characteristic

The different zones can be described as:

Zone 1: cover about 85 % of the line reactance and must not overreach (not operate for faults on the busbar and beyond), No time delay

Zone 2: shall overreach the whole line, typical reactance setting about 120 % of the line reactance, Time delay: 0.4 s (often used value). The zone is also used in communication schemes.

Zone 3: can serve as back-up protection for objects connected to the adjacent line end. Time delay: in the range 0.8 – 2.0 s

Zone 4: The reverse looking zone can serve as back-up busbar protection and in some communication schemes. In the communication schemes logics for fault current reversal and weak end infeed requires the reverse looking zone.

The principle for reach setting and time delay is mainly not changed as new numerical distance protections are introduced. As the numerical protections have stable more stable distance and time delay operation values, there is a possibility to decrease the setting margins, especially the trip time difference between the zones.

The setting of zone 3 is normally based on short circuit calculations to assure that the zone covers the intended objects. At the same time, it must be assured that zone 3 does not trip due to high load on the protected object (line).

In transmission systems the distance protection is normally used in protection schemes using telecommunication between the protection units to enable fast fault clearance for all line faults. The communication link can be:

- Fiber optic communication
- Power line carrier
- Radio link

It is considered that fiber optic communication gives the most reliable scheme.

There are different principles for the communication schemes.

Underreaching communication scheme

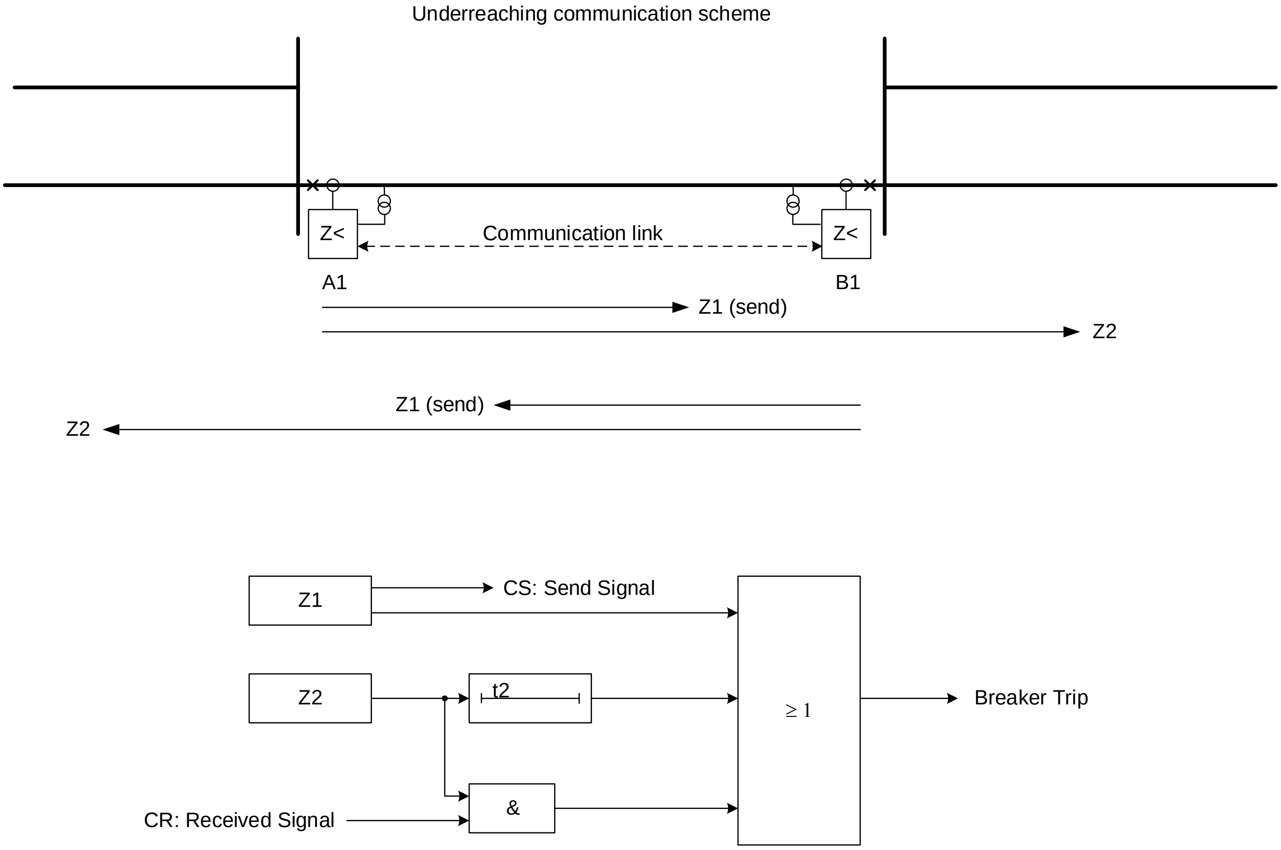


Figure 19 Underreaching communication scheme (PUTT)

The logic is identical on both line end units.

In the underreach communication scheme (PUTT) the underreaching zone 1 will send, without delay, a signal (CS) to the adjacent line end distance protection. When the distance protection receives the signal (CR) the zone 2 timer is bypassed and will trip without any delay. This scheme is used for long lines.

Overreaching communication scheme

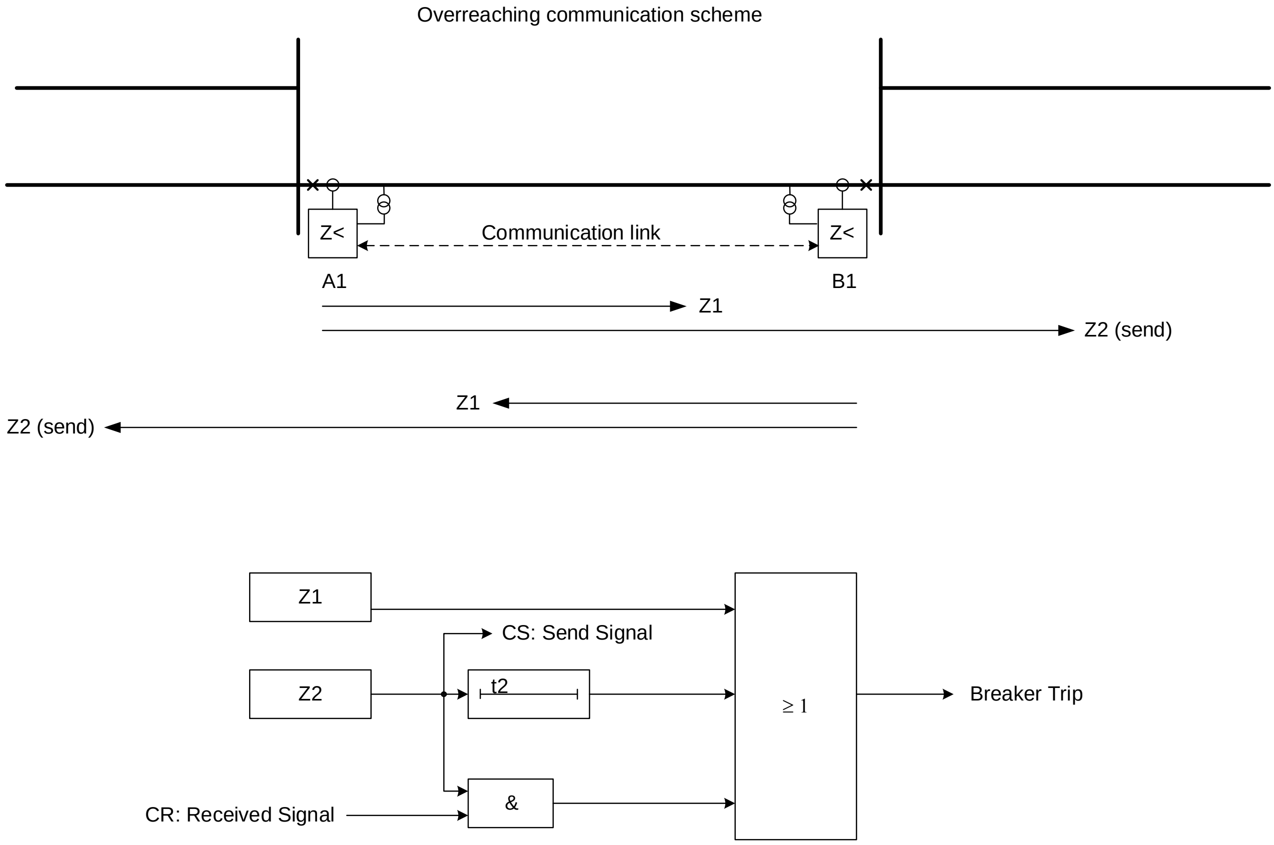


Figure 20 overreaching communication scheme (POTT)

In the overreach communication scheme (POTT) the overreaching zone 2 will send, without delay, a signal (CS) to the adjacent line end distance protection. When the distance protection receives the signal (CR), the zone 2 timer is bypassed and will trip without any delay. This scheme is used for short lines.

Blocking communication scheme

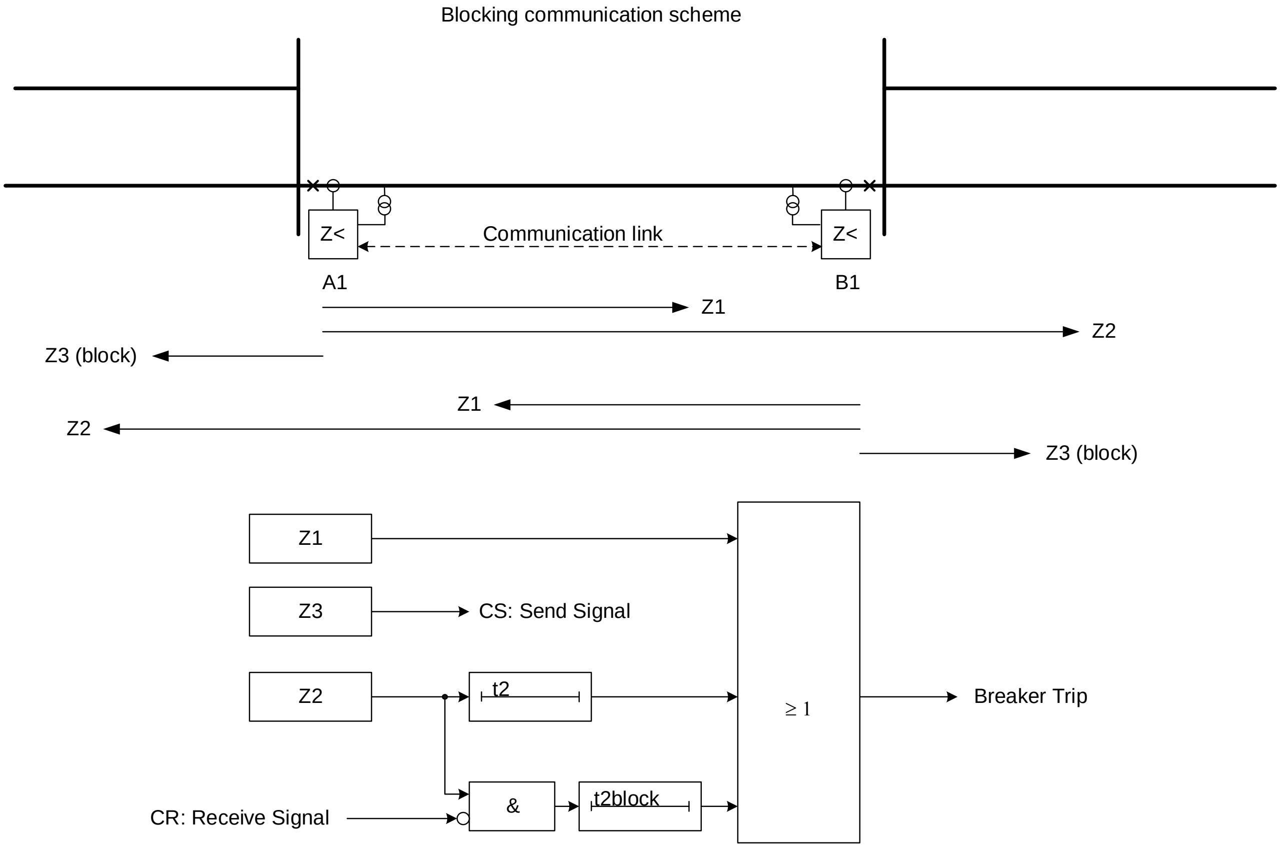


Figure 21 Blocking communication scheme

When a fault occurs on adjacent lines zone 3 (reverse) of the distance protection having the fault in reverse direction will sent, without delay, a blocking signal (CS) to the adjacent line end distance protection. The overreaching zone 2 has a time step (t2block) that will be blocked from the blocking signal received from the adjacent line end distance protection. t2block is set to a very short delay (about 70 ms), just to enable the blocking signal to be received. This system is not used in Sweden. The reason for this is probably that missed blocking signal might give unwanted trip (low security).

The distance protection used with different communication schemes have been used for very long time and it is the dominating transmission line protection. However, there are some difficulties:

The impedance reach accuracy is dependent on the source impedance in relation to the set impedance reach. A commonly used factor is the SIR: Source Impedance Ratio.

$$SIR = \frac{Z_S}{Z_M}$$

Where Z_S is the source impedance in the relay point and Z_M is the set impedance reach. Normally the impedances are considered as reactance. The protection manufacturers normally state that SIR shall be within the range 0.5 – 30 to guarantee the protection performance. This might be difficult to fulfil for **very short lines** (low Z_M) with very weak infeed (high Z_S).

The distance protection must be set for stability for apparent impedance at high load conditions and power oscillations. This is illustrated in the figure.

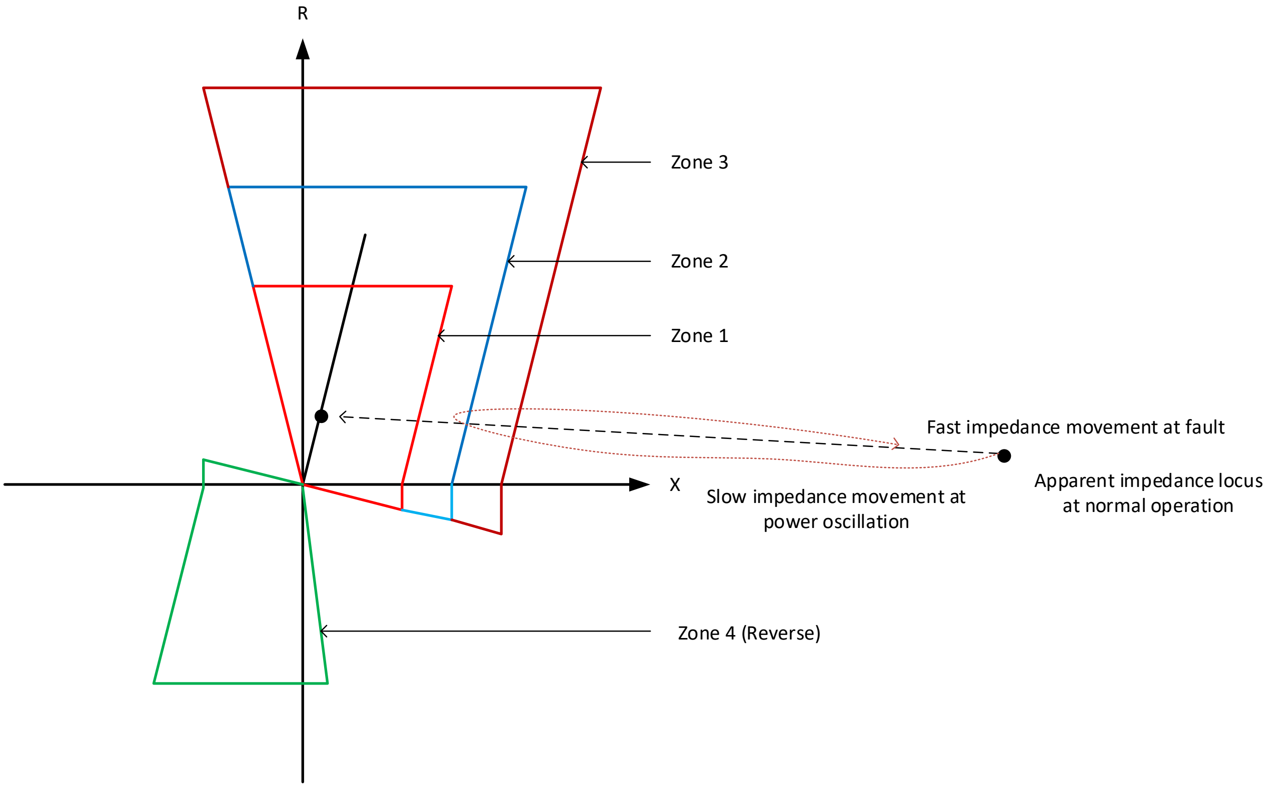


Figure 22 Distance protection apparent impedance movement at fault and at power oscillation

Distance protection have the option to integrate power swing blocking: the function will distinguish between a short circuit and an oscillation by measuring the "speed" of the apparent impedance movement into the distance protection zones. **This option is normally not used in the Swedish transmission system**.

2.4.2 Earth fault current protection with communication scheme

The earth fault current protection uses the residual current (zero sequence current: $3I_0$) out on the line to detect earth faults. As there is no or very small zero sequence currents during non-faulted conditions, the protection can be set to current levels lower that the load currents. The earth fault current protection can also have directional function, where the residual voltage (zero sequence voltage: $3U_0$) is used as directional reference (polarizing voltage).

In Sweden the earth fault current protection has 4 steps:

Step 1 (3I0>>>): Forward direction (towards line), Instantaneous operation, current setting is chosen to never overreach the line

Step 2 (3I0>>): Forward direction (towards line), delay: 0.4 s, current setting is chosen to always overreach the line but must be selective to other line protection out on the adjacent busbar

Step 3 (3I0>): Forward direction (towards line), delay: 0.8 s, current setting is chosen to be selective to other line protection out on the adjacent busbar

Step 4 (3I0 sensitive): Non-directional with inverse time delay characteristic, shall detect high resistive earth faults and series faults

The earth fault current protection has been used for long time with good experience. The main benefit is the better sensitivity compared to the distance protection.

The earth fault current amplitude is very dependent of the operational state of the transmission system: number of generators connected, lines in operation or not, switching state of directly earthed transformer. This means that comprehensive earth fault current calculations are necessary for selective and reliable settings of the protection. It is impossible to consider all possible states of operation in the transmission system. Therefore, the residual overcurrent protection without communication scheme, might not be used for fast fault clearance of low resistive earth faults. The directional residual overcurrent protection is however suitable in communication schemes.

The earth fault current protections are used in communication schemes with the same principles as for the distance protection.

2.4.3 Differential protection

New technology, especially concerning communication, has enabled the use of current differential protection for long transmission lines.

In some applications it is beneficial to use differential protection for transmission lines:

- Short lines
- Series compensated lines
- Multiterminal lines

One benefit with differential protection is the protection is absolute selective. All faults between the current transformers at the line ends will be detected and cleared. No time delay is needed for selectivity. The differential protection can also be set very sensitive as the load current will not give any differential current.

The drawback with differential protection is that it cannot serve as back-up protection for object connected to the adjacent busbar, especially the busbar.

In addition will the charging current of the line give some differential current. This should be considered in the setting of the differential protection sensitivity.

Modern numerical line differential protection often have the possibility to compensate for the charging current.

All differential current must be stabilized to avoid unwanted operation for external fault (outside the protected zone) with current transformer saturation.

It is of great importance that the communication channel, to be used by the differential protection, is reliable and accurate.

2.4.4 Transmission line protection design

The transmission line protection can be designed in many ways. Here some alternatives are described.

The basic design is that the fault clearance system has two separated subsystems, sub 1 and sub 2. Both systems have total functionality, which means that the fault clearance shall fulfil all requirements even if one subsystem is out of service.

The normally used design is that the protection system has the same functionality in both sub 1 and sub 2. In Sweden it is however stated that the protection units shall be of different make (different manufacture). Earlier was stated that one subsystem should have electromechanical protection relay and for the other subsystem electronic protection relays were accepted. In the market today almost all protection units are of numerical type.

Normal functionality for both subsystems:

Distance protection with at least 4 zones, where one zone shall be able to have reverse direction. Three forward zones are normally used where zone 1 (instantaneous) and zone 2 (0.4 s delay) shall cover the whole line length. Zone 2 is also back-up protection for adjacent busbar fault. Zone 3 (1.2 s delay) is used as back-up protection for other objects connected to the adjacent busbar.

The **distance protection communication scheme** uses permissive underreach acceleration scheme (PUTT: Zone 1 sending, and Zone 2 accelerated) for long lines and permissive overreach acceleration scheme (POTT: Zone 2 sending, and Zone 2 accelerated) for short lines.

Four step earth fault protection where step 1, 2 and 3 have directional function normally set in forward direction. Step 1 (instantaneous) and step 2 (0.4 s delay) shall detect all low resistive earth faults on the line. Step 2 is also back-up protection for adjacent busbar earth faults. Step 3 (0.8 s delay) is used for detection and selective trip of resistive earth faults not detected by step 2. Step 4 is a nondirectional sensitive earth fault function, used for detection and clearance of very high resistive faults and series faults.

The **earth fault current protection communication scheme** uses permissive underreach acceleration scheme (PUTT: Step 1 sending, and Step 2 accelerated) for long lines and permissive overreach acceleration scheme (POTT: Step 2 sending, and Step 2 accelerated) for short lines.

For short transmission lines (<25 km) and all cable lines current differential protection are added to both sub 1 and sub 2. The distance protection zone 1 is blocked in normal operation when differential protection is used.

2.5 TRANSMISSION SYSTEM BUSBAR PROTECTIONS PRINCIPLES

In case of short circuit or earth fault on busbars in the transmission system, fast and selective fault clearance are extremely important for the power system security.

2.5.1 Busbar protections

All transmission system busbars are protected by means of busbar protection of differential protection type. These protections give fast and selective fault clearance of busbar short circuits and earth faults. The design of the busbar protection for a single busbar or in a double circuit breaker switchyard, is quite straight forward.

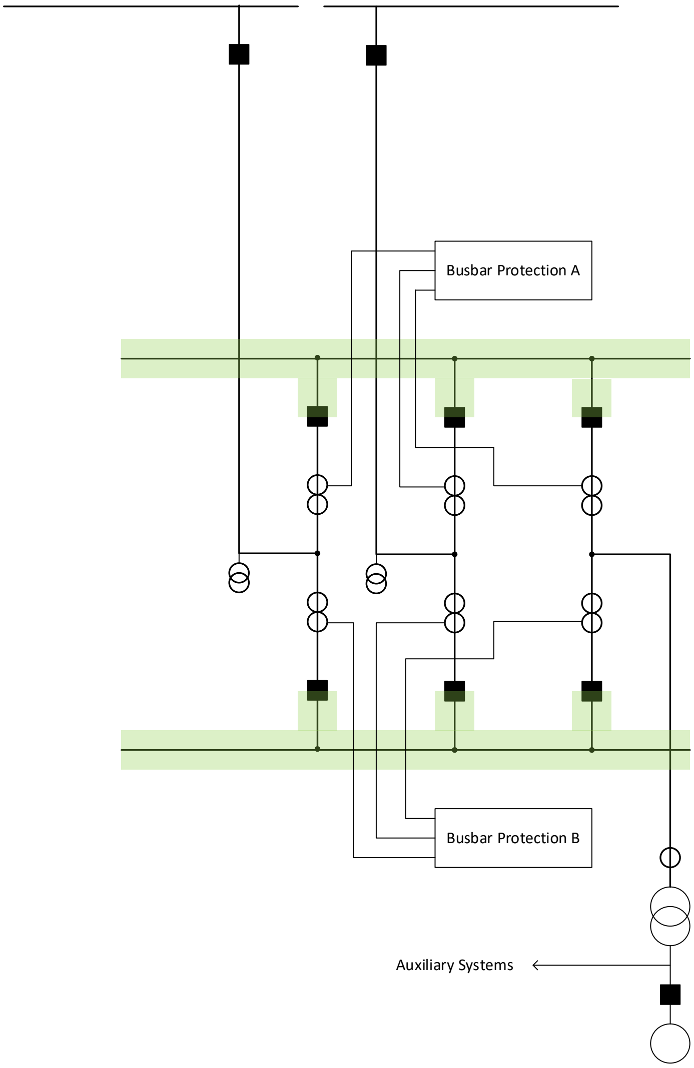


Figure 23 Busbar protection of a double breaker switchyard configuration

In switchyards with ABC busbar configuration, the busbar design is more complicated as there must be switching of current between the busbar protection and switching of trip signals, depending on the connection of each bay (to busbar section A or B). One example of ABC busbar configuration:

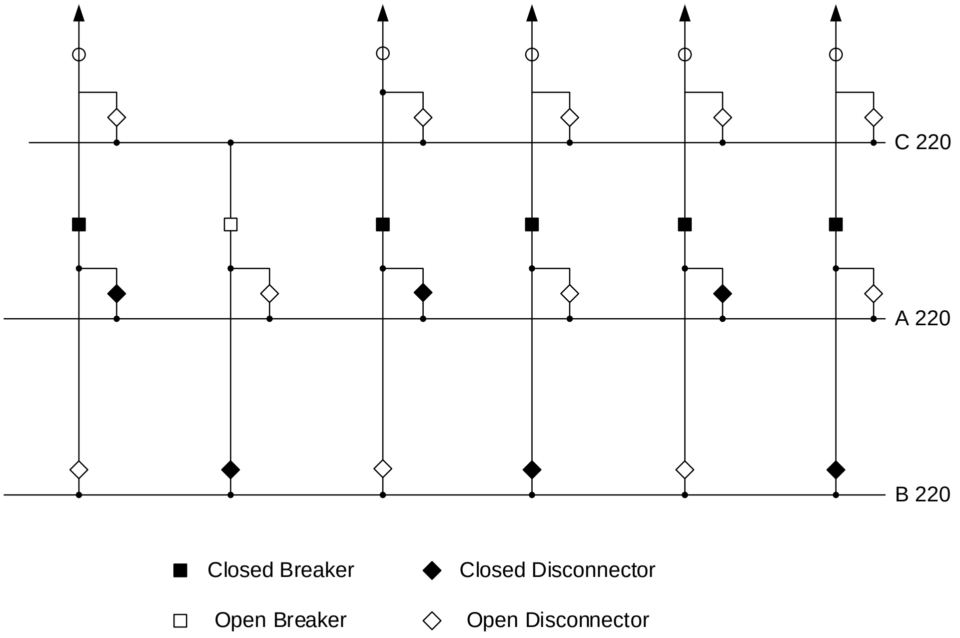


Figure 24 Busbar protection of a ABC switchyard configuration

The logic for switching of the current and trip signals are controlled by auxiliary contacts in the breakers and disconnectors. There might be **risk for error in this switching logic**. There is however supervision in the busbar protections, in modern numerical busbar protections, to identify faults in the switching. A normally used option to prevent unwanted operation is to use a check zone, covering all objects, to release the busbar protection function. This additional criterion for trip can be used also for non-numerical busbar differential protections.

In the Swedish transmission system, all new switchyards are built with two-breaker configuration. Many older switchyards are however built with ABC configuration.

In some cases, a simplified design of the switchyard can be used. An example connecting a nuclear generating unit can be shown as:

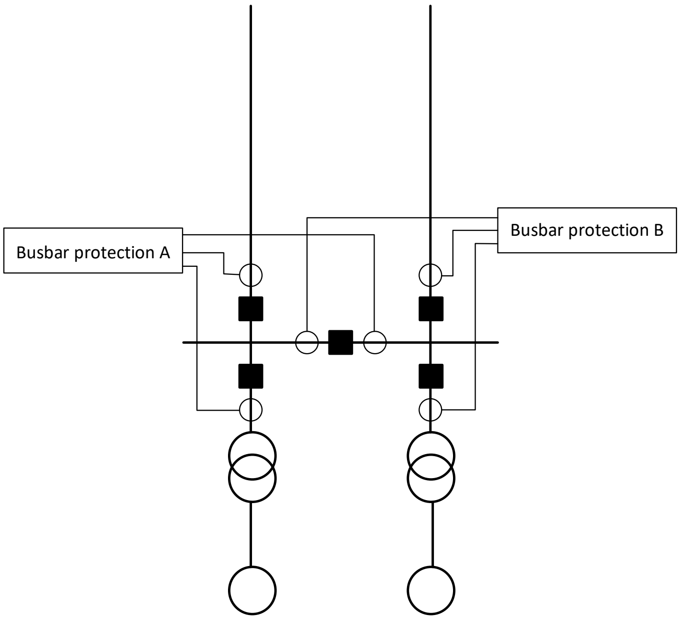


Figure 25 Simplified busbar configuration

This solution gives a relatively simple busbar protection scheme. The drawback is that a fault between the sectionalizing breaker and one of its CTs will result in the trip of both units. This can be accepted if the power system is dimensioned for trip of both the generating units.

2.6 TRANSMISSION SYSTEM TRANSFORMER PROTECTION PRINCIPLES

The transmission system transformer connects the sub-transmission systems (regional systems). The transformer protections shall fulfil the N-1 criterion, meaning that transformer faults shall be detected and cleared even if one component of the fault clearance system fails to operate.

2.6.1 Transformer differential protection

The transformer differential protection is the main protection for internal short circuits and earth faults. The transformer differential protection shall:

- Be stabilized for CT saturation
- Be stabilized for transformer inrush current
- Be stabilized for overexcitation
- Be stabilized for external earth faults giving false differential current to the protection as the neutral point current is normally not measured

In older type of transformer differentials protections, the stabilization has not been fully reliable, with risk of unwanted trip function. In numerical protections, the rate of unwanted trip from transformer differential protection has decreased.

2.6.2 Under-impedance protection

The under-impedance protection is back-up protection for internal short circuits and short circuits on adjacent objects. The under-impedance protection shall be similar to line distance protection.

2.6.3 Residual overcurrent protection

Both current in the neutral as well as residual current ($\sum I_{phase}$) shall be available. The protection shall be stabilized for inrush current.

2.6.4 Phase Overcurrent protection

Normally should not phase overcurrent protection be used for transmission system transformers but could be accepted in special cases.

2.6.5 Buchholz protection

A very reliable protection function normally used for all oil filled transformers.

3 Description and evaluation of the existing protection systems: Generator and unit transformer protection

3.1 FAULTS AND OTHER INCIDENTS IN THE NPP WITH INFLUENCE ON THE TRANSMISSION SYSTEM

Every unwanted disconnection of a big power plant will jeopardize the power system security. Therefore, it is essential to minimize the risk of such unwanted incidents.

In the power plant unit, there are many different protection functions to cope with both real faults (short circuits and earth faults) and to detect situations that might cause severe fault if no action is made. The large number of protection functions are necessary. Redundancy is required for most of the protection functions. Many protection functions will result in a relatively large risk of unwanted protection trip.

The traditional design of generator and unit transformer protection is to apply N-1 criterion. For most of the protection functions there shall be at least two separated fault clearance systems. Trip is activated if at least one of two parallel functions are activated. In some cases, the protection function is realized in the transmission system (unsymmetrical conditions in the power system giving negative sequence current, shall primally be detected by transmission system protections).

For a generating unit, the following faults/critical operation shall be detected and cleared with the possible protection functions:

Table 1 Generator Protections

Fault/critical operation state	**Protection function 1**	**Protection function 2**	**Note/Also**
Generator stator short circuit	Generator differential protection (Idiff>)	Underimpedance protection (Z<)	I>/U<, U<
Generator stator earth fault < 90 % of generator winding	Neutral point overvoltage protection (UN>)	Residual overvoltage protection (3U0>)	
Generator stator earth fault protection, covering earth faults close to the neutral point	100 % stator earth fault protection using neutral point injection	100 % stator earth fault protection using 3rd harmonic neutral point voltage	Only one protection function considered necessary
Generator voltage buswork short circuit	Unit differential protection	Generator underimpedance protection	
Generator overload	Thermal overload protection (Ith>)		Continuous evaluation of temperature
Generator unsymmetrical current	Negative sequence overcurrent protection (Insc>)		
High frequency	Overfrequency protection (f>)		
Low frequency	Underfrequency protection (f<)		
High voltage	Overvoltage protection (U>)		
Low voltage	Undervoltage protection (U<)		
Underexcitation	Underexcitation protection impedance or admittance based		Other principles available based on directional current or power
Pole slip/out of phase	Pole slip protection impedance based		
Reverse power	Reverse power protection (P <-)	Low forward power protection (P ->) (alternative)	Turbine protection/ high accuracy measurement

Fault/critical operation state	**Protection function 1**	**Protection function 2**	**Note/Also**
Inadvertent energization of generator	Overcurrent protection activated at no running generator I>(controlled)		Not used in Swedish NPP:s
Overexcitation	V/Hz protection		
Short circuits in the external grid	Generator underimpedance protection (Z<)		The requirement of this protection function is dependent of the transmission system redundancy principles.
Earth faults in the external grid	Unit transformer neutral point overcurrent protection (IN>)		The requirement of this protection function is dependent of the transmission system redundancy principles.
Unit transformer short circuit	Transformer differential protection (Idiff>)	Unit differential protection	Also I>, Z<
Generator voltage buswork short circuit	Unit differential protection	Generator underimpedance protection	
Unit transformer high voltage winding earth fault	Restricted earth fault protection (INdiff)	Neutral point overcurrent protection (IN>)	
Unit transformer high voltage winding earth fault	Restricted earth fault protection (INdiff)	Neutral point overcurrent protection (IN>)	
Unit transformer low voltage winding earth fault	Residual overvoltage protection (3U0>)		The generator stator earth fault protection detects the fault in normal operation

Table 2 Unit Transformer protection

Fault/critical operation state	Protection function 1	Protection function 2	Note/Also
Unit transformer high voltage winding earth fault	Restricted earth fault protection (INdiff)	Neutral point overcurrent protection (IN>)	
Unit transformer high voltage winding earth fault	Restricted earth fault protection (INdiff)	Neutral point overcurrent protection (IN>)	
Unit transformer low voltage winding earth fault	Residual overvoltage protection (3U0>)		The generator stator earth fault protection detects the fault in normal operation

Some of the protection functions are linked to **critical operational states** of the external system, such as unsymmetrical operation (negative sequence current), voltage deviation, frequency deviation and pole slip. Many of these unnormal situations should be detected and cleared by protection and control systems in the transmission systems. In such cases there might be less need for redundant protection in the generating unit.

NPP generating units are sometimes connected to the transmission system via a radial line, with the unit circuit breaker located at the connecting switchyard. Therefore, some of the unit transformer protection functions are located at the corresponding bay. Possible protection functions (fault current fed from the transmission system):

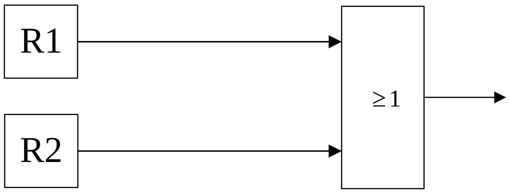
- Line differential protection (can include the unit transformer)
- Line distance protection
- Directional earth fault overcurrent protection

3.2 GENERATING UNIT PROTECTION REDUNDANCY PRINCIPLES

For clearance of fault current fed from the generating unit, at faults in the connection transmission system the normal fault clearance is achieved by the transmission system protections. When transmission lines have protection with full redundancy, no back-up protection in the generating unit protection are needed for this purpose. For fault in the busbar connecting the generating unit, it is reasonable that the generating unit provide back-up protection.

The big number of protection functions in the generating unit gives **relative high risk of unwanted disconnection of the generating unit**, due to false operation of protection function.

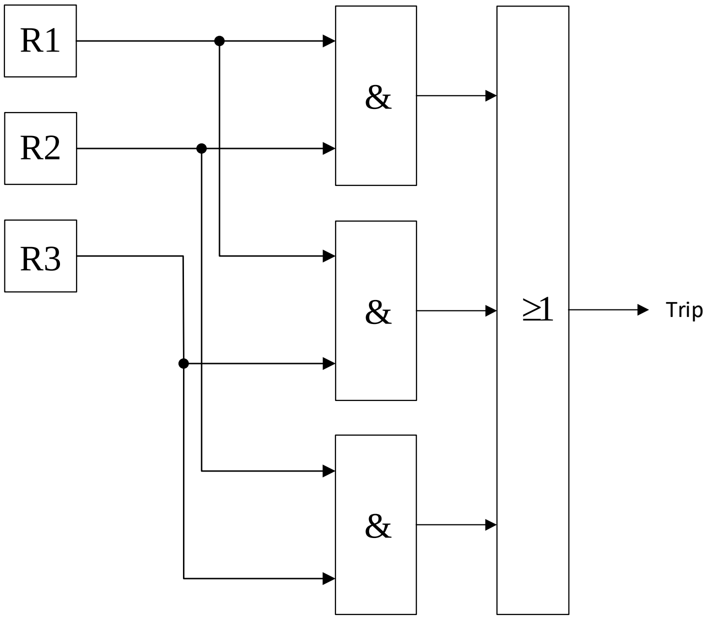
The normally used principle, **1 out of 2 logic**, can be visualized as:



R1 and R2 are the two separated fault clearance systems. The OR-gate is in praxis the separated trip coils in the circuit breaker.

Principles that can be used to increase the security without significant reduction of the dependability is to use other principles such as:

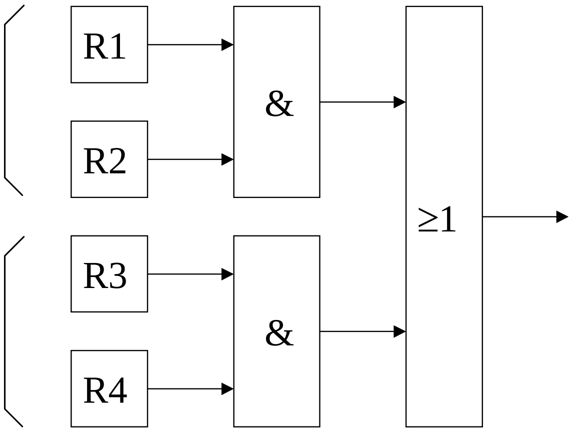
2 out of 3 logic



R1, R2 and R3 are three separate protection systems. Theoretically, it can be concluded that trip is given for a real fault, even if one of the three protection systems are out of order. In can also be seen that false operation of one of the three protection systems will not give unwanted trip.

The drawback of this system is that there will be some connection between the separate fault clearance systems in the &-gates. Furthermore, in this solution the circuit breaker must have three trip coils. Furthermore three separated should be used.

Dual 2 out of 2 logic



R1, R2, R3 and R4 are four different protection systems, where R1 and R2 belong to subsystem A and R3 and R4 belong to subsystem B. Subsystems A and B are totally separated.

This system can be applied to the existing fault clearance systems with totally separated subsystems A and B. This principle was applied to Oskarshamnsverket Block 2. The system included all protection functions for generator G2, Unit transformer T2, Auxiliary transformer T20 and Auxiliary transformer T21.

It must be stated that four parallel protection functions are unrealistic for some of the faults, for example rotor earth fault with injection.

3.3 POWER PLANT AUXILIARY SYSTEM PROTECTION

The auxiliary system is essential both for the normal operation of the NPP and for the safety systems. Therefore, it is essential that the fault clearance system has high degree of security. The auxiliary system is divided in several separated subsystems. It is however important that the fault clearance is reliable. It is especially important that external disturbances do not cause common cause incidents. This is a risk when the parallel auxiliary systems are fed from the generator bus.

The principle design of the primary auxiliary system and its connection to the external grid is shown in the figure.

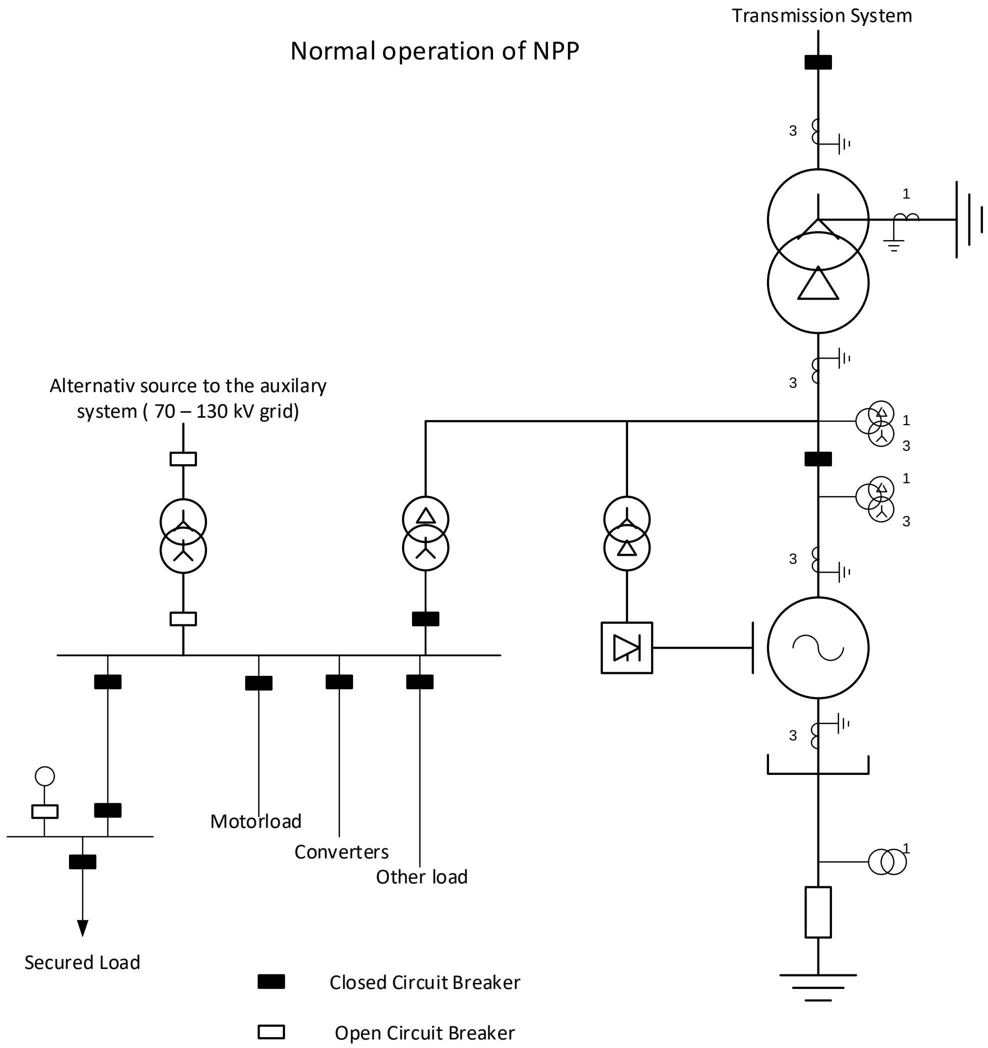


Figure 26 Example of NPP auxiliary system connection

It should be observed that only one of the auxiliary subsystems are shown.

There are several modes for the auxiliary system:

- Normal operation where the auxiliary system is fed from the generator and unit transformer via the station transformer
- Operation with the generator taken out of service and the auxiliary system fed from the unit transformer via the station transformer
- Operation with the generating unit taken out of service (generating unit revision) and the auxiliary system fed from a sub-transmission network via a stand-by transformer.
- Emergency operation of the auxiliary system secured load from the local diesel generator
- House-load operation

The short circuit protection in the auxiliary system is shown:

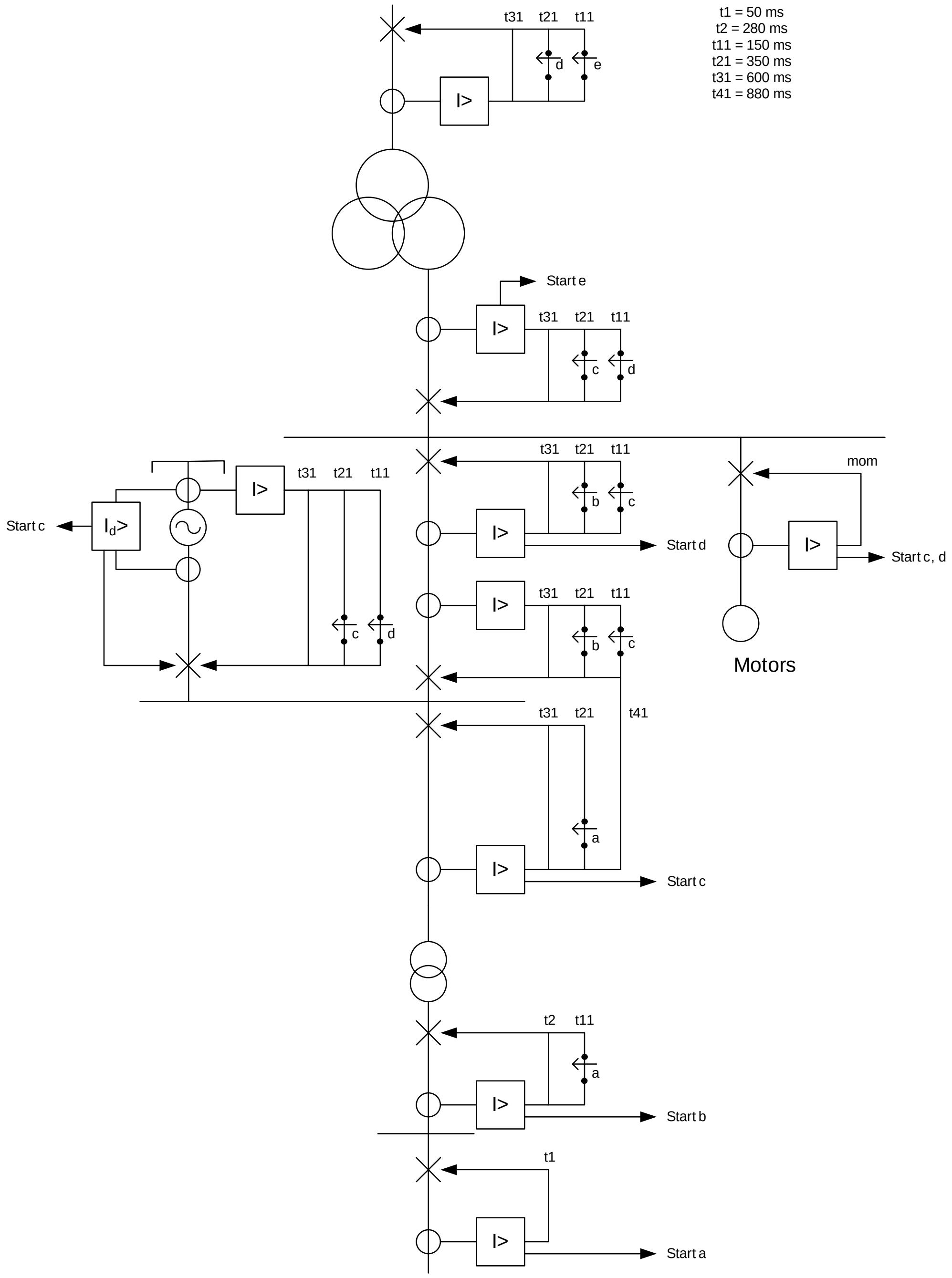


Figure 27 Principle of auxiliary system short circuit protection

The system uses blocking logics to achieve selective clearance of short circuits. The system will be very complicated as it must rely on the comprehensive communication system.

We assume, as realistic, the following data for the different parts of the fault clearance system:

- Phase overcurrent protection: pickup time: ≤ 25 ms, reset time ≤ 60 ms
- Circuit breaker: opening time: ≤ 60 ms (three periods)

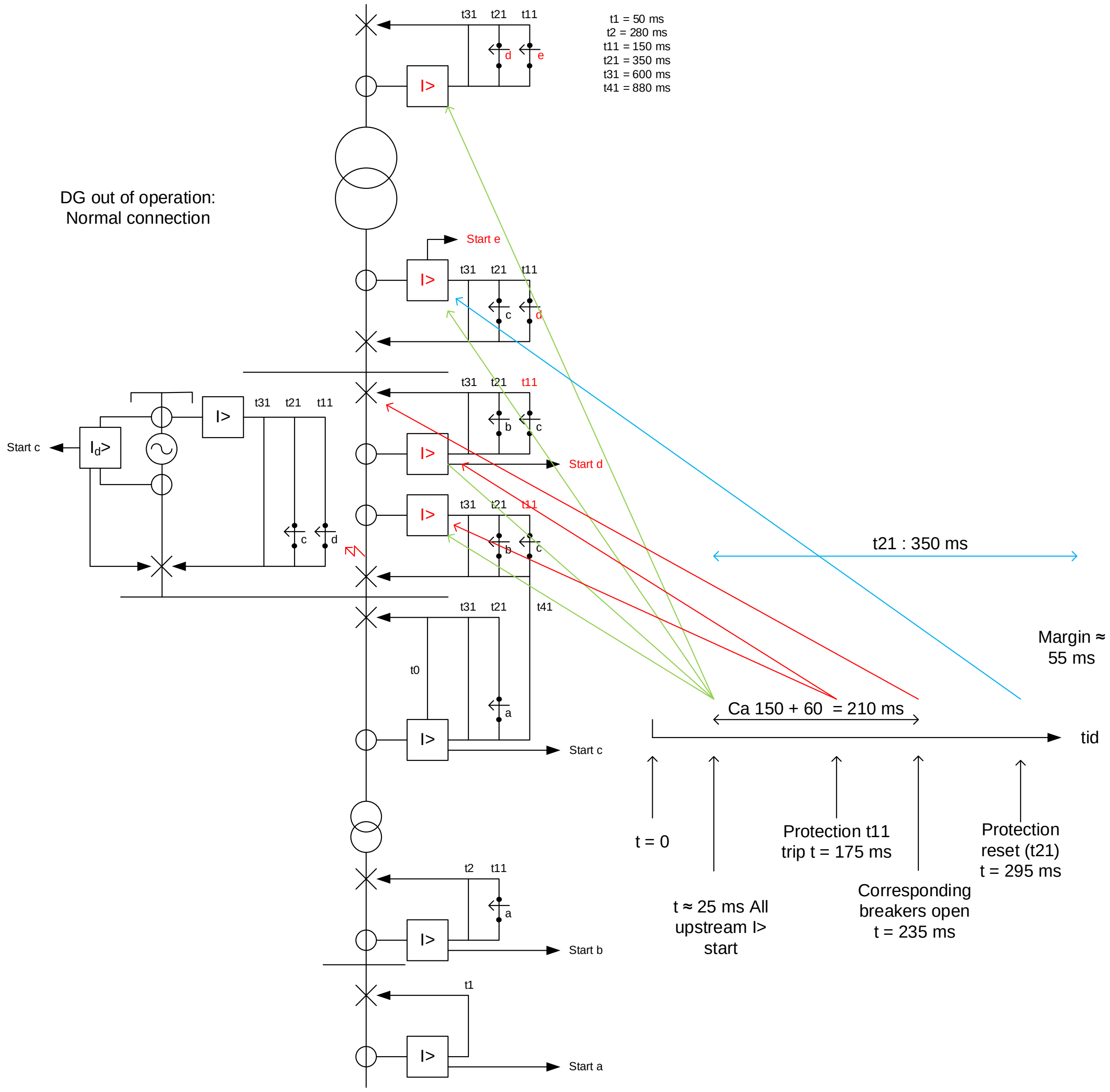


Figure 28 Example of time sequence at a short circuit

The selectivity margin seems to be shorter than what is required to guarantee selectivity. Often a margin of 300 ms is used.

There are faults and other operational states that will influence the auxiliary system:

- Short circuits in the external power system
- Earth faults in the external power system
- Unsymmetrical conditions in the external power system

Unwanted disconnection of auxiliary system must be avoided if any external fault/event is temporary (continued operation after fault/event). The risk of unwanted trip/unwanted switching can be due to:

- Low voltage due to short circuits/earth faults in the external grid
- Motor restating/reacceleration currents after faults in the external grid
- Unsymmetrical condition

3.3.1 External short circuit scenarios

In case of normal fault clearance time, the voltage profile in the auxiliary system can be:

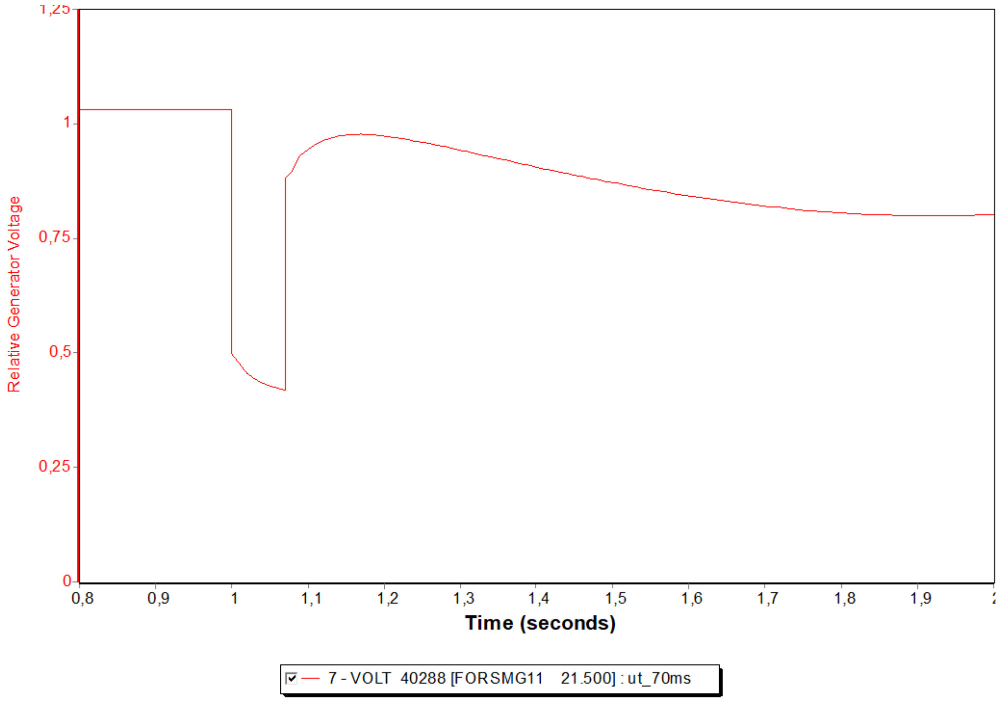


Figure 29 Example of generator voltage at transmission system short circuit

It can be seen that the voltage during the sequence after fault clearance will be down to 0.8 pu.

There is a small risk of long fault time (up to 450 ms) in case of short circuit in the transmission system. This can be the case for a short circuit between the line current transformer and the line circuit breaker, in a remote station where the fault is cleared after distance protection zone 2 operation. In many cases there is however shorter fault clearance time if the busbar protection send acceleration signal to the remote end distance protection (zone 2). A possible voltage profile (generator voltage level) for a fault with longer fault clearance time than CCT (Critical fault Clearence Time):

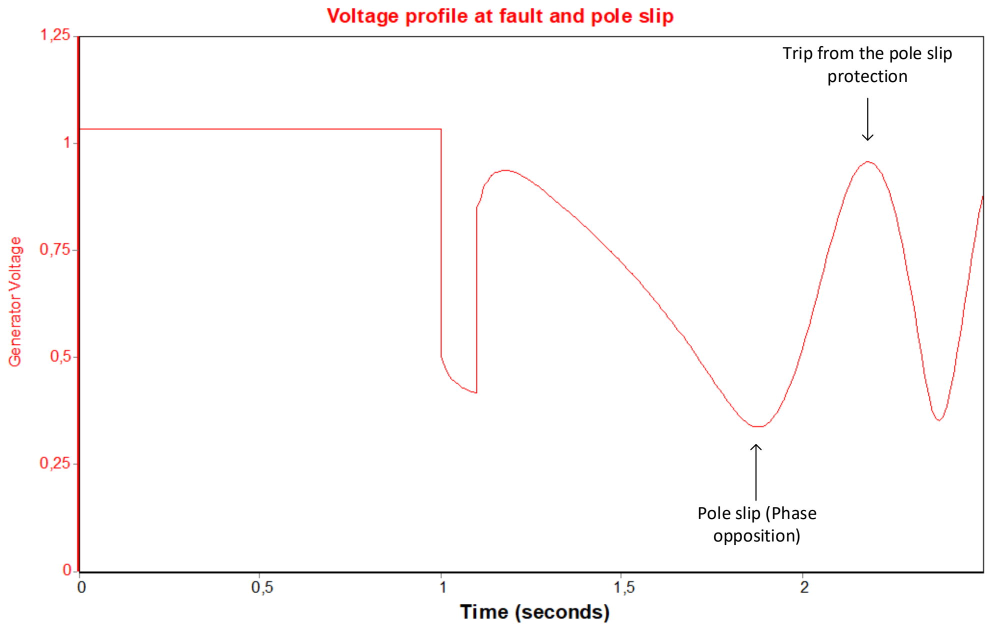


Figure 30 Example of generator voltage at pole slip

The generator pole slip protection sends trip signal to the unit breaker. Normally the unit breaker is tripped at first pole slip (setting of the pole slip protection). It is here assumed that the pole slip center is within the generating unit (generator and unit transformer). The aim is to achieve house-load operation where the generator feeds the auxiliary systems.

Consideration: What happens during the period of low voltage (about 1 s in the example). Is there a risk of large recover voltages causing overcurrent protection trip of the station transformer?

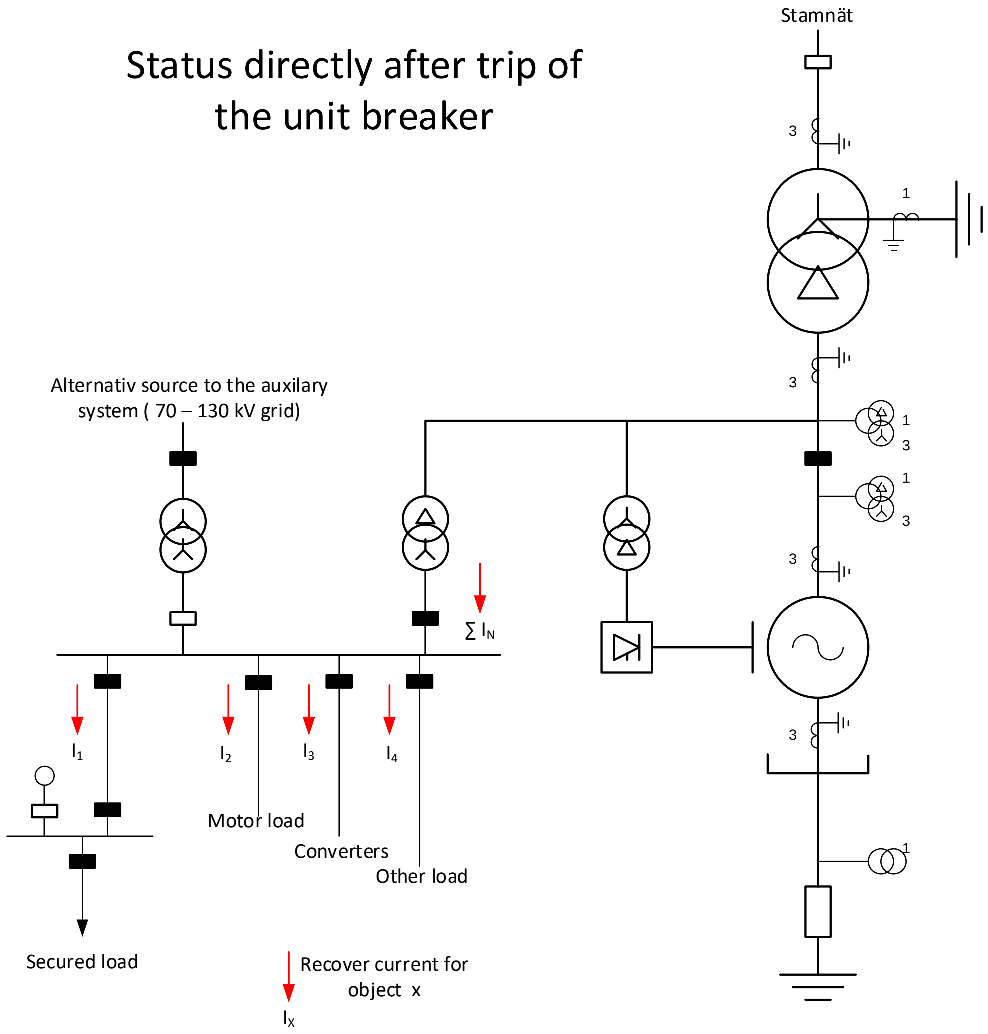


Figure 31 Recover currents after transmission system fault clearance (unit breaker trip)

1. The fault occurs giving voltage decrease in the auxiliary system. During this sequence the connected motors will slow down.
2. The primary fault disconnects, and the motors regain full voltage and reaccelerate. The motor current, for each motor at this time, might be in the range of the start current. The phase overcurrent protection of the motors is set larger than the start current, i.e. these protections does not pick up. In the auxiliary system there are several motors connected to each subsystem, reaccelerating at the same time. Therefore, there is a risk that the total reacceleration current exceeds the pickup current of the station transformer phase overcurrent protection.
3. The station transformer phase overcurrent protection might give unwanted trip after its shortest time delay, as no block signal is received to these protections.

It should be noted that the risk is worst in the cases when the fault time, before disconnection of the primary fault, exceeds the CCT giving pole slip condition for the generator and the unit shall transfer to house load operation.

3.3.2 Unsymmetrical conditions in the external system

Unsymmetrical conditions in the transmission system can occur due to different reason. Series faults can be caused by circuit breakers or disconnectors with one or two open phase condition. The consequence of this is that negative sequence currents will flow in rotating machines, causing thermal stress on rotor windings and mechanical vibrations. In the auxiliary system negative sequence current might give trip of motors if the motors have negative sequence protection. For motors not having negative sequence overcurrent protection the unsymmetrical condition can lead to overheating and damage of the motor.

Below a possible sequence, caused by transmission system unsymmetrical conditions, are visualized.

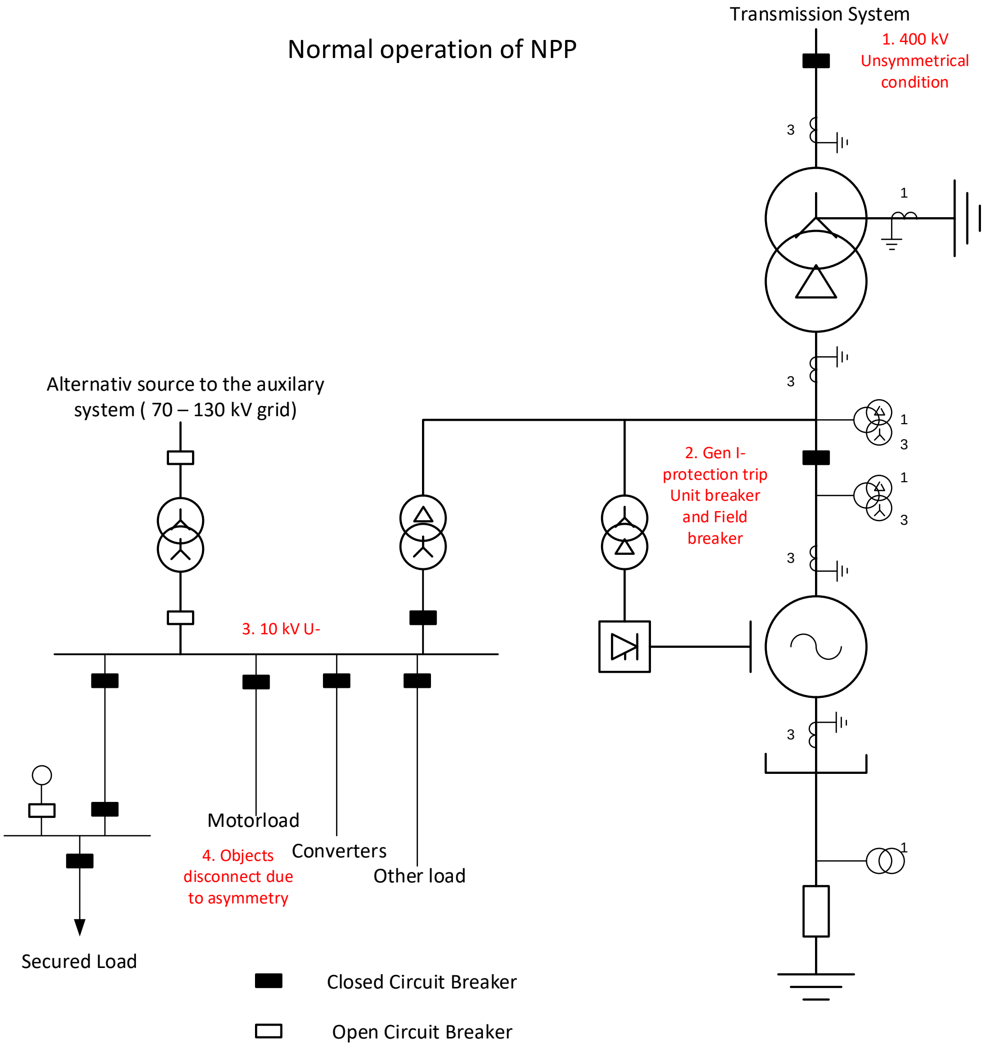


Figure 32 Unsymmetrical voltage influencing the auxiliary system

The generator negative sequence protection is assumed primary to trip the unit breaker, to enable house-load operation.

During a sequence as indicated it is essential that there is **selectivity** between the negative sequence protections on the main generator and the motors and other objects connected to auxiliary power system. The time characteristic of the generator negative sequence protection, tripping the unit breaker, can be according to the characteristic:

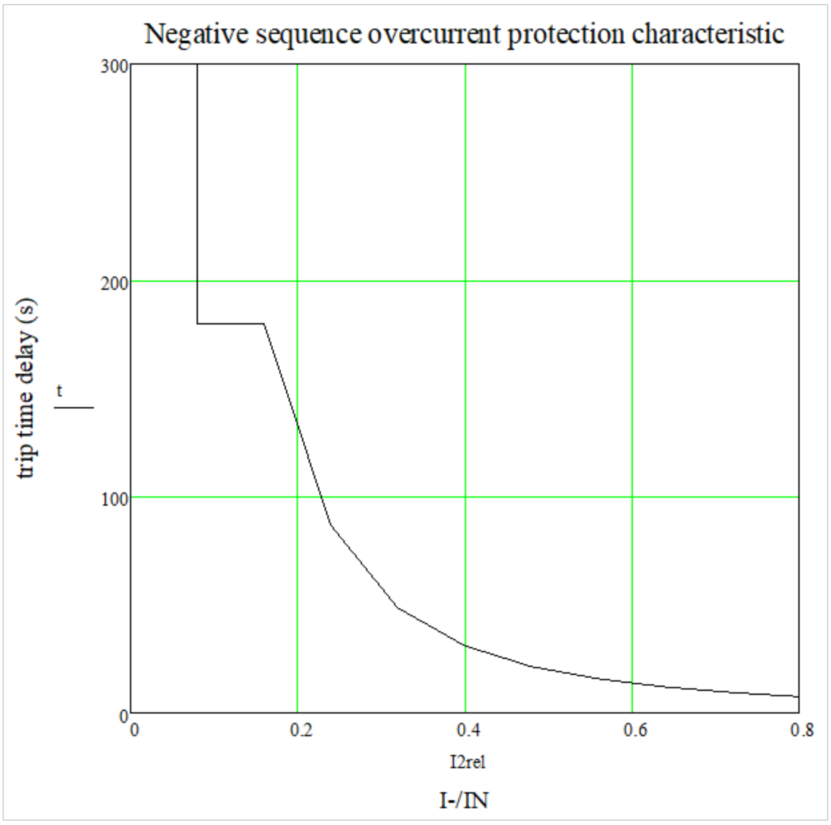


Figure 33 Negative sequence overcurrent protection time characteristic

For relatively small values of the negative sequence current the operation time will be in the range of minutes. During a situation like this it is difficult to predict the negative sequence current for the auxiliary system objects.

Old motor protection often has constant time delay characteristic. This means that there might be risk of trip of auxiliary system object before operation of main generatort negative sequence current protection. Modern motor protections can be used with inverse time characteristic for the negative sequence current protection.

4 Identification of protection system improvements

4.1 TRANSMISSION LINE PROTECTION REDUNDANCY PRINCIPLE

Investigate the possibility to reduce the number of parallel protection functions in the transmission system, to **increase security** (high probability of no unwanted disconnection of transmission system objects). With modern technology the activation of protection functions can be adaptive: for example, if one subsystem is taken out of service for maintenance, additional functions in the remaining subsystem can be activated.

Proposal of protection functions that might be taken out:

- Residual protection in one sub system $3I_0 >$
- Distance protection zone 3 Z<
- Generator Voltage controlled overcurrent protection I>/U< (if transfer trip from 400 kV bay connecting the unit)

4.2 GENERATING UNIT PROTECTION REDUNDANCY PRINCIPLE

To increase the generating unit protection security a new redundancy principle should be used. The dual 2 out of 2 principle is proposed. In implementation of this principle it is essential to diversify between every protection function for each fault/event type.

4.3 HUMAN REDUNDANCY

For redundant protection systems the parameter setting and other design related tasks, should be made by different persons/organizations, independent from each other. This is proposed to limit the risk of systematic human errors. Alternatively, deep review procedures can be used (as today?)

4.4 EQUIPMENT END OF LIFETIME

In case of protection units reaching their end of lifetime exchange should be planned.

Exchange of the old protection systems to modern numerical technology will give new advantages:

- Self-supervision of the protection unit reducing the time with devices having “hidden” faults
- Self-supervision of the protection unit reducing the need for maintenance (but not to zero maintenance)
- Increased accuracy
- Fault recording/logging enabling efficient disturbance analysis

- Reduction of the number of protection/control devices
    - Less objects that can be faulted
    - Less external wiring
- Possibilities of better adaptation of the protection functions as new protection functions have increased flexibility (example: change of setting parameters depending on operation state)
- In modern generator protection devices, many of the protection functions have been improved
    - Differential protection functions have additional options to prevent unwanted operation at external faults and CT saturation
    - Increased flexibility of generator under impedance protection: fault loop selection, characteristic offset possibilities, load encroachment
    - Separated overload protection for stator (measuring stator current) and rotor (measuring rotor current)
    - Possibility to tailor-make protection functions/logics using configuration tool. In the numerical protection it is possible to integrate and configure software logics cooperating with protection functions.

Possible disadvantages of numerical protections:

- Sensitivity for electromagnetic transients (the relay manufactures have made big improvements in this area compared to the first electronic protections)
- The complexity of the numerical protections increases the risk for “human errors” in setting and handling of the protection unit.

4.5 AUXILIARY SYSTEM PROTECTION PRINCIPLE

Introduction of differential protections as short circuit protections in the auxiliary systems, enabling simplification (exchange) of the overcurrent protection blocking system used today (see 3.3).

- Cable differential protections
- Transformer differential protections
- Busbar differential protections
- Motor differential protection (large motors)

A total short circuit protection system can be designed as shown in the figure. Delayed overcurrent protection can serve as backup.

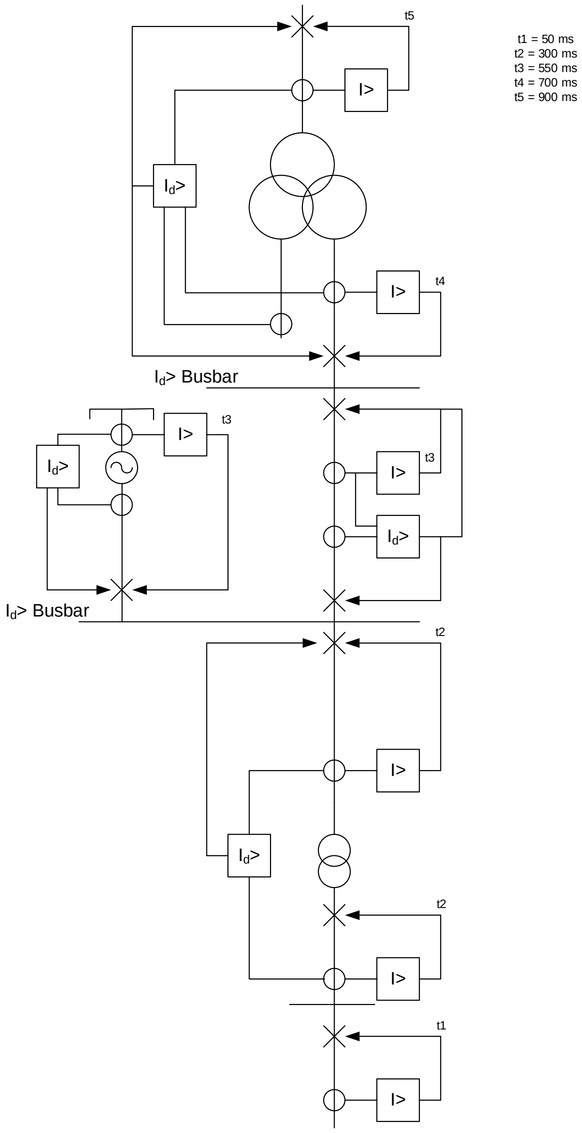


Figure 34 Proposal 1 for changed short circuit protection principle

Further simplification can be to have backup at station transformer level only.

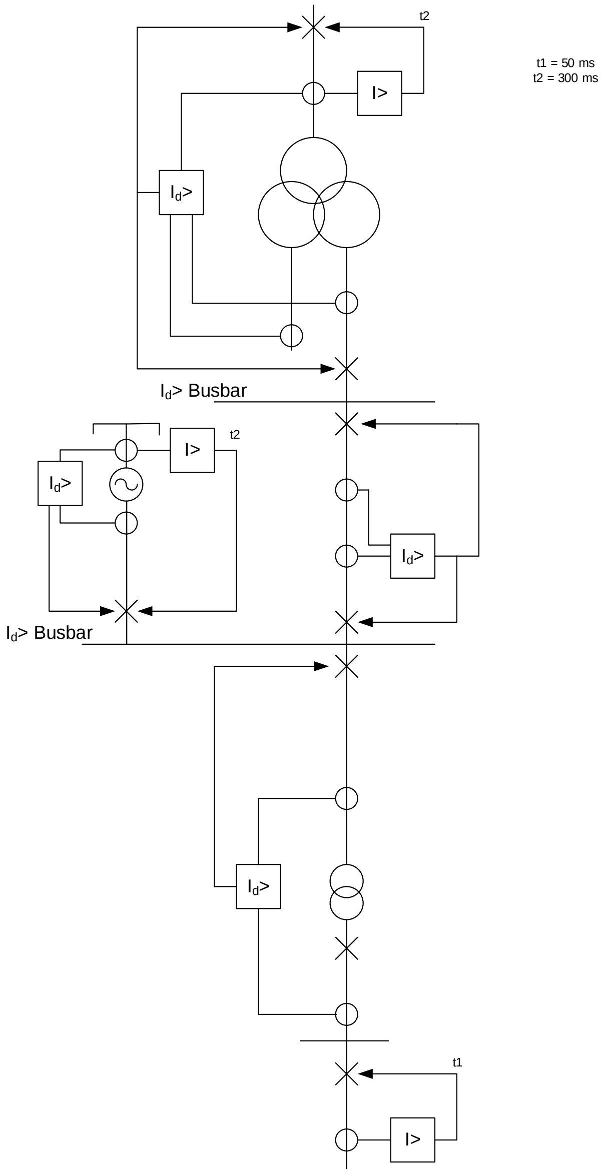


Figure 35 Proposal 2 for changed short circuit protection principle

Introduction of directional earth fault current protection with blocking principle for cables in the auxiliary systems. The system is earthed via resistance connected to the neutral point of the station transformer or an earthing transformer. There is also neutral point resistor connected to the diesel generator neutral point (at reserve operation)

The protection principle is based on the use of directional earth fault current protections where each end of the cable has two directional protection instances, one in forward direction giving trip after a set delay t1, and one in reverse direction giving block after a set delay t2. The following is giving selectivity: $t1 > t2$.

The principle is shown:

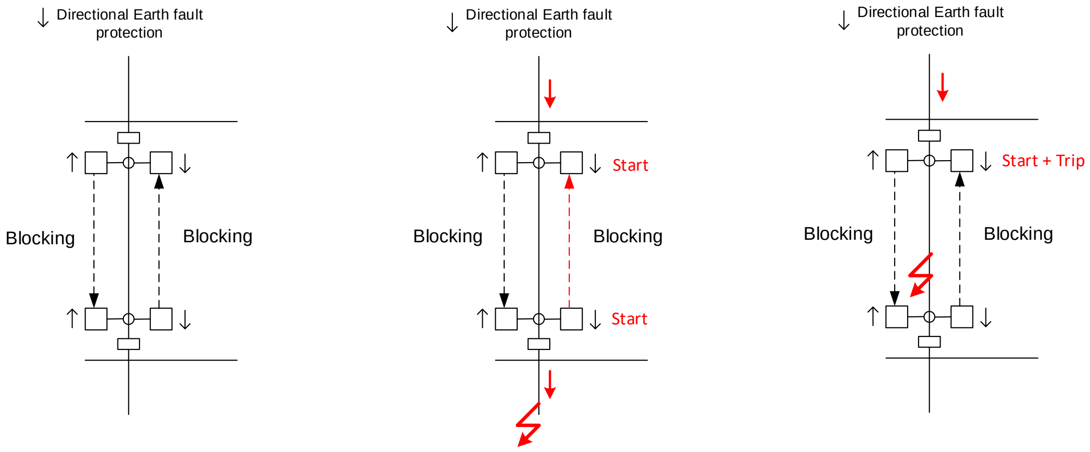


Figure 36 Earth fault protection using blocking principle

This system gives fast and selective disconnection of cable earth faults.

4.6 REDUCTION OF UNWANTED TRIP AS A CONSEQUENCE OF ASYMMETRIC CURRENT/VOLTAGE

The risk of unwanted disconnection of objects in the auxiliary system, as a consequence of unsymmetrical conditions in the external system, should be studied. One possibility can be to add one criterion for **auxiliary system switching**: Introduce a relay measuring negative sequence voltage or current in relation to positive sequence voltage/current. This relay shall be set with a time delay shorter than the negative sequence relays of the objects in the auxiliary system.

5 Influence on the protection system regarding new ancillary services to be provided by the NPP

If it is technically and economically feasible, the following ancillary services might be provided by the NPP:

- Frequency Control
  - × Frequency Containment Reserve FCR-N, to be activated at normal operation 49,9 < f < 50,1 Hz
  - × Frequency Containment Reserve FCR-D, to be activated at disturbed operation f < 49,9 or f > 50,1 Hz

The requirement is that the generating plants shall remain in operation connected to the transmission system, if the system frequency is within the range 47,5 – 52 Hz. The frequency protections are set accordingly and this is not changed if the NPP:s provide frequency containment reserves.

- Voltage Regulation/Reactive Power Control

The NPP:s provide Voltage Regulation/Reactive Power Control today as stated in the grid code, even if there is no commercial market for this type of ancillary service. Therefore, there are not any changes in the way to operate the NPP:s regarding reactive power supply and thus no changed conditions for the protection system.

- Power system oscillation damping: PSS (Power System Stabilizer)

PSS are mandatory today.

The judgement is that the new ancillary services, that might be provided by NPP, will not influence the fault clearance systems.

PROTECTION INTERACTION BETWEEN NUCLEAR POWER PLANT AND EXTERNAL POWER SYSTEM

Faults and other incidents in the transmission system and in the nuclear power plants interact with the function of the fault clearance systems. With a smarter design of fault clearance systems, a high dependability and probability of disconnecting when needed can be achieved, at the same time as the probability of unwanted disconnection is low. In this report the existing fault clearance system used and events that can challenge the system are described. Furthermore, suggestions on design changes and measures that can be taken to strengthen the fault clearance system are provided.

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