Bachelor's thesis

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Improving automatic reclosing logic "Kongik-Jord" in compensated systems

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AND TECHNOLOGY

BACHELOR THESIS

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*A thesis submitted in fulfillment of the requirements
for the degree of Bachelor of Science*

in the

Department of Electric Power Engineering

May, 2020

Preface

The bachelor thesis is the concluding project in 3rd grade on Electrical engineering at Norwegian University of Science and Technologi (NTNU). It was supervised by professor Irina Oleinikova from the Department of Electric Power Engineering and co-supervised by Tore Flatås from Statnett.

This project represents 20 credits, and therefore 500 hours per student. Our task is given by an external part, in this case by Statnett. The group consists of 4 students from the field of electrical power engineering.

We would like to thank professor Irina Oleinikova and Tore Flatås for the first-class guidance on this project. Even in challenging times with the Covid-19 pandemic, you where able to answer all of our questions in a clear and supportive way.

Abstract

Due to the increasing demand for electrical energy, it is becoming increasingly important that the power grid is stable and reliable. In order to keep the power grid operational, all devices must function optimally. One of these devices is the automatic recloser. A problem has been observed where the automatic recloser is undesirably interrupted. Upon closer investigation, it has been concluded that the problem lies in the logic "Kongik-Jord", which is part of the automatic recloser sequence.

This report presents how the power grid is structured and how coil-compensated networks work. It also addresses challenges that may arise when operating power grids, in the form of operational disturbance and other types of faults. The different types of faults affect the power grid in different ways, and the location and fault correction can be different.

The logic is written in the DIGSI software from Siemens. The analysis and alterations of the logic has been conducted in the same software. The logic was changed so that earth fault voltages detected early in the dead time should not interrupt the automatic recloser. This was achieved by using a timer, which forces the logic to check the conditions for aborting the automatic recloser, at the end of the dead time.

Sammendrag

På grunn av den økende etterspørselen etter elektrisk energi blir det stadig viktigere at kraftnettet er stabilt og driftssikkert. For å holde kraftnettet driftssikkert må alle innretninger fungere optimalt. En av disse innretningene er automatisk gjenninnkobling. Det er observert et problem der den automatiske gjenninnkoblingen blir avbrutt uten at det er ønsket. Etter nærmere etterforskning er det kommet frem til at problemet ligger i logikken "Kongik-Jord", som er en del av gjenninnkobling-sekvensen.

Denne rapporten tar for seg hvordan kraftnettet er oppbygd og hvordan spole-kompenserte nett funger. Den tar også med utfordringer som kan oppstå ved drift av kraftnett, i form av driftsforstyrrelser og andre typer feil. De forskjellige typene feil påvirker kraftnettet på ulike måter, og lokaliseringen og feilrettingen kan være ulik.

Logikken er skrevet i programvaren DIGSI fra Siemens. Analysen og endringen av logikken har foregått i programvaren. Logikken ble endret slik at jordfeilspenningen som ble detektert tidlig i pausetiden, ikke skulle avbryte den automatiske gjenningkoblingen. Dette ble realisert ved å bruke en "timer" som tvinger logikken til å sjekke betingelsene, for å avbryte gjenninnkoblingen, i slutten av pausetiden.

Contents

List of Figures

List of Abbreviations

AR	**A**utomatic **R**ecloser
BLK	**Bl**oc**k**
CENS	**C**ost of **E**nergy **N**ot **S**upplied
ENS	**E**nergy **N**ot **S**upplied
ENTSO-E	**E**uropean **N**etwork of **T**ransmission **S**ystem **O**perators for **E**lectricity
FEF	**F**orskrift om **E**lektriske **F**orsyningsanlegg
FIKS	**F**unksjonskrav **I** **K**raft**s**ystemet
FOS	**F**orskrift **O**m **S**ystemansvaret i kraftsystemet
GIK	**G**jen**i**nn**k**oblingsautomatikk
IEC	**I**nternational **E**lectrotechnical **C**ommission
JF	**J**ord**f**eil
kV	**k**ilo**V**olt
LED	**L**ight **E**mitting **D**iode
NPAG	**N**etwork **P**rotection & **A**utomation **G**uide by Alstom
PLS	**P**rogrammable **L**ogic **S**ystem
PSR	**P**ower **S**ystem **R**elaying by Stanley H. Horowitz & Arun G. Phadke
REN	**R**asjonell system **E**lektrisk **N**ettvirksomhet AS

Chapter 1

Introduction

In the introduction, the problem itself is presented, as well as the background and motivation for the thesis, and finally the scope.

1.1 Problem definition

This thesis is based on protection scheme analysis of the logic "Kongik-Jord" in compensated overhead line systems. The logic was originally designed to avoid reconnecting after a double earth fault while there still is an earth fault on one side of the circuit breaker, by cancelling the automatic recloser. Typically when there is a permanent earth fault on one side, and a temporary on the other. However it has been found that the time the measured earth fault voltage ($3U_0$) takes to reach steady state, can in some rare cases interrupt the automatic reclosers in other types of faults[1]. For example, there are cases where the automatic recloser has been canceled with a two-phase short circuit, although the circuit breaker could have reconnected.

1.2 Background and motivation

The original "Kongik-Jord" logic described in 1.1 has been implemented for decades. New attention to fault analysis has made Statnett aware that the logic, in some cases, might be generating unwanted blocking of the AR function. As Statnett has been unaware of the problem until recently, it has not been considered an issue, and therefore there is limited information available on the topic. The problem itself, has led the high voltage overhead lines being disconnected longer than needed. The system control center have to reconnect the faulted lines manually, which might result in overlooking other errors. The blocking of the AR function has not led to any significant amount of energy not supplied, not only because of the system control center operates quickly, but also the 132 kV compensated grid is largely built as a meshed network, so the power supply to the consumers has been maintained[2].

1.3 Scope

This thesis is built on obtaining extended knowledge in system protection, surrounding elements of the automatic recloser and its function. In order to achieve this there will be presented some general knowledge about the power system and how a compensated network works, as well as how energy not supplied is distributed by cause and how cost of energy not supplied is calculated. It is described generally about various short circuits, fault detection and sectioning of earth faults. Different ways to protect a system with protection relays is described, how automatic recloser work and how its function operates. The professional software DIGSI 5 has been used, which is described in further detail in the chapter 2. The case study shows the progress of the work, how it has been solved with different options and improvements of the logic with continuous feedback from Statnett. It will be discussed other possible ways to solve the problem and lastly presented the conclusion.

Chapter 2

Methods

In this report, two methods have been used to form a comprehensive picture and find a solution to the problem.

- Literature study
- Professional software SIPROTEC 5, DIGSI 5

Literature study is used to gain a broad understanding of the complexity and context of the power grid. Two books have been used as main sources, PSR and NPAG, written by Horowitz & Phadke and Alstom respectively, supplemented by research articles, instruction manuals, statistics and the current regulations. The books are considered to be reliable sources and have contributed to a broad understanding. The other sources have contributed to a deeper understanding of the various topics. A guide from Statnett, FIKS2012, and industrial practice from REN have also been used. Statistics are taken directly from Statnett and ENTSO-E reports, while regulations has been obtained from Lovdata. The supervisor from Statnett has been actively used to ensure quality assurance and to verify the work that has been done. Sources have been carefully selected and several of the claims have been checked with multiple sources or the supervisor.

SIPROTEC 5 is a product series developed by Siemens which includes devices suited for protecting, monitoring, controlling and measuring applications in electrical energy systems. One of these devices is the 7VK87 which is specifically designed for managing circuit breakers and is also the device used for applying the logic described in the case study. In order to build up an understanding of the built-in functions as well as AR logic in practice, a manual for the product series SIPROTEC 5 was used. This helped build up understanding surrounding the problem and made it possible to find potential ways to change the logic.

DIGSI 5 is an industrial software which is not suited for academic purposes. This means that the program is typically not encountered throughout electrical engineering courses and had to be learned “from scratch” while working on the thesis. Experience on programs operating on similar principles, such as GX Works2 and PSS Sincal, as well as other programming experience helped understanding how to operate the software fast. The software itself was used as it is specifically designed to operate the products from SIPROTEC 5 series, which as mentioned also includes the 7VK87. As the SIPROTEC 5 series include multiple devices to protect power equipment, such as busbars, motors and transformers, DIGSI 5 has applications for multiple real life engineering.

Chapter 3

Power system organisation

Today's society is highly reliant on instantly having access to electrical power. Having available power is reliant on the voltage and frequency in the sockets being close to completely stable. This could perhaps be viewed as a relatively simple task, however, considering that the power system is constantly affected by disturbances from wind, power losses, deviation from power sources etc, this system needs to be complex and well planned in order to be kept stable. In this chapter it will be given general information of the power system organisation in Norway, and how compensated networks operate. How the Cost of Energy Not Supplied (CENS) are calculated and Energy Not Supplied (ENS) are distributed on different causes.

3.1 Power production

Producing electrical energy is done in several ways. The most common are through hydro-, thermal- and nuclear generating stations, however other types such as solar and wind are also used. Once the power has been produced it is transformed to the correct voltage and frequency before connecting to a transmission network. It is then transported for consumers to use in real time.

Renewable power sources are often encouraged due to their sustainability as they are, as the name would suggest, renewable. They are also, compared to other non-renewable resources such as coal and oil, better for the environment. Because of this, there is a lot of investments made into renewable energy by for example the European Union. According to their official website[3] an aim for 32% of energy to come from renewable sources by 2030 is set, up from 18.9% in 2018.

Almost all the power produced in Norway comes from hydroelectric power plants, however in recent years there has been an increased investment into wind power as well, both being renewable power sources.

3.2 Power distribution

The Norwegian power grid is divided into two different levels:

- Transmissions grid (132-420 kV)
- Distribution grid (11-132 kV)

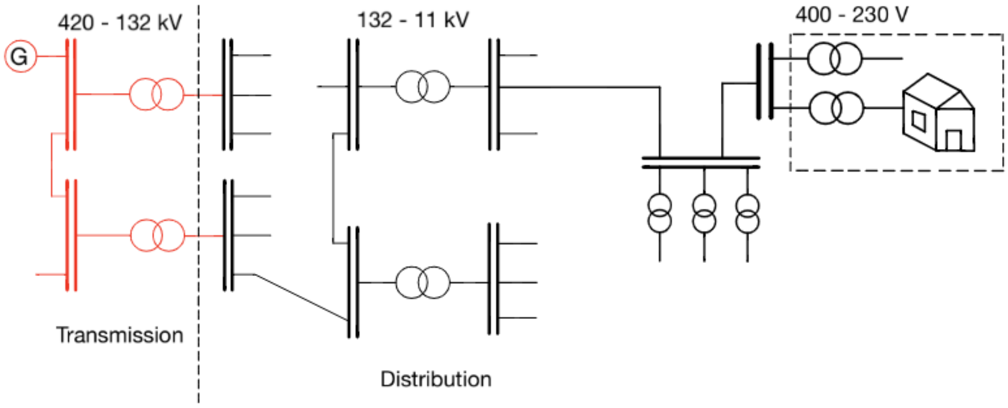


FIGURE 3.1: Sketch of a power system

The transmission networks use higher voltages as they are built to transport power through long distances, meaning power loss due to the line impedance becomes a relevant concern for optimizing income. By increasing the voltage the current will consequently decrease as the networks power must remain constant. One can conclude by using the formulas below that this will lead to less power loss in the grid thus making a more efficient system.

$$S = \sqrt{3} \cdot U \cdot I \qquad P_{loss} = 3 \cdot R \cdot I^2 \tag{3.1}$$

Formula on left showing how power depends on voltage and current in a 3-phase system.
Formula on right showing how power loss depends on current.

Statnett operates their higher voltage transmission grids (300-420 kV) with a directly earthed zero point, while networks with a voltage level of 132 kV are often compensated networks which uses a Petersen coil, also called an arc suppression coil. The purpose of the Petersen coil is to suppress earth fault currents, meaning systems with a Petersen coil are capable of continuing normal operations with a single earth fault. The Petersen coil will be covered more in chapter 3.5.

3.3 Power quality

The quality of power supplied is a key part of the modern power system. Once a disturbance occurs, whether it is through voltage dips or frequency variations, there can be shutdowns in substations, industry or power plants. Shutdowns can be expensive, both for the power supplier and consumers. Industrial consumers are often especially affected as production could potentially stop completely during the shutdown. Households are obviously also affected; however, the overall impact is rarely significant in comparison to industries. Perhaps the most significant factor to consider here is the reputation of the supplier and not the potential annoyance households experience. This is regulated through ENS and CENS.

3.3.1 Frequency

In order to secure a stable power system, it is important that the power entering the system is consistently equal to the power leaving it ($P_{in} = P_{out}$). If the system experiences an excess in power, it will cause the frequency to increase, and consequently a recess in power will cause the frequency to decrease. As the equipment used is specialised to handle a specific power frequency, they might not be able to function properly if it deviates too much, and even if it is capable it is not healthy for the longevity and/or the efficiency of the equipment[4].

Keeping the power delivered equal to the power consumed is a challenging task. There are multiple measures one can make to minimize the deviations as much as possible. Some of the ways to accomplish this are to:

- Have a larger power system with multiple power generating stations.

- Install sensors which control power production dependant on the frequency of the network.
- Keep statistics which can closely predict consumption based on trends.

From this one can conclude that frequency variations are often a bigger problem on smaller isolated systems than on larger systems[4].

Today all Nordic countries are connected to the same AC grid. This is beneficial because, as mentioned above, larger systems are easier to stabilize. Because of the larger network, there are more options to increase production if there are dropouts from one or more power suppliers. As there are more consumers in the network it is also easier to predict how the power consumption will vary throughout each day. This helps ensure a stable 50Hz operating power grid. Additionally, this helps keep stable and low electricity prices for the participating countries[4].

3.3.2 Voltage dips

The biggest cause of voltage dips in the supply system are faults that does not cause an interruption[5]. Voltage dips may also occur when large loads are starting up. The voltage dips can be very serious in industrial systems, where the equipment can trip and the process stops. The voltage dips may range from flicker in lights to tripping sensitive loads and motors. Figure 3.2 shows an actual voltage dip, captured by a Power Quality recorder.

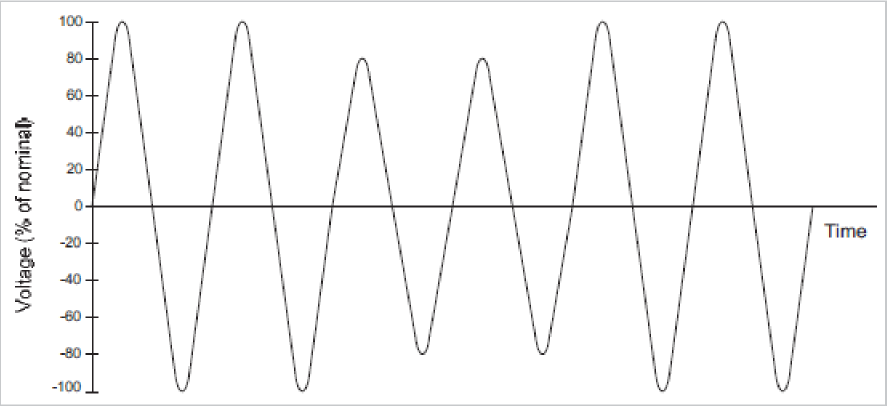


FIGURE 3.2: Recording of a voltage dip[5]

3.4 Digital substation

"The Digital Substation is a term applied to electrical substations where operation is managed between distributed intelligent electronic devices (IEDs) interconnected by communications networks"[5]. As computers continue to develop they become capable of handling larger tasks, which creates more possibilities. In order to maximize the potential of computing systems in substations it is important for the computers and devices to effectively communicate with each other, especially in automated systems. This can also help decrease manual labour due to important data from multiple sources being presented on a single device.

The international standard for Ethernet-based communication in substations is called IEC 61850[5]. This standard revolutionised the substation automation, by making standardised equipment with standardised names, reducing cost, supporting device-to-device communication, and making it simple for newer and smarter technology to be implemented. Because the information is gathered in a central system, it is easily obtained by personnel anywhere in the system.

3.5 Petersen coil

The Petersen coil is used to reduce the earth fault current in a high voltage transmission network. It is fitted to the neutral point of the transformer and once an earth fault occurs it will produce an inductive current to counteract the capacitive fault current[6]. As inductive and capacitive currents move in opposite directions (180°) they will cancel each other out, assuming both are of the same size. This means that the system can continue operations even with a single earth fault, which enhances the consistency of the system.

While the data of the network and coils would usually be given in the units Henry and Farad, as the potential fault current is the most important factor the unit Ampere is used. The ampere value indicates the size of the potential earth fault current in the capacitances and in the coil[7]. This is obviously useful for making calculations easier when deciding the reactance of the coil as well as when making changes on the network which can impact the networks reactance.

Assuming no changes are being made to a network the reactance relative to earth, X_C, will remain constant. According to REN[8] it is possible to change the reactance, X_L, of modern coils. The voltage over the coil will reach a peak value when X_L is approaching X_C. The operators of the system control centre need to consider this when dividing the grid, because of the reactance relative to earth. As mentioned earlier, the reactance relative to earth is constant, but it is dependent on the size of the network. If the operators divide the grid the reactance, X_C, may change, and the coils might need to be adjusted. On the other hand this can make it hard to locate the fault and, for example, Wischer relays can be helpful when locating earth faults.

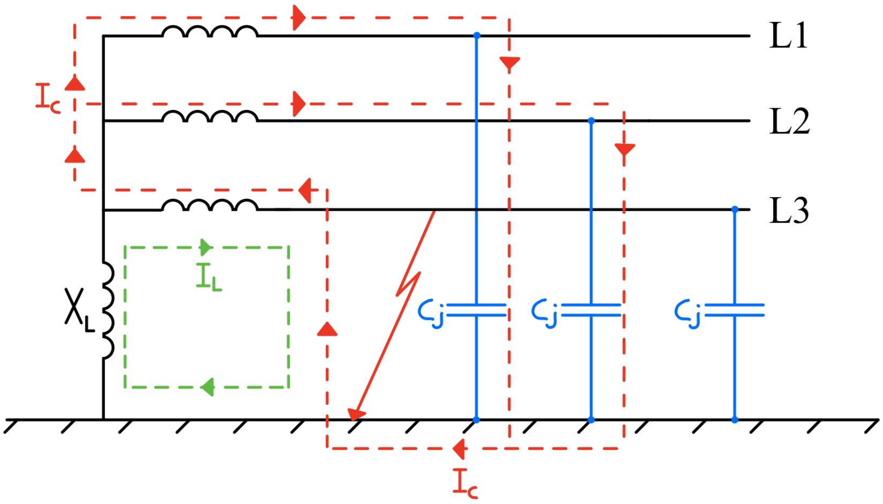


FIGURE 3.3: Earth fault in a network with a Petersen coil

3.6 Energy not supplied

Norwegian authorities use a system to financially motivate the network companies to keep a low level of costs. According to NVE[9] the CENS is used to give the network companies incentives to upgrade and operate the power system with an optimal reliability. The CENS is a representation of the customers costs. The Norwegian authorities use the incentives to reduce the profit and the companies have to keep their customers costs in mind at all times. Every time there is an interruption in the power system, there is calculated an amount of CENS. The calculation is based on the different types of customers, duration of the interruption, when the interruption occurred and if it was given notice of the interruption. In the regulation concerning financial and technical reporting, revenue framework for network operations and tariffs there is given a formula to calculate the CENS[10].

$$''K_j = k_{P,ref} \cdot f_{K,m} \cdot f_{K,d} \cdot f_{K,h} \cdot P_{ref} \tag{3.2}$$

Where:
K_j = Cost in NOK for interruption at time j
P_{ref} = Interrupted power at the point of reporting if corresponding interruption had occurred at the time of reference (kWh / h)
$k_{P,ref}$ = Specific interruption costs (in NOK / kW) at the reference time for a given duration
$f_{K,m}$ = Correction factor for interruption costs (in NOK) in month, m
$f_{K,d}$ = Correction factor for interruption costs (in NOK) on day, d
$f_{K,h}$ = Correction factor for interruption costs (in NOK) for hour, h" [10]

In the figures 3.4 and 3.5, it is shown which type of faults that caused ENS in 2018 and on a 10 year average, on the voltage level 33-420 kV. The surroundings are the biggest cause, and within surroundings wind and vegetation cause most problems.

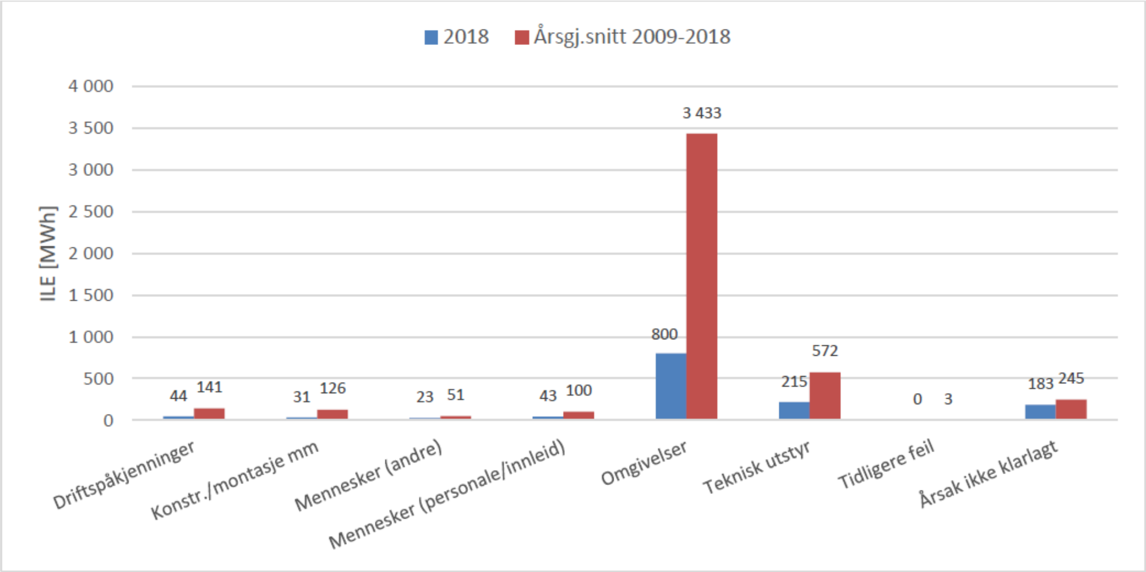


FIGURE 3.4: ENS by cause [11]

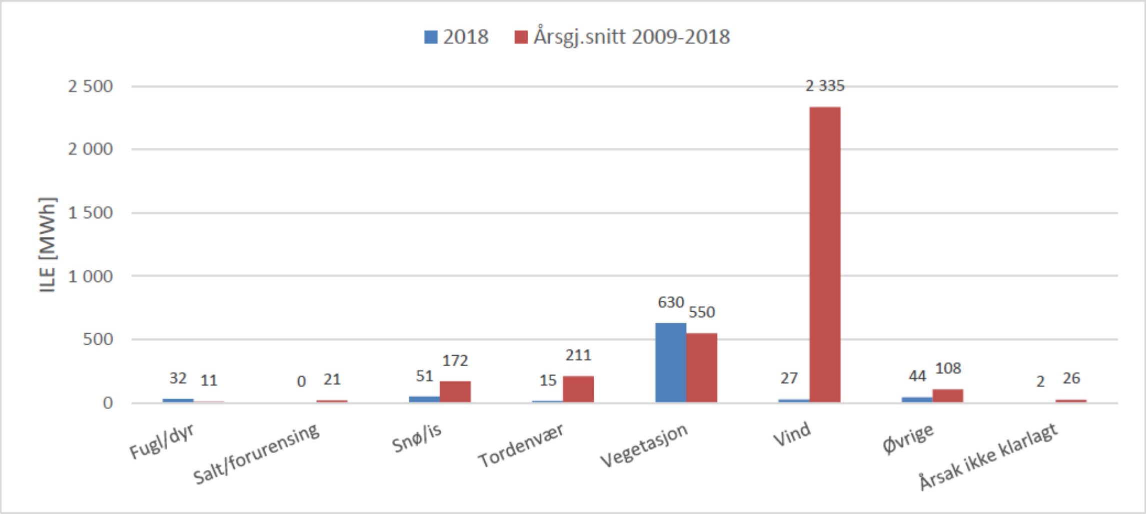
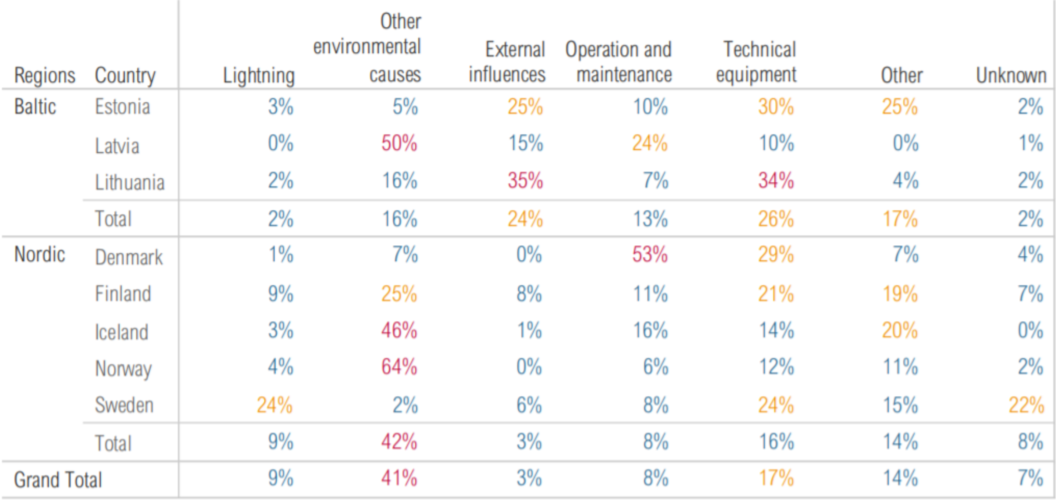


FIGURE 3.5: ENS by the cause surroundings[11]

According to ENTSO-E, in 2018, 95% of the energy not supplied in the Nordic and Baltic grids are cause in the Nordic transmission grid[12]. The Nordic grid is notably larger and it is, therefore, understandable that there are more disturbances that cause ENS.



Regions	Country	Lightning	Other environmental causes	External influences	Operation and maintenance	Technical equipment	Other	Unknown
Baltic	Estonia	3%	5%	25%	10%	30%	25%	2%
	Latvia	0%	50%	15%	24%	10%	0%	1%
	Lithuania	2%	16%	35%	7%	34%	4%	2%
	Total	2%	16%	24%	13%	26%	17%	2%
Nordic	Denmark	1%	7%	0%	53%	29%	7%	4%
	Finland	9%	25%	8%	11%	21%	19%	7%
	Iceland	3%	46%	1%	16%	14%	20%	0%
	Norway	4%	64%	0%	6%	12%	11%	2%
	Sweden	24%	2%	6%	8%	24%	15%	22%
	Total	9%	42%	3%	8%	16%	14%	8%
Grand Total		9%	41%	3%	8%	17%	14%	7%

FIGURE 3.6: Distribution of ENS according to cause, 10 year average[12]

In figure 3.6 there is also shown the statistics for the other Nordic and Baltic countries. Norway have the highest percentage of environmental causes, followed by Latvia, Iceland and Finland. This can be an indication that some of the Nordic an Baltic countries are facing some of the same disturbances, and having similar issues with overhead lines as Norway.

Chapter 4

Grid disturbances and fault treatment

As one might conclude from the previous chapter, faults in the power system can be damaging to equipment and surroundings, making it important to have a system which can appropriately respond quickly once a fault occurs. For this there is a complex automated system using relays to detect, locate and respond to system faults automatically. This chapter will go into further detail on how faults typically occurs in the power system, different types of faults and their characteristics, how one can use relays to detect and locate faults as well as the automatic reclosers (AR).

4.1 Disturbances

There are many types of errors that can occur in a power system which leads to a fault or downtime. According to Statnett yearly statistics of faults and disturbances[11], the most occurring cases are surroundings, technical equipment, human error and construction/assembly faults, shown in figure 4.1.

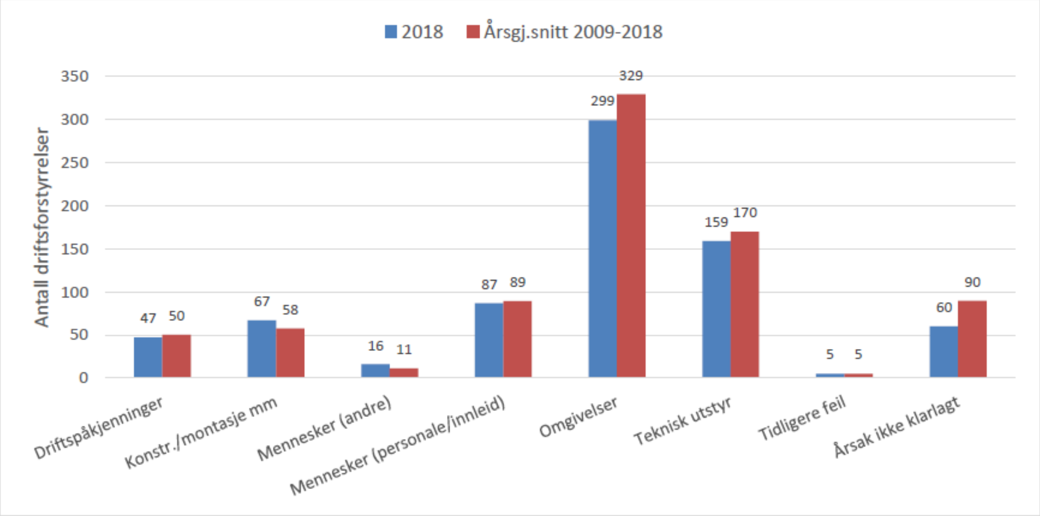


FIGURE 4.1: Number of disturbances by cause [11]

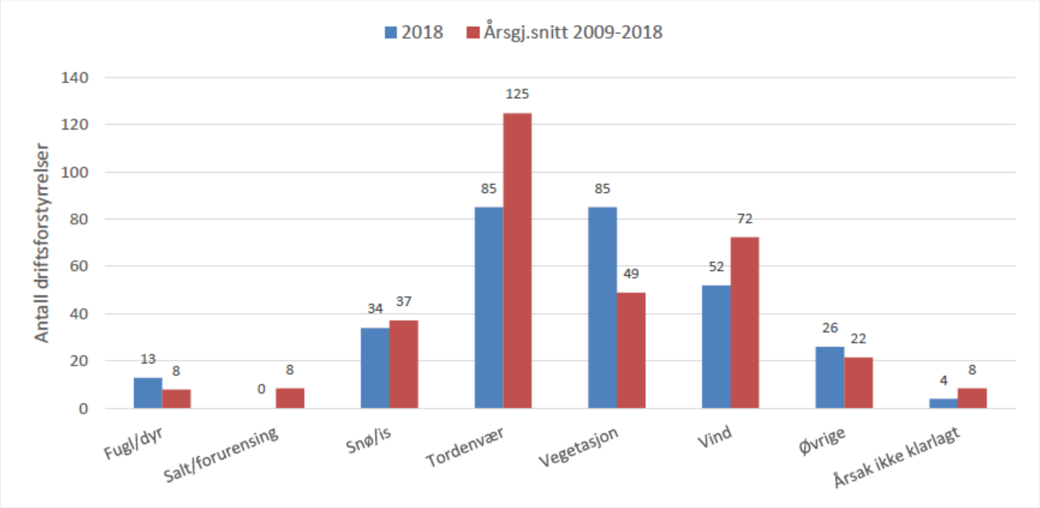
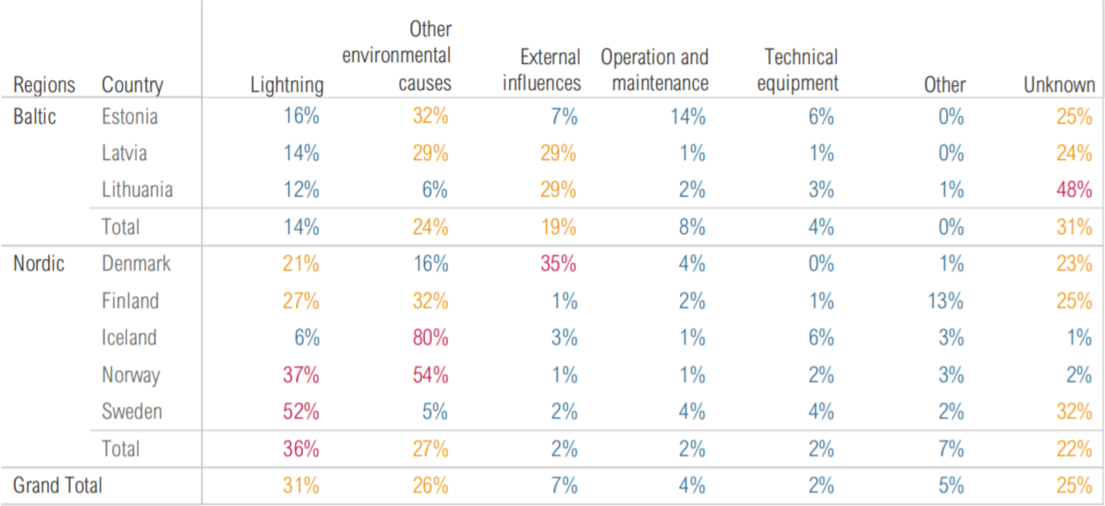


FIGURE 4.2: Number of disturbances by the cause surroundings [11]

In Norway the weather plays an important part of calculations when designing the power system. This is due to the fact that most of the faults leading to downtime are caused by the environment, as one can also see from the graphs above. Therefore it is important for the system to have a sturdy structure which can handle the big changes in weather. The environment can again be divided into some subcategories, wind, thunder, vegetation, etc, see figure 4.2. These disturbances tend to cause different types of faults. Short circuits between phases do the most damage, however they are less common than earth faults[5]. Wind in particular stands out as the most common factor which leads to a phase to phase short circuit fault, while earth fault typically are due to trees and birds. In the winter, there are usually one or more storms, which are extremely powerful and cause many disturbances, especially in Northern Norway. July and August are the months with high amounts of thunderstorms, which leads to overload in the power system. This is verified by the yearly statistics from Statnett[11].

Figure 4.3 shows the same trend as in figure 3.6. Norway, Iceland, Finland, Latvia and in addition Estonia have the highest percentages of faults by environmental causes. Iceland has a high percentage of faults caused by surroundings, this could probably be explained by the extreme environment. The Nordic and Baltic countries have some similarities and might also have the same challenges with their national power grid.



Regions	Country	Lightning	Other environmental causes	External influences	Operation and maintenance	Technical equipment	Other	Unknown
Baltic	Estonia	16%	32%	7%	14%	6%	0%	25%
	Latvia	14%	29%	29%	1%	1%	0%	24%
	Lithuania	12%	6%	29%	2%	3%	1%	48%
	Total	14%	24%	19%	8%	4%	0%	31%
Nordic	Denmark	21%	16%	35%	4%	0%	1%	23%
	Finland	27%	32%	1%	2%	1%	13%	25%
	Iceland	6%	80%	3%	1%	6%	3%	1%
	Norway	37%	54%	1%	1%	2%	3%	2%
	Sweden	52%	5%	2%	4%	4%	2%	32%
	Total	36%	27%	2%	2%	2%	7%	22%
Grand Total		31%	26%	7%	4%	2%	5%	25%

FIGURE 4.3: Distribution of faults per cause on overhead lines, 100-420 kV, 10 year average [12]

4.2 Short-circuits & earth faults

In a three phase system the most common types of short circuits are, two- and three-phase short circuit, and single and double earth fault, shown in figure 4.4, 4.5, 4.6 and 4.7

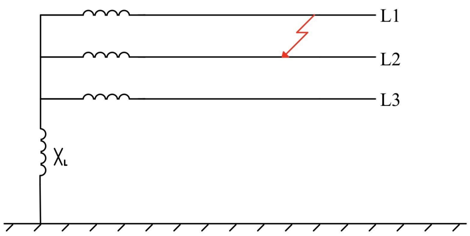


FIGURE 4.4: Two phase short circuit

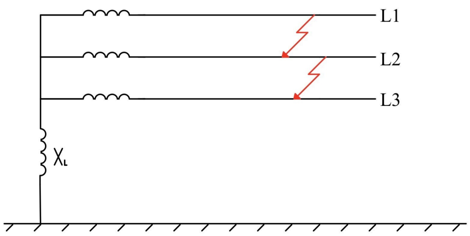


FIGURE 4.5: Three phase short circuit

As previously mentioned, short circuits are less common than earth faults, however they lead to higher fault currents which can cause major damage to both material, people and the surroundings. Due to the fault currents often being significantly larger than the load current the lines are designed for, this can lead to overheating of the conductors[13]. In a three-phase system there are two different categories of short-circuits which can occur, these being a two-phase short-circuit and a three-phase short-circuit. In both instances the fault current will be determined by the impedance in the grid. In a two phase short circuit, there is a current transition to one of the other phases, which causes a circuit similar to the one pictured in figure 4.4 to form. The current here is less than in a three phase short circuit due to network asymmetry. A three phase short circuit, seen in figure 4.5, creates a current transition between all the phases, so that a symmetrical circuit is formed. This will cause the fault current to become larger and therefore more problematic.

Earth faults are, according to PSR, the most common type of fault in power systems[14]. Earth faults are caused by a phase receiving a pathway to earth due to the capacitance of the system, causing a capacitive phase-earth current to form. This will create an overvoltage on the healthy phases, which can harm the system and the surroundings, obviously making them undesirable. In order to properly handle earth faults it is important for the system to be able to detect, locate and perform corresponding actions quickly. Such as tripping the circuit breaker closest to the fault location, to isolate the earth fault. One separates between permanent and temporary earth faults. Permanent earth fault are faults which will not go away after a trip and reconnection, while a temporary earth fault in most cases will disappear after a trip and reconnection.

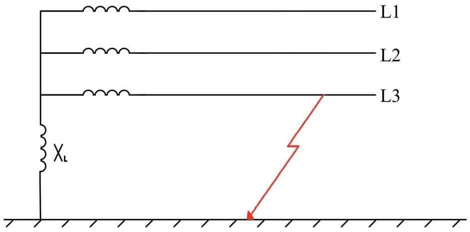


FIGURE 4.6: Single earth fault

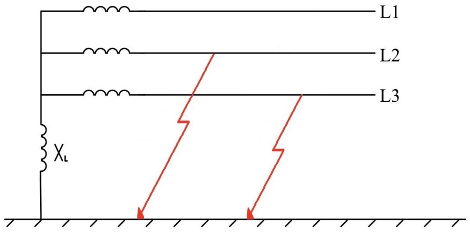


FIGURE 4.7: Double earth fault

According to the regulations relating to electric power supply systems, FEF2005[15], the circuit breakers have to disconnect within 120 minutes once a single earth fault occur in power systems with 66/132kV. Some of the components are designed to endure 2.2 times the U_n, for up to eight hours[1]. Because the two healthy phases get increased voltage, with a single earth fault, this makes them more vulnerable to a second earth fault. If a second earth fault occurs it becomes a double earth fault, which must be dealt with as quickly as possible. The second earth fault can be in a totally different place than the first fault, several kilometers away. Usually, when a double earth fault is detected, the circuit breaker will trip, leading to the system getting split into two separate system, with both systems operating with a single earth fault. Distance relays have a phase-prioritizing-logic, where L3 is the highest prioritizing and L1 is the lowest[16]. In the figure 4.8, there is an example where a double earth fault has occurred. Then both relay 1 and relay 2 check for earth fault on L3, but only relay 1 will disconnect because it is closest to the fault. Then the system is split and both operates with a single earth fault. To prevent the two separate systems to reconnect after the double earth fault, there was made a AR-logic, which measures the $3U_0$ voltage to see if there is still a fault in one of the systems. This AR-logic got the name "Kongik-Jord".

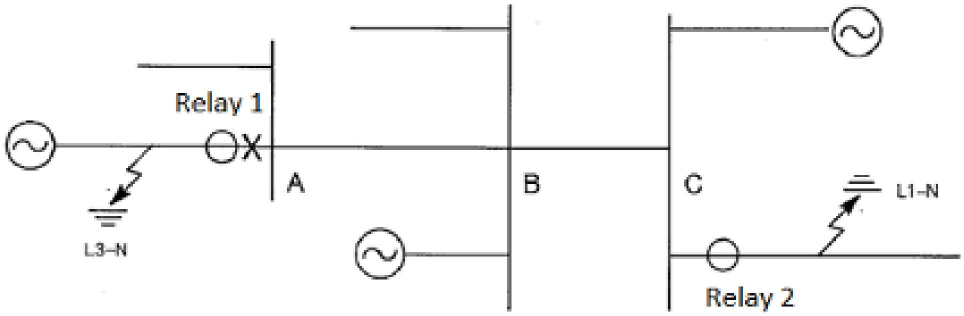


FIGURE 4.8: Double earth fault example [16]

Distance relays can not always handle double earth faults that easily. When the system runs at radial operation, the distance relay sometimes only sees a single phase short circuit. The relay will trigger independent of which phase the fault is. There is also a risk of disconnecting on both sides if the fault is in the measuring area of a differential relay[16].

4.3 Fault location

In order to secure availability and stability for the distribution network it is important to be capable of accurately locating faults before applying the necessary countermeasures. This is especially important when a fault requires physical interference in order to be fixed, for example if a tree falls on a line. This chapter will focus on distance measurement relays and Wischer relays. A distance measurement relay measures the voltage and current at the fault location in order to determine the impedance at the fault location. This can in turn be used to personally calculate the distance to the fault, as the impedance of the line is dependent on length. A Wischer relay uses a LED scheme to point to the fault. These will be described further in this chapter.

4.3.1 Distance protection

$$Z = \frac{3U_0}{3I_0} \tag{4.1}$$

$$D = \frac{Z}{Z_C} \tag{4.2}$$

Equations showcasing how one can measure distance, D, based on fault voltage, $3U_0$, fault current, $3I_0$, and cable impedance per length, Z_C.

When the relay is calculating the impedance at the fault, it is important that it knows what type of fault that has occurred. Using combinatorics one can determine that for a three phase distribution network there is three different ways for each of 2-pole short circuit, 1-pole earth fault and 2-pole earth fault to occur as well as one way for a 3-pole short circuit to occur, making it possible for 10 different faults to occur. Each of these faults requires a different set of functions to determine the relation between voltage and phases . One can thus assume such a system would require multiple distance relays with different inputs corresponding to different faults that can occur. When designing a distance relaying scheme it is expected to be capable of energizing the appropriate relay, regardless of type of fault[14].

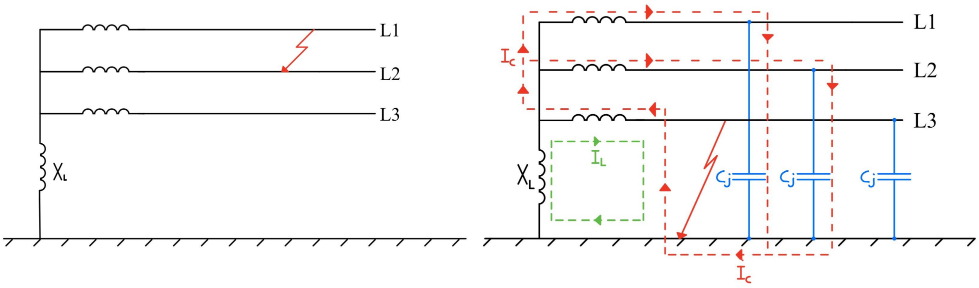


FIGURE 4.9: Showcasing a single phase-phase short circuit and a single phase-earth fault in a three-phase power system

Once a fault occurs in a large power system it is obviously undesirable for the entire power system to be disconnected. In order to enhance system stability the system is split into different protection zones meaning a fault inside a zone will only trip the circuit breakers which are within the line the zone covers. When designing the trip values one usually considers the impedance of the line in the first zone[17].

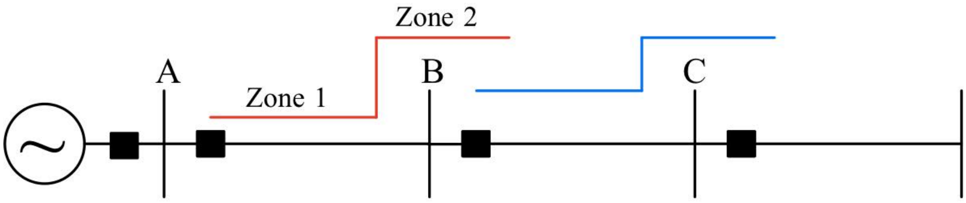


FIGURE 4.10: Example of zones according to TELE3014

As pictured above one can see that there is two different zones with different time delays. According to lectures with Hans Kr. Høidalen[17] one will typically set the first zone to 0.8-0.9 of the line 1 and the second zone to 1.2. Typically the first zone has no delay, while the second usually has a delay between 15-30 time cycles, or 0.3-0.6 seconds in a 50Hz system. This means that the first zone will cover most of the line while the second covers the rest as well as acting as a secondary insurance for relays in B. It is important to note that despite it seeming logical to just have a single zone covering the entire line, this would make the system vulnerable to equipment faults and faults near the end of the line.

As previously mentioned, it is important for the line impedance to be close to linearly dependant on its length in order for distance relays to give the information one would expect it to give. This makes it possible to create a R-X diagram (resistance impedance), which, as the name indicates, showcases the relationship between resistance and impedance. As the relationship between these values is constant under normal operation, one can use this diagram to design the trip values of the zones. In figure 4.11, two examples featuring different zone tripping characteristics is showcased in a R-X diagram. The left shows "polygon" characteristics while the right shows "circle" characteristics.

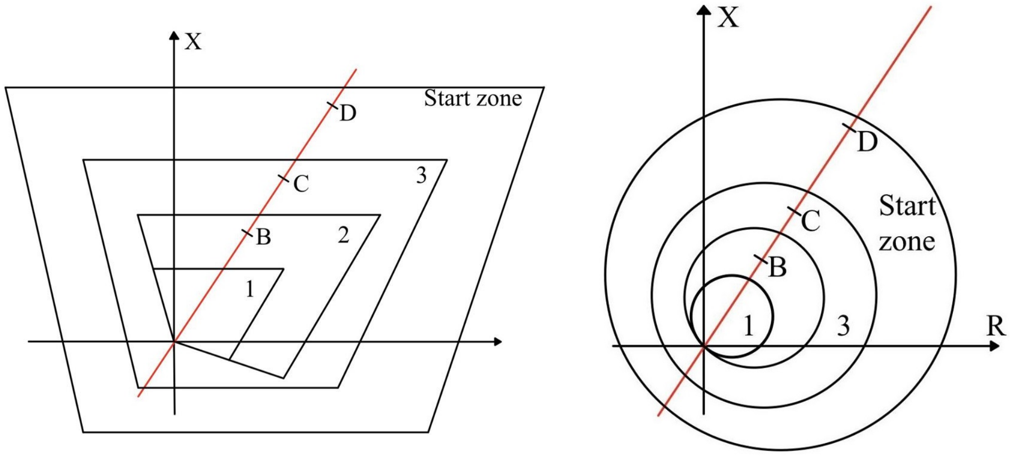


FIGURE 4.11: RX-diagrams according to TELE3014

4.3.2 Earth fault detection

One way of detecting an earth fault in systems with high-ohmic resistance is based on monitoring the zero-point voltage. Using a secondary winding with an open delta connection in the voltage transformer, in normal conditions, the voltage will be close to zero, shown in figure 4.12. In a case of an earth fault, the voltage in the other phases will increase with a factor of $\sqrt{3}$, shown in figure 4.13. The voltage over the delta connection will be up to three times the normal phase voltage[16].

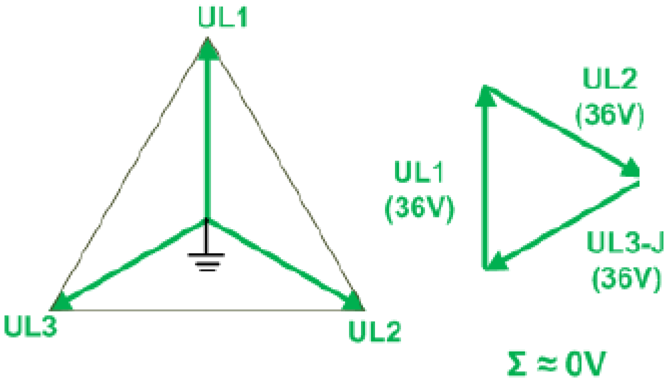


FIGURE 4.12: Phasor diagram of a healty system[16]

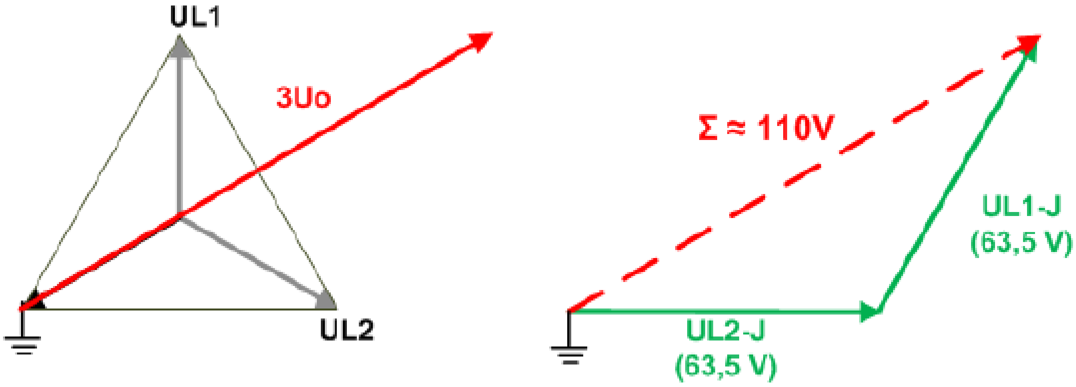


FIGURE 4.13: Phasor diagram with an earth fault[16]

Detecting the direction of an earth fault can be done in several ways. The traditional way is to use Wischer relays. In newer distance relays, the function of the Wischer relay is implemented in the software. Still there are old distance relays that do not have the proper hardware to support this, therefore physical Wischer relays are used in addition to this. When talking about Wischer relay and its function, one does not separate the two.[1]

Wischer relays are fitted to all lines in networks with a Petersen coil (132kV)[1]. When detecting an earth fault with a Wischer relay, the $3U_0$ and $3I_0$ is measured in the transient course[18]. This lasts just a short period, from which the earth fault occurs and until it has reached steady state. The system control center can use these signals to troubleshoot where the earth fault lies. The Siemens 7SN60 relay determines the direction of transient and continuous earth faults, and indicates the direction with LEDs[19]. Red LED indicates the faulted line in forward direction, while yellow LED indicates fault in reverse direction, shown in figure 4.14

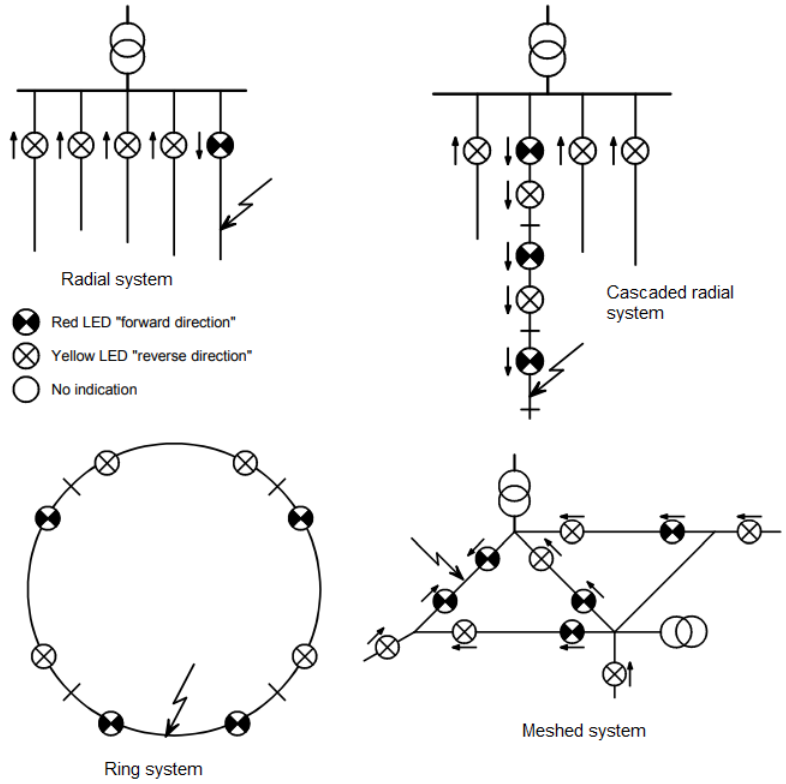


FIGURE 4.14: LED indicators[19]

The transient measurement that the Wischer relay has done, is used to see if the polarity between $3U_0$ and $3I_0$ is in phase or not. If they are in phase, as the figure 4.15 shows, this means that the fault lies in forward direction, and if they are opposite means that the fault lies in reverse direction.

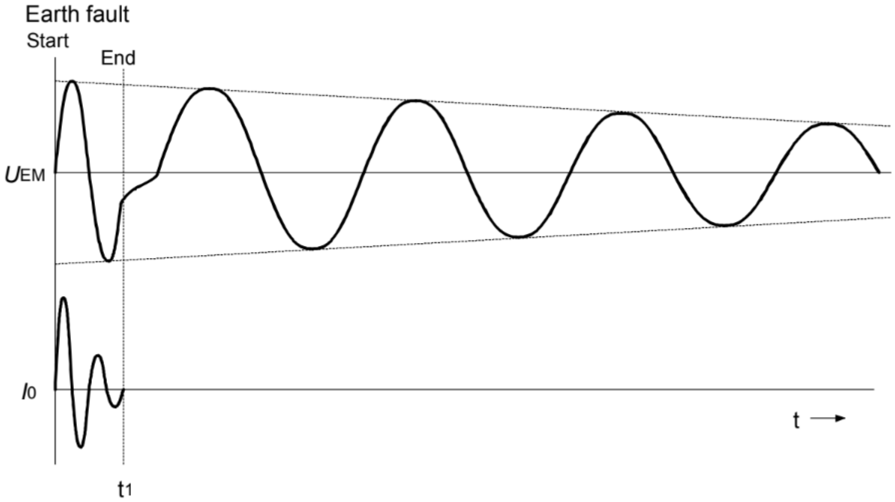


FIGURE 4.15: Transient course, U_{EM} refers to $3U_0$, I_0 refers to $3I_0$[19]

When an earth fault has occurred, the zero-point voltage can be as high as full phase voltage. The capacitances between phases and earth are charged by the transformer inductance. This leads to a charging process that builds up a strong current surge. The size of the system and the contact resistance values at the earth fault location are what decides the amplitude of the current surge. The current flows through the capacitances between phases and earth in the "healthy" phases and enters the earth faulted phase through the earth fault location and flows back to the transformer. Therefore, the direction of the current surge is identical with the short circuited current at the same location.

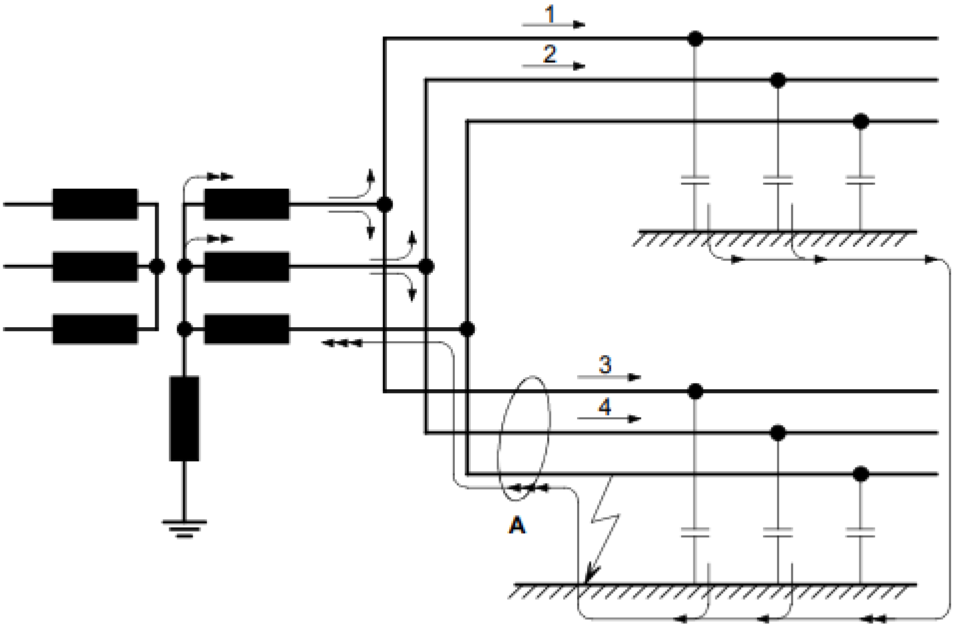


FIGURE 4.16: Fault currents in the system[19]

Sectioning is a crucial part when it comes to dealing with faults. With an earth fault, the system control center will get a warning or an alert. The Wischer relays can help the operators to determine where the fault may be in the system. The relays indicate a direction, but this is not an exact science. The relays may indicate the wrong way and cause confusion in the system control center, because of being incorrectly installed, which is a common problem. The $3U_0$-voltage is measured at every bus bar in the system, which makes the sectioning easier. By dividing the unhealthy grid into sections, the operators can figure out in which section the fault lies. Narrowing down to the specific fault can take between 5 minutes and 2 hours, depending on where the fault lies and on the knowledge of the grid. This is regulated by the "Regulation regarding the system responsibility" (Forskrift om systemansvar, FoS). "The system administrator can determine which solution for earth current compensation to be used in the regional and transmission networks"[20]. In order to solve this, Statnett[21] wants the concessionaires to cooperate with the installation, operation and maintenance. This also includes the daily operation of the system.

4.4 Relaying

“Relaying is the branch of electric power engineering concerned with the principles of design and operation of equipment (called “relays” or “protective relays”) that detects abnormal power system conditions and initiates corrective action as quickly as possible in order to return the power system to its normal state” [14]. It is usually beneficial to keep the response time and disruption to the system as low as possible, however cost, reliability etc might hinder this. Considering the consequences lack of power over time causes it would be sensible to assume investing more would be beneficial as a whole.

As previously mentioned defects in the power system can have large consequences as societal structure is built on the assumption of having power at all times. The system is also very complex and, more importantly, very expensive. While ideally it would not have any faults in the power system this is currently very unrealistic due to technological or knowledge restrictions. This makes it important to have a “defence” mechanism in the system which can quickly detect faults and automatically disconnect lines if necessary to prevent further damage, being both economically and time efficient. While it would be possible to monitor and respond to faults manually, which possibly could yield a smarter counteraction, human response is straight up too slow compared to relays who can yield a good response in the matter of milliseconds. Here it will describe different ways of detecting and dealing with faults, through relaying, as well as why and how they are used, largely based on chapter 2 of PSR[14].

As already stated, once a fault (short-circuit) occurs, typically, the current will increase while voltages decrease. This can fairly easily be explained as a short-circuit means the cables connect which will offer a significantly easier path to travel for the current as it by definition will prefer the route with lowest resistance. This is, of course, assuming the cable or line has a lower resistance than its designated load, which usually is the case. Through this one can derive measuring currents as a good method of detecting faults. One could also assume this to have a significant effect on active and reactive power, unless very specific conditions are in place. Faults can, however, also affect pretty much every relevant parameter such as phase angle, frequency etc. Different methods of relaying typically include comparing a parameter value with an arbitrary value which will determine whether or not “abnormal” conditions are met. The next paragraphs will go slightly more into detail on different relaying methods.

Level detection is described by Horowitz & Phadke[14] as the simplest way of relaying. As previously mentioned, fault currents are almost always larger than regular currents. Thus one can simply define a “maximum” current, where currents below this point are considered normal operational conditions. However passing this arbitrary value means an abnormal situation “must” have occured. According to PSR[14] uses an example where a factor of 1.25 higher current than nominal current is considered a fault. This is just examples and one could imagine the “ideal” factor would constantly vary depending on which situation it is used.

Assuming the current has passed what is defined as normal operation the relay will have to act. The act is obviously going to be dependent on what is aimed to accomplish, however PSR[14] describes two usual scenarios. Either it can sound an alarm with a warning that shows something unusual has occurred, letting it be manually performed an action deemed fitting, or it can automatically perform an action itself, for example tripping the circuit breaker. One could assume the latter action to be faster, however manually choosing an action could lead to a “smarter” decision. The more appropriate solution will vary on where it is located, type of system etc.

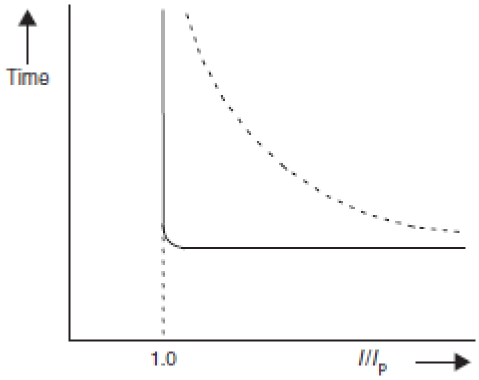


FIGURE 4.17: Characteristics of a lever detector relay[14]

Magnitude comparison relays operate under the principle of comparing different operational quantities with each other. In PSR[14] it is used an example where one compares the current in one circuit with the current in another, whose values are linearly dependent on each other. As also described in Level detection relays one must select an arbitrary number which defines which detected values fall under "normal working conditions" and which values are deemed to be "abnormal conditions". If the absolute value of a line is larger than the absolute value of another plus the value selected, faulty conditions are deemed. Usually, the correct corresponding action is to trip the open line.

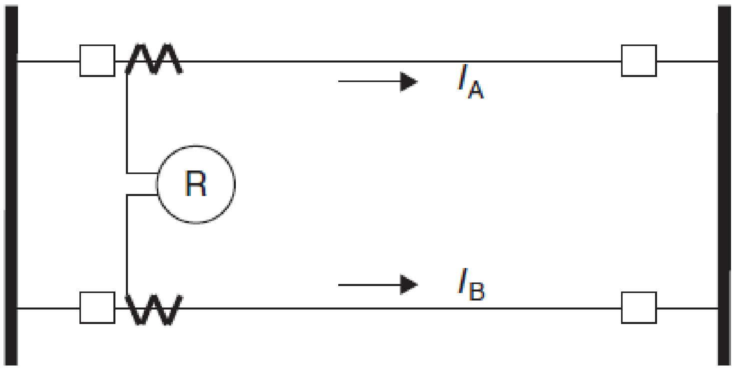


FIGURE 4.18: Magnitude comparison relaying for two parallel transmission lines [14]

Differential comparison relaying is described by Horowitz & Phadke[14] as one of the most sensitive and effective methods. This method of relaying compares the current entering a terminal or circuit with the current leaving it, meaning their normal operation relationship is known. Below an example featuring a generator winding is pictured. In this example the currents I_1 and I_2 should be equal assuming normal conditions, thus these being unequal must be caused by a fault. As this is true even for small differences in current, this type of relaying does not have to rely on someone defining abnormal conditions. This again makes it capable of consistently detecting even small fault currents. Its disadvantage is, however, that it requires currents from the "extremities" in its zone of protection, limiting its practical applications to equipment such as generators, transformers and capacitors.

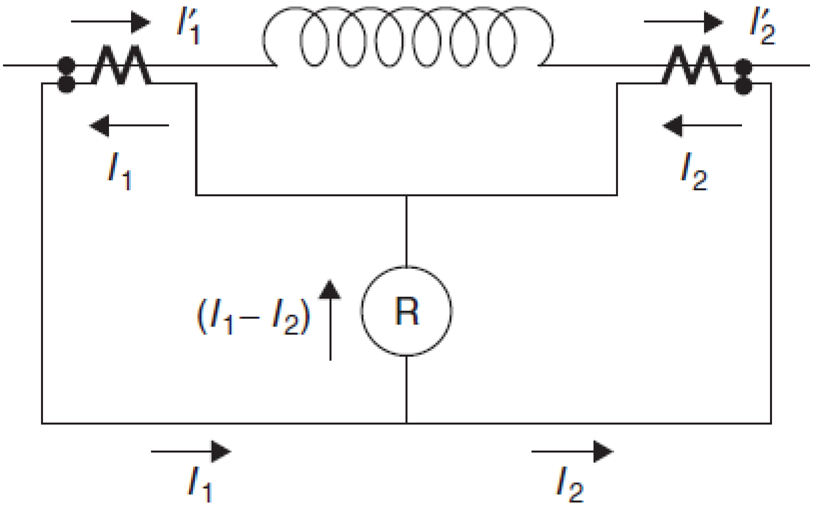


FIGURE 4.19: Differential comparison example on a generator winding[14]

While it could be considered ideal to use differential comparison for transmission lines due to its accuracy, applying this would usually be too expensive to justify implementing. This is mostly due to the sheer length and voltage which would require too many different zones of protection, due to reasons mentioned above. In order to combat this the relay method distance measurement is used instead, which compares the fault current and voltage, making it possible to calculate the impedance at the fault location. As one can make every measurement at the fault location instead of having to use the far end line current. This in practice makes it possible to accomplish the same result with less zones. It is, however, important to note that this type of relaying is reliant on the impedance being linearly dependent on another factor. For example in transmission lines, as mentioned here, it would be logical that the impedance is dependent on the length and diameter of the line[14].

4.5 Automatic recloser

An automatic recloser, known as AR, is a device whose purpose is to automatically reclose or reconnect the system once a fault has been cleared. This does, however, rely on the fault only being temporary and dealt with relatively quickly. 80-90% of faults on overhead lines are temporary[5]. In this chapter the principle behind AR in addition to important parameters to consider when designing an AR will be presented.

AR is common in all types of high voltage systems. The concept of AR is based on re-energise power lines after a fault trip. This is only used on overhead lines, as it is unfit to be used on cables, transformers and generators, since the faults are usually permanent[22]. There are two obvious benefits by using AR, improved supply continuity and reduction of substation visits. Resulting in a reduction of interruptions of supply to the consumer. It is important to allow sufficient time before reclosing after a relay trip so the fault arc has time to de-energise, otherwise the arc would re-strike.

According to Alstom[5] the most important parameters of an AR scheme are as follows: dead time, reclaim time and single or multi-shot. Furthermore these parameters are influenced by: type of protection, type of switchgear, possible stability problems and effects on the various types of consumer loads.

One factor under dead time is system stability and synchronism. In order to reclose properly in distribution networks consisting of multiple power sources, without a noticeable loss of stability, it is important to minimize all time delays. Thus, one can conclude response time plays an important factor when choosing protection equipment. According to Alstom[5] operating times less than $50ms$ is essential. Another consideration under dead time is type of load. When making decisions on a high voltage system it is important to take different types of loads on the network into consideration. This is mainly in order to predict the cost of compensation in the case of interruptions. One can assume that the industrial consumers have larger, more expensive processes than "regular" consumers, which in turn would make interruptions more impactful, which could make faster response times more beneficial. The third factor is circuit breaker characteristics. Response time of the circuit breaker is important when calculating dead time, which changes with different voltage levels.

It is important for the reclaim time to be long enough for the relays to operate assuming the circuit breaker is reclosed onto a permanent fault. The value of this reclaim time will vary depending on different factors which will be listed here.

The most common types of protection used in high voltage systems are inverse definite minimum time relays or definite time over current relays. As the names might suggest these have different time current response graphs which have previously been pictured in figure 4.17, where the dotted line is inverse definite minimum time and the other line is definite time. The typical reclaim times of these will also vary, with the former typically having an operation time of up to 30 seconds during smaller faults and lower than 10 seconds for larger faults[5]. Consecutively typical values for definite time relays will be somewhere around 3 seconds, mostly independent of fault size. Today most reclaim times are at 30 seconds in high voltage systems[5]. This can however be a problem in rare cases where multiple faults happen in quick succession, mostly during thunderstorms or other less typical events. This could cause the system to "lock out" if a second fault occurs at an inappropriate time.

Circuit breaker limitations are important to consider. As previously mentioned, it is possible for faults to occur in quick succession, making the circuit breakers ability to handle such conditions important to consider. Maintenance could also be affected by this. One must acknowledge the vulnerability of the system to semi-permanent faults, such as trees falling or similar situations. The ability of the system to handle such conditions in fewer number of shots would then be beneficial.[1]

There are some criterias when reconnecting lines that have been disconnected by a fault. Figure 4.20 shows a sketch of how AR is done. According to FIKS[23], the "voltage on both sides" and "frequency difference", must be over a given area, usually 70-100% for voltage and between 0,01-0,05Hz for the frequency. As the figure shows, the Voltage-setting logic is used, if only one side of the circuit breaker has voltage. The direction of the voltage-setting is critical for the reconnection of the grid and must be decided by the system operator. Closing under synchronous system conditions is used when the difference in phase angle ($\Delta\phi$) and voltage (ΔU) is within a certain given area. FIKS states[23], $\Delta\phi < \pm 10° - 60° \quad \text{and} \quad \Delta U < 5 - 20\%$

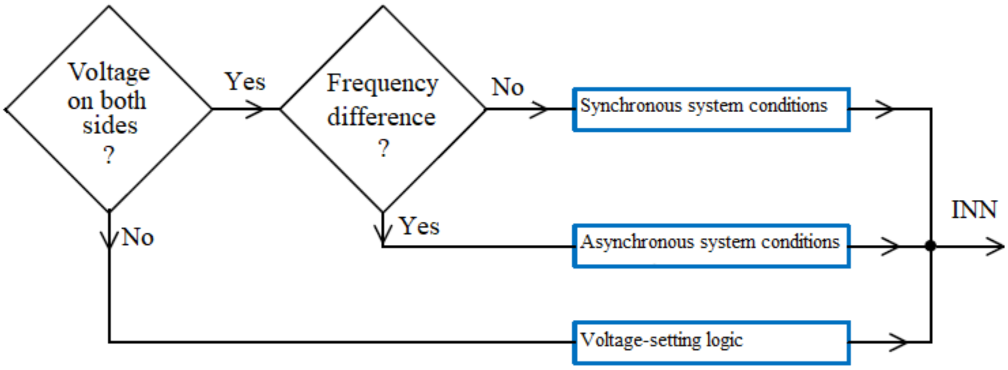


FIGURE 4.20: Controlled reconnection[22]

Closing under asynchronous system conditions is used when the frequency difference is higher than 0,01-0,05Hz, and up to 0,2Hz. If the frequency is 0,2Hz, the phase angle between the two sides varies with 72°/second. Because the AR knows the circuit breakers switching time, it can calculate when to reconnect, to get as close to 0°as possible.[22]

Figure 4.21 shows an example of an AR function, with a two phase short circuit where both relays in each end of the line will disconnect. After disconnection, the dead time starts, which in the Norwegian 132kV systems usually is set to be 10 seconds. When it ends, both relays are ready to check if it can reconnect. Because the arrow on R2 points towards the line and not to the busbar, that relay can connect first. Now that R2 can reconnect, it checks if there is voltage on B2, and that there is no voltage on the line. If this is true, it will reconnect with the line. R1 can reconnect if there is voltage on both the line and B1, but has to check if the frequency and the phase angle on the line match with busbar B1. When this is fulfilled it can reconnect the line and B1. Since the dead time is the same on both sides, the time R1 uses to reconnect after R2, might just be a few milliseconds.[1]

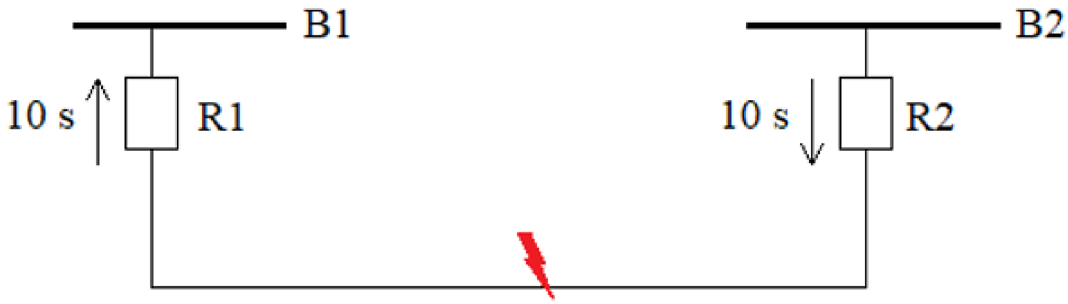


FIGURE 4.21: Example of reconnecting after a two phase short circuit, with dead time 10s.

Typical errors for the AR function can be, circuit breaker spring is uncompressed or that the spring motor is non-working, and that the AC fuse of the measure winding has blown. In AR functions these are required conditions that have to be in place before going forward with the reconnection, but in most AR functions, there are a larger amount of required conditions for reconnection.[1]

Chapter 5

Case study

The original "Kongik-Jord" logic can be seen in figure 5.1. The logic and data was given by Statnett, and the options has been made with close consultation with the external supervisor. The problem, as mentioned before, is that the "Kongik-Jord" logic sometimes cancels the AR on faults that were originally not intended. The system control center has not recognised this as an issue, assuming a correct cancellation of the AR. It has therefore not been documented as an issue[2]. Lately it has been addressed and found that the "Kongik-Jord" logic in some rare cases, abort the AR, regardless of what type of faults. As the logic was written in DIGSI, the most time consuming part of the case study was getting to know and understand the software, as well as to understand how AR works. The output which aborts the AR only depends on the inputs colored red and blue, these will be the primary focus.

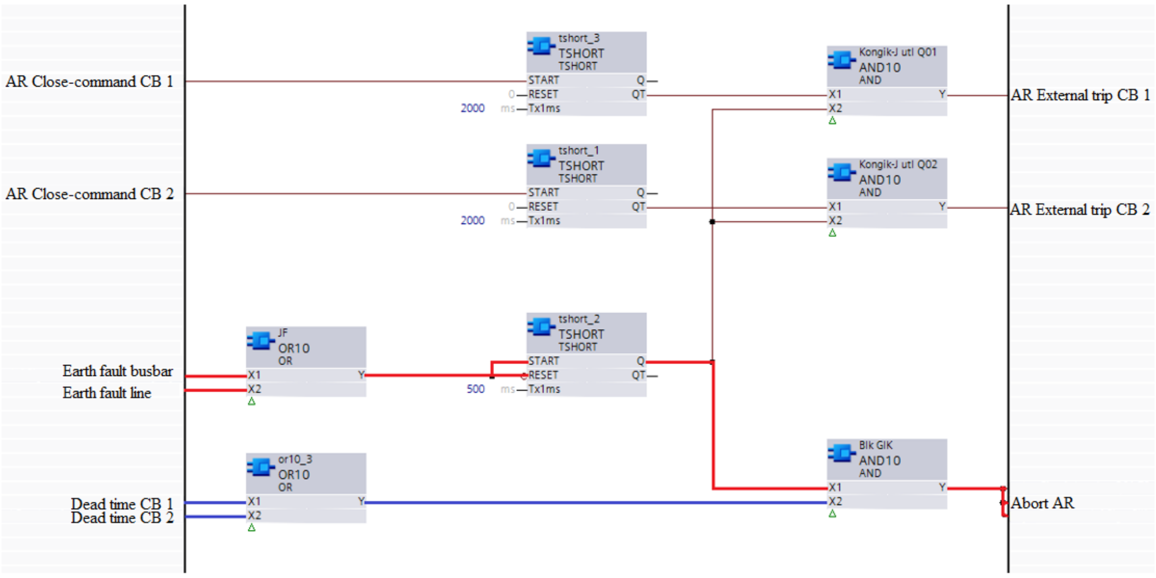


FIGURE 5.1: Original "Kongik-Jord"

After clearing a fault, the "Earth fault busbar" or "Earth fault line" measures a $3U_0$ voltage which causes the first block "JF" to give high output, as seen in figure 5.1. This happens instantly with no delay from the detection of the fault or transmission of the fault message. Next, this will start the timer "tshort_2" which will delay the $3U_0$ voltage signal and give a high output after 500ms. The dead time is set to be 10 seconds, which is standard in the Norwegian 132 kV compensated systems. This means that the "Blk GIK" block will get two high inputs, X1 if the time the $3U_0$ voltage uses to reach steady state lasts longer than 500ms, and X2 will remain high in 10 seconds. This in turn leads to the "Blk GIK" block to give high output and therefore abort the AR-logic.

FIKS states that "The automatic recloser function should be interrupted if earth fault is detected before the release of the circuit breaker"[23]. However, Statnett has had cases where the AR has been canceled without this being desired. This is because it has been observed cases where the time it takes for $3U_0$ to reach steady state, lasts longer than 500ms. It was proposed to add additional time to the existing timer "tshort_2", which would prevent longer lasting $3U_0$ voltages to abort the AR. The timer was raised from 500ms to 1000ms. In figure 5.2 there is shown the first option of the logic which was presented to Statnett.

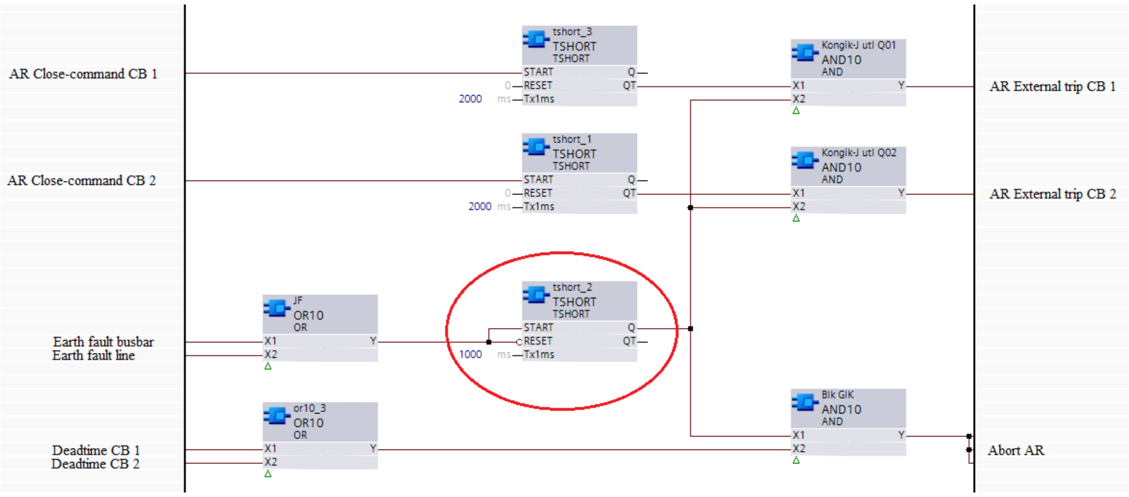


FIGURE 5.2: First option

After feedback from Statnett[1] it was apparent that changing this timer to 1000ms, could disturb other blocks outside this specific logic. To ensure that the other blocks would not be affected by the timer, it was decided to split the

$3U_0$ signal into two separate timers. The first timer "tshort_2" was set to be as the original, 500ms, and the second timer was set to be 1000ms, which was going to prevent canceling for longer steady state times for the $3U_0$ signal. The logic can be seen in figure 5.3.

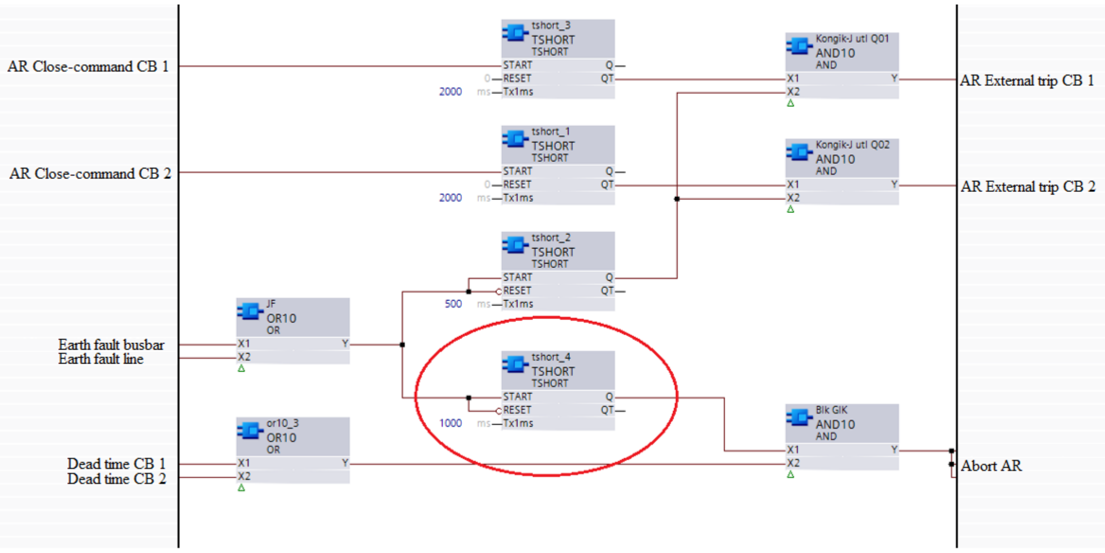


FIGURE 5.3: Second option

After further consultation with Statnett[1], it was clear that with temporary faults, the $3U_0$ voltage signal could still abort the logic early in the dead time. In order to prevent interruption too early, it was decided to make the logic check for $3U_0$ voltage later in the dead time. To achieve this, the "tshort_4" timer was moved to operate as a delay for the dead time. The timer was also changed to 8 seconds, which was a value chosen as it is fairly close to the end of the dead time. This again leads to "Blk GIK" will not get two high inputs for at least 8 seconds, and therefore assure that the "Kongik-Jord" will not abort the AR for a longer $3U_0$ voltage signal.

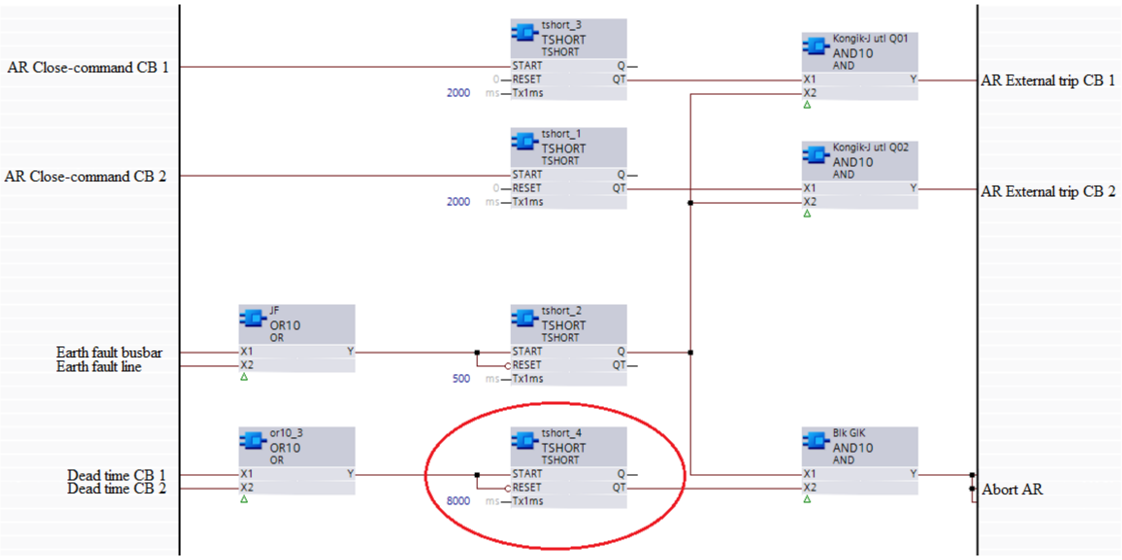


FIGURE 5.4: Third option

This would appear to be a possible way of solving the problem, which the consultant from Statnett[1] agreed with. The final logic is pictured in figure 5.4, where the red circle indicates the delayed timer "tshort_4". Another benefit of this solution, is that it will not change nor interfere with other blocks outside this logic. A bigger change of the given logic could result in several unknown issues that had to be considered. It is therefore important to note that there can be other solutions to this problem.

Chapter 6

Discussion

In this chapter other topics which potentially could yield similar results will be discussed.

6.1 Dead time

The dead time in the AR-logic is 10 seconds. This value has been unchanged for a long time. The reasoning for this value is earlier knowledge Statnett has about how the faults recover and on topics presented in chapter 4.5. As mentioned before, earth faults are very often temporary. For example, if there is a tree or other vegetation on the lines, it needs a certain time to be cleared. Snow and ice can make the line heavier and can cause the line to touch objects with earth potential. According to FIKS[23] the dead time should be between 0,1 - 20,0 seconds. Changing this value could be a solution for this problem, and can be a topic for further work.

6.2 $3U_0$ - Voltage level

The $3U_0$ level is set to 30% of nominal voltage in the logic. According to FIKS[23], the value should be between 20 - 70% of nominal voltage. The nominal secondary voltage in a 132kV compensated network will be 110V. If the transition resistance is low, the measured $3U_0$ voltage can be up to 110V. This can happen if, for example, a line falls down to the ground. The line will have direct contact to the ground and the transition resistance will be close to 0Ω. When choosing the $3U_0$ level one must consider the sensitivity of the earth fault detection. Statnett[1] is basing their level on earlier knowledge about earth faults, and they have as far as they know not experienced any trouble with this value. Still, there is a considerable gap in the voltage level interval, meaning there could be a way to solve the problem by changing the $3U_0$ voltage level. This could be a topic for further analysis.

6.3 AR-cycle

Statnett is operating with only one AR-cycle. A condition for a successful AR-cycle is that the fault is temporary, for example extinguishing an arc by cutting the power. According to Statnett[22] it is not necessary to start a new cycle if the first one fails. The probability for a successful AR in a potential second cycle is low. This is based on their statistics regarding the most common faults. The circuit breakers also have their limitations. They are not dimensioned for subsequent switching. Figure 6.1 shows a rating plate for a 300 kV circuit breaker. The red box highlights the switching sequence of the circuit breaker. O means open and CO means Close Open. According to the sequence, the circuit breaker needs a 3 minute break after an unsuccessful auto reclosing. Changing the number of cycles could have been another solution, but Statnett has good routines with one cycle. If the first one fails they try to connect manually. Another cycle might also cause safety issues that would need consideration.

ALSTOM

Type HGF 115/2B(s) Max.Driftspenning: 330 kV
PID-Nr. 17689-0010-3a 1999 IEC 56
U_r 300 kV U_P 1050 kV U_S 850 kV
I_{sc} 40 kA I_r 3150 A I_l 315 A
O-0.3s-CO-3min-CO
f_r 50 Hz / α 1.3
P_{ob} 4.2 bar (20°C) SF_6 8.5 kg
m 1560 kg FKF 2-6 Ⓜ 220 V DC
U_a 220 V DC

Hochspannungstechnik
Oberentfelden / Schweiz

FIGURE 6.1: Example rating plate, circuit breaker[22]

6.4 Further work

As one can see from the previous sections there is a wide margin between the values one can choose. For example, it is obvious that a dead time of 0.1 seconds will make the system behave differently than the one currently being used, 10 seconds. As mentioned, the reasoning for the dead time and $3U_0$ values are based on previous knowledge on the topics and might not be optimal today. It is, however, difficult to predict how changing these factors would change the behavior of the logic without properly testing it. These could be looked at in future work. This is especially relevant if the solution presented in this thesis should prove unsatisfactory.

Chapter 7

Conclusion

The goal of this thesis was to develop a solution to the problem where the automatic recloser cycle was in, rare cases, canceled by the $3U_0$ voltage. A solution could be helpful for the system control center. To be able to propose a solution, a broad understanding of power system organisation, grid distribution and fault treatment had to be established. It is important to know how the power grid is structured and how it is composed to understand the complexity. Power is produced in different types of power plants and distributed to consumers and the quality of the power is important to the consumers. The problem happens in coil-compensated networks, and the characteristics of these network has been presented. Different types of faults have different effects on the power grid and the localization of the faults can be different. The case study presents the actual changes to the logic, and how the changes was done.

As presented earlier in the thesis, there are some similarities between the Nordic and Baltic countries when it comes to types of faults. This thesis propose a solution to a very specific problem in the Norwegian power grid, but operational reliability is important for every country. It is not unlikely that other countries are facing the same issues.

Is the "Kongik-Jord" logic improved?

The logic is implemented in the automatic recloser relays, such as the 7VK87 relay, and it is not possible to test the proposed logic at the time. The logic has to be updated in the relays on site. This is an operation Statnett has to do, if the proposed solution is accepted. The supervisor from Statnett has indicated that the improved logic could be functional. It is difficult to conclude whether or not the logic is fully operating as planned. This needs to be tested and evaluated over time.

Can the "Kongik-jord" logic be improved to a greater extent?
As seen in the discussion it is possible that changing dead time, $3U_0$ or adding another cycle could potentially improve the logic. It is, however, hard to make any conclusions without further research into the subject.

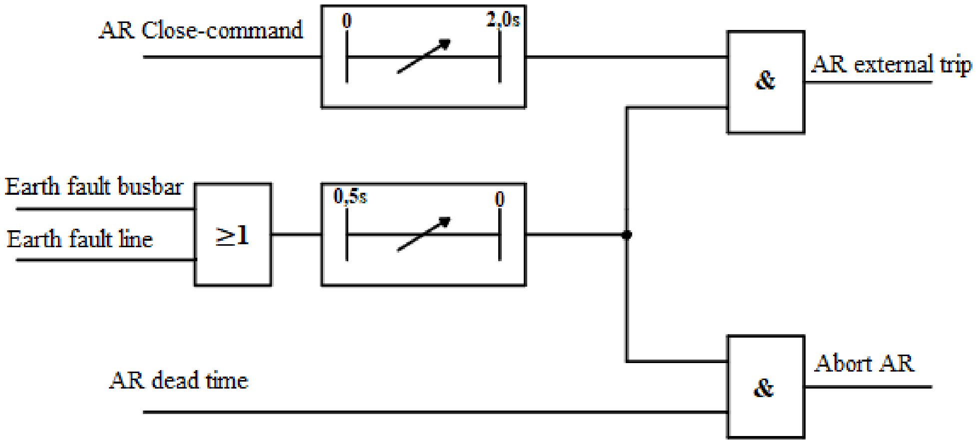


FIGURE 7.1: Simplified Original

The original logic caused the automatic recloser to abort early in the dead time. If an earth fault voltage $3U_0$ is measured in either the line or busbar, while the dead time is running, the AND block will get two high inputs and abort the automatic recloser. As seen in figure 7.1.

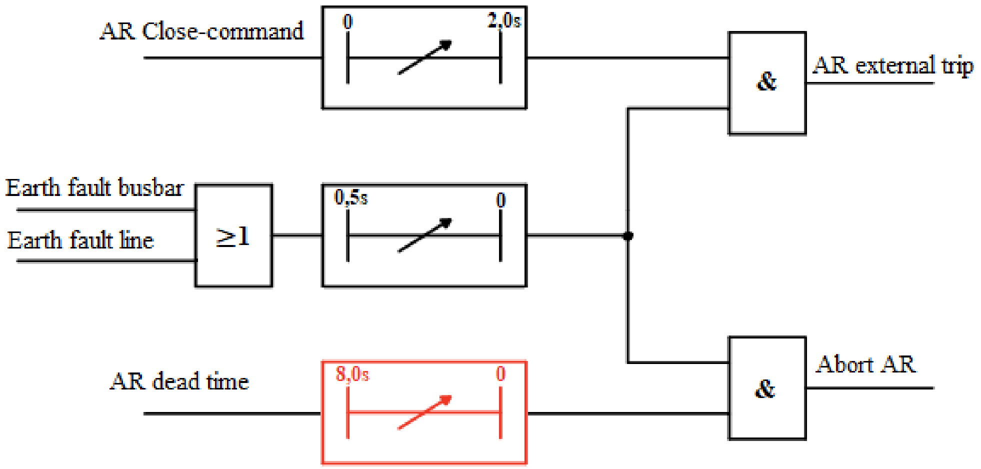


FIGURE 7.2: Simplified Solution

The modified logic includes a timer that will force the logic to wait until the end of the dead time to check the conditions, and then decide if the auto recloser should be aborted or not. The dead time is, as mentioned earlier, 10 seconds. A simplified version of the proposed solution can be seen in figure 7.2.

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