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Earth fault protection in isolated and compensated power distribution systems

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Problem description

Earth faults is the most common type of faults in the power system. In the distribution system both isolated and compensated neutrals are used and this requires in principle different earth fault detection methods.

This master thesis is written in co-operation with Statkraft. Power systems owned by Statkraft have often isolated neutrals. In parallel to this, the local utility might typically have distribution systems with a compensated (Petersen coil) neutral. These systems can serve as backup for each other in emergency situations. If the systems have a different type of earthing the earth fault detection becomes a challenge. Statkraft wants to identify if there exist measurement or relay protection methods that can handle both types of earthing methods.

The ambition of this master thesis is to identify if the same relay settings can be used for detection of earth faults in both compensated and isolated power distribution systems.

Preface

This report is the result of the work with the master thesis written during the spring of 2016 at the Department of Electric Power Engineering at the Norwegian University of Science and Technology.

The thesis is written in co-operation with Statkraft, where the aim has been to find valid relay settings to use both in isolated and compensated power distribution systems. The readers of this report is assumed to have a basic knowledge in power system theory.

I wish to express gratitude towards my supervisor, Professor Hans Kristian Høidalen, for guidance and help throughout the semester. I would also like to thank Ronny Goin at Statkraft for answering all of my questions and assisting with useful information. In addition, I really appreciate those who have taken time out of there busy schedule to answer my inquiries via email. The answers have helped me a lot.

Notice: Some of the contents used in this thesis is also a part of the specialization project with the same title completed in the fall semester of 2015. The specialization project was used as a pre-project for the master thesis. The same material used in the thesis has been edited where deemed necessary.

Trondheim, 06-juni-2016

Anniken Liland Fredriksen

Abstract

This report presents theory on transformer neutral earthing, earth fault protection and simulations on a real 22 kV power distribution system in ATPDraw provided by Statkraft.

The report consists of three main parts. The first part presents a problem description and theory, the second part presents possible solutions to the problem described, and simulations with one of the mentioned solutions. At the end, a conclusion is drawn.

In the introductory chapters the theoretical background for the report is accounted for. An introduction to the different earthing methods of a transformer neutral is given: (i) solid earthing, (ii) isolated neutral (iii) compensated neutral, and (iv) resistance earthed neutral. Unsymmetrical conditions in a power system, and how to handle these unsymmetrical conditions when performing calculations are then explained. A section on how to handle earth faults and the principal of earth fault detection is included at the end. The main focus has been on directional earth fault relays with $\mathrm{I}_0 \cos\varphi$- setting for compensated systems and $\mathrm{I}_0 \sin\varphi$-setting for isolated systems.

A chapter on detection problems for the directional earth fault relay is included as well, to clarify what can go wrong when detecting an earth fault in a power distribution system. The detection problems might demand a different solution to the normal $I_0 \cos\varphi$ and $I_0 \sin\varphi$-settings. The encountered detection problems are: (i) not enough capacitive current contribution, (ii) measuring error from the CT and VT, (iii) disconnection of the coil, and (iv) situations where a $I_0 \cos\varphi$-setting is used in an isolated system, or reversed.

In the next part of the report, proposed solutions for the detection problems are studied. The following solutions are presented:

1. Installing non-conventional measuring transformers for a more accurate measuring result

2. Adding extra functions to the component regulating the coil

3. Extended operating area in the directional earth fault relay

4. Grouping of parameter settings in the directional earth fault relay

5. Having two parameter settings active simultaneously in the directional earth fault relay

6. Installing a high ohmic resistance in the neutral point of the transformer

The extended operating area was chosen as the most feasible solution to be used in both isolated and compensated power distribution systems. To see if this was actually the case, a real power system was modeled in ATPDraw and simulations were completed with the extended operating area.

At the end a discussion on the contributing factors of the simulation is presented, and a final conclusion is given with suggestions for further work.

Sammendrag

Denne rapporten inneholder teori om jording av transformator nullpunkt, jordfeilbeskyttelse og simulering av et reelt 22 kV distribusjons nettverk i ATPDraw gitt av Statkraft.

Rapporten består av tre hoveddeler. I den første delen presenteres problemstilling og teori, i den andre delene presenteres mulige løsninger til problemstillingen, denne delen inneholder også simuleringer med en av de nevnte løsningene. Til slutt trekkes en konklusjon.

I de innledene kapitlene blir det teoretiske bakgrunnsmaterialet for oppgaven gjort rede for. Dette gir blant annet en innføring i de forskjellige jordimgsmetodene for nullpunktet til transformatoren: (i) direktejordet, (ii) isolert, (iiii) spolejordet, og (iv) motstandsjordet. Deretter blir usymmetriske tilstander i nettet, og hvordan disse skal behandles når beregninger skal gjennomføres, gjennomgått. Til sist blir jordfeil og prinsippet bak jordfeildeteksjon studert. Hovedfokuset er på retningsbestemte jordfeil reléer med $I_0 \cos\varphi$-innstilling for spolejordet nett og $I_0 \sin\varphi$-innstilling for isolerte nett.

Deteksjons problemer ved jordfeil er også belyst. Dette for å tydeliggjøre hva som kan gå galt ved deteksjon av jordfeil i distibusjonsnettet og hvorfor en annen løsning enn de normale $I_0 \cos\varphi$ og $I_0 \sin\varphi$-innstillingene er nødvendig. De vanligste deteksjons problemene er: (i) for lite kapasativ strømbidrag, (ii) målefeil fra CT og VT, (iii) frakobling av spole, og (iv) situasjoner hvor man har en $I_0 \cos\varphi$-innstilling i et isolert nett, eller omvendt.

I neste del av rapporten blir mulige løsninger for deteksjonsproblemene studert. Følgende mulige løsninger presenteres:

1. Innstallere ikke-konvensjonelle måletransformatorer for et mer nøyaktig måleresultat

2. Legge til ekstra funksjoner i regulerings komponenten til spolen

3. Utvidet utløseområdet i det retningsbestemte jordfeilreléet

4. Gruppering av parameter innstillinger i det retningsbestemte jordfeilreléet

5. Aktivering av to parameter innstillinger i det retningsbestemte jordfeilreléet samtidig

6. Innstallering av høy-ohmig motstand i transformator nullpunktet

Løsningen med det utvidete utløseområdet ble valgt som den mest gjennomførbare løsningen for bruk i både isolerte og spolejordet nett. For å sjekke om dette var tilfelle, ble et reelt nett modelert i ATPDraw og simuleringer med det utvidete utløseområdet gjennomført.

Til sist presenteres en diskusjon rundt elementene i simuleringen, og en endelig konklusjon blir gitt med forslag til videre arbeid.

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Acronyms

IED	Intelligent Electronic Device
IEC	International Electronic Commitee
CT	Current Transformer
CBCT	Core Balance Current Transformer
VT	Voltage Transformer
DT	Definite Time
IMDT	Inverse Minimum Definite Time
NTE	Nord-Trøndelag Elektrisitetsverk

1 Introduction

Earth fault protection is an important part of the power distribution system and with power systems in continuous development towards smarter solutions, the earth fault protection method needs to develop in the same direction.

In power distribution systems, there are often systems that have transformer neutrals isolated from earth. In parallel to these power systems, there can be other power systems with a compensated transformer neutral. In principal, the earth fault protection for isolated and compensated systems requires different methods. How should the earth fault protection be handled when these two different power systems need to act as backup for each other in emergency situations?

Exploring the different methods for earth fault protection is an important answer to this question. By exploring the different methods a smarter and more efficient solution to earth fault protection for the above mentioned situation can be found.

1.1 Scope and Limitations

In this report a literature survey has been completed to try and map earth fault protection methods. Through the mapping, the most feasible method was chosen for testing on a existing power distribution system with different earthing of the transformer neutral. The method chosen was an extended operating area of the directional earth fault relay. The purpose was to see if it would work as well as the existing solution for earth fault protection in the power system.

The focus in the literature survey has been on IEDs in the distribution system. IEDs here being, relays. Relays do not only have the option of earth fault protection but also distance protection, over current, over voltage and so on. To limit the scope of the relays, only usage for earth fault protection has been in focus.

To limit the amount of simulations, one solution for earth fault protection was chosen to be simulated. The intention was to model the system in ATPDraw and test it towards a real relay that offered the proposed solution. Unfortunately such a relay was not managed to get a hold of. The testing was therefore limited to simulations in ATPDraw.

1.2 Literature survey

The literature used in this report has been two sided. One part used for theoretical purpose and the other for existing methods of earth fault protection in power distribution systems.

Part of the theoretical foundation has been supplied by professor Hans Kristian Høidalen at NTNU and Ronny Goin at Statkraft. Knowledge and books from previous subjects attended at NTNU has also been used.

For the literature on existing methods of earth fault protection, the internet database IEEE Xplore has been frequently used. Typical keywords used during the search:

- Earth fault protection
- Isolated neutral
- Compensated neutral
- Earth fault protection relays
- Earth fault detection
- Distribution network

These are keywords directly related to earth fault protection in power distribution systems. Selecting articles to use was based on number of citations and referencing. However, most of the applicable information for earth fault protection was found in the technical manuals of ABB and Siemens relays. The technical manuals where found on the homepage of the companies. A newer version of one of the technical manuals from Siemens was provided by Einar Lamo, head of protection relays at Siemens Norway. Other search engines, like electropedia and wikipedia, have been used as a reference to define power system topics and non-related power system topics.

2 Theory

This chapter entails the theoretical background for the report.

2.1 System earthing

In a 22 kV distribution system it is normal, in case of wye-connected windings, to have three-phased transformers with a neutral point taken out at earth potential. Earth potential is assumed for symmetrical conditions in the system.

The neutral point can be handled in more than one way. It can be directly grounded to earth, isolated from earth, or grounded to earth through a resistance or inductance. The earthing method of the neutral point does not affect the system under normal operating conditions, but in case of an earth fault, the earthing of the neutral point can have a great impact on the system.

During normal operation there will be no flow of current to earth, theoretically. When an earth fault occurs this changes, and the resulting fault current and voltage depends on the neutral point earthing. A solidly earthed neutral will give low over voltages but a high fault current. An isolated neutral will generate small fault currents, but there is a risk of over voltages. A compensated neutral minimizes the reactive earth fault current, which results in complications of detecting the earth fault. Finally, a resistance earthed neutral will dampen the over voltages but can on the other side generate extensive earth fault currents.

2.1.1 Solid earthing

When the neutral point of a wye-connected transformer is solidly earthed, it is directly connected to earth. When the transformer neutral is directly connected to earth it forces the neutral point to stay at earth potential. This prevents a high voltage rise at the healthy phases in case of an earth fault, but it gives means to large fault currents. This earthing method is normally used in high voltage systems and 400 V TN systems, because the neutral point remain in its position and gives low over-voltages. Figure 2.1 shows a solidly earthed system.

The solidly earthed system will not be a focus area throughout this report since it is mostly used in high voltage systems and 400 V TN systems. The report will focus on system earthing used in distribution systems of 22 kV.

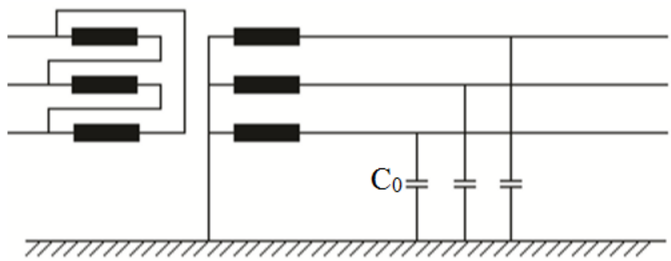


Figure 2.1: Solidly earthed system [1]

2.1.2 Isolated neutral

When the transformer neutral is isolated, there is no connection between the neutral and earth. This is shown in figure 2.2.

The system is technically unearthed, but there will always be a capacitive connection to earth between the phases. In an earth fault situation the neutral point will not be able to stay at earth potential and the voltage between the healthy phases and earth will rise and reach line voltage.[2] An arc will also occur, however, if I_f <10 A the arc will extinguish.[3] An isolated system is mainly used in medium and low voltage systems.

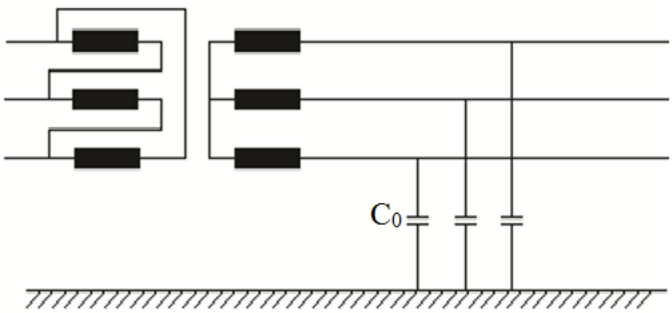


Figure 2.2: Isolated system [1]

The capacitive connection to ground between the phases will also play an important role during an earth fault. Dependent on the length and type of the lines in the power system, the capacitive connection can be either weak or strong. When an earth fault occurs in one of the phases, the thèvenin equivalent of the system will look like the one in figure 2.3.

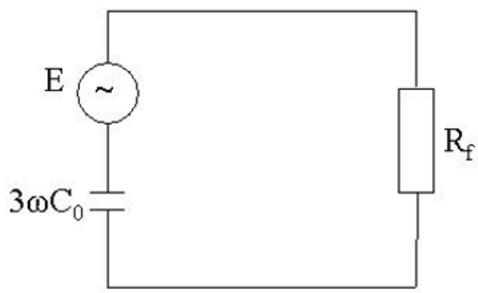


Figure 2.3: Thèvenin equivalent of an isolated system with an earth fault [2]

If the earth fault is solid, R_f in figure 2.3 can be neglected and the single-phase earth fault current will be entirely capacitive. As shown in equation 2.1.

$$I_f = I_c = 3\omega C_0 E \tag{2.1}$$

Equation 2.1 shows that the capacitive connection to ground greatly affects the earth fault current. If the connection to earth is solid and strong, it will generate extensive earth fault currents. If the earth fault is no longer solid, the earth fault current will consist of a capacitive part and a resistive part as shown in equation 2.2.

$$I_f = I_r + jI_c \tag{2.2}$$

$$I_r = \frac{R_f(3\omega C_0)^2 \cdot E}{1 + (R_f 3\omega C_0)^2}$$

$$I_c = \frac{3\omega C_0 \cdot E}{1 + (R_f 3\omega C_0)^2}$$

The parameters in equation 2.1 and equation 2.2 are interpreted as follow:

I_f Single-phase earth fault current [A]

I_r Resistive part of the earth fault current [A]

I_c Capacitive part of the earth fault current [A]

E Voltage of the faulted phase before the earth fault occurs [V]

$3\omega C_0$ Line susceptance of the system [S]

R_f Resistance to earth for the faulted phase [Ω]

An estimation can also be made for calculating the earth fault current in distribution lines and cable systems.[4]

Distribution line:

$$I_f = \frac{U \cdot l}{300} \tag{2.3}$$

Cable:

$$I_f = \frac{U \cdot l}{7.5} \tag{2.4}$$

U Line voltage [kV]

l Line length [km]

2.1.3 Compensated system

In a compensated system, a Petersen coil is connected between the transformer neutral and earth. The name of the coil comes from its inventor, Waldemar Petersen. This inductive connection limits the reactive part of the earth fault current and improves self-extinguish in the system. Electrical wise a coil will behave opposite of a capacitance, and thus limiting the capacitive part of the earth fault current. The coil can be adjustable to make sure the compensation is right if the system changes. The regulation is done continuously. The coil is, however, not set to equal the capacitances in the system. If they are equal the system will be operated in resonance and this can give rise to large differences in the voltages if the capacitances are not symmetrical. There will also be a voltage over the coil that reaches its maximum in resonance. Because of this, the coil is most of the time operated overcompensated. Which means that the inductive current is slightly larger than the capacitive current. Overcompensation is also a security measure for resonance if a line in the system where to fall out.

To give a clearer picture of under/overcompensation, equation 2.6 with Y_e can be studied. Y_e is the relationship between the capacitance to earth and the coil connected to the transformer neutral. By letting $\frac{1}{\omega L} = 0.95 \cdot 3\omega C_0$ an overcompensation of 5 % of the capacitive connection to earth has been set. If $\frac{1}{\omega L} = 1.05 \cdot 3\omega C_0$, however, an undercompensation of 5 % of the capacitive connection to earth has been set. Regulating the coil like this, allows for a proper compensation of the system in case it changes.

A compensated system, as seen in figure 2.4, is mostly used in medium and high voltage systems. When the extent of the system becomes too large, a compensated system is preferred over an isolated one.[5]

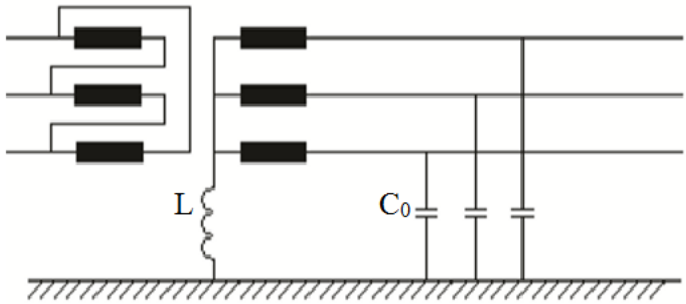


Figure 2.4: Compensated system [1]

It is normal to have a resistor in parallel with the coil. This is not shown in figure 2.4. Seeing as the coil will limit the reactive earth fault current, the earth fault current will be hard to detect. The resistor, however, generates a measurable resistive earth fault current, which will enable detection. During an earth fault the thévenin equivalent of a compensated system will look like the one in figure 2.5.

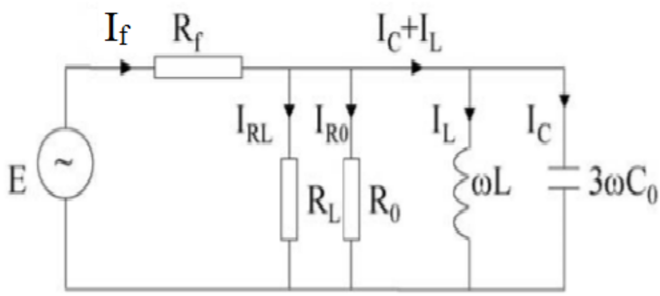


Figure 2.5: Thévenin equivalent compensated system with an earth fault [2]

The single-phase earth fault current will then be as follow, in case of a solid earth fault:

$$
\begin{aligned}
I_f &= I_{RL} + I_{R0} + j(I_L + I_c) \\
I_f &= \frac{(R_L + R_0) \cdot E}{R_L \cdot R_0} + j \cdot (3\omega C_0 - \frac{1}{\omega L})E
\end{aligned}
\tag{2.5}
$$

From equation 2.5 it can be seen that a complete compensation of the capacitive contribution will give a solely resistive earth fault current. If a fault resistance is present, the single-phase earth fault current will be as given in equation 2.6.

$$\begin{aligned} I_f &= \frac{G_e(R_f G_e + 1) + R_f Y_e^2 + jY_e}{(R_f G_e + 1)^2 + (R_f Y_e)^2} \\ G_e &= \frac{R_L + R_0}{R_L R_0} \\ Y_e &= 3\omega C_0 - \frac{1}{\omega L} \end{aligned} \tag{2.6}$$

Complete compensation will, also here, give a solely resistive earth fault current. Parameters:

I_f	Single-phase earth fault current [A]
I_{RL}	Current due to resistive losses in the coil [A]
I_{R0}	Current generated by the parallel resistance [A]
I_L	Inductive part of the earth fault current [A]
I_c	Capacitive part of the earth fault current [A]
E	Voltage of the faulted phase before the earth fault occurs [V]
$3\omega C_0$	Line susceptance of the system [S]
R_f	Resistance to earth for the faulted phase [Ω]
R_L	Resistive losses in the coil [Ω]
R_0	Parallel resistance to the coil [Ω]
ωL	Coil represented by an inductor [Ω]

2.1.4 Resistance earthed

A resistance is connected between the transformer neutral and earth in a resistance earthed system (figure 2.6). This will limit over voltages and better the detection ability of the earth fault relays. This method is in practice only used for earthing generators, and is therfore not further discussed in detail.

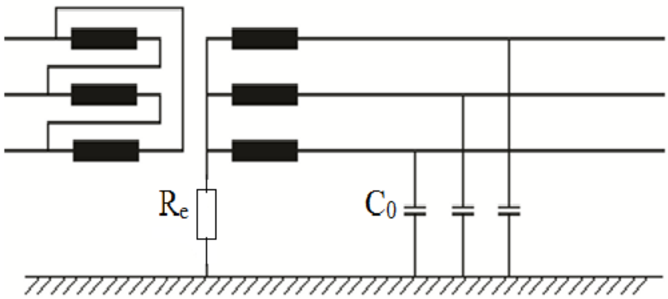


Figure 2.6: Resistance earthed neutral

2.2 Unsymmetrical conditions

When an earth fault occurs, the three-phased system will be affected by a single-phase to earth fault and this causes unsymmetrical conditions. Unsymmetrical conditions can also occur form natural events in the system, like conductive- and capacitive discharge. When these unsymmetrical conditions occur, the system can no longer be treated as a symmetrical one and analysed per phase. The theoretical approach, as stated in Fortescue's theorem, is to decompose the system into three modes, where each mode has symmetrical properties. These symmetrical properties are necessary to compute the unsymmetrical currents and voltages that arise, and consist of a positive sequence, a negative sequence and a zero sequence as seen in figure 2.7.

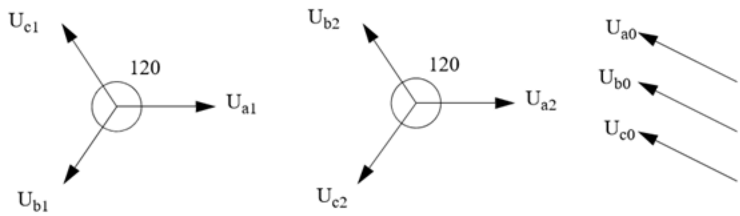


Figure 2.7: Positive(1)-, Negative(2)- and Zero(0) sequence [6]

For illustration purposes, an isolated system will have per phase sequence equivalents as shown in figure 2.8.

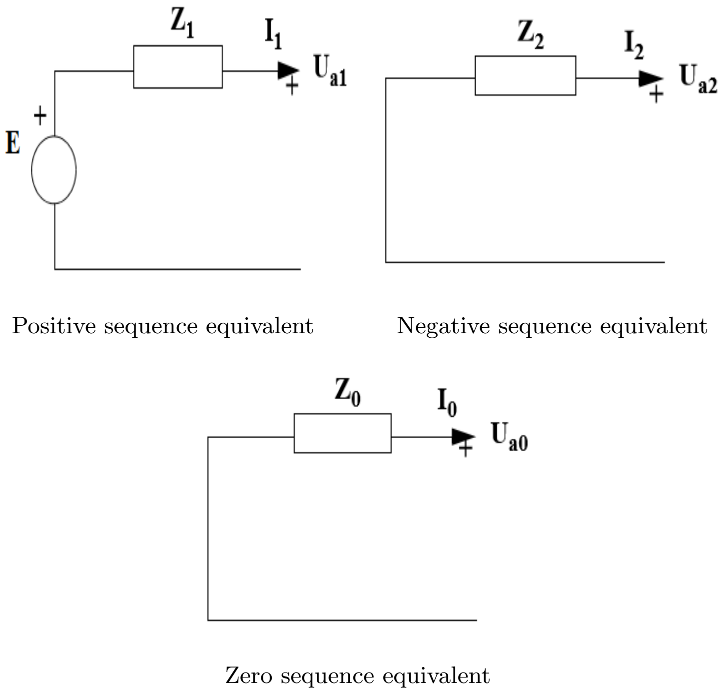


Figure 2.8: Sequence system equivalents [6]

When an earth fault occurs, the per phase sequence equivalents are superposed and the system equivalent for the isolated system will look like the one in figure 2.9.

The sequence impedances are seen from the earth fault location.

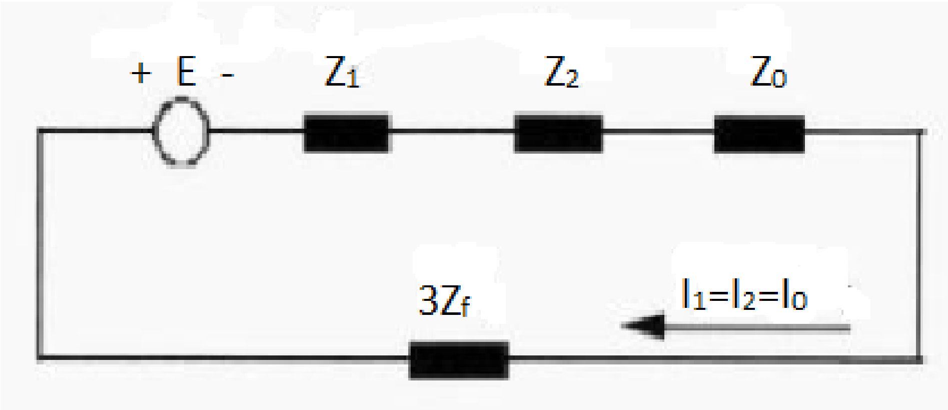


Figure 2.9: System equivalent for the isolated system with an earth fault [7]

Then the positive-,negative- and zero sequence currents can be calculated as follow:

$$I_1 = I_2 = I_0 = \frac{E}{Z_1 + Z_2 + Z_0 + 3Z_f} \tag{2.7}$$

In a symmetrical power system one often makes the assumption that $Z_1 = Z_2$.[7] The final earth fault current can then be calculated as:

$$\begin{aligned} I_f &= I_1 + I_2 + I_0 = 3I_0 \\ I_f &= 3\frac{E}{2Z + Z_0 + 3Z_f} \end{aligned} \tag{2.8}$$

If figure 2.9 is further studied, it can be shown that it will be the same as figure 2.3 and that the earth fault current will be as described in equation 2.2. Assumptions must,however, be made. Normally the positive- and negative sequence impedance will give a much smaller contribution than the zero sequence impedance and can therefor be neglected. If the zero sequence impedance is assumed dominated by the capacitances to earth in the system, then Z_0 will equal:

$$Z_0 = \frac{1}{j\omega C_0}$$

With the assumptions made above and that Z_f is solely resistive, equation 2.8 can be rewritten as equation 2.2:

$$\begin{aligned} I_f &= 3\frac{E}{\frac{1}{j\omega C_0} + 3R_f} \\ &= \frac{j3\omega C_0 \cdot E}{1 + R_f j3\omega C_0} \\ &= \frac{j3\omega C_0 \cdot E \cdot (1 - R_f j3\omega C_0)}{1 + R_f j3\omega C_0 \cdot (1 - R_f j3\omega C_0)} \\ &= \frac{R_f (3\omega C_0)^2 \cdot E}{1 + (R_f 3\omega C_0)^2} + j\frac{3\omega C_0 \cdot E}{1 + (R_f 3\omega C_0)^2} \\ &= I_r + jI_c \end{aligned}$$

The same composition of sequence systems and assumptions as above can be made for a compensated system. Which results in the same thévenin equivalent as in figure 2.5. The earth fault current will then be as stated in equation 2.6.

Parameters:

Z_1 Impedance for voltages that rotates with a positive sequence [Ω]

Z_2 Impedance for voltages that rotates with a negative sequence [Ω]

Z_0 Impedance for equal sequence voltages [Ω]

Z_f Earth fault impedance [Ω]

I_1 Positive sequence current [A]

I_2 Negative sequence current [A]

I_0 Zero sequence current [A]

I_f Single-phase earth fault current [A]

E Voltage of the faulted phase before the earth fault occurs [V]

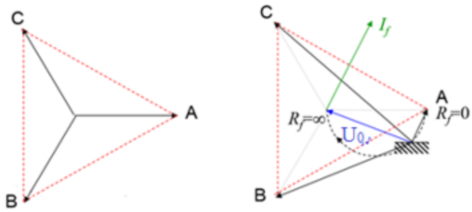
2.2.1 Neutral point displacement voltage

The neutral point displacement voltage arises in an earth fault situation. As mentioned in section 2.1.2, the neutral point will no longer manage to stay at earth potential and a voltage will build up across the capacitances to earth. This is the case both in a compensated system and an isolated one. What happens is that the fault resistance to earth forces the neutral point to move. The line voltages will not be affected, and this forces a change in the phase to earth voltage for the healthy phases. This voltage can rise as much as 105 % of the pre-fault phase-to-phase voltage in an isolated system.[2] Equation 2.9 and 2.10 gives the neutral point displacement voltage in respectively, an isolated system and in a compensated system. In an isolated system, if the earth fault is solid, the neutral point displacement voltage will be the pre-fault voltage of the faulty phase. When the earth fault is no longer solid, some of this voltage will be across the fault-resistance as well and U_n will differ from U_0. For a compensated system with a solid earth fault, the neutral point displacement voltage will be the pre-fault phase to earth voltage. The neutral point displacement voltage will be across the capacitances as well as the coil and the parallel resistance (if connected).

$$U_0 = \frac{I_f}{3\omega C_0} \tag{2.9}$$

$$U_0 = \frac{I_f}{\sqrt{\frac{1}{R_e}^2 + (3\omega C_0 - \frac{1}{\omega L})^2}} \tag{2.10}$$

Equation 2.9 and 2.10 needs to be seen in combination with respectively, equation 2.2 and 2.6. Figure 2.10 shows the movement of the neutral point for an isolated system. The stippled lines are the line-voltages and they remain, as mentioned previously, unchanged.



Healthy system System with earth fault

Figure 2.10: Phasor representation of voltages in an isolated system [8]

2.2.2 Distribution line parameters

The distribution line parameters, which are a part of the sequence system impedances in figure 2.8, can be calculated from the following equations. The deriving of some of the equations are not explained, but simply stated. For further knowledge the reader is recommended to look into reference [9].

The per phase impedance in a three-phase distribution line, with a possible return path through earth for the current, can be derived from the following equation:

$$\begin{bmatrix} U_{a-g} \\ U_{b-g} \\ U_{c-g} \end{bmatrix} = \begin{bmatrix} r_a + r_e & r_e & r_e \\ r_e & r_a + r_e & r_e \\ r_e & r_e & r_a + r_e \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} + j \begin{bmatrix} x_{aa-g} & x_{ab-g} & x_{ac-g} \\ x_{ab-g} & x_{bb-g} & x_{bc-g} \\ x_{ac-g} & x_{bc-g} & x_{cc-g} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \tag{2.11}$$

In equation 2.11 the three phases are assumed transposed to fulfill cyclic symmetrical conditions. When the phases are transposed the conductors in the line are not equilateral spaced but change geometrical position in a cyclic sequence over the total length of the line.[9] This is not normal in Norwegian power distribution systems, but are for simplicity of the calculation assumed here.[3] Further assumptions are that the conductor is non-magnetic (μ_r=1) and:

$$x_{aa-g} = x_{bb-g} = x_{cc-g} = \mu_0 f ln \frac{D_g}{g_{aa}} = 0.063 \left(\frac{f}{50} \right) ln \frac{D_g}{g_{aa}} \quad \frac{\Omega}{km}$$

$$x_{ab-g} = x_{bc-g} = x_{ac-g} = \mu_0 f ln \frac{D_g}{D} = 0.063 \left(\frac{f}{50}\right) ln \frac{D_g}{D} \quad \frac{\Omega}{km}$$

Parameters:

$U_{a,b,c-g}$ Phase to ground voltage [V]

$I_{a,b,c}$ Phase current [A]

μ_0 Permeability in air $= 4\pi \cdot 10^{-7}$

f Frequency [Hz]

r_a Conductor ac-resistance $[\frac{\Omega}{km}]$

r_e Equivalent resistance in earth $= \frac{1}{4}\mu_0 f \pi \cdot 1000 = 0.049 \frac{f}{50}$ $[\frac{\Omega}{km}]$

D_g Equivalent distance to earth $= 660\sqrt{\frac{\rho}{f}}$ [m]

ρ Specific resistivity of earth $[\Omega \cdot m]$

g_{aa} 0.39d, d = diameter of conductor [m]

D Distance between the phases [m]

x_{aa-g} Self inductance of conductor $[\frac{\Omega}{km}]$

x_{ab-g} Mutual inductance between two phases $[\frac{\Omega}{km}]$

Positive sequence

To simplify notation, the a-operator is used as the phase-shift between the phases. A reminder of the operator is given in equation 2.12.

$$\begin{aligned} a &= e^{j120} \\ a^2 &= e^{j240} \\ 1 + a + a^2 &= 0 \end{aligned} \tag{2.12}$$

For positive sequence currents it is know that:

$$\begin{aligned} I_b &= a^2 I_a \\ I_c &= a I_a \end{aligned}$$

Then from equation 2.11:

$$\begin{aligned} U_{a-g} &= (r_a + r_e)I_a + r_e \cdot a^2 I_a + r_e \cdot a I_a + jI_a(x_{aa-g} + x_{ab-g}(a^2 + a)) \\ &= r_a I_a + jI_a(x_{aa-g} - x_{ab-g}) \end{aligned}$$

Using ohms law and inserting for x_{aa-g} and x_{ab-g}, the positive sequence impedance Z_1 is found as stated in equation 2.13.

$$Z_1 = r_a + j0.063 \left(\frac{f}{50}\right) ln \frac{D}{g_{aa}} \quad \frac{\Omega}{km} \tag{2.13}$$

For the positive sequence capacitance, c_1, it can be shown that it can be approximated by equation 2.14.

$$c_1 \approx \frac{2\pi\epsilon}{ln\frac{2D}{d}} \quad \frac{nF}{km} \tag{2.14}$$

The per phase equivalent diagram for the positive sequence distribution line, will look like figure 2.11.

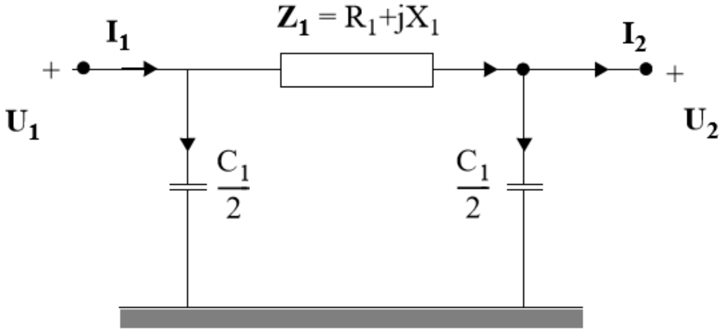


Figure 2.11: π-equivalent, positive sequence

Parameters:

l	Length [km]
R_1	Resistance, $r_a \cdot l$ [Ω]
X_1	Reactance, $(x_{aa-g} - x_{ab-g}) \cdot l$ [Ω]
C_1	Capacitance, $c_1 \cdot l$ [nF]

Zero sequence

When it comes to zero sequence currents, $I_a = I_b = I_c = I_0$. Then by using equation 2.11:

$$\begin{aligned} U_{a-g} &= (r_a + r_e)I_0 + r_e I_0 + r_e I_0 + jI_0(x_{aa-g} + 2x_{ab-g}) \\ &= (r_a + 3r_e)I_0 + jI_0(x_{aa-g} + 2x_{ab-g}) \end{aligned}$$

Inserting for x_{aa-g} and x_{ab-g} and using ohms law, gives the zero sequence impedance Z_0 in equation 2.15.

$$Z_0 = (r_a + 3r_e) + j0.063\left(\frac{f}{50}\right) ln\frac{D_g^3}{g_{aa}D^2} \quad \frac{\Omega}{km} \tag{2.15}$$

Compared to the positive sequence impedance, the zero sequence impedance has the terms $3r_e$ and D_g. These terms originates from the return path through earth for the current. For the positive sequence, there is no return path through earth for the current and the terms are thus, not present in the impedance expression. The zero sequence capacitance, c_0, equals the capacitance between phase and earth and can be derived to be as stated in equation 2.16. Figure 2.12 shows the per phase equivalent diagram for the zero sequence distribution line.

$$c_0 = c_g = \frac{2\pi\epsilon}{ln\frac{4h}{d}} \quad \frac{nF}{km} \tag{2.16}$$

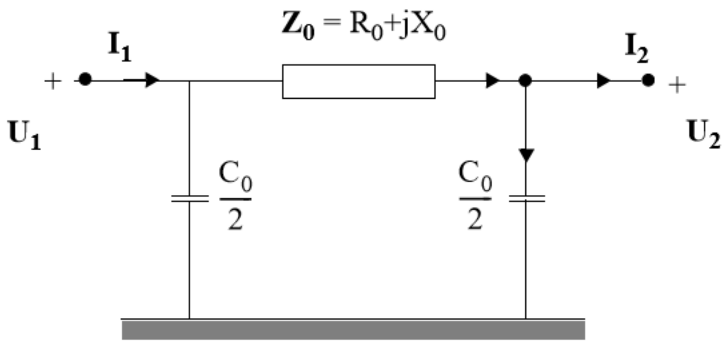


Figure 2.12: π-equivalent, zero sequence

In distribution lines with planar conductors and without overhead earth conductors, the mid phase has a 5-15 % lower capacitive connection to earth compared to the other two phases.[3] This will give rise to a ΔC and unsymmetrical conditions that will generate a neutral point displacement voltage during normal conditions. Cables are only assumed to have 1 % of asymmetry.[3]

Parameters:

l Length [km]

R_0 Resistance, $(r_a + 3r_e) \cdot l$ [Ω]

X_0 Reactance, $(x_{aa-g} + 2x_{ab-g}) \cdot l$ [Ω]

C_0 Capacitance, $c_0 \cdot l$ [nF]

ϵ Permittivity, $\epsilon_r \epsilon_0$

ϵ_r =1 Relativ permittivity, uniformly distributed charge on the surface of the conductor is assumed

ϵ_0 =8.85$\cdot 10^{-12}$ Vacuum permittivity [$\frac{nF}{km}$]

h Conductor height above earth [m]

All equations and figures from section 2.2.2 are from reference [9].

2.2.3 Conductive discharge

Conductive discharge mainly exist from bad isolation, moist in cable joints and pollution of the power system insulators. This discharge current is often called damping and is considered to be 1-15 % of the capacitive earth fault current. In a compensated power system, a rule of thumb is that 1 % of the conductive discharge originates from the coil.[3] The zero sequence system of the conductive discharge will look like the one in figur 2.13. It is here illustrated by resistances, however, it is known that the conductance is given as $G = \frac{1}{R}$.

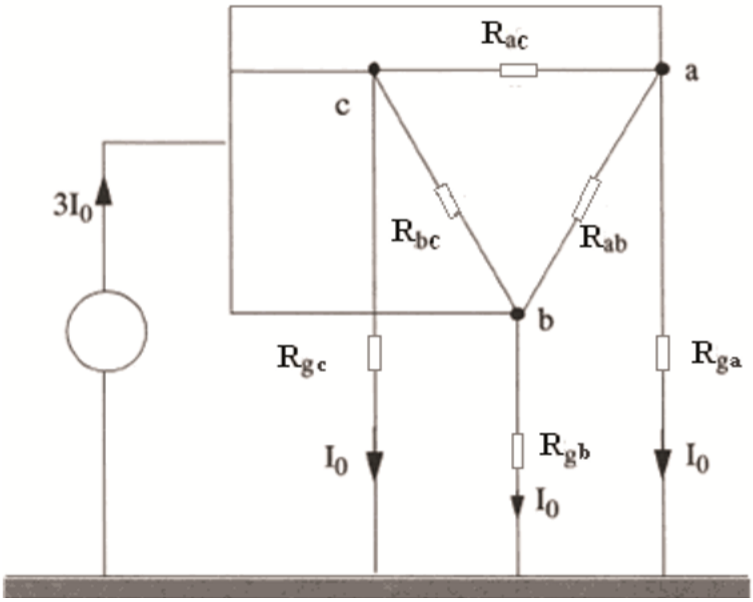


Figure 2.13: Conductive discharge, zero sequence system [1]

$$R_0 = \frac{1}{\frac{1}{R_{ga}} + \frac{1}{R_{gb}} + \frac{1}{R_{gc}}} \tag{2.17}$$

Equation 2.17 gives the zero sequence resistance. The resistance to earth for the phases are in parallel. Natural occurrences, like a different degree of pollution of the power system insulators, may lead to unsymmetrical conditions that will give rise to a neutral point displacement voltage.

2.3 Earth fault regulations

An earth fault can be a tree that falls on the line or perhaps branches that come in contact with one or more of the phase conductors. It is not exactly defined in the Norwegian regulations what an earth fault is, but there are certain requirements that need to be fulfilled in the event of one. For starters, in an isolated and compensated 22 kV power distribution system, the Norwegian regulations, in section §4-2 reads: *there should be a minimum resistance to earth. If this limit is undershot, operating personnel should be alerted automatically, alternatively the power system should be disconnected.*

These limits are:

- Cable systems: minimum 1000 Ω
- Mixed systems, cable and air: minimum 3000 Ω

The disconnection time for a given power system, in the event of an earth fault is given in table 2.1. That is, how fast the power system should be disconnected after an earth fault is registered. The disconnection time does not include any re-connections of the power system.[10]

Table 2.1: Maximum disconnection time, high voltage systems

Earthing Method	**Power System**	**Disconnection Time**
Solid		8 seconds
Resistance		30 seconds
Isolated and Compensated	Distribution line and mixed system with connected distribution transformer	10 seconds
	Distribution line and mixed system without connected distribution transformer	120 minutes
	Industrial system with distribution line and mixed system	120 minutes
	Cable system with global earthing	240 minutes

In section §4-11 of the Norwegian regulations the allowed limit of touch voltage in case of an earth fault is stated. Figure 2.14 shows the allowed touch voltage as a function of the current time span. The y-axis shows the touch voltage and the x-axis the current time span. If the current is present for an unlimited amount of time, the touch voltage should not be greater than 75 V. The touch voltage is defined as: *the voltage between conductive parts when touched simultaneously by a person or an animal.*[11] There is also another voltage defined when it comes to earth fault situations. That is the step voltage. The step voltage is the voltage between two points on the earths surface that are one meter distant from each other, which is considered the stride length of a person.[12] This voltage does not have a set limit because the allowed value of it is greater than the value of the touch voltage. So if the touch voltage is within allowed limits, the step voltage will automatically be as well.[10]

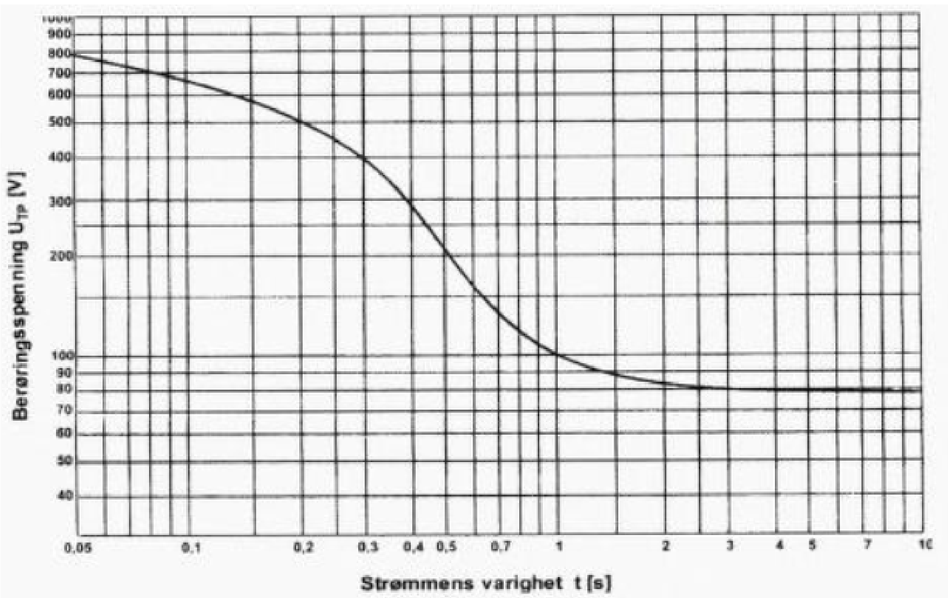


Figure 2.14: Touch voltage as a function of current time span [10]

2.4 Earth fault principle

When an earth fault occurs, the principle is that "the healthy feeds the faulty". This principle can be seen in figure 2.15, and is valid for power distribution systems feeding more than one connected line.

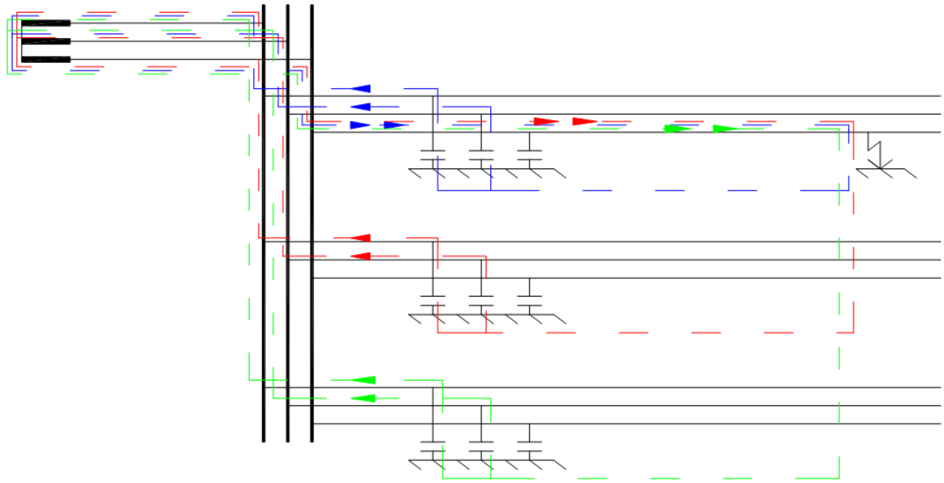


Figure 2.15: "The healthy feeds the faulty"-principle [5]

The figure shows an isolated system with three connected lines and an earth fault in phase C for the first connected line. The current from the healthy lines and the faulty line will flow through the transformer windings before flowing onto the faulty line. The faulted phase will give no current contribution and the total current contribution from the faulted line is canceled out. The protective relay associated with the faulty line, will therefore measure the current contribution from the two healthy lines.

"The healthy feeds the faulty"-approach is used for the directional earth fault relay explained in section 2.6.3. If there is only one connected line in the power system, the principle falls through for an isolated system. This is looked at closer in section 3.1.

2.5 Measuring transformers

In order to detect an earth fault, the neutral point displacement voltage and earth fault current needs to be measured. For this purpose, current- and voltage transformers are used.

2.5.1 Current transformer

The purpose of a current transformer (CT) is to transform the fault current down to a level so the IEDs can register it without being damaged. Figure 2.16 shows the different measurement methods.

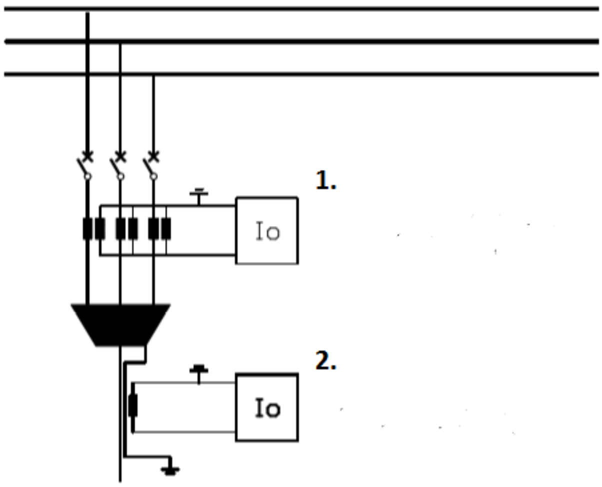


Figure 2.16: Current measurement methods [13]

1. Holmgren-connection. A CT is connected to each phase and parallel connected on the secondary side. This measuring method has its weaknesses when it comes to detecting small earth fault currents. This might be due to different magnetizing characteristics of the three phases or a high transformer ratio of the CTs.[7]

2. Core balance current transformer, CBCT. A CBCT will measure the current through all the phases of a line. In a healthy power system the sum of the current through all the phases in a line will be zero. When the sum differs from zero, a current in the secondary winding will be induced and a signal is sent to the IED. When using a CBCT the cable sheath must be taken into consideration to avoid false fault detection.[14]

2.5.2 Voltage transformer

The neutral point displacement voltage can be measured in more than one way and it will be the same regardless of where in the power system the measurement is completed. In figure 2.17 the different measurement methods can be seen.

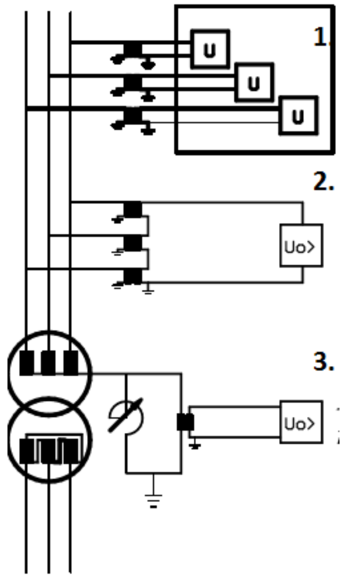


Figure 2.17: Voltage measurement methods [13]

1. The phase voltage is measured and then summed internally in the IED as $3U_0$.

2. Voltage transformer with a broken delta winding. Measures $3U_0$.

3. Direct measurement of the neutral point displacement voltage over the transformers neutral point and earth.

2.6 Earth fault protection relays

The purpose of a protection relay is to protect the power system. It operates with the measuring transformers, and processes the signals sent from them to detect faults in the power system. There are certain demands that must be fulfilled by the protective relays. If they fail to operate, large sums might be lost.[15]

A protective relay must be:

1. Reliable. Relay trips the breaker at a fault in the line it covers and does nothing when the fault is not located in its operating area.

2. Selective. The part of the power system that is disconnected during a given fault, should be as little as possible to achieve minimum interruption time.

3. Fast. To reduce damage.

4. Cheap. The purchase and maintenance should be affordable.

5. Easy to set. The setting of the relay should be easy to set and understand.

In the event of an earth fault, normal short circuit protection will not do. The current will be too small to trigger the protection mechanism. So for earth fault protection, other relays that are sensitive enough for detecting earth faults, must be implemented in the power system. The type of relays that are used are zero sequence voltage and current relays, directional earth fault relays and earth fault transient relays (Wischer relay).

2.6.1 Zero sequence voltage relay

A zero sequence voltage relay can be used for signaling earth faults. Under normal operating conditions the neutral point of the transformer in the power system will be at earth potential. That means, $U_n \approx 0$ and thus meaning, $U_0 \approx 0$. As mentioned earlier, U_0 will be the same regardless of where measurements are made in the power system. In an earth fault situation U_0 will rise and the zero sequence voltage relays will be able to detect that there is a fault situation. The detection, however, says nothing about where the fault is located. To locate the fault, the power system can be sectionalized. By dividing the power system into sections, each section can be tripped after turn to locate the earth fault. If it is a straight forward power system, one line after the other can be tripped automatically. This automatically goes on until the relay resets, then the last line that was disconnected is the faulty one. A reconnection is normally tried, to see if the fault has disappeared. If it is gone, the automatic will stop. If the fault is still present, the line is disconnected again and another reconnection might be tried after some delay. In the event that the automatic does not locate the faulty line, it indicates that the fault must be on the busbar. The breaker between transformer and busbar will then trip and this will be the final operation. This method of locating earth faults is tiresome and it might even cause customers to loose power on a healthy line.

2.6.2 Zero sequence current relay

When an earth fault occurs, a zero sequence current will flow in the system. This current will be of a different magnitude throughout the power system. The zero sequence current relay will trigger if the current is above a set limit. The problem with this method of detecting earth faults, is that the zero sequence current is normally small and it is hard to achieve a selective protection.[15]

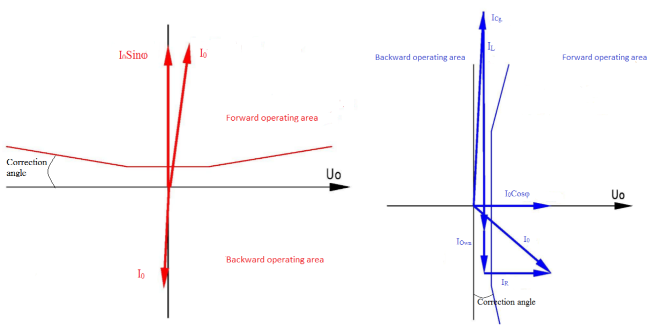
2.6.3 Directional earth fault relay

Directional earth fault relays uses both zero sequence voltage and current to detect and locate earth faults when steady state is reached. Each line will have a directional earth fault relay. In figure 2.15 where "the healthy feeds the faulty", the current has a opposite direction in the faulty line than that of the healthy lines. By using this and U_0 as a reference it is possible to decided in which direction the earth fault is. It is the angle, φ, between I_0 and U_0 that is used to determine in which direction the earth fault is.

For an isolated system, I_0 will mostly be given by the capacitive connection to earth. I_0 will then be 90° in front of U_0 or 90° behind depending of if the earth fault is in forward direction, or in backward direction. When the earth fault is in forward direction, the fault is on the line and in front of the measuring relay. If the earth fault is in backward direction, the earth fault is behind the measuring relay and located in one of the other lines. An isolated system uses the $I_0 \sin\varphi$-setting. Which is the same as measuring the reactive part of the earth fault current.

In a compensated system, the reactive part of the earth fault current will be over- or undercompensated by the current contribution from the coil connected to the neutral point of the power system transformer. To ensure selectivity, measurements of the resistive part of the earth fault current is used. The setting in the relay is then set to, $I_0 \cos\varphi$. The measurements are based on conductive discharge and losses in the coil. In other words, the active part of the earth fault current.

Figure 2.18 shows the operating area for the $I_0 \sin\varphi$ and $I_0 \cos\varphi$-setting. These operating areas might be different from manufacture to manufacture when it comes to axis definition. The x- and y-axis are defined after how the zero sequence voltage and current is measured. The zero sequence current can be measured in line direction or towards the busbar. The operating area is 180° with a correction angle for both settings.



$I_0 \sin\varphi$-setting $\qquad$ $I_0 \cos\varphi$-setting

Figure 2.18: Operating area directional earth fault relay [13]

Figure 2.19 shows the operating principle of a directional earth fault relay by ABB. The basic concept is that, the measuring transformers sends signals to the level detector, where they are compared to defined pickup values. If the measured values are higher than the pickup values, a signal is sent to the timer module and directional calculations are implemented. The timer module consist of two options; definite time (DT) or inverse definit minimum time (IDMT). Where the DT module has a predefined trip time and resets when the fault current disappears and the IDMT mode uses a current-dependent time characteristics. If the timer module reaches its trip delay time, the trip output is activated. There is also the possibility of blocking functions in the relay, when necessary.

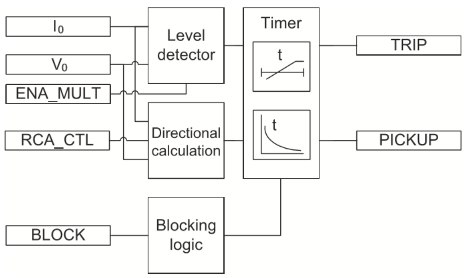


Figure 2.19: Operating principle [14]

The $I_0 \sin\varphi$ and $I_0 \cos\varphi$-settings are the most commonly used for directional earth fault protection, there are however other operating modes to choose from. For the ABB relay REF615 ANSI, these are elaborated in table 2.2. Chapter 3 will elaborate on the $I_0 \sin\varphi$ and $I_0 \cos\varphi$-settings.

Table 2.2: Operation mode ABB relay REF615 ANSI [14]

Operation mode	**Description**
Phase angle	The operating sectors for forward and reverse are defined with a min and max forward angle and a min and max reverse angle
Phase angle 80	The operating area is frozen to 80°. Only a min forward and min reverse angle can be set.
Phase angle 88	The operating area is frozen to 88°. Only a min forward and min reverse angle can be set.

2.6.4 Wischer relay

The Wischer relay, or the transient relay, measures the zero sequence voltage and current during the transient period of the earth fault. It bases its detection method on measuring at the moment the earth fault occur and before steady state is reached. This relay is used for signaling, and by combining it with other relays the earth fault location can be pin pointed.

3 Detection problems

When using the directional earth fault relay, U_0 and I_0 is set to a certain limit. When this limit is overthrown an earth fault is assumed to be present in the power system. I_0 defines where in the power system the earth fault is located.

There are different problems associated with the detection method of a directional earth fault relay, and they will now be looked at in detail.

3.1 Not enough capacitive current contribution

In an isolated system, for the $I_0 \sin \varphi$-setting to work, the power system needs to feed more than one line to give a high enough capacitive current contribution for the relay to measure on. The directional earth fault relay will be placed on each line fed from the power system, and as seen in figure 2.15, the healthy lines will feed the faulty one. The current contribution from the faulty line is canceled out, so what the relay measures is the current fed from the healthy lines that flows out on the faulty one. So, if there where to be only one line in the power system, the relay would not have enough to measure on and the $I_0 \sin \varphi$-setting would not work. The I_0-phasor seen in figure 2.18 for the $I_0 \sin \varphi$-setting will not go into the operating area as shown in the figure. For power systems like this, a zero sequence voltage relay is normally used. In a compensated system this would not be an issue, because measurements of the active part of the earth fault current is used.

3.2 Angle error

Another problem that can occur when detecting an earth fault, is that a backward fault is registered as a forward one. This happens by the means of an angle error. This angle error can be caused by the measuring transformers or the relay itself. This detection problem is more present in a compensated system than in an isolated one. This is because, in an isolated system the angle between a forward and backward earth fault will be more or less 180°. For a compensated system the angle difference between a forward and backward earth fault will not be as prominent. So if there is a measuring error made by the measuring transformers, this can cause a backward earth fault to be dragged into the operating area of a forward earth fault. The principal is shown in figure 3.1.

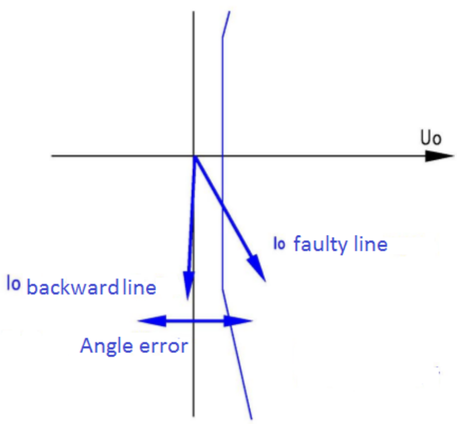


Figure 3.1: Angle error with a $I_0 \cos\varphi$-setting [13]

When it comes to angle error, another issue is that the measured angle is not big enough to reach into the operating area. This problem is related to a compensated system with a resistance connected in parallel to the coil. The operating area must be set in context with dimensioning the coil and the parallel resistance. The issue at hand is shown in figure 3.2.

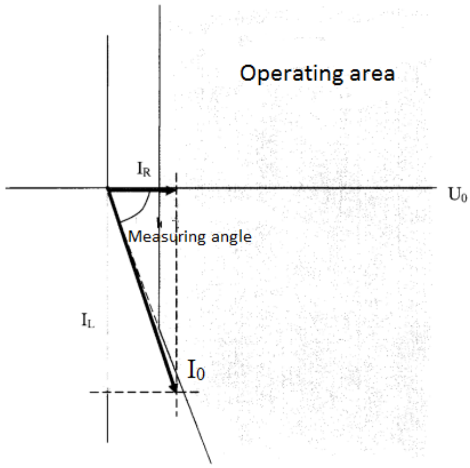


Figure 3.2: Angle error compensated system [4]

I_R, which is the contribution from the parallel resistance, reaches into the operating area in an earth fault situation, but the resulting I_0 phasor does not. The problem is, that the measuring angle between I_R and I_L (coil contribution) is miss matched compared to the defined operating area. The measuring angle can be calculated as in equation 3.1.

$$\text{Measuring angle} = \arctan \frac{I_L}{I_R} \tag{3.1}$$

3.3 Disconnection of coil

If, for some reason the coil connected to the transformer neutral in a compensated system where to disconnect, a $I_0 \cos\varphi$-setting might have troubles detecting an earth fault. The detection will then only depend on the conductive discharge in the system and since it is not more than 1-15 % of the capacitive current in the system this might no be enough to drag I_0 into the operating area. The failure of detection will look like figure 3.3.

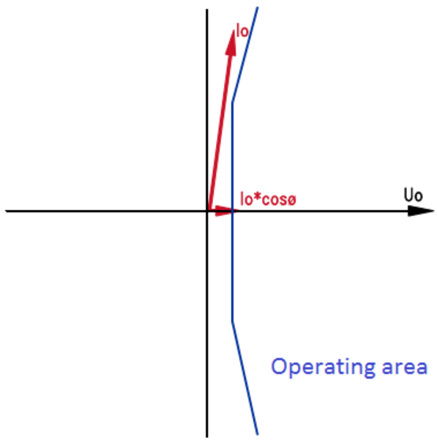


Figure 3.3: Failure to detect earth fault when the coil is disconnected [13]

3.4 Connecting isolated and compensated systems

Isolated and compensated systems have different detection settings of earth faults. If an isolated system fails to operate, the system needs to be operated by other means. If a parallel power system exists, this can be connected to operate the system. It is not given that this parallel power system is also an isolated system. In the event that it is operated as a compensated system, there will be some detection issues for the directional earth fault relays in the normally isolated system that is operated with a $I_0 \sin\varphi$-setting. The detection ability of a $I_0 \sin\varphi$-setting of earth faults in a compensated system depends on the level of compensation from the coil. Figure 3.4 shows a directional earth fault relay that is normally used in an isolated system, but is currently used in a compensated one. In this situation the coil is overcompensated and the relay fails to detect the earth fault.

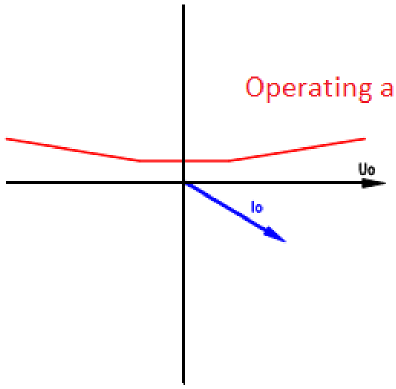
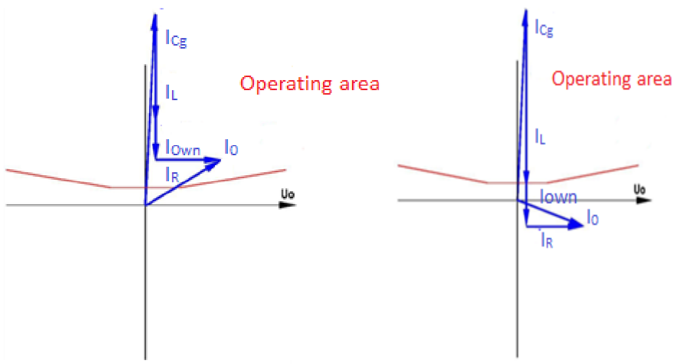


Figure 3.4: $I_0 \sin\varphi$-setting with a overcompensated coil [13]

If the coil where to be operated undercompensated, the directional earth fault relay would have a better chance of detecting the fault. Figure 3.5 illustrates a situation where the $I_0 \sin\varphi$-setting detects the fault and a situation where it is not able to. The coil is undercompensated.



Fault detected

Fails to detect fault

Figure 3.5: $I_0 \sin\varphi$-setting with a undercompensated coil [13]

Phasors in figure 3.5:

I_{Cg} Total capacitive and resistive contribution in the power system

I_L Coil contribution

I_{Own} Reactance of the line contribution

I_R Parallel resistance contribution

I_0 Resulting earth fault vector

Solutions for the issue at hand, will be discussed in chapter 4.

4 Alternative earth fault protection

As described in chapter 3 there are some issues with detecting earth faults. Since the purpose of this report is to find a solution to the earth fault detection problem of connecting an isolated and compensated power distribution system, the following chapter will discuss alternative methods for solving the problem. A literature survey has been conducted and the following findings are now presented. The methods and the relevance of the methods will be discussed at the end of the chapter.

4.1 Earth fault protection with sensors

Earth fault protection with sensors use the same IEDs as in directional earth fault protection, but the measuring transformers have changed. Instead of using conventional methods like CTs, CBCTs and VTs, non-conventional methods like Rogowski coil and voltage dividers are used. These non-conventional measuring methods are without a ferromagnetic core. Which means that they are not influenced by the non-linearity and width of the hysteresis curve. The result of this, is that they can produce linear and accurate characteristics in a full operating range.[16]

With these non-conventional measuring methods the zero sequence voltage and current can be measured more accurately and with that, reducing the measuring error which can cause unintentional tripping of healthy lines.

4.2 Extended functions of coil regulator

The coil in a compensated system is regulated according to the capacitive current contribution in the system. The regulation is made in context with a resonance curve, which shows the voltage at the neutral point and the current through the coil. Resonance will be at the maximum value of the neutral voltage. In addition to regulating the contribution of the coil, other characteristics can be added. A regulating component will then be able to conduct calculations from information gathered from the coil and the power system. This again, can be used for earth fault protection. Three different calculation methods are used to ensure quality detection; transient, zero sequence admittance and zero sequence admittance with regulation of the coil.[7] Based on these calculations, the regulator will be able to detect an earth fault and the faulty line. The way it is able to ensure this is with fuzzy-logic. Fuzzy-logic entails that the truth values of variables may be any real number between 0 and 1, in contrast to boolean logic where the truth values are either 0 or 1.[17] The method uses only measurements of existing currents and voltages in the power system and will in theory make earth fault protection relays redundant. Because the method only uses the measurements of existing currents and voltages in the power system, a connection of a parallel resistance will not be necessary.[7]

4.3 Extended operating area earth fault relay

The directional earth fault protection relay described in section 2.6.3 has, in newer protection relays, the option of an extended operating area. Instead of having a setting that is dependent of the earthing method, a operating area is set by a minimum and maximum forward angle which will detect earth faults regardless if the earthing method is isolated or compensated. The concept of detection is still the same as in section 2.6.3. Signals are received from the measuring transformers and the zero sequence voltage and current must be above the set pickup value for the tripping to commence. There is, however, different definitions of the operating area from manufacturer to manufacturer. A comparison of the ABB REF615 and Siemens SIPROTEC 7SJ62/64 relay validates this.

In the ABB REF615 the operating area is set by a minimum and maximum forward angle so that all possible directions of the I_0-phasor is covered.[14] This can be seen in figure 4.1.

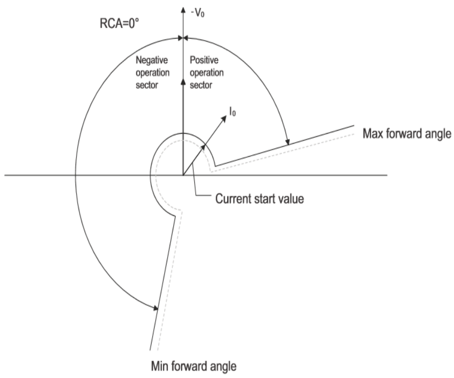


Figure 4.1: Extended operating area ABB REF615 [14]

The Siemens SIPROTEC 7SJ62/64 uses a few more parameters to set the extended operating area, see figure 4.2. To define the operating area, the angle φ, a center of the area with reference to U_0 and a $\Delta\varphi$ to extend the area on both sides of the center is used. The operating area is, as for ABB REF615, set with pickup values of zero sequence voltage and current.

In the SIPROTEC 7SJ62/64 the earthed phase can be located by measurements of the phase-to-earth voltages. To do this a VT with earthed wye configuration must be used for the measurements. If the voltage magnitude in one of the phases is below a set minimum voltage, this phase is located as the earthed phase. For this to be valid, the other phase-to-earth voltages must be above a set maximum voltage.[18]

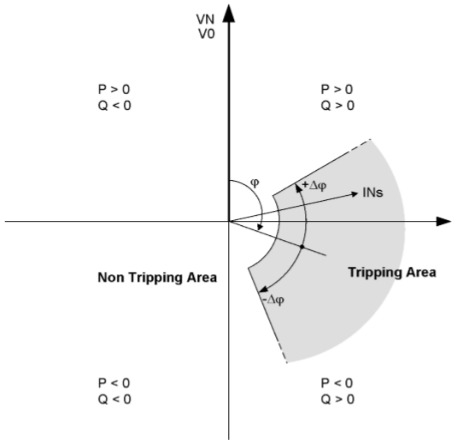


Figure 4.2: Extended operating area Siemens SIPROTEC 7SJ62/64 [18]

Another difference between the manufacturers, is the definition of the zero sequence voltage. ABB chooses to use the negative value of U_0 while Siemens uses the positive.

Jacobsen Elektro is also a company that offers directional earth fault relays with an extended operating area. In the RefleX 204/205 the operating area can be set to be between 0°- 360°.[19]

4.4 Other possibilities

In directional earth fault relays one also has the option of having a group of settings. One setting for $I_0 \sin\varphi$ and one for $I_0 \cos\varphi$. To change between the settings, a signal is sent via a binary input. There is also the possibility of having both parameter settings active at ones. The operating area will then be a combination of the $I_0 \sin\varphi$-setting area and $I_0 \cos\varphi$-setting area seen in figure 2.18.[20] There will be two pair of pickup values. One for the $I_0 \sin\varphi$-setting and another for the $I_0 \cos\varphi$-setting. The operating area is more or less set to 180° plus a correction angle. The ABB REF615 has the option of changing the number of threads the message flow in the relay can use for certain applications. This is the case for the directional earth fault protection, where it can use two instances. By doing this, it can process information both for the $I_0 \sin\varphi$-setting and $I_0 \cos\varphi$-setting.

Another alternative solution to better the premises for detection in an isolated system, is to install a high ohmic resistance in the neutral point of the transformer. The method will be as described in section 2.1.4.

4.5 Discussion

As the main ambition is to find a solution for earth fault protection that works in both compensated and isolated power systems, earth fault protection with sensors might not be the best way to go. It will give a more accurate measuring, but probably not a solution to the issue of connecting isolated and compensated power distribution systems. Especially when the coil is overcompensated. A more accurate measuring will not make the contribution from the coil any less, and the I_0-phasor will still look like the one in figure 3.4, i.e not entering the operating area. Then it is more likely, that the non-conventional measuring methods, will better the detection possibilities when the coil is undercompensated. However, since the coil most of the time is operated overcompensated, this is not probable. For the detection possibilities of a $I_0 \cos\varphi$-setting in an isolated system, by measuring a more accurate conductive discharge the chances of detecting a fault might increase. The contribution from the conductive discharge will, however, still not be more than 1-15% of the capacitive current in the system. It will also be expensive to exchange all the existing measuring transformers with the non-conventional ones.

A regulatory component that can be extended to regard earth fault protection as well as controlling the contribution from the coil, would be an efficient component to have in a power system. In the situation of section 3.4, when a power system is changed to be operated compensated, there would be no problem that the $I_0 \sin\varphi$ set relays might fail to detect an earth fault because the regulatory component would handle it. There is, however, the slight problem that when the compensated system has to be operated from a parallel isolated system there will be no directional earth fault relays in the compensated system. So the relays might not be redundant after all. Inquiries to see if the method is actually in use has not been confirmed.

An extended operating area for the directional earth fault relay would be a good solution to assure independence of earthing method. This method is also used in Norway today. An inquire with the head of protection relays in Siemens Norway confirmed that the method is in use, among others in the companies NTE Nett and Helgelandskraft. The head of substations in NTE Nett could inform that they use the extended operating area with a minimum angle of -80° and a maximum angle of +170°. The problem with the method is the chance that the I_0-phasor comes into the operating area when the fault is in backward direction. To avoid this, the relays need to be tested in earth fault situations. The pickup values of the zero sequence voltage and current is also an issue. They differ in an isolated system and a compensated one, so setting pickup values that covers both systems might be tricky. They need to be set according to the lowest I_0 and U_0 occurring in the power system during an earth fault. Having low pickup values can result in unintentional tripping due to asymmetry in the power system. The extended operating area would be a cheaper solution then to install a coil or a resistance in an otherwise isolated system to cope with the issues in section 3.4. That is, as long as the already existing protective relays has the option of an extended operating area. There is also the issue of ensuring selectivity and setting tripping times within the demands of the power system.

Changing between $I_0 \sin\varphi$-setting and $I_0 \cos\varphi$-setting is a safe way to ensure detection of earth faults. The relays can automatically adjust to the earthing method when they receive a signal that tells them to. This signal must be sent manually. There can be a problem for the relay to receive the signal if it is remote controlled. This should not be a problem though, seeing as the digital solutions now days are so good. Statkraft and Helgelandskraft are two companies that use this method in

Norway.

Having both the $I_0 \sin\varphi$-setting and $I_0 \cos\varphi$-setting active in the relay is also a good solution to ensure independence of earthing method. Especially since two sets of pickup values can be defined. The operating area will then be a combination of the $I_0 \cos\varphi$ and $I_0 \sin\varphi$-settings in figure 2.18. Having the two parameter settings active simultaneously, results in limitations when it comes to angle adjustments. The correction angle in figure 2.18 can only be adjusted between $0°$ and $10°$ for the ABB REF615 relay. This means that earth faults in backward direction in a compensated system might enter the operating area set by the forward $I_0 \sin\varphi$-setting. Hafslund is a power company that use this type of solution for earth fault protection. An inquiry with Hafslund revealed that relays seeing the earth fault in backward direction, and entering the forward operating area has not been a problem with them. A greater concern is unintentional tripping because of unsymmetrical conditions in the system. All in all, two parameter settings is a good option for earth fault protection in both isolated and compensated power distribution systems. Unsymmetrical conditions and backward earth faults entering the forward operating area must however, be looked into.

Earthing the isolated system with a resistance will give similar characteristics for detection as for a compensated system. When deciding the value of the resistance, it has to be seen in combination with the already existing compensated system and tests has to be implemented to figure out if the resistance should be connected all the time or only during earth fault situations.

5 Analysis of Refsdal power system

A analysis has been completed of Refsdal power system. This power system is a distribution system with an isolated transformer neutral owned by Statkraft. Parallel to this system, a local distrubitor Sognekraft exists. This distribution system is a compensated one and will for simplicity be called Hove. In emergency situations these two power systems can act as backup for each other. This creates the earth fault detection issues described in section 3.4. Simulations has therefor been completed in ATPDraw to see if the extended operating area described in section 4.3 can be a valid solution to the problem. ATPDraw is a simulation program with an EMTP and graphical user interface. The program was developed by professor Hans Kristian Høidalen at NTNU. The modeled implemented in ATPDraw, with directional earth fault relays, can be seen in figure A.1.

The solution used today by Statkraft, is the use of different setting groups in the directional earth fault relay. Figure 5.1 presents a single line diagram of Refsdal power system, provided by Statkraft. During normal operating conditions, the line segment called Hove is disconnected. Hove is the connection line to Hove power system. In emergency situations, Hove is connected and the total power system (Refsdal and Hove) can be operated as an isolated system or a compensated one. The line segment Fosse has a substation with a single line diagram presented in figure 5.2.

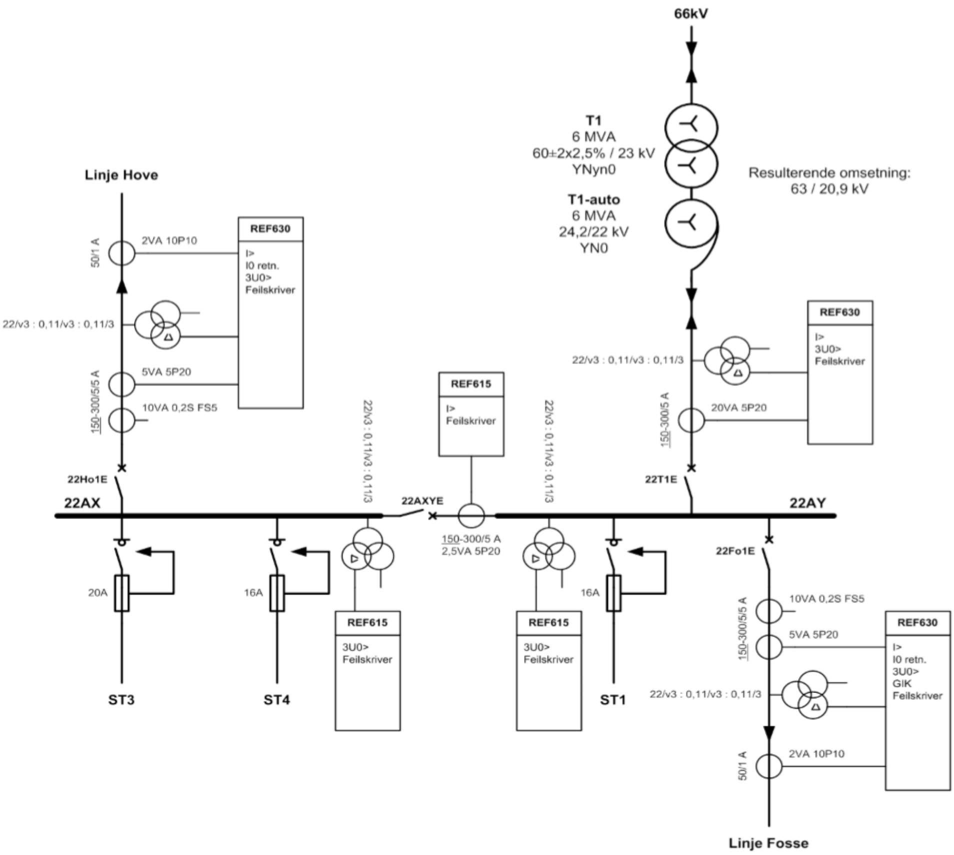


Figure 5.1: Single line diagram Refsdal power system

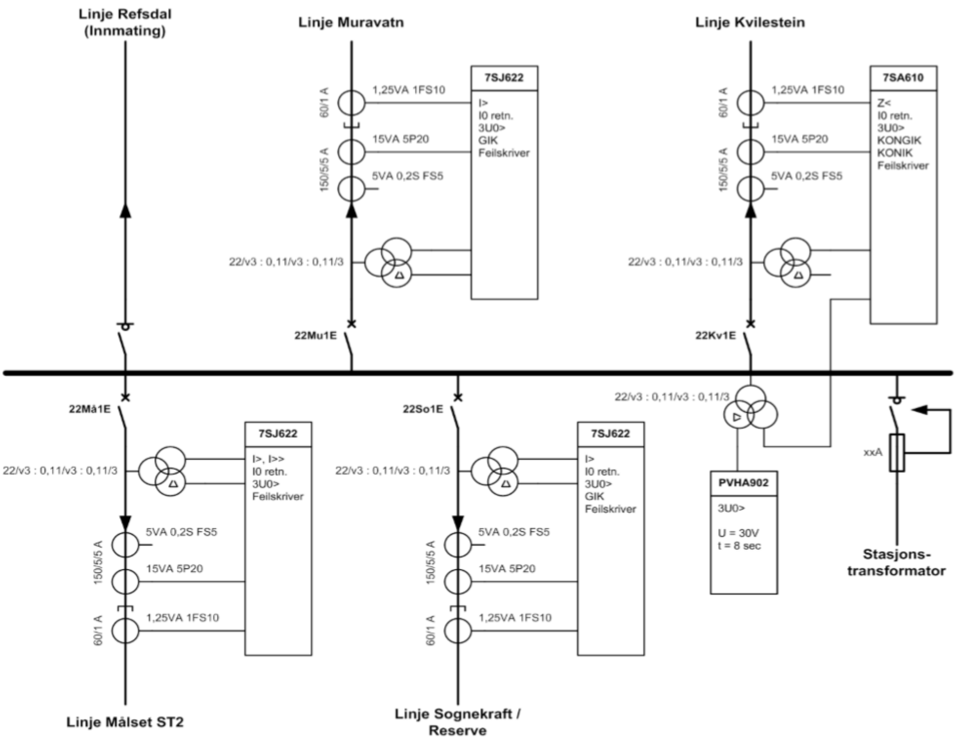


Figure 5.2: Single line diagram Fosse substation

5.1 Method

5.1.1 Parameters

In order to complete the simulation of the power system, parameters of the lines and transformers had to be specified. They were collected from a PowerFactory-file of the power system. Table 5.1 presents the transformer parameters gathered. The generators for the two power systems were modeled as a source of 66 kV.

Table 5.1: Transformer parameters

Substation	S_n [MVA]	U_n [kV]		Connection group	Positive sequence		Zero sequence
		HV	LV		U_k [%]	Copper losses [kW]	U_{k0} [%]
Refsdal T1	6	66	23	YNyn0	7.70	18.00	6.63
Refsdal Auto T1	6	24.2	22	YN0	0.38	5.82	0.32
Hove T3	15	66	22	Yyn0	8.74	15.00	7.43
ST3	0.4	22	0.24	Yyn0	6.27	5.44	5.33
ST2M	0.315	22	0.24	Yyn0	6.01	4.75	5.11

In PowerFactory, only the line parameters Z_1 and C_0 where given for most line segments. Cables where assumed to have no mutual inductance so that $Z_1 = Z_0$ and $C_1 = C_0$. The distribution line parameters, however, needed some more calculations. There was one distribution line with all parameters available. With this, equation 2.13 was used to solve for D so that equation 2.15 could be used to solve for D_g (section A.1.1). These two parameters was then assumed to be the same for all distribution lines, so that equation 2.15 could be used to calculate Z_0. The positive sequence capacitance was calculated with equation 2.14. Table 5.2 shows the final result. The distribution lines are assumed revolved, in order for the equations to be valid.

Table 5.2: Line parameters

Line segment				Positive sequence		Zero sequence	
Length [km]	From	To	Type	Z_1 [Ω/km]	C_1 [$\mu F/km$]	Z_0 [Ω/km]	C_0 [$\mu F/km$]
0.15	Refsdal 22 AY	Connector	24kV 3x1x150 Al PEX	0.188 + j0.11	0.352	0.188 + j0.11	0.352
4.93	Connector	Målsetstøl	24kV FeAl 95	0.189 + j0.353	0.010	0.336 + j1.528	0.005
0.19	Målsetstøl	Målset Dam	24kV 3x1x50 Al PEX	0.565 + j 0.12	0.23	0.565 + j0.12	0.23
0.98	Målsetstøl	Fosse	24kV 3x1x150 Al PEX	0.188 + j0.11	0.352	0.188 + j0.11	0.352
0.78	Fosse	Målset ST2	24kV 3x1x50 Al PEX	0.565 + j0.12	0.23	0.565 + j0.12	0.23
0.5	Fosse	Connector Muravatn	24kV 3x1x50 Al PEX	0.565 + j0.12	0.23	0.565 + j0.12	0.23
1.33	Connector Muravatn	Branch	24kV FeAl 50	0.359 + j0.373	0.0098	0.507 + j1.548	0.005
0.6	Branch	Årebotn ventil	24kV FeAl 50	0.359 + j0.373	0.0098	0.507 + j1.548	0.005
2.77	Branch	Muravatn	24kV FeAl 50	0.359 + j0.373	0.0098	0.507 + j1.548	0.005
0.99	Fosse	Connector Kvilestein	24kV 3x1x150 Al PEX	0.188 + j0.11	0.352	0.188 + j0.11	0.352
3.4	Connector Kvilestein	Skjellingen hatch	24kV FeAl 95	0.189 + j0.353	0.010	0.336 + j1.528	0.005
6.8	Skjellingen hatch	Kvilestein valve	24kV FeAl 50	0.359 + j0.373	0.010	0.507 + j1.548	0.005
1	Refsdal 22 AX	Connector	24kV 3x1x240 Al PEX	0.125 + j0.170	0.280	1.772 + j0.465	0.233
8	Connector	Hove	24kV FeAl 25	0.721 + j0.395	0.009	0.87 + j1.57	0.005
0.64	Refsdal 22 AX	ST3	24kV 3x1x50 Al PEX	0.565 +j 0.12	0.23	0.565 + j0.12	0.23
19.18	Hove	Sognekraft	24kV 3x1x150 Al PEX	0.188 + j0.11	0.352	0.188 +j0.11	0.352

The last line segment in table 5.2, from Hove to Sognekraft, is an estimated line segment. This line segment is owned by Sognekraft, and the details around it is not known. However, the total capacitive current contribution in the system when Hove is connected is known to be 100 A. At least it is given as 100 A in the relay setting plans developed by Statkraft. Each line segment has its own capacitive current contribution, and with equation 2.1 and E= ${}^{22\,kV}/\sqrt{3}$ it can be calculated. The result is presented in table A.2. Summing all the capacitive current contribution of the line segments and knowing that the total should be 100 A, the missing current contribution was found to be 80.8 A. Using equation 2.1, C_0 of Sognekraft's line segment was found. Then the line segment was chosen to be represented by a 3x1x150 Al PEX and knowing the C_0 contribution per km of such a cable, the equivalent length of Sognekraft's line segment was found. This line segment is from now on, called OtherHove.

5.1.2 Load

The load on line Fosse is 150 kW. That is with all associated line segments. Line Fosse has a substation and from this substation there are three branches of line segments; line Målset, line Muravatn and line Kvilestein. The total load of 150 kW is assumed to be equaly distributed between the three line segments. The load is modeled as a delta connection at the end of each line in the ATPDraw model and assumed purely resistive. The resistance is found as follow:

$$\begin{aligned} R_{load} &= 3 \cdot \frac{U^2}{P} \\ &= 3 \cdot \frac{22\,kV}{50\,kW} \\ &= 29040\,\Omega \end{aligned}$$

For line Hove a load of 80 % of the nominal current for the CT is assumed. In the relay setting plans provided by Statkraft, the CT is found to have a nominal current of 150 A. With this, the resistance is found as follow:

$$\begin{aligned} P_{Hove} &= 3 \cdot U \cdot I_n \cdot 0.8 \\ &= 3 \cdot 22\,kV \cdot 150\,A \cdot 0.8 \\ &= 7.92\,MW \end{aligned}$$

$$\begin{aligned} R_{Hove} &= 3 \cdot \frac{22\,kV}{7.92\,MW} \\ &= 183.3\,\Omega \end{aligned}$$

The load is also in this case modeled as a delta connection, and then placed at the end of the line segment OtherHove.

5.1.3 Capacitive current contribution

As mentioned in section 5.1.1, I_c was calculated for each line segment with equation 2.1. To check if the power system modeled in ATPDraw gave the same values as calculated, a solid earth fault was implemented in phase A at the end of the line segment ST3. Then the current contribution in the largest line segments was measured with a zero sequence model. The result can be seen in table 5.3. In order to explain the values measured by ATPDraw the phase voltage for the largest line segments was also measured. The result is shown in table A.1 and figure A.2. All of these measurements where completed with an isolated neutral and line Hove connected. $I_{c,eff}$ is $\sqrt{2}$ scaled. One simulation was also completed without the auto transformer Refsdal Auto T1. It was believed to be an uncertain component in the simulation.

Table 5.3: Capacitive current contribution

Line segment	Calculated	Simulated	
	I_c [A]	I_c With Auto T1 [A]	I_c Without Auto T1 [A]
		$I_{c,eff}$	$I_{c,eff}$
Fosse	14.15	15.27	14.64
ST3	1.76	1.62	1.57
Hove	84.04	92.83	89.30
Total	99.95	109.72	105.51

5.1.4 Peterson coil

Since Hove power system is compensated, the coil had to be dimensioned. Having calculated the total C_0 (table A.2) and knowing that the coil is operated 5 % overcompensated, the value of the inductor, which is how the coil will be modeled in ATPDraw, could be found. First the reactance X_c of C_0 was found.

$$\begin{aligned} X_c &= \frac{1}{3 \cdot \omega C_0} \\ &= \frac{1}{3 \cdot 2\pi 50 \cdot 8.35 \cdot 10^{-6}} \\ &= 127\,\Omega \end{aligned}$$

Then the reactance X_l of the inductor was found as 5 % overcompensated of X_c. If X_l where to equal X_c, the system would be in resonance.

$$\begin{aligned} X_l &= 0.95 \cdot X_c \\ &= 0.95 \cdot 127\,\Omega \\ &= 121\,\Omega \end{aligned}$$

The coil at Hove power system has also two parallel resistances. One, R_{p1}, is connected during normal operation and the other, R_{p2} is connected by the coil regulator when U_0 rises above 10 % of the phase voltage. R_{p1} is disconnected with a delay of 1.5 seconds when this happens and R_{p2} is connected with a delay of 2 seconds. R_{p2} is then connected for 10 seconds and as long as it is connected, R_{p1} is blocked for connection. The effect of the parallel resistances are given as:

$$R_{p1} = 62.5\,kW$$
$$R_{p2} = 125\,kW$$

To model the parallel resistances the ohmic values where found:

$$\begin{aligned} R_{p1} &= \frac{U_p^2}{P} \\ &= \frac{\frac{22\,kV}{\sqrt{3}}}{62.5\,kW} \\ &= 2581\,\Omega \end{aligned}$$

$$\begin{aligned} R_{p2} &= \frac{U_p^2}{P} \\ &= \frac{\frac{22\,kV}{\sqrt{3}}}{125\,kW} \\ &= 1291\,\Omega \end{aligned}$$

To see if the modeled system gave the same value of the inductance as calculated, a simulation was completed. The resonance curve for the system, with only the inductor connected was simulated. The value of the inductance was set to vary with the equivalent current through it, and then the current was plotted as a function of the voltage at the neutral point of the transformer. The equivalent coil current is used because this would be the current through the inductor for a solid earth fault. 70 simulations where completed to vary the current. The current was defined as:

$$I_l = 91 + 0.3 \cdot K$$

K is the simulation number and 91 and 0.3 are values chosen to adjust the span of the current. The value of the inductor was then defined as:

$$X_l = \frac{\frac{U_p}{\sqrt{3}}}{I_l}$$

The resonance curve was plotted with a max/min function built in ATPDraw. To be able to get a clear resonance curve a ΔC was added in phase B at Refsdal busbar. Phase B was calculated to have 10 % less capacitive connection to earth than phase A and C, and then $3C_0$ for this situation was calculated and ΔC was set to be the original $3C_0$ minus the unsymmetrical $3C_0$. This gave a $\Delta C = 0.0135\,\mu F$. The result is shown in figure 5.3.

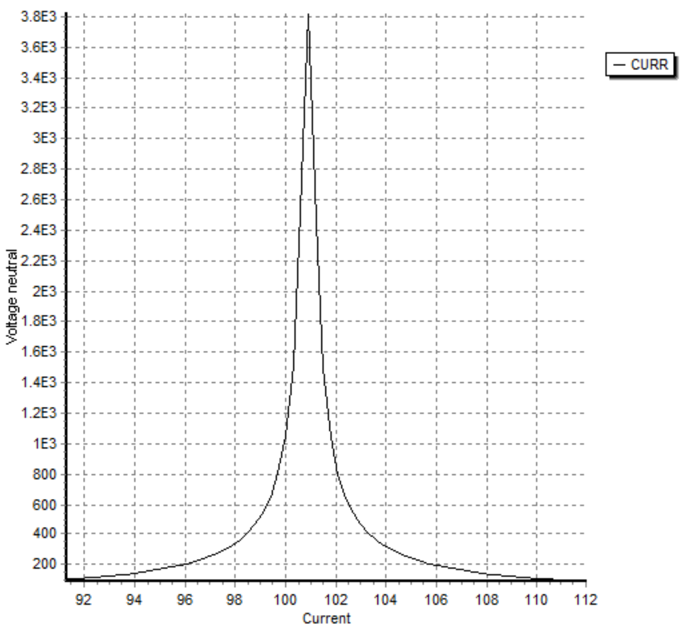


Figure 5.3: Resonance curve

Running an optimization function with the gradient method in ATPDraw on the resonance curve, gave $U_{n,max} = 3827.08\,V$ and $I_l = 100.89\,A$. With the coil being

5 % overcompensated:

$$I_l = 100.89 \cdot 1.05$$
$$= 106.029A$$

Which results in:

$$X_l = \frac{\frac{22kV}{\sqrt{3}}}{106.029A}$$
$$\approx 120\Omega$$

This is more or less the same as the calculated value of X_l.

The parallel resistance R_{p1} was then connected to see how it affected the resonance curve. Figure A.3 shows the simulation result.

Conductive discharge

Since conductive discharge will affect U_n in a compensated system, simulations of the resonance curve where completed with a conductive discharge added to Refsdal busbar and compared to analytical values. Each phase is assumed to have the same conductive discharge. The same ΔC as previously was also added. The maximum voltage at the neutral point of the transformer is given as:

$$U_{n,max} = \frac{U_p \omega \Delta C}{3G} \tag{5.1}$$

If the conductive discharge is chosen to be 10 % of the total capacitive current contribution:

$$\begin{aligned}
R_{cd,total} &= \frac{U_p}{0.1 \cdot I_c} \\
&= \frac{\frac{22kV}{\sqrt{3}}}{0.1 \cdot 100\,A} \\
&\approx 1270\,\Omega
\end{aligned}$$

In this $R_{cd,total}$, R_{p1} is also included since it is connected during normal operation. Seeing that R_{p1} is known and in parallel to the conductive discharge from the lines, the conductive discharge from the distribution lines can be found:

$$\begin{aligned}
R_{line} &= \frac{R_{cd,total} \cdot R_{p1}}{R_{p1} - R_{cd,total}}\Omega \\
&= \frac{1270 \cdot 2581}{2581 - 1270} \\
&= 2500\,\Omega
\end{aligned}$$

The per phase conductive discharge of the distribution lines is then:

$$\begin{aligned}
R_{line,ph} &= 3 \cdot 2500\,\Omega \\
&= 7500\,\Omega
\end{aligned}$$

The total per phase conductive discharge is given by:

$$\begin{aligned}
R_{cd,ph,total} &= 3 \cdot R_{cd,total} \\
&= 3 \cdot 1270\,\Omega \\
&= 3810\,\Omega
\end{aligned}$$

Using equation 5.1 the maximum voltage at the neutral point of the transformer could be calculated with $R_{cd,ph,total}$ and $R_{line,ph}$. For the last case, only the conductive discharge from the lines was taken into consideration and R_{p1} was disconnected. Comparing the calculated values with the simulated ones, gave table 5.4.

Table 5.4: Effect of conductive discharge on U_n

Situation	Calculated $U_{n,max}$ [V]	Simulated $U_{n,max}$ [V]
$R_{cd,ph,total}$	68.41	63.55
$R_{line,ph}$	134.67	180

Figure A.4 and figure A.5 shows the simulated resonance curve for the two situations. I_l remains approximately the same throughout the two situations. $U_{n,max}$ for the simulated situations, was found using an optimization function with the gradient method in ATPDraw.

5.1.5 Directional earth fault relay

The single line diagram in figure 5.1 and 5.2 also shows the installed directional earth fault relays, CTs and VTs in Refsdal power system. The CTs and VTs are not used in the simulation and will not be investigated further. For overview purposes, line segments with associated relays are listed in table 5.5.

Table 5.5: Line segments with associated relays

Substation	Line segment	Relay
Refsdal	Fosse	ABB REF630
	Hove	ABB REF630
Fosse	Muravatn	Siemens 7SJ622
	Målset	Siemens 7SJ622
	Kvilestein	Siemens 7SA610

The line segments listed in table 5.5 are the ones taken into account in the simulation. The associated relays where used as a starting point to add directional earth fault relays with extended operating area in the modeled power system. Of the relays in the real power system, 7SA610 is the only one that does not have the option of an extended operating area for directional earth fault protection, as far as found in the technical manual.[21] [18] [22]

Pickup values

The firs step of testing if the extended operating area would be a valid solution to use for Refsdal power system was to program a directional earth fault relay with an extended operating area in ATPDraw. Professor Høidalen assisted with this. Then the pickup values had to be decided. Seeing as the Norwegian regulations states that an earth fault of 3000 Ω has to be detected, an earth fault of this size was added to the modeled system at the end of each line segment, after turn. This way, each associated relay could have pickup values set. The system voltage for when the system was operated isolated, or compensated was measured. This way, U_0 could be referenced as a percentage of the system phase voltage. Table 5.6 shows the result.

Table 5.6: System voltage

System earthing	Line voltage [V]
Isolated (Refsdal busbar)	22960
Compensated (Hove busbar)	22048

The pickup values were found to be as stated in table 5.7, and are ment as pickup values on the primary side of the CT and VT. These values are gathered from the simulation results in table A.3. All values in table A.3 are found as maximum values and then scaled by $\sqrt{2}$. The values where sampled at steady state from the plotting program in ATPDraw. I_0 and U_0 were plotted as a function of time. I_0 was chosen to be measured in line direction.

Table 5.7: Pickup values, extended operating area

Relay Hove		**Relay Fosse**		**Relay Kvilestein**		**Relay Muravatn**		**Relay Målset**	
$I_0 >$ [A]	$U_0 >$ [%]	$I_0 >$ [A]	$U_0 >$ [%]	$I_0 >$ [A]	$U_0 >$ [%]	$I_0 >$ [A]	$U_0 >$ [%]	$I_0 >$ [A]	$U_0 >$ [%]
0.5	3	3	3.5	2.5	3.5	3	3.5	3	3.5

For comparison, the pickup values for the relays existing in Refsdal power system today can be seen in table 5.8.

Table 5.8: Pickup values for existing relays in Refsdal power system

	Relay Hove		**Relay Fosse**		**Relay Kvilestein**		**Relay Muravatn**		**Relay Målset**	
$\sin\varphi$	$I_0 >$ [A]	$U_0 >$ [%]	$I_0 >$ [A]	$U_0 >$ [%]	$I_0 >$ [A]	$U_0 >$ [%]	$I_0 >$ [A]	$U_0 >$ [%]	$I_0 >$ [A]	$U_0 >$ [%]
	0.5	3.6	3	3.6	2.2	3.6	3	3.6	3	3.6
$\cos\varphi$	$I_0 >$ [A]	$U_0 >$ [%]	$I_0 >$ [A]	$U_0 >$ [%]	$I_0 >$ [A]	$U_0 >$ [%]	$I_0 >$ [A]	$U_0 >$ [%]	$I_0 >$ [A]	$U_0 >$ [%]
			2.5	13.2	2.2	13.2	2.4	13.2	2.4	13.2

Relay Hove does not operate with a $\cos\varphi$-setting. The earth fault is disconnected by Sognekraft when the power system is opearted compensated. A zero sequence voltage relay is used as backup.

After setting the pickup values, the extended operating area was defined to be between 0° - 360°. The max forward angle angle of the operating area was set to be 100° and the min forward angle to 275°. U_0 was defined along the x-axis of the operating area. All relays where set with similar operating area.

5.2 Results

To see if the defined extended operating area would actually work in both an isolated and compensated system, simulations with situations that would challenge the operating area was completed. The extended operating area was tested against unsymmetrical conditions and earth faults of different magnitude.

5.2.1 Unsymmetrical conditions

In a power system there are unsymmetrical conditions like capacitive- and conductive discharge to earth of different magnitude. These unsymmetrical conditions can cause a tripping of the directional earth fault relays during normal operation. Simulations are therefor completed with unsymmetrical conditions, to see if they trigger the trip signal for the directional earth fault relays with the extended operating area.

For the capacitive discharge, a ΔC was added in phase B at Refsdal busbar. It is assumed that the distribution lines will be the only ones to contribute to ΔC. The distribution lines are also assumed to be un-revolved, with planar conductors and without earth conductors. Phase B was calculated to have 5-15 % less C_0 contribution than phase A and C and then $3C_0$ for this situation was calculated and ΔC was set to be the original $3C_0$ minus the unsymmetrical $3C_0$. Table 5.9 shows the added ΔC.

Table 5.9: Added ΔC

	5%	**10%**	**15%**
ΔC [μF]	0.007	0.0135	0.020

The results from the simulation was plotted using matlab. The pickup values, $U_0 >$ and $I_0 >$, where also plotted for comparison. In figure 5.4 the effect of ΔC on U_0 is plotted. As mentioned earlier, U_0 remains more or less the same in the entire system. U_0 is therefor plotted together for all the relays. The pickup value for U_0 is also shown as a dotted line for all the relays, except Hove which has a higher $U_0 >$ value. The situations that where simulated with an added ΔC was: (i) isolated system, (ii) compensated system, (iii) compensated system with the loss of R_{p1}, and (iv) isolated system without Hove connected.

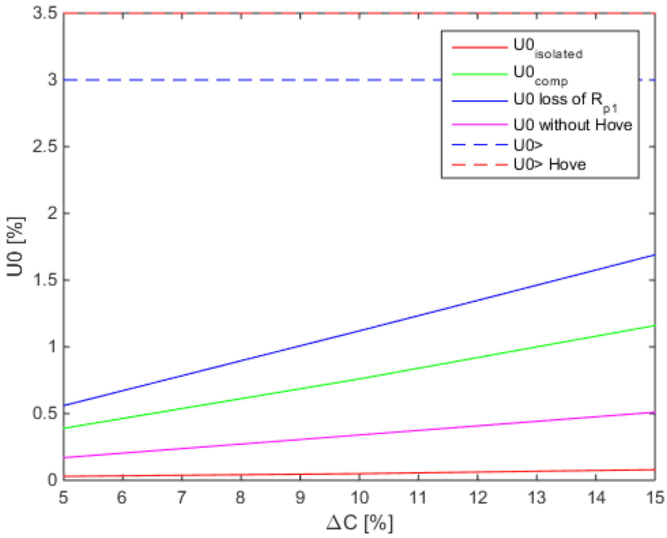


Figure 5.4: The effect of ΔC on U_0

Figure 5.5 - 5.8 shows the result of I_0 for the following situations: (i) isolated system, (ii) compensated system, (iii) compensated system with the loss of R_{p1} and (iv) isolated system without Hove connected. I_0 is the current measured by the relay at each associated line segment.

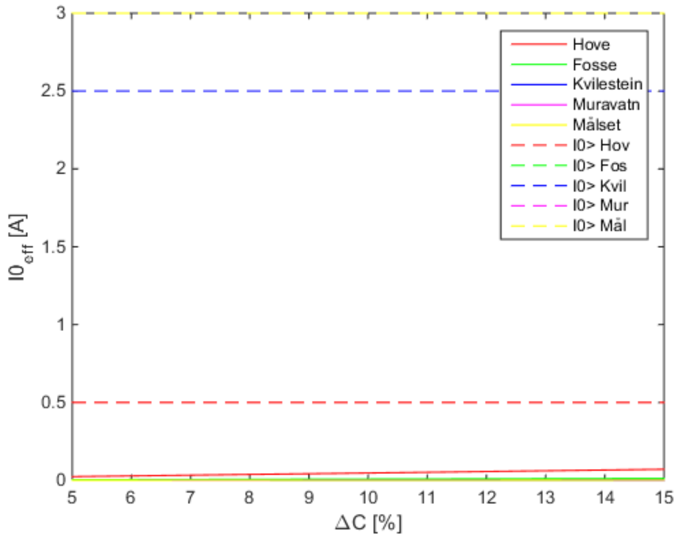


Figure 5.5: (i) The effect of ΔC on I_0, isolated system

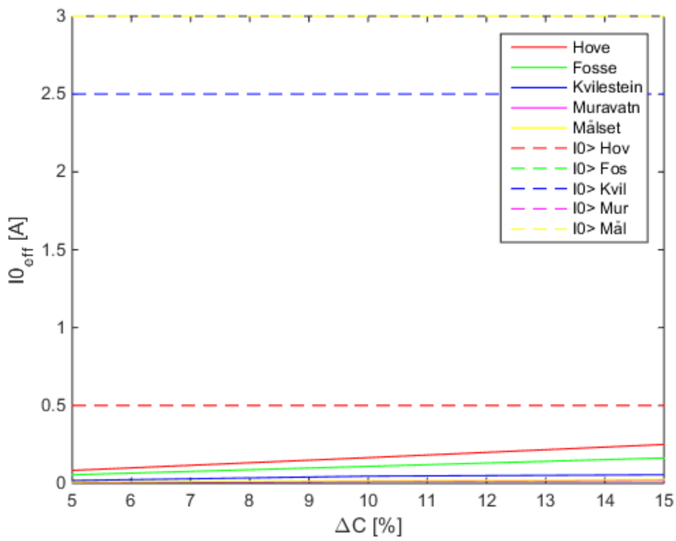


Figure 5.6: (ii) The effect of ΔC on I_0, compensated system

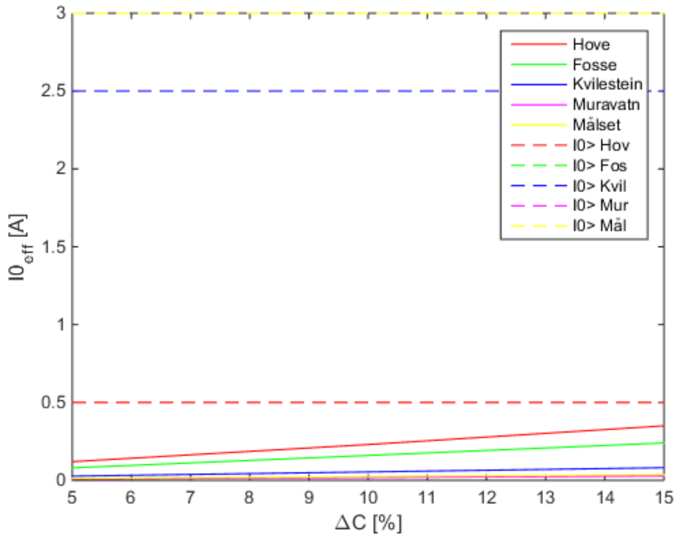


Figure 5.7: (iii) The effect of ΔC on I_0, compensated system R_{p1} disconnected

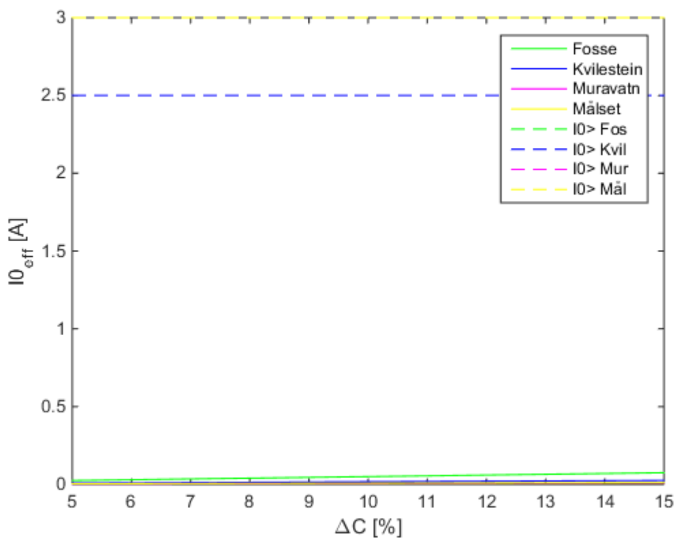


Figure 5.8: (iv) The effect of ΔC on I_0, Hove disconnected

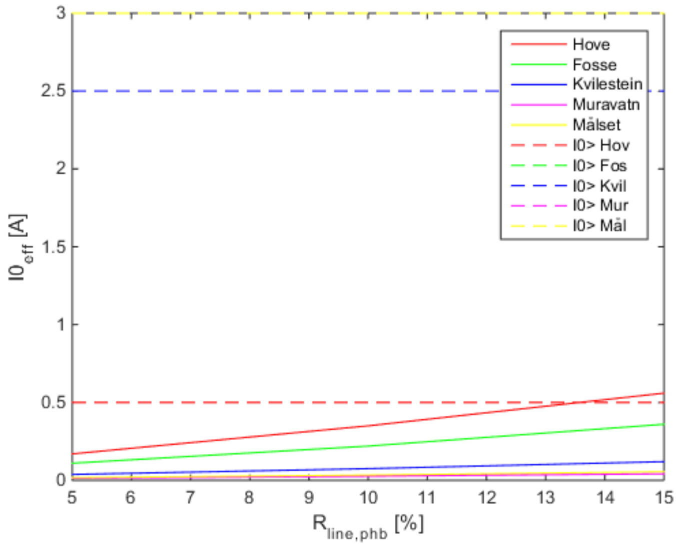
Regarding the conductive discharge, a different degree of pollution of the power system insulators may cause an increase of U_0 in a compensated system. To see how Refsdal power system reacts to asymmetry in the conductive discharge, when operated as a compensated system, a resistance between each phase and earth was added at Refsdal busbar.

In section 5.1.4 the total conductive discharge of the lines per phase, where found to be 7500 Ω. By introducing a resistance in phase B that is 5-15 % less than in phase A and C, asymmetry is achieved. Phase A and C are assumed equally distributed, with 7500 Ω for each phase. Table 5.10 shows the changes added to phase B. ΔC was not included in the simulations of the conductive discharge.

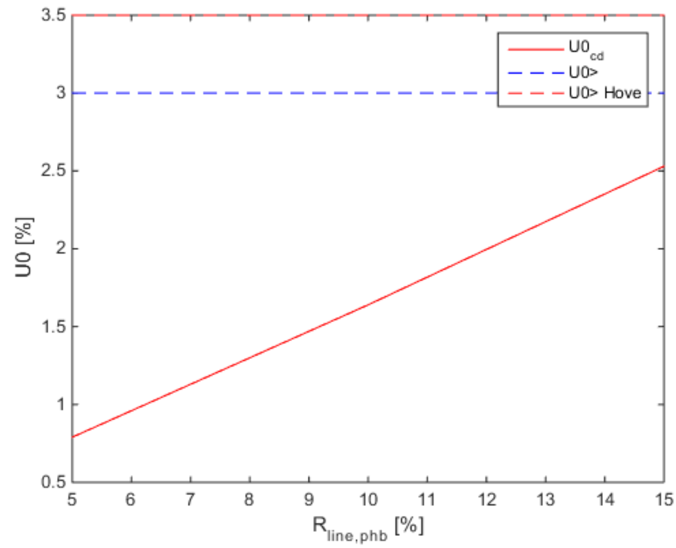
Table 5.10: Added changes to $R_{line,phb}$

	5%	**10%**	**15%**
$\boldsymbol{R_{line,phb}}$ **[Ω]**	7125	6750	6375

Figure 5.9 shows the result for the effect of asymmetry in conductive discharge for I_0 and U_0, plotted in matlab.



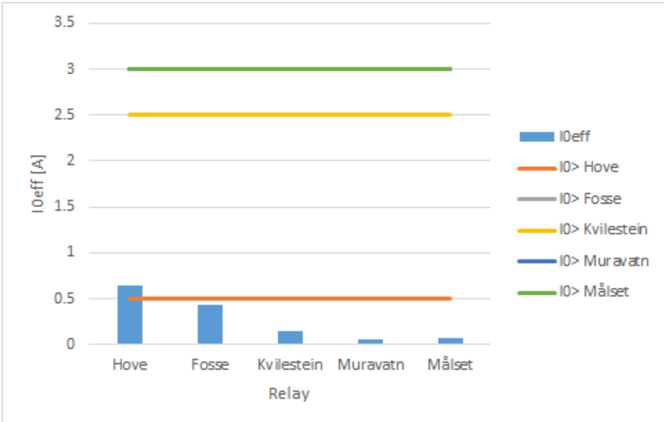
I_0



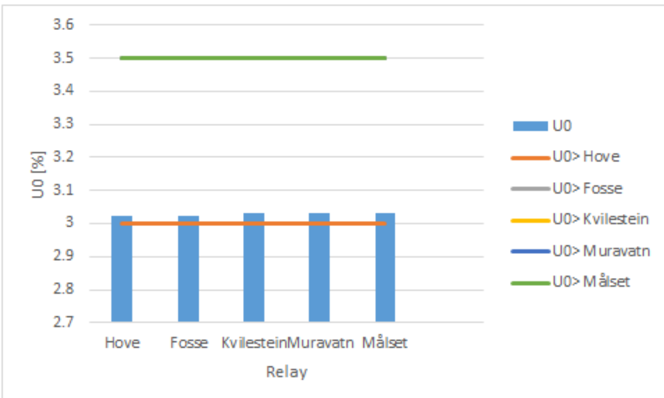
U_0

Figure 5.9: Effect of asymmetry in conductive discharge for I_0 and U_0

To try and see if an additional asymmetry in phase A would trigger the tripping for the directional earth fault relays, +5 % of $R_{line,ph}$ was added in addition to 15 % less in phase B. The result is presented in figure 5.10, where excel was used as the plotting program.



I_0



U_0

Figure 5.10: Effect of extra asymmetry in conductive discharge for I_0 and U_0

The effect of the load connected to the line segments, were assumed too small to influence U_0, in case of disconnection.

5.2.2 Earth fault

The Norwegian regulations states that an earth fault of up to 3000 Ω needs to be detected and disconnected. The power companies should also strive to detect faults up to 5000 Ω. Simulations has therefor been conducted to see if the affiliated directional earth fault relays with an extended operating area, in Refsdal power system would be able to detect earth faults. Regardless of earthing method and with earth faults ranging from 0 Ω (solid) to 5000 Ω.

The simulations where conducted without the effect of capacitive and conductive discharge, seeing as the real level of discharge is not known. When the power system is operated as compensated, R_{p1} is set to disconnect after 1.5 seconds and R_{p2} is connected via a command in the relay after 2 seconds, if the pickup value of U_0 is reached. All line segments with associated relays, where tested after turn with an earth fault connected at the end of the line segment. An earth fault at the end of the line segments was assumed to be the hardest fault for the relays to detect. The earth fault was connected in phase A, via a switch to a resistance connected to earth. The earth fault was set to connect, via the time-controlled switch, after 0.1 ms. The relays that detected the earth fault in backward direction, where kept under observation to see if I_0 entered the forward operating area. Exact values for the relays seeing the earth fault in backward direction can be found in section A.2.1.

The result of the simulations can be seen in figure 5.11 - 5.15. The figure is more for illustration purposes and does not show the exact measures of I_0 and φ (angle between U_0 and I_0). It does, however, show if I_0 entered the operating area during the different earth faults. For exact measures of I_0, U_0 and φ, see table A.4 to A.8. U_0 is referred to the system voltages in table 5.6. The situation where the power system is operated isolated, but with Hove disconnected is not shown in figure 5.11 - 5.15.

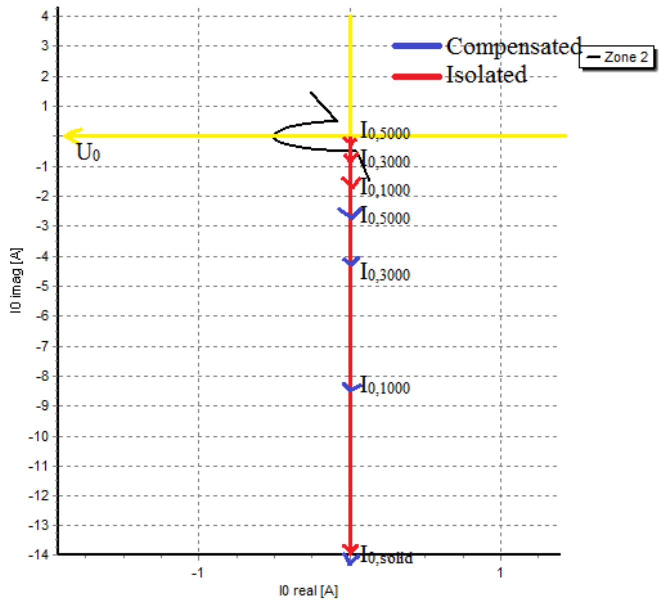


Figure 5.11: Earth fault relay Hove

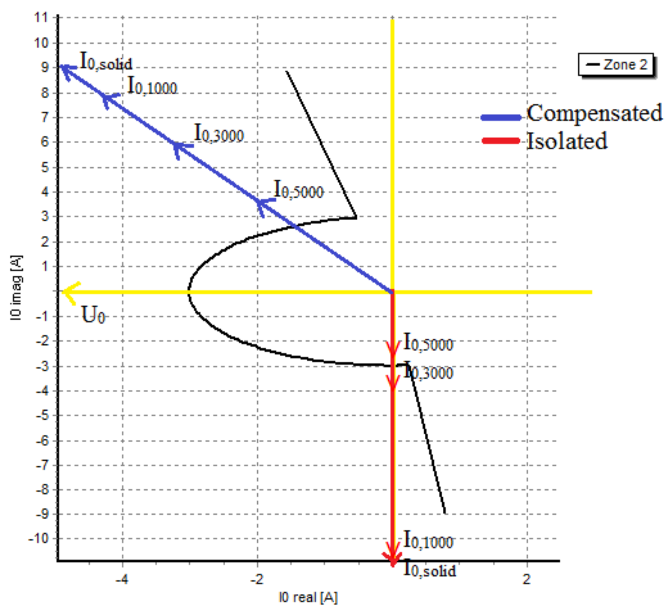


Figure 5.12: Earth fault relay Fosse

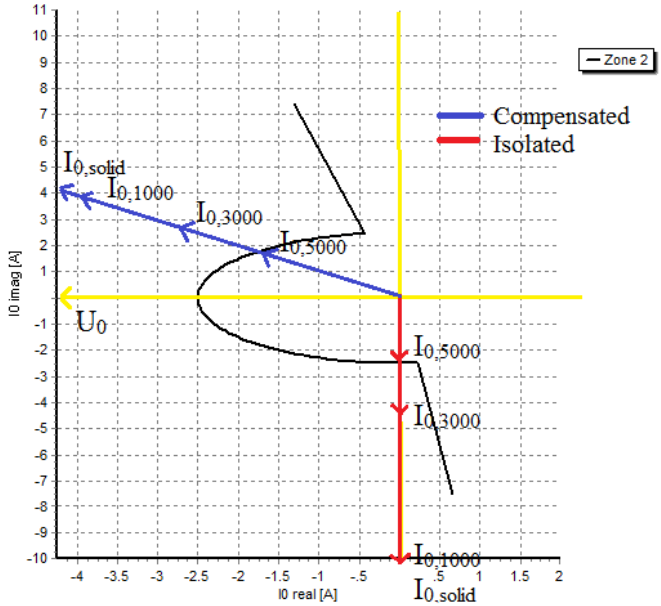


Figure 5.13: Earth fault relay Kvilestein

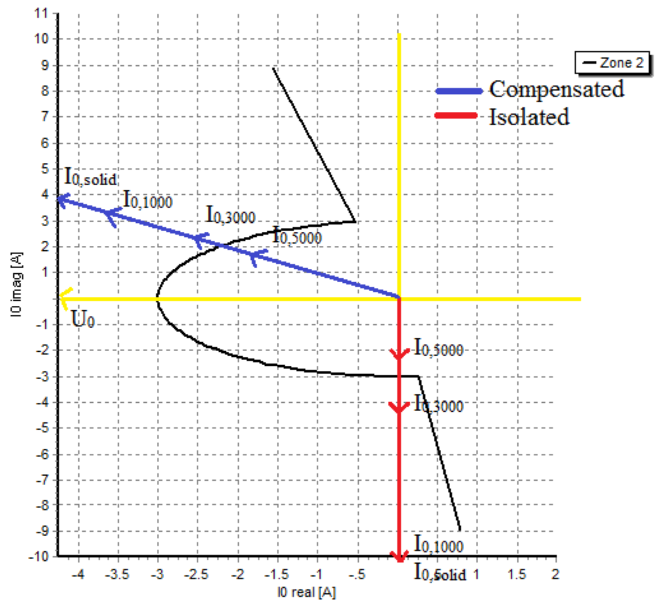


Figure 5.14: Earth fault relay Muravatn

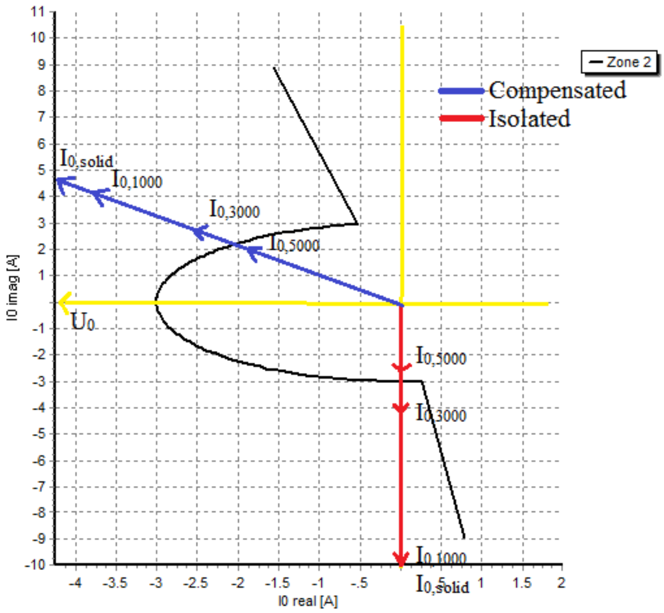


Figure 5.15: Earth fault relay Målset

6 Discussion

6.1 Parameters

Modeling the generators as 66 kV sources, without taking into account the generator impedances, was a conscious choice. Having transformers where the neutral point is isolated from earth on the high voltage side will give a disruption of the zero sequence system, so that no zero sequence currents are transferred to the high voltage side. Modeling the generator impedance would therefore, not affect the simulation result of the zero sequence voltage and currents.

Another adjustment to the modeled system was to add a large resistance to earth where the program demands it. This is to "trick" the simulation program and avoid multiplication with zero in the system matrix. Multiplication with zero takes time.

Calculations of D and D_g gave D=1.16 m and D_g=581.6 m (see section A.1.1). A normal value for the distance between the phases, D, is 1.5 m. Changing D to 1.5 m does, however, not change D_g significantly. So 1.16 m is kept throughout the calculations of the distribution line parameters. A D_g=581.6 m gives a low earth resistivity, ρ. It is only 38.83 $\Omega\cdot$ m. A low value like this, might suggest that the distribution lines are across a area near the sea and over rocks. The area below the distribution lines, will most likely change and give a different ρ. Assuming a constant ρ might therefor affect the simulation results. There is also the impact of assuming that the distribution lines are revolved, when they are most likely un-revolved in the real power system.

The estimation of the line segment OtherHove will also give uncertainties in the simulation results. However, there is not enough information to make it more accurate.

6.2 Load

The load in Refsdal power system is of a low character and assumed to be constant and completely resistive in the simulation. In reality, it might vary. A variation of the load could affect the zero sequence voltage. This might result in a higher or lower U_0 that would affect the pickup value set in the directional earth fault relays.

6.3 Capacitive current contribution

The results of the capacitive current contribution from the simulation are higher than calculated for the line segment Hove. Fosse and ST3 give a more accurate result. When making an analytical assessment, the voltage is assumed constant and for an earth fault situation, the phase with the earth fault is assumed to have zero voltage contribution. During the simulation, however, the voltage does not stay at 1 p.u throughout the power system and the phase voltage for the phase with the earth fault is not zero.

Table A.1 shows that the phase voltage rises to line voltage and more for phase B and C. U_a, where the earth fault is inflicted, is not zero as expected. The result of this and that the system voltage varies, might give a higher capacitive current contribution than calculated. This goes especially for the line segment Hove, which has the largest difference from the calculated value. This line segment also contains the estimated line segment, OtherHove which has the highest C_0 contribution. Perhaps the difference in values becomes so visible, because of this large C_0. Fosse and ST3 have a much lower C_0 contribution. The zero sequence values from the transformer might also affect the calculation of I_c.

Another reason for a higher I_c than calculated, was believed to be because of the auto transformer T1. The same simulations was therefor completed without the auto transformer connected. The results from this gave a lower I_c, but not significantly enough to be claimed as the sole reason for the high I_c. Measuring inaccuracy might also have played its role.

6.4 Peterson coil

The result for the simulation of the inductor value, was more or less the same as the calculated one. This implies that the power system is modeled correctly according to capacitive current contribution, which is a bit strange seeing as the simulations in the previous section indicated a higher capacitive current contribution than calculated. An explanation for this might be that when the system is operated as isolated it generates a higher system voltage than when it is operated as compensated. Table 5.6 can confirm this.

When R_{p1} is added to the power system, the neutral voltage decreases to 190 V, but I_l stays the same. The connected parallel resistance dampens the neutral voltage, as expected.

6.5 Conductive discharge

In a compensated system, a conductive discharge will dampen the zero sequence voltage. That is, if there is no asymmetry. The calculation and the simulation confirms this. From having a U_n = 3827.08 V with only a ΔC present, U_n is considerably lower with R_{p1} and the conductive discharge connected (see table 5.4). A damping like this, prevents over voltages in the power distribution system.

The result from the simulation with $R_{cd,ph,total}$ is somewhat belove the calculated value. The reason for this might be, as mentioned earlier, that the system voltage varies during the simulation while it is assumed constant during calculations. When R_{p1} is disconnected, the simulated value gives a larger U_n than calculated. This suggest that the estimation of $R_{line,ph}$=7500 Ω does not fit the modeled power system. The modeled power system might have other contributing factors, not taken into account in the calculations. Such as, transformer- and line parameters and load.

6.6 Directional earth fault relay

6.6.1 Pickup values

Having the right value for the pickup is important. It is the deciding factor for the detection of an earth fault. If it is set too high, a fault with a high resistance to earth might go undetected and if set too low natural asymmetry in the power system might trigger false detection.

The simulation results in table A.3 shows that when the power system is operated as isolated it generates the lowest values of I_0 and U_0. The pickup values are therefor set according to these values. If they where set according to the compensated system, earth faults of a high fault resistance would go undetected when the system is operated as isolated. The pickup values are also set a bit lower than the simulation result to ensure detection.

Comparing the simulation results with the settings for the existing relays, they are similar to the $\sin\varphi$-setting. For the $\cos\varphi$-setting, U_0 is set to have a higher pickup value. This is because a compensated system generates a higher U_0.

6.6.2 Maximum and minimum forward angle

The max/min forward angle of the extended operating area was chosen after comparison with the operating area of relays with $\mathrm{I}_0 \cos\varphi$ and $\mathrm{I}_0 \sin\varphi$-settings. Suggestions from the ABB REF630 manual was also taken into account. The manual suggests a max forward angle of 80° and a min forward angle of 170°. However, for the ABB REF630 the reference U_0 is defined upwards on the y-axis, so this differs from the ATPDraw model where U_0 is defined along the x-axis. This will result in different max/min forward angles. Figure 4.1 can be seen for comparison.

Setting a correct max/min forward angle for the extended operating area is important. Especially regarding the relays seeing the earth fault in backward direction. If the angles are set incorrectly it might result in I_0 entering the forward operating area, even though the relay sees the earth fault in backward direction.

A capacitive current contribution will give a 90° angle difference from U_0. A max forward angle equal to 100° should therefore give a large enough margin if the measuring transformers or IEDs where to make an error. Setting the min forward angle to 275° might not give a large enough margin to allow for errors in the measuring transformers or IEDs. A 5° margin to 270° (-90°) is perhaps, not enough and maybe it instead should have been set to 280°. It does not seem to be a concern in the simulations, but in reality there are more contributing factors.

6.7 Results

6.7.1 Unsymmetrical conditions

From theory it is know that the middle phase for un-revolved distribution lines have 5-15 % lower capacitive connection to earth. Simulating this is not straight forward. The distribution lines modeled in ATPDraw are modeled with a $3C_0$ line component. So it is not possible to change the middle phase to be 5-15 % lower such that a natural ΔC is added to the system. Instead an extra capacitor had to be added in phase B. The values calculated for ΔC are not of a great magnitude. Perhaps setting ΔC to be 5-15 % of the total capacitive contribution would have been a better approach to trigger I_0 and U_0. Including the cables in the ΔC calculations would also give a larger contribution. Assuming that the distribution lines are un-revolved contradicts the earlier assumption of revolved distribution lines in order to calculate Z_0 and C_1. Making these, contradicting, assumptions were necessary in order to run simulations in a proper way. They will, however, not reflect the real power system.

The effect of ΔC on U_0 is largest when the system is operated compensated and without R_{p1} connected (figure 5.4). It is, however, not close to the pickup value set for U_0. The adding of ΔC does not seem to affect U_0 when the system is operated isolated. Disconnecting Hove gives a rise in U_0, but not noticeable.

When it comes to I_0, the largest effect of ΔC is seen for the compensated system when R_{p1} is disconnected (figure 5.7). ΔC does not affect I_0 when the system is operated isolated, as seen in figure 5.5 and 5.8. Neither of the simulations with ΔC reaches the pickup value for I_0.

A conductive discharge is known to dampen the voltage across the transformer neutral in a compensated system. When asymmetry is introduced it can however, increase U_0, which in turn can reach pickup value during normal operation. Adding a three phase resistance to earth with phase B being 5-15 % less than phase A and C was used to see if the pick up values for the relays in Refsdal power system could be reached. The reason why ΔC was not included in the simulation was to see the sole effect of the conductive discharge.

When a 15 % asymmetry in the conductive discharge is introduced, the pickup value for I_0 for relay Hove is reached. U_0 is not reached. In order for the relay to react, both pickup values need to be reached.

After introducing an additional asymmetry for the conductive discharge, both pickup values are reached for relay Hove with I_0=0.64 A and U_0=3.02 %, and the angle between them enters the operating area. This will result in a false detection of an earth fault on the line segment Hove, when the system is operated compensated. It is hard to say how this will relate to the real power system, when the conductive discharge is unknown. The cables were also taken into account when calculating the conductive discharge, but it is not known how much they actually contribute. In the real power system an earth fault on line segment Hove is handled by Sognekraft. This means that the relay operated by Sognekraft will be selective over relay Hove. The Sognekraft relay will probably have a $I_0 \cos\varphi$-setting with higher pickup values than relay Hove, which means that it will probably not be triggered by asymmetry in the same way as relay Hove. If the pickup values in relay Hove, where to be adjusted it would result in detection problems when the power system is operated as isolated. Setting higher pickup values would mean that relay Hove would not be able to detect earth faults with a fault resistance equal to 3000 Ω.

6.7.2 Earth fault

Simulation with an earth fault of different magnitude is important to see if the relays with the extended operating area are able to detect the fault. Choosing to simulate without unsymmetrical conditions does not affect the power system when it is operated as isolated, but could have a say when it is operated as compensated.

The results in figure 5.11 - 5.15 shows that all relays are able to detect earth faults with a fault resistance up to 3000 Ω. Relay Fosse is also able to detect earth faults with a fault resistance up to 5000 Ω when the system is operated as compensated. The result for relay Hove is more or less the same in both operating modes. The reason for this is because the coil current contribution does not flow through the relay when the system is operated compensated. It will flow directly to the earth fault location at the end of line segment OtherHove, which is in front of relay Hove. Relay Hove will therefor only measure the current that flows behind it and towards the earth fault location. The current behind relay Hove, flowing towards the earth fault location are contributions from line segment Fosse and ST3, and this current contribution is mainly capacitive. Which explains why the simulation results for both operating systems are similar. I_0 is also defined to be measured in line direction, but when the system is operated compensated the I_0 that relay Hove measures will not be in line direction because the supply is in front of the relay.

For relay Fosse, simulation results with Hove disconnected is not included. This is because the relay will not have enough capacitive current contribution to measure on and I_0 will not enter the operating area. Relay Kvilestein, Muravatn and Målset all have enough capacitive current contribution to measure on when Hove is disconnected and they are all able to detect earth faults with a fault resistance of 3000 Ω. Except for relay Målset they also detect earth faults with a fault resistance of 5000 Ω.

Some of the measuring for when the system is operated isolated generates a very high U_0 during the solid fault situation. For example, relay Fosse has a U_0 as high as 122 % (table A.5). This is more than expected. It is expected to be 100 % or up towards 105 %. A reason for this can be that the system voltage is higher than 22 kV, but then again U_0 is calculated as a percentage of the same system voltage. If the voltage varies throughout the system, this could be a valid explanation for the high U_0. $I_{f,eff}$ also varies when the earth fault is solid. This is expected to be the same. Regardless of where the earth fault is simulated in the system the current to earth should be the same. This can be seen in connection with the high U_0. It can seem like the line segment Hove, for some reason, is to blame for the high U_0. When disconnecting Hove, U_0 declines for the solid fault situation and $I_{f,eff}$ is the same regardless of where the earth fault is simulated. This is observed at relay Kvilestein, Muravatn and Målset. Line Hove is a large line segment, and disconnecting it might result in less voltage variation throughout the power system. Some of the differences in the measuring result can most likely be blamed on measuring inaccuracy.

When the system is operated compensated and R_{p1} is set to disconnect after 1.5 seconds regardless if U_0 has reached 10 % of U_p, is probably not the most ideal way to represent the switching between parallel resistances. However, for the simulations with the different earth faults the compensated system is known to have a higher U_0 than the isolated one and it is quite certain that U_0 will reach 10 % of U_p.

Section A.2.1 shows the simulation results for the relays seeing the earth fault in backward direction and it gives a clear indication that the operating area is set correctly regarding backward faults entering the operating area. Relay Fosse will see an earth fault in forward direction when it occurs at line Kvilestein, Muravatn or Målset. In the real power system relay Fosse is set to be selective over the relays in Fosse substation.

The tripping time for the relays have not been taken into account during the simulations. Neither has the selectivity of the relays. The focus has been to see if the relays are able to detect earth faults with an extended operating area. Selectivity and tripping time will of course play an important role in the real power system.

As a sidebar, the use of two parameter settings simultaneously can be included. Using two parameter settings will give a similar operating area as for the extended operating area. Setting the pickup values according to the simulation results in table A.3 will most likely give a satisfactory detection of earth faults for both operating systems. The issue is with the relays seeing the earth fault in backward direction. For example, a solid earth fault on line Fosse will result in relay Hove detecting an earth fault in forward direction, even though it sees the earth fault in backward direction. It has $\varphi = -65°$ and this is inside the operating area of the forward $I_0 \sin\varphi$-setting. Again the problem is that relay Hove no longer measures I_0 in line direction when the system is operated compensated. Where it to be measured in line direction, I_0 would not enter the forward $I_0 \sin\varphi$ operating area. The only issue left to deal with then, is the affect of asymmetry in the power distribution system.

7 Conclusion

The ambition of this master thesis was to identify if the same relay setting could be used for detection of earth faults in both compensated and isolated power distribution systems. An extended operating area in the directional earth fault relay is such a setting.

Simulations of a real power distribution system in ATPDraw, shows that it will detect earth faults according to the Norwegian standards in both isolated and compensated power distribution systems.

The modeled system in ATPDraw is, however, based on assumptions. It will not be able to represent the real power distribution system to a full extent. This means that it is not given that the extended operating area will function as well in reality. There is the issue of natural asymmetry in the power distribution system that can affect the set pickup values.

Nevertheless, the simulations give a good indication of what to expect from the extended operating area.

7.1 Recommendations for further work

As further work, the use of two parameter settings simultaneously in the directional earth fault relay should be looked more into and compared to the extended operating area. Selectivity and tripping time of the relays should also be studied.

The trend in todays power systems, is that there are more and more small hydro plants developing. If a small hydro plant were to be connected to the power distribution system, and in the event of an earth fault it would be interesting to see in what direction the earth fault current would flow. Without the small hydro plant, the fault current flows through the windings of the distribution transformer. How will it behave when the small hydro plant is present? Will it split up and flow through the windings of the small hydro plant transformer as well? In addition to this, how will it affect the earth fault protection? These are all relevant and interesting questions to be explored upon.

A Appendix

A.1 Simulation model

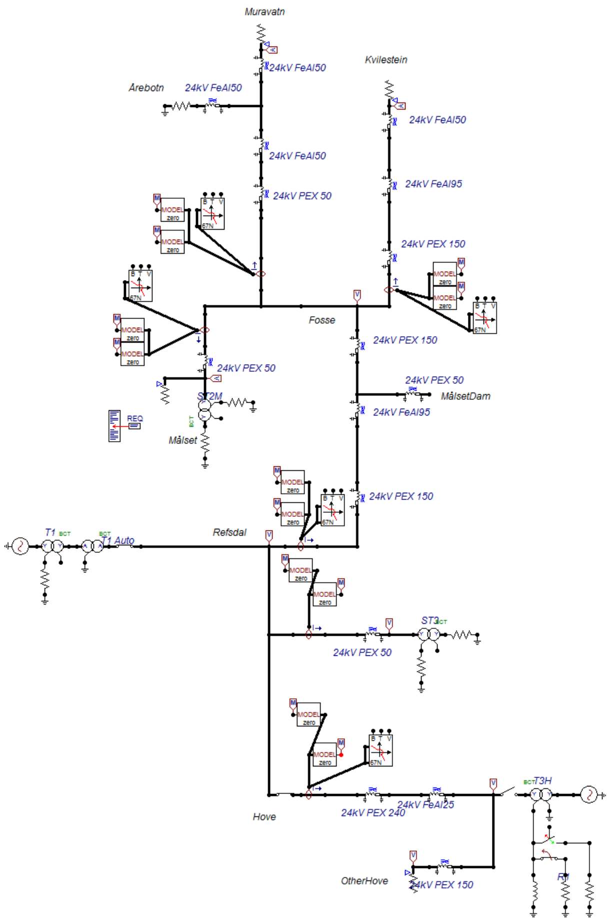


Figure A.1: ATPDraw model of Refsdal power system

A.1.1 Calculation of D and D_g in line parameters

Line FeAl 25 has Z_1 and Z_0 given, and is therefor used to solve for D and D_g.

$$Z_1 = r_a + j0.063\left(\frac{f}{50}\right) ln\frac{D}{g_{aa}} \quad (ohm/km)$$

$$Z_0 = (r_a + 3r_e) + j0.063\left(\frac{f}{50}\right) ln\frac{D_g^3}{g_{aa}D^2}$$

$$Z_1 = 0.721 + j0.395\frac{\Omega}{km}$$
$$Z_0 = 0.87 + j1.57\frac{\Omega}{km}$$

$$g_{aa} = 0.39 \cdot d$$
$$d = 2\sqrt{\frac{25mm^2}{\pi}}$$
$$= 5.64mm$$
$$= 0.00564m$$

$$R_0 = r_a + 3r_e$$
$$0.87 = 0.721 + 3r_e$$
$$r_e = 0.049\frac{\Omega}{km}$$

$$
\begin{aligned}
Z_1 &= r_a + j0.063\left(\frac{f}{50}\right) ln\frac{D}{g_{aa}} \\
0.721 + j0.395 &= 0.721 + j0.063\left(\frac{f}{50}\right) ln\frac{D}{0.39 \cdot 0.00564} \\
6.27 &= ln\frac{D}{2.2 \cdot 10^{-3}} \\
e^{6.27} \cdot 2.2 \cdot 10^{-3} &= D \\
&\rightarrow D = 1.16m
\end{aligned}
$$

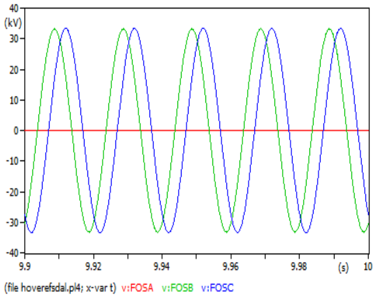
$$
\begin{aligned}
Z_0 &= (r_a + 3r_e) + j0.063\left(\frac{f}{50}\right) ln\frac{D_g^3}{g_{aa}D^2} \\
0.87 + j1.57 &= 0.721 + 3 \cdot 0.049 + j0.063\left(\frac{f}{50}\right) ln\frac{D_g^3}{2.2 \cdot 10^{-3} \cdot 1.16^2} \\
24.92 &= ln\frac{D_g^3}{2.96 \cdot 10^{-3}} \\
e^{24.92} \cdot 2.96 \cdot 10^{-3} &= D_g^3 \\
\rightarrow D_g &= \sqrt[3]{e^{24.92} \cdot 2.96 \cdot 10^{-3}} \\
&= 581.6m
\end{aligned}
$$

$$
\begin{aligned}
D_g &= 660\sqrt{\frac{\rho}{f}} \\
\rightarrow \rho &= (\frac{D_g}{660})^2 \cdot f \\
&= (\frac{581.6}{660})^2 \cdot 50 \\
\rho &= 38.83\Omega \cdot m
\end{aligned}
$$

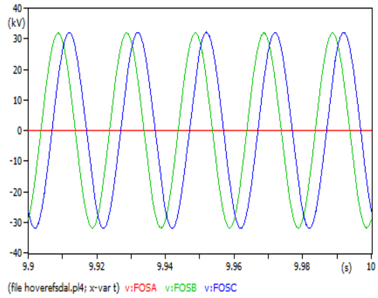
A.2 Simulation results

Table A.1: Phase voltages

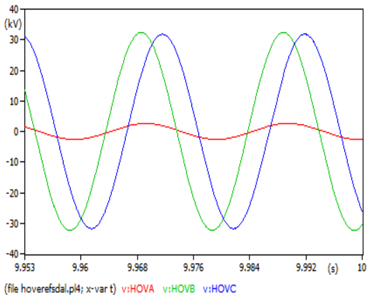
Line segment	**With Auto T1**						**Without Auto T1**					
	$\boldsymbol{U_a}$ [V]		$\boldsymbol{U_b}$ [V]		$\boldsymbol{U_c}$ [V]		$\boldsymbol{U_a}$ [V]		$\boldsymbol{U_b}$ [V]		$\boldsymbol{U_c}$ [V]	
	Max	Effective	Max	Effective	Max	Effective	Max	Effective	Max	Effective	Max	Effective
Fosse	75.2	53.2	33175	23458	33419	23631	57	40	31806	22490	31945	22588
ST3	3738	2643	29069	20555	32261	22812	3567	2522	28033	19822	31026	21939
Hove	1581	1118	32368	22888	31809	22492	2524	1785	31029	21941	30495	21563



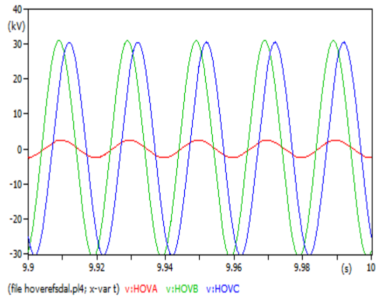
Fosse



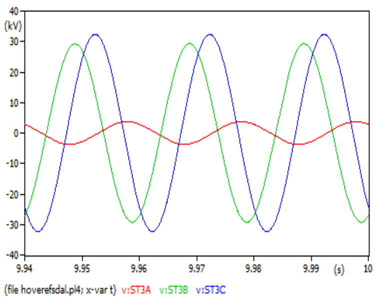
Fosse, without auto T1



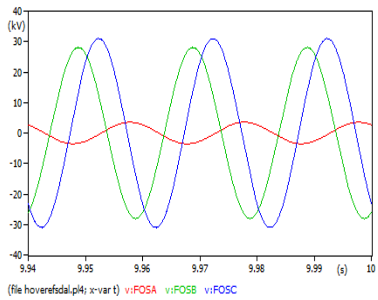
Hove



Hove, without auto T1



ST3



ST3, without auto T1

Figure A.2: Phase voltages, solid earth fault

Table A.2: Calculated capacitive current contribution, all line segments

Line segment		$C_0 \cdot l[\mu F]$	I_c [A]
From	To		
Refsdal 22 AY	Connector	0.053	0.63
Connector	Målsetstøl	0.025	0.29
Målsetstøl	Målset Dam	0.04	0.52
Målsetstøl	Fosse	0.345	4.13
Fosse	Målset ST2	0.180	2.15
Fosse	Connector Muravatn	0.115	1.38
Connector Muravatn	Branch	0.006	0.08
Branch	Årebotn ventil	0.003	0.03
Branch	Muravatn	0.013	0.16
Fosse	Connector Kvilestein	0.348	4.17
Connector Kvilestein	Skjellingen hatch	0.017	0.20
Skjellingen hatch	Kvilestein valve	0.033	0.39
Refsdal 22 AX	Connector	0.233	2.79
Connector	Hove	0.038	0.45
Refsdal 22 AX	ST3	0.147	1.76
Hove	Sognekraft	6.75	80.81
Total		8.35	99.95

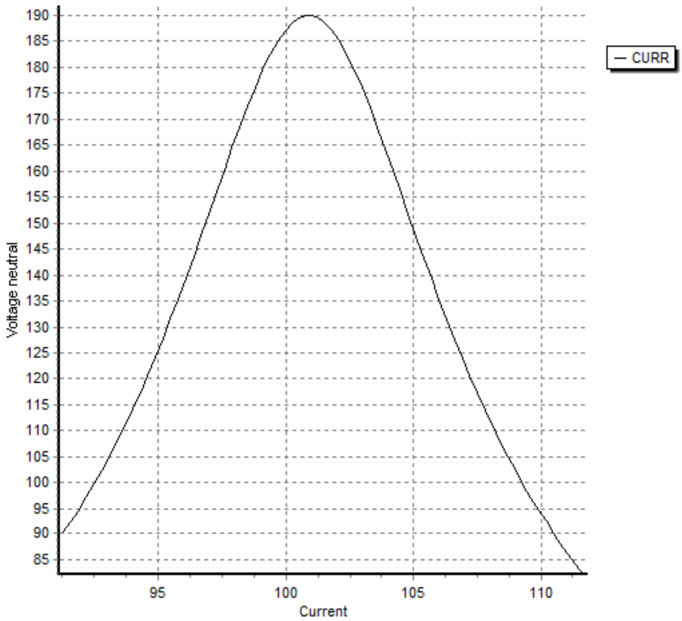


Figure A.3: Resonance curve with R_{p1} connected

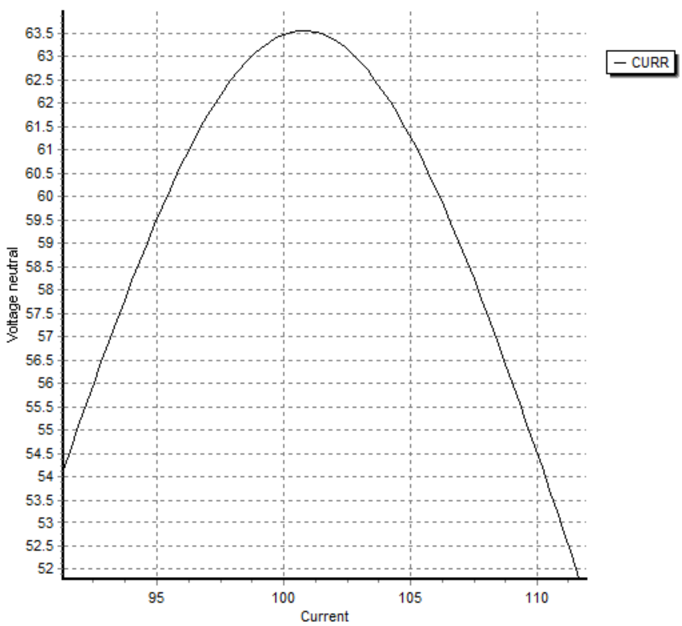


Figure A.4: Resonance curve with R_{p1} and conductive discharge

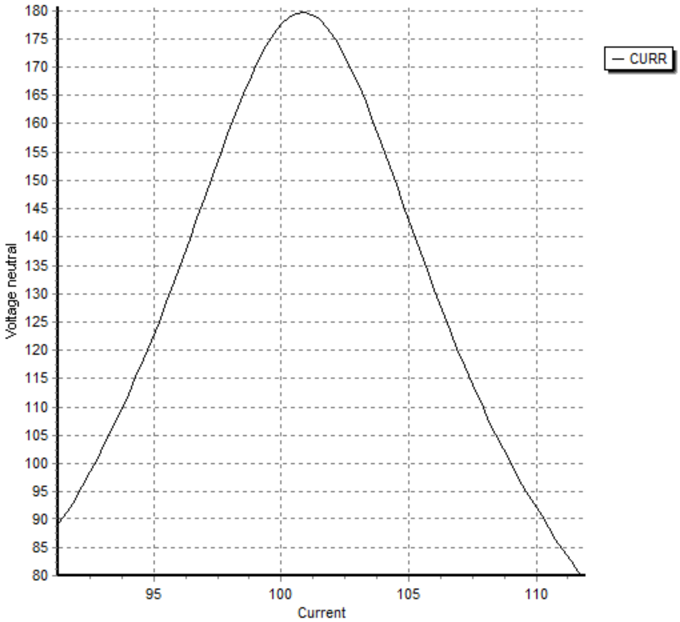


Figure A.5: Resonance curve conductive discharge

Table A.3: Simulation results, pickup values

System earthing	Relay Hove					Relay Fosse					Relay Kvilestein					Relay Muravatn					Relay Målset				
	$I_{0,max}$ [A]	$I_{0,eff}$ [A]	$U_{0,max}$ [V]	$U_{0,eff}$ [V]	U_0 [%]	$I_{0,max}$ [A]	$I_{0,eff}$ [A]	$U_{0,max}$ [V]	$U_{0,eff}$ [V]	U_0 [%]	$I_{0,max}$ [A]	$I_{0,eff}$ [A]	$U_{0,max}$ [V]	$U_{0,eff}$ [V]	U_0 [%]	$I_{0,max}$ [A]	$I_{0,eff}$ [A]	$U_{0,max}$ [V]	$U_{0,eff}$ [V]	U_0 [%]	$I_{0,max}$ [A]	$I_{0,eff}$ [A]	$U_{0,max}$ [V]	$U_{0,eff}$ [V]	U_0 [%]
Isolated	0.84	0.60	676	478	3.6	5.39	3.81	775	548	4.13	5.94	4.2	761	538	4.06	6.11	4.32	761	538	4.06	6.11	4.32	762	539	4.06
Isolated, Hove disconnected						0.69	0.47	4840	3422.4	25.82	4.2	2.97	4820	3408.25	25.71	5.43	3.84	4837	3420.28	25.80	5.25	3.71	4843	3424.52	25.83
Compensated, R_{p2}	6.05	4.28	4830	3415.33	26.83	8.63	6.11	5131	3628.16	28.50	5.54	3.91	5150	3641.60	28.61	4.74	3.35	5153	3643.72	28.62	4.86	3.43	5156	3645.84	28.64
Compensated, R_{p1}	8.58	6.07	6862	4852.17	38.12	11.27	7.97	7265	5137.13	40.36	6.20	4.38	7294	5157.64	40.52	4.70	3.32	7295	5158.34	40.52	4.93	3.49	7301	5162.59	40.56
Compensated	13.6	9.62	10780	7622.61	59.88	17.18	12.15	11450	8096.37	63.60	8.68	6.14	11460	8103.44	63.66	5.87	4.15	11470	8110.51	63.71	6.32	4.47	11460	8103.44	63.66

Table A.4: Earth fault Hove

Relay	**System earthing**	**Measuring values**	**Solid**	**1000 Ω**	**3000 Ω**	**5000 Ω**
Hove	Isolated	$\lvert I_0 \rvert$ [A]	14.86	1.78	0.60	0.36
		φ [°]	-90	-90	-90	-90
		U_0 [%]	89.26	10.70	3.61	2.20
		$I_{f,eff}$ [A]	92.63	11.10	3.73	2.25
	Compensated	$\lvert I_0 \rvert$ [A]	15.12	8.32	4.29	2.88
		φ [°]	-90	-90	-90	-90
		U_0 [%]	90.40	49.73	25.71	17.30
		$I_{f,eff}$ [A]	10.44	5.74	2.96	2.00

Table A.5: Earth fault Fosse

Relay	**System earthing**	**Measuring values**	**Solid**	**1000 Ω**	**3000 Ω**	**5000 Ω**
Fosse	Isolated	$\lvert I_0 \rvert$ [A]	97.81	11.33	3.81	2.29
		φ [°]	-89	-89	-89	-89
		U_0 [%]	122.50	12.31	4.13	2.50
		$I_{f,eff}$ [A]	113.21	13.11	4.41	2.65
	Compensated	$\lvert I_0 \rvert$ [A]	21.23	11.78	6.11	4.11
		φ [°]	63	63	63	63
		U_0 [%]	95.20	49.73	28.50	18.43
		$I_{f,eff}$ [A]	10.83	6.01	3.11	2.10

Table A.6: Earth fault Kvilestein

Relay	System earthing	Measuring values	Solid	1000 Ω	3000 Ω	5000 Ω
Kvilestein	Isolated	$\lvert I_0 \rvert$ [A]	115.52	12.48	4.20	2.52
		φ [°]	-89	-89	-89	-89
		U_0 [%]	111.61	12.06	4.10	2.44
		$I_{f,eff}$ [A]	120.91	13.08	4.41	2.65
	Isolated, Hove disconnected	$\lvert I_0 \rvert$ [A]	11.86	7.31	3.00	1.84
		φ [°]	-90	-90	-90	-90
		U_0 [%]	102.10	62.90	25.82	15.83
		$I_{f,eff}$ [A]	16.97	10.42	4.31	2.63
	Compensated	$\lvert I_0 \rvert$ [A]	13.53	7.54	3.92	2.63
		φ [°]	44	44	44	44
		U_0 [%]	98.85	54.92	28.53	19.20
		$I_{f,eff}$ [A]	10.77	5.94	3.11	2.09

Table A.7: Earth fault Muravatn

Relay	System earthing	Measuring values	Solid	1000 Ω	3000 Ω	5000 Ω
Muravatn	Isolated	$\lvert I_0 \rvert$ [A]	114.43	12.89	4.33	2.61
		φ [°]	-89	-89	-89	-89
		U_0 [%]	107.11	12.06	4.10	2.44
		$I_{f,eff}$ [A]	115.96	13.11	4.41	2.65
	Isolated, Hove disconnected	$\lvert I_0 \rvert$ [A]	15.11	9.35	3.84	2.36
		φ [°]	-90	-90	-90	-90
		U_0 [%]	101.11	62.70	25.82	15.80
		$I_{f,eff}$ [A]	16.97	10.42	4.31	2.63
	Compensated	$\lvert I_0 \rvert$ [A]	11.62	6.45	3.35	2.25
		φ [°]	33	33	33	33
		U_0 [%]	99.20	55.10	28.62	19.18
		$I_{f,eff}$ [A]	10.81	6.01	3.11	2.10

Table A.8: Earth fault Målset

Relay	System earthing	Measuring values	Solid	1000 Ω	3000 Ω	5000 Ω
Målset	Isolated	$\lvert I_0 \rvert$ [A]	110.93	12.84	4.32	2.59
		φ [°]	-89	-89	-89	-89
		U_0 [%]	104.50	12.10	4.10	2.41
		$I_{f,eff}$ [A]	113.14	13.08	4.41	2.65
	Isolated, Hove disconnected	$\lvert I_0 \rvert$ [A]	14.52	9.01	3.7	0.79
		φ [°]	-90	-90	-90	-90
		U_0 [%]	101.10	62.80	25.83	15.83
		$I_{f,eff}$ [A]	16.97	10.42	4.31	2.63
	Compensated	$\lvert I_0 \rvert$ [A]	11.93	6.62	3.44	2.31
		φ [°]	35	35	35	35
		U_0 [%]	99.50	55.10	28.64	19.30
		$I_{f,eff}$ [A]	10.83	6.01	3.11	2.10

A.2.1 Simulation results for relays seeing the earth fault in backward direction

Table A.9: Earth fault Hove, Relay Fosse

Relay	System earthing	Measuring values	Solid	1000 Ω	3000 Ω	5000 Ω
Fosse (backward direction)	Isolated	$\lvert I_0 \rvert$ [A]	13.22	1.58	0.53	0.32
		φ [°]	90	90	90	90
		U_0 [%]	89.26	10.70	3.61	2.20
	Compensated	$\lvert I_0 \rvert$ [A]	13.46	7.40	3.81	2.56
		φ [°]	90	90	90	90
		U_0 [%]	90.40	49.73	25.71	17.30

Table A.10: Earth fault Hove, Relay Kvilestein

Relay	System earthing	Measuring values	Solid	1000 Ω	3000 Ω	5000 Ω
Kvilestein (backward direction)	Isolated	$\lvert I_0 \rvert$ [A]	4.46	0.53	0.18	0.11
		φ [°]	90	90	90	90
		U_0 [%]	89.26	10.70	3.61	2.20
	Compensated	$\lvert I_0 \rvert$ [A]	4.54	2.50	1.29	0.86
		φ [°]	90	90	90	90
		U_0 [%]	90.40	49.73	25.71	17.30

Table A.11: Earth fault Hove, Relay Muravatn

Relay	System earthing	Measuring values	Solid	1000 Ω	3000 Ω	5000 Ω
Muravatn (backward direction)	Isolated	$\|I_0\|$ [A]	1.54	0.24	0.07	0.04
		φ [°]	90	90	90	90
		U_0 [%]	89.26	10.70	3.61	2.20
	Compensated	$\|I_0\|$ [A]	1.57	0.86	0.44	0.30
		φ [°]	90	90	90	90
		U_0 [%]	90.40	49.73	25.71	17.30

Table A.12: Earth fault Hove, Relay Målset

Relay	System earthing	Measuring values	Solid	1000 Ω	3000 Ω	5000 Ω
Muravatn (backward direction)	Isolated	$\|I_0\|$ [A]	2.01	0.18	0.09	0.54
		φ [°]	90	90	90	90
		U_0 [%]	89.26	10.70	3.61	2.20
	Compensated	$\|I_0\|$ [A]	2.04	1.12	0.58	0.39
		φ [°]	90	90	90	90
		U_0 [%]	90.40	49.73	25.71	17.30

Table A.13: Earth fault Fosse, Relay Hove

Relay	System earthing	Measuring values	Solid	1000 Ω	3000 Ω	5000 Ω
Hove (backward direction)	Isolated	$\|I_0\|$ [A]	95.86	11.10	3.73	2.24
		φ [°]	89	89	89	89
		U_0 [%]	122.50	12.31	4.13	2.50
	Compensated	$\|I_0\|$ [A]	22.80	12.65	6.56	4.41
		φ [°]	-65	-65	-65	-65
		U_0 [%]	95.20	49.73	28.50	18.43

Table A.14: Earth fault Fosse, Relay Kvilestein

Relay	System earthing	Measuring values	Solid	1000 Ω	3000 Ω	5000 Ω
Kvilestein (backward direction)	Isolated	$\|I_0\|$ [A]	5.26	0.60	0.20	0.12
		φ [°]	90	90	90	90
		U_0 [%]	122.50	12.31	4.13	2.50
	Compensated	$\|I_0\|$ [A]	4.81	2.64	1.37	0.92
		φ [°]	90	90	90	90
		U_0 [%]	95.20	49.73	28.50	18.43

Table A.15: Earth fault Fosse, Relay Muravatn

Relay	System earthing	Measuring values	Solid	1000 Ω	3000 Ω	5000 Ω
Muravatn (backward direction)	Isolated	$\|I_0\|$ [A]	1.81	0.21	0.06	0.04
		φ [°]	90	90	90	90
		U_0 [%]	122.50	12.31	4.13	2.50
	Compensated	$\|I_0\|$ [A]	1.66	0.91	0.47	0.32
		φ [°]	90	90	90	90
		U_0 [%]	95.20	49.73	28.50	18.43

Table A.16: Earth fault Fosse, Relay Målset

Relay	System earthing	Measuring values	Solid	1000 Ω	3000 Ω	5000 Ω
Målset (backward direction)	Isolated	$\|I_0\|$ [A]	2.37	0.27	0.08	0.05
		φ [°]	90	90	90	90
		U_0 [%]	122.50	12.31	4.13	2.50
	Compensated	$\|I_0\|$ [A]	2.17	1.19	0.62	0.41
		φ [°]	90	90	90	90
		U_0 [%]	95.20	49.73	28.50	18.43

Table A.17: Earth fault Kvilestein, Relay Hove

Relay	System earthing	Measuring values	Solid	1000 Ω	3000 Ω	5000 Ω
Hove (backward direction)	Isolated	$\|I_0\|$ [A]	102.50	11.07	3.73	2.24
		φ [°]	89	89	89	89
		U_0 [%]	111.61	12.06	4.10	2.44
	Compensated	$\|I_0\|$ [A]	22.66	12.61	6.55	4.41
		φ [°]	-65	-65	-65	-65
		U_0 [%]	98.85	54.92	28.53	19.20

Table A.18: Earth fault Kvilestein, Relay Fosse

Relay	System earthing	Measuring values	Solid	1000 Ω	3000 Ω	5000 Ω
Fosse (forward direction)	Isolated	$\|I_0\|$ [A]	104.60	11.29	3.80	2.29
		φ [°]	-89	-89	-89	-89
		U_0 [%]	111.61	12.06	4.10	2.44
	Compensated	$\|I_0\|$ [A]	21.10	11.75	6.10	4.11
		φ [°]	63	63	63	63
		U_0 [%]	98.85	54.92	28.53	19.20

Table A.19: Earth fault Kvilestein, Relay Muravatn

Relay	**System earthing**	**Measuring values**	**Solid**	**1000 Ω**	**3000 Ω**	**5000 Ω**
Muravatn (backward direction)	Isolated	$\lvert I_0 \rvert$ [A]	1.92	0.21	0.07	0.04
		φ [°]	90	90	90	90
		U_0 [%]	111.61	12.06	4.10	2.44
	Isolated, Hove disconnected	$\lvert I_0 \rvert$ [A]	1.75	1.08	0.44	0.27
		φ [°]	90	90	90	90
		U_0 [%]	102.10	62.90	25.82	15.83
	Compensated	$\lvert I_0 \rvert$ [A]	1.63	0.91	0.47	0.32
		φ [°]	90	90	90	90
		U_0 [%]	98.85	54.92	28.53	19.20

Table A.20: Earth fault Kvilestein, Relay Målset

Relay	**System earthing**	**Measuring values**	**Solid**	**1000 Ω**	**3000 Ω**	**5000 Ω**
Målset (backward direction)	Isolated	$\lvert I_0 \rvert$ [A]	2.29	1.41	0.58	0.35
		φ [°]	90	90	90	90
		U_0 [%]	111.61	12.06	4.10	2.44
	Isolated, Hove disconnected	$\lvert I_0 \rvert$ [A]	1.75	1.08	0.44	0.27
		φ [°]	90	90	90	90
		U_0 [%]	102.10	62.90	25.82	15.83
	Compensated	$\lvert I_0 \rvert$ [A]	2.13	1.18	0.62	0.41
		φ [°]	90	90	90	90
		U_0 [%]	98.85	54.92	28.53	19.20

Table A.21: Earth fault Muravatn, Relay Hove

Relay	**System earthing**	**Measuring values**	**Solid**	**1000 Ω**	**3000 Ω**	**5000 Ω**
Hove (backward direction)	Isolated	$\lvert I_0 \rvert$ [A]	98.45	11.07	3.73	2.24
		φ [°]	89	89	89	89
		U_0 [%]	107.11	12.06	4.10	2.44
	Compensated	$\lvert I_0 \rvert$ [A]	22.73	12.63	6.56	4.42
		φ [°]	-65	-65	-65	-65
		U_0 [%]	99.20	55.10	28.62	19.18

Table A.22: Earth fault Muravatn, Relay Fosse

Relay	System earthing	Measuring values	Solid	1000 Ω	3000 Ω	5000 Ω
Fosse (forward direction)	Isolated	$\lvert I_0 \rvert$ [A]	100.46	11.29	3.80	2.29
		φ [°]	-89	-89	-89	-89
		U_0 [%]	107.11	12.06	4.10	2.44
	Compensated	$\lvert I_0 \rvert$ [A]	21.16	11.76	6.10	4.11
		φ [°]	63	63	63	63
		U_0 [%]	99.20	55.10	28.62	19.18

Table A.23: Earth fault Muravatn, Relay Kvilestein

Relay	System earthing	Measuring values	Solid	1000 Ω	3000 Ω	5000 Ω
Kvilestein (backward direction)	Isolated	$\lvert I_0 \rvert$ [A]	5.35	0.60	0.20	0.12
		φ [°]	90	90	90	90
		U_0 [%]	107.11	12.06	4.10	2.44
	Isolated, Hove disconnected	$\lvert I_0 \rvert$ [A]	5.06	3.13	1.29	0.79
		φ [°]	90	90	90	90
		U_0 [%]	101.11	62.70	25.82	15.80
	Compensated	$\lvert I_0 \rvert$ [A]	4.75	2.64	1.37	0.92
		φ [°]	90	90	90	90
		U_0 [%]	99.20	55.10	28.62	19.18

Table A.24: Earth fault Muravatn, Relay Målset

Relay	System earthing	Measuring values	Solid	1000 Ω	3000 Ω	5000 Ω
Målset (backward direction)	Isolated	$\lvert I_0 \rvert$ [A]	2.50	0.27	0.09	0.05
		φ [°]	90	90	90	90
		U_0 [%]	107.11	12.06	4.10	2.44
	Isolated, Hove disconnected	$\lvert I_0 \rvert$ [A]	2.29	1.41	0.58	0.35
		φ [°]	90	90	90	90
		U_0 [%]	101.11	62.70	25.82	15.80
	Compensated	$\lvert I_0 \rvert$ [A]	2.14	1.19	0.62	0.41
		φ [°]	90	90	90	90
		U_0 [%]	99.20	55.10	28.62	19.18

Table A.25: Earth fault Målset, Relay Hove

Relay	System earthing	Measuring values	Solid	1000 Ω	3000 Ω	5000 Ω
Hove (backward direction)	Isolated	$\|I_0\|$ [A]	95.92	11.10	3.73	2.24
		φ [°]	89	89	89	89
		U_0 [%]	104.50	12.10	4.10	2.41
	Compensated	$\|I_0\|$ [A]	22.79	12.64	6.65	4.41
		φ [°]	-65	-65	-65	-65
		U_0 [%]	99.50	55.10	28.64	19.30

Table A.26: Earth fault Målset, Relay Fosse

Relay	System earthing	Measuring values	Solid	1000 Ω	3000 Ω	5000 Ω
Fosse (forward direction)	Isolated	$\|I_0\|$ [A]	97.87	11.32	3.80	2.29
		φ [°]	-89	-89	-89	-89
		U_0 [%]	104.50	12.10	4.10	2.41
	Compensated	$\|I_0\|$ [A]	21.18	11.77	6.11	4.11
		φ [°]	63	63	63	63
		U_0 [%]	99.50	55.10	28.64	19.30

Table A.27: Earth fault Målset, Relay Kvilestein

Relay	System earthing	Measuring values	Solid	1000 Ω	3000 Ω	5000 Ω
Kvilestein (backward direction)	Isolated	$\|I_0\|$ [A]	5.21	0.60	0.20	0.12
		φ [°]	90	90	90	90
		U_0 [%]	104.50	12.10	4.10	2.41
	Isolated, Hove disconnected	$\|I_0\|$ [A]	5.04	3.13	1.29	1.84
		φ [°]	90	90	90	90
		U_0 [%]	101.10	62.80	25.83	15.83
	Compensated	$\|I_0\|$ [A]	4.76	2.64	1.37	0.92
		φ [°]	90	90	90	90
		U_0 [%]	99.50	55.10	28.64	19.30

Table A.28: Earth fault Målset, Relay Muravatn

Relay	**System earthing**	**Measuring values**	**Solid**	**1000 Ω**	**3000 Ω**	**5000 Ω**
Muravatn (backward direction)	Isolated	$\|I_0\|$ [A]	1.79	0.21	0.07	0.04
		φ [°]	90	90	90	90
		U_0 [%]	104.50	12.10	4.10	2.41
	Isolated, Hove disconnected	$\|I_0\|$ [A]	1.75	1.08	0.44	0.27
		φ [°]	90	90	90	90
		U_0 [%]	101.10	62.80	25.83	15.83
	Compensated	$\|I_0\|$ [A]	1.64	0.91	0.47	0.32
		φ [°]	90	90	90	90
		U_0 [%]	99.50	55.10	28.64	19.30

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