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Use-Cases of Phase-Earthing Circuit Breakers in Self-Healing Power Networks

Department of electrical engineering

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DIPLOMITYÖN TIIVISTELMÄ

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Tässä työssä tutkitaan vaiheenmaadoitusmenetelmää, jota voidaan käyttää vähentämään pikajälleenkytkentöjen lukumäärää. Käytännössä viallinen vaihe kytketään maahan syöttävällä sähköasemalla. Jos viallinen vaihe voidaan maadoittaa pidemmäksi aikaa, voisi olla mahdollista ylläpitää sähkönjakelua pysyvissä vikatilanteissa.

Tässä työssä vaiheenmaadoitusmenetelmää tarkastellaan esimerkiksi turvallisuusmääräysten ja maasulkusuojauksen näkökulmasta. Turvallisuusmääräykset määräävät suurimman sallitun vian kestoajan. Kyseinen aika on riippuvainen verkon maadoitusjännitteistä. Näin ollen maapotentiaalin nousu määrää myös vaiheenmaadoitusajan.

Erityisesti on tutkittu prototyyppi vaiheenmaadoitusjärjestelmän käyttöönottoa. Työssä tarkastellaan kuinka maasulkusuojausasetteluja tulisi muuttaa, jotta suojaus toimisi oikealla tavalla. Tätä varten kenttäkokeista saatuja häiriötallenteita on tutkittu. Maksimi jäännösvikavirran suuruus on arvioitu sähköteknisillä laskelmilla.

Vaiheenmaadoitusmenetelmää tarkastellaan myös taloudellisesta näkökulmasta. Kompensointikelan ja vaiheenmaadoituskatkaisijan keskeytyskustannussäästöjä on vertailtu. Tämä vertailu on tehty tietyssä keskijänniteverkossa käyttämällä LuoVa luotettavuusanalyysiohjelmistoa.

Lisäksi vaiheenmaadoitusmenetelmän käyttöä tarkastellaan vyöhykekonseptin näkökulmasta. Tämä konsepti mahdollistaa nopean vian paikannuksen ja nopean vian erotuksen. Nämä ominaisuudet aikaansaadaan hyödyntämällä uusia suojausominaisuuksia ja lisäämällä verkkoon suojaus- ja kytkinlaitteita. Tulevaisuudessa tällainen järjestelmä voi pystyä automaattiseen vian erotukseen ja sähkönsyötön palauttamiseen. Vaiheenmaadoitusmenetelmän hyötyä tämänkaltaisessa itsestään korjautuvassa verkossa on arvioitu käyttämällä LuoVa luotettavuusanalyysiohjelmistoa.

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ABSTRACT OF THE MASTER’S THESIS

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The topic of this thesis is the phase-earthing method which can be used to reduce the number of high speed automatic reclosing functions. In practice, the faulty phase is connected to the ground at a feeding substation for a few tenths of a second. If the faulty phase can be earthed for a longer time, it might be possible to maintain electricity distribution in permanent fault situations.

This thesis discusses phase-earthing method for example from safety regulations and earth fault protection points of view. The safety regulations determine the maximum fault duration. The duration depends on earth potential rise in the network. For this reason, the earth potential rise also determines the maximum phase-earthing time.

Especially, the introduction of a prototype phase-earthing system is discussed. It is studied how earth fault protection setting could be modified in order that earth fault protection would function properly. In this task, disturbance recordings, which were recorded in field tests, have been examined. The maximum residual current is approximated by means of electrotechnical calculations.

Phase-earthing method is also evaluated from the economic point of view. Interruption cost savings between a compensation coil and a phase-earthing circuit-breaker are compared. In the comparison, a certain medium voltage network is used and it is analysed by using LuoVa reliability analysis software.

In addition, the use of phase-earthing method is studied from the zone concept point of view. The concept enables fast fault localization and fast fault isolation. These features are achieved by utilizing new protection features and adding protection and switching devices in network. In the future, this kind of system might be able to isolate faults and restore power independently. The benefit of phase-earthing method in this kind of self-healing network is estimated by using LuoVa reliability analysis software.

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Preface

This thesis was done in Fortum Sähkönsiirto Oy as a part of Smart Grid and Energy Market project. I would like to thank everyone who has helped me in my work. Special thanks to my instructor Jarmo Saarinen for his advices and thanks to Professor Matti Lehtonen for inspecting the thesis. I would also like to thank my family for supporting me through my life. Last, but most, I want to thank Matilda for her understanding and support.

March 2012, Jori Tervo

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Abbreviations and symbols

Abbreviations

CAIDI	Customer average interruption duration index
CLEEN	Cluster for Energy and Environment
DT	Definite Time
EMV	Energy Market Authority
ET	Finnish Energy Industries
GMD	Geometric Mean Diameter
GOOSE	Generic Object Oriented Substation Event
IDMT	Inverse Definite Minimum Time
IEC	International Electrotechnical Commission
IED	Intelligent Electric Device
IVO	Imatran Voima
MAIFI	Momentary Average Interruption Frequency Index
PECB	Phase-earthing circuit-breaker
PLC	Programmable Logic Controller
SAIDI	System Average Interruption Duration Index
SAIFI	System average Interruption Frequency Index
SENER	Finnish Electricity Association
SGEM	Smart Grids and Electric Markets

Symbols

$\underline{\mathbf{a}}$	Unit vector
$\mathbf{a}_{\mathbf{ij}}$	Distance between phase conductors i and j
$\mathbf{C}$	Total earth capacitance per phase
$\mathbf{C}_{\mathbf{j}}$	Earth capacitance of line j per phase
$\mathbf{D}$	Mean diameter of metallic covering
$\mathbf{d}$	Damping
$\mathbf{E}_{\mathbf{R}}$	Voltage of phase R
$\mathbf{f}$	Frequency
$\mathbf{I}_{\mathbf{C}}$	Capacitive fault current component
$\mathbf{I}_{\mathbf{coil}}$	Current of compensation coil
$\mathbf{I}_{\mathbf{E}}$	Current of earth electrode
$\mathbf{I}_{\mathbf{ef}}$	Earth fault current
$\mathbf{I}_{\mathbf{ej}}$	Earth fault current generated by feeder j
$\mathbf{I}_{\mathbf{f}}$	Fault current
$\mathbf{I}_{\mathbf{h}}$	Threshold current
$\mathbf{I}_{\mathbf{L}}$	Load current
$\mathbf{I}_{\mathbf{n}}$	Nominal current

$\mathbf{I_R}$	Resistive fault current component
$\mathbf{I_r}$	Zero sequence current sensed by a relay
$\mathbf{I_{res}}$	Residual fault current
$\mathbf{I}_{\mathrm{setting}}$	Current setting of a relay
$\mathbf{I_0}$	Zero sequence current
$\mathbf{I_1}$	Positive sequence current
$\mathbf{I_2}$	Negative sequence current
$\mathbf{I>}$	Current setting of low-set stage
$\mathbf{I>>}$	Current setting of high-set stage
$\mathbf{K}$	key parameter of extinction
$\mathbf{L}$	Inductance of compensation coil
$\mathbf{m}$	Mismatch
$\mathbf{R}$	Resistance of compensation coil
$\mathbf{R_E}$	Earth resistance
$\mathbf{r_{eq}}$	Equivalent radius of a wiring loom
$\mathbf{R_f}$	Fault resistance
$\mathbf{R_L}$	Load resistance
$\mathbf{R_p}$	Radius of a phase conductor
$\mathbf{R_S}$	Phase-earthing resistance
$\mathbf{t}$	Time
$\mathbf{t_{BU}}$	Operate delay of backup protection
$\mathbf{t_{delay}}$	Delay of phase-earthing circuit-breaker
$\mathbf{t_{max}}$	Longest arcing time
$\mathbf{t_{PE}}$	Phase-earthing time
$\mathbf{t_X}$	Effective phase-earthing time
$\mathbf{t>}$	Operate delay of the low-set stage
$\mathbf{t>>}$	Operate delay of the high-set stage
$\mathbf{U}$	Phase to phase voltage
$\mathbf{U_E}$	Earth potential rise
$\mathbf{U_n}$	Nominal voltage of the network
$\mathbf{U_{ph}}$	Phase voltage
$\mathbf{U_{SS}}$	Maximum step voltage
$\mathbf{U_{ST}}$	Maximum touch voltage
$\mathbf{U_{TP}}$	Touch voltage
$\mathbf{U_0}$	Zero sequence voltage
$\mathbf{U_1}$	Positive sequence voltage
$\mathbf{U_2}$	Negative sequence voltage
$\mathbf{V}$	Potential of the ground
$\mathbf{x_0}$	Zero sequence reactance per length
$\mathbf{Z}_{\mathrm{f}}$	Fault impedance
$\mathbf{Z_N}$	Neutral point impedance
$\mathbf{Z_0}$	Zero sequence impedance
$\mathbf{Z}_{\mathrm{0,on}}$	Zero sequence impedance of other network

Z_1	Positive sequence impedance
Z_2	Negative sequence impedance
μ_0	Vacuum permeability
ρ	Resistivity of the soil
φ	Phase angle difference
φ_0	Characteristic angle
ω	Angular frequency

1 Introduction

Fortum was founded in 1998. It was created by combining the businesses of state owned Imatran Voima (IVO) and listed company Neste Oyj. Today Fortum Oyj consists of four divisions: Power, Heat, Russia and Electricity Solutions and Distribution. Electricity Solutions and Distribution Division consists of two business areas: Distribution and Electricity Sales. Fortum's Distribution business area owns, operates and develops local and regional electricity distribution networks. It supplies electricity with 99,98% reliability to a total of 1,6 million customers in Finland, Sweden, Norway and Estonia. [34]

Distribution business area continuously invests in its electricity network in order to improve reliability and quality of electricity supply. Furthermore, the objective is to take a step towards intelligent networks where outages occur less frequently and interruptions are shorter. Fortum is participating in a research program called Smart Grids and Electric Markets (SGEM). The Finnish Cluster for Energy and Environment (CLEEN) manages the program which started in 2009 and will last until 2014. This thesis is carried out as a part of SGEM program at Fortum.

Medium voltage distribution networks are responsible for 90% of interruptions experienced by electricity consumers [2]. For this reason, the easiest way to affect the reliability of supply is to reduce faults in medium voltage networks. A significant proportion of medium voltage network faults are temporary arcing faults. Typically, 70-80% of these faults are cleared by automatic reclosing functions. However, these rapid reclosing functions cause short interruptions to electricity consumers and this way reduce the reliability of electricity distribution. This thesis investigates the use of a phase-earthing system. This kind of system operates in cases of single phase to ground faults and it is able to clear some of the faults without an outage. The system reduces the number of high speed automatic reclosing functions but it might also be able to prevent longer interruptions.

The basic principle of the phase-earthing method is to connect the faulty phase to the ground at a high/medium voltage substation. In practice, a switching device called phase-earthing circuit-breaker (PECB) is connected to the medium voltage busbar of the substation. When an earth fault occurs on an outgoing feeder, the PECB operates. When the faulty phase is connected to the ground, the most of the earth fault current flows to the ground at the substation and the fault has a better possibility to self-extinguish.

The aim of this thesis is to consider different phase-earthing-related aspects. One major point is earth fault protection point of view. The text discusses how earth fault protection could be implemented when a phase-earthing system is used. Another important factor is the safety regulations. This thesis tends to clarify which kind of demands the safety regulations impose from the phase-earthing point of view.

Fortum has a prototype phase-earthing system installed on a high/medium voltage substation. This system has been tested in field tests but it has not been in real use. The introduction of the system is discussed in Chapter5. Disturbance recordings of the field tests are used to clarify the behaviour of the zero sequence current during phase-earthing. The recordings are analysed because some earth fault protection malfunctions occurred in the tests. The maximum residual fault current is also estimated by means of electrotechnical calculations.

In Chapter6, phase-earthing systems and Petersen coils are compared to each other. Benefits and drawbacks of both alternatives are discussed and the economical point of view is also taken into account. In this context, both techniques are thought to reduce the number of high speed automatic reclosing functions. The estimation is done for a certain medium voltage network by means of reliability analysis.

Fortum has a pilot project running where a self-healing features-related concept is tested on two medium voltage line departures. The concept is meant to isolate faults faster and confine the impacts of a fault on a limited area. In the future, the system might be able to isolate faults and restore power independently. In Chapter7, it is considered if the phase-earthing method could be used to improve self-healing features of this kind in medium voltage networks. The utility of the phase-earthing method is estimated by means of reliability analysis. Finally, it is studied if new protection features could be useful when the phase-earthing method is used.

2 Earth faults in medium voltage networks

An earth fault emerges when a conductive path between a phase conductor and the ground appears. There are different causes for earth faults in medium voltage networks. In overhead line networks, most of the earth faults are caused by natural phenomena. For example, wind fall trees on lines and large snow loads bend trees on lines. During the summer, a common reason for earth faults is lightning-induced overvoltages. Animals cause earth faults for example in distribution transformers and disconnectors but some of the earth faults are also caused by human errors.

2.1 Earth fault current in a neutral isolated system

In a network with isolated neutral, there is no conductive path from the system to the ground (except voltage transformers). In the healthy state, the sum of charging currents of earth capacitances is zero [1]. When a phase conductor gets in a conductive connection with the ground, an earth fault happens. In this situation, the earth capacitance of the faulty phase discharges and the capacitances of healthy phases charges. As a result, the sum of the charging currents is nonzero and the earth fault current starts to flow.

In the ground, the current flows in both parallel directions in relation to the line: towards the feeding network and towards loads. The ground current is largest in the fault point and it gets smaller when the distance to the fault location increases. This is because the current flows to healthy phases through the earth capacitances. In the end of the line, the ground current is zero. [1]

In single-phase to ground fault situations, load currents do not change. However, the phase currents change. The fault current flows from the substation to a fault point via a faulty phase conductor. After flowing through the fault point to the ground, the fault current flows from the ground to healthy phase conductors through the earth capacitances. The fault currents of the healthy phases are smallest close to the fault location and they increase when the distance to the fault location increases. [1]

In healthy feeders, the zero sequence current flows to the opposite direction compared to a faulty feeder and the current increases towards the substation. In the faulty feeder, the current decreases when the distance to the substation decreases. The zero sequence current of a healthy line is proportional to a capacitance ratio C_j/C. In the ration, C_j denotes the earth capacitance of line j and C denotes the earth capacitance of background network. Corresponding parts of the earth fault current flows through healthy lines to the substation and through the medium voltage busbar system to the faulty feeder. For this reason, the measured zero sequence current of the faulty feeder correspond the capacitance $C\text{-}C_j$. In this context, C_j is the earth capacitance of the faulty line. [1]

In a system with isolated neutral, the earth fault current has a path from the fault location to the ground only via fault resistance, which reduces the fault current. As described above, the current flows through the earth capacitances and through the phase conductors to the feeding substation. Before flowing back to the faulty feeder, the current circulates through the windings of the high/medium voltage transformer. [2]

The series impedances of phase conductors and the impedances of transformer windings are small compared to the earth capacitances of the phase conductors. For this reason, these impedances are expected to be zero. The earth fault current can be expressed as shown in equation (2.1). [2]

$$\bar{I}_{ef} = \frac{\overline{U}_{ph}}{R_f + \frac{1}{j3\omega C}} \tag{2.1}$$

In (2.1), R_f is the fault resistance and C is the phase capacitance of the galvanic connected medium voltage network. It can be seen from the equation that the fault current is almost purely capacitive if the fault resistance is small.

2.2 Earth fault current in a compensated system

In a compensated system there is a neutral reactor (Petersen coil) connected to the neutral point of the system. The coil compensates the earth capacitances of the galvanic connected network. Under the circumstances, the earth fault current becomes smaller and the recovery voltage of a fault point is also lower. The current of the coil is tuned to be approximately equal current with the current that flows through the earth capacitances of the network. The capacitive current is opposite to the current that flows from the ground to the coil. For this reason, the sum of these currents is small and the fault current which flows to the faulty feeder becomes small. The earth fault current of a compensated system can be calculated by using equation (2.2). In the equation, R is the resistance and L is the inductance of the compensation coil. [2]

$$\bar{I}_{ef} = \frac{\overline{U}_{ph}}{R_f + \frac{R}{1 + jR(3\omega C - \frac{1}{\omega L})}} \tag{2.2}$$

In compensated systems, the earth fault current is approximately resistive. The resistive current is produced by the leakage resistance of the network and the resistance of the compensation coil. However, in real compensated systems, there is a reactive component in the fault current. This is a result of the fact that compensation coils are never absolutely tuned. In totally compensated systems, there is no reactive fault current component and the current is purely resistive. Harmonic components, which are a result of the saturation of a compensation coil, increase the magnitude of the earth fault current. However, in a compensated system, the earth fault current is usually 5-10% of the earth fault current of a corresponding neutral isolated system. [1]

2.3 Occurrences in earth fault situations

When the fault resistance R_f is zero, the voltage of the faulty phase is zero, respectively. This is because the faulty phase is directly connected to the ground. In this situation, the voltages of the healthy phases rise up to the same level with the phase-to-phase voltage of the system. In the above-mentioned situation, the neutral point voltage of the system becomes equal with the normal phase voltage [2].

When the fault resistance increases, the neutral point voltage decreases. Furthermore, the voltages of the healthy phases decrease. High fault resistances might cause problems for earth fault protection. When the fault resistance is about the same order of magnitude with the leakage resistance of the network, fault identification is difficult.

The earth fault current becomes larger when the total length of the network grows. On the contrary, the value of the neutral point voltage reduces when the length of the network grows. The earth fault current is typically about 5-100A in a system with isolated neutral and the average earth fault current produced by a 20kV overhead line is about 0,067A/km. In underground cable systems, the respective value is higher. Cables typically produce the earth fault current of 2,7-4 A/km. However, this value varies a lot depending on the structures of cables in the network. [2]

2.3.1 Neutral point voltage

In normal use situations, loads are symmetric and the sum of phase voltage phasors is a null vector. When one of the phases has a conductive connection to the ground, the balance of the phase voltages is disturbed and the zero sequence voltage, which is the sum of the phase voltages, has a nonzero value. The neutral point voltage affects between the neutral point of the system and the ground. In this text, the neutral point voltage is equivalent with the zero sequence voltage. If the series impedances are neglected and only the earth capacitances of lines are observed, the fault location does not have impact to the earth fault current or the zero sequence voltage. Traditionally, this assumption is done in earth fault analysis and the zero sequence voltage has the same value in the whole galvanic connected network. The assumption is also done in this thesis. The zero sequence voltage in a system with isolated neutral is shown in equation (2.3) [2].

$$\overline{U}_0 = \frac{1}{j\omega C}(-\bar{I}_{ef}) = \frac{-1}{1 + j3\omega C R_f}\overline{U}_{ph} \tag{2.3}$$

The zero sequence voltage in a compensated system is presented in equation (2.4) [2]. As can be seen from the equation, the inductance of the compensation coil and the resistance of the compensation coil affect the neutral point voltage.

$$\overline{U}_0 = \frac{-R}{R_f + R + jRR_f(3\omega C - \frac{1}{\omega L})}\overline{U}_{ph} \tag{2.4}$$

In earth fault situations, the maximum neutral point voltage is the phase voltage of the system. The value is reached when the fault resistance is zero. The voltage becomes smaller when the fault resistance grows. When the size of the galvanic connected network grows, the neutral point voltage becomes smaller because of the growing capacitance C. The influence of the capacitance and the influence of the fault resistance can be seen from equations (2.3) and (2.4). As can be noticed, there is R_f and C in the denominator of both equations.

2.3.2 Earth fault current at the substation

The earth fault current flows from the fault location to the medium voltage busbar through the earth capacitances and the phase conductors of galvanic connected medium voltage feeders. At the substation, the fault current flows from the busbar to the transformer windings and back to the busbar. Further, the current flows via the faulty feeder back to the fault location.

In a compensated system, the current that flows through the compensation coil is opposite and equal to the capacitive fault current. The capacitive current is a result of the capacitance 3(C-C_j). In this case, C_j is the capacitance of the faulty phase and C is the phase capacitance of the whole galvanic connected network. In compensated systems, the current transformer of a faulty feeder senses current $\underline{\mathbf{I}}_r$ which consists of the neutral point voltage $\underline{\mathbf{U}}_0$ and the resistance of the compensation coil R. The leakage resistance of the network and the resistance of the phase conductors also affect the magnitude of $\underline{\mathbf{I}}_r$. [2]

In a system with isolated neutral, the zero sequence current sensed by the current transformer of a faulty feeder consists of capacitance 3(C-C_j) and the neutral point voltage $\underline{\mathbf{U}}_0$. In this situation, $\underline{\mathbf{I}}_r$ has approximately 90 ° phase angle difference to voltage $\underline{\mathbf{U}}_0$. This is because the current is capacitive. Because the earth fault current divides between capacitances 3(C-C_j) and 3C_j, it is possible to solve the earth fault current sensed by the relay of the faulty feeder. Corresponding currents through the capacitances are $\underline{\mathbf{I}}_r$ and $\underline{\mathbf{I}}_{ef}$ –$\underline{\mathbf{I}}_r$. Because the voltage over the both capacitances is $\underline{\mathbf{U}}_0$, the earth fault current in faulty feeder bay j can be written as shown in equation (2.5). [2]

$$I_r = \frac{C - C_j}{C} I_{ef} = (1 - \frac{C_j}{C}) I_{ef} \tag{2.5}$$

2.4 Symmetrical components

Symmetrical components are used to calculate voltages and currents in fault situations. Especially, these components are useful when there is only one asymmetry in network. Symmetrical components consist of three different subsystems: a zero-sequence system, a positive sequence system a negative sequence system.

The components form similar counterclockwise rotating systems as normal phase phasors. The positive sequence system is similar to the normal three phase system R-S-T. In the positive sequence system, voltages can be written as shown below.

$$\overline{U}_{R1} = \overline{U}_1, \overline{U}_{S1} = \overline{a}^2 \overline{U}_1 \ \& \overline{U}_{T1} = \overline{a} \overline{U}_1$$

The magnitude of vector $\underline{\mathbf{a}}$ is 1 and the phase angle of the vector is 120°. The negative sequence system has an inverse phase order compared to the positive sequence system. The phase order of the negative sequence system is R-T-S. In the negative sequence system, voltages can be expressed as shown below.

$$\overline{U}_{R2} = \overline{U}_2, \overline{U}_{S2} = \overline{a} \overline{U}_2 \ \& \overline{U}_{T2} = \overline{a}^2 \overline{U}_2$$

The phase phasors of the zero-sequence system are parallel and equal to each other. They are expressed as follows.

$$\overline{U}_{R0} = \overline{U}_{S0} = \overline{U}_{T0} = \overline{U}_0$$

The normal phase voltages are the sum of responding symmetrical components. Following equations express the normal phase voltages by means of the symmetrical components.

$$\begin{aligned}\overline{U}_R &= \overline{U}_{R0} + \overline{U}_{R1} + \overline{U}_{R2}\\ \overline{U}_S &= \overline{U}_{S0} + \overline{U}_{S1} + \overline{U}_{S2}\\ \overline{U}_T &= \overline{U}_{T0} + \overline{U}_{T1} + \overline{U}_{T2}\end{aligned}$$

If there are only self-impedances and impedances between the neutral point and the ground in the network, the impedances of sequence networks can be written as follows [3]. $\underline{\mathbf{Z}}_{\text{line}}$ is the impedance of a phase conductor and $\underline{\mathbf{Z}}_{\text{N}}$ is the impedance between the neutral point and the ground. As can be seen, the impedance between the neutral point and the ground appears threefold in the zero sequence impedance. This is because the zero sequence current of each phase flows through the neutral point. In addition, this relates all impedances in the return circuit of the zero sequence current.

$$\overline{Z}_1 = \overline{Z}_2 = \overline{Z}_{line} \;\&\; \overline{Z}_0 = \overline{Z}_{line} + 3\overline{Z}_N$$

The positive and the negative sequence impedances are always equal if the system is symmetrical. Systems can also be made to behave symmetrically for example by means of the transposition of phase conductors. However, the zero-sequence impedance is usually clearly different compared to the positive and negative sequence impedances. If the zero sequence current does not have a return circuit, the zero sequence impedance is infinity. In delta connected networks, there is no return conductor. For this reason, the zero sequence impedance is large in neutral isolated distribution networks and the impedance consists of the total earth capacitance. [3]

2.4.1 Earth faults and symmetrical components

When there is an earth fault in phase R, the following conditions are valid. [3]

$$\overline{U}_R = \overline{Z}_f \overline{I}_R, \overline{I}_S = 0 \,\&\, \overline{I}_T = 0$$

According to the conditions and equations mentioned earlier, the fault current can be expressed as shown in equation (2.6).

$$\overline{I}_{ef} = 3\overline{I}_0 = \frac{3\overline{E}_R}{\overline{Z}_1 + \overline{Z}_2 + \overline{Z}_0 + \overline{Z}_f} \tag{2.6}$$

In this equation, $\underline{\mathbf{Z}}_{\text{f}}$ is the fault impedance between phase R and the ground. $\underline{\mathbf{Z}}_0$ is the total zero sequence impedance. The equation can also be expressed as written in (2.7).

$$\bar{I}_{ef} = \frac{3\bar{E}_R}{\bar{Z}_{0,on} + \bar{Z}_1 + \bar{Z}_2 + 3(\bar{Z}_N + \bar{Z}_f)} \tag{2.7}$$

In this form, $\underline{\mathbf{Z}}_{0,\mathrm{on}}$ is the zero sequence impedance of the other network. This means that the impedance between the neutral point and the ground is excluded. The total zero sequence impedance can be written $\underline{\mathbf{Z}}_0 = \underline{\mathbf{Z}}_{0,\mathrm{on}} + 3\underline{\mathbf{Z}}_\mathrm{N}$. The path of the zero sequence current determines $\underline{\mathbf{Z}}_{0,\mathrm{on}}$. For example, in neutral isolated distribution networks, the zero sequence current flows though the earth capacitances and the earth circuit.

According to the conditions of the earth fault situation, it follows that $\underline{\mathbf{I}}_0 = \underline{\mathbf{I}}_1 = \underline{\mathbf{I}}_2$ and the component networks are series connected. The connection diagram of the networks is shown in Figure 2.1. However, it must be noticed that the total zero sequence impedance is denoted by $\underline{\mathbf{Z}}_0 + 3\underline{\mathbf{Z}}_\mathrm{N}$ in the figure. In Section 3.3, the symmetrical components are used in a phase-earthing situation. In this case, there are two separated earth faults in the network.

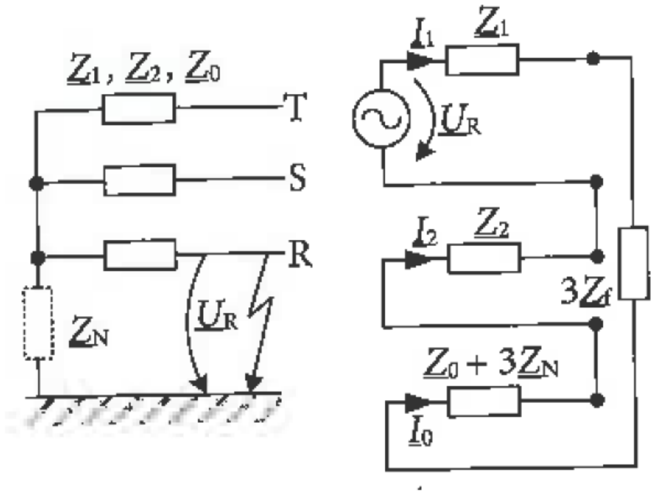


Figure 2.1: The connection of the component networks in earth fault situations [3]

2.5 Earth fault protection

Earth fault protection can be arranged by using over current relays to measure the zero sequence current (I_0-relay), which is the sum of the phase currents: $\underline{\mathbf{I}}_\mathrm{R} + \underline{\mathbf{I}}_\mathrm{S} + \underline{\mathbf{I}}_\mathrm{T} = 3\underline{\mathbf{I}}_0$. Relays of this kind cannot detect the direction of an earth fault. Faults ahead and beyond the relay are tripped if the fault current is large enough. However, it is also possible to arrange earth fault protection by using distance relays or directional earth fault relays. Both of these can also detect the direction of the fault. Distance relays can only detect earth faults when the fault current is large and therefore they cannot detect large fault resistances. [4]

I_0-relays are either rough or sensitive. The sensitive I_0-relay has a low current adjustment and a long delay-time. The settings of rough I_0-relays are determined by means of fault current calculations and a short time delay is used. The current setting of the rough relays is large compared to sensitive I_0-relays. If the delay is not used, I_0-relays work as fast as normal over current relays. [4]

Directional earth fault relays also measure the direction of the fault. The measurement is implemented by using the phase angle between the zero sequence current and the zero sequence voltage. Directional earth fault relays require that the fault current sensed by the current transformer of a faulty feeder and the neutral point voltage exceed their set limits. Earth fault protection must only operate when the direction of the fault current is from the busbar to the fault point. The relay must not operate if the current flows towards the substation. [2]

Directional earth fault relays monitor the angle between the voltage phasor $-\underline{\mathbf{U}}_0$ to the current phasor $\underline{\mathbf{I}}_r$ in order that the direction of the fault current can be determined. The angle must be on a certain operating zone and directional earth fault relays operate when the following independent criterions are fulfilled: the zero sequence current is larger than the set value, the zero sequence voltage is higher than the set value and the phase angle criterion is met. The angle between the zero sequence voltage and the zero sequence current must fulfill the condition (2.8).

$$\varphi_0 - \Delta\varphi < \varphi \leq \varphi_0 + \Delta\varphi \tag{2.8}$$

The tolerance that is denoted by $\Delta\varphi$ is dependent of the earthing method of the network. In neutral isolated systems, the tolerance $\Delta\varphi$ can be quite small but in compensated networks the phase angle can alternate widely and the tolerance is usually something like 80° [2]. In unearthed systems, the basic angle $\varphi_0 = 90^\circ$ and in compensated systems the basic angle $\varphi_0 = 0^\circ$, respectively. The difference is a consequence of the fact that in a neutral isolated system the earth fault current is almost purely capacitive and in compensated systems the fault current is almost resistive (depends of the compensation degree of the network). When all the three conditions are met, the relay starts.

The functioning of directional earth fault protection is depicted in Figure 2.2. I_r is the current sensed by the relay, U_0 is the magnitude of the neutral point voltage and I_h is a threshold current for starting. The figure also presents the angle condition of (2.8). The basic angle is denoted by φ_0 and as can be seen the angle changes when the earthing method of the network is changed.

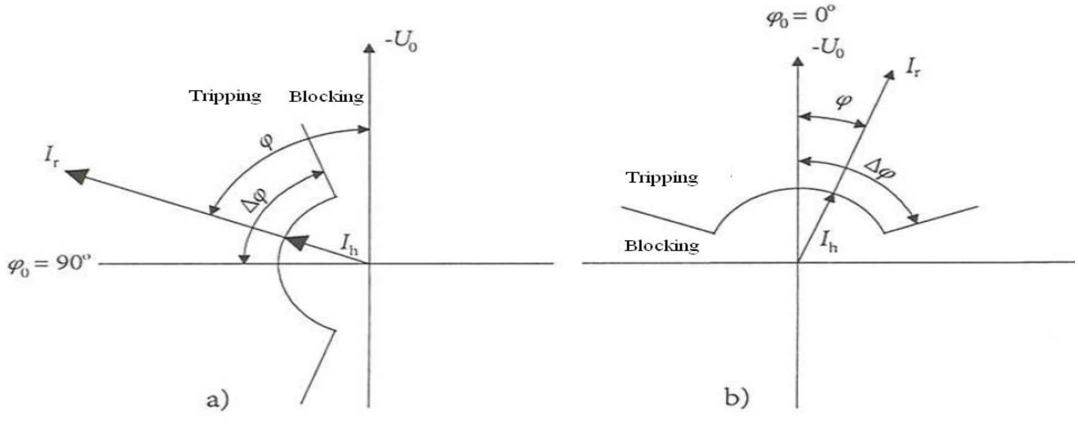


Figure 2.2: Directional earth fault protection: a) neutral isolated systems b) compensated systems. [2]

The basis of earth fault protection design is the minimum fault current and the minimum neutral point voltage that must be indicated. The zero sequence current is small when the fault impedance is large and the galvanic connected network is small. The neutral point voltage is low when the fault resistance is high and the galvanic connected network is large. In addition, the safety regulations must be fulfilled. Fault durations affect the permitted touch voltage values. Further, the earth fault current affect the generating earth potential rise and touch voltages. The safety regulations must be observed when operation delays times are determined. It must also be observed that earth faults are easier to localize when the fault duration is longer. In addition, earth faults have also better ability to heal themselves when the fault duration is long. [2]

3 Theory of phase-earthing method

Normally, when an earth fault is detected, automatic reclosing functions are performed. Earth fault protection gives a tripping signal to a feeder circuit-breaker, which trips the faulty line. When the faulty feeder is disconnected, the fault current vanishes because electromotive force does not sustain the fault. However, these automatic reclosing functions cause short outages to customers. For this reason, the reclosing functions are economically adverse and they have adverse effect on the quality of supply.

In medium voltage overhead line networks, a significant amount of faults have temporary nature. The phase-earthing method provides an opportunity clear the temporary faults without interruptions to low/medium voltage customers. The technique might also be usable in long-term fault situations. However, the use as a supplementary function to the automatic reclosing functions could already have remarkable benefits. In this chapter, the phase-earthing method and occurrences in the network when a faulty phase is connected to the ground are discussed.

3.1 Operating principle

The idea of the phase-earthing method is to divert the earth fault current away from a fault point. The faulty phase is connected to the ground at a substation. In this case, a major part of the capacitive fault current flows to the ground at the substation and the current of the fault point reduces, respectively. The faulty phase is earthed by using a coupling device called a phase-earthing circuit-breaker (PECB). [5]

The PECB-device is a circuit-breaker with single-pole closing and tripping characteristics. The device is located at a high/medium voltage (110kV/20kV in Finland) substation and it is connected to a medium voltage busbar-system. When an earth fault occurs on a medium voltage feeder, the PECB connects the faulty phase to the ground.

During phase-earthing, a major part of the earth fault current flows to the ground through the substation earthings. For this reason, a part of the fault current that flows to the fault point through the faulty phase conductor substantially decreases. The principled path of the earth fault current in a phase-earthing situation is presented by red arrows in Figure 3.2. The capacitive fault current flows through the earth capacitances back to the network and onwards to the medium voltage busbar of the substation. The capacitive fault current that flows through the fault point is the normal earth fault current minus the current that flows through the PECB-device.

When the faulty phase is connected to the ground, the voltage of the fault point also reduces. As can be seen from Figure 3.1, points A and C have nearly the same potential because the phase-earthing resistance, which is denoted by $R_{S,}$ is very small. The voltage of the fault point is the voltage between points B and C. This voltage is equal with the voltage reduction between points A and B if R_S is assumed to be zero. The voltage drop is proportional to the load current of the conductor. Because the voltage of the fault point reduces and the capacitive fault current of the fault point becomes smaller, arcing faults have better possibility to self-extinguish. [8]

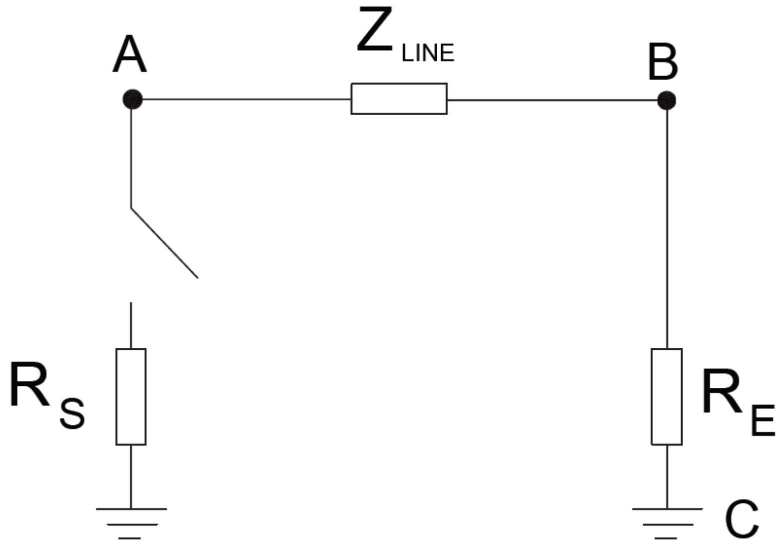


Figure 3.1: The equivalent circuit of a faulty line

However, a sufficient part of the load current might flow through the earth circuit and affect the above described situation. The path of the load current is denoted by green arrows in Figure 3.2. Because a part of the load current flows through the fault point back to the line, the current of the fault point increases. The effect of the load current is discussed more accurately in Section 3.4 when the behavior of the residual fault current is concerned. In Figure 3.1, it is also expected that the capacitive fault current of the fault point is approximately zero and for this reason it is neglected. In other words, it is assumed that the whole earth fault current flows through the phase-earthing circuit-breaker. In spite of all, the phase-earthing method reduces the current of a fault point and the voltage of the fault point in most of the cases.

When the faulty phase is connected to the ground, the voltage of the phase is approximately zero. The phase voltages of healthy phases increase to the level of the phase-to-phase voltage of the system. Although the phase voltages change, the phase-to-phase voltages remain in the normal values. Because primary sides of medium/low voltage transformers are delta connected the phase-to-phase voltages affect over the transformer windings. For this reason, phase-earthing does not cause outage to low voltage customers behind distribution transformers. In other words, customers fed by a faulty feeder do not suffer an outage when the faulty phase is earthed.

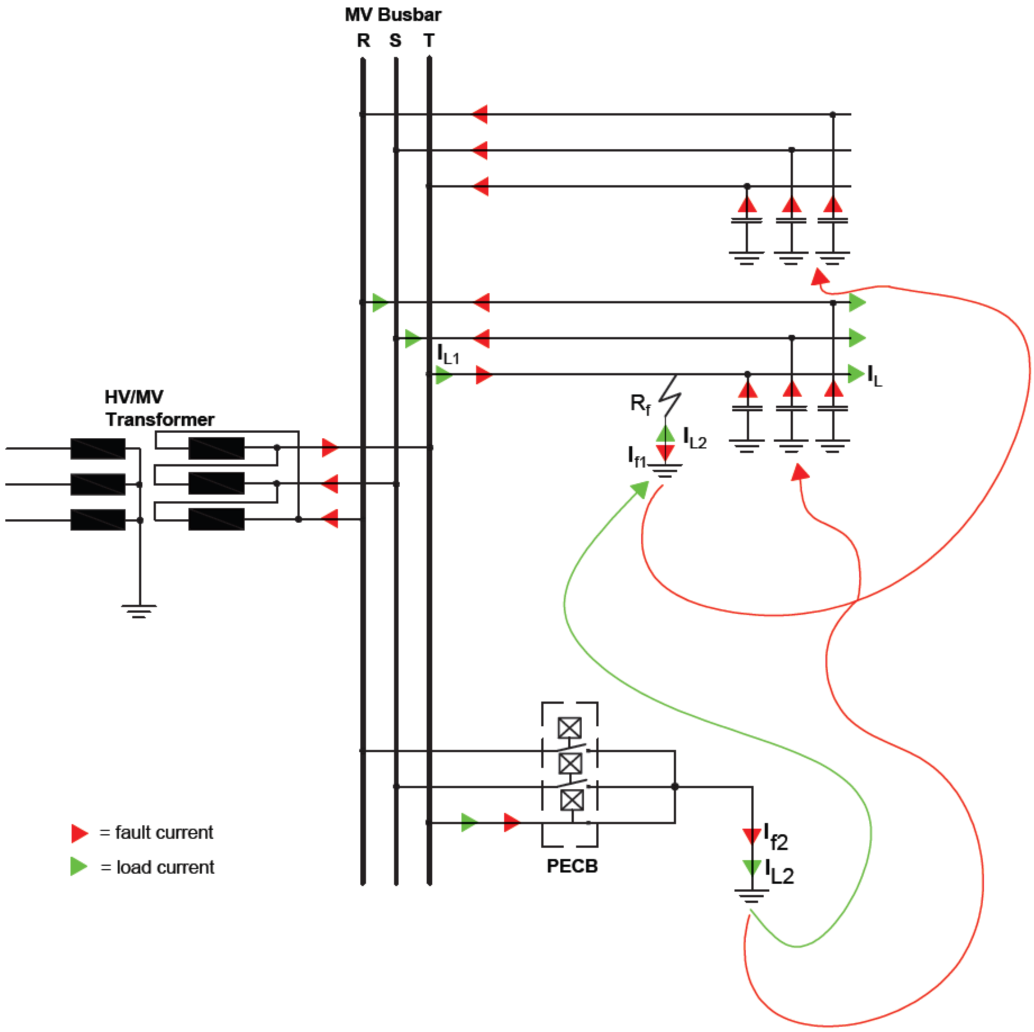


Figure 3.2: Currents in a phase-earthing situation

3.2 Use methods

In practice, there is two ways to utilize the phase-earthing method in medium voltage networks. One way is to connect the faulty phase to the ground for a short time (few tenths of a second). Another way is to connect the faulty phase to the ground for a longer time or even permanently. In both cases, the limiting factor is the safety regulations which are discussed in Section 4.2.

3.2.1 Short-term phase-earthing

When a short phase-earthing time is used, the system is aimed to replace/decrease the number of high speed automatic reclosing functions. In this case, the idea is to remove faults by extinguishing electric arcs in most of the cases. The PECB reduces short interruptions to customers and increases the quality of supply. The PECB must be closed for a long time enough in order that electric arcs have a sufficient time to extinguish. The phase-earthing system reduces the number of high speed automatic reclosing functions and it does not affect the number of delayed automatic reclosing functions.

The relay of a phase-earthing system and the actual PECB-device cause a time delay. After this approximately 100ms period of time [6], the PECB connects the faulty phase to the ground for a predetermined time t_{PE}. If the fault disappears during the phase-earthing time, the normal use of the network is continued. If the fault still exists after the PECB opens, automatic reclosing functions are carried out. In this case, the phase-earthing system supplements the automatic reclosing cycle.

3.2.2 Long-term phase-earthing

In the other use method, the faulty phase is connected to the ground for a longer time. This method could enable the continuous use of a faulty feeder in permanent earth fault situations. It might be possible to maintain electricity distribution while searching the fault location. Phase-earthing might reduce the residual fault current enough to permit the use of network in spite of a fault. However, the PECB might have to be opened and reclosed few times if a trial and error method is used in fault localization. This is because the relay of the faulty feeder might not stay picked up when the faulty phase is connected to the ground. However, this kind of use could reduce interruption durations in permanent fault situations.

In compensated systems, electric arc faults usually self-extinguish. This is mainly because the recovery voltage increases slowly in the faulty phase [7]. The long-term phase-earthing method could be used to maintain electricity distribution in permanent earth fault situations. In compensated systems, the earth fault current is usually small. For this reason, the safety regulations are easier to fulfill and the long-term phase-earthing method might be useful.

3.3 Modelling

In reference [8], there is a model deduced for phase-earthing situation by means of the symmetrical components. The current of the fault point depends on the load current and the distribution of loads on the faulty line. In addition, it depends on the fault location on the line. In the model, the fault is expected to occur close to loads. Furthermore, the loads are assumed to be located in the end of the distribution line. This kind of situation is the most unfavourable when the effect of the load current on the current of the fault point is considered. [8]

In phase-earthing situations, there is in a way two separated faults in the network: the actual fault and the phase-earthing point. Both faults have the same type but different location. The situation can be considered by means of symmetrical components when the phase-earthing point and the actual fault are treated as two separated earth faults. These faults must be galvanic separated because they occur in different points, concurrently. For this reason, there are ideal transformers which have the conversion ratio of 1:1 in the connection diagram of the component networks. The circuit diagram of the situation is presented in Figure 3.2. [8]

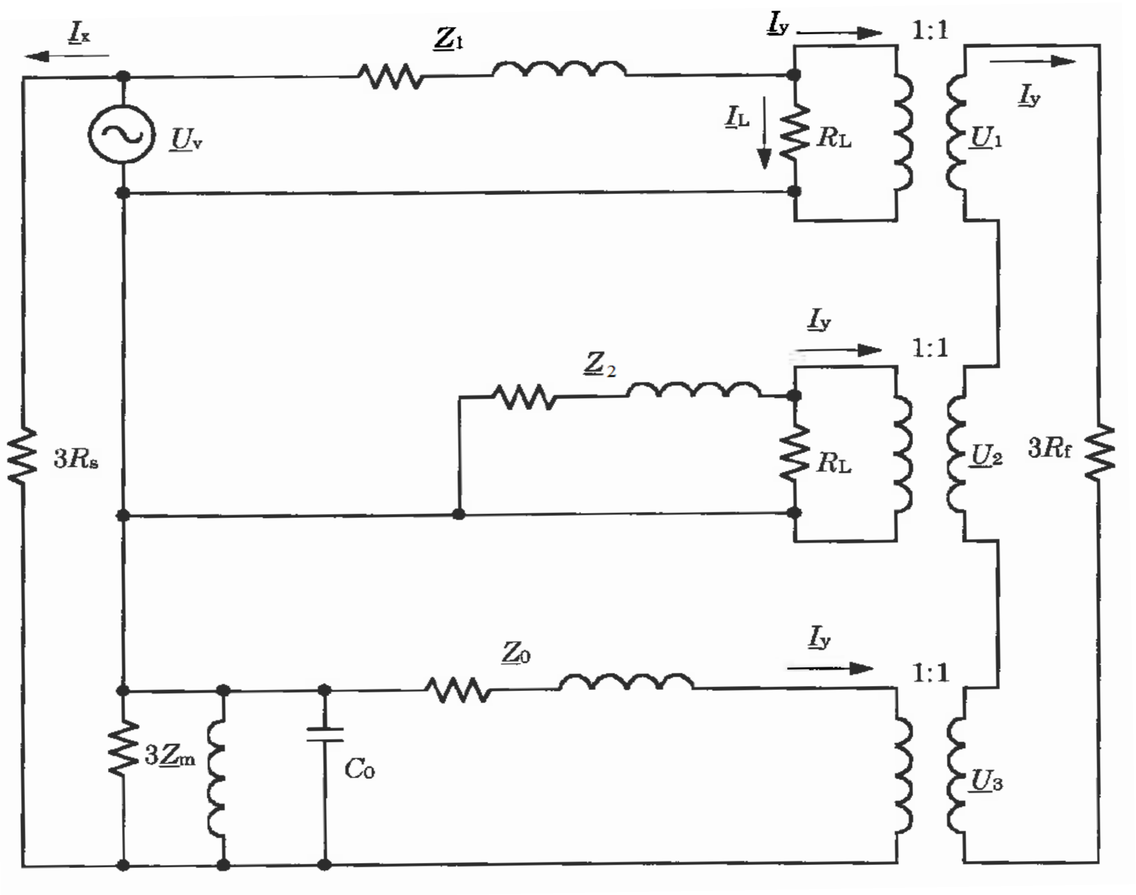


Figure 2.2: Circuit diagram of phase-earthing model [8]

The current of a fault point is expressed in equation (3.1) [8].In the equation, $\underline{\mathbf{Z}}_1$, $\underline{\mathbf{Z}}_2$ & $\underline{\mathbf{Z}}_0$ are the positive, negative and zero sequence impedances of the faulty line. R_L is the load resistance and R_f is the fault resistance. $\underline{\mathbf{Z}}_{mc}$ is the impedance of the parallel connection of the neutral point impedance and the impedance of the earth capacitance C. In neutral isolated networks, the impedance between the neutral point and the ground is infinitely large and $\underline{\mathbf{Z}}_{mc} = 1/j\omega C$. R_S is the phase-earthing resistance.

$$\bar{I}_{res} = \frac{3\overline{U}_{ph}(\bar{Z}_L 3R_S - \bar{Z}_{mc}\bar{Z}_1)}{2\bar{Z}_1 R_L(3R_S + \bar{Z}_{mc}) + 3R_S\bar{Z}_{mc}(\bar{Z}_1 + R_L) + (\bar{Z}_1 + R_L)(3R_S + \bar{Z}_{mc})(\bar{Z}_0 + 3R_f)} \qquad (3.1)$$

In (3.1), different loading situations are taken into account by changing R_L. When R_L increases, power consumption decreases. When R_L decreases, power consumption increases, respectively. For example, the load resistance values of 200,400 and 800Ω correspond load powers 2, 1 and 0,5 MW in 20kV systems. More accurately, the voltage drop of a considered line can be taken into account in the load resistance value.

3.4 Residual current

When the faulty phase is connected to the ground at the substation, there appears a parallel path for the load current. Because the PECB constitutes a connection to the ground, a part of the load current flows through the earth circuit and through the fault point back to the line. The rest of the load current flows through the faulty line. The mentioned load current components are denoted by I_{L1} and I_{L2} in Figure 3.2. Because of phase-earthing, a major part of the earth fault current flows to the ground via the PECB. In Figure 3.2, this part of the earth fault current is denoted by I_{f2}. I_{f1} is the part that flows through the fault point to the ground.

The ratio of current components I_{L1} and I_{L2} depends on the impedance ratio of the earth circuit and the line. The total current that flows through the fault point is called a residual fault current. This current is the sum of the earth fault current component I_{f1} and the load current component I_{L2}. The following factors affect the magnitude of the residual current: [9]

- Capacitive earth fault current
- Load current of the faulty feeder
- Earth resistance of the substation
- Fault resistance
- Distance between the fault point and the substation (impedance of the line)

3.4.1 Residual current in neutral isolated networks

The load current component that flows via the PECB to the ground and through the earth circuit to the fault point has 90° phase-angle difference compared to the capacitive fault current. For this reason, these components are not compensating each other. The increase of the load current increases the magnitude of the residual fault current. [10]

The phase-earthing resistance has an impact on the residual fault current. When the phase-earthing resistance increases, the proportion of the load current in the residual fault current becomes smaller. This is because the impedance ratio of the faulty line and the earth circuit becomes smaller. On the other hand, the earth fault current component that flows through the fault point increases when R_S increases. This is also a result of a different impedance ratio. When the phase-earthing resistance decreases, inverse phenomena occur.

When the load current is small, the increase of the phase-earthing resistance increases the value of the residual fault current. This is because a larger part of the earth fault current flows through the fault point and smaller part trough the PECB at the substation. Conversely, if the load current is large, the residual fault current decreases when the phase-earthing resistance grows.

The use of the phase-earthing resistance is not practical in neutral isolated systems. This is because the benefits of the resistance will only be achieved in cases where the load current already causes major voltage reductions. The load current has the largest effect when the fault point is far away from the substation. The residual fault current becomes smaller when the distance of the fault shortens. This is because the load current has a small resistance through the line when the fault occurs close to the substation. The benefits of the phase-earthing resistance reduce when the distance of the fault shortens. The resistance can even be harmful when the fault occurs close to the substation. [8]

Figure 3.3 presents the residual current of the fault point as a function of the load resistance. The load current decreases when the load resistance R_L increases. The separated curves present the different lengths of the faulty feeder. In Figure 3.3, parameters are: phase-to-phase voltage 21kV, the length of galvanic connected network 490km, conductor type Raven, fault resistance 12Ω and phase-earthing resistance 2Ω. The curves are drawn by using (3.1), which presents the situation where the load current has the most harmful influence on the residual fault current. In this model, loads are placed to the end of the feeder and the fault point is also in the end of the line. The earth fault current of 490km galvanic connected overhead line network is approximately 34 A. [8]

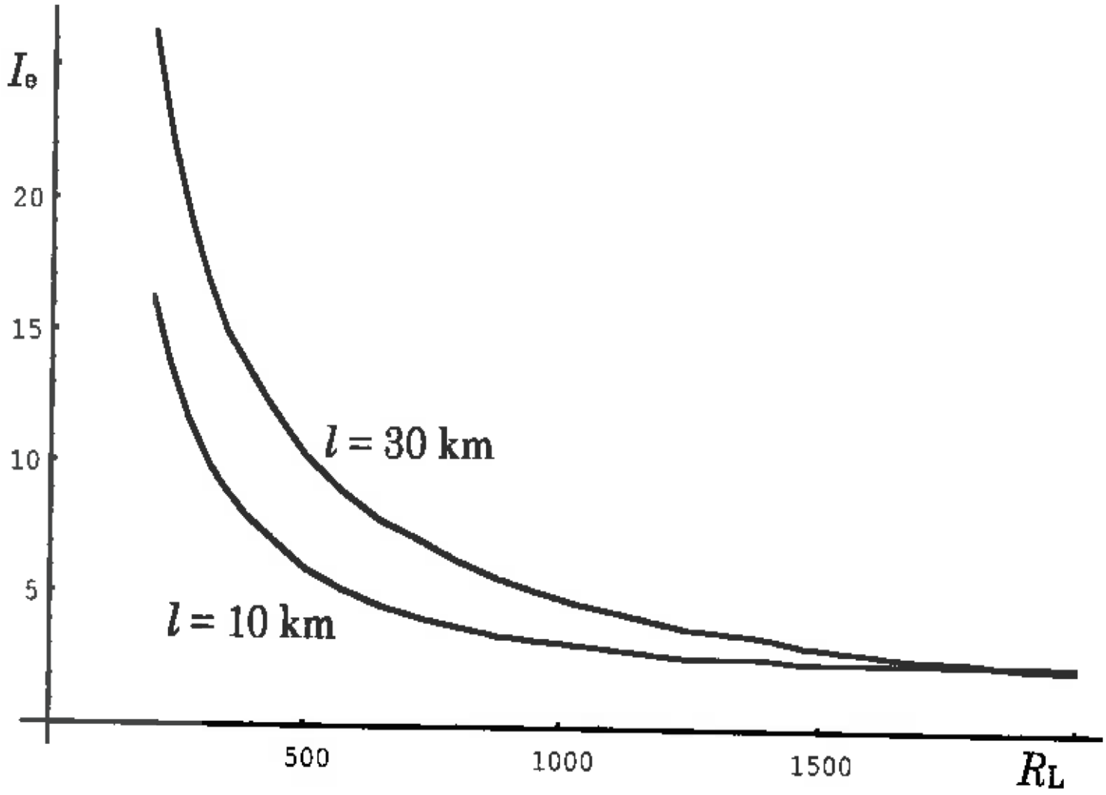


Figure 3.3: Residual current in a neutral isolated system [8]

3.4.2 Residual current in compensated systems

In compensated systems, the residual current consists of two components: a component caused by an additional resistance which is connected parallel with the compensation coil and the load current component. Precisely, this is only the case in completely compensated networks. In real situations, the network is usually over or under compensated. The earth fault current of a compensated network is usually 5-10% of the value of a corresponding neutral isolated system [1].The use of the additional resistance is case-specific and the resistance is used to increase the resistive fault current component in order that earth fault protection can detect earth faults. In compensated networks, the load current has a dominant part of the residual current and the phase-earthing resistance does not substantially increase the residual current even when the load current is small. [8]

Figure 3.4 presents the residual current as a function of the load resistance. The same parameters are used as in Figure 3.3. The separated curves present the different values of the phase-earthing resistance R_S. In Figure 3.4, the compensation degree of the network is 100% and there is 1470Ω resistance connected parallel with the compensation coil. As can be seen from the figure, the use of the phase-earthing resistance might be beneficial in compensated systems.

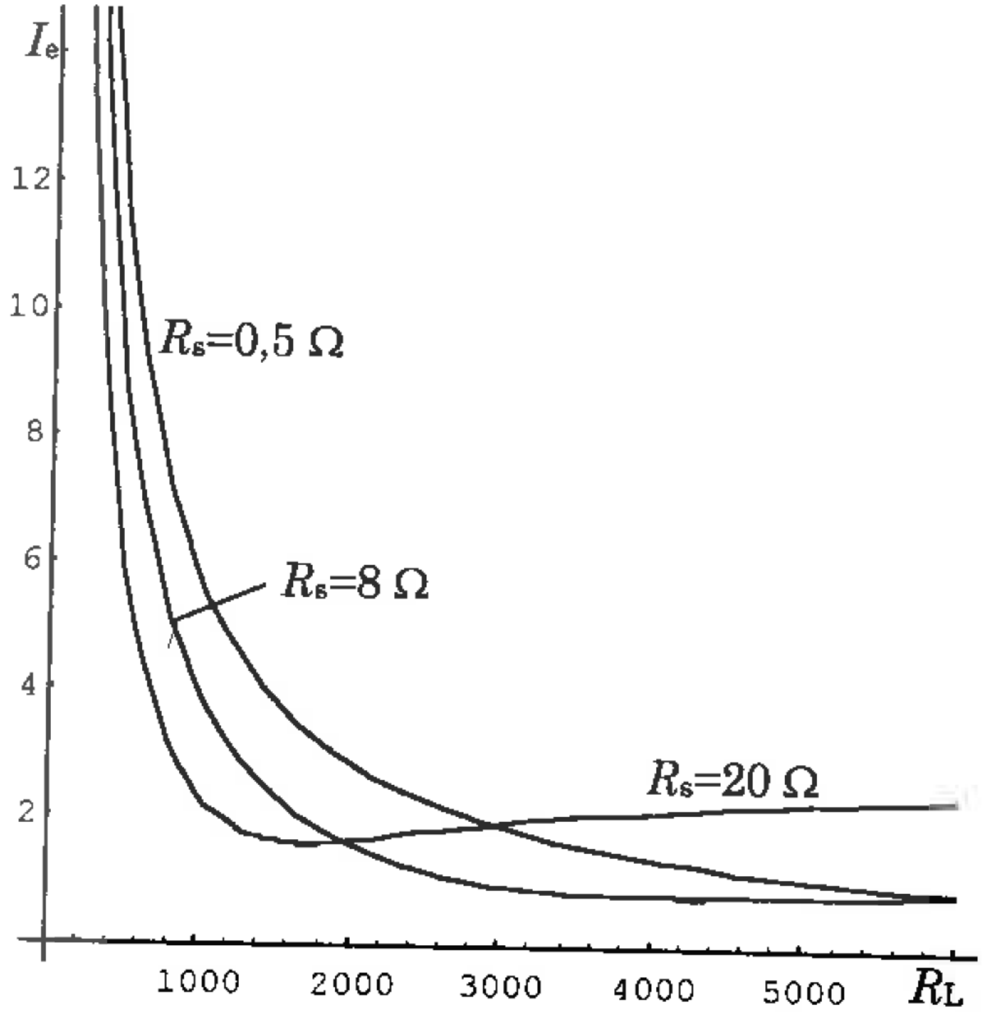


Figure 3.4: Residual current in a compensated system [8]

4 General aspects to the introduction of phase-earthing systems

When the use of the phase-earthing method is considered, the main point is the fulfilment of the safety regulations. In practice, this means that the earth potential rise, which determines allowed fault durations must be calculated. Tripping delays must be long enough in order that the phase-earthing method can be used.

Earth resistance data is needed in earth potential rise calculations. In addition, the earth fault current must be known. The earth potential rise of an earthing point is calculated by multiplying the earth fault current and the earth resistance of the earthing point. In addition, the earthing manner of equipment must be known in order that proper requirements can be used. For example, the safety requirements are more stringent if the protective earthing of the medium voltage system is connected to the system earth of the low voltage system. The effect of the phase-earthing on the fault current must also be examined.

The use of the phase-earthing method imposes challenges for earth fault protection. Relays must function properly when the faulty phase is connected to the ground. In this chapter, setting modifications for conventional earth fault protection are discussed. In addition, safety regulations and self-extinction of electric arcs are discussed. The chapter handles things on general level.

4.1 Extinction of electric arcs

Electric arc extinction is important issue when the number of short interruptions is reduced. If an arc self-extinguishes, the faulty line does not need to be disconnected and electricity distribution to customers is not interrupted. However, faults must self-extinguish fast enough in order that safety regulations are not violated.

4.1.1 Arcing time

Arc extinction depends on many factors. The rising speed of the recovery voltage and the amplitude of the voltage are important factors. In addition, the increase of the fault current makes the self-extinction of a fault more improbable. The rate of rise of the recovery voltage has the largest influence [9]. On the other hand, arcing time is a random value which has statistical characteristics [12].

The voltage of an arc is proportional to the length of the arc. Electric arcs have a resistive nature and they can be modeled by using a pure resistance. In a simplified manner, the resistance of an arc is proportional to the length of the arc. When the length of an arc increases, the current of the arc reduces. However, the length of an arc is a random value and it changes during the arcing time. The length has a tendency to increase while the arcing time becomes longer. [13]

Arc extinction occurs when the fault current is in the zero point of its cycle. If the voltage of an arc is small enough in the zero point, the arc cannot re-ignite and extinction takes place [8]. Electric arcs cause ionization in ambient air and constitute a conducting plasma channel in which the arc actually burns [11]. The idea of the automatic reclosing method is to break the fault circuit and enable the de-ionization of the arcing channel. In 20kV networks, the de-energized period of a reclosing function must be 70 ms in order that ionization caused by a short circuit fault vanishes [1].

The self-extinguishing properties of arcs depend on the neutral point earthing manner of the network. In a compensated network, arcs self-extinguish when the earth fault current is one and a half-fold compared to a corresponding neutral isolated system. In compensated 20kV networks, the earth fault current of 60A should break itself. Electric arcs extinguish more easily in compensated systems because the rising speed of the recovery voltage is slower and the amplitude of the recovery voltage is smaller. In a neutral isolated system, the voltage can reach the twofold phase voltage value. In a compensated system, the voltage does not rise over the steady state phase voltage. [9]

In addition, a fault location has impact to the self-extinction probability of the fault. When the fault is in the end of the feeder, the arcing time is longer compared to a case where the fault occurs close to the substation. This is because of the voltage drop, which is caused by the residual fault current in the impedance of the line. The voltage drop produces high frequency oscillations to the recovery voltage at the fault location and makes arc extinction more difficult. When the voltage drop is over 4 % of the nominal voltage, the arcing time begins to increase. [10]

In protective spark gaps, electric arcs have different self-extinguishing characteristics compared to other arcing faults. In a spark gap, the fault has a start point and an end point. For this reason, the arc cannot move unlike in other cases. The following facts affect arc extinction [9]:

- Neutral point earthing method
- Magnitude of the earth fault current
- Structure of the spark gap
- Weather conditions (wind speed and direction)
- Starting moment of the fault

In spark gaps, the earth fault current does not trip out itself as easily as in other cases. For example, in 20kV neutral isolated systems, the limit value is only 5A. If the fault current is larger than this, arcs do not self-extinguish. In compensated networks, the corresponding value is 20A. [1]

4.1.2 Mathematical estimation of electric arc extinction

The rising speed of the recovery voltage can be estimated by using equation (4.1). This equation is only valid immediately after the breakdown of the fault current. In the equation, the mismatch of system is denoted by m and the damping of the system is denoted by d. These are determined as follows: $m = (I_{Coil} - I_C)/I_C$ & $d = I_R/I_C$. I_{coil} is the current of the compensation coil, I_C is the capacitive fault current and I_R is the resistive fault current. U_n is the nominal voltage of the network. The simplified form of (4.1) is valid when m<< 1. [10]

$$\frac{dU_{rec}}{dt} = \frac{\sqrt{2}U_n}{\sqrt{3}}\frac{\omega}{2}\sqrt{(2\sqrt{m+1}-2)^2 + d^2} \approx \frac{\sqrt{2}U_n}{\sqrt{3}}\frac{\omega}{2}\sqrt{m^2 + d^2} \qquad (4.1)$$

The square root term of simplified part of equation (4.1) is called a key parameter of extinction. When the value of the parameter is large, the extinguishing unreliability of the arc is high. The key parameter is shown in equation (4.2) and it is directly proportional to extinguishing unreliability. [10]

$$K = \sqrt{m^2 + d^2} = \frac{I_{res}}{I_C} \tag{4.2}$$

It can be seen that extinguishing unreliability is directly proportional to the residual fault current. The increase of the compensation degree also decreases the value of the key parameter and faults have a higher probability to self-extinguish.

The longest arcing time is empirically noticed to follow inequality (4.3). This formula is based on 775 earth fault tests which were carried out in a 20kV medium voltage network. The inequality gives the arcing time in seconds and it was valid in 99,5% of the cases. [10]

$$t_{\max} < 0.1 + 25K^2 \tag{4.3}$$

In the above mentioned tests, the fault location was a medium voltage busbar. It must be taken into account that the arcing time is longer when the fault is located further away from the substation. The impact of distance is described in the previous section. When the faulty phase is connected to the ground, the residual fault current reduces and the voltage of the fault point is low. These factors assist arc extinction. It can be concluded from (4.3) that 0,1s is the absolute minimum for the arcing time.

4.2 Earth potential rise and hazard voltages

The earth fault current causes earth potential rise in a fault location. Earth potential rise produces touch and step voltages which are dangerous for people and animals. SFS 6001 standard determines the maximum values for the touch voltage U_{TP}. These limits are based on the dangerous nature of electricity and they are independent of the operating voltage of the network. SFS 6001 must be followed if equipment is built after the effective date of the standard which is 2.1.2000. Older parts of the network must fulfil the old safety regulations which are discussed in 4.2.3.

4.2.1 Earthings

The purpose of an earthing point is to connect a device or a part of the electrical circuit effectively to the ground. Contacts between the system and the ground are formed by using metallic components called earth electrodes. According to SFS 6001, earthing systems must fulfil four separated requirements: a) adequate mechanical strength and corrosion resistance, b) thermal strength towards the maximum fault current, c) prevent the damage of property and devices and d) assure the safety of people towards the voltage which appears in earthing systems during the maximum fault current. [14].

As can be seen from equation (4.4), the current of the earth electrode I_E generates an earth potential rise U_E whose magnitude depends on the earth resistance R_E. [4]

$$R_E = \frac{U_E}{I_E} \tag{4.4}$$

The earth potential rise is calculated by using (4.4). In calculations, it is assumed that the earth fault current flows through the earth electrode in its entirety. The regulations of SFS 6001 relate touch and step voltages and Figure 4.1 presents the definitions of these voltages. In the figure, the maximum touch voltage is denoted by U_{ST}, the maximum step voltage is denoted by U_{SS} and the potential of the earth surface is denoted by V. As can be seen from Figure 4.1, the earth potential of the fault location has risen and it approaches the absolute earth potential when distance to the fault location increases.

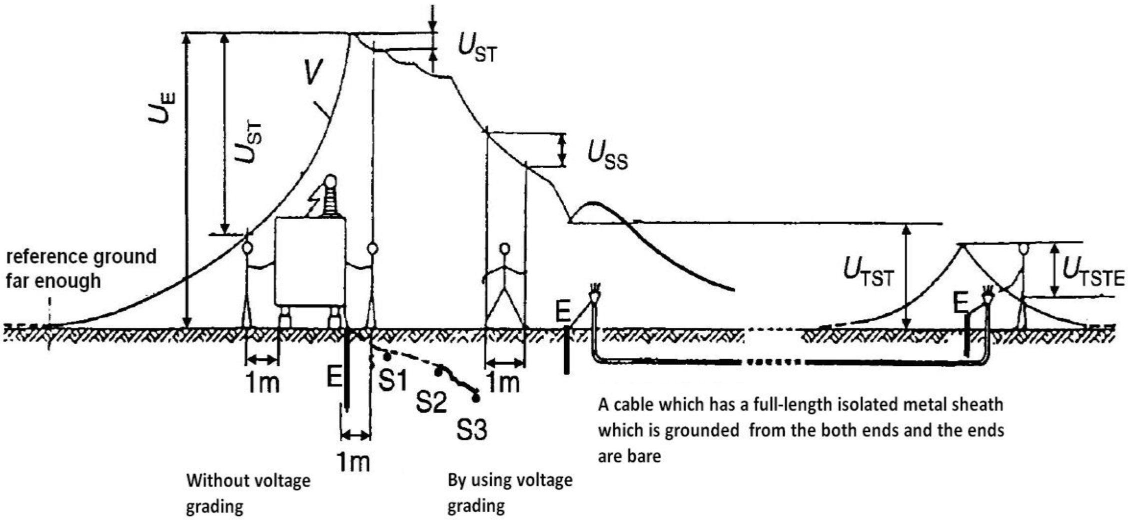


Figure 4.1: Hazard voltages [14]

4.2.2 Present touch voltage requirements

In practice, only touch voltages are observed and step voltages are not taken into account. According to SFS 6001, permitted touch voltages are obtained from Figure 4.2. The figure presents the voltage between a bare hand and bare foot. The curve is based on the fact that the effect of the electric current on human body depends on the magnitude and duration of the current. [14]

According to SFS 6001, earth faults must be disconnected automatically or manually. In normal cases, automatic tripping functions are used. The manual disconnection method can be used if the nature of network usage demands that interruption must be postponed. In these cases, an earth fault alarm must be used and following rules must be met. [14]

- Network structure is that kind that arcing faults are improbable. In addition, the network must be cabled. If the network consists of overhead lines, arcing faults must self-extinguish.

- In earth fault situations, the alarm must be given and the supervisor of network usage must be informed. Fault detection must begin immediately. If it is not obvious that the fault would cause immediate danger to human beings or property or cause unreasonable disturbances to other apparatus, electricity distribution can be continued for two hours. The use of the network can be continued for a longer time if the fault is localized and it is confirmed that the fault does not cause any danger. If the fault is on a distribution transformer station, which is not a part of wide earthing system, the use of the network must be interrupted.

- The earth potential rise must be below the allowed long-term value and however under 150V.

- Requirements of telecommunication networks must be taken into account.

When the magnitude of the earth fault current is determined, exceptional connection situations must be taken into account. However, short-term situations can be ignored. When fault durations are calculated, the proper functioning of protective relays and switching devices must be observed. According to SFS 6001, touch voltage requirements are fulfilled when another of the following conditions (C1 & C2) is met: [14]

C1: Installation is a part of wide earthing system

C2: The earth potential rise is measured or calculated. In addition, it is lower than the touch voltage of Figure 4.2 multiplied by two. ($U_E = 2*U_{TP}$)

If the above mentioned requirements are not fulfilled, special measures must be met. These measures are discussed in Appendix D of SFS 6001. If low and medium voltage earthing systems are separate, condition C2 can be applied by using an additional resistance. This resistance takes into account the resistance of footwear and surface materials. In these cases, the earth potential rise is allowed to be larger because condition C2 is followed but the additional resistance is observed in the curve of Figure 4.2. If conditions C1 and C2 are not fulfilled and the special measures are not performed, the earth potential rise must usually be proved by measuring. [14]

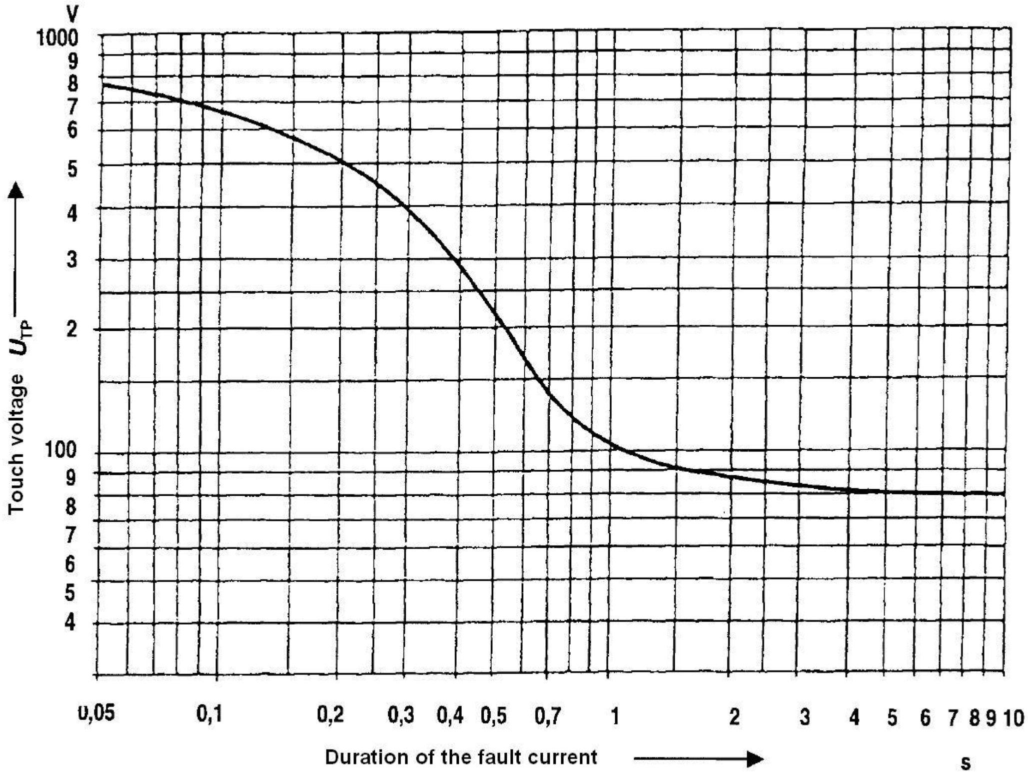


Figure 4.2: Permitted touch voltage as a function of fault duration [14]

4.2.3 Old safety regulations

According to the decision of the Finnish Ministry of Trade and Industry, the present safety regulations were taken in the use in 2.1.2000. Older electrical equipment do not need to be modified to fulfil the present regulations if they do not cause mortal danger, danger to health or danger to people’s property. Therefore, when evaluating touch voltages in equipment built before the year 2000, the old safety regulations can be used. Essentially, these regulations have been in the force since 1974. The new regulations which must be used in networks built after the beginning of the year 2000 are for the most part harder to fulfil. Consequently, higher touch voltage values are allowed when the old regulations can be applied.

According to the old electrical safety regulations, earth potential rise caused by a single phase to ground fault is not allowed to cause dangerous touch voltages at the switch plant or in places where people frequently moves and stays. Earthed systems or the system parts which have conductive connection to earthed systems are divided in following groups (a…e). The division is based on safety risks caused by generating touch voltages in systems.

a) Equipment has a part which is protective earthed and can be touched from the ground or from a corresponding footwall.

b) The protective earthed parts of the system cannot be touched from the ground or from a corresponding footwall. The protective earthed parts can simultaneously be touched with other parts that have a conductive connection to the ground, for example by climbing on a transformer column.

c) The earth electrode is located under the ground surface.

d) The protective earth and the system earth of a low voltage system are connected together and the low voltage system is at least partially located on the outside of the high voltage earthing system.

e) The low voltage earthing system is exposed to the voltage of the high voltage system. In the case of common pylons a medium voltage conductor can touch a low voltage conductor, a carrier cable or a metal shield of the low voltage system (case e1). In the case of insulation faults the voltage can transfer to the low voltage system between the windings of medium/low voltage transformers (case e2).

Table 4.1: Permitted earth potential rise [14]

Group	Earth potential rise V	
	Earth fault is automatically disconnected in time t(s)	Earth fault is not disconnected automatically
a	$750/\sqrt{t}$	125
b	$2000/\sqrt{t}$	250
c	$3000/\sqrt{t}$	400
d	$500/\sqrt{t}$	100
e_1	$750/\sqrt{t}$	125
e_2	$100/\sqrt{t}$	150

Table 4.1 presents allowed earth potential rises for the different earthing groups (a…e_2). As can be seen from the table, the faster the tripping time is higher earth potential rise is permitted. Table 4.1 also presents permitted earth potential rise values for cases where the earth fault is not automatically disconnected.

4.3 Phase-earthing and safety regulations

4.3.1 Influence of phase-earthing on touch voltages

In normal situations, the magnitude of the direct earth fault current determines the maximum touch voltage value. As can be seen from (4.4), the other affecting factor is the earth resistance of the fault point. When the faulty phase is connected to the ground, the fault current substantially decreases in most of the cases. The reduced fault current decreases the generating touch voltage value, respectively.

Although the phase-earthing has usually reducing effect on the residual fault current, inverse impacts are also possible. This is because phase-earthing constitutes a parallel path for the load current to flow through the earth circuit as described in Section 3.4. This part of the load current flows through the fault point back to the line and is thus increases the residual fault current value. This kind of behaviour is problematic because the current of the fault point might be larger than the actual earth fault current of the network. This is possible especially when the load current is large.

When the introduction of the phase-earthing system is contemplated, the maximum residual fault current must be estimated. After the network calculations are carried out, the loads of medium voltage feeders are known. When the faulty phase is earthed most of the earth fault current flows to the ground via the PECB at the substation. For this reason, the capacitive part of the residual fault current is small and without the effect of the load current the residual fault current value would not be more than 10% of the normal earth fault current value. However, this is only a rough estimation and the increase of the phase-earthing resistance increases the capacitive part of the residual fault current. However, in many cases, the maximum load current determines the maximum residual fault current value. Furthermore, the residual fault current value determines the generating touch voltage value.

The residual fault current can be estimated by using equation (3.1). When carrying out the calculation, the real impedance of the considered feeder must be used. As can be seen from Figure 3.3, the residual fault current increases when the length of the feeder increases. However, in a real situation, the load current divides between the branches of a feeder and gets smaller when the length of the feeder increases.

The maximum residual fault current can be estimated by choosing a heavily loaded feeder that has a relatively large load current when approaching the end of the line. The calculation is done with a part of the line which begins from the substation and ends to a point where the load current still has a significant value. This part should be as branchless as possible because the branches are ignored in the calculations. The calculated part is assumed to be a branchless line which has a single load in the end of the line. Furthermore, the fault is assumed to occur close to the load point.

The examination is performed as described because the residual fault current increases when the length of the line increases. On the other hand, if there would be two parallel lines that have an equal length and load current but the different cross-sections of conductors, the thinner line would have a larger residual fault current value. The growth of the line impedance increases the residual fault current because a larger part of the load current flows through the earth circuit. [8]

If it is not clear which feeder is going to have the largest residual fault current, all potential cases must be studied. For example, there might be many feeders that have almost equal load currents with the maximum load current. Cases of this kind must be evaluated separately. In addition, it might also be reasonable to calculate feeders by using a short part from the beginning of the line. Although the feeder length increases the residual fault current, the load current still has its maximum in the beginning. This way it can be confirmed that the residual fault current does not exceed the normal earth fault current. Furthermore, it is confirmed that phase-earthing does not actually tighten the safety regulations in the network. In Section 5.4, there is an example study made for a real 110/20kV substation. The section also clarifies the calculation of the sequence impedances which are needed for the use of equation (3.1).

Residual fault current calculations are reasonable to implement by varying the load current value and the earth fault current value. The ranges of variation must be chosen based on real current values and the upper limits should not be exceeded in the real network. In this way, the estimate for the largest residual fault current value can be found. When the earth resistances of earthing points are known, the earth potential rise can be calculated by using (4.4). After the calculation, the fulfilment of the safety regulations can be observed. The safety regulations are discussed in Section 4.2.

Although it would be confirmed that the residual fault current does not attain the normal earth fault current, the generating earth potential rise must still be evaluated by using the normal earth fault current value. This is because the normal earth fault current flows through the fault point for a short time before the faulty phase is connected to the ground. The safety regulations do not recognize cases where the fault current value varies during a fault. For this reason, the phase-earthing method does not give any reliefs from the safety regulations point of view.

4.3.2 Sufficient phase-earthing time

When the earth potential rise of a medium voltage network area is determined, the required tripping times for the earth fault current must be specified by following the safety regulations which are described in Section 4.2. Although these requirements must be fulfilled, the tripping time must be long enough from the phase-earthing point of view.

The demanded phase-earthing time depends on the self-extinction properties of electric arcs in the particular network. In phase-earthing situations, the faulty feeder is not disconnected and the arc extinction demands a longer time compared to de-energized situations. Although inequality (4.3) is debatable in phase-earthing situations, it can be seen that most of the faults need at least 100ms time to extinguish. Depending on the cause of a fault, the clearance of the fault causing factor increases the demanded phase-earthing time. In phase-earthing systems, which have been used in France, the faulty phase was earthed for 200ms [8]. In Finnish operating conditions the phase-earthing time of 200-300ms might be needed [8].

According to (4.2), the ratio of the residual fault current and the original earth fault current determines the value of key parameter of extinction. The growth of the parameter increases the arcing time. According to (4.3), the maximum arcing time grows along with the second power of the key parameter of extinction. Based on (4.3), the maximum arcing time of 300ms allows the residual fault current to be 9% of the original earth fault current. Magnitudes of this kind might be attainable when the phase-earthing system is used. In general, electric arcs extinguish more easily when the faulty phase is connected to the ground. Phase-earthing assists the arc extinction because the voltage of a fault point reduces when the faulty phase is connected to the ground.

4.4 Phase-earthing and conventional earth fault protection

Earth fault protection must guarantee the selective tripping of a faulty feeder. Relay settings for the zero sequence current, the neutral point voltage, and the operate delay must be well-defined. Normally, the zero sequence current setting is based on the minimum earth fault current value. The minimum value can be calculated based on the minimum size of the galvanic connected background network. In addition, the maximum fault resistance, which needs to be detected, must be used in the calculation. Each medium voltage feeder must be considered case-specific.

The neutral point voltage setting is based on the maximum size of the galvanic connected background network. This is because the neutral point voltage increases when the capacitance of the network decreases. In addition, the maximum fault resistance must also be used in this consideration.

The operate delay is based on the generating earth potential rise in the network. The delay must be chosen in such a way that the safety regulations are fulfilled. Earth potential rise calculations are based on the maximum earth fault current and the earth resistance data of the network. The maximum earth fault current is calculated based on the maximum size of the galvanic connected background network and the fault resistance of 0Ω must be used when the maximum earth fault current is estimated.

The tolerance of the phase angle difference between the neutral point voltage and the zero sequence current depends on the earthing manner of the network. In compensated networks, the operating zone is usually wide-ranging but in neutral isolated networks it can be quite small.

Earth fault protection is usually backed up with a busbar earth fault relay [1]. This kind of relay is based on the neutral point voltage. If the relay of the faulty feeder does not give a tripping command for the circuit-breaker, the busbar earth fault relay trips all the outgoing feeders. However, the tripping is usually performed in two steps. First, the feeders which have high defect density and the least important feeders are disconnected. If the neutral point voltage still exists, the rest of the feeders are tripped off. If there is still a fault when all the outgoing feeders are disconnected, the fault is in the busbar. In this situation, the incoming feeder is tripped off and the whole substation is without power supply.

When a phase-earthing system is installed on a medium voltage busbar, relay settings must be revised. During phase-earthing, the zero sequence current felt by the relay of a faulty feeder is small compared to normal earth fault situations. This is because a major part of the capacitive fault current flows to the ground via the PECB.

The small amplitude of the zero sequence current is one problem. In addition, a part of the load current that flows through the earth circuit has also effect on the fault current measured by relays. Because the zero sequence current is measured by summing the phase currents, the load current component that flows through the ground affects the measured sum current. The effect intensifies when a larger part of the load current flows through the ground. The phenomenon also affects the measured phase angle between the zero sequence current and the zero sequence voltage.

For these reasons, phase-earthing might be a problem for conventional protective relays but earth fault protection must be reliable although the phase-earthing method is used. The proper functioning of relays must be revised and present relays must be renewed if they are unable to perform the task.

4.4.1 Basic problems

The main problem between earth fault protection and a phase-earthing system is the resetting and re-starting operations of relays. Essentially, earth fault protection can operate in two different ways. In the first method, the relay of the faulty feeder stays in the picked up the whole phase-earthing time. In the other method, the relay stays in the normal state when the faulty phase is connected to the ground.

That kind of functioning where the relay might pick up or might not pick up must be prevented. In this case, it is not possible to guarantee that the tripping function is carried out in a demanded time. If the relay starts and then resets, the tripping function is delayed. In the worst case, the relay does not re-pick up until the phase-earthing time has passed. In this case, the time between the occurrence of the fault and the tripping function is the sum of the phase-earthing delay, the phase-earthing time, the start time of the relay and the operate delay.

Another problem is to accommodate the operating delay of the PECB, the phase-earthing time and the operate delay of earth fault protection together. The functioning of the PECB might take for example about 0,3 seconds. In some of the cases earth faults might have to be tripped off faster than the delay of the PECB. In these cases the phase-earthing method cannot be used. In addition, the allowed fault duration must be long enough to include the phase-earthing cycle.

Usually relays have two set stages for earth fault protection: a low-set stage and a high-set stage. Normally, the low-set stage is only used. When the phase-earthing system is taken into use, the high-set stage can also be useful. After two different relay setting methods are discussed in Sections 4.4.2 and 4.4.3, the use of the high-set stage is discussed in Section 4.4.4.

4.4.2 Earth fault protection stays picked up

If the ambition is that relays stay picked up the whole phase-earthing time, the minimum zero sequence current value must be determined. During phase-earthing, the zero sequence current might only be a few percent of the value that the relay detects when the faulty phase is not earthed. For this reason, it might be necessary to set the current setting to its minimum but it is also possible that relays are not sensitive enough. The conversion ratio of current transformers affects the smallest detectable zero sequence current value. The larger the conversion ratio, the smaller current can be detected. In theory, network asymmetry sets the lower limit for the current setting.

Different relays have different measurement principles. Some relays have separated zero sequence current, zero sequence voltage and phase-angle conditions for starting. However, some other relays monitor $I_0\sin\varphi$ and $I_0\cos\varphi$ magnitudes. In these cases, it might be hard to keep the relay picked up during phase-earthing because a small current amplitude is multiplied by a trigonometric function.

The phase-angle between the zero sequence current and the zero sequence voltage might fluctuate when the faulty phase is connected to the ground. This kind of behaviour was observed in field tests which are discussed in Section 5.3.2. The zero sequence current pointer can fluctuate on both sides of the zero sequence voltage pointer. The deviation can be even more than 90° from the characteristic angle. If the zero sequence current pointer is out of the operating zone for long enough, the relay resets. This kind of behaviour might prevent relays to stay picked up when a faulty phase is earthed.

If earth fault protection is expected to stay picked up during phase-earthing, there must be a sufficient marginal between the relay settings and the minimum zero sequence current value. In normal cases, the minimum value for each feeder can be estimated based on the minimum earth capacitance of the background network. This capacitance is needed in equation (2.5). In addition, the earth fault current is needed for the use of (2.5). The earth fault current can be calculated by using (2.1) or (2.2). In this calculation, the maximum fault resistance, which needs to be detected, must be used. However, the minimum zero sequence current is much smaller when the faulty phase is connected to the ground. It can be approximated to be at most 10% of the normal state value. In practice, it might be reasonable to measure the zero sequence current in a phase-earthing situation. The measurements would also reveal the behaviour of the angle between the zero sequence current and the zero sequence voltage.

When the phase-earthing system is used, earth faults must be tripped as fast as in normal situations. As discussed in Section 4.3.1, the phase-earthing method does not give any reliefs from the safety regulations point of view. Figure 4.3 illustrates operating time characteristics in a case where earth fault protection stays picked up when the faulty phase is connected to the ground. The operate delay of the low-set stage is denoted by t>, the phase-earthing time is denoted by t_{PE} and the operate delay of the backup protection, which trips the feeding connection of the whole substation, is denoted by $t_{BU.}$ The sufficient phase-earthing time is already discussed in Chapter 4.3.2. In this case, the operate delay of each relay actually determines the effective phase-earthing time of each feeder. The effective time is denoted by t_x in Figure 4.3. If the PECB is wanted to be opened when t> has passed, t_{PE} must set to be equal with $t_{x.}$ The relay of the PECB feeder bay must be set to trip the feeder faster than $t_{BU.}$ Otherwise the PECB might cause the tripping of backup protection if the PECB-device locks for some reason.

When an earth fault occurs, earth fault protection starts and stays picked up although the faulty phase is connected to the ground. If the fault has not vanished, the relay gives a tripping command after t>. However, if the relay resets during phase-earthing and re-starts when the PECB opens, the fault duration is t_{delay} + t_{PE} + t> instead of t>. In addition, the delay of the feeder circuit-breaker must be added in these times. When this earth fault protection method is used, it must be confirmed that the relay does not reset if the fault still exists. Otherwise, the safety regulations are violated when the resetting occurs.

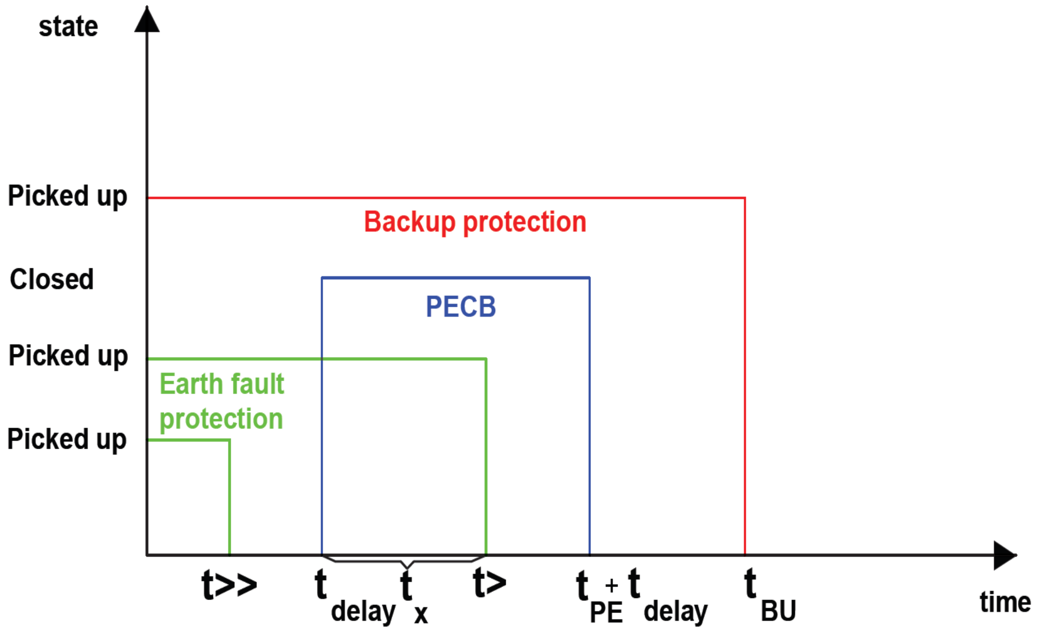


Figure 4.3: Earth fault protection stays picked up in phase-earthing situations

4.4.3 Earth fault protection starts after phase-earthing

Another way to execute the cooperation between a phase-earthing system and earth fault protection is illustrated in Figure 4.4. Now earth fault protection resets when the faulty phase is connected to the ground and re-starts after the PECB opens. However, the re-starting occurs only if the fault still exists. When this method is used, the time between the occurrence of the fault and the line tripping is the sum of the phase-earthing delay, the phase-earthing time and the operate time of earth fault protection. If the fault disappears during the phase-earthing, the normal use of the network is continued.

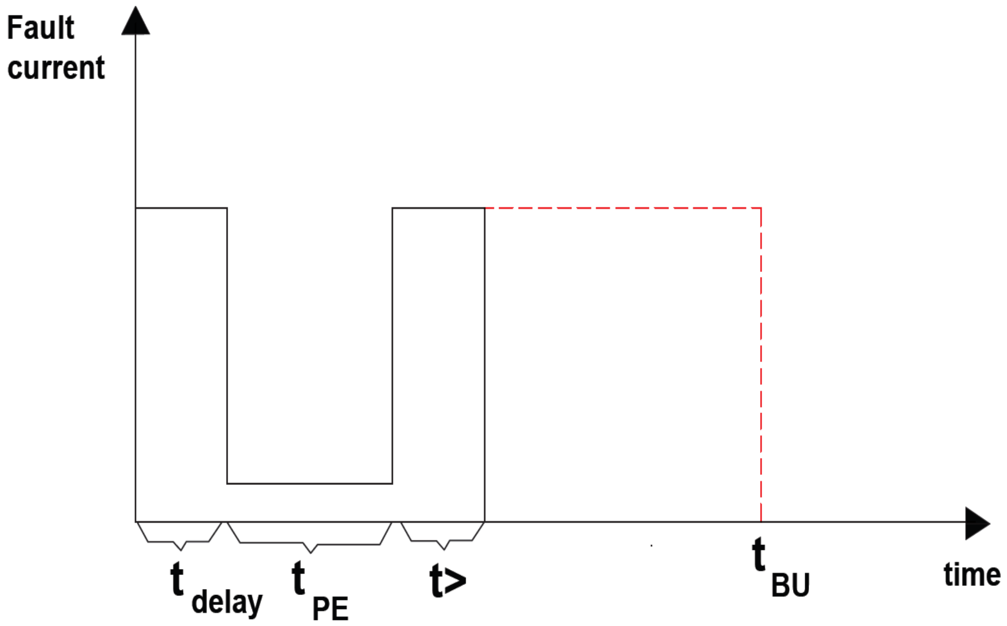


Figure 4.4: Earth fault protection picks up after the phase-earthing.

When a relay is meant to operate as described above, the current setting must be higher than the maximum zero sequence current felt by the relay during the phase-earthing. However, the setting must be low enough the guarantee the tripping in normal use situations. Earth fault protection settings can be determined by using normal methods. The minimum fault current value for each feeder is calculated based on the minimum size of the galvanic connected background network. This kind of examination is done in Section 5.5.

The main problem of this method is that it might not be possible to set the current setting high enough to guarantee the resetting of the relay. The maximum zero sequence current of a phase-earthing situation might be larger than the minimum zero sequence current that needs to be detected. If the relay does not reset, the consequence is exclusively a premature line tripping. This does not cause any dangerous situations and the safety regulations are not violated. In addition, phase-earthing substantially reduces the capacitive fault current in most of the cases. In general, small fault resistances are most troublesome.

The operate delay of earth fault protection t> must be longer that the delay of the phase-earthing system t_{delay}. In fact, t> must be at least the sum of the phase-earthing delay and the resetting time of the relay. Otherwise the relay does not have enough time to reset. The time between the occurrence of the fault and the line tripping is the sum of the times $t_{delay,}$ $t_{PE,}$ and t> as can also be seen from Figure 4.4. In addition, the delay of the feeder circuit-breaker must be taken into account. The allowed fault duration must be at least equal to this time. The relay of the PECB feeder bay must be set to trip the feeder faster than $t_{BU.}$ Otherwise the PECB might cause the tripping of backup protection if the PECB-device locks for some reason.

4.4.4 Use of high-set stage

Earth fault protection is usually arranged by using only the low-set stage of relays. However, the high-set stage can be useful to eliminate problems caused by a phase-earthing system. In this section, two different use methods for the high-set stage are presented. The first method can be used when the earth fault protection method of Section 4.4.2 is used. The other method can be used when the earth fault protection method of Section 4.4.3 is used. In the following discussions, the delay of the feeder circuit-breaker is ignored.

As noted above, it might be impossible to confirm that earth fault protection stays picked up during phase-earthing. However, the high-set stage can be used to complete the functioning of relays. If the relay resets during phase-earthing, the fault is tripped by the high-set stage after the PECB opens. The operate delay of the high-set stage t>> is shorter than the delay of the low set stage t>.

When the high set stage is used this way, t_{PE} must be equal with t_x (Figure 4.3).This means that t> is equal with $t_{delay} + t_{PE}$. In cases where the low-set stage resets, the total time delay is t> + t>>. In this kind of use, both t> and t>> must be longer than t_{PE}. Otherwise the relay would give a tripping command before the PECB closes. The resetting time must also be taken into account because the high-set stage must resets when the faulty phase is connected to the ground.

The current setting of the high set stage I>> must be sensitive enough to detect faults after the opening of the PECB. This means that the phase-earthing system is not allowed to function when the capacitive fault current is smaller than I>>. On the other hand, I>> must be rough enough in order that it does not cause tripping when the PECB is closed. This means that I>> must be larger than the maximum zero sequence current felt by the relay during the phase-earthing. For example, if it is known that the maximum value is 3A, the phase-earthing system is not allowed to function in cases where the zero sequence current is less than or equal to 3A before phase-earthing. If the low-set stage resets during phase-earthing and the high-set stage would not be able to start after phase-earthing, the total delay would be t> + t> instead of t> + t>>.

When the fault current is smaller than the minimum operating current of the phase-earthing system, the fault is tripped by the feeder circuit-breaker. The high-set stage operates if there is a gap between I>> and the sensitivity of the phase-earthing system. For example, if I>> is 5A and the phase-earthing system operates when the current is larger than 10A, the high-set stage operates when the capacitive fault current is from 5A to 10A. These faults are tripped in time t>>. In any case, the maximum fault duration is t> because the low-set stage is more sensitive than the high-set stage.

The high-set stage can also be used in another way. It can be used to determine an upper limit for the use of a phase-earthing system. In this kind of use, the high-set stage trips some of the faults before the PECB closes. For example, the upper limit can be based on time $t_{delay} + t_{PE}$ + t>>. When the maximum earth resistance value is known, the maximum current value for the preceding time can be solved. This value is used in I>>. When the high-set stage is used this way, the safety regulations are not violated because large fault currents are tripped before the PECB closes.

When some of the faults are tripped before phase-earthing, t>> must be shorter than or equal to t_{delay}. Otherwise the high-set stage resets when the PECB closes. I>> must be larger than the minimum operate value of the phase-earthing system. If these limits are close to each other, the functioning of the phase-earthing system is very marginal. Another drawback is that faults, which are allowed to be tripped between times t>> and t>, are prematurely tripped in time t>>.

4.4.5 Faulty phase identification in neutral isolated systems

Phase-earthing systems have a separated relay which detects an earth fault and indentifies the faulty phase. In this thesis two different faulty phase identification methods are presented. The both methods are based on the comparison of the phase voltages. The faulty phase can be identified by measuring all the three phase voltages but the actual earth fault is detected by measuring the neutral point voltage. In Fortum's prototype phase-earthing system, the identification is based only on the undervoltage of the faulty phase. The prototype system is discussed more accurately in Chapter 5.

The method that is based on the undervoltage of the faulty phase is simple. During earth faults, the faulty phase voltage decreases depending on the magnitude of the fault resistance. This voltage is denoted by R_fI_f in Figure 4.5. The voltage reduction of the faulty phase increases when the fault resistance decreases. This means that the fault point moves towards neutral point along the circular arch in Figure 4.5. The fault point is the starting point of $\underline{U}_0$-pointer and the neutral point is the arrowhead of $\underline{U}_0$-pointer.

When the undervoltage method is used, the ratio of the faulty phase voltage and the normal phase voltage should not be higher than 0.8 [8]. This is because the faulty phase voltage is actually not the lowest phase voltage when the fault resistance is large. In Figure 4.5, the normal state phase voltages are denoted by U_{ph1}, U_{ph2} and U_{ph3}. The fault state voltages are denoted by U'_{ph1}, U'_{ph2} and R_fI_f, respectively. As can be seen from the figure, R_fI_f increases and both $U'_{ph1}$and U'_{ph2} decrease when the fault resistance increases. When the fault resistance is large enough, U'_{ph1} is actually smaller than R_fI_f. In this kind of situation, the undervoltage based identification method causes the earthing of a healthy phase. Furthermore, this causes a double earth fault to the network.

When the above mentioned voltage condition is used, the fault current value with the fault resistance of 500Ω is about 18A. The corresponding value with the fault resistance of 0Ω is about 30A. This means that the undervoltage method cannot be used if the earth fault current of the network is larger than 30A and fault resistances up to 500Ω need to be detected. As can be seen from Figure 4.6, the neutral point voltage setting could be around 60% in this particular case. Generally speaking, the undervoltage method cannot be used if the phase-earthing system is meant to operate when the fault resistance is large. This is the case at least if the earth fault current of the network is not very small.

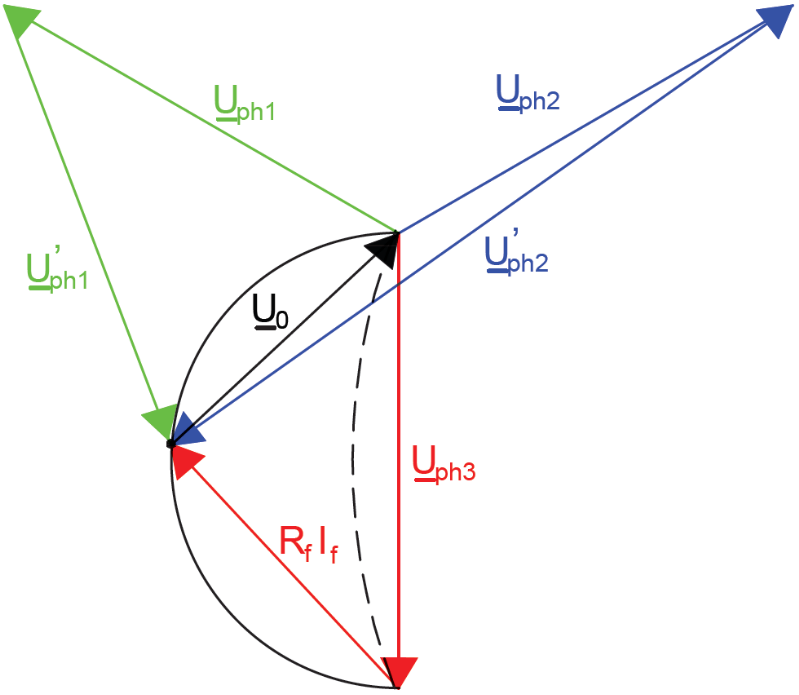


Figure 4.5: Voltages in an earth fault situation

Another relatively simple faulty phase identification method is based on both under- and overvoltages of the phases. The faulty phase is indentified by means of two conditions. There must be undervoltage in the faulty phase. In addition, there must be overvoltage in a healthy phase which is anticlockwise next to the faulty phase. If the overvoltage condition is also used, a wrong phase cannot be earthed as described earlier.

As can be seen from Figure 4.5, when U'_{ph1} is the lowest phase voltage there is still undervoltage in the faulty phase and the overvoltage condition is not fulfilled. In the other words, phase1 cannot be earthed when there is an earth fault in phase3. When this method is used, the neutral point voltage displacement must be at least 15% [8]. This means that the fault resistance of 500Ω can be detected when the earth fault current in a 20kV network is 150A. It can be seen from Figure 4.6 that, for example, the earth fault current of 40A allows the faulty phase identification up to fault resistances of 2000Ω.

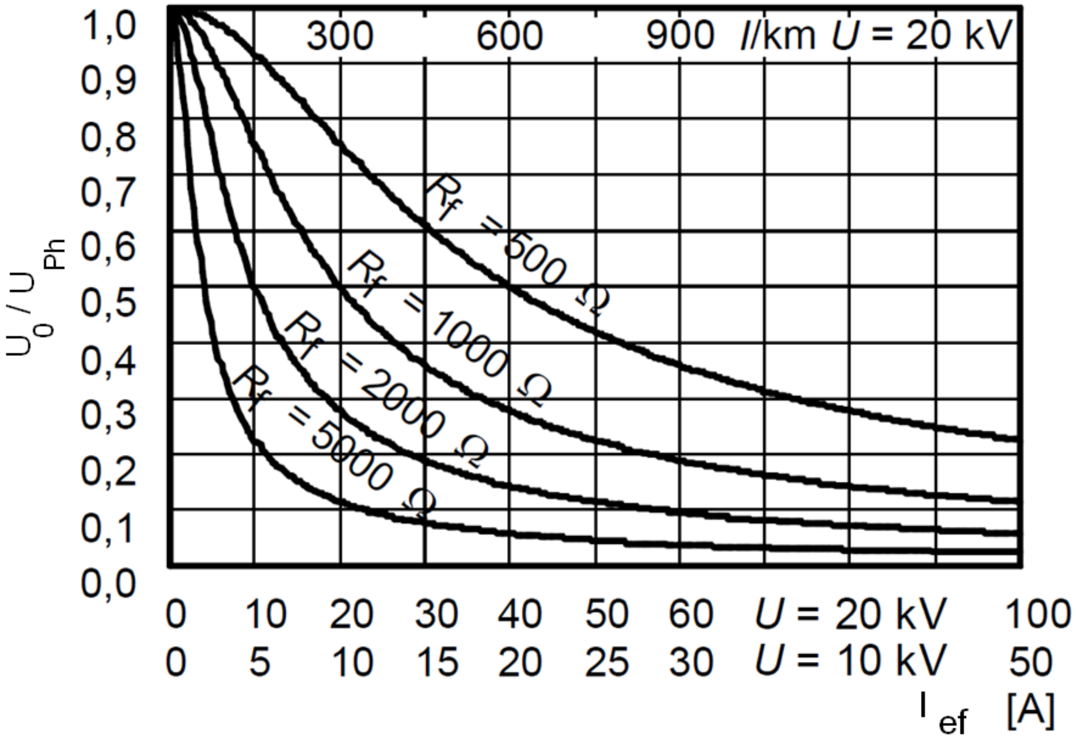


Figure 4.6: The neutral point voltage in a neutral isolated medium voltage network during an earth fault. [17]

4.4.6 Faulty phase identification in compensated systems

In a compensated system, the neutral point voltage is higher than in the corresponding neutral isolated system. This can be seen by comparing equations (2.3) and (2.4). However, the compensation degree of the network and the resistance of the compensation coil affects the magnitude of the neutral point voltage. Figure 4.7 presents the neutral point voltage of a totally compensated system as a function of the earth fault current of the corresponding uncompensated system. In compensated networks, there appears a neutral point voltage in the healthy state of the system [1]. This might cause problems for protective relaying.

In totally compensated networks the faulty phase voltage is always the lowest phase voltage because the fault current is purely resistive [8]. This means that the faulty phase can always be identified by using the undervoltage method. In real terms, medium voltage networks are either under- or overcompensated. However, the undervoltage method, which is described in Section 4.4.5, can be used with a higher voltage ratio than the mentioned 0.8.

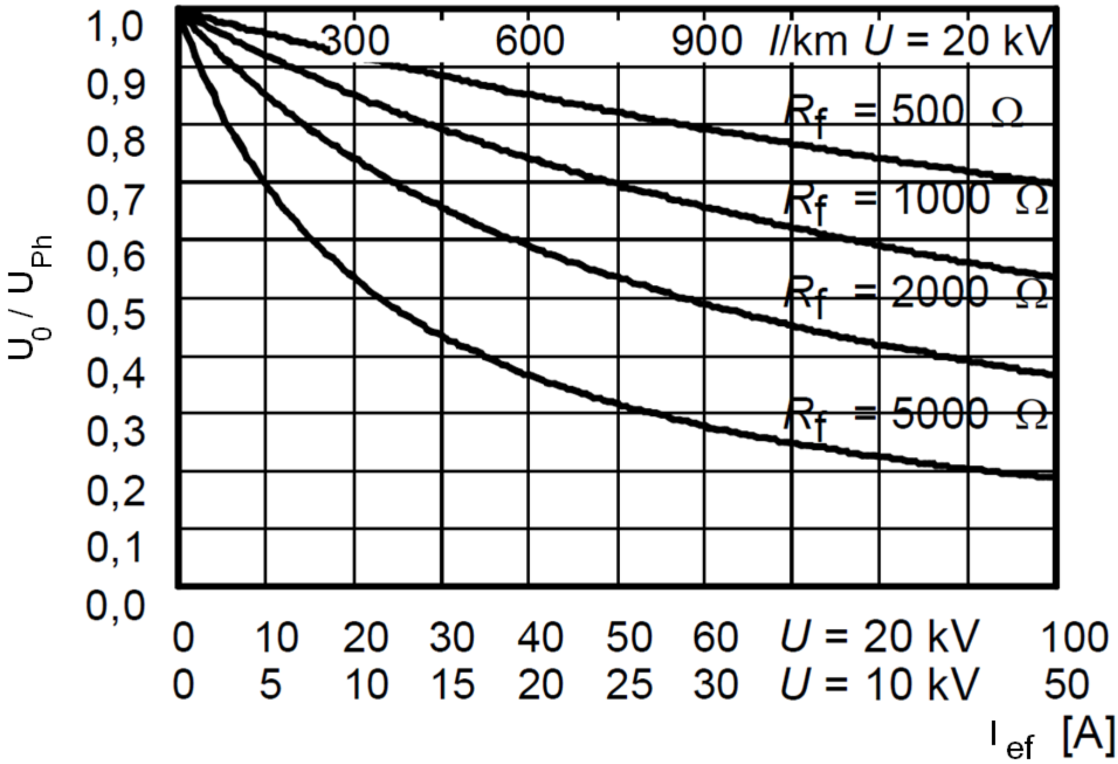


Figure 4.7: The neutral point voltage of a compensated medium voltage network as a function of the earth fault current of the corresponding uncompensated system. [17]

If the faulty phase identification method based on both under- and overvoltage is used, the under- or overcompensation of the network must be observed. In neutral isolated networks the fault point moves along the circular arch when the voltage pointers are drawn and the fault resistance is changed. In partially compensated systems the arc changes between the circular arch and a straight line. The straight line presents the totally compensated network. In Figure 4.5 the dashed arc presents an undercompensated system. If the system would be overcompensated, the dashed arc would be mirrored across the U_{ph3}-phasor.

4.5 Conclusions

When the phase-earthing system is used to reduce the number of high speed automatic reclosing functions, a sufficient phase-earthing time is needed to give an electric arc a sufficient time to self-extinguish. The minimum phase-earthing time is 0,2s but in reality 0,3s might be needed. The growth of the phase-earthing time increases the self-extinction probability of earth faults.

The safety regulations determine the maximum earth fault duration and the time depends on the maximum earth potential rise. Although the phase-earthing method would substantially reduce the residual fault current, the generating earth potential rise must be estimated by using the normal earth fault current value. This is because the normal earth fault current flows through the fault point for a short time before the faulty phase is connected to the ground. The safety regulations do not recognize cases where the fault current alternates during the fault. The phase-earthing time cannot either be interpreted as a separate fault because in this kind of situation two fault durations would be summed. For this reason, the phase-earthing method does not give any reliefs from the safety regulations point of view.

On the other hand, it cannot be assumed that the maximum residual fault current and the normal earth fault current are equal. If the load of the faulty feeder is large enough, the residual fault current exceeds the original earth fault current value. Before taking the phase-earthing system into use, it must be confirmed that the safety requirements are fulfilled in the case of the maximum residual fault current. If it can be proved that the residual fault current does not reach the original earth fault current value, the use of the phase-earthing system does not affect allowed fault durations.

Because of the safety regulations, the phase-earthing system can only be utilized when the earth fault current is small. Otherwise the maximum earth resistance value must be very small. In Finnish conditions, the small earth resistances are hard to attain. In addition, the improvement of earthings is expensive operation.

The high-set stage of earth fault protection can be used to trip large fault currents before the PECB closes. In this kind of use the phase-earthing system functions when the fault current value is below the current setting of the high-set stage. However, it must be remembered that the faulty phase identification sets the lower limit for the use of the system.

The growth of the earth fault current weakens the faulty phase identification. Especially, this might be a problem when the undervoltage method is used. For example, only fault resistances up to 500Ω can be detected when the earth fault current of the network is 30A. When the earth fault current value is 15A, fault resistances up to 1kΩ can be detected, respectively.

The phase-earthing method might cause problems for earth fault protection. The main problem is the small capacitive fault current in the faulty feeder when the PECB is closed. However, the high-set stage can be used to back up the low-set stage. If the low-set stage resets during the phase-earthing, the high-set stage trips the fault after the PECB opens. This way the high-set stage guarantees the operating rate and the low set stage guarantees the sensitivity.

5 Prototype phase-earthing system

Fortum Sähkönsiirto Oy has a prototype phase-earthing circuit-breaker device installed to a high/medium voltage substation called Kalkulla. The substation is neutral isolated and it has nine medium voltage feeders. The line departures are divided between two galvanic separated busbars which both are fed by own 110/20kV transformer. The PECB is connected to another busbar. Physically the device is located in a distribution transformer substation cell on the substation area.

At the moment, the prototype phase-earthing system is not in the use. This chapter has aim to indicate and analyse inconveniences related to the introduction of the system. The main points have proved to be the fulfilment of the safety regulations and the proper functioning of protective relays.

5.1 Devices and implementation

The PECB-device is created by modifying Noja Power's OSM27-203 recloser so that each of the three phases can operate separately. This is executed by removing a camshaft which normally connects all three phases together and produces the three phase operation of the device. After the modification, the recloser can operate single-pole because there are separated magnetic actuators in each phase. The rated maximum voltage and the rated maximum current of OSM27-203 are 27kV and 630A, respectively. The fault break capacity of the device is 12,5kA and it has a mechanical durability for 30 000 full load operations. The break capacity should be large enough to break the short-circuit fault current.

The electronics of the prototype system include VAMP 255 protective relay, Siemens's programmable logic controller (PLC), two Semikron's six pulse controllers and IGBT transistors. The open and close pulses of the PECB are produced by the PLC. The transistors are connected to the output stage of the logic circuit and they are controlled by the IGBT-controllers. Pulse widths are trimmed to respond the normal control pulses of the recloser device.

5.1.1 Faulty phase identification

The faulty phase is indentified by the relay of the PECB. In the prototype system, VAMP 255 feeder manager is used. The relay is capable to make three voltage measurements and in this case these channels are used to measure the phase voltages. Voltage measuring coils are connected to a star-connection and the relay compares the measured phase voltages to the zero sequence voltage calculated by the relay.

The comparison between the phase voltages and the calculated U_0 is done by means of AND-condition. There is threshold values set for the zero sequence voltage and the phase voltages. When an earth fault occurs, the faulty phase voltage decreases and the zero sequence voltage increases. The increase of the fault resistance reduces the zero sequence voltage and the voltage drop of the faulty phase. For this reason, the threshold values determine the maximum fault resistance that can be indicated. When both separate voltage conditions are fulfilled, the AND-condition is fulfilled and the relay has indentified the faulty phase.

As described in Section 4.4.5, this undervoltage based faulty phase identification method is not reliable when the fault resistance is large. If the healthy phase is connected to the ground, there is a double earth fault in the network. In this kind of situation the fault current is larger than in a normal earth fault situation. The relay of the PECB feeder bay can be used to disconnect the PECB in double earth fault situations. However, if proper settings for the faulty phase identification are used, double earth faults can be avoided.

5.2 Earth fault protection of Kalkulla substation

In Kalkulla, ABB's feeder terminals SPAC 531 C1 are used. SPAC 531 C1 includes overcurrent relay module SPCJ 3C3, earth fault relay module SPCS 3C4, control module SPTO 6D3 and few other modules which are used among others for data transmission and measurements. The control module includes automatic reclosing automatics which enable five sequential high speed/delayed automatic reclosing functions. Each automatic reclosing function can be set into action by three different start signals given by the earth fault module or the overcurrent module. These signals can either be starting or tripping signals given by the protective relay modules. [15]

SPCS 3C4-module, which is responsible for earth fault protection, operates based on the active or reactive zero sequence current measurement. In addition, it monitors the zero sequence voltage value. The relay starts when both operation conditions are fulfilled. The zero sequence voltage must exceed the set value and $I_0\cos\varphi$- or $I_0\sin\varphi$-measurement must exceed the set value. In addition, the angle between the zero sequence current and the zero sequence voltage must be on the operating zone. In Kalkulla $I_0\sin\varphi$-characteristic, which is the reactive zero sequence current characteristic, is used because the medium voltage network is neutral isolated. [16]

SPCS 3C4 has two different set stages for directional earth fault protection. Setting ranges for the current settings, the operate delays and the voltage setting are shown in Table 5.1. Notation > refers to the low-set stage and notation >> refers to the high-set stage, respectively. I_n and U_n are the nominal current of the relay and the nominal voltage of the relay, respectively. The typical starting delay of the relay is 150 ms and the typical resetting time of the relay is 100ms. These delays are same for both set stages. [16]

Table 5.1: Earth fault protection setting ranges for SPCS 3C4.

Setting	**Setting range**
I>	1…10%*I_n
t>	0,1…1,0 s or 1…10 s
I>>	1…8%*I_n or 5…40%*I_n or ∞
t>>	0,1….1,0 s
U_0	2%, 5%, 10% or 20%*U_n

It is possible to programme a self-hold for a pick-up indicator and for a tripping indicator. This means that a pilot light stays on although the signal which caused the activity decreases below the set value. The low-set stage can only operate in the forward direction but the high-set stage can be programmed to operate either the forward direction or the backward direction. [16]

5.2.2 Present earth fault protection settings

Present earth fault protection settings are shown in Table 5.2. I>-values in amperes are primary values. For this reason, a percentual I>-value is received when the corresponding ampere value is divided by the conversion ratio of a cable type current transformer and this value is compared to the nominal current of the relay. As can be seen from the table, current settings are equal in all feeder terminals and the high-set stage is not in use.

Table 5.2: Earth fault protection settings of Kalkulla substation

Feeder	Conversion ratio	I_n [A]	I> [A]	I> [%]	t> [s]	basic angle [deg]	angle of action [deg]	U_0 [%]	U_0 [V]
J04	40/1	1,0	0,8	2	0,6	90	90	20	2300
J05	40/1	1,0	0,8	2	0,6	90	90	20	2300
J06	40/1	1,0	0,8	2	0,5	90	90	20	2300
J07	40/1	1,0	0,8	2	0,5	90	90	20	2300
J10	40/1	1,0	0,8	2	0,8	90	90	20	2300
J11	40/1	1,0	0,8	2	0,5	90	90	20	2300
J12	40/1	1,0	0,8	2	0,9	90	90	20	2300
J13	40/1	1,0	0,8	2	0,9	90	90	20	2300
J14	40/1	1,0	0,8	2	0,5	90	90	20	2300

5.3 Tests and measurements

The prototype phase-earthing system has been tested in field tests. The tests were carried out by causing artificial earth faults on feeder J05 Linkulla. In the experiments, the fault resistance was roughly zero because earth faults were made by connecting a phase conductor directly to the groundings of a disconnector station called Linkulla. The length of feeder J05 is about 25km and it was unloaded during the experiments.

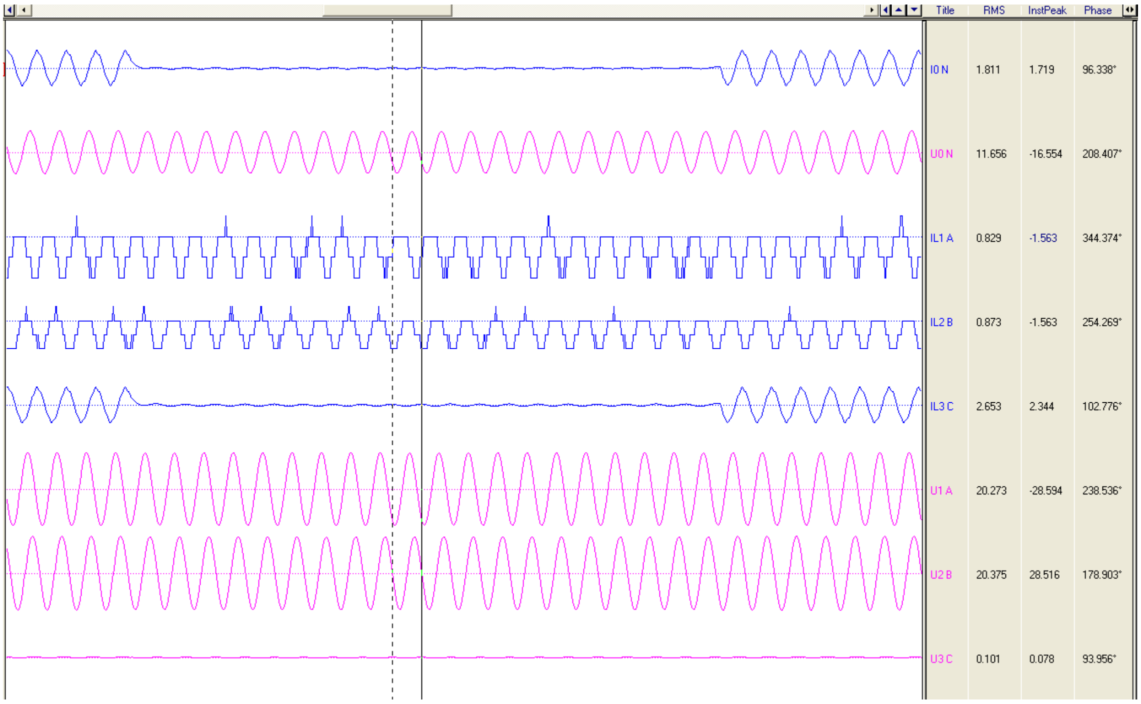
The tests were carried out by causing earth faults in all the three phase conductors. The distance between the disconnector station and the substation is about 8km. The earth resistance of Linkulla disconnector station is 10,3Ω. The functioning delay of the PECB was 300ms and the faulty phase was earthed for 400ms. The operate delay of earth fault protection was set to be 1,0s. Other earth fault protection settings were not changed.

The system has also been tested in commissioning tests. These tests were similar with the above mentioned field tests but fewer measurements were carried out. In both field and commissioning tests, collected test data includes disturbance recordings recorded by the feeder terminal of the faulty line departure and disturbance recordings recorded by the feeder terminal of the PECB feeder bay. In the field tests, the fault current and the faulty phase voltage were also measured in the fault location.

5.3.1 Measurement results

In the commissioning tests, the fault current measured by the feeder terminal of the faulty feeder was about 40 A before the faulty phase was connected to the ground. The corresponding value in the field tests was 36A. According to PowerGrid network data system, the direct earth fault current value of the network is about 35A. Differences in the earth fault current are a result of different switching states in the galvanic connected medium voltage network.

When the PECB connects the faulty phase to the ground, the current measured by the feeder terminal of the faulty feeder substantially decreases. During the phase-earthing, the value of the capacitive fault current was on the average 7 % of the current which was measured before the faulty phase was connected to the ground. The value alternated between 4% and 11% and after the PECB was opened the current increased to the same level as it was before phase-earthing. Figure 5.1 presents an example disturbance recording. In the figure, the current of the faulty phase is denoted by IL3C and the faulty phase voltage is denoted by U3C, respectively.



Title	RMS	InstPeak	Phase
I0 N	1.811	1.719	96.338°
U0 N	11.656	-16.554	208.407°
IL1 A	0.829	-1.563	344.374°
IL2 B	0.873	-1.563	254.269°
IL3 C	2.653	2.344	102.776°
U1 A	20.273	-28.594	238.536°
U2 B	20.375	28.516	178.903°
U3 C	0.101	0.078	93.956°

Figure 5.1: Disturbance recording measured by the relay of the faulty feeder

Appendix 1 presents measurement results for the zero sequence current and the zero sequence voltage of the faulty feeder. This data has been collected from disturbance recordings which are similar with the recording of Figure 5.1. The amplitude and the phase-angle values have been picked up on discrete moments. Although only discrete moments are considered, the real behaviour of the zero sequence current is revealed. The results of the date 4.3.2010 are the commissioning test results and the results of the date 29.6.2010 are the field test results, respectively. The measurements are denoted by the combination of a letter and a number. The letter denotes the faulty phase and the number denotes the ordinal number of the measurement. For example, the first measurement in phase X is denoted by X1.

Measurements at the fault location proved that the magnitude of the capacitive earth fault current decreases to a fraction of the original value when the PECB closes. Figure 5.2 presents the current measurement of the fault point when the PECB closes and opens. As can be seen from the figure, the fault current is small when the PECB is closed. After the PECB opens, the current grows to the same level as it was before phase-earthing.

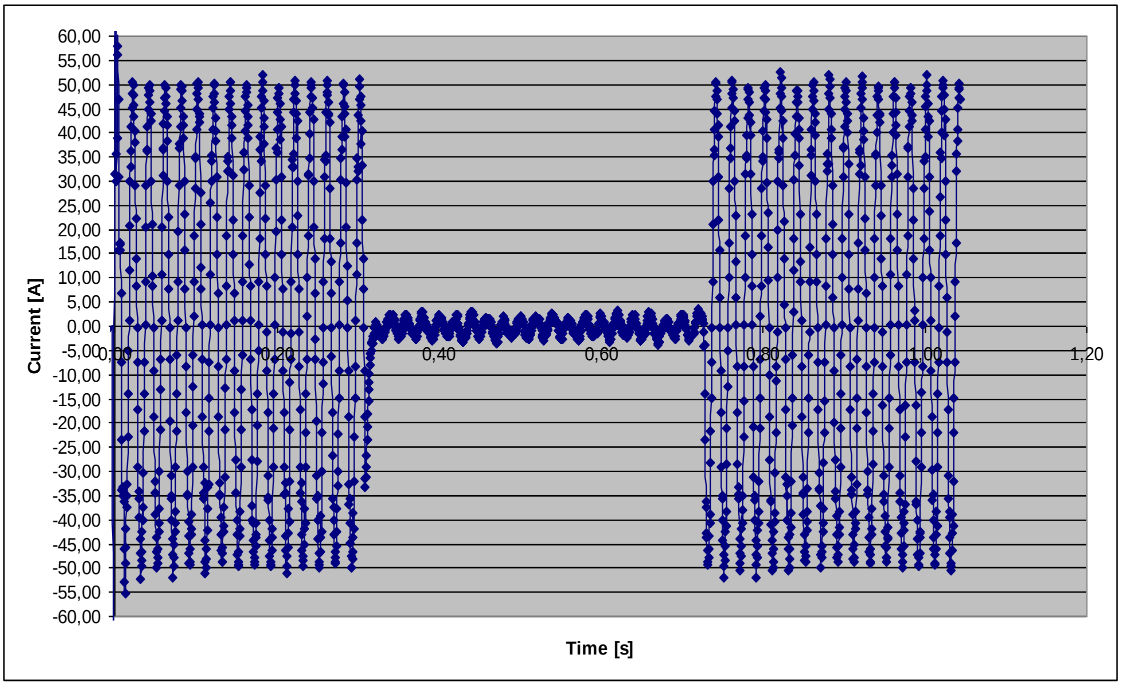


Figure 5.2: The current of the fault point in a phase-earthing situation.

Figure 5.3 presents the voltage of the fault point in the phase-earthing situation. As can be seen from the figure, the voltage behaves the same way as the current does when the faulty phase is connected to the ground. The voltage over the fault point is small when the PECB is closed. After the PECB opens, the voltage increases to the original level.

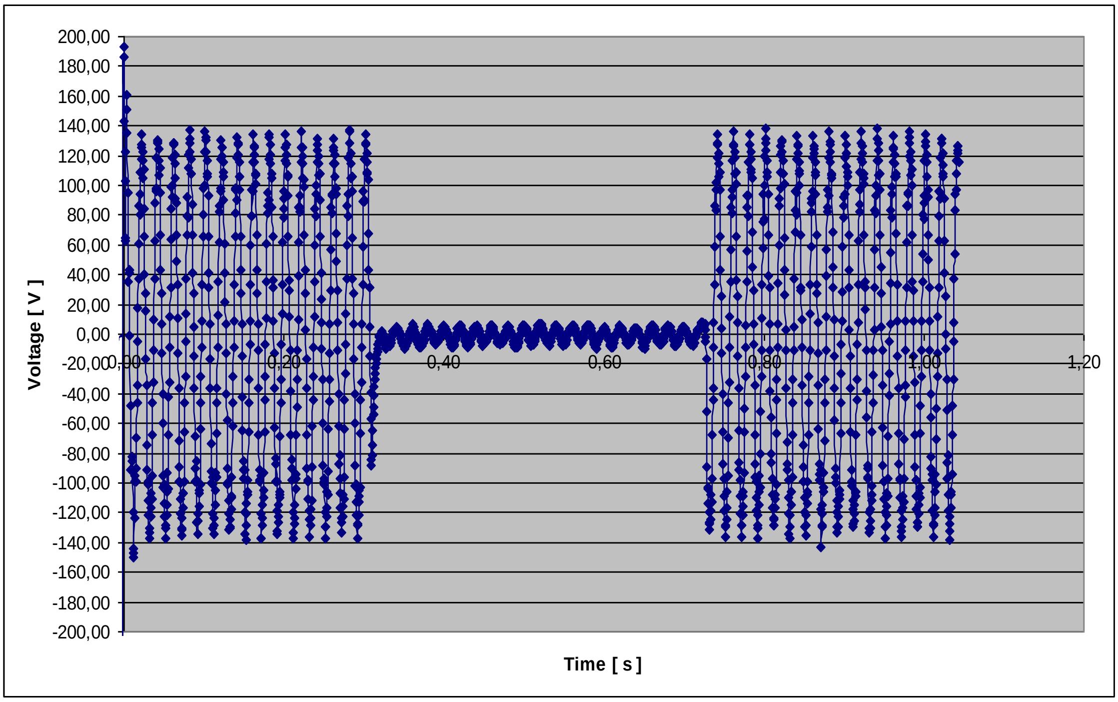


Figure 5.3: The voltage of the fault point in a phase-earthing situation.

5.3.2 Functioning of earth fault protection

When the disturbance recordings of field and commissioning tests are examined, it can be noticed that the relay of the faulty feeder does not operate properly in all the cases. In both tests, the operate delay of earth fault protection was set to be 1,0s. However, the tripping did not occur at the right moment in some of the measurements. In these cases the functioning of the feeder circuit-breaker took place about 1,7-1,8s after the fault emergence. When the relay operated properly, the tripping occurred before 1,1s had passed. The malfunction cases are presented in Table 5.3. The measurements are denoted as described in the previous section.

Table 5.3: Earth fault protection malfunctions

Measurement	**Date**	**Tripping time [s]**
Y1	29.6.2010	1,80
Y2	29.6.2010	1,75
Y3	29.6.2010	1,76
Y1	4.3.2010	1,74
Y2	4.3.2010	1,68
Y3	4.3.2010	1,76
Z1	4.3.2010	1,80
Z2	4.3.2010	1,76
Z3	4.3.2010	1,77

The circuit-breaker action falls behind because the relay of the faulty feeder resets during phase-earthing. The resetting occurs because an operational condition is not fulfilled for a long time enough. The typical resetting time of SPCS 3C4 relay module is 100ms [16]. Because the delay of the PECB is 0,3s and the phase-earthing time is 0,4s, it can be concluded that the re-starting of the relay has occurred immediately after the PECB has opened. In these cases, the tripping takes about 1,8s. In any case, this kind of functioning is problematic as discussed in Section 4.4.

In Appendix1, the text “fail” in the last column refers to a case where the tripping function did not occur at the right moment. These events are the same as the cases in Table 5.3. When the values of Appendix1 are considered, it is noticed that the reactive zero sequence current component (column $I_0\sin\varphi$) decreases below the current setting of earth fault protection exactly in these particular cases. For this reason, the relay resets and the functioning of the feeder circuit-breaker is delayed.

As can be seen from Table 5.2, the current setting of the low-set stage is 0,8A. For this reason, the reactive zero sequence current must be larger than 0,8A in order that the relay would not reset. However, it can be seen from Appendix1 that the pure amplitude of the zero sequence current (column I_0) decreases to the level of 0,8A. When amplitudes are multiplied by the sine function, the result is even smaller. The value of the sine depends on the argument of the function which is the angle between the zero sequence current and the zero sequence voltage.

Figure 5.4 presents the fluctuation range of the phase angle difference φ in the tests. The maximum deviations are shown in red in the figure. In normal earth fault situations, the value of φ should be 90°. As can be seen from Figure 5.4, φ alternates between values $\varphi = -4^\circ$ and $\varphi = 173^\circ$ when the faulty phase is connected to the ground. However, it can be seen from Appendix1 that the value of φ is quite accurately 90° before the phase-earthing.

When **I**$_0$-pointer is parallel with the basic angle-axis φ=90º. In these cases, the reactive zero sequence current component is equal with **I**$_0$-pointer because sin90º = 1. However, when φ differs from φ_0, the sine function decreases the reactive zero sequence current component. For example, when φ=173º, the zero sequence current amplitude should be at least 6,7A in order that the reactive component would be 0,8A. This is because sin173º≈ 0,12 and 0,12*6,7A = 0,8A. However, the maximum amplitude is 3,4A as can be seen from Appendix1. In addition, it can be seen that the reactive zero sequence current component is so small that the relay would not stay picked up although the minimum setting, which is 0,4A, would be used. Furthermore, the operating zone cannot be expanded sufficiently.

In both tests, each phase was tested three times and the behaviour of the angle was similar in each set of three measurements. However, the zero sequence current behaves differently when the fault is done in another phase. In any case, it can be noticed that these particular relays cannot stay pick up when the faulty phase is connected to the ground. As mentioned in Section 4.4, the load current component, which flows through the ground, affects the measured sum current. For this reason, the phase angle difference might behave even more incorrectly compared to a normal earth fault situation when the effect of the load current increases.

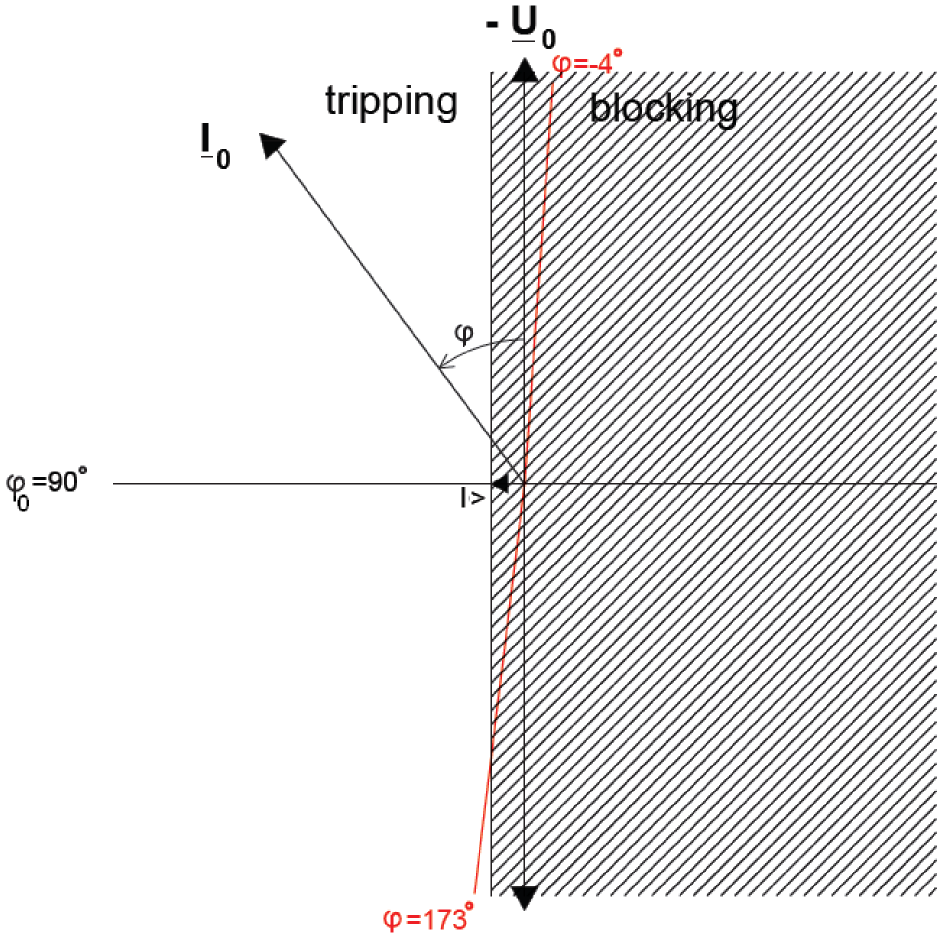


Figure 5.4: The behaviour of φ in the tests

5.4 Estimation of residual fault current

The maximum residual fault current must be estimated in order that the fulfilment of the safety regulations can be confirmed when a phase-earthing system is used. The subject is discussed on a general level in Section 4.3.1. In this case, feeder J11 was chosen to be used in the calculations that prove the maximum magnitude of the residual fault current. The phase-earthing system is connected to the busbar of transfomer2. Feeders fed by transformer2 are the non-shaded rows in Table 5.3. As can be seen from the table, feeder J11 has clearly the highest load current value in the galvanic connected network.

Table 5.3: The peak load of Kalkulla substation

Feeder	Power [kW]	Current [A]	Maximum Voltage Drop [%]
J04	1031	29,9	1,2
J05	159	4,5	0,2
J06	435	12,6	0,4
J07	472	13,6	0,5
J10	796	23,2	0,5
J11	2521	72,5	2,8
J12	4298	125,0	2,6
J13	3555	104,0	5,3
J14	138	4,0	0,0

The medium voltage network of Kalkulla substation is depicted in Figure 5.5. Different colours present different feeders and J11 is the yellow-brown feeder. As can be seen from the figure, feeder J11 is knotty and it contains a significant amount of cable. In fact, the cabling is the main reason for the relatively large earth fault current.

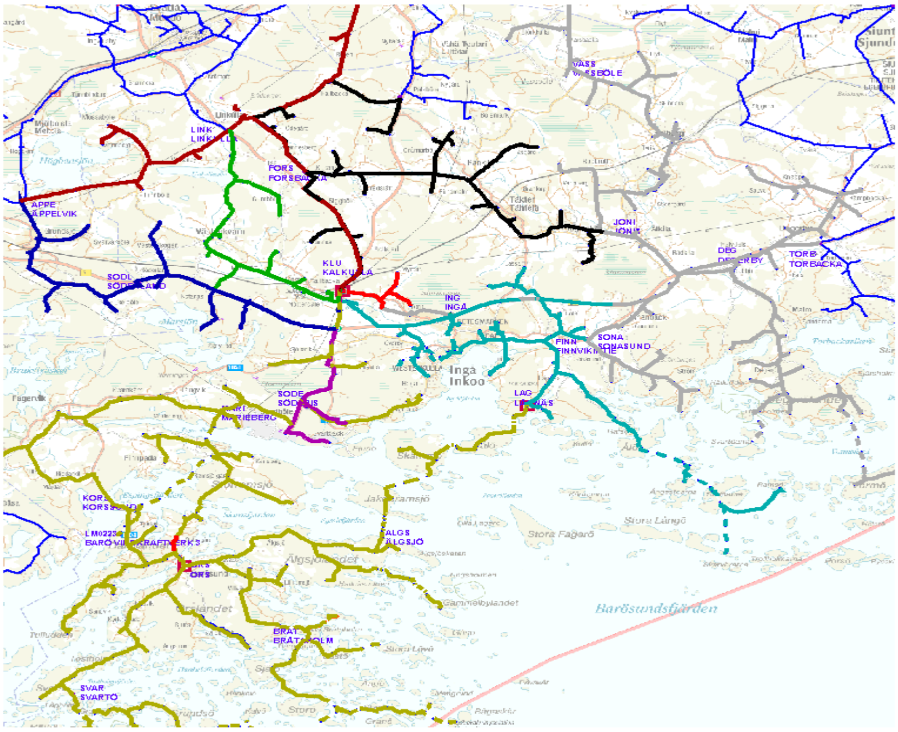


Figure 5.5: The medium voltage network of Kalkulla substation

The part of feeder J11, which is used in the calculations, is shown in red in Figure 5.6. The part is chosen in such a way that the load current is still relatively large at the end of the part. The distribution of the load current is also sketched in Figure 5.5. As can be seen from the figure, the value is 33A at the end of the part. This means that roughly half of the load locates downstream from the considered part. The length of the part is approximately 13km and roughly 10% of the length consists of cables.

In addition, the residual fault current is also calculated by using the first 4,5km part of feeder J11. This is done because the load current is largest close to the substation. In Figure 5.6, this part can be seen as a line between Kalkulla substation and Söderis disconnector station. In practice, this part consists entirely of overhead lines. As can be seen from Figure 5.6, the load current is 65A at Söderis disconnector station.

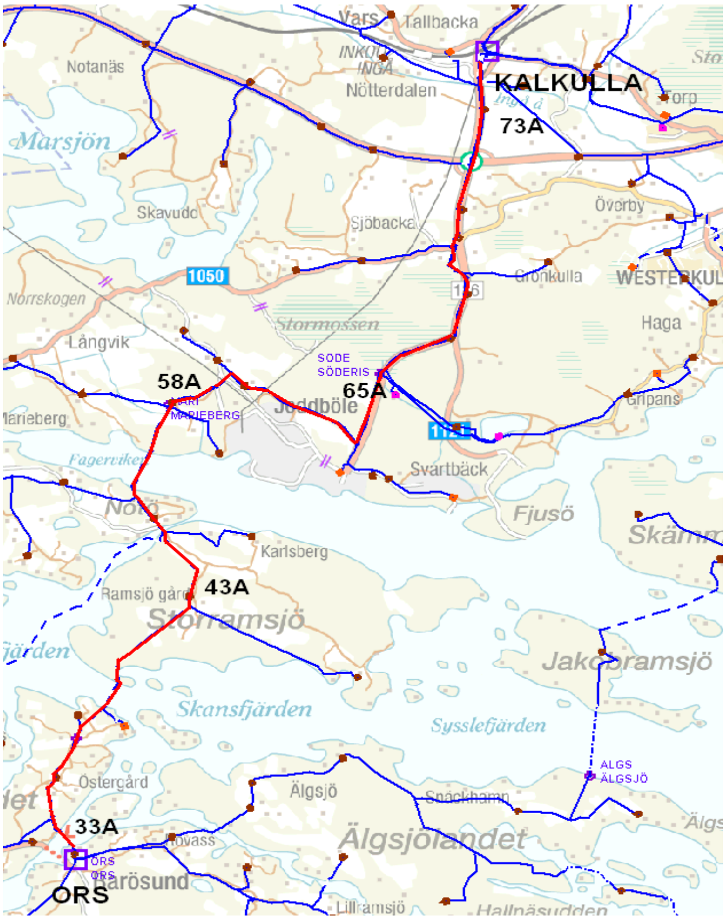


Figure 5.6: The part of feeder J11 which is used in calculations

5.4.1 Sequence impedance calculations

The residual fault current is calculated by using (3.1). For this reason, the positive sequence impedance and the zero sequence impedance of the considered line must be determined. First, the partial impedances of different conductor types and cables must be calculated. After this, the total impedance is calculated by summing the partial impedances. The positive sequence impedance is equal with the normal resistance and reactance values of the line. The resistive part of the zero sequence impedance of an overhead line can be calculated by adding 0,15Ω/km to the normal phase resistance value [3]. The reactive part can be calculated by using equations (5.1) and (5.2) [3].

In (5.1), a_{ij} is the distance between phase conductors i and j, r_{eq} is the equivalent radius of a wiring loom and $\mu_0 = 4\pi*10^{-7}$ Vs/Am is the permeability of vacuum. When a phase conductor does not consist of partial conductors $r_{eq} = R_p*e^{-1/4}$ where R_p is the radius of the phase conductor. In (5.2) f is the frequency used in the network and ρ is the resistivity of the soil. In this thesis, the resistivity value ρ = 2300Ωm is used.

$$x_0 = \frac{\omega\mu_0}{2\pi}\ln\frac{H_{eq}^3}{r_{eq}\sqrt[3]{a_{12}^2 a_{23}^2 a_{31}^2}} \tag{5.1}$$

$$H_{eq} = 0{,}7386*\sqrt{\frac{\rho}{f\mu_0}} \tag{5.2}$$

The central rope of a cable and the resistance of the earth circuit (0,15Ω/km) are parallel connected. The reactive part of the zero sequence impedance of a cable is calculated by using (5.3) [22].In this equation D is the mean diameter of metallic covering and GMD is the geometric mean diameter.

$$x_0 = 0{,}434*\log_{10}\left(\frac{D}{GMD}\right)\ \ [\Omega/\text{km}] \tag{5.3}$$

As can be seen from Figure 5.2, the peak-to-peak value of the residual fault current was about 6A in the field tests of the PECB. The corresponding effective value is 2,1A. The earth fault current of the network is approximately 35A which can also be seen from Figure 5.2. Before phase-earthing, the peak-to-peak value of the fault current is 100A which is equivalent with the effective value of 35A.

The residual fault current can be estimated by using (3.1). The sequence impedances of this particular line can be calculated as described above. The results are $\underline{Z}_1$ = (2,4+j2,5)Ω and $\underline{Z}_0$ = (3,6+j16,3)Ω. Other needed parameters are: R_f =0Ω, $R_L = \infty$ (no load), R_S = 0,43Ω (the earth resistance of Kalkulla substation), $1/\omega C_0$ = 1014Ω (the earth fault current of 35A) and U = 20500V. The result given by (3.1) is 2,0A. This result is uniform with the measured value and it shows that the calculated impedances are acceptable.

5.4.2 Calculation results

Calculation results for the above mentioned parts of feeder J11 are presented in Appendix 2. Figures 5.7, 5.8, 5.9 and 5.10 present the results graphically. Parameters, which were used in calculations, are shown in Table 5.4. The calculations were carried out by varying the earth fault current and the load current. The earth fault current can be varied by changing the earth capacitance C and the load current can be varied by changing the load resistance R_L. The phase-to-phase voltage of 20,5kV was used and the phase-earthing resistance of 0,43Ω, which is the earth resistance of Kalkulla substation, was used.

Table 5.4: Calculation parameters

	J11 (4,5km)	**J11 (12,8km)**
$\underline{U}$	20,5kV	20,5kV
$\underline{Z}_0$	(1,6+j7,7)Ω	(5,8 + j10,2)Ω
$\underline{Z}_1$	(1,0+j1,4)Ω	(4,3+j3,9)Ω
R_S	0,43Ω	0,43Ω
R_f	0Ω	0Ω

As can be seen from Figure 5.7, the earth fault current does not have significant impact on the residual fault current when the length of the line is 12,8km. The impact of the earth fault current can only be seen when the load current is very small. Figure 5.8 shows that the residual fault current increases in a linear fashion when the load current increases. The angular coefficient is approximately 0,7A/A but the coefficient is not valid when the load current is very small. It can also be seen from Figure 5.8 that the earth fault current dominates before the load current is large enough. In the real situation, the earth fault current is 35A and the load current is 33A.The corresponding residual fault current value is 23A. The residual fault current exceeds the normal earth fault current when the load current is larger than 50A. For this reason, there is a margin of 17A between the peak load current and this load current value.

When the length of the line is 4,5km, the earth fault current value has a greater effect on the residual fault current. The effect can be seen by comparing Figures 5.7 and 5.9, which present the residual fault current as a function of the earth fault current. When the line is shorter, a smaller part of the load current flows through the earth circuit. For this reason, the earth fault current has relatively larger impact on the residual fault current. Figure 5.10 presents the residual fault current as a function of the load current. It can be noticed that the residual fault current starts to increase in a linear fashion when the load current is large enough. In this case, the angular coefficient of the linear growth is approximately 0,4A/A. This also proves the smaller impact of the load current because the corresponding value in the case of 12,8km line was 0,7A/A. As can be seen from Figure 5.10, the residual fault current at the Söderis disconnector station is 26A when the earth fault current is 35A and the load current is 65A. The residual fault current exceeds the normal earth fault current when the load current is 86A. For this reason, there is a margin of 21A between the peak load current and this load current value.

In summary, it can be concluded that the residual fault current does not exceed the normal earth fault current on feeder J11. Consequently, the earth fault current is not exceeded anywhere in the network because J11 is the most potential feeder where the earth fault current can be exceeded. The peak load current should grow 17A in order that the residual fault current would exceed the normal earth fault current. For this reason, there is a margin for errors. For example, the soil resistivity might fluctuate widely and cause errors to the calculated zero sequence impedances. In addition, the model itself causes an error to calculation results.

It must be remembered that the residual fault current was only estimated in the normal operating situation of the network. In reserve feeding situations, the current might be significantly larger because of different earth capacitance and different load. In this thesis, it is assumed that the phase-earthing system is only used in the normal operating situation of the network.

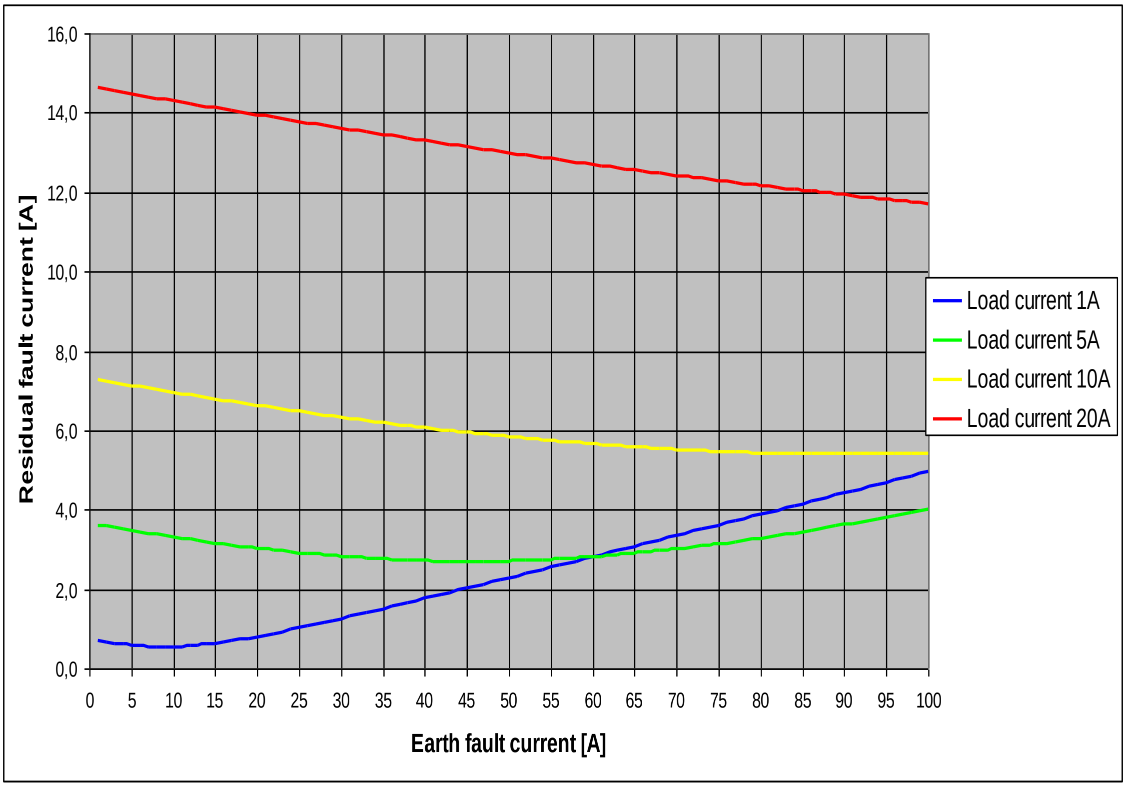


Figure 5.7: The residual fault current as a function of the earth fault current. Feeder J11, length 12,8km

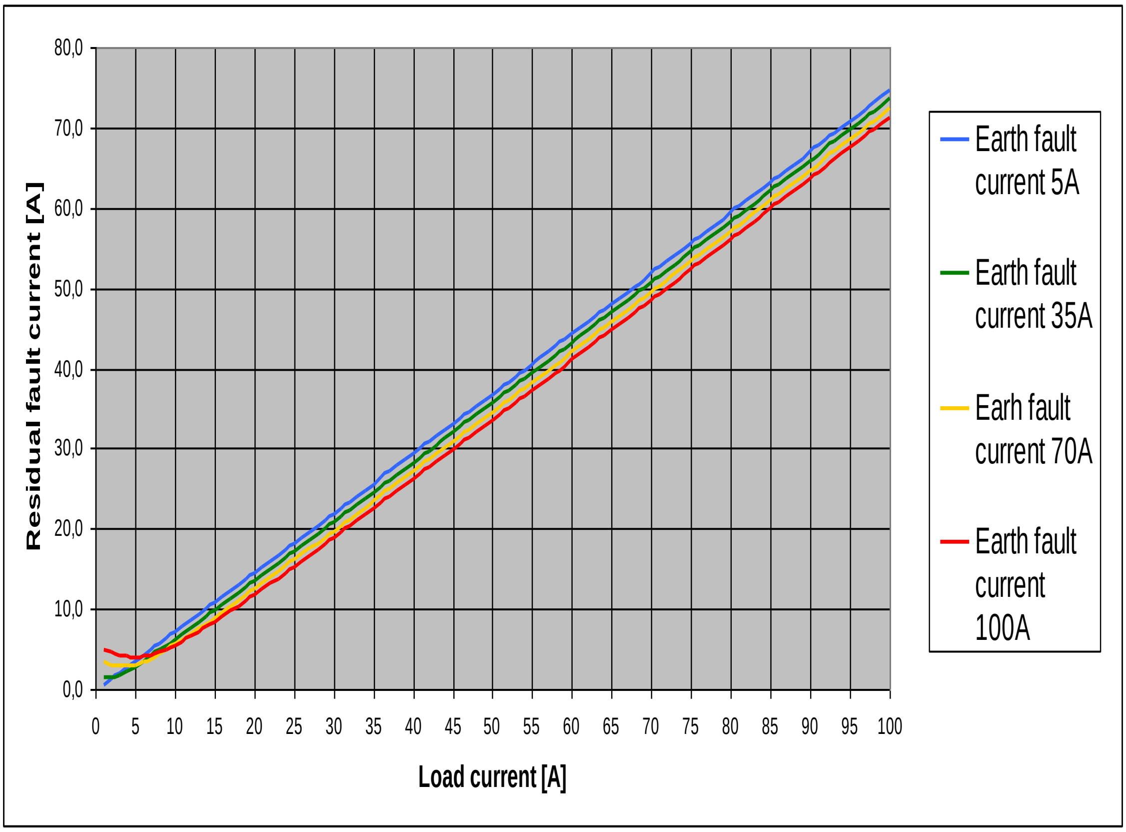


Figure 5.8: The residual fault current as a function of the load current. Feeder J11, length 12,8km

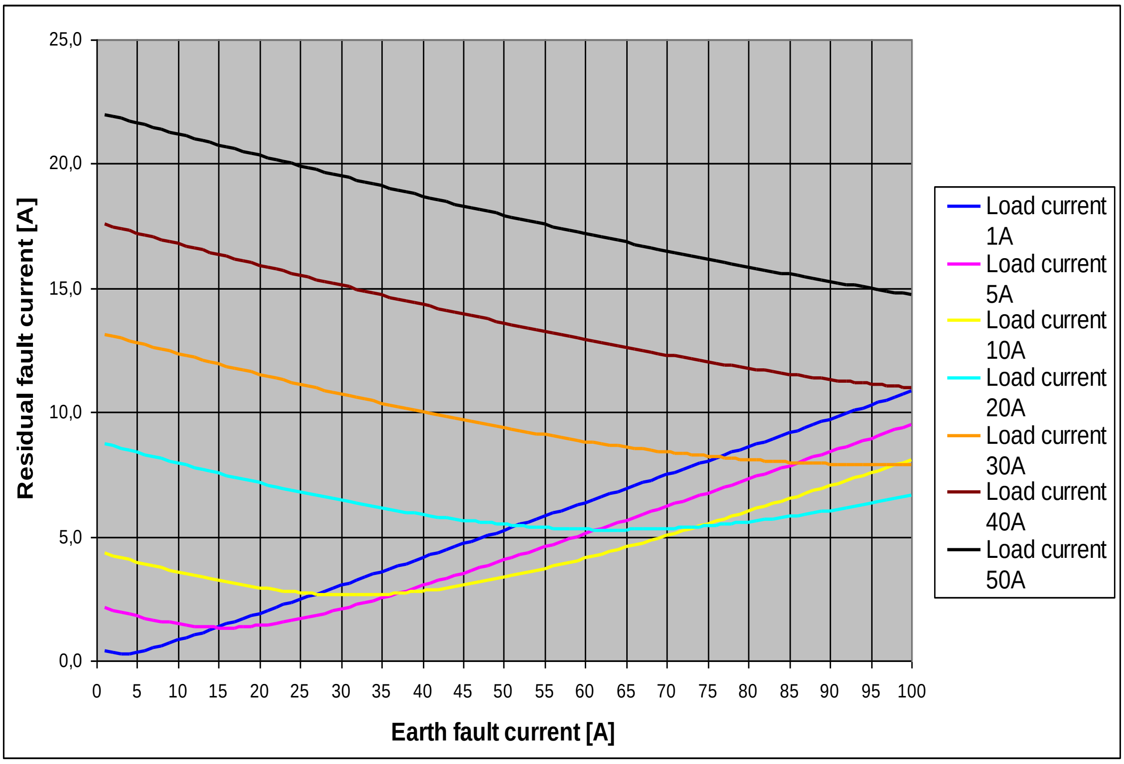


Figure 5.9: The residual fault current as a function of the earth fault current. Feeder J11, length 4,5km

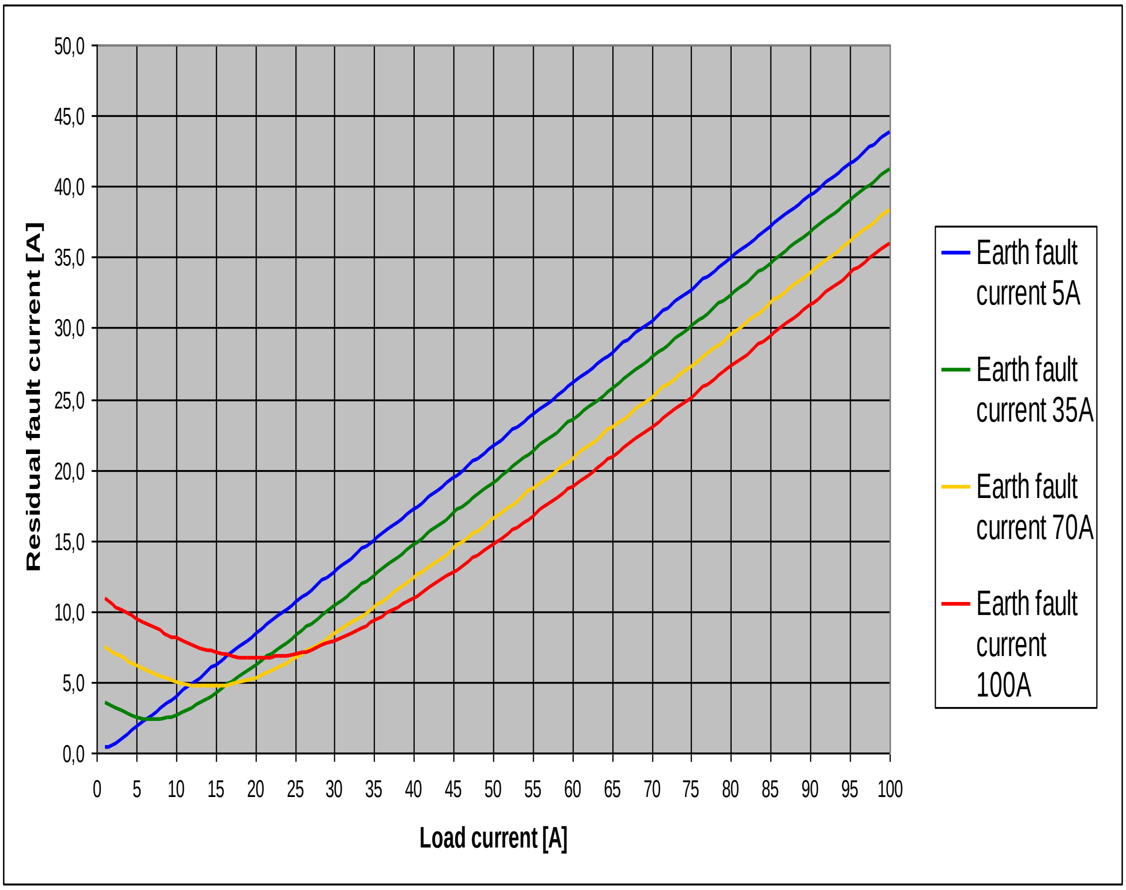


Figure 5.10: The residual fault current as a function of the load current. Feeder J11, length 4,5km

5.5 New earth fault protection settings - alternative 1

As observed in Section 5.3.2, it is not possible that earth fault protection would stay picked up during phase-earthing. For this reason, it is studied if it is possible to change relay settings in such a way that relays would pick up after the phase-earthing time. This kind of operation is described in Chapter 4.4.3. It must be examined if the current settings can be magnified. For this reason, the minimum zero sequence current for each relay is clarified. Earth fault protection settings are determined as in normal cases where the phase-earthing system is not used. As described in Section 4.4.4, the high-set stage can also be used to trip some of the faults before the PECB closes.

According to the network data of Kalkulla substation, some of the earth resistances are very large. In addition, the earth fault current is relatively large. For these reasons, the earth potential rise is high in some of the earthing points and very short tripping times should be used. In this thesis, it is assumed that the maximum earth resistance is 25Ω and earth fault protection settings are considered based on this assumption.

5.5.1 Fault current calculations

First, the earth capacitance of each feeder must be calculated. The total earth capacitance per phase can be calculated by using (2.1) when the direct earth fault current is known. If impedance is purely capacitive, the current is directly proportional to the capacitance. Consequently, the earth capacitance of each feeder can be calculated from (5.4). In this equation, I_{ej} is the earth fault current generated by feeder j and I_{ef} is the earth fault current generated by the whole galvanic connected network. I_{ej} values are taken from PowerGrid network data system.

$$C_j = \frac{I_{ej}}{I_e} C \tag{5.4}$$

Calculated earth capacitances are shown in Table 5.5. The shaded feeders are fed by transformer1. The other feeders are fed by transformer2 and these feeders form a galvanic connected network. The total earth capacitance can be calculated by summing the capacitances of the galvanic connected feeders.

Table 5.5: Earth capacitances per phase

Feeder	**C_j [nF]**
J04	421
J05	251
J06	305
J07	341
J10	377
J11	1712
J12	273
J13	153
J14	45

As can be seen from Table 5.5, J13 has the smallest earth capacitance in the network of transformer1. Feeder J14 has the smallest capacitance in the network of transformer2, respectively. Table 5.6 presents the earth fault currents in different connection situations. The connections are chosen in such a way that the earth capacitance of the galvanic connected network is the smallest possible. For this reason, situations where only two feeders are connected to the busbar are considered. The fault current is calculated by using (2.1) and the fault resistance in the calculations is 500Ω.

Table 5.6: The smallest fault current values

Connection	**I_f [A] (R_f =500Ω)**
J06 & J12	19,4
J06 & J13	15,5
J14 & J04	5,1
J14 & J05	3,3
J14 & J07	4,2
J14 & J10	4,6
J14 & J11	15,1

The minimum zero sequence current for each relay can be calculated based on Table 5.6. The calculation is performed by using equation (2.5). Calculation results are shown in Table 5.7. As can be seen from the table, the values are small in the network of transformer2 (non-shaded rows). This is because feeder J14 has very small earth capacitance. As can be seen from Table 5.6, J14 forms the background network in cases: J04, J05, J07, J10 and J11. As mentioned earlier, the smallest zero sequence current that can be detected is 0,4A. Table 5.7 shows that it might be reasonable to use 0,4A settings instead of 0,8A settings. In any case, there is no room to magnify the settings.

Table 5.7: The minimum zero sequence current felt by relays

Feeder	**I_r [A]**
J04	0,5
J05	0,5
J06	2,1
J07	0,5
J10	0,5
J11	0,4
J12	2,0
J13	2,6
J14	2,8

If feeder J14 is ignored, feeder J05 has the smallest earth capacitance in the network of transformer2. Table 5.8 presents the minimum zero sequence current for each relay in this situation. As can be seen from the table, the smallest current value is 2,0A and the current settings could be magnified. As can be seen from Appendix1, the maximum reactive zero sequence current component is 3,3A. Because of this, relays would still start in some of the cases when a faulty phase is connected to the ground. On the other hand, the value of 2A is exceeded only in 6 of 18 measurements. Moreover, the fault resistance was 0Ω in the field tests. In real fault situations, the fault resistance is usually larger and this reduces the fault current value.

Table 5.8: The minimum zero sequence current felt by relays when J14 is neglected

Feeder	I_r [A]
J04	2,7
J05	4,0
J06	2,1
J07	2,7
J10	2,7
J11	2,0
J12	2,0
J13	2,6
J14	2,8

5.5.2 Operate times and high-set stage

The delay of the low-set stage must be at least 0,4s. This is because the phase-earthing delay is 0,3s and relays need 0,1s to reset when the PECB is closed. The phase-earthing time of 0,3s is used. When the phase-earthing system operates and the fault does not disappear, it takes 0,3s + 0,3s + 0,4s + 0,1s = 1,1s to trip off the fault. In this calculation, the delay of the feeder circuit-breaker is assumed to be 0,1s.

In earthing group D, the earth potential rise is allowed to be 477V if the fault duration is 1,1s. In practice, this group sets the heaviest demand for the earth potential rise when the old safety regulations are followed. This means that the earth fault current must be smaller than 19A, if the maximum earth resistance is 25Ω. According to the present safety regulations (2xU_{TP} -requirement), 200V earth potential rise is allowed when the fault duration is 1,1s. However, the 2xU_{TP} -requirement is only applied in one earthing point on Kalkulla network area. This point is disconnector station MARI on feeder J11. Because the earth resistance of this point is 19,2Ω, the earth fault current must be smaller than 10,4A.

Because the earth fault current is 35A, the high-set stage is used to trip some of the faults. In the case of feeder J11, the high-set stage must operate when the fault current is larger than 10A. The corresponding current setting is 25%*I_n. In the cases of other feeders, the high-set stage must operate when the fault current is larger than 19A. However, the maximum current setting for the high-set stage is 40%*I_n. For this reason, the high-set stage operates when the fault current is larger than 16A.

The operation delay of the high-set stage is based on the maximum earth fault current. Because the maximum earth resistance is assumed to be 25Ω and the earth fault current is 35A, the earth potential rise is 875V. For this reason, the fault duration is allowed to be 0,32s when the old regulations are followed and 0,25s when the present regulations are followed.

5.5.3 New settings

New earth fault protection settings are presented in Table 5.9. The table includes new settings for the low-set stage and settings for the high-set stage. When the high-set stage is used, the phase-earthing system must be able to identify large fault resistances. This is because the high-set stage operates before the phase-earthing system when the current is larger than 16A (or larger than 10A). The required sensitivity cannot be reached when the undervoltage method is used. For this reason, some other faulty phase identification method should be used. Feeder bay J03 is the PECB feeder bay. The relay of this feeder bay is used to disconnect the PECB in malfunction cases. The operation delay of the backup protection must be changed from 2,0s to 3,0s. This is because the relay of J03 operates in 2,0s.

Table 5.9: New earth fault protection settings

Feeder	I> [A]	I> [%]	t> [s]	I>> [A]	I>> [%]	t>> [s]	U_0 [%]
J04	2,4	6	0,4	16	40	0,3	20
J05	3,6	9	0,4	16	40	0,3	20
J07	2,4	6	0,4	16	40	0,3	20
J10	2,4	6	0,4	16	40	0,3	20
J11	1,6	4	0,4	10	25	0,2	20
J14	2,4	6	0,4	16	40	0,3	20
J03	0,8	2	2,0	-	-	-	20

5.6 New earth fault protection settings – alternative 2

As observed in Section 5.3.2, it cannot be confirmed that earth fault protection would stay picked up during phase-earthing. However, the high-set stage can be used as a backup in case the low-set stage resets. In this kind of use, the high set-stage operates after phase-earthing. In that case, the capacitive fault current has grown to its normal level. The operation delay of the high-set stage is shorter than the delay of the low-set stage. For this reason, the fault is tripped off in a shorter period of time. This kind of use of the high-set stage is described in Section 4.4.4. In Section 5.5, it is assumed that the maximum earth resistance is 25Ω. The same assumption is used in this section.

5.6.1 Low-set stage

In the present situation, the current setting of the low-set stage is 0,8A.This setting is used in all the feeders of Kalkulla substation. Because this setting is functional, it does not need to be modified. However, the operate delays need to be changed. The delay must be long enough to cover the phase-earthing function. The delay of the phase-earthing system is 0,3s. In addition, the faulty phase is connected to the ground for 0,3s. The delay of the low-set stage is determined by summing these two times. For this reason, the operation delay of 0,6s is used.

5.6.2 High-set stage

The operation delay of the high-set stage must be longer than the delay of the phase-earthing system. Otherwise, the high-set stage would trip faults before the PECB closes. In addition, the high-set stage must reset when the faulty phase is connected to the ground. The typical resetting time of SPCS 3C4 relay module is 0,1s. For this reason, the operation delay of 0,4s is used. However, it should be tested that the high-set stage resets in this 0,1s period of time.

If the low-set stage resets and the fault still exists after the PECB opens, the total fault duration is the sum of the phase-earthing delay, the phase-earthing time, the delay of the high-set stage and the operating time of the feeder circuit-breaker. For this reason, the fault duration is 0,3s + 0,3s + 0,4s + 0,1s = 1,1s. In the case of earthing group D, the earth potential rise of 477V is allowed when the fault duration is 1,1s. According to the present safety regulations, the earth potential rise must be lower than 200V if the fault is tripped in 1,1s.

Because the earth fault current is 35A, these earth potential rise values are reached when the earth resistance value is 13Ω and 5Ω, respectively. Conversely, if the maximum earth resistance is 25Ω, the corresponding earth fault currents are 19A and 8A. As noticed, the safety regulations are hard to fulfill although the high-set stage is used. In practice, the earth fault current should be reduced.

The current setting of the high-set stage must be lower than the sensitivity of the phase-earthing system. Otherwise, the high-set stage does not start after the PECB opens if the fault still exists. In this case, a suitable value for the current setting of the high-set stage could be 7A. The setting is large enough to prevent the starting of the high-set stage during phase-earthing because the maximum reactive zero sequence current component was 3,4A in the tests. If the undervoltage based faulty phase identification method is used and the earth fault current is 35A, the minimum operating current of the phase-earthing system is approximately 20A. The current setting of 7A is very adequate in this point of view. However, the safety regulations cannot be fulfilled if the maximum earth resistance is 25Ω.

5.6.3 New settings

New earth fault protection settings are presented in Table 5.10. The high-set stage is used to backup the low-set stage. The phase-earthing system is not allowed to operate when the capacitive fault current is smaller than the current setting of the high set stage. However, this is not a problem if the undervoltage based faulty phase identification method is used. The faulty phase identification sensitivity of 8A is reached when the earth fault current is approximately 13A.

The safety regulations are not fulfilled if the settings of Table 5.10 are used. If the earth fault current would be reduced to 19A, the maximum earth resistance of 25Ω would be adequate. The earth potential rise of 477V, which is the value of earthing group D, would not be exceeded. There is only one earthing point where the new regulations are followed. This earthing could be improved from 19,2Ω to 10Ω. The undervoltage based faulty phase identification method would be reliable when the fault current is larger than 11,7A. This means that fault resistances up to 800Ω could be detected.

Feeder bay J03 is the PECB feeder bay. The relay of the feeder bay is used to disconnect the PECB in malfunction cases. The operation delay of the backup protection must be changed from 2,0s to 3,0s. This is because the relay of J03 operates in 2,0s.

Table 5.10: New earth fault protection settings

Feeder	**I> [A]**	**I> [%]**	**t> [s]**	**I>> [A]**	**I>> [%]**	**t>> [s]**	**U_0 [%]**
J04	0,8	2	0,6	7,2	18	0,4	20
J05	0,8	2	0,6	7,2	18	0,4	20
J07	0,8	2	0,6	7,2	18	0,4	20
J10	0,8	2	0,6	7,2	18	0,4	20
J11	0,8	2	0,6	7,2	18	0,4	20
J14	0,8	2	0,6	7,2	18	0,4	20
J03	0,8	2	2,0	-	-	-	20

5.6 Conclusions

The PECB tests proved that the capacitive fault current reduces to a small value when the faulty phase is connected to the ground. In addition, the tests showed that the phase angle difference between the zero sequence current and the zero sequence voltage fluctuates when the PECB is closed. For these reasons, earth fault protection settings must be modified.

Section 5.5 and Section 5.6 present two different alternatives for the earth fault protection settings. In both cases, it is assumed that the maximum earth resistance is 25Ω. The earth fault current must be reduced if the settings of Section 5.6 are used. Otherwise, the safety regulations are violated although the maximum earth resistance would be 25Ω. On the other hand, the settings of Section 5.5 require that the faulty phase can be identified although fault resistances are large. For this reason, the undervoltage-based faulty phase identification method cannot be used because the settings of Section 5.5 do not leave a margin for the operation of the phase-earthing system.

In conclusion, present relays and the phase-earthing system are hard to adapt to operate together. If modern relays would be used instead of SPAC 531 C1s, the earth fault protection-related problems could be avoided. In addition, the safety regulations would be easier to fulfil if the phase-earthing system would function faster.

In some of the cases, the use of the phase-earthing system might raise the residual fault current because a part of the load current flows through the earth circuit. However, this is not a problem in this case. The calculations, which are presented in Section 5.4, proved that the residual fault current does not exceed the normal earth fault current value.

6 Phase-earthing method and compensation of earth fault current

The phase-earthing method and the compensation of earth fault current are in a way competing techniques. Both methods can be use to reduce the number of high speed automatic reclosing functions. On the other hand, these methods can also be used in tandem with each other. This kind of use might enable electricity distribution during long-lasting faults. In this chapter, benefits and drawbacks of both techniques are discussed. In addition, the interruption costs savings of both techniques are evaluated. The evaluation is based on the number of high speed automatic reclosing functions. The co-operation of the techniques is also discussed.

6.1 Compensated systems

In systems with isolated neutral, the earth fault current mostly consists of the capacitive reactive current caused by the earth capacitances of the network. This current can be compensated with a coil connected between the neutral point of the system and the ground. The device is called a Petersen coil. The zero sequence voltage of the network causes an inductive current trough the coil which compensates the capacitive earth fault current [9]. In totally compensated systems, the residual fault current has only a resistive component which is caused by the leakage resistance of the network and the resistance of the coil [18].

The compensation can be implemented as a decentralized compensation or as a centralized compensation. The latter method is more widely used in Finland. In cases of the centralized compensation the coil is connected to the medium voltage side of a high/medium voltage transformer. Because of the star-delta connection of transformers, a separated earthing transformer is usually needed to expose the neutral point of the system. In cases of the decentralized compensation, small compensation units are placed in different parts of the medium voltage network.

In compensated networks, the increase of the recovery voltage and the decrease of the zero sequence voltage are slow compared to the corresponding neutral isolated networks [19]. This fact has a significant impact on the self-extinctive behaviour of electric arc faults. Actually, the rate of rise of the recovery voltage has the larges impact on the arcing time. This is discussed more accurately in Section 4.1 but it can already be seen from (4.1) that the rate of rise of the recovery voltage decreases when the compensation degree increases.

Compensation coils are usually slightly out of tune because the zero sequence voltage has its peak value in the resonance point. The point is reached when the impedance of the compensation coil and the impedance of earth capacitances are equal. For this reason, the compensation degree is usually under or over 100% and the inductive current produced by the coil is not precisely matched to the earth fault current. In Finland, compensated networks are usually undercompensated. The inductive current of an undercompensated network is smaller than the capacitive earth fault current. For this reason, the reduction of galvanic connected network size pushes undercompensated networks towards the resonant point. In overcompensated networks, the tripping of a faulty line raises the compensation degree, respectively. The current of the compensation coil is usually adjustable. The adjustment is executed by changing the impedance of the coil. If the impedance is infinitely variable, it can usually be changed from the 10% to 100% of the nominal current [9].

6.1.1 Resonance tuning

Because operating situations change, the inductances of compensation coils must change together with phase-to-earth capacitances. Nowadays, the coils are usually continuously adjustable but there are also coils which are controlled through a sequence switch. In these cases, the coil must be de-energized when the inductance is adjusted. The adjustment of continuously adjustable coils is carried out by a motor-drive mechanism which is controlled by an automatic adjusting device.

The automatic adjustment is based on the zero sequence voltage measurement of the healthy state network. The voltage has its peak value when the inductive reactance of the coil is accordant with the capacitive reactance of the network (the resonant point) [9]. When phase-to-earth capacitances change, the compensation degree of the network also changes. This has an effect on the zero sequence voltage of the network. When the controller detects a change in the compensation degree, it searches a new resonant point via the motor-drive mechanism. The inductance of the coil is not adjusted during earth faults because of risk of damage [9].

6.1.2 Additional load resistance

In some of the cases, an additional resistance is connected parallel with the compensation coil. The basic idea of the resistance is to raise the zero sequence current value and facilitate the functioning of earth fault protection [1]. In compensated networks, the earth fault current is sometimes so small that relays cannot detect it. The additional resistance decreases the resistance R in equation (2.2) and this way it increases the earth fault current value.

There are at least three methods to use the additional load resistance parallel with the compensation coil [9]:

1) The resistance is connected to the network for a short time when an earth fault is detected. When this method is used, the resistor is disconnected in the healthy state of the network.

2) The resistance is connected to the network all the time.

3) The resistance is connected to the network in the healthy state but it is disconnected for a short time during earth faults.

The first method is purely designed to guarantee the functioning of earth fault protection. The resistance increases the resistive component of the fault current and this way assures the functioning of relays during earth faults. However, this method conflicts with the basic idea of the compensation which is the restriction of the earth fault current.

The idea of the second method is partly the same as the idea of the first one. The resistance is connected to the network in the healthy state and the zero sequence voltage, which might have a high value in compensated networks, decreases. When the resistance is connected to the network during faults, it facilitates the functioning of earth fault protection.

As well as in the second method, the third method is used to restrict the zero sequence voltage in the healthy state. However, the resistance is disconnected during earth faults. This way arcing faults have a better possibility to self-extinguish. The method avoids the negative influence of the resistance on the fault extinction.

6.1.3 Benefits of compensation coils

The benefits of a compensation coil are based on the fact that the coil suppresses the earth fault current. Another important factor is the small rate of rise of the recovery voltage which increases the self-extinction probability of electric arcs. According to [19], about 90% of the faults in Finnish medium voltage networks are temporary arcing faults. In addition, from 70% to 80% of the faults are usually eliminated by automatic reclosing functions [19]. The introduction of the compensation coil reduces the number of high speed automatic reclosing functions caused by earth faults from 70% to 90% [1].

According to the recommendation for the number of high speed automatic reclosing functions given by Finnish Electricity Association (SENER), the compensation degree of 70% reduces the number of high speed automatic reclosing functions by 50% [21].If the compensation degree is higher, automatic reclosing functions reduces even more. The automatic adjusting full compensation can reduce the number of high speed automatic reclosing functions from 80% to 90% [21]. According to statistics collected from eleven of Finnish electricity distribution companies, the compensation reduces the number of high speed automatic reclosing functions by 50% and the number of delayed automatic reclosing functions by 25% [23].

Because the compensation coil reduces the residual fault current, which flows through the fault point, the generating earth potential rise is lower. This means that the compensation of the network is one option to fulfil the touch voltage requirements. From this point of view, the compensation coil could be installed instead of improving earthings which is usually an expensive operation. However, it must be remembered that the safety regulations might not be fulfilled if the coil is disconnected for some reason.

When the number of automatic reclosing functions is reduced, the number of circuit-breaker operations also reduces. Because circuit-breakers wear in every disconnection event, the reduction of the automatic reclosing functions has a positive effect on maintenance expenses. This way the introduction of a compensation coil spares money from the maintenance point of view.

6.3.2 Drawbacks of compensation coils

In compensated systems, there might appear a significant zero sequence voltage even in the healthy state of the system [1], which can cause problems for relay protection. The voltage is a consequence of the fact that there is always some asymmetry between the phase-to-earth capacitances of the phase conductors. The zero sequence voltage increases because of the vicinity of the resonance point. As discussed earlier, the zero sequence voltage has its maximum in the resonant point. For this reason, compensated networks must be more symmetrical compared to neutral isolated systems.

The rise of the neutral point voltage can cause problems for medium voltage busbar protection. Busbar earth faults are detected based on the zero sequence voltage. An intermittent earth fault can cause the unselective tripping of all outgoing feeders. Furthermore, intermittent earth faults occur especially in compensated cable networks and faults arise usually as a result of insulator damages [20]. As described earlier, the compensation decreases the rate of rise of the recovery voltage. However, the inductance between the neutral point and the ground also decelerates the decrease of the neutral point voltage. If the ignition frequency of an intermittent earth fault is high, the neutral point voltage does not have enough time to decrease. Normal earth fault protection cannot usually detect the fault because the current condition is not fulfilled. However, busbar protection operates based on the neutral point voltage and unselective tripping takes place.

The adjustment of the compensation coil must operate accurately enough to get through different operating situations in the network [1]. The coil must also be observed when replacement situations are considered. Substations have to be replaceable through the medium voltage network during fault or service situations. In these situations, the compensation coil might have to be disconnected.

Earth fault protection settings must be changed depending on if the coil is connected to the network or if it is not. For this reason, the position data of a switching device, which connects the coil to the network, must be conveyed to medium voltage feeder terminals. If the compensation coil is disconnected for some reason, the earth fault current multiplies. In this situation, the earth potential rise is higher and faults must be tripped faster. It might even be impossible to fulfil the safety regulations when the coil is not connected to the network.

Although the use of a compensation coil reduces automatic reclosing functions, it also debilitates the positive effect of time between the high speed automatic reclosing function and the delayed automatic reclosing function. The purpose of this time is to burn off for example branches and animals which commonly cause faults in medium voltage networks. For this reason, compensated networks might have to be cleaned more often compared to neutral isolated networks and maintenance expenses increase.

Economically, the introduction of a compensation coil is relatively expensive operation. Usually, all the following components are needed: the compensation coil, the earthing transformer, the controller of the coil and the additional load resistor. According to the Energy Market Authority (EMV), which is the regulator of the electrical network business in Finland, the unit price for the compensation equipment is about 125 000€.

6.2 Phase-earthing systems

The basic idea of phase-earthing systems is to connect the faulty phase to the ground which reduces the current of the fault point and improves the extinction probability of earth faults. The theory of the technique is discussed in Chapter 3. Essentially, the method can be used in two ways. When the faulty phase is connected to the ground for a short time, the ambition is to reduce the number of high speed automatic reclosing functions. The faulty phase can also be earthed for a longer period of time. In this kind of use, the phase-earthing system might enable the use of the network during long-lasting faults.

6.2.1 Usability of the long-term phase-earthing method

When the long-term phase-earthing method is used, the safety regulations for long-lasting earth faults must be followed. In any case, the long-term requirements are reached when the fault duration is approximately 10s. According to the present safety regulations, the maximum earth potential rise at the fault location must be below 150V. This regulation relates equipments which are installed after 2.1.2000. Otherwise, the old safety regulations are followed. According to the old regulations, the strictest demand is set for earthing group D. If earth faults are not automatically disconnected, the earth potential rise must be below 100V. In practice, this value must be followed because earthing group D is common among distribution transformer stations. When earth faults are not automatically disconnected, an alarm must be used. The safety regulations are discussed in Section 4.2.

Figure 6.1 presents earth potential rise curves of 150V and 100V, which are the above mentioned maximum earth potential rise values. As can be seen from the figure, the maximum earth resistance value should be smaller than or equal to 5Ω in order that the maximum fault current of 20A would be allowed. For this reason, the earth resistances must be on very low level if the long-term phase-earthing method is intended to use.

The capacitive fault current decreases with a substantial amount when the faulty phase is connected to the ground. However, a part of the load current flows through the earth circuit and through the fault point back to the line, which increases the residual fault current. For this reason, the load current determines the maximum residual fault current and the maximum earth resistance value. If the network is not heavily loaded, the maximum residual fault current could be around 10A. In this case, the maximum earth resistance should be around 10Ω.

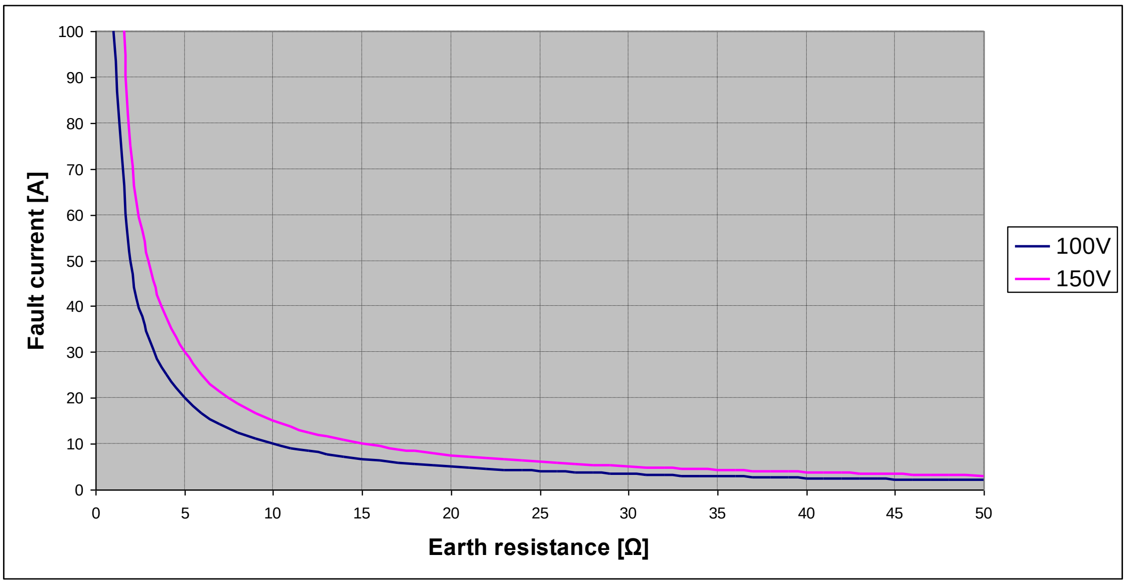


Figure 6.4: Earth potential rise curves of 100V and 150V

6.2.2 Benefits of phase-earthing systems

The functioning of the phase-earthing system does not cause interruptions in electricity distribution. In earth fault situations, the voltage of the faulty phase decreases and the voltages of healthy phases increase but the phase-to-phase voltages do not change. The normal phase-to-phase voltages enable normal electricity supply to low voltage networks. This is because distribution transformers are delta-star connected. In this respect, the functioning of a phase-earthing system does not differ from normal earth fault situations. If the long-term phase-earthing method could be used, the electricity supply could be maintained during fault localization. The short-term phase-earthing method can be used to extinguish arcing faults without short interruptions caused by high speed automatic reclosing functions.

When a faulty phase is earthed, a major part of the capacitive fault current flows to the ground via the PECB. A part of the capacitive fault current which flows through the fault point reduces, respectively. Because the fault current is smaller, the generating earth potential rise decreases. In addition, electric arcs have a higher probability to extinguish. For this reason, the number of high speed automatic reclosing functions can be reduced.

Before a phase-earthing system is tested, it is difficult to estimate how much the system reduces the number of high speed automatic reclosing functions. In Switzerland a phase-earthing system were tested in two separated neutral isolated medium voltage networks. During this two-year test period, 52 faults were detected and 34 of the faults were earth faults [24]. The phase-earthing system managed to prevent 18 supply interruptions which represent 35% of the total faults and 53% of the earth faults [24]. According to foreign researches, the use of a phase-earthing system can reduce the number of high speed automatic reclosing functions even from 75% to 80% [8]. A phase-earthing system, which was tested by the power company of Helsinki city in the 1960s, removed 60% of single phase to earth faults but the period under review was short [8]. In addition, reference [8] supposes that phase-earthing systems reduce the number of high speed automatic reclosing functions 10-50% less than compensation coils.

When a phase-earthing circuit breaker is used, the normal earth fault current flows through the fault point before the faulty phase is connected to the ground. This is a beneficial feature from one point of view. The large fault current can burn off some of the fault sources. In compensated systems, the coil restricts the fault current all the time and for example branches and small animals does not burn off as efficiently as in neutral isolated networks.

The investment costs of phase-earthing systems are relatively low. The costs can be approximated by using EMV’s unit prices for electrical network components. The price of a PECB device can be estimated by using the unit price of an additional air-insulated 20kV feeder bay. The price of relaying of the phase-earthing system can be estimated by using the unit price of relaying of additional 20kV feeder bay. In addition, the PECB must be placed in an enclosed space and thus the unit price of a distribution transformer cell is taken into account. This way the investment costs are calculated to be 13 500€ + 6 200€ + 23 700 = 43 400€. Because the unit price of compensation equipment is 130 500€ the ratio of the prices is roughly 1: 3. In references [24] and [8] this ratio is estimated to be 1: 4.

6.2.3 Drawbacks of phase-earthing systems

Phase-earthing systems are only usable in networks where the earth potential rise is low. The normal earth fault current flows through the fault point before the faulty phase is connected to the ground. For this reason, the normal earth fault current must be used when the earth potential rise is estimated. The safety regulations might be hard to fulfil because the phase-earthing function takes at least 0,5s and in some of the cases over one second might be needed. In practice, the use of the phase-earthing method is very restricted if earthings are not improved or the earth fault current is not decreased.

When the PECB is closed, a part of the load current flows through the earth circuit and via the fault point back to the line. For this reason, the residual fault current increases when the load current increases. The increased fault current deteriorates the self-extinction ability of electric arcs and increases the residual fault current. The level of the maximum residual fault current must be verified. Otherwise, it is not known if the safety regulations are fulfilled or not. Moreover, it is hard to prove the maximum residual fault current because different factors vary widely.

When the faulty phase is connected to the ground, the zero sequence current felt by the relay of a faulty feeder bay is uncertain. The angle between the zero sequence current and the zero sequence voltage might fluctuate. In some of the cases, the zero sequence current might be very small. However, the current might be much larger in some other cases. For this reason, it might be hard to find suitable earth fault protection settings. This subject is discussed more accurately earlier in this text.

The phase-earthing method is only usable in single phase to ground fault situations. In fact, a double earth fault or a two phase short-circuit fault might cause the unwanted operation of a phase-earthing system. This is because the current and voltage characteristics can be similar to the single phase to ground faults [8]. In addition, the use of a phase-earthing system might increase the number of double earth faults in the network. This is because risen voltages in the healthy phases might exceed the electric strength of deteriorated insulations. However, this should not be a remarkable problem when the short-term phase-earthing method is used. Some of the earth faults mutate into short circuit faults in uncompensated networks but this is rare in compensated networks [9]. Compared to compensation coils, phase-earthing systems do not have this beneficial feature.

If the faulty phase is identified by using the undervoltage method, which is described in Section 4.4.5, the phase-earthing system might be unsensitive. The increase of the earth fault current decreases the sensitivity of phase-earthing systems. The undervoltage method cannot be used if the faulty phase voltage does not decrease below 80% of the normal phase voltage value [8]. The limit is reached with lower fault resistances when the earth fault current increases.

The future requirements must be taken into account in network design. Although the phase-earthing method would be workable in present state, it might not be usable in the future. As mentioned earlier, the increase of the earth fault current and the increase of the load current decreases the usability of phase-earthing. For example, if the network includes more cables in the future, the earth fault current is larger and the phase-earthing system might be useless. Compensation coils can be overdimensioned in order that they are adequate in the future.

6.3 Economic point of view

In network design, different solution alternatives must be economically compared. For this reason, building costs, power loss costs and interruption costs must be estimated in different situations. The minimum estimation for interruption costs can be calculated by using the unit-specific margin profit of energy and the amount of unsupplied energy during an interruption [2]. However, the valuation of detriments of customers has much more significant effect when the economical effect of interruptions is considered. The detriment-based costs are many ten-fold compared to electricity price-based costs [2].

Electricity distribution network business is regulated in Finland. Distribution companies are allowed to make well-defined allowed return which depends on the quality of supply. The Energy Market Authority (EMV) supervises electricity distribution companies in Finland. The supervision is divided in four-year regulatory periods and the next period comprehends years 2012-2015. During the next regulatory period, interruption costs are calculated as presented in Table 6.1. The values of Table 6.1 are received when the values given by EMV are converted from the 2005 value of money to the 2012 value of money. The conversion is done by using a consumer price index.

Table 6.2: Interruption costs in the 2012 value of money

Unexpected interruptions		Planned interruptions		Delayed automatic reclosing	High speed automatic reclosing
€/kWh	€/kW	€/kWh	€/kW	€/kW	€/kW
12,62	1,26	7,80	0,57	1,26	0,63

As can be seen from Table 6.1, interruptions are divided in unexpected interruptions, planned interruptions, delayed automatic reclosing functions and high speed automatic reclosing functions. In this context, the interruption costs savings of a phase-earthing system and interruption cost savings of a compensation coil are compared by estimating the reduction of automatic reclosing functions. Both techniques are considered by using a same 20kV medium voltage network.

6.3.1 LuoVa-application

Interruption cost savings are estimated by using LuoVa-application. The application came into existence as a result of a reliability-based network analysis-project [23]. In the application, network components are divided in following categories: overhead lines, covered overhead lines, underground cables, distribution transformers, disconnectors and other components. Different factors affect the failure frequencies of different components. Overhead lines, covered overhead lines, distribution transformers and disconnectors affect the total number of automatic reclosing functions.

In the application, overhead lines are modelled in such a way that wind + snow and lightning cause automatic reclosing functions. In addition, there is an item which includes all other fault sources. The model of covered overhead lines is similar to the model of normal overhead lines except faults caused by lightning are included in the other fault sources. Distribution transformers are modelled in such a way that only animals cause automatic reclosing functions. In the model of disconnectors, fault sources are not specified.

The type of surrounding terrain affects the number automatic reclosing functions caused by wind + snow. The line has a different failure frequency depending on its location. Alternatives are: on the field, in the forest and on the edge of road. In addition, the maintenance level affects the number of automatic reclosing functions caused by wind + snow. The number of automatic reclosing functions caused by other fault sources depends on the condition of the line. The amount of valve type arresters affects the number of faults caused by lightning. The protection against animals affects the number of automatic reclosing functions caused by distribution transformers and disconnectors.

In LuoVa-project, the basic failure frequencies of above mentioned network components were determined. These frequencies are based on fault data collected from eleven electricity distribution companies which were involved in the project. Collected data includes 2 500 permanent faults and 18 417 automatic reclosing functions. Involved network material includes 8500km overhead lines, 2600km cables and 12 000 distribution transformers. The number of automatic reclosing functions consists of 13 256 high speed automatic reclosing functions and 5 161 delayed automatic reclosing functions. The basic failure frequencies for automatic reclosing functions are shown below. [23]

- Overhead lines
    - wind + snow: 20 pcs/a,100km
    - lightning: 20 pcs/a, 100km
    - other: 10 pcs/a, 100km

- Covered overhead lines
    - wind + snow: 0 pcs /a, 100km
    - other: 10 pcs/a, 100km

- Distribution transformers
    - animal caused faults 20 pcs/a, 100pcs
- Disconnectors
    - failure frequency 10 pcs/ a, 100pcs

In LuoVa-application there is a parameter which determines the proportion of delayed automatic reclosing functions in the total amount of automatic reclosing functions. Default setting of this parameter is 20%. According to annual interruption statistics of 2005, 2006, 2007 and 2008 collected by Finnish Energy Industries (ET), the proportion of delayed automatic reclosing functions alternates from 22% to 33% in neutral isolated systems and from 26% to 31% in compensated systems. Based on the statistics of LuoVa-project, the proportion of delayed automatic reclosing functions is 28%. However, it is not known which proportion of this data is collected from compensated networks and vice versa. In general, the proportion of delayed automatic reclosing functions is higher in compensated networks because compensation coils reduce the number of high speed automatic reclosing functions.

6.3.2 Network

The network that is used in this study is a part of the medium voltage network of Kalkulla substation. This network was chosen to be used because there is a prototype phase-earthing system installed at the substation. The PECB device is connected to the busbar of transformer2. For this reason, only feeders fed by transformer2 are taken into account. The prototype phase-earthing system has already been discussed in Chapter 5.

The considered network comprehends six medium voltage feeders which feed 191 distribution transformers. The total length of the network is 240km and it consists of normal overhead lines (65%), covered overhead lines (23%) and cables (12%). The number of automatic reclosing functions in the present situation is estimated by using the basic failure frequencies of LuoVa-application. The frequencies are presented in the previous section. The calculation results are shown in Table 6.2. As can be seen from the table, there occur 186 automatic reclosing functions in a year and the interruptions cause costs are about 67 000€ per year.

Table 6.2: Calculation results in the present situation.

Feeder	Interruption costs [€ / a]	High speed automatic reclosing [pcs /a]	Delayed automatic reclosing [pcs / a]
J04	11522	26	6,5
J05	1957	18,3	4,6
J06	2384	11	2,7
J07	2913	15,6	3,9
J11	48315	75,4	18,8
J14	137	2,5	0,6
	67228		

The present situation was estimated by using 20% proportion of delayed automatic reclosing functions. The proportion might be a bit low. On the other hand, it is better to use too large proportion than too small proportion when the present situation is considered. Otherwise, the savings of the compensation coil and the savings of the phase-earhing system are too large. This is because delayed automatic reclosing functions are more expensive compared to high speed automatic reclosing functions.

6.3.3 Compensation coil

Fault data that were collected in LuoVa-project shows that a compensation coil reduces the number of high speed automatic reclosing functions by 50% and the number delayed automatic reclosing functions by 25% [23]. However, the effect of a coil is evaluated differently in different sources of information and the compensation degree also affects the efficiency of the coil. The topic is already discussed in Section 6.1.3. In this calculation, it is assumed that the compensation reduces the total number of automatic reclosing functions by 50%. However, if the source of faults is lightning, the effect is slightly different. In these cases, most of the high speed automatic reclosing functions are caused by the overvoltage of phase conductors. In approximately 40% of the cases, the resulted fault is a single-phase fault and the compensation is able to clear the fault. In the rest of the cases the coil is ineffective. The failure frequencies, which are used to model the compensation coil, are shown below.

- Overhead lines
    - wind + snow: 10 pcs/a,100km
    - lightning: 15 pcs/a, 100km
    - other: 5 pcs/a, 100km

- Covered overhead lines
    - wind + snow: 0 pcs /a, 100km
    - other: 5 pcs/a, 100km

- Distribution transformers
    - animal caused faults 10 pcs/a, 100pcs

- Disconnectors
    - failure frequency 5 pcs/ a, 100pcs

In this study, the proportion of delayed automatic reclosing functions is assumed to be 40%. The above-mentioned value was chosen because the proportion must reach the real value. If a too small value would be used, the savings of the compensation coil would be too large.

Calculation results are shown in Table 6.3. The total number of automatic reclosing functions reduced by 41% compared to the present situation. As can be seen from the table, interruption costs are about 47 000€ in a year. The compensation coil produces interruption cost savings of about 20 000€ per year.

Table 6.3: Calculation results in the compensated situation.

Feeder	Interruption costs [€ / a]	High speed automatic reclosing [pcs / a]	Delayed automatic reclosing [pcs / a]
J04	8038	11,7	7,8
J05	1398	8,4	5,6
J06	1683	5	3,3
J07	2059	7,1	4,7
J11	33279	33,1	22
J14	92	1,1	0,7
	46549		

6.3.4 Phase-earthing system

As discussed in Section 6.2.2, the phase-earthing method reduces the number of high speed automatic reclosing functions. However, a phase-earthing system only operates in single phase to ground fault situations. In this study, it is assumed that the PECB reduces automatic reclosing functions 40% less than the compensation coil. However, the PECB reduces automatic reclosing functions 30% less than the compensation coil when the fault is caused by an animal. This is because most of these faults are single phase to ground faults. The use of phase-earthing is also assumed to extinguish some of the electric arcs faults caused by lightning. The failure frequencies that are used to model the phase-earthing situation are shown below.

- Overhead lines
    - wind + snow: 14 pcs/a,100km
    - lightning: 17 pcs/a, 100km
    - other: 7 pcs/a, 100km

- Covered overhead lines
    - wind + snow: 0 pcs /a, 100km
    - other: 7 pcs/a, 100km

- Distribution transformers
    - animal caused faults 13 pcs/a, 100pcs

- Disconnectors
    - failure frequency 7 pcs/ a, 100pcs

The proportion of delayed automatic reclosing functions is assumed to be 40%. The same value is also used in the case of the compensation coil. Phase-earthing systems have smaller effect on the number automatic reclosing functions than compensation coils and the proportion of 40% is sufficient. If the proportion would be smaller than the real value, interruption cost saving would be larger than in reality. For this reason, it is better to use a too large value than a too small value.

The calculation results are shown in Table 6.4. The total number of automatic reclosing functions reduced by 25% compared to the present situation. As can be seen from the table, interruption costs are about 59 000€ per year. The phase-earthing system produces interruption cost savings of about 8 000€ per year.

Table 6.4: Calculation results in the phase-earthing situation.

Feeder	Interruption costs [€ / a]	High speed automatic reclosing [pcs / a]	Delayed automatic reclosing [pcs / a]
J04	10059	14,6	9,7
J05	1737	10,5	7
J06	2094	6,2	4,1
J07	2564	8,8	5,9
J11	41933	41,8	27,9
J14	117	1,4	0,9
	58504		

6.4 Cooperation

As discussed earlier, the earth fault current might prevent the use of the phase-earthing method in many cases. If the earth fault current is large, faults must be tripped fast and there is no time to use the method. This is the case at least if earth resistances are not on a very low level. For this reason, the use of the phase-earthing method is restricted even in the short-term use. The method might be usable in relatively small overhead line networks. This is because the earth fault current is small in small galvanic connected networks. On the other hand, the short-term phase-earthing method is only useful in overhead line networks because faults are usually permanent in cabled networks.

The earth fault current can be reduced by reducing the size of galvanic connected network. Alternatively, the earth fault current can be compensated. Because the compensation reduces high speed automatic reclosing functions more than phase-earthing, it is not reasonable to use the both techniques in this purpose of use. However, if the compensation degree is below 50%, the coil does not have significant effect on the number of high speed auto reclosing functions [21] [19].

Economical and small decentralized compensation units could be used to reduce the earth fault current. In addition, these units could enable the use of the short-term phase-earthing method. In this kind of situation, the compensation units would only reduce the earth fault current and a phase-earthing system would reduce the number of automatic reclosing functions.

However, decentralized compensation units might cause problems from the protective relays point of view. For example, when a switching operation is performed, a compensated line might become overcompensated. In this case directional earth fault protection cannot operate selectively and an earth fault somewhere else in the network causes an erroneous tripping of the healthy line [19]. This is because the overcompensated line feeds the inductively reactive current to the substation busbar. Furthermore, if a compensation unit is disconnected for some reason, the earth fault current might exceed the allowed value.

When a centralized compensation unit is used, the compensation degree is usually higher than 70% and the coil is efficient to extinguish electric arcs. The earth fault current reduces about to a tenth of the normal earth fault current. For this reason, longer fault durations are allowed. In some cases, it might even be possible to use the network during earth faults. If a compensation coil reduces most of the high speed automatic reclosing functions, these functions might even be gratuitous. In these cases, the high speed automatic reclosing function could be removed a phase-earthing system could be used to help arc extinction. If a fault does not self-extinguish, the delayed automatic reclosing function would be carried out.

In compensated networks, the operation delay of earth fault protection can be much longer compared to neutral isolated networks. For this reason, a longer phase-earthing time can be used and the functioning of a phase-earthing system could be delayed. This way the coil has more time to clear the fault before the phase-earthing system operates. If the fault still exists after the delayed automatic reclosing function, the faulty feeder could be tripped permanently. Another alternative is to connect the faulty phase to the ground permanently. In this case, the whole network could be used until the fault repair starts.

The long-term phase-earthing method might be useful for example in cabled networks where faults are usually permanent. In cabled networks, there also appear intermittent earth faults, which arise when a fault extinguishes in the zero point of the fault current and re-ignites because of the recovery voltage [20]. However, phase-earthing reduces the voltage of the fault point and it could be used to extinguish intermittent earth faults. If the network can be used in earth fault situations, interruption durations are shorter and interruption cost savings are larger, respectively. However, the use of network during fault localization and fault isolation might be problematic.

In compensated networks, directional earth fault protection is based on the effective component of the zero sequence current. Because the component is already small, earth fault protection might have problems to detect faults when the faulty phase is connected to the ground. If relays cannot stay picked up during phase-earthing, the PECB might have to be opened in order that automatic reclosing functions can be carried out. The PECB could be closed for a few seconds and after that the PECB would open. If the fault still exists after the opening, the delayed automatic reclosing function would be performed. After the reclosing function, the PECB could be closed permanently or the feeder could be tripped off.

The capacitive earth fault current is small in compensated networks. When the phase-earthing method is used, a part of the load current flows through the earth circuit and via the fault point back to the line. Because of the small earth fault current, the load current has proportionally larger impact on the residual fault current. This might limit the use of the phase-earthing method in heavy loaded networks. As can be seen from Figure 6.1, the residual fault current must be small if earth resistances are not on a very low level. In practice, the pervious demands might prevent the use of the long-term phase-earthing method.

6.5 Conclusions

The results of the evaluation show that a phase-earthing system might be able to produce approximately half of interruption cost saving produced by a compensation coil. In the evaluation, the short-term phase-earthing method, which reduces the number high speed automatic reclosing functions, was assumed to be used. However, it must be remembered that the calculations were based on suggestive guesses. The investment costs of a phase-earthing system are between one fourth and one third of investment costs of a compensation coil.

The phase-earthing method is only usable in relatively small overhead line networks. This is because the earth fault current is large in cabled networks and most of temporary arcing faults occur in overhead line networks. The earth fault current restricts the use of phase-earthing because the original earth fault current flows through the fault point for a short time before the faulty phase is connected to the ground. A compensation coil restricts the earth fault current continuously and it can be used to facilitate the fulfillment of the safety regulations. In phase-earthing situations, the load current increases the residual fault current when the faulty phase is connected to the ground. The residual fault current might even exceed the normal earth fault current. For this reason, phase-earthing might be useless in some cases.

On the other hand, the phase-earthing method might be usable in overhead line networks where the earth fault current is small. Alternatively, the earth resistances of the network should be on a very low level. In fact, the use of the phase-earthing method might require earth resistance improvements in many cases and the use of a compensation coil might be more reasonable. Future requirements must also be taken into account. If the load of the network increases or the earth fault current increases, the phase-earthing system might become useless. This is because the safety regulations might be violated in the future.

In spite of all, phase-earthing might be a viable solution in certain networks and the quality of electricity supply can be improved with relatively low investments. In addition, the long-term phase-earthing method might be usable in parallel use with the compensation.

7 Phase-earthing method in self-healing networks

Advances in communication and information technology have been utilized to improve efficiency, reliability, security and quality of service in various engineering fields over the years. In today’s society, different parties have become more and more dependent on the availability of electricity supply. Even short interruptions cause significant detriments among normal housekeeping customers. Network, which is envisioned to take advantage of all modern technologies and which functions more intelligently, is called “smart grid” [25].

This kind of smarter network is intended to achieve by advancing and deploying various technologies. The development of smart grid can be categorised into following trends: [25]

- Reliability
- Renewable Sources
- Demand Response
- Electric storage
- Electric transportation

Reliability has always been in foreground in electrical network design. When reliability increases, investment costs increase and usually operational costs also increase but outage costs decrease. The optimum reliability level has been found when total costs have its minimum. In the “Smart Grid” vision, autonomous control actions are used to enhance the reliability of network [25]. Resiliency against component failures and natural disasters is increased and frequency and magnitude of power outages are minimized [25]. Autonomous control actions can be more efficient than human operator actions [25].

In this chapter a concept, which limits the impacts of faults to limited areas and shortens interruption durations, is discussed. The functionality of the zone concept is implemented by utilizing new protection features and adding switching devices to network. In the future, the system might be able to operate independently. The main point of this chapter is to clarify if the phase-earthing method is able to produce additional benefit from the zone concept point of view.

7.1 Reliability of electricity supply

Electric power distribution reliability indices are used to describe electric power distribution reliability from a customer’s point of view. The indices can be calculated by using real interruption data. This way the reliability of the network can be estimated. On the other hand, the indices can be calculated by using simulated data. This way the effect of different solutions can be evaluated. Because the indices describe reliability from a customer’s point of view, they are not giving any information about fault causing factors.

Standard SFS–EN 50160 defines that supply interruptions are situations where the voltage of the system is below 1% of its nominal value. Interruptions are divided in two different groups: short interruptions and long interruptions. Interruptions that are longer than 3 minutes are long interruptions and interruptions that are shorter than 3 minutes are short interruptions, respectively.

7.1.1 Reliability indices

System Average Interruption Frequency Index (SAIFI) gives information about the average frequency of sustained interruptions per customer over a predefined area. The index can be calculated by using (7.1). [31]

$$SAIFI = \frac{\text{Total number of customer interruptions}}{\text{Total number of customers served}} \tag{7.1}$$

System Average Interruption Duration Index (SAIDI) gives information about the average time that customers are interrupted. The index can be calculated by using equation (7.2). [31]

$$SAIDI = \frac{\sum \text{Customer interruption durations}}{\text{Total number of customers served}} \tag{7.2}$$

Customer Average Interruption Duration Index (CAIDI) gives information about the average time that is required to restore service to average customer per sustained interruption [31]. As presented in (7.3), SAIDI can be calculated as the quotient of SAIDI and SAIFI.

$$CAIDI = \frac{SAIDI}{SAIFI} \tag{7.3}$$

Momentary Average Interruption Frequency Index (MAIFI) gives information about the average frequency of momentary interruptions [31]. MAIFI and SAIFI are congruent with the exception that only short interruptions are taken into account when SAIFI is calculated. The index can be calculated by using equation (7.4).

$$MAIFI = \frac{\text{Total number of customer momentary interruptions}}{\text{Total number of customers served}} \tag{7.4}$$

7.1.2 Reliability analysis

Network component malfunctions cause different interruption durations for different customers. Consumers that are situated close to a fault location, usually suffer the longest interruption. Disconnectors are reclosers are used to perform switching operations in network. When a fault occurs, the closest disconnectors are opened. After the faulty zone is isolated, electricity supply can be restored to the other parts of the network.

The interruption duration of customers of the faulty zone is equal with the repair time of the faulted component. This is time between the failure moment and the moment when the component is taken back into use. If it is not possible to form a backup connection, customers downstream of the fault zone also suffer the same interruption duration. In other cases, customers suffer the interruption duration of a switching time which is time between the failure moment and the moment when the faulty component is isolated and electricity supply is restored to the healthy parts of the network. Automation in network shortens the switching time. For example, remote controlled disconnectors enable fast fault isolation and fast power restoration compared to manual controlled disconnectors.

When all electricity distribution network components are analysed, it is known how long interruption duration each component causes for each customer. Different components have different failure frequencies. When the failure frequencies are known, the interruption duration of a single customer over a given period of time can be calculated. Furthermore, when interruption durations and loads are known, interruption costs can be calculated. For this reason, reliability analysis gives a means of assessing the economical impacts of different solutions. Reliability can also be estimated from a customer's point of view. Changes in reliability cause changes in electric power distribution reliability indices which are presented in Section 7.1.1. Reliability analysis requires a large number of systematic calculations. For this reason, different computer applications are used.

7.2 Zone concept

The basic principle of the zone concept is to limit the impacts of disturbances to as small area as possible. The limitation is accomplished by adding switching devices and equipment that have protection features to the network. When switching functions are performed deeper in the network, a smaller number of customers suffer faults. Traditionally, relays and circuit-breakers are situated in high/medium voltage substations. For this reason, all customers on a faulty medium voltage feeder suffer at least a short interruption. This is because the feeder circuit-breaker disconnects the whole line from the network. Interruption duration felt by a single customer depends on the fault location from the customer's point of view.

When the zone concept is utilized, a medium voltage feeder is divided into separated zones. Each zone is either a protection zone or a control zone [32]. Protection zones are equipped with zone-selective protection features and breaking /reclosing functionalities [26]. Control zones enable disconnection operations. In practice, a single zone is either a remote controlled recloser protected zone or a remote controlled disconnector zone.

The boundary of a remote controlled recloser protected zone is a recloser which disconnects the zone from the network when a fault appears downstream from the device. The area between the substation and the recloser can be called a substation zone. Faults on recloser zones do not cause interruptions to customers on the substation zone. For this reason, it is reasonable to locate the recloser before the fault-prone parts of the network.

Remote controlled recloser protected zones include several remote controlled disconnector zones. The disconnector zones are needed to demarcate faults on small areas. When a fault occurs on a recloser zone, the recloser disconnects the end of the line. After the disconnection, a reclosing operation is performed. If the fault has vanished, the normal use of the network is continued. If the fault is permanent, the faulted disconnector zone is disconnected from the network. After the faulty zone is isolated, electricity distribution is restored to the other parts of the network. Customers on the fault zone suffer interruption duration of a repair time. Other customers suffer shorter interruptions depending on how fast power restoration can be done.

The system is able to localize faults independently. Fault localization is based on fault current measurements in the network and the automation devices use public wireless networks to data transmission [32]. Because of fast fault localization and remote controlled switching devices, fault durations become shorter. The primary reason for shorter interruptions is that fault isolation and power restoration can be done fast.

7.2.1 Pilot project

Fortum has a pilot project running where the zone concept is tested on two medium voltage feeders of Masala substation in Kirkkonummi, Finland. These feeders are divided into 20 remote controlled disconnector zones. In addition, both feeders have one remote controlled recloser protected zone. The feeders are depicted in Figure 7.1. The red areas are the remote controlled disconnector zones and the blue areas are the remote controlled recloser protected zones. [32]

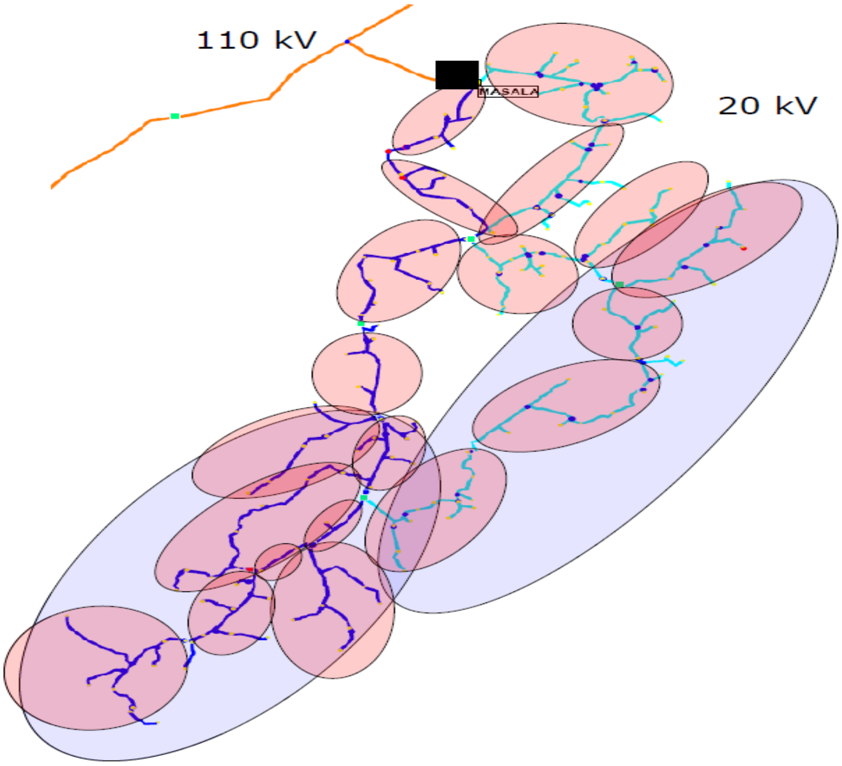


Figure 7.1: Piloted feeders. Red areas are remote controlled disconnector zones and blue areas are remote controlled recloser protected zones. [32]

Disconnectors and reclosers are equipped with fault indicators which gather fault current data from overhead lines. The data is used in fault localization and it is transmitted to a central computer which is installed at the substation. The computer communicates with the Supervisory Control and Data Acquisition (SCADA) system. The SCADA system cooperates with the Distribution Management System (DMS).

Data transmission between field devices and the central computer is implemented by using GPRS connection. The pilot project includes the installation of switching devices and fault indicators. In addition, new relays and the central computer are installed in the substation. The system is depicted in Figure 7.2.

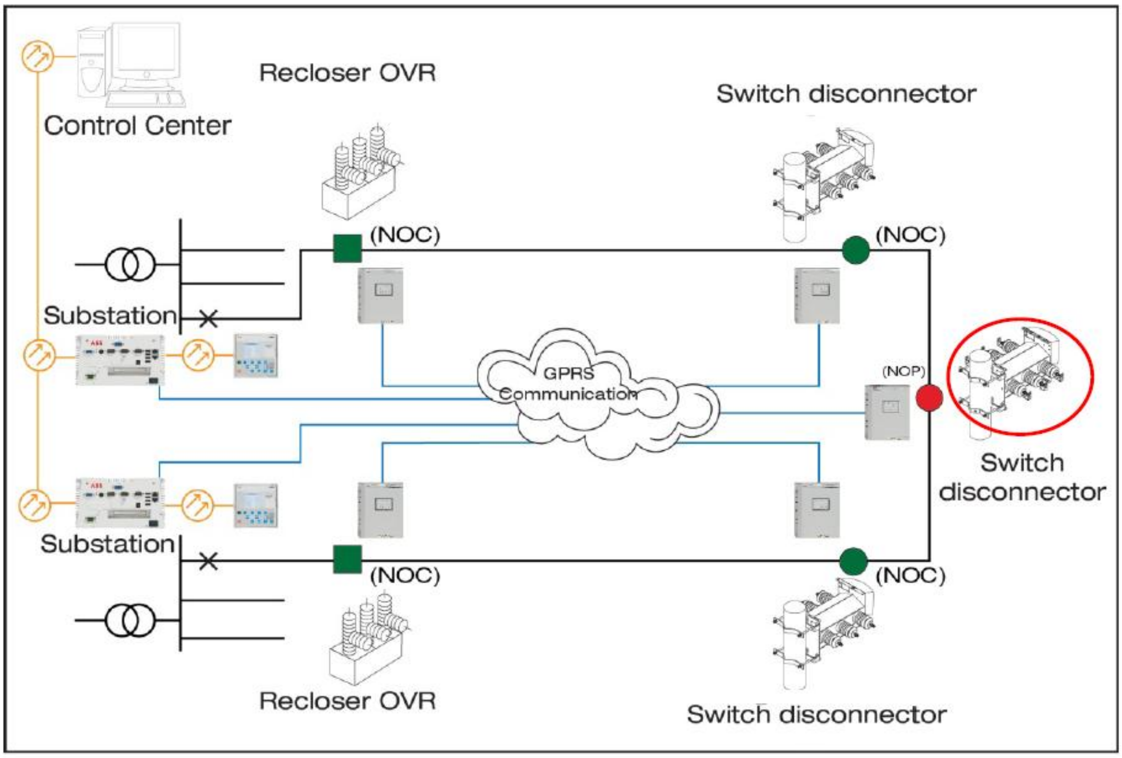


Figure 7.2: Automation functionality. [32]

When a fault occurs on a remote controlled recloser protected zone, the recloser operates within one second. The system has analysed and localized the fault within ten seconds. The process is performed by the central computer on the basis of data collected by fault indicators. Within a minute, the system has isolated the end of the faulty feeder. In this point, electricity distribution is restored to upstream from the fault point but the zones downstream from the fault point are without power supply. After two minutes, electric power is also restored in these zones. An adjacent feeder is used to form a backup connection. In this point, only the faulty zone is without electricity supply. The customers of the fault zone suffer the interruption duration of a repair time. The described situation is presented in Figure 7.3.

As can be seen from Figure 7.3, customers on the substation zone do not suffer interruptions when faults are on the remote controlled recloser protected zone. Customers between the faulty zone and the recloser suffer shorter interruption compared to customers behind the faulty zone. This is because it takes a longer time to restore electricity from the adjacent feeder. However, the system enables faster fault localization compared to a trial and error-method which is normally used and remote controlled devices enable fast switching operations. For these reasons, faults can be isolated fast and power restoration takes a shorter time.

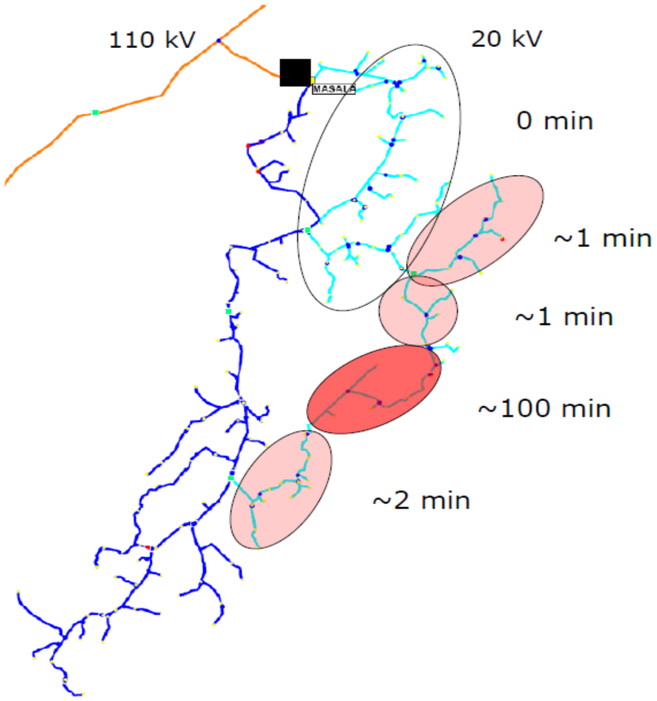


Figure 7.3: Fault durations in different zones. The fault zone is shown in dark red. [33]

The substation system provides a fault data package for the DMS [32]. In the control centre, network operators can perform required actions for power restoration. In the future, the system is meant to isolate faults independently and it provides switching schemes for the optimal backup connections. The functionality enables even faster fault isolation and power restoration. Further in the future, the system might be able to operate totally independently. The SAIDI reduces because interruption durations are shorter and the SAIFI reduces because interruptions affect fewer customers.

7.3 Phase-earthing

In this text, the self-healing properties of electricity distribution networks are considered through the zone concept. In a self-healing system, different automation levels merge together. The system isolates faults independently and restores electricity by forming backup connections. The self-healing functioning of distribution networks can be reached by utilizing the zone concept. However, automatically restoring power is a challenging task compared to fault localization and fault isolation [27]. For this reason, self-healing functionalities are introduced gradually.

The phase-earthing method might be useful as a supplementary part in self-healing distribution networks. The method could be used to shorten interruption durations in earth fault situations. In addition, it might be possible to limit the impact of an earth fault to a smaller area. The cooperation of the phase-earthing method and the zone concept could increase the reliability of electricity supply. The SAIDI improves as a result of shorter interruption durations. The SAIFI improves as a result of the fact that interruptions affect fewer consumers. In addition, the MAIFI improves because phase-earthing reduces the number of high speed automatic reclosing functions.

7.3.1 Operating principle

The PECB connects the faulty phase to the ground when an earth fault is detected and the method reduces the number of high speed automatic reclosing functions. In addition, if the fault is permanent, phase-earthing can be used to restrict the fault current. This way the voltage of the fault point also becomes smaller. Although the phase-earthing method would be used, it might be reasonable to carry out the automatic reclosing cycle. At least the delayed automatic reclosing function might be useful.

First, the PECB could be closed for a short time. After that, the PECB is opened and the delayed automatic reclosing function is carried out if the fault still exists. After the delayed reclosing, the PECB re-closes if the fault has not vanished. On the other hand, the automatic reclosing cycle can also be implemented differently or the automatic reclosing functions can even be removed from the use. In any case, it is now assumed that the fault is permanent.

After the fault is localized, the disconnectors of the faulty zone isolate the fault. In this point, the PECB could be opened. However, customers downstream from the fault zone are still without electricity supply. An adjacent feeder is used to form a backup connection in order that power restoration can be done. In Figure 7.3, customers between the recloser and the faulty zone would not suffer the outage. Customers in the end of the faulty feeder would suffer the interruption of 1min. As can be seen from Figure 7.3, the interruption duration is 2min if the phase-earthing method is not used. The customers of the fault zone suffer the interruption duration of a repair time.

If the backup connection can be formed before the faulty zone is disconnected, only the customers of the faulty zone suffer the outage. In this case, there is a ring connection in the network for a short time. In order that this can be done, disconnectors must be able to operate energized. The PECB is opened after the fault is isolated and the method limits the impact of the fault to the faulted zone. In other words, the customers of healthy zones do not suffer the outage.

Phase-earthing systems produce interruption cost savings in two ways. In permanent fault situations, the system shortens interruption durations. In addition, the system reduces the number of high speed automatic reclosing functions which also produces interruption cost savings.

7.3.2 Safety regulations

When electricity distribution is continued until the fault is isolated, the fault current flows through the fault point for a switching time. The allowed fault duration depends on the earth potential rise which is a result of the fault current and the earth resistance. In this case, the maximum earth potential rise must allow the fault duration of a switching time.

The pilot system can localize earth faults within ten seconds. Communication between devices and the operation time of switching devices causes an additional delay to fault isolation. For this reason, it is assumed that the system can isolate earth faults in 20 seconds. First, the phase-earthing system connects the faulty phase to the ground for 20 seconds. After the backup connection is formed, remote controlled disconnectors isolate the faulty zone. For this reason, the fault duration of 20 seconds must be allowed.

In practice, the earthing group D sets strictest demands for the earth potential rise. As a result, the voltage of $500\text{V}/\sqrt{t}$ is allowed when the fault duration is t. When the fault duration is 20s, the earth potential rise is allowed to be 112V. If the fault is not tripped automatically, the earth potential rise must be below 100V. It is noticed that this value does not remarkably differ from 112V.

The usability of the long-term phase-earthing method is already discussed in Section 6.2.1. The earth potential rise curve of 100V is shown in Figure 6.4. For example, if the maximum earth resistance is10Ω, the fault current is allowed to be 10A. If the maximum earth resistance is 5Ω, the fault current is allowed to be 20A, respectively. It can be concluded that the use of the phase-earthing method requires small earth resistances. In many cases, the residual fault current of 10A might be attainable by using the phase-earthing method. However, the residual fault current depends on many factors.

The present safety regulations allow the earth potential rise to be 150V in cases where the fault is not tripped automatically. In practice, this value is reached when the fault duration is 20s. The regulations allow the maximum earth resistance to be a bit larger compared to earthing group D. For example, when the fault current is 10A, the maximum earth resistance can be 15Ω.

In summary, the use of the phase-earthing system is not possible if the maximum earth resistance of the network is substantially larger than 10Ω. The residual fault current increases when the load current increases. For this reason, the earth potential rise increase, respectively. If the phase-earthing method seems to be useless solution, the compensation coil might be able to carry out the same function. If the compensation degree is high enough, it might be possible to use the network in earth fault situations.

7.4 Reliability calculations

The parallel use of the phase-earthing method and the zone concept is estimated by using LuoVa-application. In this section, the safety regulations are not taken into account. In addition, the phase-earthing system and zone concept-related devices are supposed to function seamlessly together. Interruption durations and interruption cost savings are estimated by using relatively rough approximations for failure frequencies and switching times.

7.4.1 LuoVa-application

ABB’s reliability analysis software LuoVa is a result of a reliability-based network analysis-project and it is already discussed in Section 6.3.1. In LuoVa, there are failure frequency models for different components. In the failure frequencies, the effect of operating conditions and the condition of a component is taken into account. The actual medium voltage network in its entirety is modelled in a system model.

When carrying out calculations, the application analyses the whole medium voltage network, one feeder at a time. Each feeder is divided in disconnector zones and the failure frequency of a zone is the sum of failure frequencies of components within the zone. Fault isolation and power restoration analysis is performed in two phases. First, remote controlled disconnectors are taken into account. In the second phase, manual controlled disconnectors are also observed. When all disconnector zones are analysed, interruption durations and the number of interruptions of each loading point can be defined. [23]

The system model includes parameters for switching times and repair times. There are three different parameters for the switching time. The first parameter describes how fast faults are isolated when disconnectors are remote controlled. The second parameter describes how fast faults are isolated when disconnectors are manually controlled. The third parameter describes how fast power restoration can be done when disconnectors are manually controlled. It must also be defined how often manual power restoration is used. However, in cable fault situations or transformer exchanges, power restoration is always done even manually.

The system model has also three different parameters for the repair time. The basic repair time is used unless the fault is a cable fault or a transformer fault because there is own repair times for these two exceptions. In addition, it must also be defined how much automatic fault localization speeds up the manual fault isolation and the repair time. The impact of different solutions on fault clearing times can be estimated by modifying the system model parameters.

7.4.2 Calculation parameters

The effect of the zone concept is estimated by changing a switching time parameter and a repair time parameter. Default setting for the switching time is 5 minutes in cases where switching functions are carried out by using remote controlled devices. Default setting for the repair time is 120 minutes in cases where the fault is not a cable fault or a transformer fault. The effect of the zone concept is estimated by changing the switching time from 5 min to 1 min and by changing the repair time from 120 min to 100 min.

The impact of the phase-earthing system can be estimated by reducing the switching time even more. As discussed in Section 7.3.1, customers suffer different interruption durations depending on how the phase-earthing system is used. If only the customers of the fault zone suffer an interruption, the switching time is zero. Otherwise, the average switching time is something between 0 min and 1 min. In this estimation, it is assumed that only the customers of the fault zone suffer the outage. For this reason, the switching time is 0 min.

It must be remembered that the phase-earthing system only functions in single phase to ground fault situations. Based on default failure frequency model settings, it is assumed that 30% of permanent faults are single phase faults. For this reason, the switching time is 1 min in 70% of cases and 0 min in 30% of cases and the average switching time of 0,7 min is used. In LuoVa-application, the switching time parameter must be an integer. Switching times between 0 min and 1 min are calculated by using linear extrapolation.

The phase-earthing system is assumed to reduce the number of high speed automatic reclosing functions as described in Section 6.3.4. In this case, it is also assumed that the proportion of delayed automatic reclosing functions in the total number of automatic reclosing functions is 40%. LuoVa-application has independent models for permanent faults and automatic reclosing functions. For this reason, assumptions that are made for permanent faults do not affect automatic reclosing functions and vice versa.

The network that is used in the estimation consists of two medium voltage feeders. These are the same feeders where the zone concept will be tested in reality. The pilot project is discussed in Section 7.2.1 and the feeders are depicted in Figure 7.1. The switching devices that will be installed to the real network are used in the estimation. As a result, two remote controlled reclosers and four remote controlled disconnectors were added to the network model. Interruption costs are based on the parameters of Table 6.1.

7.4.3 Results

The effects of the phase-earthing method and the zone concept were estimated by calculating five different situations. The baseline of the estimation is the present state of the network and the final state is the situation where the zone concept and the phase-earthing method are utilized in their entirety. Different situations are denoted by Case1, Case2, Case3, Case4 and Case5. The results are shown in Table 7.1 and Table 7.2. Table 7.1 shows results for feeder J12 Honskby and Table 7.2 shows results for feeder J14 Tolls. The tables include SAIDI values, automatic reclosing functions (AR-column), the interruption costs of permanent faults (PF costs-column) and the interruption costs of automatic reclosing functions (AR costs-column). Total costs and savings are calculated based on these values. Case-notations are clarified below.

- Case1: The present network is used in calculations.
- Case2: Four remote controlled disconnectors and two remote controlled reclosers are added to the network model.
- Case3: Fault localization is used and the zone concept is utilized.
- Case4: The zone concept is utilized and the phase-earthing system is used to reduce high speed automatic reclosing functions.
- Case5: The zone concept is utilized. In addition, the phase-earthing system operates in permanent earth fault situations and reduces the number of high speed automatic reclosing functions.

Table 7.1: Calculation results for feeder J12.

	SAIDI [min/a]	**AR [pcs]**	**PF costs [€]**	**AR costs [€]**	**Total costs [€]**	**Savings [€]**
Case1	214,6	69	129 153	107 112	236 265	0
Case2	179,1	69	113 639	107 420	221 059	15 206
Case3	140,5	69	97 775	107 420	205 195	31 070
Case4	140,5	52	97 775	92 952	190 726	45 539
Case5	138,2	52	96 852	92 952	189 803	46 462

As can be seen from Table 7.1, most of the SAIDI reduction is achieved between Case1 and Case2 and between Case2 and Case3. Interruption cost savings are 15 000€/year and 16 000€/year, respectively. It is also noticed that the impact of the phase-earthing system is small in permanent fault situations. Interruption costs savings between Case4 and Case5 are only 1 000€/year and SAIDI reduction is only 2%. For this reason, it is concluded that automation and fault localization produces most of the interruption cost savings and SAIDI reduction. The phase-earthing system does not have a remarkable impact from this point of view. However, the phase-earthing system substantially reduces the interruption costs of automatic reclosing functions. As can be seen from Table 7.1, savings between Case3 and Case4 are 14 000€/year.

Table 7.2: Calculation results for feeder J14.

	SAIDI [min/a]	**AR [pcs]**	**PF costs [€]**	**AR costs [€]**	**Total costs [€]**	**Savings [€]**
Case1	351,1	80	143 175	101 799	244 974	0
Case2	222,7	80	105 210	101 803	207 013	37 961
Case3	180,9	80	92 043	101 803	193 846	51 128
Case4	180,9	60	92 043	88 971	181 014	63 960
Case5	178,9	60	91 387	88 971	180 358	64 616

The results of Table 7.2 are very similar compared to the results of Table 7.1. However, total costs differ 38 000€/year between Case1 and Case2. For this reason, it is concluded that the recloser and three disconnectors which will be installed on this feeder are very profitable. It can also be seen that the phase-earthing system is not efficient to shorten switching times but it produces interruption cost savings of 13 000€/year by reducing high speed automatic reclosing functions.

When feeders J12 and J14 are contemplated as a consistent network, the phase-earthing system reduces the total number of automatic reclosing functions by 25%. The total SAIDI reduction is 44% but the phase-earthing system has only 1% effect on this value. In summary, switching devices and fault localization produces approximately equal interruption costs savings. The results might not be truthful because used failure frequencies are not based on real fault data. However, relative changes are suggestive and it can be concluded that the phase-earthing system is only useful from the automatic reclosing functions point of view.

7.5 New protection features

As observed in Section 5.3.2, the zero sequence current does not behave as in normal earth fault situations when the faulty phase is connected to the ground. The zero sequence current pointers might fluctuate on a wide range and the amplitude of the current is usually very small. For these reasons, it might be hard to implement reliable earth fault protection if relays use for example the reactive current measurement. However, modern relays have different features which can be utilized to avoid these problems. In addition, communication between Intelligent Electric Devices (IED) could also be used to make phase-earthing systems more reliable. In this section, some features of ABB’s feeder protection and control IED REF615 are examined. This relay was chosen because relays of this kind are installed as a part of the pilot project. In addition, REF615 supports GOOSE communication which is a feature of IEC 61850 standard.

7.5.1 IEC 61850 and GOOSE

International Electrotechnical Commission (IEC) published a standard for Communication Networks and Systems in Substations between years 2002 and 2005. This IEC 61850 standard defines a horizontal communication method between IEDs. In IEC 61850, the communication method is described as Generic Object Oriented Substation Event (GOOSE). IEDs like modern relays can publish and subscribe GOOSE messages. These messages are transferred over an Ethernet bus. [29]

Traditionally, hardwired signal paths between protection and control devices have been used. Devices of this kind have a limited number of binary inputs and outputs. Because of wireless communication, GOOSE enables savings in wiring costs and IEDs can have a higher number of virtual inputs and outputs. By utilizing GOOSE communication, different blocking-based protection schemes can be implemented. For example, a well-known scheme is blocking-based busbar protection. When a fault occurs on an outgoing feeder, the IED of the feeder starts. In addition, the IED of the incoming feeder starts. When starting, the IED of the outgoing feeder blocks the IED of the incoming feeder. However, when a fault occurs on the busbar, the IED of the outgoing feeder does not start and the IED of the incoming feeder operates. [30]

Blocking features of this kind might also be useful when the phase-earthing system is used. In high/medium voltage substations, busbar earth faults are detected by using zero sequence voltage relays [1]. The busbar earth fault relay also backs up the earth fault protection of medium voltage feeders. If the faulty phase is connected to the ground for a long time enough, the busbar earth fault relay operates because of the zero sequence voltage. By using GOOSE communication the busbar earth fault function could be blocked when the PECB is closed. This way busbar earth fault protection settings do not need to be modified when the PECB is taken into use.

Furthermore, the earth fault protection of outgoing feeders could be blocked when the PECB is closed. REF615 has three operation modes for the blocking functionality when directional earth fault protection function is used. The block signal can be given by a binary input, a horizontal communication input or an internal program of the IED [28]. Different operation modes are: Freeze timers, Block all and Block OPERATE output [28]. For example, the Freeze timers blocking mode could be used when the PECB is closed. In this mode, the operation timer is frozen to the prevailing value [28]. After the PECB opens, the operation timer would continue to run if the fault still exists.

7.5.2 Directional earth fault protection

New relays offer flexible setting possibilities for directional earth fault protection. First of all, relays have different operation modes. For example, REF615 has following operation modes: Phase angle, I0sin, I0cos, Phase angle80 and Phase angle88 [28]. Some older relays might only include the active and reactive current measurements which are the I0cos and I0sin operation modes. In phase-earthing situations, the proper functioning of earth fault protection is difficult to arrange if only these operation modes can be used.

In “Phase angle” mode, the operating sector of the relay is defined by minimum forward angle and maximum forward angle settings. The angles are measured from the characteristic angle to the boundaries of the operating sector. Both the maximum forward angle and the minimum forward angle are always positive. Because these angles can be set from 0° to 180º, the operating sector can be set to cover even a full circle. In addition, the characteristic angle can also be adjusted from -179° to 180° and relays can also be set to operate on backward direction. Figure 7.4 clarifies setting possibilities. [28]

By extending the forward operating zone, it is possible to keep the relay of a faulty feeder picked up when the faulty phase is connected to the ground. For example, as noticed in Section 5.3.2, the zero sequence current pointer can fluctuate between the maximum forward angle of 94° and the minimum forward angle of 83° by using notations of Figure 7.4. If the forward operating zone is extended to include this zone, the relay cannot reset because of phase angle fluctuation. In addition, the phase angle difference does not affect the operating value because neither the active nor the reactive current measurement is used. For this reason, the current setting can be set sensitive enough to enable the proper functioning of earth fault protection during phase-earthing.

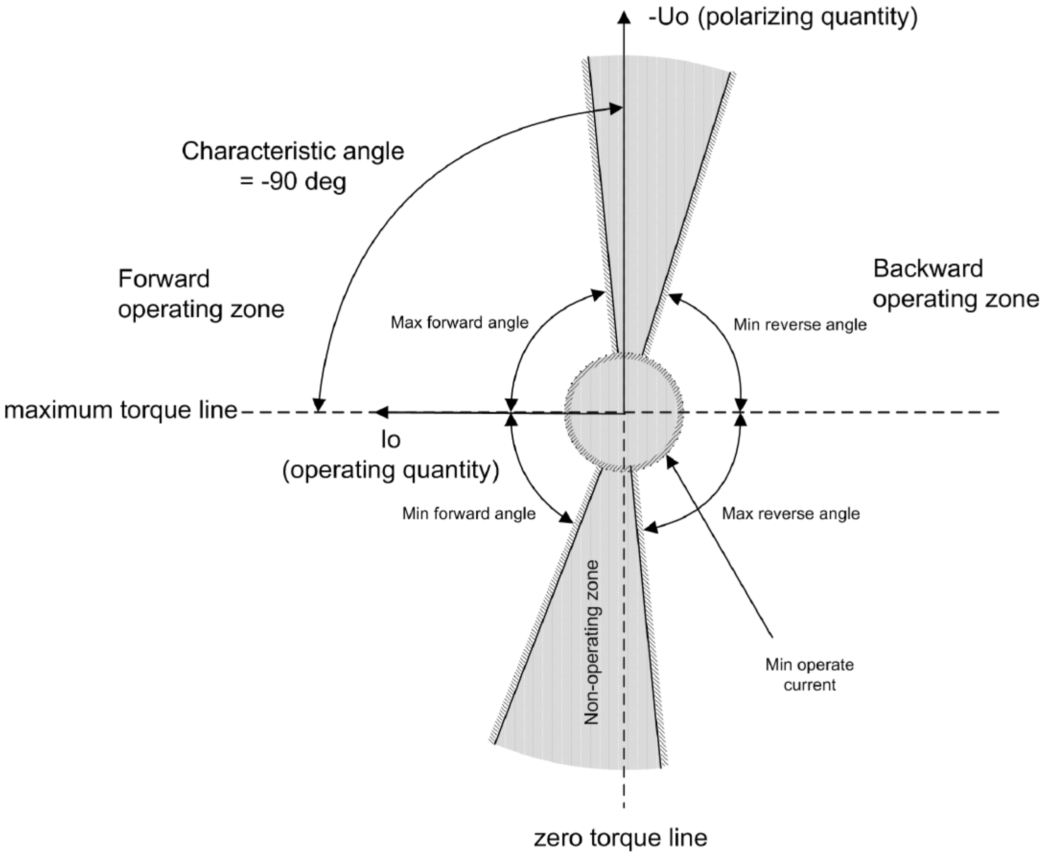


Figure 7.4: Directional earth fault protection. REF615 in”Phase angle” mode [28]

7.5.3 Transient based earth fault protection

In the initiation of earth faults, the voltage of the faulty phase decreases and the voltages of the healthy phases increase. When the voltage decreases, the capacitance discharges and when the voltage increases the capacitance charges. For these reasons, when earth faults emerge, there are discharge transients and charge transients in currents and voltages. Earth fault protection can be based on these transients. [28]

In intermittent earth faults situations, the transients are repetitive because the fault ignites and extinguishes alternately. However, when the fault is permanent, the transients can only be detected for a short time after the beginning of the fault. For this reason, permanent faults can be detected based on initial fault transients and intermittent earth faults can be detected based on repetitive transients. Earth fault protection, which is based on initial transients, could be useful in phase-earthing situations.

REF 615 has two different modes for transient based earth fault protection: Intermittent EF and Transient EF. The Transient EF mode might be usable when the phase-earthing method is used. In this mode, the relay detects zero sequence current and zero sequence voltage transients. Earth faults and their directions are detected by applying predefined criterions. There are separated criterions for zero sequence current and zero sequence voltage transients. In addition, the zero sequence voltage level is monitored. When all the three conditions are fulfilled, the relay function starts. The function stays picked up as long as the set zero sequence voltage level is exceeded. After the set delay time, the function operates.

Transient based earth fault protection might be useful when a phase-earthing system is used. Small zero sequence current amplitudes and the fluctuation of the phase-angle might cause problems for conventional earth fault protection. However, these occurrences do not affect transient based earth fault protection and the relay stays picked up the whole phase-earthing time. This is because the zero sequence voltage is elevated when the faulty phase is connected to the ground. When the PECB opens, the zero sequence voltage vanishes if the fault has disappeared. Otherwise, the fault still exists and the tripping function is carried out. The operation delay must be suitable in order that the proper functioning is achieved.

7.5.4 Operation time characteristics

The operate time characteristics of new relays are more versatile compared to older ones. For example, in REF615, the operate time characteristic can be selected to be either definite time (DT) or inverse definite minimum time (IDMT). When the DT mode is used, the relay function operates after a predefined delay and resets if the fault current disappears. In IDMT mode, the relay function operates when a maximum value is exceeded. This maximum value is defined by an inverse time curve. [28]

It is also possible to use user programmable IDMT curves. In REF615, the programming is executed by defining values for five curve parameters. When these parameters and a set start value are entered to a standard formula, the operate time is obtained as a result [28]. Suitable parameter values can be found by carrying out calculations with different fault current values.

Inverse time curves might be useful when the phase-earthing method is used. By using a suitable curve, it might be possible to determine an upper limit for the use of a phase-earthing system. When the fault current exceeds a certain value, the operate time given by the curve is shorter than the delay of the phase-earthing system. For this reason, the relay operates before the PECB closes.

That kind curve should be found that earth fault protection has enough time to reset when the phase-earthing system is meant to operate. The resetting takes place when the PECB closes. If the fault still exists after the PECB opens, the relay re-starts. In these cases, the tripping must take place as fast as possible.

Some relays enable adjustable reset delay times. This feature could be very useful when the phase-earthing system is used. The resetting operation can be delayed in order that the phase-earthing cycle can be carried out. After the PECB opens, the relay resets if the fault has disappeared. On the contrary, if the fault still exists after the phase-earthing time, the relay operates. The use of the reset delay time is a simple solution if unwanted resetting functions cause problems.

8 Conclusions

The basic idea of the phase-earthing method is to remove the earth fault current away from the fault point. The faulty phase is connected to the ground at a substation. Because the earth resistance of the substation is small, a major part of the earth fault current flows to the ground at the substation. In the fault point, the capacitive fault current reduces, respectively.

If the faulty phase is connected to the ground for a short-time, some of the temporary arcing faults self-extinguish. Because the phase-earthing method does not interrupt electricity distribution, some of the short interruptions are avoided. This way the number of high speed automatic reclosing functions can be reduced. If it is possible to connect the faulty phase to the ground for a longer time, electricity distribution could be maintained even in permanent fault situations. This way the impact of the fault could be limited to a smaller area. In addition, interruptions would become shorter. For these reasons, the phase-earthing method might be able to produce notable interruption costs savings.

However, the phase-earthing method is problematic from the safety regulations point of view. Although the current of the fault point usually decreases to a fraction of the preceding value, the normal earth fault current flows through the fault point for a short time before the faulty phase is connected to the ground. This is the case when the short-term phase-earthing method is used. For this reason, the earth potential rise must be calculated by using the normal earth fault current value. Because the permitted fault duration depends on the earth potential rise, it might be difficult to include the phase-earthing time in the operation delay of earth fault protection.

In addition, a part of the load current flows through the earth circuit to the fault point and through the fault point back to the line. For this reason, it is hard to prove the real value of the residual fault current. If the faulty feeder is heavily loaded, the current of fault point might be larger than the normal earth fault current. However, the effect of the load current can be controlled by increasing the phase-earthing resistance. In any case, this phenomenon is a problem from the safety regulations point of view. In order that the phase-earthing method can be used in permanent earth fault situations, a reliable method should be developed to prove the real earth potential rise [10].

The earth potential rise can be decreased by reducing the earth fault current. Alternatively, earthings can be improved. The short-term phase earthing method is only usable in relatively small overhead line networks. This is because the earth fault current grows when the size of galvanic connected network grows. In addition, cables generate the multifold earth fault current per unit of length compared to overhead lines. On the other hand, most of the temporary arcing faults occur in overhead line networks. Roughly speaking, the short-term phase-earthing method might be useful if the multiplication of the earth fault current and the maximum earth resistance is smaller than 500V.

In general, the compensation of earth fault current is more reasonable solution than phase-earthing. Although the compensation is more expensive alternative, it also reduces more high speed automatic reclosing functions than the phase-earthing method. In addition, the safety regulations are not a problem in the same way because the coil restricts the fault current continuously. Actually, the compensation of earth fault current is the most practical way to reduce high earth potential rise values in most of the cases. In addition, it is very likely that cabling degrees will substantially increase in future, which is a problem from the phase-earthing point of view.

Economically, the short-term phase-earthing method might be able to produce about half of interruption cost savings in comparison with the compensation coil. The purchase price of a phase-earthing system is approximately 25-35% of the purchase price of a compensation coil. From this point of view, the phase-earthing method might be useful in certain cases. However, the compensation coil is a more sensible solution in most of the cases.

In this thesis it was studied if the phase-earthing system could be useful in parallel use with the zone concept. This way it might be possible to limit the impact of a permanent earth fault to a faulty disconnector zone. In this case, the customers of healthy zones would not suffer interruptions. However, the result of the estimation was that most of the benefit is produced by fast fault localization and remote controlled switching devices. The phase-earthing system is only useful from the high speed automatic reclosing functions point of view.

The phase-earthing method might cause problems for earth fault protection. This is because the zero sequence current of the faulty feeder bay is small when the faulty phase is connected to the ground. In addition, the phase angle between the zero sequence current and the zero sequence voltage might fluctuate when the PECB is closed. For these reasons, earth fault protection settings have to be revised when the phase-earthing system is taken into use. It might be possible to avoid problems by using the high-set stage of earth fault protection. However, new relays offer more feasible protection features. In some of the cases, the introduction of the phase-earthing system might require the renewal of relays.

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APPENDIX 1: Disturbance recordings based values

Measu-rement	Date	Time [ms]	U_0 [kV]	U_0-angle [deg]	I_0 [A]	I_0-angle [deg]	φ[deg]	$I_0\sin\varphi$	U_0/U_{ph} [%]	Pick-up
X1	29.6.2010	50	11,2	53	34,4	324	91	34,4	97,4	
X1	29.6.2010	100	11,6	230	34,5	141	91	34,5	100,9	
X1	29.6.2010	250	11,9	41	34,5	312	91	34,5	103,5	
X1	29.6.2010	350	11,7	36	1,9	283	67	1,7	101,7	
X1	29.6.2010	500	11,7	207	1,8	95	68	1,7	101,7	
X1	29.6.2010	650	11,7	19	1,7	266	67	1,6	101,7	
X1	29.6.2010	800	11,9	189	34,6	100	91	34,6	103,5	
X1	29.6.2010	950	11,9	1	34,6	272	91	34,6	103,5	
X2	29.6.2010	50	11,8	283	34,8	194	91	34,8	102,6	
X2	29.6.2010	100	11,9	101	34,8	12	91	34,8	103,5	
X2	29.6.2010	250	11,9	275	34,8	186	91	34,8	103,5	
X2	29.6.2010	350	11,7	273	1,6	163	70	1,5	101,7	
X2	29.6.2010	500	11,7	87	1,6	338	71	1,5	101,7	
X2	29.6.2010	650	11,7	261	1,6	152	71	1,5	101,7	
X2	29.6.2010	800	11,9	75	34,9	346	91	34,9	103,5	
X2	29.6.2010	950	11,9	249	34,9	160	91	34,9	103,5	
X3	29.6.2010	50	11,9	307	35,0	217	90	35,0	103,5	
X3	29.6.2010	100	11,9	127	35,0	38	91	35,0	103,5	
X3	29.6.2010	250	12,0	307	35,0	218	91	35,0	104,3	
X3	29.6.2010	350	11,7	308	1,7	197	69	1,6	101,7	
X3	29.6.2010	500	11,7	128	1,6	18	70	1,5	101,7	
X3	29.6.2010	650	11,7	309	1,5	198	69	1,4	101,7	
X3	29.6.2010	800	12,0	128	35,0	39	91	35,0	104,3	
X3	29.6.2010	950	12,0	308	35,0	219	91	35,0	104,3	
Y1	29.6.2010	50	12,0	294	35,2	205	91	35,2	104,3	fail
Y1	29.6.2010	100	12,0	114	35,2	25	91	35,2	104,3	fail
Y1	29.6.2010	250	12,0	294	35,2	205	91	35,2	104,3	fail
Y1	29.6.2010	350	11,7	295	1,0	269	154	0,4	101,7	fail
Y1	29.6.2010	500	11,7	115	1,0	92	157	0,4	101,7	fail
Y1	29.6.2010	650	11,7	295	0,9	274	159	0,3	101,7	fail
Y1	29.6.2010	800	12,0	114	35,2	25	91	35,2	104,3	fail
Y1	29.6.2010	950	12,0	293	35,2	204	91	35,2	104,3	fail
Y1	29.6.2010	1100	12,0	113	35,2	24	91	35,2	104,3	fail
Y2	29.6.2010	50	11,6	85	35,0	355	90	35,0	100,9	fail
Y2	29.6.2010	100	11,8	265	35,1	176	91	35,1	102,6	fail
Y2	29.6.2010	250	12,0	86	35,1	357	91	35,1	104,3	fail
Y2	29.6.2010	350	11,7	89	1,1	64	155	0,5	101,7	fail
Y2	29.6.2010	500	11,8	270	1,0	249	159	0,4	102,6	fail
Y2	29.6.2010	650	11,7	92	0,9	70	158	0,3	101,7	fail
Y2	29.6.2010	800	12,0	272	35,2	183	91	35,2	104,3	fail
Y2	29.6.2010	950	12,0	94	35,2	5	91	35,2	104,3	fail
Y2	29.6.2010	1100	12,0	276	35,2	187	91	35,2	104,3	fail

Y3	29.6.2010	50	11,4	52	35,1	322	90	35,1	99,1	fail
Y3	29.6.2010	100	11,8	233	35,2	143	90	35,2	102,6	fail
Y3	29.6.2010	250	12,0	56	35,3	327	91	35,3	104,3	fail
Y3	29.6.2010	350	11,8	59	0,8	27	148	0,4	102,6	fail
Y3	29.6.2010	500	11,8	242	0,8	211	149	0,4	102,6	fail
Y3	29.6.2010	650	11,8	66	0,8	34	148	0,4	102,6	fail
Y3	29.6.2010	800	12,0	248	35,3	159	91	35,3	104,3	fail
Y3	29.6.2010	950	12,0	72	35,3	343	91	35,3	104,3	fail
Y3	29.6.2010	1100	12,0	255	35,3	166	91	35,3	104,3	fail
Z1	29.6.2010	50	11,8	0	35,0	271	91	35,0	102,6	
Z1	29.6.2010	100	11,9	181	35,1	92	91	35,1	103,5	
Z1	29.6.2010	250	11,9	4	35,1	275	91	35,1	103,5	
Z1	29.6.2010	350	11,7	7	2,5	312	125	2,0	101,7	
Z1	29.6.2010	500	11,7	191	2,5	129	118	2,2	101,7	
Z1	29.6.2010	650	11,7	14	2,5	312	118	2,2	101,7	
Z1	29.6.2010	800	12,0	196	35,1	107	91	35,1	104,3	
Z1	29.6.2010	950	12,0	12	35,1	290	98	34,8	104,3	
Z2	29.6.2010	50	11,5	86	34,8	356	90	34,8	100,0	
Z2	29.6.2010	100	11,8	266	35,0	177	91	35,0	102,6	
Z2	29.6.2010	250	11,8	89	25,5	349	80	25,1	102,6	
Z2	29.6.2010	350	11,7	91	2,6	28	117	2,3	101,7	
Z2	29.6.2010	500	11,7	274	2,6	210	116	2,3	101,7	
Z2	29.6.2010	650	11,7	96	2,6	29	113	2,4	101,7	
Z2	29.6.2010	800	12,0	279	35,0	189	90	35,0	104,3	
Z2	29.6.2010	950	12,0	102	35,0	12	90	35,0	104,3	
Z3	29.6.2010	50	11,4	65	34,8	335	90	34,8	99,1	
Z3	29.6.2010	100	11,8	245	34,8	155	90	34,8	102,6	
Z3	29.6.2010	250	11,9	67	34,9	338	91	34,9	103,5	
Z3	29.6.2010	350	11,7	70	2,5	6	116	2,2	101,7	
Z3	29.6.2010	500	11,8	252	2,5	189	117	2,2	102,6	
Z3	29.6.2010	650	11,7	75	2,5	11	116	2,2	101,7	
Z3	29.6.2010	800	11,9	256	34,9	167	91	34,9	103,5	
Z3	29.6.2010	950	11,9	79	35,0	349	90	35,0	103,5	
X1	4.3.2010	50	11,8	286	39,4	197	91	39,4	102,6	
X1	4.3.2010	100	11,9	106	39,5	17	91	39,5	103,5	
X1	4.3.2010	250	12,0	286	39,5	197	91	39,5	104,3	
X1	4.3.2010	350	11,7	287	3,4	207	100	3,3	101,7	
X1	4.3.2010	500	11,7	107	3,3	27	100	3,2	101,7	
X1	4.3.2010	650	11,7	287	3,3	207	100	3,2	101,7	
X1	4.3.2010	800	12,0	106	39,5	16	90	39,5	104,3	
X1	4.3.2010	950	12,0	286	39,5	196	90	39,5	104,3	
X2	4.3.2010	50	11,7	102	39,3	12	90	39,3	101,7	
X2	4.3.2010	100	11,9	281	39,4	191	90	39,4	103,5	
X2	4.3.2010	250	11,7	100	2,9	7	87	2,9	101,7	
X2	4.3.2010	350	11,7	98	3,4	19	101	3,3	101,7	
X2	4.3.2010	500	11,7	276	3,4	197	101	3,3	101,7	
X2	4.3.2010	550	11,7	95	3,4	16	101	3,3	101,7	

X2	4.3.2010	650	11,8	93	27,7	1	88	27,7	102,6	
X2	4.3.2010	800	12,0	270	39,5	181	91	39,5	104,3	
X2	4.3.2010	950	12,0	88	39,5	358	90	39,5	104,3	
X3	4.3.2010	50	11,8	296	39,3	207	91	39,3	102,6	
X3	4.3.2010	100	11,9	116	39,4	26	90	39,4	103,5	
X3	4.3.2010	250	12,0	293	39,5	204	91	39,5	104,3	
X3	4.3.2010	350	11,7	293	3,3	215	102	3,2	101,7	
X3	4.3.2010	500	11,7	112	3,3	32	100	3,2	101,7	
X3	4.3.2010	650	11,7	290	3,3	211	101	3,2	101,7	
X3	4.3.2010	800	12,0	106	39,5	17	91	39,5	104,3	
X3	4.3.2010	950	12,0	285	39,4	195	90	39,4	104,3	
Y1	4.3.2010	50	12,0	307	39,7	218	91	39,7	104,3	fail
Y1	4.3.2010	100	12,0	127	39,8	37	90	39,8	104,3	fail
Y1	4.3.2010	250	12,0	306	39,8	217	91	39,8	104,3	fail
Y1	4.3.2010	350	11,7	308	2,3	298	170	0,4	101,7	fail
Y1	4.3.2010	500	11,7	127	2,3	119	172	0,3	101,7	fail
Y1	4.3.2010	650	11,7	307	2,3	299	172	0,3	101,7	fail
Y1	4.3.2010	800	12,0	125	39,8	36	91	39,8	104,3	fail
Y1	4.3.2010	950	12,0	305	39,8	216	91	39,8	104,3	fail
Y1	4.3.2010	1100	12,0	125	39,8	36	91	39,8	104,3	fail
Y2	4.3.2010	50	11,4	232	39,3	142	90	39,3	99,1	fail
Y2	4.3.2010	100	11,8	50	39,5	321	91	39,5	102,6	fail
Y2	4.3.2010	250	11,7	228	2,4	221	173	0,3	101,7	fail
Y2	4.3.2010	350	11,7	226	2,4	218	172	0,3	101,7	fail
Y2	4.3.2010	500	11,7	42	2,3	35	173	0,3	101,7	fail
Y2	4.3.2010	650	11,8	42	2,3	35	173	0,3	102,6	fail
Y2	4.3.2010	800	12,0	34	39,7	305	91	39,7	104,3	fail
Y2	4.3.2010	950	12,0	211	39,7	122	91	39,7	104,3	fail
Y2	4.3.2010	1100	12,0	28	39,7	299	91	39,7	104,3	fail
Y3	4.3.2010	50	11,4	249	39,3	159	90	39,3	99,1	fail
Y3	4.3.2010	100	11,8	68	39,5	338	90	39,5	102,6	fail
Y3	4.3.2010	250	12,0	246	39,7	157	91	39,7	104,3	fail
Y3	4.3.2010	350	11,7	247	2,6	237	170	0,5	101,7	fail
Y3	4.3.2010	500	11,7	65	2,5	57	172	0,3	101,7	fail
Y3	4.3.2010	650	11,8	244	2,5	235	171	0,4	102,6	fail
Y3	4.3.2010	800	12,0	62	39,8	332	90	39,8	104,3	fail
Y3	4.3.2010	950	12,0	240	39,8	151	91	39,8	104,3	fail
Y3	4.3.2010	1100	12,0	59	39,8	330	91	39,8	104,3	fail
Z1	4.3.2010	50	11,6	281	39,2	191	90	39,2	100,9	fail
Z1	4.3.2010	100	11,8	100	39,4	10	90	39,4	102,6	fail
Z1	4.3.2010	250	12,0	277	39,5	188	91	39,5	104,3	fail
Z1	4.3.2010	350	11,8	277	1,2	112	15	0,3	102,6	fail
Z1	4.3.2010	500	11,7	94	1,2	279	5	0,1	101,7	fail
Z1	4.3.2010	650	11,7	272	1,1	97	5	0,1	101,7	fail
Z1	4.3.2010	800	12,0	89	39,6	359	90	39,6	104,3	fail
Z1	4.3.2010	950	12,0	265	39,6	176	91	39,6	104,3	fail
Z1	4.3.2010	1100	12,0	83	39,6	354	91	39,6	104,3	fail

Z2	4.3.2010	50	11,6	85	39,3	355	90	39,3	100,9	fail
Z2	4.3.2010	100	11,8	265	39,4	175	90	39,4	102,6	fail
Z2	4.3.2010	250	12,0	84	39,6	354	90	39,6	104,3	fail
Z2	4.3.2010	350	11,7	84	1,4	265	1	0,0	101,7	fail
Z2	4.3.2010	500	11,7	264	1,2	82	-2	0,0	101,7	fail
Z2	4.3.2010	650	11,8	83	1,2	264	1	0,0	102,6	fail
Z2	4.3.2010	800	12,0	261	39,6	172	91	39,6	104,3	fail
Z2	4.3.2010	950	12,0	81	39,6	351	90	39,6	104,3	fail
Z2	4.3.2010	1100	12,0	260	39,6	171	91	39,6	104,3	fail
Z3	4.3.2010	50	12,0	298	39,5	209	91	39,5	104,3	fail
Z3	4.3.2010	100	12,0	117	39,6	28	91	39,6	104,3	fail
Z3	4.3.2010	250	12,0	295	39,6	206	91	39,6	104,3	fail
Z3	4.3.2010	350	11,8	295	1,1	111	-4	-0,1	102,6	fail
Z3	4.3.2010	500	11,8	112	1,1	290	-2	0,0	102,6	fail
Z3	4.3.2010	650	11,8	290	1,1	108	-2	0,0	102,6	fail
Z3	4.3.2010	800	12,0	106	39,6	17	91	39,6	104,3	fail
Z3	4.3.2010	950	12,0	284	39,6	195	91	39,6	104,3	fail
Z3	4.3.2010	1000	12,0	103	39,6	14	91	39,6	104,3	fail
Z3	4.3.2010	1200	12,0	100	39,6	11	91	39,6	104,3	fail

APPENDIX 2: Residual fault current calculation results

Residual fault current [A], feeder J11, length 12,8km

I_L [A]	I_{ef} = 1A	I_{ef} = 5A	I_{ef} = 10A	I_{ef} = 20A	I_{ef} = 30A	I_{ef} = 35A	I_{ef} = 40A	I_{ef} = 50A	I_{ef} = 60A	I_{ef} = 70A	I_{ef} = 80A	I_{ef} = 90A	I_{ef} = 100A
1	0,7	0,6	0,5	0,8	1,3	1,5	1,8	2,3	2,8	3,3	3,9	4,4	5,0
2	1,4	1,3	1,2	1,1	1,3	1,4	1,6	2,0	2,5	3,0	3,5	4,0	4,6
3	2,2	2,0	1,9	1,7	1,6	1,7	1,8	2,0	2,4	2,8	3,3	3,8	4,3
4	2,9	2,7	2,6	2,3	2,2	2,2	2,2	2,3	2,5	2,8	3,2	3,6	4,1
5	3,6	3,5	3,3	3,0	2,8	2,8	2,7	2,7	2,8	3,0	3,3	3,6	4,0
6	4,3	4,2	4,0	3,7	3,5	3,4	3,3	3,2	3,2	3,3	3,5	3,8	4,1
7	5,1	4,9	4,8	4,5	4,2	4,1	4,0	3,8	3,8	3,8	3,9	4,0	4,3
8	5,8	5,7	5,5	5,2	4,9	4,8	4,7	4,5	4,4	4,3	4,3	4,4	4,6
9	6,5	6,4	6,2	5,9	5,6	5,5	5,4	5,2	5,0	4,9	4,9	4,9	5,0
10	7,3	7,1	7,0	6,6	6,3	6,2	6,1	5,8	5,7	5,5	5,4	5,4	5,4
11	8,0	7,9	7,7	7,4	7,0	6,9	6,8	6,5	6,3	6,2	6,0	6,0	5,9
12	8,7	8,6	8,4	8,1	7,8	7,6	7,5	7,2	7,0	6,8	6,7	6,6	6,5
13	9,5	9,3	9,2	8,8	8,5	8,3	8,2	7,9	7,7	7,5	7,3	7,2	7,1
14	10,2	10,1	9,9	9,5	9,2	9,1	8,9	8,7	8,4	8,2	8,0	7,8	7,7
15	10,9	10,8	10,6	10,3	10,0	9,8	9,7	9,4	9,1	8,9	8,7	8,5	8,3
16	11,7	11,5	11,4	11,0	10,7	10,5	10,4	10,1	9,8	9,6	9,4	9,2	9,0
17	12,4	12,3	12,1	11,7	11,4	11,3	11,1	10,8	10,5	10,3	10,1	9,8	9,7
18	13,1	13,0	12,8	12,5	12,1	12,0	11,8	11,5	11,3	11,0	10,8	10,5	10,3
19	13,9	13,7	13,6	13,2	12,9	12,7	12,6	12,3	12,0	11,7	11,5	11,2	11,0
20	14,6	14,5	14,3	13,9	13,6	13,5	13,3	13,0	12,7	12,4	12,2	11,9	11,7
21	15,4	15,2	15,0	14,7	14,3	14,2	14,0	13,7	13,4	13,1	12,9	12,6	12,4
22	16,1	15,9	15,8	15,4	15,1	14,9	14,8	14,4	14,1	13,9	13,6	13,3	13,1
23	16,8	16,7	16,5	16,2	15,8	15,7	15,5	15,2	14,9	14,6	14,3	14,1	13,8
24	17,6	17,4	17,2	16,9	16,6	16,4	16,2	15,9	15,6	15,3	15,0	14,8	14,5
25	18,3	18,2	18,0	17,6	17,3	17,1	17,0	16,6	16,3	16,0	15,8	15,5	15,2
26	19,0	18,9	18,7	18,4	18,0	17,9	17,7	17,4	17,1	16,8	16,5	16,2	15,9
27	19,8	19,6	19,5	19,1	18,8	18,6	18,4	18,1	17,8	17,5	17,2	16,9	16,7
28	20,5	20,4	20,2	19,8	19,5	19,3	19,2	18,8	18,5	18,2	17,9	17,7	17,4
29	21,3	21,1	20,9	20,6	20,2	20,1	19,9	19,6	19,3	19,0	18,7	18,4	18,1
30	22,0	21,9	21,7	21,3	21,0	20,8	20,6	20,3	20,0	19,7	19,4	19,1	18,8
31	22,7	22,6	22,4	22,1	21,7	21,5	21,4	21,1	20,7	20,4	20,1	19,8	19,6
32	23,5	23,3	23,2	22,8	22,5	22,3	22,1	21,8	21,5	21,2	20,9	20,6	20,3
33	24,2	24,1	23,9	23,5	23,2	23,0	22,9	22,5	22,2	21,9	21,6	21,3	21,0
34	25,0	24,8	24,6	24,3	23,9	23,8	23,6	23,3	22,9	22,6	22,3	22,0	21,7
35	25,7	25,6	25,4	25,0	24,7	24,5	24,3	24,0	23,7	23,4	23,1	22,8	22,5
36	26,4	26,3	26,1	25,8	25,4	25,3	25,1	24,7	24,4	24,1	23,8	23,5	23,2
37	27,2	27,0	26,9	26,5	26,2	26,0	25,8	25,5	25,2	24,8	24,5	24,2	23,9
38	27,9	27,8	27,6	27,3	26,9	26,7	26,6	26,2	25,9	25,6	25,3	25,0	24,7
39	28,7	28,5	28,4	28,0	27,6	27,5	27,3	27,0	26,6	26,3	26,0	25,7	25,4

40	29,4	29,3	29,1	28,7	28,4	28,2	28,0	27,7	27,4	27,1	26,7	26,4	26,1
41	30,2	30,0	29,8	29,5	29,1	29,0	28,8	28,5	28,1	27,8	27,5	27,2	26,9
42	30,9	30,8	30,6	30,2	29,9	29,7	29,5	29,2	28,9	28,5	28,2	27,9	27,6
43	31,7	31,5	31,3	31,0	30,6	30,5	30,3	29,9	29,6	29,3	29,0	28,6	28,3
44	32,4	32,3	32,1	31,7	31,4	31,2	31,0	30,7	30,4	30,0	29,7	29,4	29,1
45	33,1	33,0	32,8	32,5	32,1	31,9	31,8	31,4	31,1	30,8	30,4	30,1	29,8
46	33,9	33,7	33,6	33,2	32,9	32,7	32,5	32,2	31,8	31,5	31,2	30,9	30,6
47	34,6	34,5	34,3	34,0	33,6	33,4	33,3	32,9	32,6	32,3	31,9	31,6	31,3
48	35,4	35,2	35,1	34,7	34,4	34,2	34,0	33,7	33,3	33,0	32,7	32,4	32,0
49	36,1	36,0	35,8	35,4	35,1	34,9	34,8	34,4	34,1	33,7	33,4	33,1	32,8
50	36,9	36,7	36,6	36,2	35,8	35,7	35,5	35,2	34,8	34,5	34,2	33,8	33,5
51	37,6	37,5	37,3	36,9	36,6	36,4	36,2	35,9	35,6	35,2	34,9	34,6	34,3
52	38,4	38,2	38,0	37,7	37,3	37,2	37,0	36,7	36,3	36,0	35,7	35,3	35,0
53	39,1	39,0	38,8	38,4	38,1	37,9	37,7	37,4	37,1	36,7	36,4	36,1	35,8
54	39,9	39,7	39,5	39,2	38,8	38,7	38,5	38,1	37,8	37,5	37,1	36,8	36,5
55	40,6	40,5	40,3	39,9	39,6	39,4	39,2	38,9	38,6	38,2	37,9	37,6	37,2
56	41,4	41,2	41,0	40,7	40,3	40,2	40,0	39,6	39,3	39,0	38,6	38,3	38,0
57	42,1	42,0	41,8	41,4	41,1	40,9	40,7	40,4	40,1	39,7	39,4	39,1	38,7
58	42,9	42,7	42,5	42,2	41,8	41,7	41,5	41,1	40,8	40,5	40,1	39,8	39,5
59	43,6	43,5	43,3	42,9	42,6	42,4	42,2	41,9	41,6	41,2	40,9	40,6	40,2
60	44,4	44,2	44,0	43,7	43,3	43,2	43,0	42,6	42,3	42,0	41,6	41,3	41,0
61	45,1	45,0	44,8	44,4	44,1	43,9	43,7	43,4	43,1	42,7	42,4	42,1	41,7
62	45,9	45,7	45,6	45,2	44,8	44,7	44,5	44,1	43,8	43,5	43,1	42,8	42,5
63	46,6	46,5	46,3	45,9	45,6	45,4	45,2	44,9	44,6	44,2	43,9	43,6	43,2
64	47,4	47,2	47,1	46,7	46,3	46,2	46,0	45,7	45,3	45,0	44,6	44,3	44,0
65	48,1	48,0	47,8	47,5	47,1	46,9	46,8	46,4	46,1	45,7	45,4	45,1	44,7
66	48,9	48,7	48,6	48,2	47,9	47,7	47,5	47,2	46,8	46,5	46,1	45,8	45,5
67	49,6	49,5	49,3	49,0	48,6	48,4	48,3	47,9	47,6	47,2	46,9	46,6	46,2
68	50,4	50,2	50,1	49,7	49,4	49,2	49,0	48,7	48,3	48,0	47,6	47,3	47,0
69	51,1	51,0	50,8	50,5	50,1	49,9	49,8	49,4	49,1	48,7	48,4	48,1	47,7
70	51,9	51,8	51,6	51,2	50,9	50,7	50,5	50,2	49,8	49,5	49,2	48,8	48,5
71	52,7	52,5	52,3	52,0	51,6	51,5	51,3	50,9	50,6	50,2	49,9	49,6	49,2
72	53,4	53,3	53,1	52,7	52,4	52,2	52,0	51,7	51,3	51,0	50,7	50,3	50,0
73	54,2	54,0	53,8	53,5	53,1	53,0	52,8	52,4	52,1	51,8	51,4	51,1	50,8
74	54,9	54,8	54,6	54,2	53,9	53,7	53,5	53,2	52,9	52,5	52,2	51,8	51,5
75	55,7	55,5	55,4	55,0	54,7	54,5	54,3	54,0	53,6	53,3	52,9	52,6	52,3
76	56,4	56,3	56,1	55,8	55,4	55,2	55,1	54,7	54,4	54,0	53,7	53,4	53,0
77	57,2	57,1	56,9	56,5	56,2	56,0	55,8	55,5	55,1	54,8	54,4	54,1	53,8
78	58,0	57,8	57,6	57,3	56,9	56,7	56,6	56,2	55,9	55,5	55,2	54,9	54,5
79	58,7	58,6	58,4	58,0	57,7	57,5	57,3	57,0	56,6	56,3	56,0	55,6	55,3
80	59,5	59,3	59,2	58,8	58,4	58,3	58,1	57,7	57,4	57,1	56,7	56,4	56,1
81	60,2	60,1	59,9	59,6	59,2	59,0	58,9	58,5	58,2	57,8	57,5	57,1	56,8
82	61,0	60,8	60,7	60,3	60,0	59,8	59,6	59,3	58,9	58,6	58,2	57,9	57,6
83	61,8	61,6	61,4	61,1	60,7	60,5	60,4	60,0	59,7	59,3	59,0	58,7	58,3
84	62,5	62,4	62,2	61,8	61,5	61,3	61,1	60,8	60,4	60,1	59,8	59,4	59,1

85	63,3	63,1	63,0	62,6	62,2	62,1	61,9	61,5	61,2	60,9	60,5	60,2	59,8
86	64,0	63,9	63,7	63,4	63,0	62,8	62,7	62,3	62,0	61,6	61,3	60,9	60,6
87	64,8	64,7	64,5	64,1	63,8	63,6	63,4	63,1	62,7	62,4	62,0	61,7	61,4
88	65,6	65,4	65,2	64,9	64,5	64,4	64,2	63,8	63,5	63,1	62,8	62,5	62,1
89	66,3	66,2	66,0	65,6	65,3	65,1	64,9	64,6	64,2	63,9	63,6	63,2	62,9
90	67,1	66,9	66,8	66,4	66,1	65,9	65,7	65,4	65,0	64,7	64,3	64,0	63,7
91	67,8	67,7	67,5	67,2	66,8	66,6	66,5	66,1	65,8	65,4	65,1	64,7	64,4
92	68,6	68,5	68,3	67,9	67,6	67,4	67,2	66,9	66,5	66,2	65,8	65,5	65,2
93	69,4	69,2	69,1	68,7	68,3	68,2	68,0	67,6	67,3	67,0	66,6	66,3	65,9
94	70,1	70,0	69,8	69,5	69,1	68,9	68,8	68,4	68,1	67,7	67,4	67,0	66,7
95	70,9	70,8	70,6	70,2	69,9	69,7	69,5	69,2	68,8	68,5	68,1	67,8	67,5
96	71,7	71,5	71,3	71,0	70,6	70,5	70,3	69,9	69,6	69,2	68,9	68,6	68,2
97	72,4	72,3	72,1	71,8	71,4	71,2	71,1	70,7	70,4	70,0	69,7	69,3	69,0
98	73,2	73,1	72,9	72,5	72,2	72,0	71,8	71,5	71,1	70,8	70,4	70,1	69,8
99	74,0	73,8	73,6	73,3	72,9	72,8	72,6	72,2	71,9	71,5	71,2	70,9	70,5
100	74,7	74,6	74,4	74,1	73,7	73,5	73,3	73,0	72,7	72,3	72,0	71,6	71,3

Residual fault current [A], feeder J11, length 12,8km

I_{ef} [A]	I_L= 1A	I_L= 5A	I_L= 10A	I_L= 20A	I_L= 30A	I_L= 40A	I_L= 50A	I_L= 60A	I_L= 70A	I_L= 80A	I_L= 90A	I_L= 100A
1	0,7	3,6	7,3	14,6	22,0	29,4	36,9	44,4	51,9	59,5	67,1	74,7
2	0,7	3,6	7,2	14,6	22,0	29,4	36,8	44,3	51,9	59,4	67,0	74,7
3	0,6	3,5	7,2	14,5	21,9	29,3	36,8	44,3	51,8	59,4	67,0	74,7
4	0,6	3,5	7,2	14,5	21,9	29,3	36,8	44,3	51,8	59,4	67,0	74,6
5	0,6	3,5	7,1	14,5	21,9	29,3	36,7	44,2	51,8	59,3	66,9	74,6
6	0,6	3,4	7,1	14,4	21,8	29,2	36,7	44,2	51,7	59,3	66,9	74,6
7	0,6	3,4	7,1	14,4	21,8	29,2	36,7	44,2	51,7	59,3	66,9	74,5
8	0,5	3,4	7,0	14,4	21,7	29,2	36,6	44,1	51,7	59,2	66,8	74,5
9	0,5	3,3	7,0	14,3	21,7	29,1	36,6	44,1	51,6	59,2	66,8	74,4
10	0,5	3,3	7,0	14,3	21,7	29,1	36,6	44,0	51,6	59,2	66,8	74,4
11	0,5	3,3	6,9	14,3	21,6	29,1	36,5	44,0	51,5	59,1	66,7	74,4
12	0,6	3,2	6,9	14,2	21,6	29,0	36,5	44,0	51,5	59,1	66,7	74,3
13	0,6	3,2	6,9	14,2	21,6	29,0	36,4	43,9	51,5	59,0	66,7	74,3
14	0,6	3,2	6,8	14,2	21,5	29,0	36,4	43,9	51,4	59,0	66,6	74,3
15	0,6	3,2	6,8	14,1	21,5	28,9	36,4	43,9	51,4	59,0	66,6	74,2
16	0,7	3,1	6,8	14,1	21,5	28,9	36,3	43,8	51,4	58,9	66,5	74,2
17	0,7	3,1	6,7	14,1	21,4	28,8	36,3	43,8	51,3	58,9	66,5	74,2
18	0,7	3,1	6,7	14,0	21,4	28,8	36,3	43,8	51,3	58,9	66,5	74,1
19	0,8	3,1	6,7	14,0	21,4	28,8	36,2	43,7	51,3	58,8	66,4	74,1
20	0,8	3,0	6,6	13,9	21,3	28,7	36,2	43,7	51,2	58,8	66,4	74,1
21	0,8	3,0	6,6	13,9	21,3	28,7	36,2	43,7	51,2	58,8	66,4	74,0
22	0,9	3,0	6,6	13,9	21,3	28,7	36,1	43,6	51,2	58,7	66,3	74,0
23	0,9	3,0	6,5	13,8	21,2	28,6	36,1	43,6	51,1	58,7	66,3	73,9
24	1,0	2,9	6,5	13,8	21,2	28,6	36,1	43,5	51,1	58,7	66,3	73,9
25	1,0	2,9	6,5	13,8	21,2	28,6	36,0	43,5	51,0	58,6	66,2	73,9
26	1,1	2,9	6,4	13,7	21,1	28,5	36,0	43,5	51,0	58,6	66,2	73,8
27	1,1	2,9	6,4	13,7	21,1	28,5	36,0	43,4	51,0	58,5	66,2	73,8
28	1,2	2,9	6,4	13,7	21,0	28,5	35,9	43,4	50,9	58,5	66,1	73,8
29	1,2	2,8	6,4	13,6	21,0	28,4	35,9	43,4	50,9	58,5	66,1	73,7
30	1,3	2,8	6,3	13,6	21,0	28,4	35,8	43,3	50,9	58,4	66,1	73,7
31	1,3	2,8	6,3	13,6	20,9	28,4	35,8	43,3	50,8	58,4	66,0	73,7
32	1,4	2,8	6,3	13,5	20,9	28,3	35,8	43,3	50,8	58,4	66,0	73,6
33	1,4	2,8	6,2	13,5	20,9	28,3	35,7	43,2	50,8	58,3	65,9	73,6
34	1,5	2,8	6,2	13,5	20,8	28,3	35,7	43,2	50,7	58,3	65,9	73,6
35	1,5	2,8	6,2	13,5	20,8	28,2	35,7	43,2	50,7	58,3	65,9	73,5
36	1,6	2,7	6,2	13,4	20,8	28,2	35,6	43,1	50,7	58,2	65,8	73,5
37	1,6	2,7	6,1	13,4	20,7	28,2	35,6	43,1	50,6	58,2	65,8	73,5
38	1,7	2,7	6,1	13,4	20,7	28,1	35,6	43,1	50,6	58,2	65,8	73,4
39	1,7	2,7	6,1	13,3	20,7	28,1	35,5	43,0	50,6	58,1	65,7	73,4
40	1,8	2,7	6,1	13,3	20,6	28,0	35,5	43,0	50,5	58,1	65,7	73,3
41	1,8	2,7	6,0	13,3	20,6	28,0	35,5	43,0	50,5	58,1	65,7	73,3
42	1,9	2,7	6,0	13,2	20,6	28,0	35,4	42,9	50,5	58,0	65,6	73,3

43	1,9	2,7	6,0	13,2	20,5	27,9	35,4	42,9	50,4	58,0	65,6	73,2
44	2,0	2,7	6,0	13,2	20,5	27,9	35,4	42,9	50,4	58,0	65,6	73,2
45	2,0	2,7	5,9	13,1	20,5	27,9	35,3	42,8	50,3	57,9	65,5	73,2
46	2,1	2,7	5,9	13,1	20,4	27,8	35,3	42,8	50,3	57,9	65,5	73,1
47	2,1	2,7	5,9	13,1	20,4	27,8	35,3	42,7	50,3	57,8	65,5	73,1
48	2,2	2,7	5,9	13,0	20,4	27,8	35,2	42,7	50,2	57,8	65,4	73,1
49	2,2	2,7	5,9	13,0	20,3	27,7	35,2	42,7	50,2	57,8	65,4	73,0
50	2,3	2,7	5,8	13,0	20,3	27,7	35,2	42,6	50,2	57,7	65,4	73,0
51	2,3	2,7	5,8	13,0	20,3	27,7	35,1	42,6	50,1	57,7	65,3	73,0
52	2,4	2,7	5,8	12,9	20,3	27,6	35,1	42,6	50,1	57,7	65,3	72,9
53	2,4	2,7	5,8	12,9	20,2	27,6	35,1	42,5	50,1	57,6	65,2	72,9
54	2,5	2,7	5,8	12,9	20,2	27,6	35,0	42,5	50,0	57,6	65,2	72,9
55	2,5	2,7	5,7	12,8	20,2	27,5	35,0	42,5	50,0	57,6	65,2	72,8
56	2,6	2,8	5,7	12,8	20,1	27,5	35,0	42,4	50,0	57,5	65,1	72,8
57	2,7	2,8	5,7	12,8	20,1	27,5	34,9	42,4	49,9	57,5	65,1	72,8
58	2,7	2,8	5,7	12,8	20,1	27,4	34,9	42,4	49,9	57,5	65,1	72,7
59	2,8	2,8	5,7	12,7	20,0	27,4	34,9	42,3	49,9	57,4	65,0	72,7
60	2,8	2,8	5,7	12,7	20,0	27,4	34,8	42,3	49,8	57,4	65,0	72,7
61	2,9	2,8	5,6	12,7	20,0	27,4	34,8	42,3	49,8	57,4	65,0	72,6
62	2,9	2,8	5,6	12,6	19,9	27,3	34,8	42,2	49,8	57,3	64,9	72,6
63	3,0	2,9	5,6	12,6	19,9	27,3	34,7	42,2	49,7	57,3	64,9	72,6
64	3,0	2,9	5,6	12,6	19,9	27,3	34,7	42,2	49,7	57,3	64,9	72,5
65	3,1	2,9	5,6	12,6	19,8	27,2	34,7	42,1	49,7	57,2	64,8	72,5
66	3,1	2,9	5,6	12,5	19,8	27,2	34,6	42,1	49,6	57,2	64,8	72,4
67	3,2	2,9	5,6	12,5	19,8	27,2	34,6	42,1	49,6	57,2	64,8	72,4
68	3,2	3,0	5,5	12,5	19,8	27,1	34,6	42,0	49,6	57,1	64,7	72,4
69	3,3	3,0	5,5	12,4	19,7	27,1	34,5	42,0	49,5	57,1	64,7	72,3
70	3,3	3,0	5,5	12,4	19,7	27,1	34,5	42,0	49,5	57,1	64,7	72,3
71	3,4	3,0	5,5	12,4	19,7	27,0	34,5	41,9	49,5	57,0	64,6	72,3
72	3,5	3,1	5,5	12,4	19,6	27,0	34,4	41,9	49,4	57,0	64,6	72,2
73	3,5	3,1	5,5	12,3	19,6	27,0	34,4	41,9	49,4	57,0	64,6	72,2
74	3,6	3,1	5,5	12,3	19,6	26,9	34,4	41,8	49,4	56,9	64,5	72,2
75	3,6	3,1	5,5	12,3	19,5	26,9	34,3	41,8	49,3	56,9	64,5	72,1
76	3,7	3,2	5,5	12,3	19,5	26,9	34,3	41,8	49,3	56,9	64,5	72,1
77	3,7	3,2	5,5	12,2	19,5	26,8	34,3	41,7	49,3	56,8	64,4	72,1
78	3,8	3,2	5,4	12,2	19,5	26,8	34,2	41,7	49,2	56,8	64,4	72,0
79	3,8	3,3	5,4	12,2	19,4	26,8	34,2	41,7	49,2	56,8	64,4	72,0
80	3,9	3,3	5,4	12,2	19,4	26,7	34,2	41,6	49,2	56,7	64,3	72,0
81	3,9	3,3	5,4	12,1	19,4	26,7	34,1	41,6	49,1	56,7	64,3	71,9
82	4,0	3,3	5,4	12,1	19,3	26,7	34,1	41,6	49,1	56,7	64,3	71,9
83	4,0	3,4	5,4	12,1	19,3	26,6	34,1	41,5	49,1	56,6	64,2	71,9
84	4,1	3,4	5,4	12,1	19,3	26,6	34,0	41,5	49,0	56,6	64,2	71,8
85	4,2	3,4	5,4	12,0	19,2	26,6	34,0	41,5	49,0	56,6	64,2	71,8
86	4,2	3,5	5,4	12,0	19,2	26,6	34,0	41,4	49,0	56,5	64,1	71,8
87	4,3	3,5	5,4	12,0	19,2	26,5	33,9	41,4	48,9	56,5	64,1	71,7

88	4,3	3,5	5,4	12,0	19,2	26,5	33,9	41,4	48,9	56,5	64,1	71,7
89	4,4	3,6	5,4	12,0	19,1	26,5	33,9	41,3	48,9	56,4	64,0	71,7
90	4,4	3,6	5,4	11,9	19,1	26,4	33,8	41,3	48,8	56,4	64,0	71,6
91	4,5	3,7	5,4	11,9	19,1	26,4	33,8	41,3	48,8	56,4	64,0	71,6
92	4,5	3,7	5,4	11,9	19,0	26,4	33,8	41,2	48,8	56,3	63,9	71,6
93	4,6	3,7	5,4	11,9	19,0	26,3	33,7	41,2	48,7	56,3	63,9	71,5
94	4,6	3,8	5,4	11,8	19,0	26,3	33,7	41,2	48,7	56,3	63,9	71,5
95	4,7	3,8	5,4	11,8	19,0	26,3	33,7	41,1	48,7	56,2	63,8	71,5
96	4,7	3,8	5,4	11,8	18,9	26,3	33,7	41,1	48,6	56,2	63,8	71,4
97	4,8	3,9	5,4	11,8	18,9	26,2	33,6	41,1	48,6	56,2	63,8	71,4
98	4,9	3,9	5,4	11,8	18,9	26,2	33,6	41,1	48,6	56,1	63,7	71,4
99	4,9	4,0	5,4	11,7	18,9	26,2	33,6	41,0	48,5	56,1	63,7	71,3
100	5,0	4,0	5,4	11,7	18,8	26,1	33,5	41,0	48,5	56,1	63,7	71,3

Residual fault current [A], feeder J11, length 4,5km

I_L [A]	I_{ef} = 1A	I_{ef} =5A	I_{ef} =10A	I_{ef} =20A	I_{ef} =35A	I_{ef} =50A	I_{ef} =70A	I_{ef} =100A
1	0,4	0,3	0,8	1,9	3,6	5,2	7,5	10,8
2	0,8	0,5	0,7	1,6	3,2	4,9	7,1	10,5
3	1,2	0,9	0,8	1,4	3,0	4,6	6,8	10,1
4	1,7	1,4	1,1	1,3	2,7	4,3	6,5	9,8
5	2,1	1,8	1,5	1,4	2,5	4,0	6,2	9,5
6	2,6	2,2	1,9	1,6	2,4	3,8	5,9	9,2
7	3,0	2,7	2,3	1,9	2,3	3,6	5,7	8,9
8	3,4	3,1	2,7	2,2	2,4	3,5	5,4	8,6
9	3,9	3,5	3,1	2,5	2,5	3,4	5,2	8,3
10	4,3	4,0	3,6	2,9	2,7	3,3	5,0	8,1
11	4,8	4,4	4,0	3,3	2,9	3,4	4,9	7,8
12	5,2	4,9	4,4	3,7	3,2	3,4	4,8	7,6
13	5,6	5,3	4,9	4,2	3,5	3,6	4,7	7,4
14	6,1	5,7	5,3	4,6	3,8	3,7	4,7	7,2
15	6,5	6,2	5,8	5,0	4,2	4,0	4,7	7,1
16	7,0	6,6	6,2	5,4	4,6	4,2	4,7	6,9
17	7,4	7,1	6,6	5,9	4,9	4,5	4,8	6,8
18	7,8	7,5	7,1	6,3	5,3	4,8	4,9	6,7
19	8,3	7,9	7,5	6,7	5,7	5,1	5,1	6,7
20	8,7	8,4	7,9	7,1	6,1	5,5	5,3	6,7
21	9,2	8,8	8,4	7,6	6,5	5,8	5,5	6,7
22	9,6	9,3	8,8	8,0	7,0	6,2	5,8	6,7
23	10,1	9,7	9,3	8,5	7,4	6,6	6,1	6,8
24	10,5	10,1	9,7	8,9	7,8	7,0	6,3	6,9
25	10,9	10,6	10,1	9,3	8,2	7,3	6,7	7,0
26	11,4	11,0	10,6	9,8	8,6	7,7	7,0	7,1
27	11,8	11,5	11,0	10,2	9,1	8,1	7,3	7,3
28	12,3	11,9	11,5	10,6	9,5	8,5	7,7	7,5
29	12,7	12,3	11,9	11,1	9,9	9,0	8,0	7,7
30	13,1	12,8	12,4	11,5	10,4	9,4	8,4	7,9
31	13,6	13,2	12,8	12,0	10,8	9,8	8,7	8,2
32	14,0	13,7	13,2	12,4	11,2	10,2	9,1	8,4
33	14,5	14,1	13,7	12,8	11,7	10,6	9,5	8,7
34	14,9	14,6	14,1	13,3	12,1	11,0	9,9	9,0
35	15,4	15,0	14,6	13,7	12,5	11,5	10,3	9,3
36	15,8	15,4	15,0	14,2	13,0	11,9	10,7	9,6
37	16,2	15,9	15,4	14,6	13,4	12,3	11,1	9,9
38	16,7	16,3	15,9	15,0	13,8	12,7	11,5	10,3
39	17,1	16,8	16,3	15,5	14,3	13,2	11,9	10,6
40	17,6	17,2	16,8	15,9	14,7	13,6	12,3	11,0
41	18,0	17,6	17,2	16,4	15,1	14,0	12,7	11,3
42	18,4	18,1	17,7	16,8	15,6	14,5	13,1	11,7

43	18,9	18,5	18,1	17,2	16,0	14,9	13,5	12,0
44	19,3	19,0	18,5	17,7	16,5	15,3	14,0	12,4
45	19,8	19,4	19,0	18,1	16,9	15,7	14,4	12,8
46	20,2	19,9	19,4	18,6	17,3	16,2	14,8	13,2
47	20,7	20,3	19,9	19,0	17,8	16,6	15,2	13,5
48	21,1	20,7	20,3	19,4	18,2	17,0	15,6	13,9
49	21,5	21,2	20,8	19,9	18,7	17,5	16,1	14,3
50	22,0	21,6	21,2	20,3	19,1	17,9	16,5	14,7
51	22,4	22,1	21,6	20,8	19,5	18,4	16,9	15,1
52	22,9	22,5	22,1	21,2	20,0	18,8	17,3	15,5
53	23,3	23,0	22,5	21,7	20,4	19,2	17,8	15,9
54	23,8	23,4	23,0	22,1	20,8	19,7	18,2	16,3
55	24,2	23,8	23,4	22,5	21,3	20,1	18,6	16,7
56	24,6	24,3	23,9	23,0	21,7	20,5	19,1	17,1
57	25,1	24,7	24,3	23,4	22,2	21,0	19,5	17,5
58	25,5	25,2	24,7	23,9	22,6	21,4	19,9	18,0
59	26,0	25,6	25,2	24,3	23,1	21,8	20,3	18,4
60	26,4	26,1	25,6	24,8	23,5	22,3	20,8	18,8
61	26,9	26,5	26,1	25,2	23,9	22,7	21,2	19,2
62	27,3	26,9	26,5	25,6	24,4	23,2	21,6	19,6
63	27,7	27,4	27,0	26,1	24,8	23,6	22,1	20,0
64	28,2	27,8	27,4	26,5	25,3	24,0	22,5	20,5
65	28,6	28,3	27,8	27,0	25,7	24,5	22,9	20,9
66	29,1	28,7	28,3	27,4	26,1	24,9	23,4	21,3
67	29,5	29,2	28,7	27,9	26,6	25,4	23,8	21,7
68	30,0	29,6	29,2	28,3	27,0	25,8	24,3	22,1
69	30,4	30,1	29,6	28,7	27,5	26,2	24,7	22,6
70	30,9	30,5	30,1	29,2	27,9	26,7	25,1	23,0
71	31,3	30,9	30,5	29,6	28,4	27,1	25,6	23,4
72	31,7	31,4	30,9	30,1	28,8	27,6	26,0	23,8
73	32,2	31,8	31,4	30,5	29,2	28,0	26,4	24,3
74	32,6	32,3	31,8	31,0	29,7	28,4	26,9	24,7
75	33,1	32,7	32,3	31,4	30,1	28,9	27,3	25,1
76	33,5	33,2	32,7	31,8	30,6	29,3	27,8	25,6
77	34,0	33,6	33,2	32,3	31,0	29,8	28,2	26,0
78	34,4	34,0	33,6	32,7	31,5	30,2	28,6	26,4
79	34,8	34,5	34,1	33,2	31,9	30,7	29,1	26,8
80	35,3	34,9	34,5	33,6	32,3	31,1	29,5	27,3
81	35,7	35,4	34,9	34,1	32,8	31,5	29,9	27,7
82	36,2	35,8	35,4	34,5	33,2	32,0	30,4	28,1
83	36,6	36,3	35,8	35,0	33,7	32,4	30,8	28,6
84	37,1	36,7	36,3	35,4	34,1	32,9	31,3	29,0
85	37,5	37,2	36,7	35,8	34,6	33,3	31,7	29,4
86	38,0	37,6	37,2	36,3	35,0	33,8	32,1	29,9
87	38,4	38,0	37,6	36,7	35,4	34,2	32,6	30,3

88	38,8	38,5	38,1	37,2	35,9	34,6	33,0	30,7
89	39,3	38,9	38,5	37,6	36,3	35,1	33,5	31,2
90	39,7	39,4	38,9	38,1	36,8	35,5	33,9	31,6
91	40,2	39,8	39,4	38,5	37,2	36,0	34,3	32,1
92	40,6	40,3	39,8	39,0	37,7	36,4	34,8	32,5
93	41,1	40,7	40,3	39,4	38,1	36,9	35,2	32,9
94	41,5	41,2	40,7	39,8	38,6	37,3	35,7	33,4
95	42,0	41,6	41,2	40,3	39,0	37,7	36,1	33,8
96	42,4	42,1	41,6	40,7	39,4	38,2	36,6	34,2
97	42,9	42,5	42,1	41,2	39,9	38,6	37,0	34,7
98	43,3	42,9	42,5	41,6	40,3	39,1	37,4	35,1
99	43,7	43,4	42,9	42,1	40,8	39,5	37,9	35,5
100	44,2	43,8	43,4	42,5	41,2	40,0	38,3	36,0

Residual fault current [A], feeder J11, length 4,5km

I_{ef} [A]	I_L = 1A	I_L = 5A	I_L = 10A	I_L = 20A	I_L = 30A	I_L = 40A	I_L = 50A	I_L = 60A	I_L = 70A	I_L = 80A	I_L = 90A	I_L = 100A
1	0,4	2,1	4,3	8,7	13,1	17,6	22,0	26,4	30,9	35,3	39,7	44,2
2	0,3	2,0	4,2	8,6	13,1	17,5	21,9	26,3	30,8	35,2	39,7	44,1
3	0,3	1,9	4,1	8,5	13,0	17,4	21,8	26,2	30,7	35,1	39,6	44,0
4	0,3	1,9	4,1	8,5	12,9	17,3	21,7	26,2	30,6	35,0	39,5	43,9
5	0,3	1,8	4,0	8,4	12,8	17,2	21,6	26,1	30,5	34,9	39,4	43,8
6	0,4	1,7	3,9	8,3	12,7	17,1	21,5	26,0	30,4	34,8	39,3	43,7
7	0,5	1,6	3,8	8,2	12,6	17,0	21,5	25,9	30,3	34,8	39,2	43,7
8	0,6	1,6	3,7	8,1	12,5	16,9	21,4	25,8	30,2	34,7	39,1	43,6
9	0,7	1,5	3,6	8,0	12,4	16,9	21,3	25,7	30,1	34,6	39,0	43,5
10	0,8	1,5	3,6	7,9	12,4	16,8	21,2	25,6	30,1	34,5	38,9	43,4
11	0,9	1,4	3,5	7,9	12,3	16,7	21,1	25,5	30,0	34,4	38,9	43,3
12	1,0	1,4	3,4	7,8	12,2	16,6	21,0	25,4	29,9	34,3	38,8	43,2
13	1,1	1,4	3,4	7,7	12,1	16,5	20,9	25,4	29,8	34,2	38,7	43,1
14	1,2	1,3	3,3	7,6	12,0	16,4	20,8	25,3	29,7	34,1	38,6	43,0
15	1,3	1,3	3,2	7,5	11,9	16,3	20,8	25,2	29,6	34,1	38,5	43,0
16	1,5	1,3	3,2	7,5	11,8	16,3	20,7	25,1	29,5	34,0	38,4	42,9
17	1,6	1,3	3,1	7,4	11,8	16,2	20,6	25,0	29,4	33,9	38,3	42,8
18	1,7	1,3	3,0	7,3	11,7	16,1	20,5	24,9	29,4	33,8	38,2	42,7
19	1,8	1,4	3,0	7,2	11,6	16,0	20,4	24,8	29,3	33,7	38,2	42,6
20	1,9	1,4	2,9	7,1	11,5	15,9	20,3	24,8	29,2	33,6	38,1	42,5
21	2,0	1,4	2,9	7,1	11,4	15,8	20,2	24,7	29,1	33,5	38,0	42,4
22	2,1	1,5	2,8	7,0	11,4	15,8	20,2	24,6	29,0	33,5	37,9	42,3
23	2,2	1,5	2,8	6,9	11,3	15,7	20,1	24,5	28,9	33,4	37,8	42,3
24	2,3	1,6	2,8	6,9	11,2	15,6	20,0	24,4	28,8	33,3	37,7	42,2
25	2,5	1,7	2,7	6,8	11,1	15,5	19,9	24,3	28,8	33,2	37,6	42,1
26	2,6	1,7	2,7	6,7	11,0	15,4	19,8	24,2	28,7	33,1	37,5	42,0
27	2,7	1,8	2,7	6,6	11,0	15,3	19,7	24,2	28,6	33,0	37,5	41,9
28	2,8	1,9	2,7	6,6	10,9	15,3	19,7	24,1	28,5	32,9	37,4	41,8
29	2,9	2,0	2,6	6,5	10,8	15,2	19,6	24,0	28,4	32,9	37,3	41,7
30	3,0	2,1	2,6	6,4	10,7	15,1	19,5	23,9	28,3	32,8	37,2	41,7
31	3,1	2,1	2,6	6,4	10,7	15,0	19,4	23,8	28,2	32,7	37,1	41,6
32	3,2	2,2	2,6	6,3	10,6	14,9	19,3	23,7	28,2	32,6	37,0	41,5
33	3,3	2,3	2,6	6,3	10,5	14,9	19,3	23,7	28,1	32,5	37,0	41,4
34	3,5	2,4	2,6	6,2	10,4	14,8	19,2	23,6	28,0	32,4	36,9	41,3
35	3,6	2,5	2,7	6,1	10,4	14,7	19,1	23,5	27,9	32,3	36,8	41,2
36	3,7	2,6	2,7	6,1	10,3	14,6	19,0	23,4	27,8	32,3	36,7	41,1
37	3,8	2,7	2,7	6,0	10,2	14,6	18,9	23,3	27,7	32,2	36,6	41,1
38	3,9	2,8	2,7	6,0	10,1	14,5	18,8	23,2	27,7	32,1	36,5	41,0
39	4,0	2,9	2,8	5,9	10,1	14,4	18,8	23,2	27,6	32,0	36,4	40,9
40	4,1	3,0	2,8	5,9	10,0	14,3	18,7	23,1	27,5	31,9	36,4	40,8
41	4,2	3,1	2,8	5,8	9,9	14,2	18,6	23,0	27,4	31,8	36,3	40,7
42	4,3	3,2	2,9	5,8	9,9	14,2	18,5	22,9	27,3	31,8	36,2	40,6

43	4,5	3,3	2,9	5,7	9,8	14,1	18,5	22,8	27,3	31,7	36,1	40,5
44	4,6	3,4	3,0	5,7	9,7	14,0	18,4	22,8	27,2	31,6	36,0	40,5
45	4,7	3,5	3,0	5,6	9,7	13,9	18,3	22,7	27,1	31,5	35,9	40,4
46	4,8	3,6	3,1	5,6	9,6	13,9	18,2	22,6	27,0	31,4	35,9	40,3
47	4,9	3,7	3,1	5,6	9,5	13,8	18,1	22,5	26,9	31,3	35,8	40,2
48	5,0	3,8	3,2	5,5	9,5	13,7	18,1	22,4	26,8	31,3	35,7	40,1
49	5,1	3,9	3,3	5,5	9,4	13,7	18,0	22,4	26,8	31,2	35,6	40,0
50	5,2	4,0	3,3	5,5	9,4	13,6	17,9	22,3	26,7	31,1	35,5	40,0
51	5,4	4,1	3,4	5,4	9,3	13,5	17,8	22,2	26,6	31,0	35,4	39,9
52	5,5	4,3	3,5	5,4	9,2	13,5	17,8	22,1	26,5	30,9	35,4	39,8
53	5,6	4,4	3,5	5,4	9,2	13,4	17,7	22,1	26,4	30,9	35,3	39,7
54	5,7	4,5	3,6	5,4	9,1	13,3	17,6	22,0	26,4	30,8	35,2	39,6
55	5,8	4,6	3,7	5,3	9,1	13,2	17,5	21,9	26,3	30,7	35,1	39,5
56	5,9	4,7	3,8	5,3	9,0	13,2	17,5	21,8	26,2	30,6	35,0	39,5
57	6,0	4,8	3,9	5,3	9,0	13,1	17,4	21,7	26,1	30,5	35,0	39,4
58	6,1	4,9	3,9	5,3	8,9	13,0	17,3	21,7	26,0	30,5	34,9	39,3
59	6,2	5,0	4,0	5,3	8,9	13,0	17,3	21,6	26,0	30,4	34,8	39,2
60	6,4	5,1	4,1	5,3	8,8	12,9	17,2	21,5	25,9	30,3	34,7	39,1
61	6,5	5,2	4,2	5,3	8,8	12,8	17,1	21,4	25,8	30,2	34,6	39,1
62	6,6	5,3	4,3	5,3	8,7	12,8	17,0	21,4	25,7	30,1	34,5	39,0
63	6,7	5,4	4,4	5,3	8,7	12,7	17,0	21,3	25,7	30,1	34,5	38,9
64	6,8	5,5	4,5	5,3	8,6	12,7	16,9	21,2	25,6	30,0	34,4	38,8
65	6,9	5,7	4,6	5,3	8,6	12,6	16,8	21,1	25,5	29,9	34,3	38,7
66	7,0	5,8	4,6	5,3	8,5	12,5	16,8	21,1	25,4	29,8	34,2	38,6
67	7,1	5,9	4,7	5,3	8,5	12,5	16,7	21,0	25,4	29,7	34,1	38,6
68	7,3	6,0	4,8	5,3	8,5	12,4	16,6	20,9	25,3	29,7	34,1	38,5
69	7,4	6,1	4,9	5,3	8,4	12,4	16,6	20,9	25,2	29,6	34,0	38,4
70	7,5	6,2	5,0	5,3	8,4	12,3	16,5	20,8	25,1	29,5	33,9	38,3
71	7,6	6,3	5,1	5,3	8,3	12,2	16,4	20,7	25,1	29,4	33,8	38,2
72	7,7	6,4	5,2	5,3	8,3	12,2	16,4	20,6	25,0	29,3	33,7	38,2
73	7,8	6,5	5,3	5,4	8,3	12,1	16,3	20,6	24,9	29,3	33,7	38,1
74	7,9	6,6	5,4	5,4	8,2	12,1	16,2	20,5	24,8	29,2	33,6	38,0
75	8,0	6,7	5,5	5,4	8,2	12,0	16,2	20,4	24,8	29,1	33,5	37,9
76	8,1	6,9	5,6	5,4	8,2	12,0	16,1	20,4	24,7	29,0	33,4	37,8
77	8,3	7,0	5,7	5,5	8,1	11,9	16,0	20,3	24,6	29,0	33,4	37,8
78	8,4	7,1	5,8	5,5	8,1	11,9	16,0	20,2	24,5	28,9	33,3	37,7
79	8,5	7,2	5,9	5,5	8,1	11,8	15,9	20,1	24,5	28,8	33,2	37,6
80	8,6	7,3	6,0	5,6	8,1	11,8	15,8	20,1	24,4	28,7	33,1	37,5
81	8,7	7,4	6,1	5,6	8,0	11,7	15,8	20,0	24,3	28,7	33,0	37,4
82	8,8	7,5	6,2	5,7	8,0	11,7	15,7	19,9	24,2	28,6	33,0	37,4
83	8,9	7,6	6,3	5,7	8,0	11,6	15,7	19,9	24,2	28,5	32,9	37,3
84	9,0	7,7	6,4	5,7	8,0	11,6	15,6	19,8	24,1	28,4	32,8	37,2
85	9,2	7,8	6,5	5,8	8,0	11,5	15,5	19,7	24,0	28,4	32,7	37,1
86	9,3	8,0	6,6	5,8	8,0	11,5	15,5	19,7	24,0	28,3	32,7	37,1
87	9,4	8,1	6,7	5,9	7,9	11,4	15,4	19,6	23,9	28,2	32,6	37,0

88	9,5	8,2	6,8	5,9	7,9	11,4	15,4	19,5	23,8	28,1	32,5	36,9
89	9,6	8,3	6,9	6,0	7,9	11,4	15,3	19,5	23,7	28,1	32,4	36,8
90	9,7	8,4	7,0	6,0	7,9	11,3	15,3	19,4	23,7	28,0	32,4	36,7
91	9,8	8,5	7,1	6,1	7,9	11,3	15,2	19,3	23,6	27,9	32,3	36,7
92	9,9	8,6	7,2	6,2	7,9	11,2	15,1	19,3	23,5	27,9	32,2	36,6
93	10,0	8,7	7,3	6,2	7,9	11,2	15,1	19,2	23,5	27,8	32,1	36,5
94	10,2	8,8	7,4	6,3	7,9	11,2	15,0	19,2	23,4	27,7	32,1	36,4
95	10,3	8,9	7,5	6,3	7,9	11,1	15,0	19,1	23,3	27,6	32,0	36,4
96	10,4	9,1	7,7	6,4	7,9	11,1	14,9	19,0	23,3	27,6	31,9	36,3
97	10,5	9,2	7,8	6,5	7,9	11,0	14,9	19,0	23,2	27,5	31,8	36,2
98	10,6	9,3	7,9	6,5	7,9	11,0	14,8	18,9	23,1	27,4	31,8	36,1
99	10,7	9,4	8,0	6,6	7,9	11,0	14,8	18,8	23,1	27,3	31,7	36,1
100	10,8	9,5	8,1	6,7	7,9	11,0	14,7	18,8	23,0	27,3	31,6	36,0