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EARTH FAULT PROTECTION OF COMPENSATED RURAL AREA CABLED MEDIUM VOLTAGE NETWORKS

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Elina Määttä

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SYMBOLS AND ABBREVIATIONS

Symbols

φ	Phase angle
φ_0	Relay characteristic angle
$\Delta\varphi$	Relay tolerance
ω	Angular frequency
$3\underline{I}_0$	Residual current
$3\underline{I}_{0\_fault}$	Residual current during fault
$3\underline{I}_{0\_prefault}$	Residual current before fault
a_0	Zero sequence network coordinate base of three phasors
a_1	Positive sequence network coordinate base of three phasors
a_2	Negative sequence network coordinate base of three phasors
B	Susceptance
B_{Bg}	Background network susceptance of local compensation coil
B_{Bgtot}	Total susceptance of background network
B_{cCC}	Susceptance of compensation coil at the substation
B_{Fd}	Protected feeder susceptance of local compensation coil
B_{Fdtot}	Total suceptance of protected feeder
B_{whole}	Total network susceptance
C	Total phase-to-earth capacitance
C_0	Phase-to-earth capacitance per phase
C_{Fd}	Capacitance per phase of faulted feeder
d	Distance between conductors
d_{i0}	Distance between cable's conductor and earthing wire
$\underline{E}$	Phase-to-earth voltage
$\underline{E}_{\mathrm{a}}$	Phase-to-earth voltage in phase a
G	Conductance
G_{Bg}	Background network conductance of local compensation coil
G_{Bgtot}	Total conductance of background network
G_{cCC}	Conductance of compensation coil at the substation
G_{cc}	Parallel resistor conductance

G_{FBg}	Fault conductance of background network
G_{Fd}	Protected feeder conductance of local compensation coil
G_{Fdtot}	Total conductance of protected feeder
G_{FFd}	Fault conductance of protected feeder
G_{whole}	Total network conductance
$\underline{I}_0$	Zero sequence current
$\underline{I}_0{}^*$	Complex conjugate of $\underline{I}_0$
$\underline{I}_{\mathrm{C}}$	Capacitive earth fault current
$\underline{I}_{\mathrm{e}}$	Returning residual current via earth
$\underline{I}_{\mathrm{ew}}$	Returning residual current in additional earthing wire
$\underline{I}_{\mathrm{f}}$	Earth fault current
I_{h}	Current threshold value
$\underline{I}_{\mathrm{L}}$	Inductive earth fault current
$\underline{I}_{\mathrm{r}}$	Residual current
I_{R}	Resistive earth fault current
$\underline{I}_{\mathrm{sh}}$	Returning residual current in sheat
X_{C}	Capacitive reactance
K	Compensation degree
L	Coil inductance
L_{BG}	Total coil inductance of background network
L_{Fd}	Total coil inductance of faulted feeder
r_{c}	Radius of one conductor
R_{er}	Earthing resistance
r_{ew}	Radius of earthing wire
R_{f}	Fault resistance
R_{FBg}	Fault resistance of background network
R_{FFd}	Fault resistance of protected feeder
R_{L}	Parallel resistor
r_{sh}	Radius of cable
$\underline{U}'_{\mathrm{A}}$	Voltage-to-earth in phase A
$\underline{U}'_{\mathrm{B}}$	Voltage-to-earth in phase B
$\underline{U}'_{\mathrm{C}}$	Voltage-to-earth in phase C
$\underline{U}_0$	Zero sequence voltage

$\underline{U}_{0\_fault}$	Zero sequence voltage during fault
$\underline{U}_{0\_prefault}$	Zero sequence voltage before fault
$\underline{U}_{0q}$	Phase-to-earth voltage of zero sequence network
$\underline{U}_{1eq}$	Equivalent phase-to-earth voltage
$\underline{U}_{1q}$	Phase-to-earth voltage of positive sequence network
$\underline{U}_{2q}$	Phase-to-earth voltage of negative sequence network
$\underline{U}_{A}$	Phase-to-phase voltage in phase A
$\underline{U}_{B}$	Phase-to-phase voltage in phase B
$\underline{U}_{C}$	Phase-to-phase voltage in phase C
$\underline{U}_{e}$	Voltage-to-earth
U_{oh}	Voltage threshold value
U_{r}	Residual voltage
U_{ST}	Step voltage
U_{TP}	Touch voltage
$\underline{U}_{v}$	Phase-to-earth voltage
W	Power measured by wattmetric method
$\underline{Y}_{0}$	Neutral admittance
$\underline{Y}_{Bg}$	Background network admittance of local compensation coil
$\underline{Y}_{Bga}$	Background network admittance in phase a
$\underline{Y}_{Bgb}$	Background network admittance in phase b
$\underline{Y}_{Bgc}$	Background network admittance in phase c
$\underline{Y}_{Bgtot}$	Total admittance of background network
$\underline{Y}_{cCC}$	Admittance of compensation coil at the substation
$\underline{Y}_{CC}$	Admittance of compensation coil and parallel resistor
$\underline{Y}_{Fd}$	Protected feeder admittance of local compensation coil
$\underline{Y}_{Fda}$	Protected feeder admittance in phase a
$\underline{Y}_{Fdb}$	Protected feeder admittance in phase b
$\underline{Y}_{Fdc}$	Protected feeder admittance in phase c
$\underline{Y}_{Fdtot}$	Total admittance of ptotected feeder
$\underline{Y}_{uBg}$	Asymmetrical part of phase-to-earth background network admittance
$\underline{Y}_{uFd}$	Asymmetrical part of phase-to-earth protected feeder admittance
$\underline{Y}_{whole}$	Total network admittance
Z_{0}	Impedance of zero sequence network equivalent

Z_1	Impedance of positive sequence network equivalent
Z_2	Impedance of negative sequence network equivalent
Z_{T0}	Zero sequence network impedance of transformer
Z_{T1}	Positive sequence network impedance of transformer
Z_{T2}	Negative sequence network impedance of transformer

Abbreviations

ABB	Asea Brown Boveri
ACF	Active Current Forcing
AC	Alternating Current
AHXAMK-W	A medium voltage power cable
APYAKM	A medium voltage power cable
BG	Background
CENELEC	The European Committee for Electrotechnical Standardization
CT	Current Transformer
DC	Direct Current
DNO	Distribution Network Operator
E/F	Earth Fault
HV	High Voltage
IEC	The International Electrotechnical Commission
IEEE	The Institute of Electrical and Electronics Engineers
IED	Intelligent Electronic Device
IT	Instrument Transformer
LV	Low Voltage
MV	Medium Voltage
OHL	Overhead Line
PSCAD	Power System Computer Aided Design, a simulation software
RCC	Residual Current Compensation
SFS	The Finnish Standards Association
UGC	Underground Cabling
VT	Voltage Transformer

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ABSTRACT

Recent storms in Nordic countries have damaged MV distribution networks and caused major outages. Furthermore, new quality requirements of electricity supply, and customers' demands for more uninterruptable and better quality of supply have led to build weatherproof and reliable networks by replacing overhead lines by underground cables in rural areas. However, the rising level of cabling increases earth fault currents and produces dangerously high touch voltages in surrounding areas. Earth fault current through human body and related consequences depend on its magnitude and duration. In worst case even a low current can be fatal to victim.

Because earth fault current consists of increased capacitive component and resistive part due to considered zero sequence series impedance with longer feeders, protection has to be implemented in different ways ensuring safety and selectivity during earth faults. Resistive part can not be compensated with Petersen coils, but it can be limited with decentralized compensation. Moreover, network structure and earthing method impact on the magnitude of earth fault current.

Earth fault phenomenon with phase angle and admittance criteria was studied. Typical MV distribution network models using PSCAD simulation software were created. The aim was to find out how earth fault protection should be arranged with defined fault scenarios in different cases and what is the sensitivity that can be reached. The impacts of phase angle errors on protection were also studied in one situation. The results showed that admittance criterion is reliable and sensitive in radial networks, and protection even operates without the parallel resistor in some cases. However, it requires careful setting of certain admittance boundaries. When using phase angle criterion, parallel resistor should be connected or wider tolerance should be set in some cases. Phase angle criterion was not affected by errors, which was accounted for parallel resistor connection. In theory the admittance method was vulnerable to errors, but false operations can be avoided by placing the boundaries with sufficient margins. Consequently, threshold settings and accurate calculations of protection quantities should be done carefully.

KEYWORDS: earth fault protection, cable network, compensation, sensitivity

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TIIVISTELMÄ

Viime aikoina Pohjoismaihin iskeneet myrskyt ja siitä aiheutuneet laajamittaiset katkokset keskijännitejakeluverkossa, uudet sähkön laatuvaatimukset ja asiakkaiden entistä tiukemmat kriteerit häiriöttömälle ja parempilaatuiselle sähkölle ovat saaneet jakeluverkkojen haltijat korvaamaan avojohtoverkkoa maakaapeleilla yhä enemmän myös maaseudulla. Kaapeloinnin lisääntyminen nostaa maasulkuvirtoja ja aiheuttaa vaarallisen korkeita kosketusjännitteitä. Virran suuruus ja kestoaika vaikuttavat sen aiheuttamiin vaurioihin ihmiskehossa. Jopa melko pienet virta-arvot voivat aiheuttaa kuoleman.

Koska maasulkuvirta sisältää nyt suuremman kapasitiivisen komponentin ohella resistiivisen osan, joka syntyy huomioidusta nollaverkon sarjaimpedanssista eli nollaimpedanssista kasvavilla johtopituuksilla, suojaus tulee toteuttaa eri tavalla. Siten varmistetaan edelleen verkon turvallisuus ja selektiivisyys maasuluissa. Resisistiivistä virtakomponenttia ei voi kuitenkaan kompensoida kuristimella, mutta sen suuruutta voidaan rajoittaa riittävän alhaiselle tasolle hajautetun kompensoinnin avulla. Verkon rakenne ja maadoitustapa vaikuttavat myös maasulkuvirran suuruuteen.

Maasulkusuojausta tutkittiin vaihekulma- ja admittanssikriteerien avulla luomalla erilaisia keskijännitejakeluverkkomalleja PSCAD-simulointiohjelmassa. Työn tavoitteena oli selvittää eri vikatilanteiden avulla kuinka maasulkusuojaus tulisi toteuttaa ja kuinka suureen suojauksen herkkyyteen päästään eri tilanteissa. Myös vaihekulmavirheiden vaikutusta tutkittiin yhdessä tilanteessa. Tuloksien perusteella admittanssimenetelmä on luotettava ja herkkä perinteisillä verkkomalleilla, ja se toimii myös joissain tilanteissa ilman rinnakkaisresistanssia. Tiettyjen admittanssirajojen asettelussa täytyy olla kuitenkin huolellinen. Vaihekulmakriteeriä käytettäessä rinnakkaisresistanssin tulee olla kytketty tai asettaa laajempi toimintakulmasektori. Virheet vaihekulmamittauksessa eivät vaikuttaneet suojauksen toimintaan vaihekulmakriteerissä. Tämä johtuu rinnankytketystä resistanssista. Teoriassa vaihekulmavirheet voisivat vaikuttaa admittanssimenetelmään ja siten myös suojaukseen, mutta virheiden vaikutukset voidaan välttää asettamalla rajat riittävillä marginaaleilla. Kaiken kaikkiaan suojausasetteluiden määrittely tulee tehdä huolellisesti.

AVAINSANAT: maasulkusuojaus, kaapeliverkko, kompensointi, herkkyys

1 INTRODUCTION

In the today's power systems safety, quality issues and continuity of supply have noticeable importance. For customers the continuity of supply is an important issue especially, considering new power electronic equipment, which is very vulnerable to sudden blackouts. Also major part of the industrial plants is dependent of steady electricity supply. Even a short outage can cause problems in their production and result in loss of profit. The quality of supply has to fulfil the stated requirements, which are also regulated by standards.

Earth faults or related faults originated initially from medium voltage (MV) distribution networks, where the voltage level is mainly 20 kV or 10 kV (Guldbrand 2009: 3), are the most common faults in Nordic countries (Nikander & Järventausta 2005). For example, weather conditions, human errors or excavation works, which are random failures, can cause earth faults (Guldbrand 2007: 5). More than 90 % of the disturbances, which electricity users are experiencing, are caused by faults in MV distribution networks (Lakervi & Partanen 2008: 125).

During the past few years there have been some major storms, e.g. Gudrun in Sweden and Tapani in Finland, causing extensive and long outages for customers, and destroying and damaging MV distribution networks. (Guldbrand 2009: 1; Jaakkola & Kauhaniemi 2013.) It was investigated that majority of the customers in rural areas, which were supplied by overhead lines (OHLs), experienced much more outages than those with underground cables during Gudrun storm (ER 16:2005). Consequently, the vulnerability of MV distribution networks raised great attention towards distribution network's operators (DNOs) and the question, how the quality of supply should be improved? As a solution, the amount of underground cables was increased, and by year 2011, 12 % of MV distribution networks in Finland were cabled (Suvanto 2013: 18). For example Elenia, which is one of the largest DNOs in Finland, has planned to increase their underground cabling (UGC) degree up to 70 % of their MV networks during the next 15 years (Elenia 2014). On the other hand, increasing the UGC in large extent is not without consequences. UGC increases earth fault current causing rising touch voltages, which must be considered in network protection. It also generates more reactive power, but this issue is not in the scope of this work.

Large amount of underground cables can no longer be evaluated with conventional earth fault analysis, because in case of OHLs and limited lengths of underground cables, network was possible to be represented without considering series impedance. When UGC is extensive, series impedance is not negligible. Cable can be represented as a cylindrical capacitor, which produces higher capacitive earth fault current. Earth fault analysis with longer feeder lengths has to be done now differently, because current consists of larger reactive and also resistive components. Resistive component can not be compensated by using a compensation coil similarily as inductive current produced by compensation coil and capacitive current produced by cable feeders cancel each other out. Therefore, network protection arrangements will be changed. Moreover, network structure and earthing method affect earth fault current. Compared to OHLs, electrical characteristics of cables are also different. (Guldbrand 2009: 37–47.)

Higher voltages can be very dangerous or in worst case lethal. Network equipment may be also damaged. The magnitude and the duration of current define how severe the consequences are for victim. Even small current, 30 mA passing through human body, is very dangerous unless situation is interrupted very quickly. (ABB 2013a: 2.) Hence, network protection system and related safety issues are very essential.

Earth fault (E/F) protection in MV distribution networks is based on functioning of circuit breakers, according to directional earth fault relay measurements. Relay operation is achieved, when the threshold values of zero sequence voltage and zero sequence current are exceeded, and phase angle between them is in the defined sector. The main purpose is to detect a fault, isolate the faulted feeder by giving an order to circuit breaker to function for removing the fault as soon as possible avoiding dangerous voltages and minimizing outage costs. (Nikander & Järventausta 2005.) The novel admittance based protection method, which has shown very promising results, is also studied in this work. Unfortunately, the method it is still rarely used. (Lakervi & Partanen 2008: 190–191; Wahlroos, Altonen, Hakola & Kemppainen 2011.)

E/F phenomenon in MV distribution networks with long feeders and related protection issues has recently raised discussion in Nordic countries, especially in Sweden and in Finland. Moreover, this phenomenon has not yet been under of many researches, because traditional MV distribution networks in rural areas comprise still mainly of OHLs and urban networks with shorter and limited lengths of underground cables. Therefore, the subject being rather topical at the moment, it was chosen to be studied in this thesis.

The arisen problem of protection issues in mixed and cabled MV networks is under consideration in this thesis. The main purpose of this work is to find out by simulations: how the protection should be arranged in different cases using partly decentralized compensation? What is the maximum protection sensitivity in terms of fault resistance that can be still reached? Could errors in measurements affect on the functioning of earth fault protection? The above mentioned questions are studied during this thesis with the help of computer simulations. Selected network topologies with defined fault scenarios are simulated and studied with PSCAD network modelling tool.

The structure of this work consists of six chapters. After the introduction part, Chapters 2 and 3 comprise the basic theory of earth faults for creating better understanding for protection issues. Chapters 4 and 5 concentrate on the empirical part of this work. Chapter 4 introduces the main features of the created network simulation models, and to Chapter 5 the simulated results are gathered and presented. In the final Chapter 6, the results and their accuracy are analysed, and based on them, conclucions are made. Possible further study subjects in related field are also discussed in Chapter 6.

2 EARTH FAULTS IN MEDIUM VOLTAGE NETWORKS

2.1 Earth fault

Earth fault is an insulation fault, where a phase line and earth are connected or there is a connection between phase line and earth via a conductive part. When one of the phases is connected to earth, earth fault is called a single phase earth fault or in case of two phases are connected, it is called a two-phased earth fault. Earth faults are mainly single-phased, and therefore this study is primarily focusing on single phase earth faults. Earth faults in underground cabled networks are mostly caused by, e.g. excavation work or insulation breakdowns. In OHL networks, earth faults are caused by leaning trees or fallen lines. (ABB 2000: 248; Elovaara & Haarla 2011b: 340,342; Vehmasvaara 2012: 15–16.)

2.2 Single phase earth fault and symmetrical components

When there are no faults in network, system is nearly symmetrical. Phase voltages and currents have 120° phase shift and the same magnitude compared to each other. Symmetry indicates that there is normally neither zero sequence voltage $\underline{U}_0$, which is sum of phase-to-earth voltages, nor zero sequence current $\underline{I}_0$ present in network. When a single phase earth fault occurs, voltages and currents no longer cancel each other out. Voltages in two healthy phases rises and voltage of faulted phase reduces. This asymmetry raises zero sequence voltage or sometimes called as residual voltage $\underline{U}_r$ or neutral point displacement voltage. In the same way, voltage drop in the faulted phase caused by asymmetry affects currents. It means that the zero sequence current, which can be also called as a residual current $\underline{I}_r$ or $3\underline{I}_0$, is no longer zero. (Lakervi & Holmes 1996: 50–56; Pekkala 2010:15; Elovaara & Haarla 2011a: 177–181; Elovaara & Haarla 2011b: 14–16; Siirto, Loukkalahti, Hyvärinen, Heine & Lehtonen 2012.)

Zero sequence voltage can be measured in different locations in network. Normally, it is measured at the substation, but it can be also measured at different points along the feeder. Therefore, zero sequence voltage measured at the substation may differ from $\underline{U}_0$ measured at the feeder. This is evident, when UGC increases, and series impedance has to be considered. This is an important aspect, which DNOs should consider, when planning the earth fault protection settings of networks in future. (Lakervi & Holmes 1996: 50–56; Pekkala 2010:15; Elovaara & Haarla 2011a: 177–181; Elovaara & Haarla 2011b: 14–16; Siirto, Loukkalahti, Hyvärinen, Heine & Lehtonen 2012.)

Because earth faults are unsymmetrical, network will be analyzed by using symmetrical components and sequence networks. Symmetrical component analysis, which is a mathematical method, is achieved by converting the phasors to sequence coordinates. Asymmetrical network can be represented now by a combination of three sequence networks, which are positive, negative and zero sequences, which are illustrated in Fig. 1. Furthermore, it is also possible represent a three-phased network as two-terminal equivalents, which are introduced in Fig. 2. In Fig 2, Z_1, Z_2 and Z_0 represent the equivalent impendances in positive-, negative and zero sequence networks, $\underline{U}_{1q}$, $\underline{U}_{2q}$ and $\underline{U}_{0q}$ are the phase-to-earth voltages in positive-, negative and zero sequence networks, and $\underline{U}_{1eq}$ is the voltage source representing the positive sequence voltage calculated from all three source voltages of the three-phased network. (Guldbrand 2009: 13–15.)

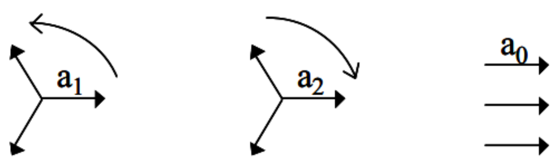


Figure 1. Positive (a_1), negative (a_2), and zero (a_0) sequence network coordinate bases. (Guldbrand 2009: 13.)

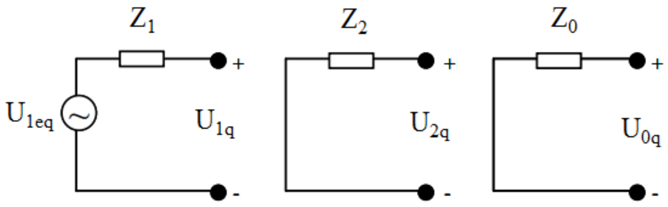


Figure 2. Two-terminal equivalents of sequence networks. (Guldbrand 2009: 14.)

In addition to voltage level of the MV distribution network, the earth fault current $\underline{I}_f$ is defined by the length and type of the lines, which are galvanically-connected, and their phase-to-earth capacitances. Earth fault current increases, when the total length of network increases. (Lakervi & Partanen 2009: 186–187.) In the traditional earth fault analysis the series impedance is negligible and shunt capacitance is dominant. Because cable can be represented as a cylindrical capacitor, and in case of longer cable feeders, the capacitance-to-earth will naturally increase, and series impedance can no longer be excluded. Compared to OHLs in 20 kV system, which capacitance is ca. 6 nF/km per phase and earth fault current 0.067 A/km, cables produce earth fault current apprx. from 2.7 A to 4 A/km, and phase-to-earth capacitance is 230–360 nF/km per phase. Also cable type, geometry, and structure of cables have an effect on earth fault current. (Lakervi & Partanen 2009: 186.)

2.3 Network earthing

Earthing, which has a major effect on earth fault behavior with series impedance and shunt capacitance of the lines, can be defined as a used combination of the components connected between earth and neutral point of the transformer. (Guldbrand 2006: 1). System earthing controls the value of unsymmetrical earth fault current, and by that the potential rise in live parts and dangerous voltage levels in system. Earth fault current defines also the zero sequence voltage. (Lakervi & Holmes 1996: 40; Lehtonen & Hakola 1996: 11; Roberts, Altuve & Hou 2001: 2; Guldbrand 2009: 19.)

Moreover, earthing protect network equipment from thermal stress, reduce overvoltages, avoid interference in communications systems, guarantee safety for operational personnel and to general public, and help to detect and remove earth faults as quickly as possible. (Lakervi & Holmes 1996: 40; Roberts et al. 2001: 2.) In Finland MV distribution networks are either isolated neutral and compensated neutral systems. Compensated neutral network will be studied in this thesis, because compensation reduces earth fault current to 3–10 % of isolated neutral system earth fault current (Roberts et al. 2001: 7).

2.3.1 Earth fault in isolated neutral network

When neutral point of the transformer has no connection to earth, network is called an isolated neutral or an unearthed neutral system. Isolated neutral system with a single phase earth fault is illustrated in Fig. 3 and corresponding Thévenin's equivalent in Fig. 4.

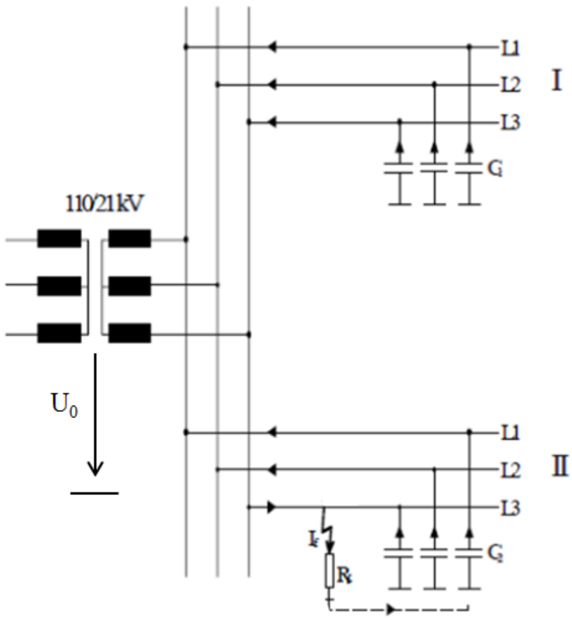


Figure 3. Single phase earth fault in isolated neutral system. (Lakervi & Partanen 2009: 183.)

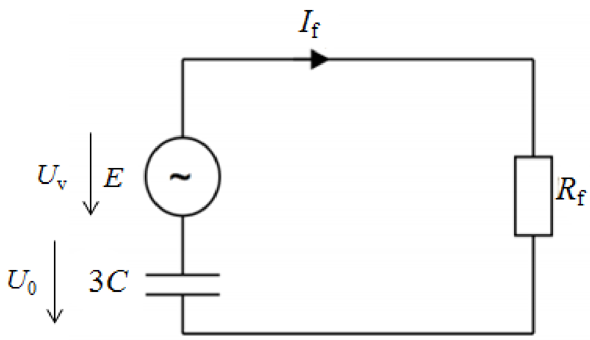
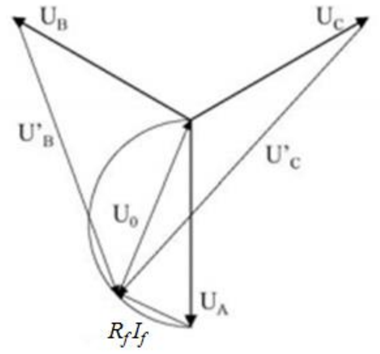


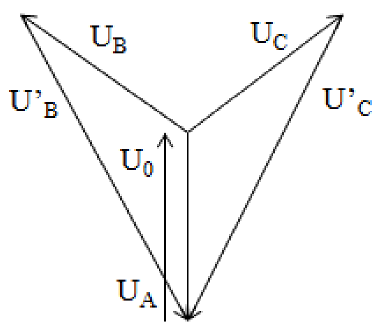
Figure 4. Thevenin's equivalent of single phase earth fault in isolated neutral network. (Lakervi & Partanen 2009: 184.)

Earth fault current $\underline{I}_f$, which is a sum current produced by feeder capacitances, has a route from the fault point to earth via a fault resistance R_f through the phase-to-earth capacitances C to the neutral point of the transformer, and finally it reaches the fault point. $\underline{U}_0$ represents zero sequence voltage during the fault, which is affected by fault resistance. (Lakervi & Partanen 2008: 186–187; Elovaara & Haarla 2011b: 14–15.)

Figures 5a and 5b show the voltage phasors during a single phase earth fault in case of a solid earth fault and a presence of a fault resistance. However, there is always some asymmetry in network due to natural unbalances and leakage currents. Thus, solid earth fault is merely theoretically studied. The faulted phase A, when R_f equals to zero in Fig. 5b, the voltage-to-earth at the faulty phase is zero, i.e. $\underline{U}'_A$ equals to zero. The voltage-to-earth at the healthy phases equal phase-to-phase voltages, i.e. $\underline{U}'_B$ equals to $\sqrt{3} \cdot \underline{U}_B$ and $\underline{U}'_C$ equals to $\sqrt{3} \cdot \underline{U}_C$. According to Fig. 5a, the phase and the magnitude of the zero sequence voltage depend on the fault resistance, as well as voltages in healthy phases $\underline{U}'_B$ and $\underline{U}'_C$. The maximum value of the healthy phase voltage during a single phase earth fault can reach 105 % of the prefault phase-to-phase voltage. (Guldbrand 2006: 3; Elovaara & Haarla 2011b: 15.)



a)



b)

Figure 5. Phase voltages U_A, U_B and U_C, zero sequence voltage U_0 and and healthy phase voltages U'_B and U'_C in single phase earth fault in an isolated neutral network. a) $R_f \neq 0$ b) $R_f = 0$. (Guldbrand 2006: 3; Elovaara & Haarla 2011b: 15.)

Earth fault current can be solved according to Fig. 4, and it can be calculated according to equations (Guldbrand 2009: 22; Lakervi & Partanen 2009: 184.)

$$\underline{I}_f = \frac{\underline{E}}{R_f + \frac{1}{j3\omega C}} = \frac{j3\omega C}{1+j3\omega CR_f}\underline{U}_v, \tag{2.1}$$

and

$$\underline{I}_f = I_R + jI_C = \frac{R_f (3\omega C)^2 U_v}{1+(R_f 3\omega C)^2} + j\frac{3\omega CU_v}{1+(R_f 3\omega C)^2}, \tag{2.2}$$

where

ω is the angular frequency,

C is the total phase-to-earth capacitance of the network,

$\underline{E}$ is the phase-to-earth voltage,

I_C is the capacitive part of the earth fault current,

$\underline{I}_f$ is the earth fault current,

I_R is the resistive part of the earth fault current,

R_f is the fault resistance, and

$\underline{U}_v$ is the phase-to-earth voltage.

The fault resistance reduces both the earth fault current, which is comprised by both resistive and capacitive components, and the magnitude of zero sequence voltage. Zero sequence voltage can be defined as follows (Lakervi & Partanen 2009: 184.):

$$\underline{U}_0 = \frac{1}{j3\omega C}(-\underline{I}_\mathrm{f}) = \frac{-1}{1+j3\omega CR_\mathrm{f}}\underline{U}_\mathrm{v}. \tag{2.3}$$

Earth fault current can be calculated in case of a solid earth fault from equation (Guldbrand 2009: 21.)

$$\underline{I}_f = jI_C = j3\omega C\underline{U}_\mathrm{v}. \tag{2.4}$$

It can be seen from Eq. 2.4 that fault current is proportional to the total capacitive connection to earth. Earth fault current has only the capacitive component, and zero sequence voltage reaches the prefault phase-to-earth voltage at the faulty phase. (Guldbrand 2009: 21) In the faulty phase, the current flows towards the fault place being opposite to the sum current and in the healthy phases the current flows towards the busbar. Because of the component of fault current flowing in both directions, the effect of capacitances of faulted feeder has to be ignored, when calculating the residual current in the beginning of the faulted feeder. The residual current of faulted feeder can be calculated according to equation (Lakervi & Partanen 2009: 191.)

$$\underline{I}_\mathrm{r} = 3\underline{I}_0 = \frac{C - C_\mathrm{Fd}}{C}\underline{I}_\mathrm{f}, \tag{2.5}$$

where

C_Fd represents the phase-to-earth capacitance of faulted feeder, and

$\underline{I}_\mathrm{r}$ is the residual current of faulted feeder.

Isolated neutral network is inexpensive and easy to construct and earth fault current is minor due to high impedance. (Guldbrand 2009: 20). However, networks with large total phase-to-earth capacitance creating high earth fault currents are not advantageous to apply unearthed neutral earthing method. Therefore, compensation has to be used for extent use of UGC in order to limit earth fault current. (Guldbrand 2009: 24.)

2.3.2 Earth fault in compensated neutral network

In a compensated neutral network or a resonant earthed system, where neutral point of the network is connected via a Petersen coil or an arc suppression coil to earth, inductive current of the coil is adjusted to compensate almost all the capacitive current during an earth fault. Petersen coil was invented by Waldemar Petersen in the early 20th century, in purpose of limiting earth fault current near to zero (Wahlroos, Altonen & Fulczyk 2013). (Lakervi & Partanen 2009: 184–185; Wahlroos & Altonen 2011: 3.)

Single phase earth fault in compensated neutral network is represented in Fig. 6. Coil is tuned to cancel the capacitive current almost entirely. Because $\underline{I}_L$ and $\underline{I}_C$ have opposite direction, the earth fault current $\underline{I}_f$ is reduced considerably, and it is mainly resistive. Therefore, relays in compensated networks are set to measure the resistive component of the residual current. (Lakervi & Partanen 2009: 184–185.)

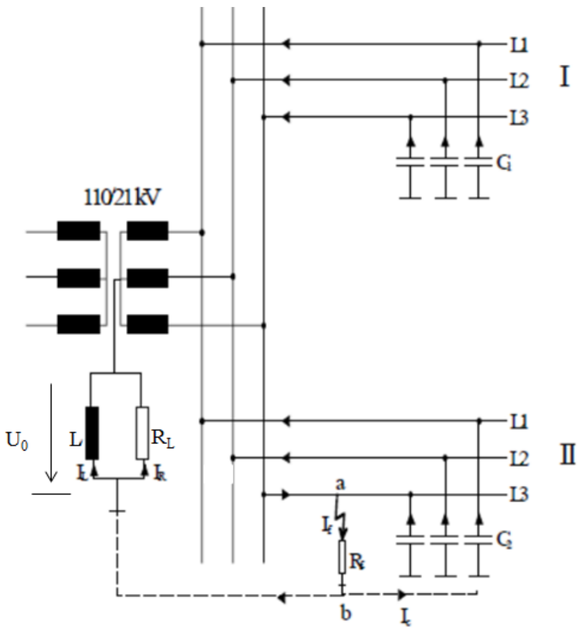


Figure 6. Single phase earth fault in compensated neutral network. (Lakervi & Partanen 2009: 185.)

When series impedance is negligible, earth fault current $\underline{I}_f$ and zero sequence voltage $\underline{U}_0$ can be calculated in compensated neutral network according to equations (Lakervi & Partanen 2009: 185–186.)

$$\underline{I}_f = \frac{1}{R_f + \frac{R_L}{1 + jR_L(3\omega C - \frac{1}{\omega L})}}\underline{U}_v, \tag{2.7}$$

and

$$\underline{U}_0 = \frac{-R_L}{R_f + R_L + jR_f R_L(3\omega C - \frac{1}{\omega L})}\underline{U}_v, \tag{2.8}$$

where

L is the coil inductance, and

R_L is the parallel resistor.

Because earth fault protection relays measure in addition to magnitudes also phase angles, calculations describing relay operation quantities in this thesis are represented by phasors. However, considering the empirical part of this work, also the absolute value of the zero sequence voltage is needed and it can be calculated as follows (Mörsky 1992: 317; Lakervi & Partanen 2009: 186.):

$$U_0 = \frac{R_L}{\sqrt{(R_f + R_L)^2 + R_f^2 R_L^2 (3\omega C - \frac{1}{\omega L})^2}} \frac{E}{\sqrt{3}}. \tag{2.9}$$

If the system is exactly tuned i.e. compensation degree K equals to 1 (or 100 %), fault current contains only a resistive component (Guldbrand 2009: 30–31). If the K has a value more than 1, network is overcompensated and respectively if K has a value less than 1, network is undercompensated. Compensation degree can be calculated according to equation (ABB 2000: 254.)

$$K = \frac{\underline{I}_\mathrm{L}}{\underline{I}_\mathrm{C}}, \tag{2.6}$$

where

$\underline{I}_\mathrm{C}$ is capacitive earth fault current,

$\underline{I}_\mathrm{L}$ is inductive earth fault current, and

K is the compensation degree.

Coil(s) can be installed either centrally at the neutral point of the main transformer at substation or locally along the feeders (decentralized compensation). Locally installed coils have usually fixed value of inductance and smaller rating. In practice, there is also a parallel resistor R_L connected to coil. It helps to increase earth fault current for better fault detection and selective relay operation. (Hänninen, Lehtola & Antila 1998; Guldbrand 2009: 33; Lakervi & Partanen 2009: 182–185; Elovaara & Haarla 2011a: 210–211; Wahlroos & Altonen 2011: 3–5.) In this thesis the network is partly decentrally compensated. At the neutral point of the transformer at the substation is one coil compensating the beginning of the feeders, and the locally installed coils compensate the rest of the feeders. Fig. 7 shows the single phase equivalent of partly decentrally compensated network.

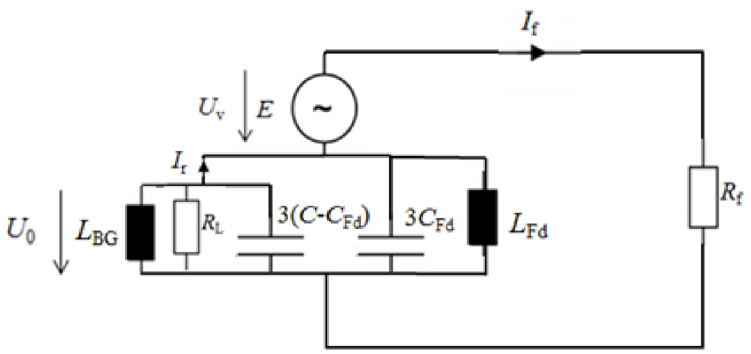


Figure 7. Single phase equivalent of partly decentrally compensated network modified from (Lakervi & Partanen 2009: 185).

The absolute value of residual current in partly decentrally compensated networks, which derivation can be found in Appendix 1, can be defined for the faulted feeder according to Fig. 7 as follows:

$$I_{\mathrm{r}} = \frac{\sqrt{1 + \left(R_{\mathrm{L}}\left(3\omega(C - C_{\mathrm{Fd}}) - \frac{1}{\omega L_{\mathrm{BG}}}\right)\right)^2}}{\sqrt{(R_{\mathrm{f}} + R_{\mathrm{L}})^2 + \left(R_{\mathrm{f}} R_{\mathrm{L}}\left(3\omega C - \frac{1}{\omega L}\right)\right)^2}} U_{\mathrm{v}}, \tag{2.10}$$

where

L_{BG} is the coil inductance located in the BG network,

L_{Fd} is the coil inductance located in the faulted feeder, and

$L = \frac{L_{\mathrm{BG}} L_{\mathrm{Fd}}}{L_{\mathrm{BG}} + L_{\mathrm{Fd}}}$.

Fig. 8 presents the relative zero sequence voltage behaviour in unearthed neutral network and compensated neutral network with overhead line and in underground cable networks with different values of fault resistances as a function of the feeder length. In compensated neutral network, it is assumed $R_{\mathrm{L}} = 10/3\omega C$. It can be noticed in Fig. 8 that U_0 is much bigger in compensated (dashed line) than in isolated neutral (solid line) network. (Mörsky 1992: 318–319.)

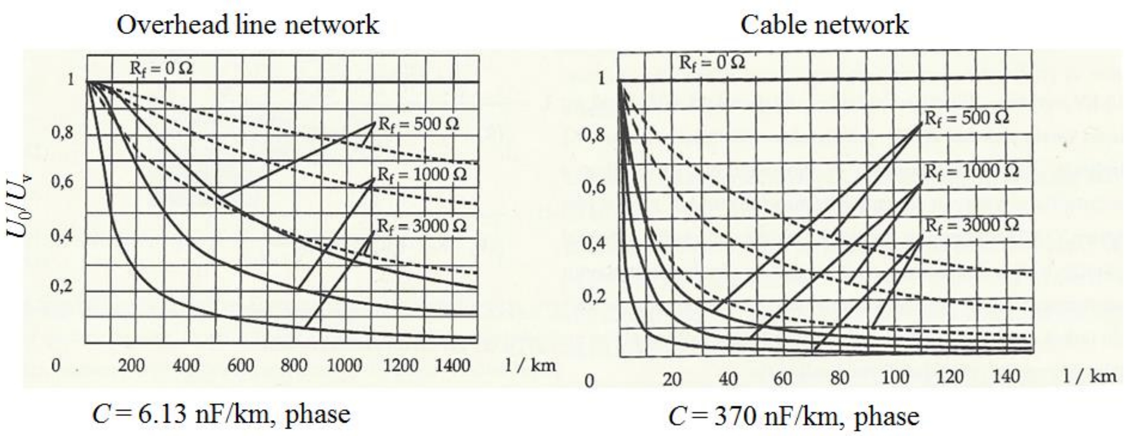


Figure 8. Zero sequence voltage behaviour in case of a single phase earth fault in 20 kV OHL network and APYAKM 3·185 mm^2 underground cable network. Solid line represents isolated neutral network and dashed line represents compensated neutral network. (Mörsky 1992: 318–319.)

In compensated neutral networks fault detection is more difficult, and the probability of double and intermittent faults is increased due to voltage rise (Zamora, Mazon, Eguia, Valverde & Vicente 2004). Personnel have to be also trained for assimilating new technology and fault analysis pattern (Loukkalahti 2013).

2.4 Admittance theory

2.4.1 Background

The earth fault analysis can be also made by using admittances between three phases and earth. This admittance-based theory has been implemented originally into earth-fault protection in Poland in 1980s among a group of researchers, which was headed by Józef Lorenc from Poznan University of Technology. Later, the idea by using admittance-based protection has become a requirement for local utilities in Poland. Still, it is less known among protection engineers in other countries, but it has a great potential in protection field due to already good and promising results. (Wahlroos 2012; Wahlroos et al. 2013.) Therefore, the basics from admittance theory according to Wahlroos & Altonen (2011) are introduced in the following section.

2.4.2 Fundamentals of admittance-based earth fault protection

The admittance criterion is based on the fundamental frequency components of $3\underline{I}_0$ and $\underline{U}_0$. Neutral admittance $\underline{Y}_0$ can be now determined in symmetrical networks dividing residual current phasor by zero sequence voltage phasor, according to equation

$$\underline{Y}_0 = G_0 + jB_0 = \frac{3\underline{I}_{0\_fault}}{-\underline{U}_{0\_fault}}, \tag{2.11}$$

where

$3\underline{I}_{0\_fault}$ is the residual current during the fault,

B_0 is the neutral susceptance,

G_0 is the neutral conductance,

$\underline{U}_{0\_fault}$ is the zero sequence voltage during the fault, and

$\underline{Y}_0$ is the neutral admittance.

The shunt admittance for a single phase line can be defined as follows:

$$\underline{Y}_0 = G_0 + jB_0 = G_0 + j(\omega C_0), \tag{2.12}$$

where G_0 is the shunt conductance being usually rather small (10–100 times smaller than the susceptance value) due to efficient dielectric features of cables. Shunt conductance illustrates the resistive leakage current flowing via dielectric material, air and insulators, and hence it produces resistive losses of the system. C_0 is the phase-to-earth capacitance per phase.

Modern microprocessor based intelligent electronic devices (IEDs) utilize the calclulation, which was presented in Eq. 2.11. Alternatively, eliminating the effect of network asymmetry and under specific conditions the effect of fault resistance, admittance can be calculated by "delta-quantities" as follows:

$$\underline{Y}_0 = \frac{(3\underline{I}_{0\_fault} - 3\underline{I}_{0\_prefault})}{-(\underline{U}_{0\_fault} - \underline{U}_{0\_prefault})} = \frac{\Delta 3\underline{I}_0}{-\Delta \underline{U}_0}, \tag{2.13}$$

where

$3\underline{I}_{0\_prefault}$ is the residual current before fault, and

$\underline{U}_{0\_prefault}$ is the zero sequence voltage before fault.

For networks, consisting of underground cables, the admittance calculation according to Eq. 2.11 can be used. In case of mixed networks, which contain also a large amount of OHLs in addition to underground cables causing the network becoming very unsymmetrical, the use of delta-quantities in admittance calculation is recommended. Fig. 9 shows a three-phased distribution network including two feeders, protected feeder (Fd), which is the feeder where the protection relay quantities are studied and the background network (Bg), which represents the rest of the whole galvanically-connected network.

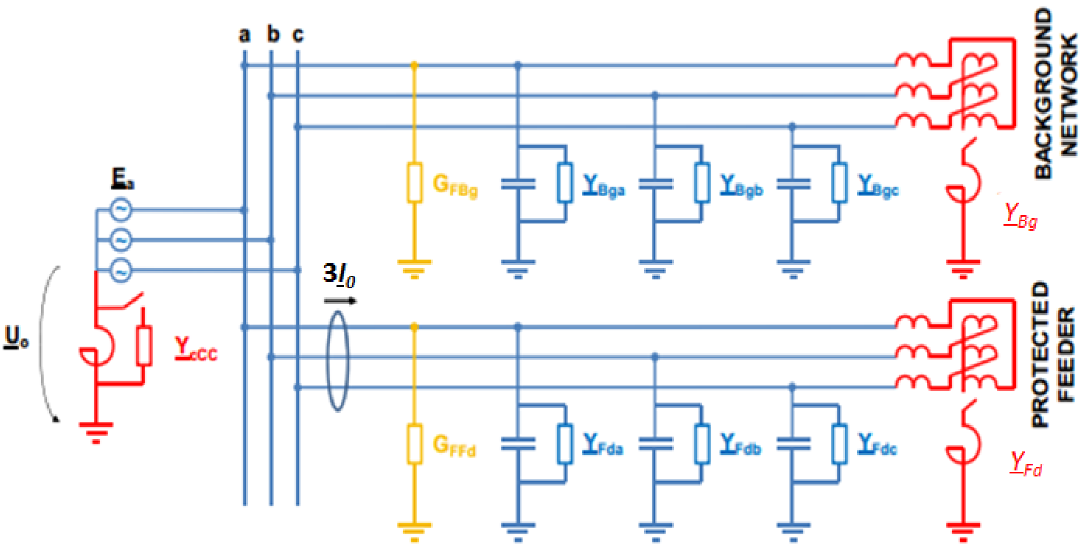


Figure 9. Three-phased distribution network model consisting of two feeders: protected feeder and background network in a single phase earth fault situation in phase a. (Wahlroos & Altonen 2011: 6.)

Dominant shunt admittances are presented, but series impedance being rather small can be left out consideration. Neither loads nor phase to phase capacitances are being evaluated. $\underline{Y}_{Fd}$ and $\underline{Y}_{Bg}$ are the total admittances of the coils located in the protected feeder and in the BG network. $\underline{Y}_{cCC}$ is the admittance of the compensation coil at the substation.

The total admittance of the network $\underline{Y}_{whole}$, which represents the total network admittance including the whole BG network and feeder admittances, can be defined according to equation

$$\underline{Y}_{whole} = \underline{Y}_{Fdtot} + \underline{Y}_{Bgtot} = G_{whole} + jB_{whole}, \tag{2.14}$$

where

$\underline{Y}_{Bgtot} = \underline{Y}_{Bga} + \underline{Y}_{Bgb} + \underline{Y}_{Bgc} = G_{Bgtot} + jB_{Bgtot}$, and

$\underline{Y}_{Fdtot} = \underline{Y}_{Fda} + \underline{Y}_{Fdb} + \underline{Y}_{Fdc} = G_{Fdtot} + jB_{Fdtot}$,

and

$\underline{Y}_{Bga}$, $\underline{Y}_{Bgb}$, $\underline{Y}_{Bgc}$ are background network admittances in phases a,b, and c, and

$\underline{Y}_{Fda}$, $\underline{Y}_{Fdb}$, $\underline{Y}_{Fdc}$ are protected feeder admittances in phases a,b, and c.

Equation for $\underline{U}_0$ according to Fig. 9 can be defined as follows:

$$\underline{U}_0 = -\underline{E}_a \left(\frac{\underline{Y}_{uFd} + \underline{Y}_{uBg} + G_{FFd} + G_{FBg}}{\underline{Y}_{cCC} + \underline{Y}_{Fd} + \underline{Y}_{Bg} + \underline{Y}_{Fdtot} + \underline{Y}_{Bgtot} + G_{FFD} + G_{FBg}}\right), \tag{2.15}$$

and for residual current of the protected feeder as follows:

$$3\underline{I}_0 = \underline{U}_0 \left(\underline{Y}_{Fdtot} + \underline{Y}_{Fd} + G_{FFd}\right) + \underline{E}_a \left(\underline{Y}_{uFd} + G_{FFd}\right), \tag{2.16}$$

where

$\underline{Y}_{uBg} = \underline{Y}_{Bga} + \underline{a}^2\,\underline{Y}_{Bgb} + \underline{a}\,\underline{Y}_{Bgc}$, $\underline{a} = \cos(120°) + j\sin(120°)$, and

$\underline{Y}_{uFd} = \underline{Y}_{Fda} + \underline{a}^2\,\underline{Y}_{Fdb} + \underline{a}\,\underline{Y}_{Fdc}$.

$\underline{Y}_{uBg}$ and $\underline{Y}_{uFd}$ are asymmetrical parts of the total phase-to-earth feeder and BG network admittances, $\underline{Y}_{Bgtot}$ and $\underline{Y}_{Fdtot}$. If the phase-to-earth admittances can be assumed to be completely symmetrical in the network ($\underline{Y}_{uFd} = \underline{Y}_{uBg} = 0$), Equations 2.15 and 2.16 will be shortened. Fault analysis can be calculated either in case of fault is located at the protected feeder, when $G_{FBg} = 1/R_{FBg} = 0$ and $G_{FFd} = 1/R_{FFd} > 0$ or when fault is located at the BG network, when $G_{FFd} = 0$ and $G_{FBg} > 0$.

Admittance calculation is evaluated either fault locating in the protected feeder or in the BG network. When fault is at the protected feeder, admittance seen by admittance criterion can be calculated according to equation

$$\underline{Y}_0 = \underline{Y}_{Bgtot} + \underline{Y}_{cCC} + \underline{Y}_{Bg} = ((G_{Bgtot} + G_{cCC} + G_{Bg}) + j(B_{Bgtot} - (B_{cCC} + B_{Bg})). \tag{2.17}$$

By replacing $B_{cCC} = K \cdot B_{whole}$, and $B_{Bgtot} = B_{whole} - B_{Fdtot}$, where K is the compensation degree, the admittance will be

$$\underline{Y}_0 = ((G_{Bgtot} + G_{cCC} + G_{Bg}) + j((B_{whole}(1 - K) - B_{Fdtot} - B_{Bg})). \tag{2.18}$$

The total admittance, which is positive-signed, is now defined by the admittance measured from the BG network according to Eq. 2.18, and including the admittances of the coils in the BG network. The conductance is positive all the time, and the sign of the susceptance is affected by *K*. The effect of susceptances of decentralized compensation coils has to be also considered.

For the fault locating in the BG network, the admittance seen by admittance criterion can be calculated as follows:

$$\underline{Y}_0 = -\,(\underline{Y}_{\mathrm{Fdtot}} + \underline{Y}_{\mathrm{Fd}}) = -\,((G_{\mathrm{Fdtot}} + G_{\mathrm{Fd}}) + j(B_{\mathrm{Fdtot}} - B_{\mathrm{Fd}})). \tag{2.19}$$

As can be seen from the Eq. 2.19, the admittance method measures total admittance of the protected feeder, which is negative-signed and contain coil admittances of the protected feeder. When using central compensation, admittance is negative-signed admittance of the protected feeder. Consequently, the conductance and the susceptance are always negative-signed. However, it is possible that the conductance of the protected feeder is rather small to be measured accurately. Errors in $\underline{U}_0$ and $3\underline{I}_0$ measurements might lead to the false conductance value by turning it into positive-signed. Also, decentralized compensation might lead to unpreferred overcompensation situation, where the measured susceptance is positive. In order to implement E/F protection, and to prevent malfunctions of protection, such situation demands particular attention.

As can be seen from the Equations 2.18 and 2.19 by theoretical point of view, the fault resistance does not have an effect on admittance calculation. Therefore, settings for admittance based criterion can be defined by a very simple way.

2.5 Other earth fault types

2.5.1 Double earth fault

When two phases are in a conductive connection with earth in network, fault is then called a double earth fault or a cross country fault. Fault points can be in same locations, when it is called a phase-to-phase-to-earth fault, or locate very far from each other not having a short circuit connection. Usually, double earth fault is due to single phase earth fault. Voltage rise in healthy phases can inflict to function of overvoltage protection. Especially, in distribution networks double earth fault is problematic. Fault current is rather substantial: it can reach almost the value of short circuit current. Moreover, it is problematic to calculate precisely and it flows rather well via different conductive routes, including water mains or sheaths of communication cables. Poor conductivity of soil can cause major damages, when fault current flows in sheaths. Thermal stress and electric breakdowns between sheath and conductor can arise. To prevent double earth faults, fast and secure functioning of earth fault and overvoltage protections is needed. (Lakervi & Partanen 2009: 198.)

2.5.2 Arcing and intermittent faults

Arc fault is typically a very short and can be cleared by self-extinction (Guldbrand 2009: 11). The recovery voltage is defined by a voltage at the fault place after it has been eliminated. In isolated neutral networks the recovery voltage is quite steep. The rising speed of recovery voltage is high and may cause problems with self-extinguishing, despite rather small fault current. This is a drawback in isolated neutral network due to an absence of inductance, compared to the compensated neutral network. Arc re-ignitions are more likely to arise in isolated neutral networks. Phase-to-earth voltages in the healthy feeders might reach to the magnitude of the phase-to-phase voltage level and evolve to cross country faults due to overvoltages. (Lehtonen & Hakola 1996: 26–28; Roberts et al. 2001: 7–8.)

By using Petersen coils, self-extinguishment is more evident and power quality via reduced number of reclosings is improved. Recovery voltage's rising speed will be decreased by coils, but the compensation degree has to be more than 75 % enabling the more improved self-extinguishment. (Hänninen 2001: 26–28.)

Intermittent earth fault is common in compensated neutral systems consisting mainly of underground cables. This special fault type has arisen in attention particularly recently due to demand for more uninterruptable power supply (Mäkinen 2001: 1–2). Intermittent fault, or so-called restriking earth fault, is a special fault type, which is caused by a series of cable insulation breakdowns or deterioration of insulation due to diminished voltage withstand (Altonen, Mäkinen, Kauhaniemi & Persson 2003). Intermittent earth fault is introduced in this study only briefly, because the focus is to concentrate only to permanent single phase earth faults.

Insulation breakdowns can occur due to moisture, water, dirt, chemical reactions, material ageing, mechanical stress or insulation layer damages. Because of reduced insulation of faulted place, fault will appear when the phase-to-earth voltage reaches the breakdown voltage. However, the fault will be cleared mostly by itself, when the fault current reaches its zero point for the first time. (Altonen et al. 2003.)

Conventional earth fault protection relays are not capable of detecting very irregular wave shapes of current and voltage, as illustrated in Fig. 10. Relay may not be able to trip the faulted feeder and situation can lead to unselective operation of protection. Therefore, network protection in case of intermittent faults is challenging. And a lot of attention should be paid for detecting and removing them. Especially, because the general trend is going towards increased use of UGC and the natural ageing of the existing cables will increase the probability of intermittent earth faults. However, residual voltage, which is presented in Fig. 11 with recovery voltage (sum of the phase-to-earth voltage and residual voltage), has more stable waveform compared to current. Therefore, back-up protection of substation based on residual overvoltage may operate, if feeder protection can not clear the fault. Nonetheless, unnecessary relay operations of the substation protection and related high outage costs can occur. (Altonen et. al 2003.)

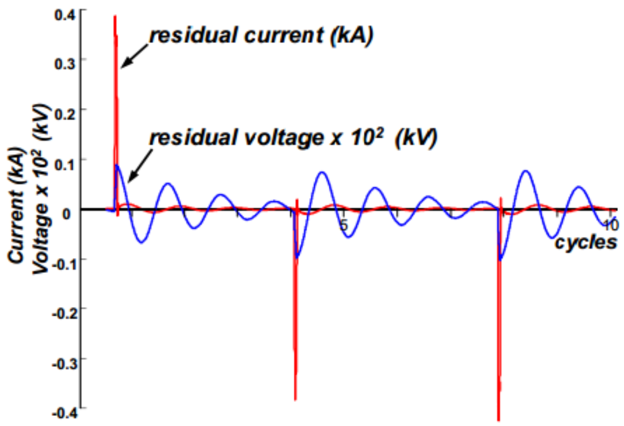


Figure 10. Residual voltage and current waveforms in the intermittent earth fault situation. (Altonen et al. 2003.)

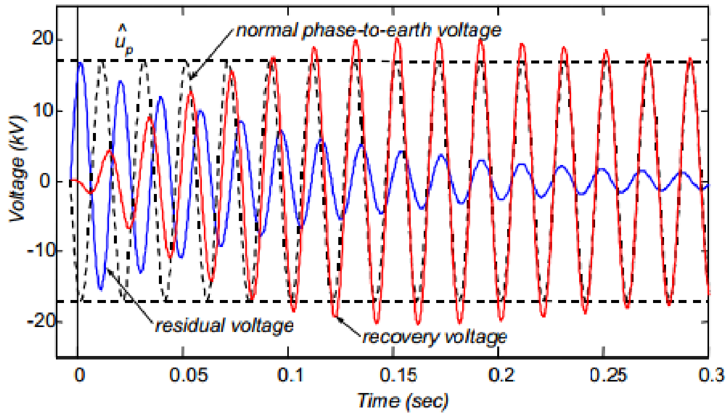


Figure 11. Recovery voltage in the intermittent fault situation. (Altonen et al. 2003.)

2.6 Extensive underground cabling and conventional earth fault analysis

Distribution system has composed merely with OHLs in rural areas and limited lengths of underground cables in urban networks due to restricted space and high expenses. In urban networks, feeders are short and can be presented by pi-sections, which are parallel connected. High voltage (HV) network and series impedances (transformer impedances) can be considered negligible, $Z_{T1} = Z_{T2} = Z_{T0} = 0$, whereas the shunt capacitance has a major effect on earth fault analysis, see Fig. 12. (Guldbrand 2009: 46–47.)

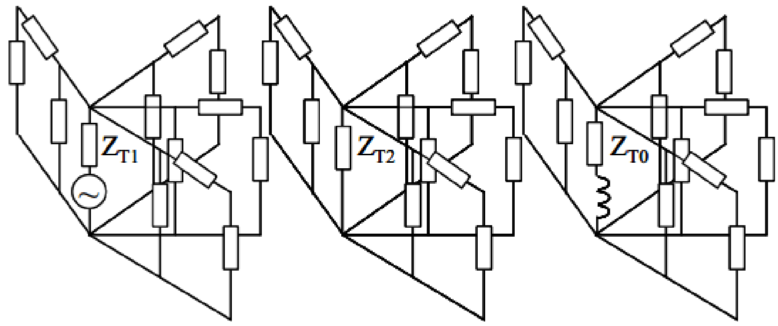


Figure 12. Urban network consisting of positive, negative and zero sequence networks. (Guldbrand 2009: 46.)

According to Guldbrand (2009: 38–39), the conventional earth fault analysis assumptions are valid in systems consisting of limited cable lengths. These assumptions for traditional analysis state the earth fault behaviour is defined by total cable length, hence it does not define whether network consists a couple of long feeders or several short cable lines. Secondly, the whole earth fault current can be compensated via Petersen coil, which is in relation to total cable length. If the capacitive and inductive currents cancel each other out completely, zero sequence voltage can be defined by the fault resistance and the coil resistance. Moreover, earth fault behaviour is not affected by fault place. It gives same earth fault current values and zero sequence voltages in the bus bar fault like fault e.g at the end of the feeder.

In case of longer cable lines the situation is now different and traditional analysis and assumptions are not anymore valid according to Guldbrand (2009: 39–40). Analyzing the effects with longer cable feeders requires different modeling methods to achieve accurate results and avoid false results. The increased lengths of feeders stipulate to use several pi-section connections (like in this thesis) instead of one section. These pi-sections are in series; see Fig. 13, compared to parallel line connections in urban network. It is also possible to compensate the non-linear behaviour of the reactive impedance by using correction factors. Because of larger series impedance, it has a bigger influence on earth fault situation. Now, the series impedance is taken into account, which impacts the earth fault current consisting in addition to capacitive, also a resistive component. This is proved in Guldbrand (2009: 41–45). Resistive component has to be kept within limited set of values because of the safety issues. Fault place influences zero sequence voltage in case of long cable lines compared to conventional system assumptions. From this, zero sequence voltage measured by the substation, differs now from the zero sequence voltage measured at the feeder. (Guldbrand 2009: 42–45.)

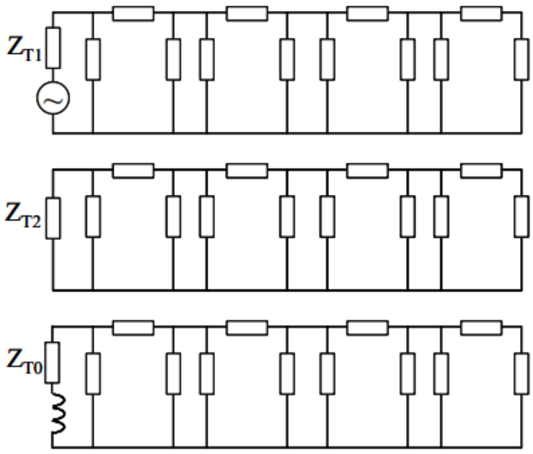


Figure 13. Rural network consisting of positive, negative, and zero sequence networks, which are connected in series, when fault occurs. (Guldbrand 2009: 47.)

2.7 Cable characteristics and zero sequence impedance

Compared to OHLs, underground cables have slightly different features in zero sequence network parameters and they affect on the zero sequence impedance. Fig. 14 illustrates a simplified model of a three-phased cable and its dimensions. According to Fig. 14, the diameter of the total cable is represented by $2r_{\mathrm{sh}}$, the diameter of the one conductor is represented by $2r_{\mathrm{c}}$, the distance between the conductors is represented by d. d_{i0} defines the distance between the cable's conductor and earthing wire and $2r_{\mathrm{ew}}$ is the diameter of the earthing wire. (Guldbrand 2009: 16–17; 92–93.)

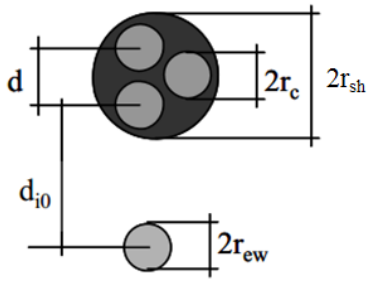


Figure 14. Underground cable dimensions and earthing wire in a cross-section view. (Guldbrand 2009: 93.)

According to conventional earth fault analysis, the series impedance can be ignored. However, recently arised interest for zero sequence impedance among researchers was resulted from increased cabling and longer lengths in rural areas. Gunnar Henning from ABB has developed a schema for analyzing zero sequence impedance, which is presented with more details in Pekkala (2010: 33–34) and Guldbrand (2006: 14). There are still many uncertainties among researchers concerning the zero sequence impedance. (Guldbrand 2009: 91–100.)

Many factors are affecting to zero sequence impedance. Zero sequence capacitance, cable characteristics, which are presented in Fig. 15, ground resistivity, earthing wire and its distance to earth and earthing resistance, all impact the zero sequence impedance. Fig. 15 shows the cable characteristics of underground installation. Cable is three-phased, $\underline{U}_{\mathrm{v}}$ equals in all phases, the residual current $3\underline{I}_0$ flows in conductors, along the sheat $\underline{I}_{\mathrm{sh}}$, through the earthing wire $\underline{I}_{\mathrm{ew}}$ and earth $\underline{I}_{\mathrm{e}}$. Cable has also a conductive connection to earth both at the beginning and at the end of the cable via an earthing resistance R_{er}. Arised self- and mutual impedances as a result of different current routes in the cable and between the cable and earthing wire, have an effect on zero sequence impedance. Moreover, these values are affected by cable features and current return routes. (Guldbrand 2009: 42–44; 91–100.)

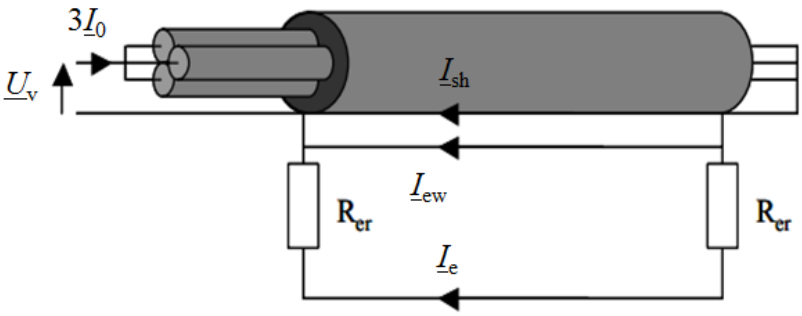


Figure 15. Cable characteristics for underground installations and related current flows. (Guldbrand 2009: 92.)

The feeder length has a minor influence to the magnitude of the zero sequence impedance, whereas the change in the argument of the impedance is more evident. Due to longer cable lengths, fault current consists of reactive and resistive components, which can be seen in Fig. 16. As a result, the traditional earth fault analysis isn't accurate anymore.

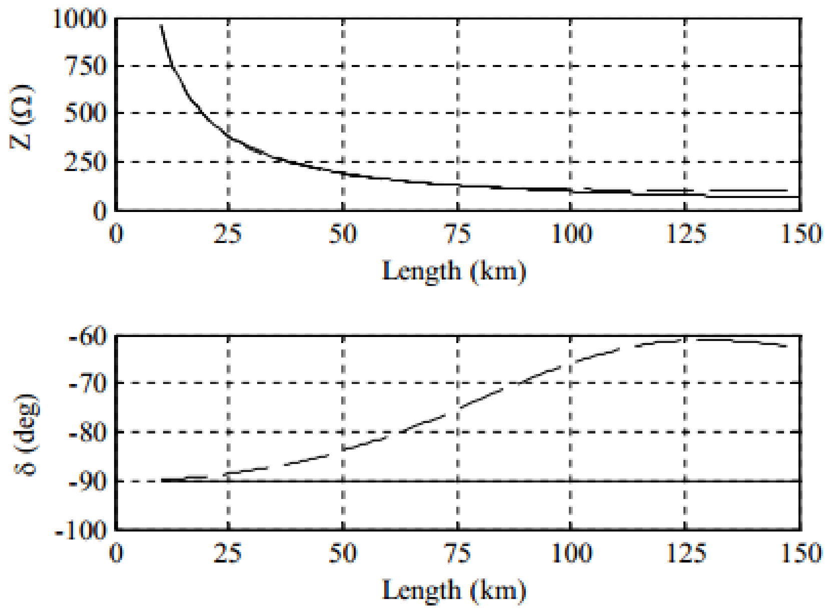


Figure 16. Magnitude and angle of the zero sequence impedance of cables. Dashed line represents cable modelling by pi-sections and solid line by capacitance only. (Guldbrand 2009: 43.)

3 COMPENSATION AND PROTECTION METHODS

3.1 Network safety

Guaranteeing safety is the main priority in network protection and after that come reliability and economic issues. The purpose is to ensure safety for customers, operation personnel and surrounding areas and animals during and after fault situations. Ensuring safety in network there has to be determined certain limiting values in currents and voltages and fault duration time. (Guldbrand 2009: 7.)

When the primary coil of the distribution transformer is coupled in delta-connection and without taking care of asymmetry due to earth fault in MV network, the voltages are in the secondary side e.g. in low voltage (LV)-side at normal state. Therefore, LV customers will not notice any disturbances or problems and normal usage of network could be possible during an earth fault. The magnitude of earth fault current can be rather slight, which may not damage household devices. (Lakervi & Partanen 2009: 189.)

The increase of earth fault current is possible to limit, e.g by adding a new main transformer to power station. Because of high costs, it is not reasonable just for limiting earth fault. It it also possible to limit earth fault current by decreasing earthing resistance, but due to low soil conductivity it would not be suitable. One possible solution could be to shorten the clearing times, which would however impacts to the quality of supply by giving less time for faults to be removed by themselves. (Lakervi & Partanen 2009: 189.) On the other and, current flow duration would be shorter, which could be beneficial by safety point of view (Nikander & Järventausta 2005). Consequently, the best alternative for earth fault current to be in limited values is to use Petersen coils (Vehmasvaara 2012: 23).

3.1.1 Current effects on human body

During human contact with energized part of the network, voltage is formed due to potential difference, and it will produce current. Current flows through certain non-linear body impedance, which is resistive and slightly differs in everyone due to different factors, e.g. amount of water and mass of body. Supposing large contact extents and affected voltage over 1000 V, the body resistance varies between 575 Ω, which consists 5 % of the population and 1050 Ω, which have the majority, 95 % of the population (IEC 2005). (Guldbrand 2009: 7–10.)

Current amplitude and duration define how severe the consequences can be to human body. Current flowing through hearth can lead to ventricular fibrillation, which can cause dramatic consequences to victim. Also tetanic contractions, respiratory arrests and burns can occur. According to IEC 60479-1 standard, which is illustrated in Fig. 17, time-current diagram divided in four different zones is presented, where the effects of alternating current (AC) can be seen, see Table 1. AC-current is much more dangerous than direct current (DC) (Elovaara & Haarla 2011b: 498–500.), and therefore DC-evaluation can be left out consideration. According to Fig. 17, current being larger than 30 mA flowing from hand to feet (c1-curve), there is only a minor chance to survive alive unless situation can be interrupted quickly. (Siirto et al. 2012; ABB 2013a: 2/2.)

Table 1. AC current effects on human body. (ABB 2013a: 2/3.)

Zone	Effects
1	Usually no reaction
2	Usually no harmful physiological effects
3	Usually no organic damage to be expected. Likelihood of cramp-like muscular contractions and difficulty in breathing; reversible disturbances of formation and conduction of impulses in the heart, including atrial fibrillation and transient cardiac arrest without ventricular fibrillation increasing with current magnitude and time
4	In addition to the effects of zone 3, the probability of ventricular fibrillation increases up to about 5% (curve c2). 50% (curve c3) and above 50% beyond the curve c3. Pathophysiological effects such as cardiac arrest, respiratory arrest and severe burns may occur, increasing with current magnitude and time

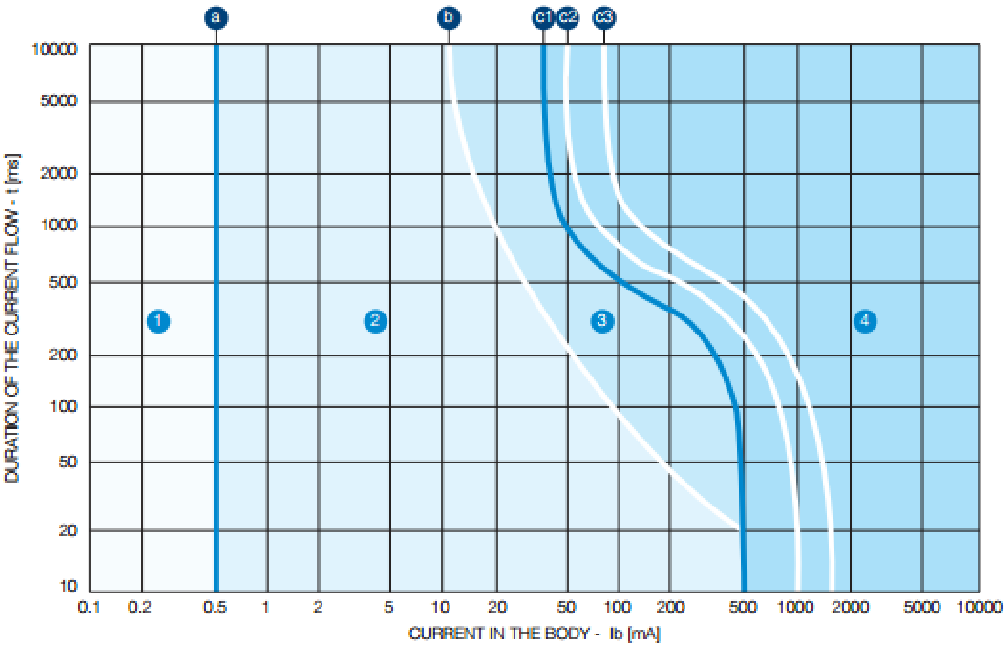


Figure 17. Time-current diagram divided into four zones. (ABB 2013a: 2/2.)

3.1.2 Step and touch voltages

Danger can occur in earth fault situations if person or animal touches live parts or is even near the fault place, where potential difference is changing and generating step voltage U_{ST} between person's feet, which is illustrated in Fig. 18. Fig. 18 shows also touch voltage U_{TP}, which is a part of the voltage-to-earth. It is the connection voltage between energized part and person's feet, voltage-to-earth and earth fault current to ground. Earth fault current $\underline{I}_f$ flows through a resistance to earth R_{er}, and causes in a fault place a voltage to earth $\underline{U}_e$, which can be calculated from the equation (Lakervi ja Partanen 2009: 186–187.)

$$\underline{U}_e = \underline{I}_f R_{er}. \tag{3.1}$$

Current magnitude, which causes danger when passing through human body, is difficult to determine. Therefore, the voltage limits, which are corresponding the currents are presented as step and touch voltages (Siirto et al. 2012; Nikander & Järventausta 2005.) Fig. 19 shows permissible touch voltages as a function of current flow duration time assuming with 10 % probability of ventricle fibrillation by SFS-6001 standard. It can be seen that the lower the voltage is, the longer is the time it can be allowed (Siirto et al. 2012). In isolated or compensated neutral networks the common tripping delays vary between 0.2 s or 0.3 s, and 1.0 s (Nikander & Järventausta 2005). (Lehtonen & Hakola 1996: 55–59; Lakervi & Partanen 2009: 187–188; Elovaara & Haarla 2011b: 428–432.)

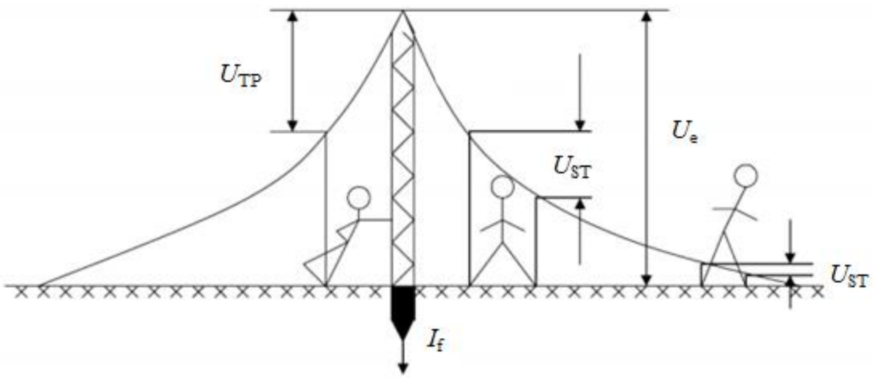


Figure 18. Generated different voltages during an earth fault situation. (Lehtonen & Hakola 1996: 58.)

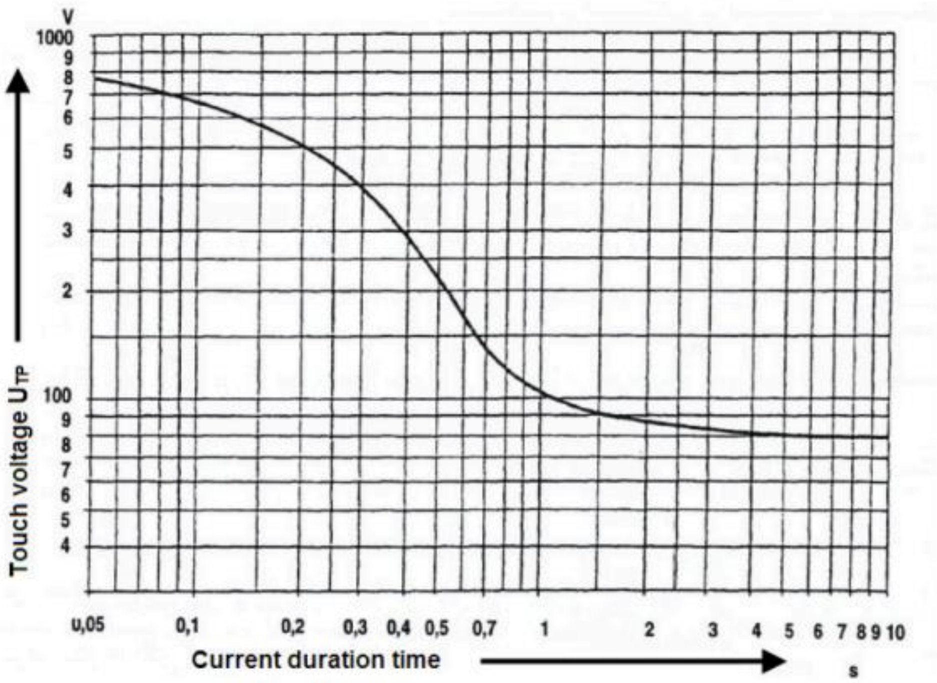


Figure 19. Permissible touch voltage U_{TP} as a function of current duration time. (SFS 2005: 78.)

3.1.3 Earth fault regulations and standardization and legislation

Earth fault legislation is based on regulations and definitions by different authorities both in globally and national level. Distribution network safety is mainly a concern of DNOs, which have to ensure safe conditions during normal network usage and also in fault circumstances, limit access from normal people e.g. power stations and restrict consequences as small as possible due to faults by following earth fault related safety regulations. Compared to short circuit legislation, issues dealing with earth fault current legislation are more specifically controlled by SFS 6001 regulation in Finland and ELSÄK-FS in Sweden. Earth faults have to be removed either automatically or manually. However, SFS 6001 standard advises to use automatic system. Higher voltage levels may create danger for customers and network equipment even in LV-side. (ELSÄK-FS 2008: 1; Pekkala 2010: 48–49.)

In Finland SFS 6001 standard defines limiting touch voltage values as a function of current duration flow. According to ELSÄK-FS (2008: 1), there are specific values for earth voltage in Sweden. (Pekkala 2010: 48–49.) High-impedance earth faults are not so dangerous in cabled systems compared to OHLs, because cables are out of reach of normal people. In Sweden, in case of cable systems, detecting fault is enough. If network contains partly or entirely OHLs and fault impedance is either under 3 kΩ or 5 kΩ in case of covered lines, fault will be detected and removed (ELSÄK-FS 2008: 1). In Finland, protection is based on electrical safety regulation. Earth faults have to be cleared up to 500 Ω fault resistances. Faults have to be also cleared during two hours from the fault detection. If it is possible, even higher fault resistance faults would be beneficial to detect. (ABB 2000: 258; Guldbrand 2009: 10.)

Due to storms and related power failures and outage costs in distribution network, the Finnish government has finished its new energy market legislation by Ministry of Employment and the Economy, which came into effect in the fall 2013. It takes stand more precisely to the quality of supply. According to the new legislation, distribution networks has to be designed, implemented and maintained in case of storms and mass of snow, in such way that it can not cause supply outages to customers over six hours in urban areas or over 36 hours in other areas. These requirements have to be implemented stepwise during the next 15 years. 50 % of the delivery reliability requirements have to be achieved by the end of 2019, 75 % by the end of 2023, and 100 % by the end of 2028. In case of extraordinary extent cabling, DNOs may have time to meet the requirements by end of the year 2036. (Ministry of Employment and the Economy 2013.) In Sweden the parliament decided to change the power supply regulation by new law regulation 2005, which improves customers' rights compensating power outages (Guldbrand & Samuelsson 2007). Consequently, these new requirements for quality of supply will definitely set more pressure on DNOs in near future.

3.2 Compensation methods

Petersen coils are an effective way to limit earth fault current. Therefore, it is discussed with more details and studied via computer simulations in this work. Compensation with Petersen coils has not yet been widely used in Finland compared to Sweden, where compensation covers nearly all the MV distribution networks. Compensation with coils is increasing in Finland and will replace isolated neutral networks in future. (Pekkala 2010: 52.) This method and its redeeming features in MV distribution networks have gained more awareness among DNOs. Especially with this method, reliability and quality of supply are guaranteed. It has also noticed that compensation diminish outages, in case of faults consisting mainly of momentary faults. (Wahlroos & Altonen 2011: 3.)

The residual current compensation (RCC) is a compensation method, which was originally developed by Swedish Neutral. It eliminates the fundamental frequency fault current, and dangerous high voltage levels in compensated networks. It does not trip the faulted feeder, it cancels fault current out by injecting opposite current to neutral point, and single-phased earth faults can be removed without disconnections. As a result, the distribution network during earth fault situations can be used. (Nikander & Järventausta 2005.) However, this residual current compensation is not studied with more details in this work.

Network can be compensated practically in three different ways; centrally, decentrally or partly decentrally, when it can be also called as a *hybrid*, like in Wahlroos & Altonen (2011) or *mixed* like in Jaakkola & Kauhaniemi (2013). Earlier, centralized compensation was used due to costs and more easiness, but decentralized and partly decentralized compensation methods have shown their good potential in compensation field. (Wahlroos & Altonen 2011: 3.)

In practice, there is also a resistance R_L connected parallel to the coil, which is used to increase active earth fault current for fault detection and selective relay operation (Hänninen et al. 1998; Wahlroos & Altonen 2011: 4). It is called “Active Current Forcing” (ACF) scheme by Wahlroos & Altonen (2011: 4). The connection logic of the parallel resistor can be implemented in three different ways: connected all the time, connected a short time interval after fault appears, but it is not connected during normal network usage or disconnect it a short time interval after fault and connect it again if fault has not been cleared.

By permanent connection of the parallel resistor, the aim is to limit $\underline{U}_0$ at the healthy state in totally cabled networks. However, it might be eliminated totally due to resistor and hindering coil control. In the second alternative, self-extinguishment of arc is more likely to happen and before connecting the resistance, $\underline{U}_0$ might reach large values due to compensation degree and capacitive unbalance. By disconnecting the resistance after a short time period, the advantages from previously mentioned two methods are combined: reducing $\underline{U}_0$ and enabling self-extinguishment of arc. However, parallel resistor has to withstand higher continuous power. (Mörsky 1992: 336–337; Isomäki 2010: 30; Wahlroos & Altonen 2011: 4.) There are varying viewpoints of how the parallel resistor should be connected, and some DNOs are just using the method, which they have noticed to function properly, e.g via practical experience. In this thesis, the differences between on and off situations of the parallel resistor are studied.

3.2.1 Centralized compensation

When compensation coil is connected to neutral point of the main transformer's secondary side, i.e. MV side at the substation, see Fig. 20, or via grounding transformer, the system is centrally compensated. Main transformers in Finland are basically YNd-coupled and distribution transformers Dy-coupled. Due to delta-wiring in the MV-side, there is not a neutral point for coil connection. YNyn-coupled transformers would be suitable considering costs and unbalanced loadings, but are inconvenient in parallel use with Yd-coupled transformers. Therefore, neutral point has to be generated via a seperate, Znyn-coupled grounding transformer. (Mörsky 1992: 319–321; Pekkala 2010: 52–54.)

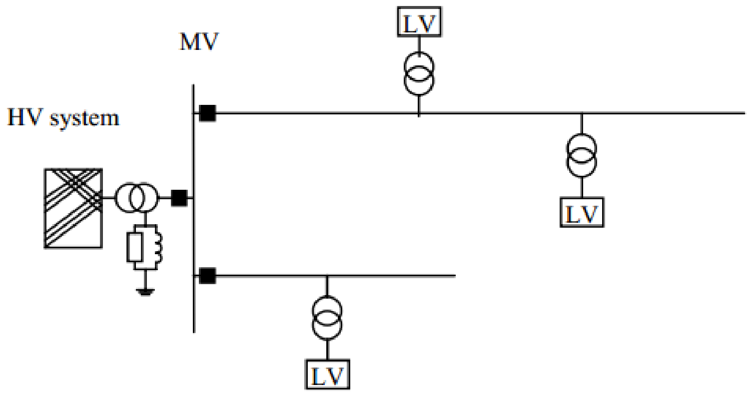


Figure 20. Centrally compensated network. (Guldbrand & Samuelsson 2007.)

Centralized compensation is beneficial in case of poor earthing and when the value of earth fault current is larger than 35 A. Costs are a major factor in centralized compensation. Therefore, in the long run, careful planning of the network is needed. (Lehtonen & Hakola 1996: 70; Pouttu 2007: 30.) However, based on the results from Pekkala (2010) using centralized compensation with long cables, the resistive part of the earth fault current might be a problem. Therefore, decentralized compensation should be used to reduce high resistive part of the earth fault current to allowed levels. (Lehtonen & Hakola 1996: 69–70; Wahlroos & Altonen 2011: 5.)

3.2.2 Decentralized compensation

Decentralized or distributed, or sometimes called as local compensation, which is illustrated in Fig. 21, is based on placing several fixed coils along the feeders, which are tuned to compensate almost the total capacitive part of the specific feeder sections. This is advantageous in feeder disconnection situations deactivating the same amount of compensation, which is extracted. By doing this, the right compensation degree remains, the balance in the network will be guaranteed, and harmful overcompensation situations leading to false relay operations can be avoided. (Guldbrand & Samuelsson 2007; Wahlroos & Altonen 2011: 5–6.)

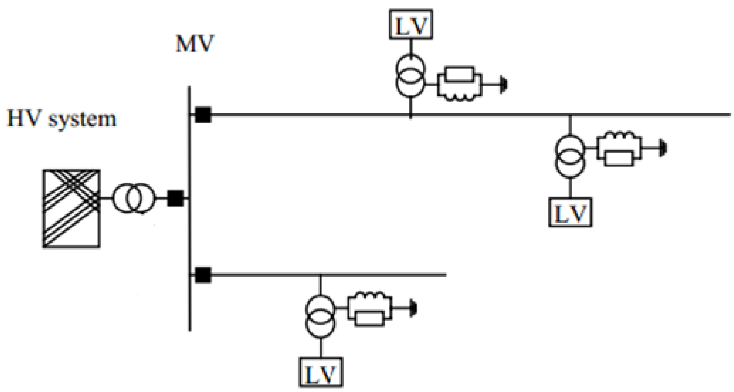


Figure 21. Decentrally compensated network, where Petersen coils are located along the feeders. (Guldbrand & Samuelsson 2007.)

However, careful placing of the coils is needed. The balance of the network is ensured if coils would be disconnected for some reason. This kind of situation responds to earth fault behaviour situation in isolated neutral system. (Guldbrand & Samuelsson 2007; Wahlroos & Altonen 2011: 5–6.)

In practise, decentralized compensation coils are rated to compensate a fixed value varying typically between 5 A and 15 A. It is useful method in rural areas and with long feeder lengths. (Hänninen & Lehtonen 1997.) Coils are connected to distribution transformers' neutral. A lack of neutral point in distribution transformers due to delta-connection (Dy-coupling), ZNzn0- or Zn(d)yn-coupled transformers have to be used. These couplings also prevent earth fault current flow to LV-side. The distance of coils between each other has also to be determined accurately due to the influence of the series impedance. When the distance between coils is increased, resistive part of the equivalent impedance and resistive part of the earth fault current increase, i.e. resistive losses increase, and these depend on size of coils. (Guldbrand 2009: 32–34; Pekkala 2010: 55; Vehmasvaara 2012: 24–25.)

According to Guldbrand's (2009) thesis, the most reasonable distance between coils would be 5 km or 10 km, and same results were achieved by Jaakkola & Kauhaniemi (2012). If the coil density of 10 km is used, there would be needed a smaller amount of expensive transformers. On the other hand, if the distance was 10 km, there might be a problem to maintain the steady compensation degree if part of the system would be disconnected. If the coil distance was 20 km, the series impedance would increase the resistive earth fault current. Compensating feeder with only locally installed compensation coils, the optimal coil distance would be at least 6.7 km. (Guldbrand 2009: 76; Pekkala 2010: 121.)

3.2.3 Practical aspects

Leakage resistances and resistances of the coil and network cause the resistive part of the residual current (Hänninen et al. 1998). Typically the resisitive part of the residual current in MV networks is ca. between 5 % and 8 % of the capacitive residual current (Hubensteiner 1989). With OHLs, residual current might reach 15 % (Claudelin 1991). When network consists of only cables, residual current is smaller, 2.3 % (Hubensteiner 1989).

In many European countries, compensation is implemented by overcompensation, like in Sweden, but it requires different relay settings compared to network configurations in case of undercompensated networks. Overcompensation is an optimal solution in case of a part of the network would be disconnected. Distance to resonance point would be increased. In Finland the systems are mainly undercompensated, 95 % or in practice most DNOs are using ampere values in order to explain compensation degree. (Guldbrand 2009:30; Pekkala 2010: 20,54; Elovaara & Haarla 2011a: 210–211; Vehmasvaara 2012: 21.)

It is not reasonable to operate network with full compensation degree; i.e. resonance, because zero sequence voltage is increased during normal network use. Fundamental frequency situation with OHLs is achieved with quite long feeder distances. In case of underground cables, the resonance point is achieved by relative short line lengths, because of different line features, e.g. zero sequence parameters. According to experiences in MV distribution networks, tuning value can vary ca. 25 % from full compensation degree before causing any dramatic disadvantages in protection scheme or unacceptable fault current levels (Lakervi & Holmes 1996: 43; Guldbrand 2009: 114; Pekkala 2010: 20.)

3.3 Earth fault protection

Earth fault protection system has to be designed and implemented in such a way that it follows standards, does not cause dangerous voltages to customers and guarantees safety in every part of the network. What kind of qualifications and definitions systems must consider in fault situations? Earth fault protection system is based on directional relays, which are usually located at substations, and functioning of circuit breakers, which compose overlapping protection zones. Circuit breaker is a part of the primary circuit, which operates according to instructions of relays via on or off contact terminals. Overlapping protection zones means that every part of the network is covered by at least two different relay protection zones. (Elovaara & Haarla 2011b: 342–344.)

Relays' *doubling* is implemented either with two different main protection or delayed stage of relay working as a non-selective back-up protection. Usually, neutral overvoltage relays are used, and threshold settings should be above the feeder protection setting value, e.g. 10 %. Neutral overvoltage relays protect a substation busbar from earth faults. To gain the sufficient sensitivity, back-up protection should be set to be independent of the feeder protection or to use different equipment for voltage measurement. (Lehtonen & Hakola 1996: 88–94; Guldbrand 2009: 23–24; Lakervi & Partanen 2009: 190–191; Elovaara & Haarla 2011b: 342–344.)

Networks can be divided into smaller sections by reclosers. Those help to minimize the number of customers, which experience interruptions, and hence improve the quality of supply. According to Pekkala (2010: 123), the quality of supply, which can be measured by certain indexes, may improve 30–40 % with accurate recloser placements. Recloser can be defined as “a protective device that combines the sensing, relaying, fault-interrupting and reclosing functions in one integrated unit” (IEEE 2008: 31). Reclosers detect faults, remove them and restore supply, and those can be categorized into three different groups, “by their interrupting medium, by their means of control and by their number of phases” (IEEE 2008: 31). However, planning of reclosers involves extreme meticulousness, because it influences the network protection issues (Pekkala 2010: 61). In this study, the protected feeder is studied considering also a recloser at the middle point of the protected feeder in addition to normal feeder protection at the substation.

Sensitivity is defined by protection relay settings, which means relay operation threshold values. U_{oh} can be defined as a threshold voltage and I_{h} a threshold current. In practise, todays’ relays can measure less than 1 A zero sequence current values and zero sequence voltages ca. 3–5 % of the phase-to-earth voltages. Considering errors in current measurements, the value of 1–2 A is more reasonable for setting in compensated neutral systems. Due to higher zero sequence voltage in compensated neutral networks (Fig. 8) U_{oh} value has to be set also higher. (Pekkala 2010: 82–83.) Calculated threshold values used in this work are discussed more precisely later. Moreover, these values have to be more precise in compensated neutral networks than in isolated neutral networks. Because of this, the implementation of protection in compensated neutral networks is more challenging. (Mörsky 1992: 332; Lakervi & Partanen 2009: 190–191.)

A good relay protection is selective, which means relay detects only the faulted part and disconnect it from the network. In compensated neutral networks higher selectivity is needed, because of considerably low earth fault current (Roberts et al. 2001: 2). Disconnected part of the network is supposed to be as small as possible to minimize outages: the smaller the disconnected part the smaller the outage costs. Altogether, the protection has to be fast, selective and reliable. Reliability consists of security of protection (tripping does not happen if protection zone does not include fault) and dependability, which means relay operates only when fault is in its own zone. The stabillity of network has to be ensured in every condition. Good protection system withstands an absence of a one network component without adjustment changes. (Guldbrand 2009: 23–24; Pekkala 2010: 57–60; Elovaara & Haarla 2011b: 342–344.)

3.3.1 Protection system in MV distribution networks

Relays, which are placed in MV distribution networks for observing fault situations, have developed enormously and nowadays there are a huge number of different relay types for certain purposes: from old electromechanical relays to static, digital, and numerical relays. Relays can be also divided in primary (main circuits) and secondary (connected to secondary side of instrument transformers) relays. It has to take some factors into account, when choosing relays, e.g. nominal values, adjustment region, operational accuracy, loading capacity of contact makers, dynamic and thermal resistance, and operation and resetting values. (Mörsky 1992: 328–334; Lakervi & Partanen 2009: 190.)

Typical relays nowadays, which are used in E/F protection, are numerical microprocessor-based, directional and secondary side relays. Different protection functions are combined to a single relay and self-supervision is implemented via communication system to control the system. (Javora, Stefanka, Mähönen, Niemi & Rintamäki 2009.) In Finland, relays can also include settings both for isolated and compensated neutral networks. The new settings due to changes, e.g. coil disconnection, can be then adjusted automatically. (Mörsky 1992: 328–334; Lakervi & Partanen 2009: 190–194; Elovaara & Haarla 2011b: 353.)

There are many other components, which are needed for protection: instrument transformers (ITs), transducers, auxiliary power sources, alarm- and reporting centers, and measurement, launching and data transfer connections. Auxiliary power source is normally a battery, which guarantees the functioning of important network equipment during faults, e.g. circuit breakers, and it completes the relay protection system. In order to have fast and reliable fault situation summary, alarm and reporting centers are needed. Those gather information concerted from several different places located relays, and information can be particularly useful for post-analysis. (Mörsky 1992: 15–18.)

The aim of ITs, which are current transformer (CT) and voltage transformer (VT), is to convert measured value into right scale for relays or measuring equipment. Relays are then able to process the values in their scaling and to function or not according measured protection quantities. It makes possible to manage very large measured values from primary circuits. ITs also seperate measuring circuit from primary circuit, protect measuring circuit from overloadings, and enable measuring equipment or relays to locate a quite long distance from the measuring point. Protection relay perfomance is highly depending on the ITs performance, because relays' responses are based on the signals transferred from ITs (IEEE 2008: 32–33). (Mörsky 1992: 16,85; Uski 2001: 6,25; Javora et al. 2009.)

Other ITs, non-conventional tranducers, are voltage dividers, Rogowski coils, low power current transducers and optical sensors. Those are, safe, proper-sized, possess linear characteristics, reliable, and have good energy efficiency, and of course the most important thing: those produce extremely accurate measurement values (Celko & Prokop 2013.) Rogowski coils, which are current sensors, have the same operating principles than traditional iron-core CTs. However, Rogowski coils are wound over an air core (linear due to air core non-saturation) compared to traditional CTs, which are wound over an iron core. Compared to traditional CTs, Rogowski coils are e.g. very precise in measuring current, current range can be very broad, and lower power consumption (no core losses). These coils, which function in all voltage levels, could replace traditional CTs, but instead of producing a secondary current (in relation to primary), coils generate voltage (in relation to time derivative of the primary current). Signal processing is needed and receiving devices (microprocessors) design has to be able to process these signals. (Öhström 2003: 23–24; Kojovic, Beresh, Bishop, Javora, Magruder, McLaren, Mugalian & Offner 2010.)

Cable type current transformer is a special type of current transformer, which is more sensitive than normal current transformers. It is possible to measure smaller than 0.5 A zero sequence current values. Therefore, cable type current transformer is used with cable feeders. The nominal current of the primary coil have to be chosen by considering the earth fault current of the network (Lakervi & Partanen 2009: 193). (Mörsky 1992: 125–127.)

Directional earth fault protection is based on measured protection quantities. Relay will function if the magnitudes of $\underline{U}_0$ and $3\underline{I}_0$ are exceeding the threshold values, and the angle between them is in the defined operating sector. U_{oh} is typically used for the start function for E/F protection, which has to be set above the magnitude of healthy state $\underline{U}_0$ to avoid false starts (Wahlroos & Altonen 2009; Wahlroos et al. 2011). $\underline{U}_0$ is measured by the secondary winding of voltage transformer (open delta-connection). Zero sequence current is measured by current transformer's sum or by cable type current transformer. (Mörsky 1992: 328–334; Lakervi & Partanen 2009: 192.)

According to Fig. 22a in isolated neutral network, the operation sector is $90°–\Delta\varphi < \varphi < 90°+\Delta\varphi$. Practically, earth fault current in isolated neutral network is capacitive, i.e current is 90° ahead compared to voltage. The difference between compensated neutral networks is the phase angle between current and voltage. It is $\pm\ \Delta\varphi$, which can be also written by $0°–\Delta\varphi < \varphi < 0°+\Delta\varphi$, see Fig. 22b. According to Fig. 22, $\underline{U}_0$ is the zero sequence voltage, $3\underline{I}_0$ is the residual current, $\underline{I}_h$ is the threshold current, $\Delta\varphi$ represents the tolerance, φ is the phase angle between $\underline{U}_0$ and $3\underline{I}_0$, and φ_0 is the relay characteristic angle. (Mörsky 1992: 328–334; Lakervi & Partanen 2009: 191–194.)

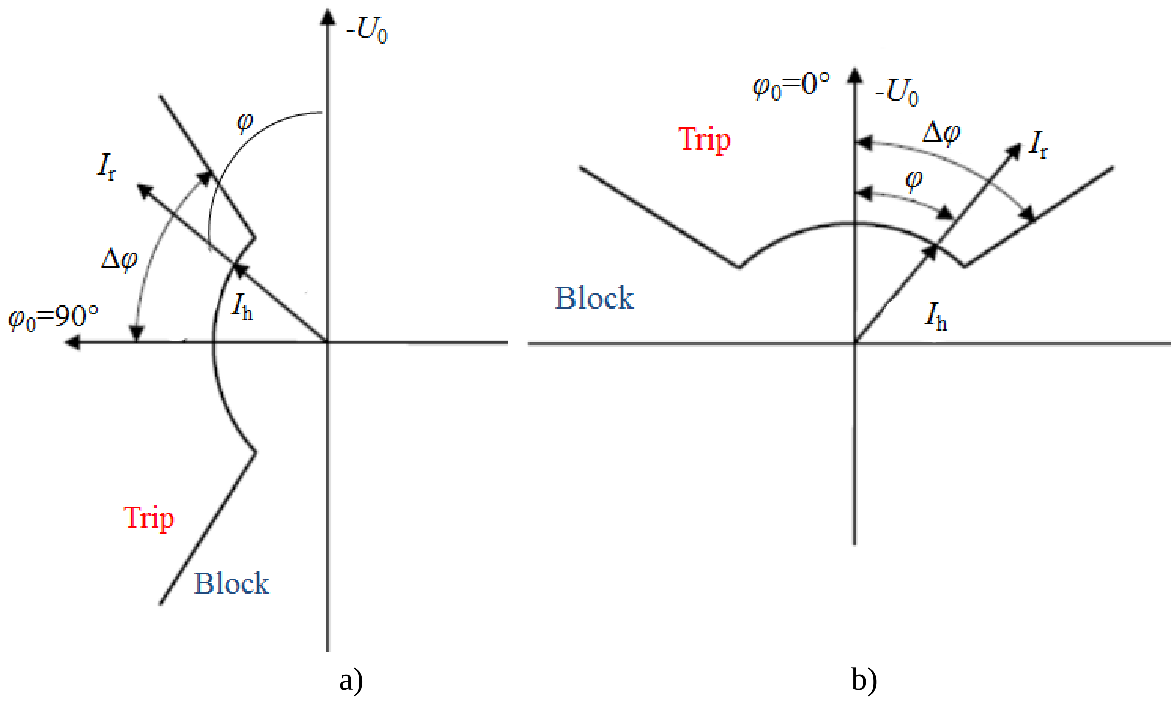


Figure 22. Directional earth fault relay operation criterion (phase-angle criterion) for isolated neutral network a) and, compensated neutral network b). (Lakervi and Partanen 2009: 192.)

3.3.2 Errors in protection quantity measurements

The whole measuring chain is composed mainly by VTs, CTs, relays' own transformers and filters. ITs are not completely ideal. All of these equipments produce some error for total result. A minor error in one component does not have a notable meaning for result compared to error, which is produced by all of these components together. Especially it has to be very careful with measuring CTs, because variations in currents are larger. CT should be select carefully, because CT specifications, magnitude of fault current, burden and aim of the protection application on the CT selection (ABB 2013b: 781). (Mörsky 1992: 85–140; Pouttu 2007: 40–52.)

According to IEC 60044 standard for ITs, certain accuracy limits for CTs and VTs are defined. CTs and VTs, which can be divide into measuring and protection purposes or both consisting of several cores, have different relevance ratios (declared by numbers). Core intended for measuring puposes has to be very precise, because traditional E/F protection methods depend highly on the accuracy of CT. (Mörsky 1992: 85–140; Pouttu 2007: 40–52.)

According to IEC 60044 standard for protection purpose CTs, the accuracy limit gives the highest fault current magnitude, which is allowed to achieve the desired precision. Current error is ± 1 % and angle error ± 1° according to accuracy class 5P for MV networks in fundamental frequency. Angle error is the phase angle difference between secondary current and primary current, which is reduced to secondary. Combined maximum error is ± 5 %. For measuring purposes, current and voltage ratios have to be more precise. Typically, the ratios for VTs are based on accuracy class 3P. Voltage error is then ± 3 % and angle error ± 2°. (IEC 60044-1 2003: 76; IEC 60044-2 2003: 75.) A few degree errors in phase angle measurement might lead to unslective relay operation, where the phasor is turned into wrong sector. Moreover, E/F protection relays can cause some error for the results, e.g. ± 1–2°. As a result, it can be concluded that the worst error situation in phase angle measuring can be apprx. ± 4–5°. (Mörsky 1992: 85–140; Pouttu 2007: 40–52; ABB 2013b: 357,781.) Therefore, the effect of errors is studied in this thesis only in this worst case.

3.4 Directional earth fault protection methods in compensated neutral networks

E/F protection can be implemented by using different methods. The traditional methods, which are universally well-known among protection engineers, are introduced first. The drawbacks with these are the decreasing sensitivity, when fault resistance increases, and problems with intermittent earth faults. These methods are $I_0\cos\varphi$, phase angle and wattmetric methods. (Wahlroos et al. 2011.) After these the novel admittance criterion is introduced. The first three methods have rather small variations compared to each other. Phase angle method is chosen to be evaluated with the simulated results in this thesis. In addition to phase angle criterion, the novel admittance criterion, which has proven to have a good performance, is studied in this thesis (Wahlroos et al. 2011).

3.4.1 $I_0\cos\varphi$ method

$I_0\cos\varphi$-method is based on the magnitude of resistive component of zero sequence current. When the resistive component of zero sequence current has exceeded the start current I_h setting value, and also the amplitude of $\underline{U}_0$ has exceed U_{oh} value, the operation is achieved. (Roberts et al. 2001: 25; Wahlroos et al. 2011.) However, changes in feeder lengths and fault resistances have an affect on zero sequence current and hence, protection sensitivity. Therefore, maintaining selectivity can be problematic. (Mörsky 1992: 329.)

3.4.2 Phase angle criterion

Phase angle criterion, which was already introduced in Fig. 22, is based on three requirements. The operation requires both magnitudes of $3\underline{I}_0$ and $\underline{U}_0$ values to exceed their threshold values. The phase angle between voltage and current has to be also between certain values. Typically operation sector width can be set to ± 80° (ABB 2013b: 233), like it is used in this thesis. In compensated neutral networks the relay characteristic angle have to be set to 0° and in isolated neutral network to 90°. (Mörsky 1992: 332–333; Wahlroos et al. 2011.)

Because the aim of this work was to find out how large fault resistance values can be detected by earth fault protection, so that the fault is still being detected in different situations, R_f basis was chosen to equal 5000 Ω. For example, within Elenia, earth faults can be be detected up to 5000 Ω fault resistances, in some cases even up to 10 kΩ (Pekkala 2010: 73). However, high-resistance faults are rare in networks that are consisting only cable. Therefore the desired sensitivity for detecting faults up to 5000 Ω can be assumed to be quite adequate. The magnitudes of $\underline{U}_0$ and $3\underline{I}_0$ were first calculated according to created PSCAD models by using Eq. 2.9 and 2.10. According to calculated results, the threshold values U_{oh} and I_h were set.

Because the network models differ compared to each other, the relay threshold settings have some variations. Achieving more uniform and definent threshold settings, and also ensuring the zero sequence voltage threshold setting to be above the healthy state zero sequence voltage, U_{oh} was set to be either to 7 % or to 4 %. In the same way was done with I_h value by setting it to 1 A in all cases. Calculated values can be found precisely solved in Appendix 2. Values are gathered and discussed in case of every network model situation seperately and presented later on this thesis. Values for the relay characteristic angle and the tolerance were explained earlier in this work.

3.4.3 Wattmetric method

According to IEEE (2008: 2) the relays, which are using wattmetric method for earth fault protection "respond to the in-phase (real) component current as compared to the polarizing voltage". In other words, wattmetric relays measure the real component of the product of $\underline{I}_0$ and $\underline{U}_0$ (the active power), which can be obtained also from equation (Roberts et al. 2001: 26.)

$$W = \mathrm{Re}\,(\underline{U}_0 \cdot \underline{I}_0^*) = U_0 \cdot I_0 \cos(\varphi), \tag{3.3}$$

where

W is the active power measured by wattmetric method, and

$\underline{I}_0^*$ is the complex conjugate of $\underline{I}_0$.

The sign of calculated product defines either fault locating at the protected feeder or in the BG network. Wattmetric method is commonly used in compensated neutral networks, but due to low earth fault currents, the use of method is restricted. Wattmetric method is selective up to a few kilohoms, but usually there are additional devices for helping the earth fault protection to be selective in case of high-ohmic and intermittent earth faults. There are varying viewpoints among authors of how sensitive wattmetric method can be. Some think parallel resistor can not help protection to detect faults selectively over 3 kΩ resistances within the newest digital relays, but others think the wattmetric method is reliable only up to 1 kΩ. (Roberts et al. 2001: 26; Kulis, Marusic & Zutobradic 2004.)

Threshold values have an effect on sensitivity, and by that the minimum values, which relays can measure reliably. Wattmeric method can be perceived as easy, safe and reliable in case of low-resistance faults, but inappropriate for high-resistance earth fault detection. Despite the usage of parallel resistor, high-resistance faults due to small zero sequence current values are not detected reliably. Moreover, in compensated neutral networks the problem is the low magnitude of zero sequence voltage, and by that the wattmetric value is even more decreased, because it is the product of resistive component of zero sequence current, and zero sequence voltage. (Kulis et al. 2004; Pouttu 2007: 63–65.)

3.4.4 Admittance-based criterion

Admittance-based protection method or Y_0-principle is based on calculating the quantitent of phasors of $3\underline{I}_0$ and $\underline{U}_0$, which gives the neutral admittance value. The calculated admittance value is checked in the admittance plane with adequate boundaries if it is located inside or outside these boundaries. When located outside the boundaries, the relay operates and respectively, when the calculated admittance is located inside the boundaries, relay does not operate, which can be seen in Fig. 23. There are many variations of admittance protection characteristics depending on the network and protection principle (ABB 2013b: 270–279). Fig. 23 shows the *box*-characteristic, which is valid both in isolated and in compensated neutral networks enabling good sensitivity (Wahlroos 2012). The *box*-characteristic is also used representing the simulated results in this thesis, because decentralized compensation is used.

The aim is to cover the $-\underline{Y}_{\mathrm{Fdtot}}$ (the total neutral admittance of protected feeder) value with sufficient margins. A guidline for different fault situations, see Fig. 24, either the fault is located in reverse direction, i.e. located in the BG network or in forward direction, i.e. at the protected feeder. (Wahlroos et al. 2011; Wahlroos & Altonen 2011: 8–11.)

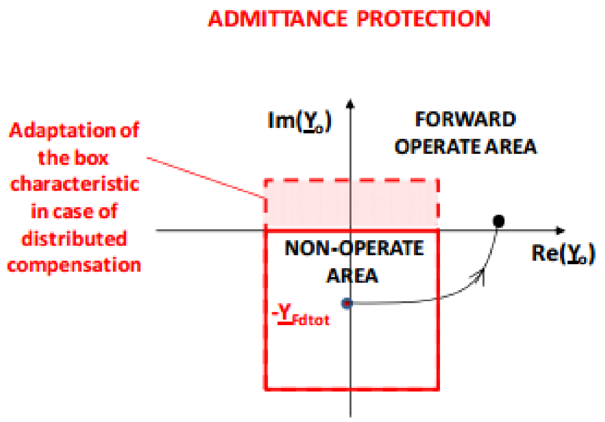


Figure 23. Admittance criterion with *box*-shaped characteristic. (Wahlroos & Altonen 2011: 11.)

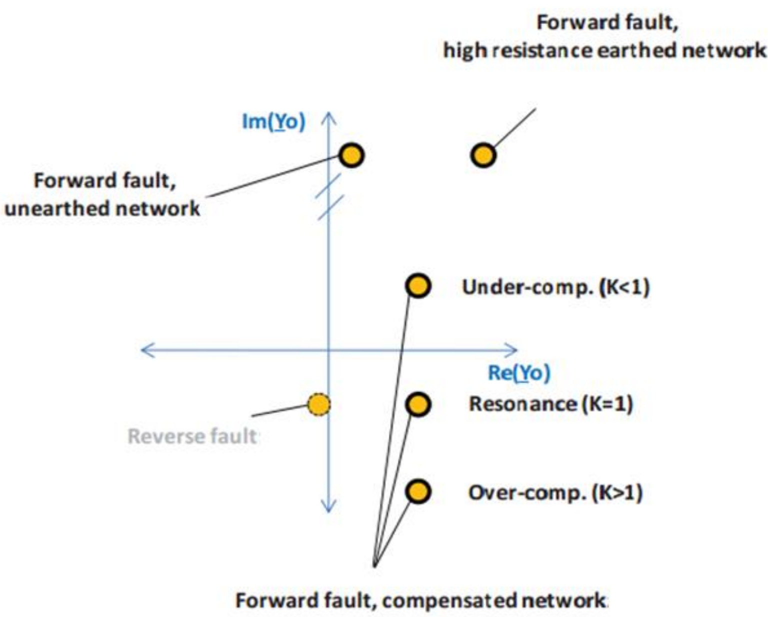


Figure 24. Measured admittances in reverse and forward fault situations. (ABB 2013b: 267.)

U_0 overvoltage condition (E/F start function) has to be always considered with the admittance method for E/F detection in the same way with traditional E/F protection methods. U_{oh} value must be above the healthy state U_0 to avoid false starts. The minimum current threshold value, which have to be set also with admittance criterion, is

0.5 A (Lorenc, Marszalkiewicz & Andruszkiewicz 1997; Wahlroos & Altonen 2009; Wahlroos et al. 2011.)

Admittance-based E/F protection with *box*-characteristic will function properly in case of coil disconnection and setting changes defining the operation characteristics are not needed. The admittance criterion enables adjustment calculation being unproblematic, selectivity is ensured, distributed compensation can be considered, and sensitivity is easy to set by U_{oh}. Protection will function even without the parallel resistor of the coil, but only in specific circumstances (Wahlroos 2012.) Despite of the benefits introduced by the admittance principle, the amount of relays containing the admittance method is low. One solution to make the admittance method more highlighted in relaying field, could be by converting the the $\underline{Y}_0$-domain into the $\underline{I}_0$-domain, where settings would be more familiar for protection engineers, and the application of this method would be more simple. (Wahlroos et al. 2011.)

The admittance characteristic boundaries used in this thesis can be calculated according to Fig. 25, where settings for conductance forward, conductance reverse, susceptance forward and susceptance reverse values are considered. Tilt angles are not applied. The setting values, which are used in this work for above mentioned four parameters, are calculated according to ABB (2013: 282–283). Calculated values for each network can be found in Appendix 3.

All E/F protection methods, which are based on resistive component of fault current, power or admittance, require good accuracy of current and voltage measurement. Especially, the accuracy of phase angle measurement is critical. When using admittance criterion, the produced errors have to be taken into account with cable type CT.

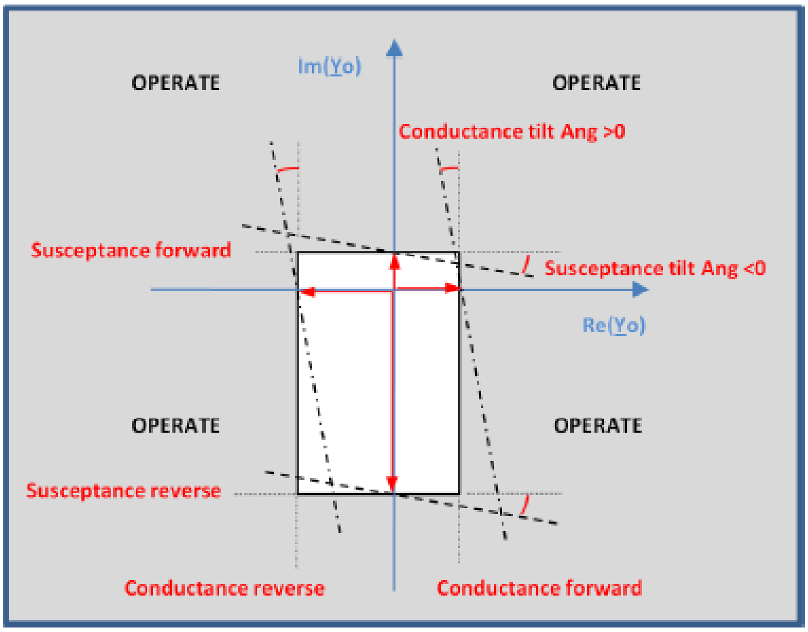


Figure 25. The *box*-characteristic of novel admittance criterion. (Wahlroos 2014.)

The conductance boundary, which limits the operating area in the positive direction of the Re(Y_0)-axis, has to be select carefully. When the fault is located in the BG network, the measured admittance in the protected feeder is negative-signed and represents the total admittance of the protected feeder. The real part of this admittance i.e. conductance is rather small, because of the small losses of network. However, the resistive part might even become positive and the admittance may be located now in the operating area. Therefore, the conductance boundary of the positive Re(Y_0)-direction have to be set taking into account the measuring errors of CTs and VTs. (Wahlroos & Altonen 2011: 11.)

According to Wahlroos (2014), a default setting value for conductance forward can be 2 A in a primary voltage level, which equals 0.17 mS in the secondary side. With decentralized compensation, fault locating at the protected feeder and fault locating in the BG network, the imaginary part of measured admittance at the protected feeder, i.e. the susceptance, may turn into positive in case of overcompensation. Earth fault current of the feeder is then inductive. Positive imaginary part has to be taken into account by placing the sufficient boundary line in the direction of the positive Im(Y_0)-axis. (Wahlroos & Altonen 2011: 11.)

There are also few variations of admittance principle: delta-quantity method (uses prefault values), cumulative multi-frequence admittance method (uses fundamental frequency and harmonics and calculates admittance utilizing accumulated phasors) by Wahlroos, Altonen, Uggla & Wall (2013), and admittance protection principle utilizing harmonics (the 5th harmonic component). Only the basic fundamental frequency admittance criterion is analyzed in this thesis. The novel multi-frequency admittance criterion is also capable of operating selectively during intermittent earth faults. (Wahlroos 2012). However, restriking faults, which are very common in cabled distribution networks, are not in scope of this work, because of their large extent.

4 SIMULATION MODELS

The simulated network model was created to match a typical Finnish MV distribution network as closely as possible. Therefore, the protected feeder was comprised of OHL and cable, which was matched closely to situation in a near future, when UGC increases gradually. It is likely that cables will be installed by starting first from the beginning of the feeder, which was taken into account by adding cabling to be started from the beginning of the protected feeder. Also, the BG network was consisted of partly by cables. In other two situations the protected feeder consisted of only a cable, because it is evident that all feeders are containing cable at some point. As it was mentioned earlier about the sectionalizing network into smaller zones, the recloser was placed to the middle point of the protected feeder to analyze protection operations at this point. A closed ring-shaped network model was also created to be able to study the earth fault protection in this special case.

The PSCAD-model, which is used in this thesis, was based partly on the earlier reports by Kauhaniemi, Lågland, Hietalahti and Jaakkola (2010) relating to WP 2.1 large-scale cabling in distribution task, and its continuation by Jaakkola & Kauhaniemi (2012). The basic structure used in radial models was the same as used in earlier studies conducted by Jaakkola (2012), but in this thesis only a few parameters were varied and studied.

The network model consisted of 110 kV main supply, 110/20 kV main transformer, parallel resistor, and a busbar. In the model there was one protected feeder, which was studied with its varying structure. The BG network consisted of four feeders (two OHLs and two cables) and their loads. The length of the BG network was also possible to adjust. According to partly decentralized compensation scheme, the compensation coil was connected to system neutral point at the substation with the adjustable parallel resistor, which was adjusted to produce resistive current of 5 A at primary voltage level, with decentrally installed coils. The load in the BG network was 8 MW and in the protected feeder, 2 MW or 2 MW per feeder. Loads were connected all the time, and the resistances of loads were delta-connected. The healthy state U_0 was adjusted to be 2 % of the main voltage, which was created by star-connected resistances referrering to shunt conductances. 2 % was an estimation of the typical asymmetry of a real network. The cable type AHXAMK-W 3·185+35, and the OHL type Raven 54/9 were used. The total length of the network was 220 km. Also the effect of parallel resistor in two network models was studied.

4.1 Simulation parameters and constant values

There were different parameters, which were varied in the models:

- fault place selection: at the protected feeder or in the BG network,
- the parallel reistor connection: open or closed,
- the length of the BG network: full or one OHL or two OHLs, and
- fault resistances: 500 Ω–20 kΩ.

The created model consisted of the following constant parameters. The cable and OHL parameters, which were already defined in earlier research projects at the University of Vaasa, were also used in this thesis. These parameters were valid in every model for cable and for OHL, and are represented in Table 2. Compensation equipment values were calculated based on these values, and they can be found in simplified network model diagrams in each case. On the whole, protected feeder length in radial network models (60 km), current produced by the parallel resistor (5 A), fault start time (0.405 s), simulation time (2 s), fault type (in phase A) were kept constant in all situations.

Table 2. Constant parameters for cable and OHL.

CABLE: 3*185+35 AHXAMK-W 20 kV		OVERHEAD LINE: RAVEN 54/9	
K_R1	0.22 Ω/km	O_R1	0.543 Ω/km
K_XL1	0.113 Ω/km	O_XL1	0.372 Ω/km
K_XC1	0.0122 MΩ·km	O_XC1	0.3238 MΩ·km
K_R0	0.882 Ω/km	O_R0	0.691 Ω/km
K_XL0	0.365 Ω/km	O_XL0	1.891 Ω/km
K_XC0	0.0119 MΩ·km	O_XC0	0.7267 MΩ·km

4.2 Simulation models

There were four different simulated network model types. Cabled radial network (simulated already earlier relating to Jaakkola (2012), mixed and cabled radial networks with recloser and ring-shaped network. In the next following sections, all network models are introduced. In each case, the simplified diagrams of the networks are presented. Because partly decentralized compensation was used, in addition to central coil, there were also several locally installed coils along the feeders. However, due to graphical reasons only one local coil for compensating each feeder in the diagrams was drawn. The calculated relay settings for each case can be found in Appendices 2–3.

4.2.1 Cabled radial network

In this case the already existing simulated results of the radial network model by Jaakkola (2012) were used. In this simulation model, which is presented in Fig. 26, the beginning (10 km) of the feeders were centrally compensated. The parallel resistor was continuously closed, there was not a recloser at the middle point of the protected feeder, and the rest of the feeders were decentrally compensated in every 10 km. Fault resistances were: 500 Ω, 1000 Ω, 3000 Ω, 5000 Ω, 10 kΩ, and 20 kΩ. The fault locations were at the beginning of the feeder (1), at the end of the feeder (5), and in the BG network (9) or (7). Fig. 26 illustrates also the capacitive earth fault currents produced by the feeders, the resisitive earth fault current I_R produced by the parallel resistor, and the inductive current of the central compensation coil. Moreover, the number of decentrally installed compensation coils and their inductive currents can be found in Fig. 26.

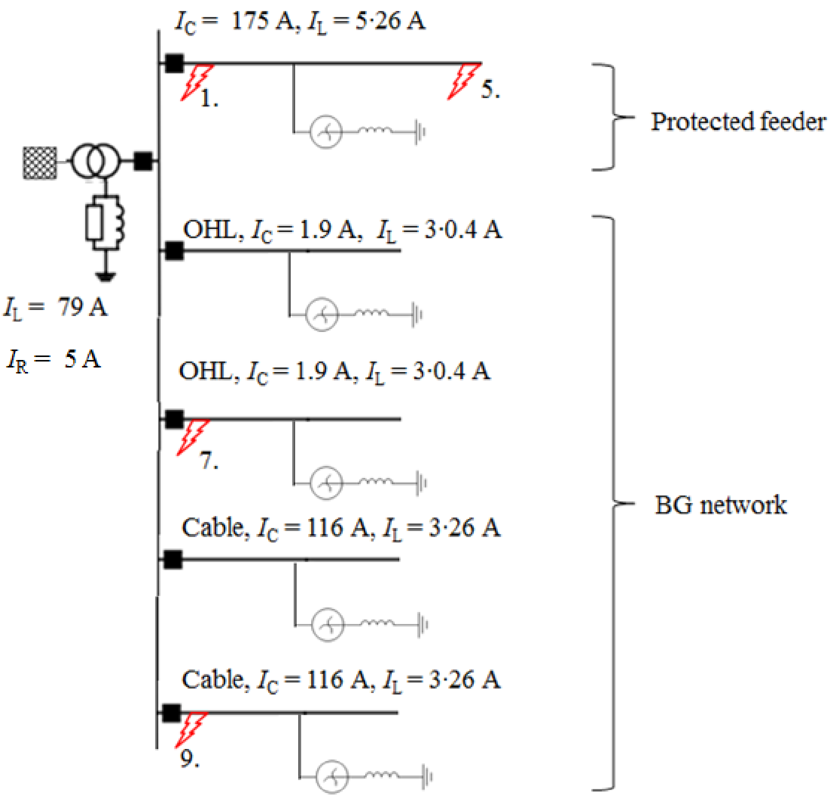


Figure 26. Simplified diagram of cabled radial network model.

Varying compensation degrees and feeder lengths were simulated earlier, but simulation cases with 0.9 compensation degree and 60 km feeder length at three fault points in case of full BG network, and BG network consisting of only two OHLs were chosen for further analysis. In order to set reliable earth fault protection, it is important to calculate the desired quantities of zero sequence voltage and residual current with the smallest and largest network situations. The full BG situation was examined in order to find the smallest detectionable zero sequence voltage. When BG network consists of only one OHL, the smallest residual current value can be defined. However, in this case the results of the BG network comprising two OHLs were utilized. BG network consisting of two OHLs illustrates now the smallest detectionable zero sequence current at the protected feeder. Therefore, it has to be remembered that the results from BG network consisting two OHLs are slightly higher than the desired in case of BG network consisting only one OHL. Based on the results from these simulations, the performance of phase angle and admittance criterion was analysed, and the results can be found in Section 5.1. The chosen threshold settings of relays, which were used in analysis, can be found in Tables 3–4.

Table 3. Relay settings in case of phase angle criterion in cabled radial network.

Phase angle criterion settings	
U_{oh} (V)	4 % ≈ 460
I_h (A)	1
± $\Delta\varphi$ (°)	± 80
φ_0 (°)	0

Table 4. Relay settings in case of admittance criterion in cabled radial network.

Admittance criterion settings	
Conductance forward (mS)	0.09
Conductance reverse (mS)	-1.0
Susceptance forward (mS)	0.1
Susceptance reverse (mS)	-5.67
U_{oh} (V)	4 % ≈ 460
I_h (A)	0.5

4.2.2 Mixed radial network with recloser

In this model the main difference compared to the earlier radial network model was the recloser place at the middle point of the protected feeder. The beginning of the protected feeder (30 km) was cable. Moreover, the rest of the protected feeder (30 km) was replaced by OHL and there was one coil, which compensated this part of the feeder. The first 10 km of the feeder were centrally compensated and the rest of the cable part was decentrally compensated in every 5 km. The above mentioned differences compared to radial network model can be found in Fig. 27. Fig. 27 shows also the capacitive earth fault currents of each feeder, the inductive currents produced by decentrally installed compensation coils and the number of those in each feeder, the inductive current of the central coil, and the resistive current produced by the parallel resistor.

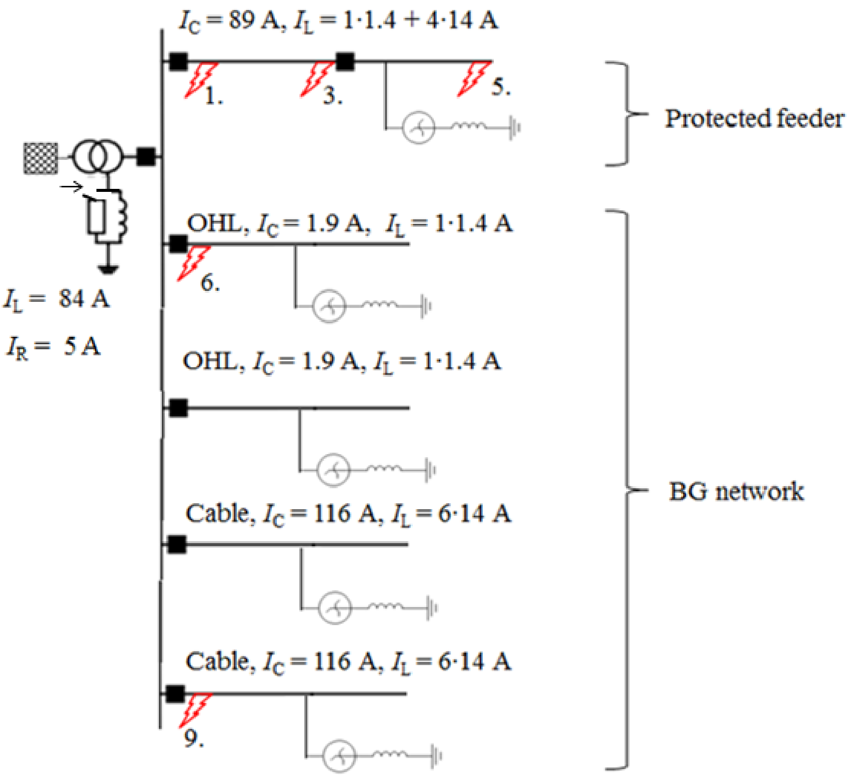


Figure 27. Simplified diagram of mixed radial network model with recloser.

In the BG network, there were six coils compensating the cable feeders, because the length of the feeder was now 40 km, the decentrally compensated part was 30 km, and the coil density was 5 km. OHL feeders in the BG network were compensated by one coil in both feeders located at the middle of the feeder. Two different cases were simulated in this model: full BG network and BG network consisting only one OHL. Fault resistances were: 500 Ω, 1000 Ω, 2500 Ω, 5000 Ω, 10 kΩ, and 20 kΩ. The fault locations were at the beginning of the feeder (1), at the middle of the feeder (3) at the end of the feeder (5), and in the BG network (9) or (6). The results from the analysis of the protection schemes can be found in Section 5.2. The chosen threshold settings of relays can be found in Tables 5–6.

Table 5. Relay settings in case of phase angle criterion in mixed radial network with recloser.

Phase angle criterion settings	
U_{oh} (V)	7 % ≈ 810
I_h (A)	1
± $\Delta\varphi$ (°)	± 80
φ_0 (°)	0

Table 6. Relay settings in case of admittance criterion in mixed radial network with recloser.

Admittance criterion settings	
Conductance forward (mS)	0.09
Conductance reverse (mS)	-1.0
Susceptance forward (mS)	0.1
Susceptance reverse (mS)	-4.17
U_{oh} (V)	7 % ≈ 810
I_h (A)	0.5

4.2.3 Cabled radial network with recloser

In this model, which is presented in Fig. 28, the whole protected feeder was cable, and there was a recloser at the middle point of the protected feeder. The beginning of the protected feeder was 10 km centrally compensated and the rest was decentrally compensated in every 5 km. This was also identical for BG network feeders. Fig. 28 shows also the capacitive earth fault currents of the feeders, the inductive currents of decentrally installed compensation coils and the amount of them in each feeder, the inductive current of the central coil and the produced resistive current of the parallel resistor. The simulations were carried out in two different situations: with a full BG network and with BG network containing only one OHL feeder. Fault resistances were also in this model: 500 Ω, 1000 Ω, 2500 Ω, 5000 Ω, 10 kΩ, and 20 kΩ. The fault places were at the beginning of the feeder (1), at the middle of the feeder (3) at the end of the feeder (5), and in the BG network (9) or (6). The results from the analysis of the protection schemes can be found in Section 5.3. The chosen threshold settings of relays, which were utilized in this model type, can be found in Tables 7–8.

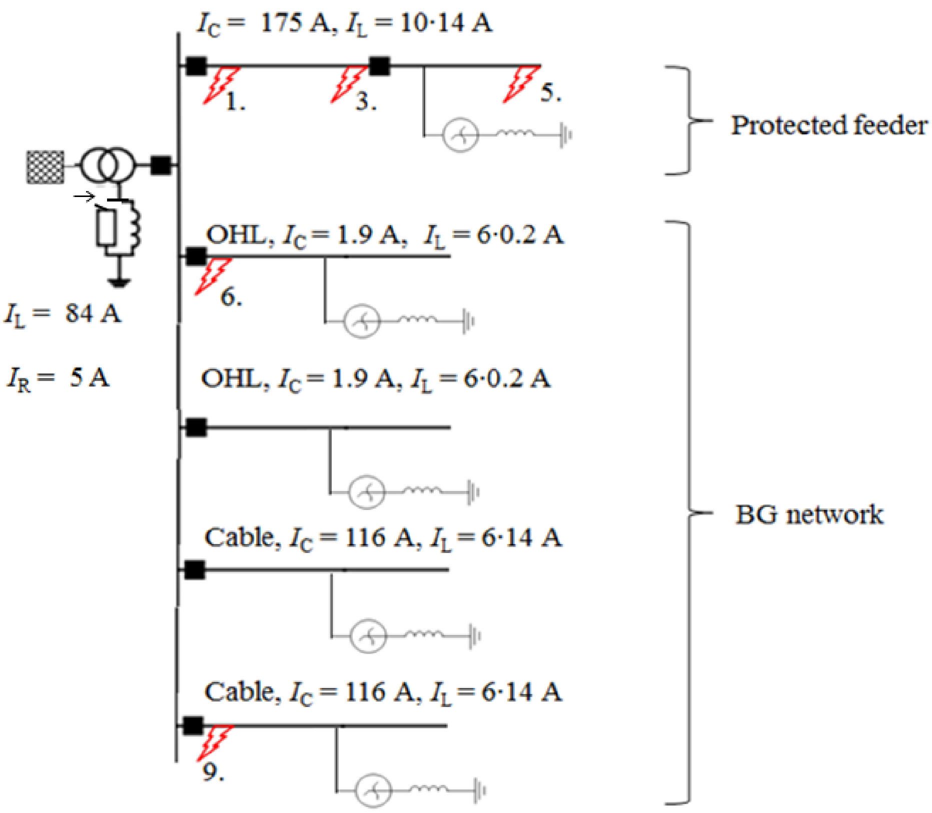


Figure 28. Simplified diagram of cabled radial network model with recloser.

Table 7. Relay settings in case of phase angle criterion in cabled radial network with recloser.

Phase angle criterion settings	
U_{oh} (V)	7 % ≈ 810
I_h (A)	1
± $\Delta\varphi$ (°)	± 80
φ_0 (°)	0

Table 8. Relay settings in case of admittance criterion in cabled radial network with recloser.

Admittance criterion settings	
Conductance forward (mS)	0.09
Conductance reverse (mS)	-1.0
Susceptance forward (mS)	0.1
Susceptance reverse (mS)	-4.73
U_{oh} (V)	7 % ≈ 810
I_h (A)	0.5

4.2.4 Ring-shaped network

In addition to traditional configurations of typical radial MV distribution network models, the closed ring-shaped model was also created. Because the structure of this kind of network is rather exceptional compared to traditional radial network models, the aim of this network model was mainly to study how the protection methods behave during different fault locations with varying fault resistances in this kind of unique network situation. In this case the threshold settings of relays were unimportant and therefore not considered more thoroughly.

The total length of the protected ring was 120 km. Fig. 29 shows the ring-shaped network model with the capacitive earth fault currents of the ring and the BG feeders, the inductive currents of decentrally installed compensation coils and the amount of those in each feeder and in the protected ring, and the inductive current of the central coil and the resistive current of the parallel resistor. The model was used to simulate relay quantities both at the beginning of the ring's other end (lower in the Fig. 29), and at the middle point of the ring, 60 km from the beginning. The ring was compensated centrally 10 km from the beginning of both ends. The first halves of the both ends were cabled and they were compensated in every 5 km after the part covered with centralized compensation. The rest (the middle part of the ring) was OHL, and there were two coils for compensating 30 km. Compensation coils were placed in the middle of the OHL parts.

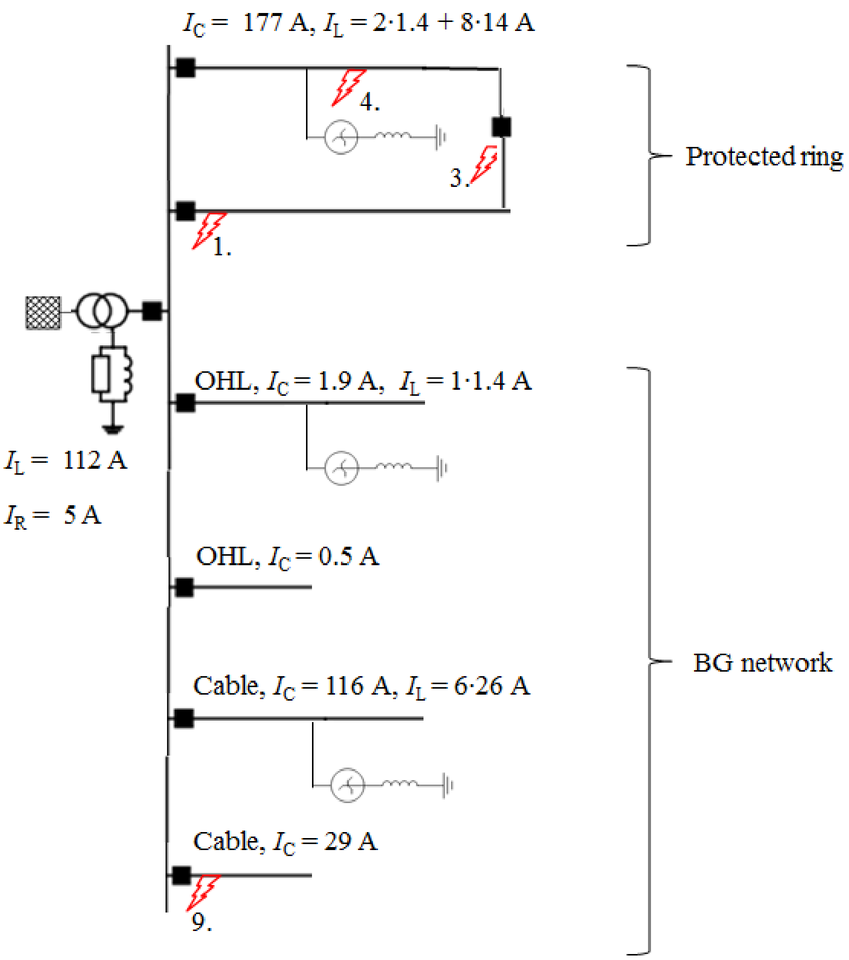


Figure 29. Simplified diagram of ring-shaped network model.

The length of the total network was kept at 220 km. Therefore, the length of the BG network was reduced. There were four feeders in the BG network, but now one OHL and one cable feeder was only 10 km long. The beginnings of two other feeders (cable and OHL) were centrally compensated 10 km from the beginning. Cable was compensated in every 5 km and there was only one coil located at the middle for compensating the rest of the OHL feeder. Fault places were studied in four different places; at the beginning of the ring (1), 60 km from the beginning of the ring (3), 90 km from the beginning of the ring (4), and in the BG network (9). Fault resistances were: 500 Ω, 1000 Ω, 2500 Ω, 5000 Ω, 10 kΩ, and 20 kΩ. The parallel resistor was continually closed. The other parameters, which were introduced in Section 4.2.2, were the same as network simulation models with reclosers. The results can be found in Section 5.4.

5 SIMULATION RESULTS

After the simulations, the results were gathered from separate files created by the multirun blocks. Next they were brought into Excel for processing and excecuting essential calculations. Finally, the graphs for the protection schemes, phase angle and admittance criteria were created with Matlab® calculation program. Two scripts were created, which can be found in Appendix 4. Following the conventional way to illustrate the phase angle criterion the graphs were drawn so that the phase angle (φ = 0°) corresponded to the direction of positive y-axis. In case of phase angle criterion, the faults with varying fault resistances were located in such a way that the larger the fault resistance is, the closer it is to the threshold setting boundary and origin. In the admittance criterion the effect of fault resistance is in some cases negligible, which was also proved earlier in the admittance theory-section. However, in practise considering also the U_{oh}-condition, the fault resistance may impact on the protection sensitivity.

There were apprx. 500 simulation runs executed in this study. To help this time-consuming process to simulate all situations, multirun-block was used. Multirun simulates automatically all possible combinations according to user's definitions, and save the data into a separate file. Using multirun also the human errors can be minimized. Two multirun-blocks for measuring magnitudes of $3\underline{I}_0$ and $\underline{U}_0$ and phase angles of both at the beginning of the protected feeder and at the middle point of the protected feeder were used.

Results for different fault locations were marked by different colours. In cabled radial network, there was no fault location at the middle of the feeder. The colour codes were: blue equaled to begin, green equaled to end, and red equaled to BG network. In mixed and cabled networks with reclosers: blue equaled to begin, green equaled to middle, cyan equaled to end, and red equaled to BG network. In the ring-shaped model: blue equaled to begin, green equaled to middle (60 km from the beginning), cyan equaled to end (90 km from the beginning), and red equaled to BG network. In some graphs, the calculated results have only little variation, which can be observed by seeing only one or possible two colour marked results in graphs. It was noticed that the calculations for

20 kΩ were exactly the same as the results in case of 10 kΩ faults even though they should not equal. This must be accounted for the asymmetry (2 %), which was created to network model. After a certain point, in this case when the fault resistance was above 10 kΩ, the value of fault resistance became insignificant. In practise, the maximum fault resistance value, which the computer was able to simulate, and was used in calculations, was 10 kΩ.

5.1 Cabled radial network

Two different simulations were carried out with this model. The network was first simulated by full BG network situation; i.e. consisting of all four feeders and then BG network consisting of only two OHLs. The operations of phase angle and admittance criteria were analyzed according to these situations assuming relay location at the beginning of the feeder. The results from these two network topologies can be found in the following sections.

5.1.1 Full background network

In case of a full BG network, the phase angle criterion is illustrated in Fig. 30 and the admittance criterion in Fig. 31. The simulated results and calculated protection quantities can be found in Table 9. According to Fig. 30 and Table 9, the faults at the beginning of the feeder and the end of the feeder were detected up to 1000 Ω by phase angle criterion with the setting applied. The sensitivity is limited by the magnitude of the residual current, because current threshold setting was exceeded after R_f equaled to 1000 Ω, compared to magnitudes of $\underline{U}_0$, which would have allowed the faults with 5000 Ω fault resistances to be detected. The faults in the BG network were located correctly outside the operating sector. According to Fig. 31, and considering the magnitudes of $\underline{U}_0$ in Table 9 and the set minimum I_h-condition, admittance protection method detected the faults at the protected feeder up to 3000 Ω and they located correctly outside the *box*, whereas the BG network faults were located inside the *box*, where relay operation was restrained.

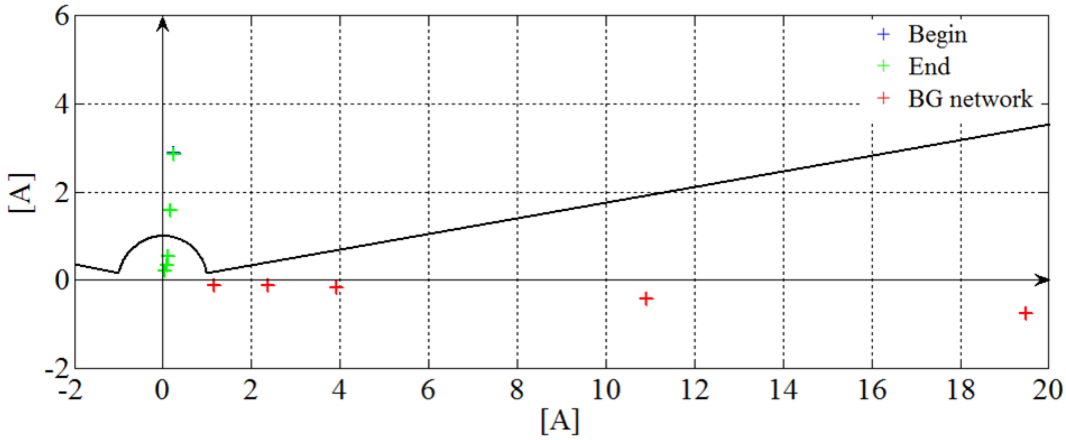


Figure 30. Phase angle criterion in cabled radial network in a full BG network situation.

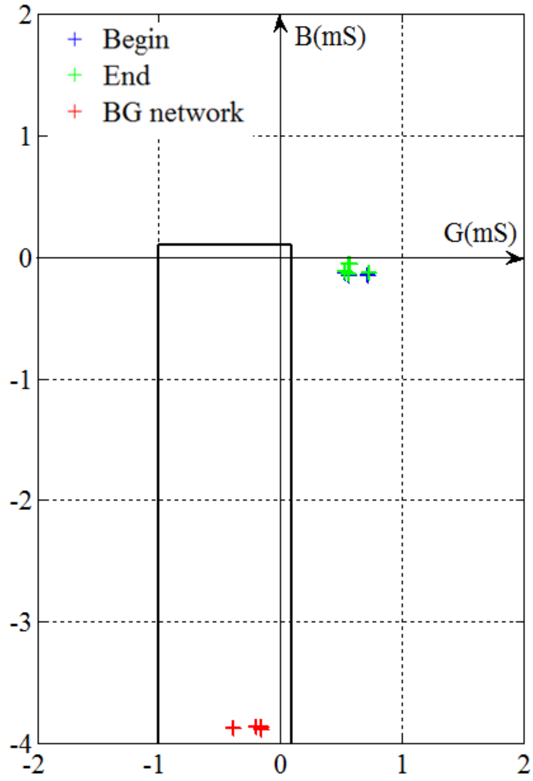


Figure 31. Admittance criterion in cabled radial network in a full BG network situation.

Table 9. Results and current and voltage thresholds in cabled radial network in a full BG network situation.

Radial network Part 10 km					
Fault place	**Fault resistance (Ω)**	**U_0 Mag (V)**	**$3I_0$ Mag (A)**	**Phase Angle (deg)**	**Y_0 Mag (mS)**
1	500	5017.031	2.891	-5.030	0.576
1	1000	2809.722	1.596	-5.866	0.568
1	3000	1010.495	0.549	-13.059	0.543
1	5000	611.089	0.353	-14.584	0.578
1	10000	298.208	0.220	-11.626	0.737
1	20000	298.208	0.220	-11.626	0.737
5	500	4938.656	2.848	-4.956	0.577
5	1000	2775.013	1.582	-5.915	0.570
5	3000	999.437	0.547	-12.721	0.547
5	5000	603.427	0.350	-13.819	0.580
5	10000	292.799	0.217	-10.098	0.740
5	20000	292.799	0.217	-10.098	0.740
9	500	5016.925	19.507	-92.237	3.888
9	1000	2809.663	10.926	-92.253	3.889
9	3000	1010.473	3.911	-92.294	3.870
9	5000	611.075	2.365	-92.999	3.870
9	10000	298.201	1.161	-95.743	3.892
9	20000	298.201	1.161	-95.743	3.892
Relay settings:					
	Admittance criterion		**Phase angle criterion**		
	U_{oh} = 460 V		U_{oh} = 460 V		
	I_h = 0.5 A		I_h = 1 A		

5.1.2 Two overhead lines in the background network

When there were only two OHLs in the BG network, it was possible to detect all faults at the protected feeder with phase angle protection method up to 20 kΩ (10 kΩ) according to Table 10, and Fig 32. Faults in the BG network were located correctly outside the operating sector, because the phase angle differences were varied between -92…-94°. Because of the size of the whole network was smaller, the magnitudes of $\underline{U}_0$ were higher compared to full BG network situation.

Table 10. Results and current and voltage thresholds in cabled radial network with two OHLs in the BG network.

Radial network Part 10 km 2 OHL					
Fault place	**Fault resistance (Ω)**	**U_0 Mag (V)**	**$3I_0$ Mag (A)**	**Phase Angle (deg)**	**Y_0 Mag (mS)**
1	500	7524.575	17.134	-77.974	2.277
1	1000	4996.928	11.382	-77.716	2.278
1	3000	1972.967	4.506	-76.696	2.284
1	5000	1201.631	2.757	-75.665	2.294
1	10000	589.484	1.380	-73.080	2.341
1	20000	589.484	1.380	-73.080	2.341
5	500	7463.247	16.992	-77.961	2.277
5	1000	4965.598	11.306	-77.701	2.277
5	3000	1955.501	4.460	-76.661	2.281
5	5000	1187.491	2.719	-75.598	2.289
5	10000	578.396	1.349	-72.882	2.331
5	20000	578.396	1.349	-72.882	2.331
7	500	7524.410	29.215	-92.103	3.883
7	1000	4996.820	19.409	-92.248	3.884
7	3000	1972.925	7.668	-92.726	3.887
7	5000	1201.605	4.669	-93.212	3.886
7	10000	589.472	2.282	-94.668	3.871
7	20000	589.472	2.282	-94.668	3.871
Relay settings:					
	Admittance criterion		**Phase angle criterion**		
	U_{oh} = 460 V		U_{oh} = 460 V		
	I_h = 0.5 A		I_h = 1 A		

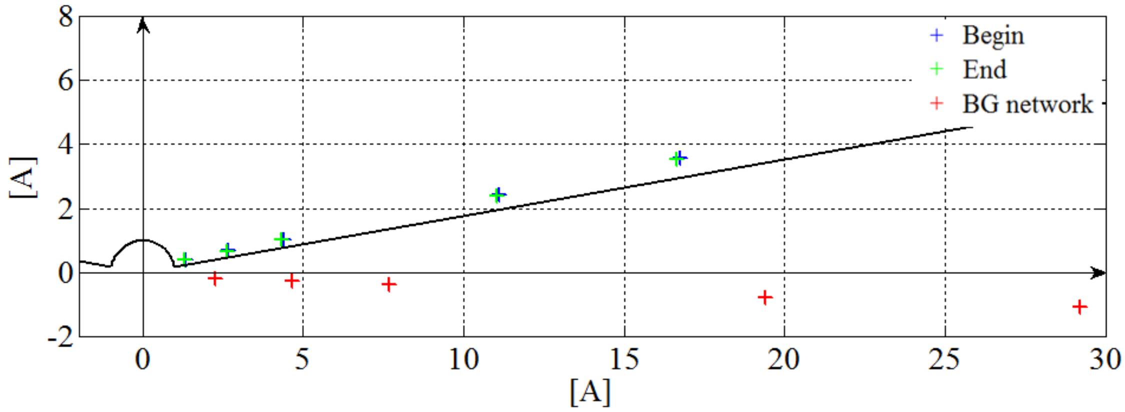


Figure 32. Phase angle criterion in cabled radial network with two OHLs.

With admittance criterion, the faults in the BG network were located correctly inside the *box*, and faults at the protected feeder in the operating area, which can be seen in Fig. 33. The faults at the protected feeder were detected up to the 10 kΩ according to Table 10. Due to the connected parallel resistor, there was a sufficient margin to boundary line with protected feeder faults. Therefore, it ensured better protection dependability. In this network configuration, both methods reached the same sensitivity (10 kΩ) compared to the situation with full BG network, where the phase angle method detected feeder faults up to 1000 Ω and admittance method up to 3000 Ω.

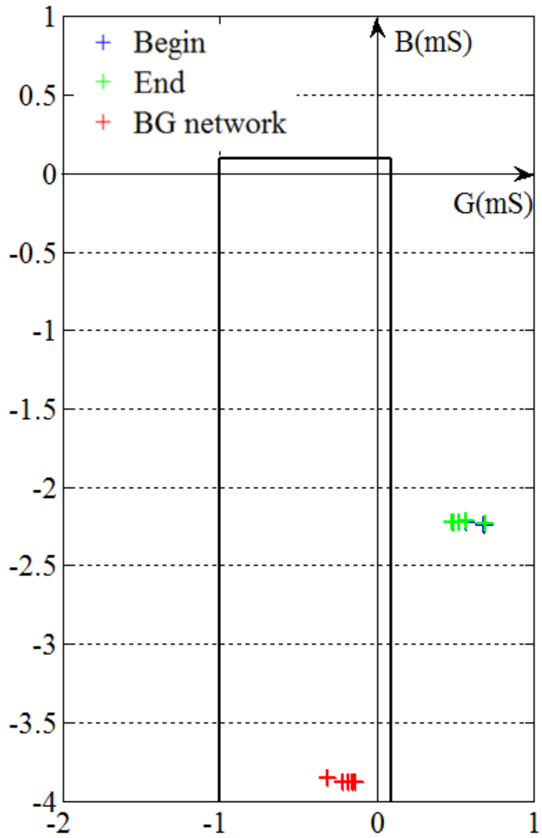


Figure 33. Admittance criterion in cabled radial network with two OHLs.

5.2 Mixed radial network with recloser

In in this situation, there were simulated eight different cases with phase angle and admittance criteria the relay locations at the beginning of the feeder and at the middle of the feeder. The purpose was to study the earth fault protection performance in case of the smallest and the largest network situations. Therefore, the network was simulated with full BG, and with only one OHL connected in the BG network. In these cases the parallel resistor was either connected or disconnected. The results from these situations can be found in the following sections. The simulation results from each case can be found in Appendix 5.

5.2.1 Full background network

Phase angle criterion in case of relay located at the beginning of the protected feeder

As can be seen from the Fig. 34, when the parallel resistor was not connected, the faults at the protected feeder (begin, middle, end) were detected only with fault resistance being 5000 Ω. In case of 500–2500 Ω feeder faults, the phase angle was smaller than -80°, and in case of 10 kΩ faults, the magnitudes of $\underline{U}_0$ were too small to be detected, when faults were located in the beginning of the feeder. Respectively, the magnitude of the residual current was too small with the magnitude of $\underline{U}_0$ faults locating at the middle and the end of the feeder. It can be concluded that the results are only theoretical, and the phase angle criterion is incapable of detecting the above mentioned faults. When the resistance was connected in Fig. 35, faults at the protected feeder were detected up to 5000 Ω. 10 kΩ faults were not detected because of the magnitudes of $\underline{U}_0$ and $3\underline{I}_0$ did not exceed the threshold settings.

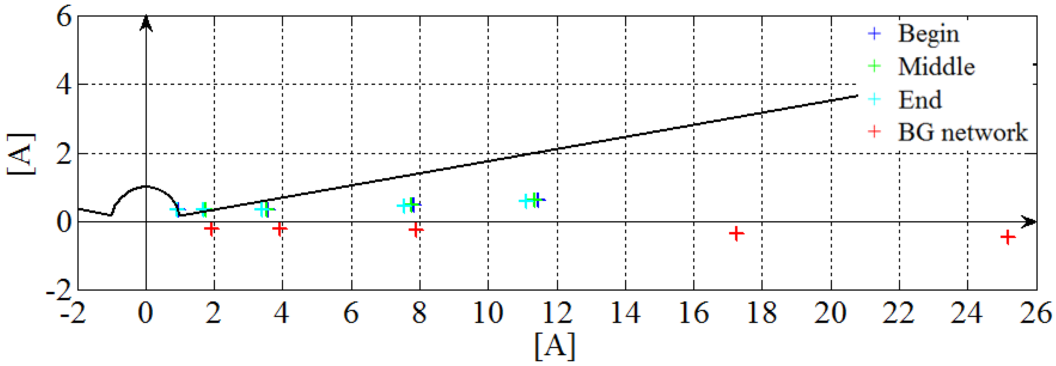


Figure 34. Phase angle criterion in a full BG situation at the beginning of the feeder, when R_L was not connected.

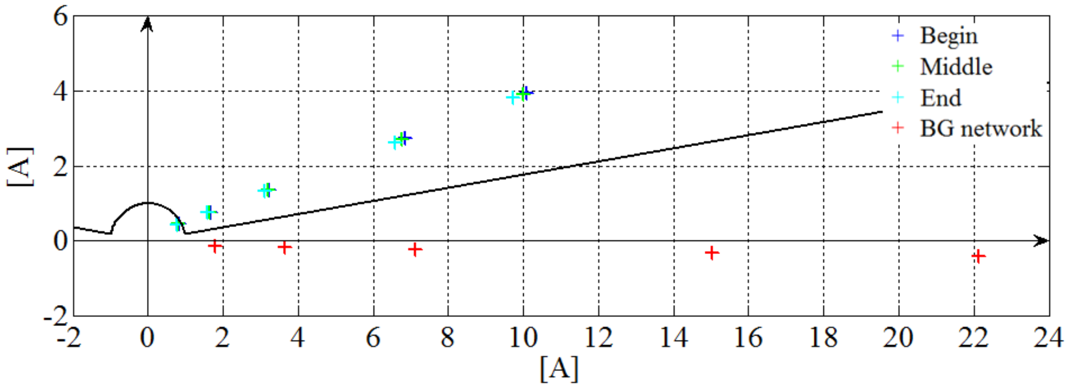


Figure 35. Phase angle criterion in a full BG situation at the beginning of the feeder, when R_L was connected.

Admittance criterion in case of relay located at the beginning of the protected feeder

According to Fig. 36, when the parallel resistor was not connected, the BG network faults were located correctly in the non-operating zone (inside the *box*). The faults at the protected feeder were detected up to 5000 Ω according to calculated admittance values from Appendix 5, and also considering the thresholds. According to Fig. 37, when the parallel resistor (producing 5 A resistive current) was connected, the faults located at the protected feeder were detected up to 5000 Ω, as it was without the parallel resistor connection above. There was a sufficient margin in this case to boundary line ensuring the better protection dependability and provides more margin for possible errors in measurements.

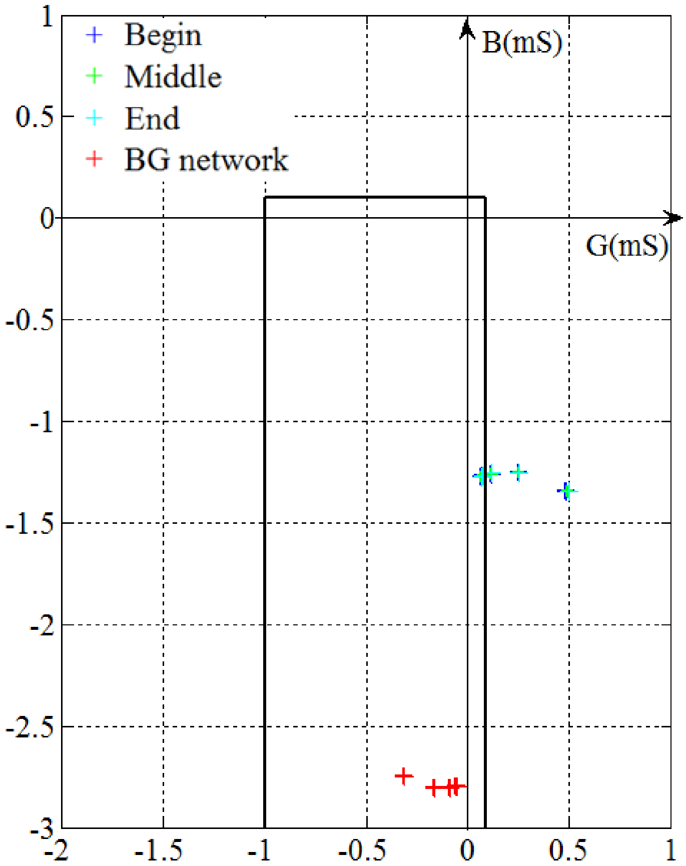


Figure 36. Admittance criterion in a full BG situation at the beginning of the feeder, when R_L was not connected.

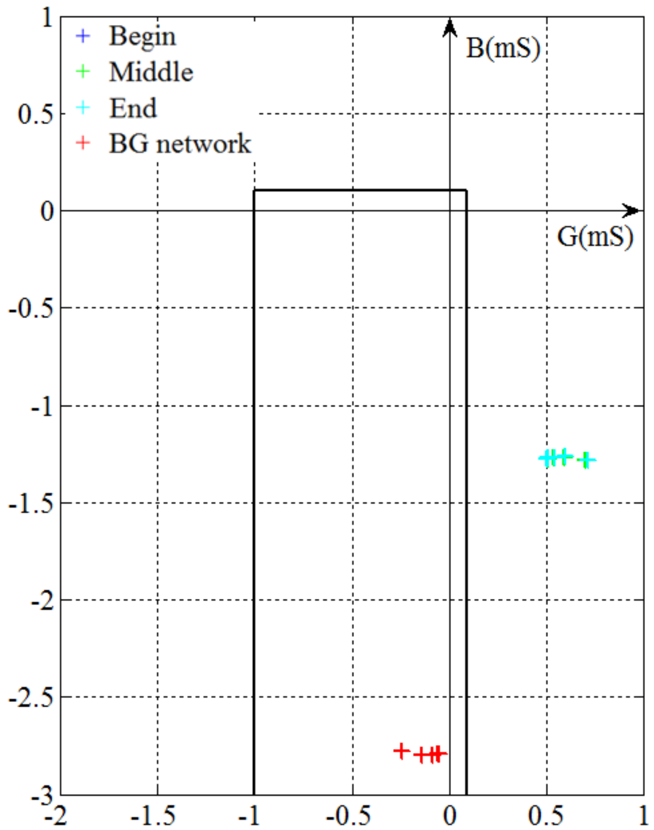


Figure 37. Admittance criterion in a full BG situation at the beginning of the feeder, when R_L was connected.

Phase angle criterion in case of relay located at the middle of the protected feeder

When studied phase angle criterion for a relay located at the middle point of the protected feeder, only the faults in a forward direction, i.e at the end of the feeder, should be detetced. In case of R_L was not connected, see Fig. 38, the fault at the end of the feeder with 5000 Ω fault resistance was only detected. In case of 500–2500 Ω faults, the phase angle condition was not achieved, and with 10 kΩ the magnitude of $\underline{U}_0$ did not exceed the U_{oh}. This kind of result can be assumed to be only theoretically valid, and it is likely that earth fault protection does not detect the faults in this situation at all. Faults at the beginning and at the middle of the protected feeder were located correctly with BG network faults in the non-operating zone.

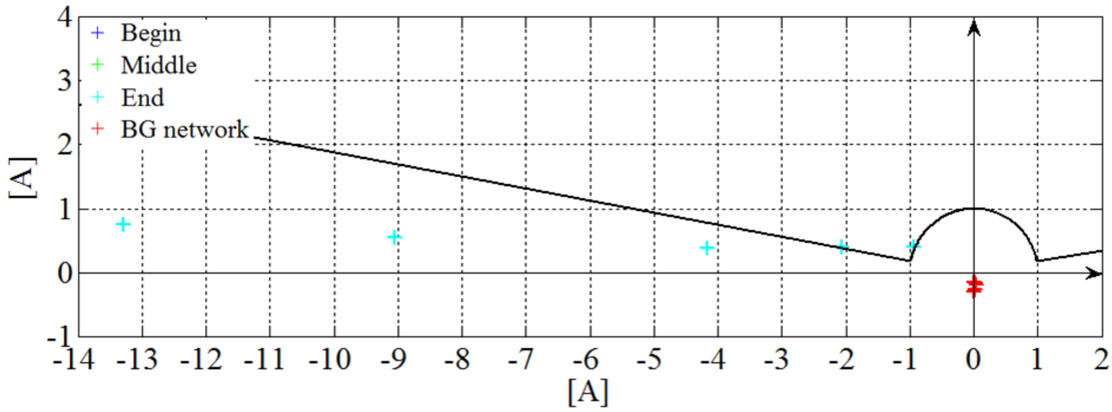


Figure 38. Phase angle criterion in a full BG situation at the middle point of the feeder, when R_L was not connected.

After the parallel resistor connection according to Fig. 39, and considering also the U_{oh}-condition, the faults located at the end of the protected feeder were detected from 500 Ω up to 5000 Ω. It can be seen that the network situation seen by the relay refers to isolated neutral network. This should be considered by setting the relay characteristic angle to 90°, when it responds to isolated neutral network situation or set extended operating sector. When the fault is located in a reverse direction, the feeder does not seem to produce current at all, which means that the feeder is almost completely compensated.

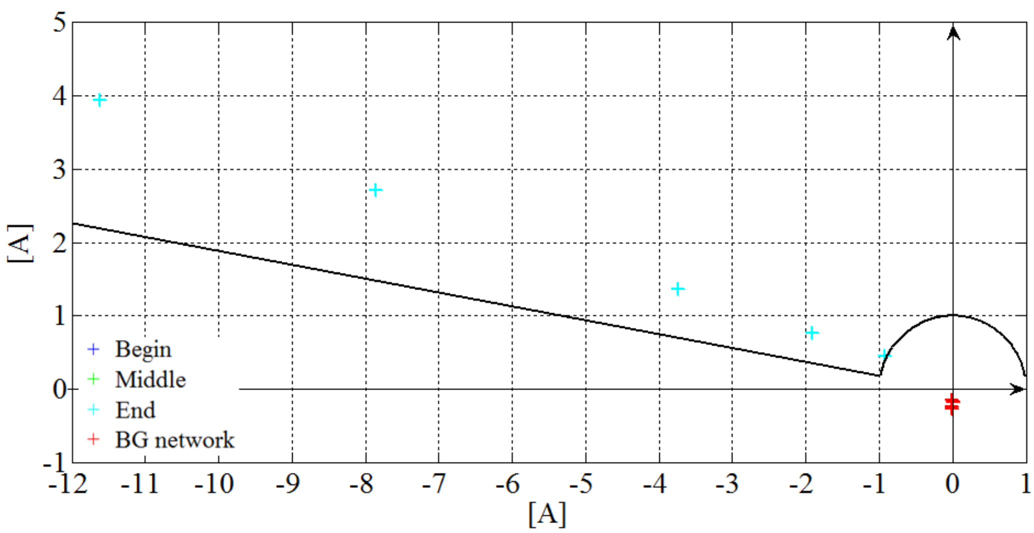


Figure 39. Phase angle criterion in a full BG situation at the middle point of the feeder, when R_L was connected.

Admittance criterion in case of relay located at the middle of the protected feeder

Admittance criterion, when the parallel resistor was not connected, and which is illustrated in Fig. 40, detected the feeder end faults up to 5000 Ω considering the current and voltage thresholds. The BG network faults and the other faults locating at the protected feeder were located in the non-operating zone. After the parallel resistor connection, see Fig. 41, the situation did not change that much and the feeder end faults were similarly detected up to 5000 Ω. When the fault was in a forward direction, the relay saw the network undercompensated. But on the other hand, when the fault was in a reverse direction, the earth fault current of the protected feeder was almost completely compensated by decentrally installed compensation coils (the measured admittances located near the origin). The real part of the measured admittances in case of the reverse faults was negative. This has to be accounted for the resisitive losses of the decentralized coils. The above mentioned aspects should be considered carefully, when placing the sufficient margins.

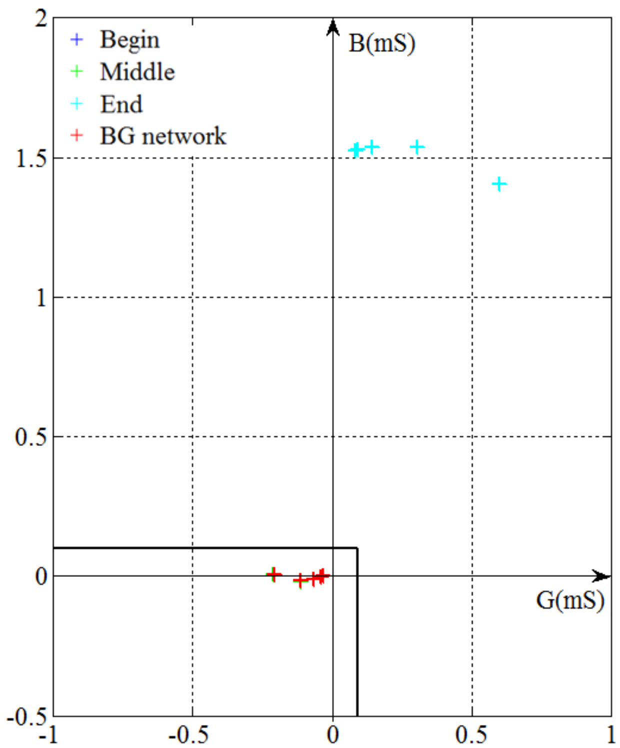


Figure 40. Admittance criterion in a full BG situation at the middle point of the feeder, when R_L was not connected.

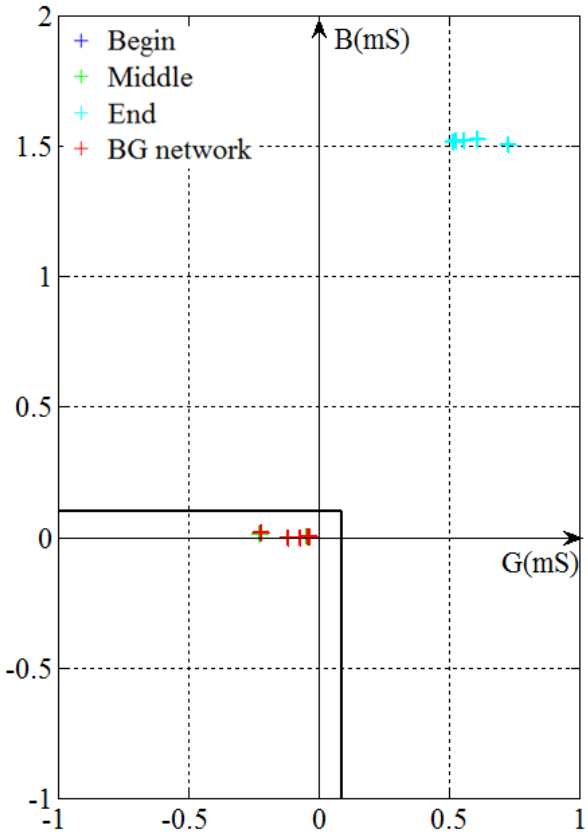


Figure 41. Admittance criterion in a full BG situation at the middle point of the feeder, when R_L was connected.

5.2.2 One overhead line in the background network

Phase angle criterion in case of relay located at the beginning of the protected feeder

When only one OHL was connected in the BG network without the parallel resistor, faults at the protected feeder and in the BG network remained undetected. Phase angles were smaller than -80° according to Fig. 42. After the parallel resistor connection in Fig. 43, the phase angles of the feeder faults were turned into operating sector. Now it was possible to detect even the highest fault resistance feeder faults. The BG network faults were not detected due to phase angles of being still smaller than -80°. Because there was now only one OHL connected in the BG network, the system was seen by the relay overcompensated due to smaller capacitive strength of the BG network according to

Figs. 42–43. It can be also seen in Fig. 43 that the feeder faults are located near the operating sector, because of the phase angles. This might endanger the functioning of the protection, if errors would arise.

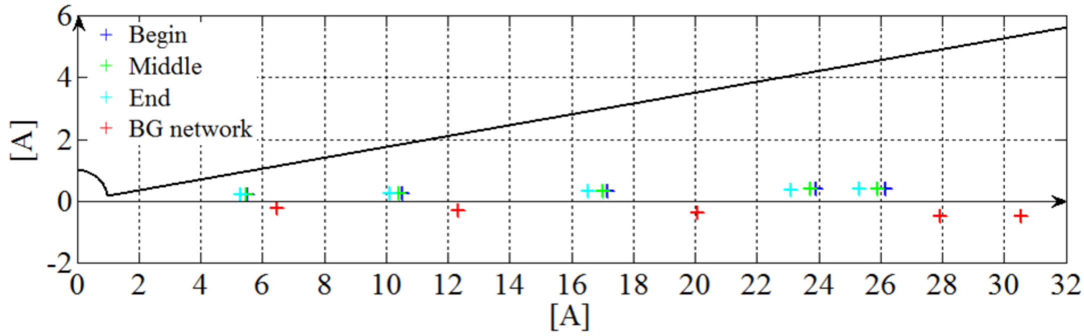


Figure 42. Phase angle criterion in case of only one OHL in the BG network at the beginning of the feeder, when R_L was not connected.

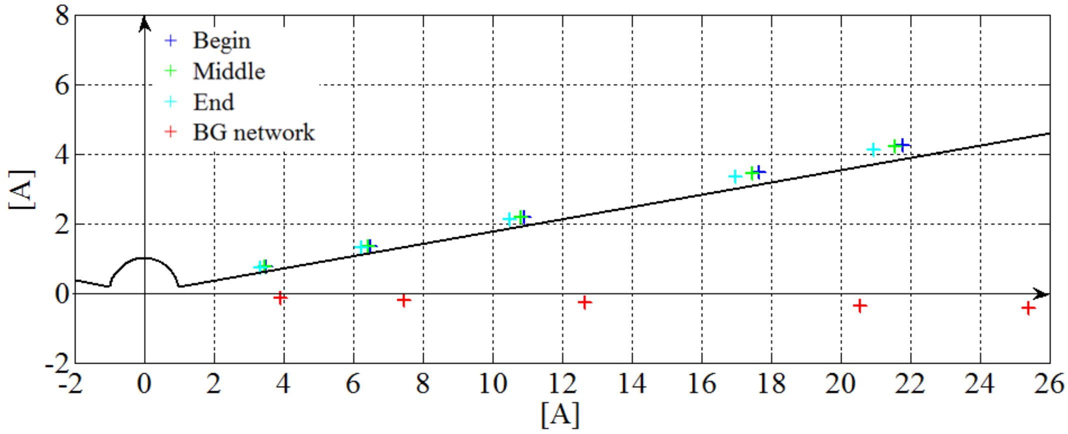


Figure 43. Phase angle criterion in case of only one OHL in the BG network at the beginning of the feeder, when R_L was connected.

Admittance criterion in case of relay located at the beginning of the protected feeder

As it was noticed earlier in case of phase angle criterion, the capacitance of the BG network was small, and hence the network was seen by the relay overcompensated. The admittance-based protection method did not detect the feeder faults, because the calculated admittances were located inside the *box*, which was referring to non-operating zone according to Fig. 44. When the parallel resistor was connected, see Fig 45, the admittance-based protection method detected feeder faults up to 10 kΩ and BG network faults were located correctly in the non-operating zone. It can be noticed that the resistive losses of the BG network were small, which could cause problems to detect the feeder faults without the parallel resistor. By connecting the parallel resistor, the resistive current is increased, which facilitate the detection of the feeder faults according to Fig. 45.

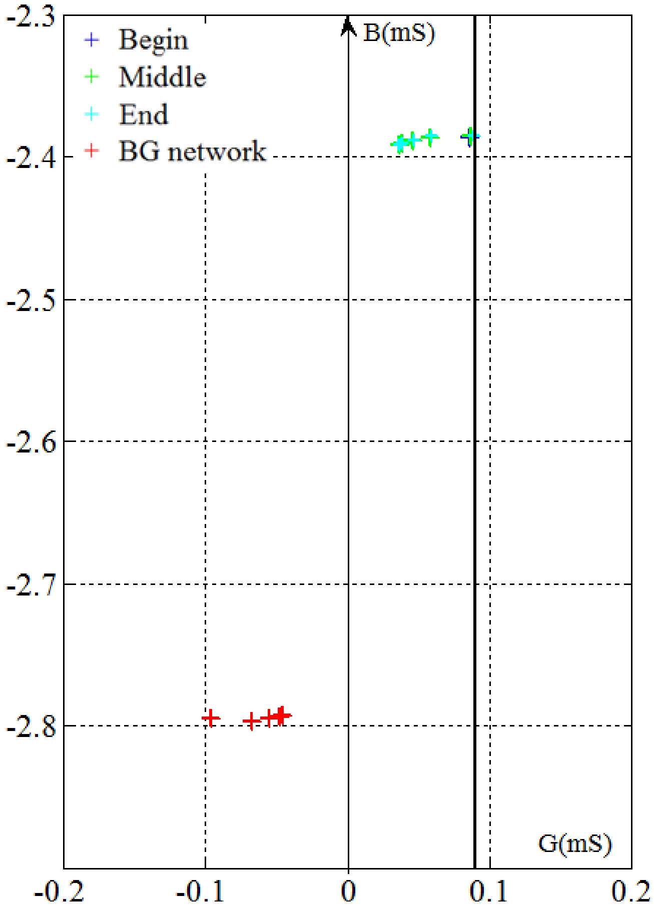


Figure 44. Admittance criterion in case of only one OHL in the BG network at the beginning of the feeder, when R_L was not connected.

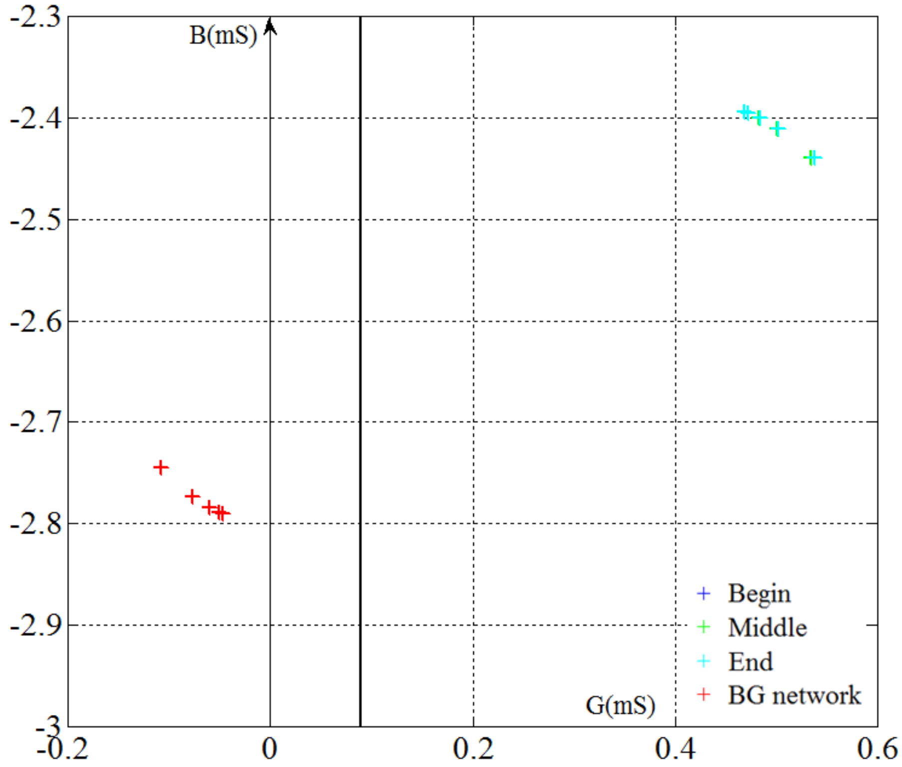


Figure 45. Admittance criterion in case of only one OHL in the BG network at the beginning of the feeder, when R_L was connected.

Phase angle criterion in case of relay located at the middle of the protected feeder

Phase angle criterion considered for a relay located at the middle point of the feeder should be able to detect only the feeder end faults. When the parallel resistor was not connected, only the feeder end fault was detected, when R_f equaled to 5000 Ω, see Fig. 46. The phase angle was located very near (79.62°) the boundary (80°) and therefore, it would be very vulnerable to even minor errors turning the phasor in the non-operating zone. With 500–2500 Ω faults, the limiting factor was the phase angle, and with 10 kΩ faults the residual current. It can be concluded that the protection is incapable of detecting the fault locating at the end of the protected feeder.

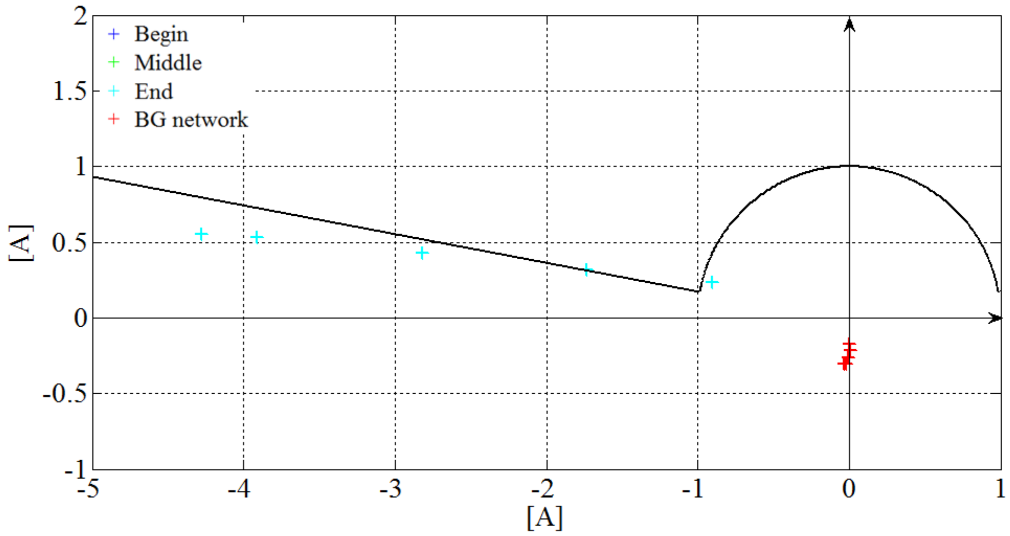


Figure 46. Phase angle criterion in case of only one OHL in the BG network at the middle point of the feeder, when R_L was not connected.

When the parallel resistor was connected in Fig. 47, the feeder end faults were detected up to 5000 Ω considering the threshold voltage to be exceeded. In addition to BG network faults, the other feeder faults (begin and middle) were located also in the non-operating zone. It seems that the earth fault current of the protected feeder was almost completetly compensated by its own decentralized compensation coils, when the fault was in a reverse direction.

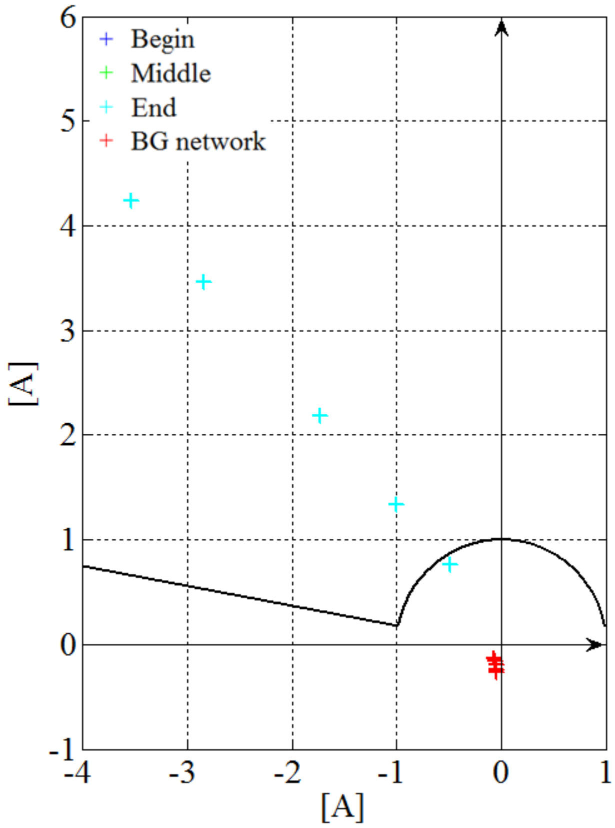


Figure 47. Phase angle criterion in case of only one OHL in the BG network at the middle point of the feeder, when R_L was connected.

Admittance criterion in case of relay located at the middle of the protected feeder

The admittance method detected the feeder end faults up to the largest fault resistances, which is illustrated in Fig. 48, even without the parallel resistor connection. Other faults at the protected feeder (in the first half) and in the BG network were not detected, which showed protection to be selective. After the parallel resistor connection, which is illustrated in Fig. 49, the highest fault resistance faults were detected similarily as in case of without the parallel resistor connection. However, it can be noticed in Fig. 49 that the calculated admittances of the BG network faults and other feeder faults moved to the positive side of the *y*-axis. Similarily, with some fault resistances in case of feeder and BG network faults, this kind of behaviour was noticed earlier in Fig. 40 and 41. Usually, the value of the BG network admittance is very small and negative, and due to natural unbalances and errors, the susceptance, i.e. the imaginary part, may therefore turn into positive. In practice, this happens with decentralized compensation in case of BG network faults. Consequently, the sufficient boundary has to set to the direction of the positive y-axis to avoid malfunctions. In this way, unnesessary relay operations in case of BG network faults can be avoided.

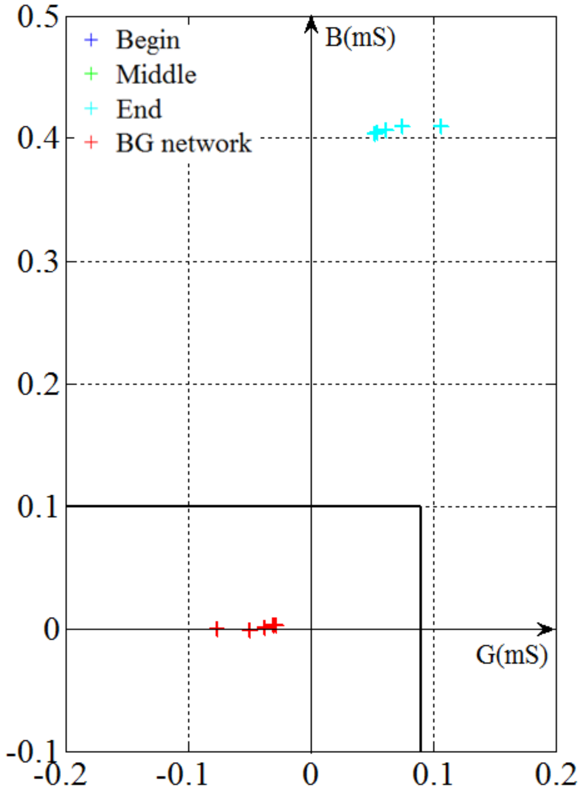


Figure 48. Admittance criterion in case of only one OHL in the BG network at the middle point of the feeder, when R_L was not connected.

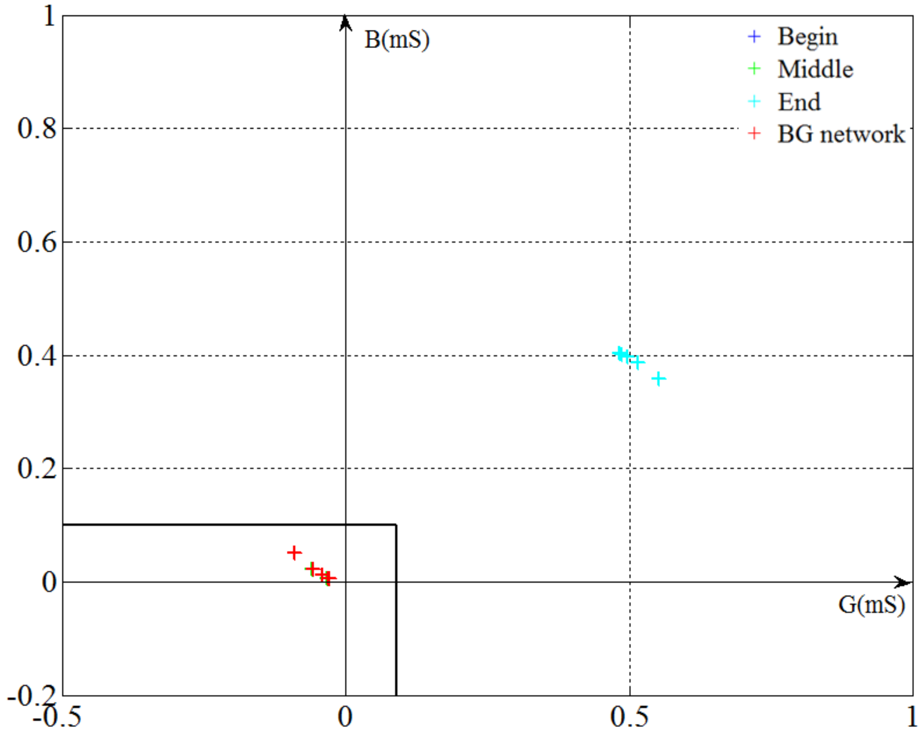


Figure 49. Admittance criterion in case of only one OHL in the BG network at the middle point of the feeder, when R_L was connected.

5.3 Cabled radial network with recloser

With the cabled radial network with recloser the same situations than in mixed radial network with recloser in Chapter 5.2 were simulated. The simulated results from these situations were created in both protection methods, but it was noticed there were no significant differences in each situation compared to mixed radial network model regarding the sensitivity of the protection schemes. Therefore, most of the results of this model are not analyzed again. The simulated and calculated results from each case can be found in Appendix 6. However, when only one OHL feeder was connected in the BG network and studied at the beginning of the protected feeder without the parallel resistor, the admittance criterion detected only the highest fault resistance feeder faults (10 kΩ) according to Figures 50–51 and Appendix 6.

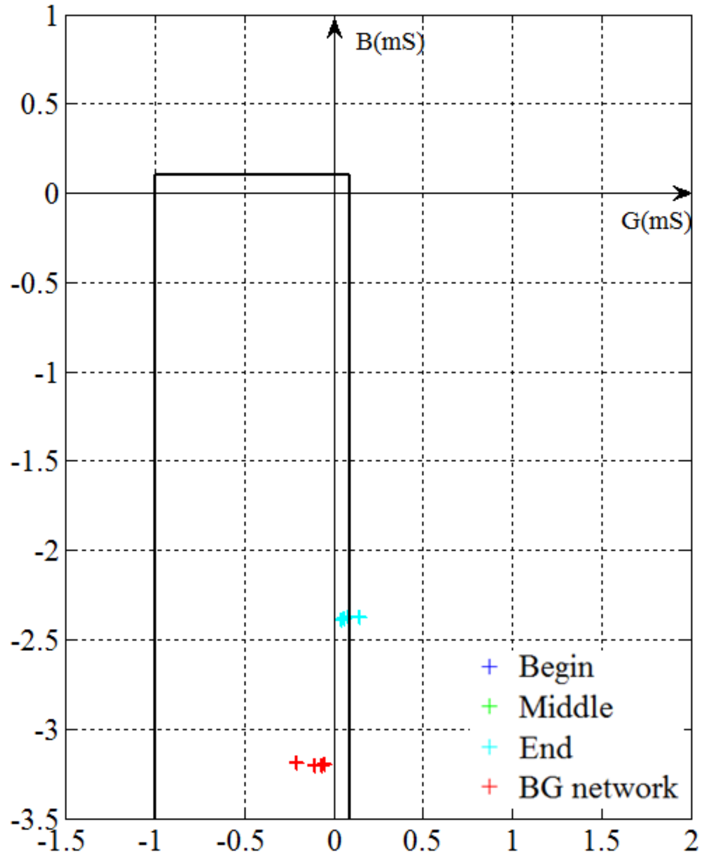


Figure 50. Admittance criterion in cabled network in case of one OHL in the BG network at the beginning of the feeder, when R_L was not connected.

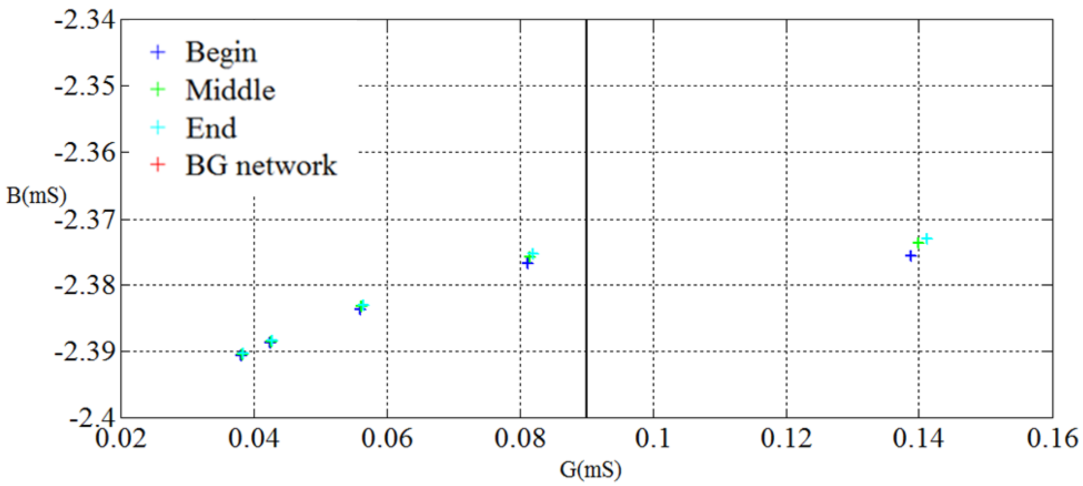


Figure 51. Close-up of the admittance criterion in cabled network in case of one OHL in the BG network at the beginning of the feeder, when R_L was not connected.

Moreover, in case of one OHL in the BG network studied at the middle point of the protected feeder, the admittances of the BG network were measured minus-signed according to Fig. 52–53, compared to mixed protected feeder situation, see Fig. 48–49. Earth fault protection with admittance method was in this case more reliable, and there was no concern about reaching the positive side of the *y*-axis and possible maloperations.

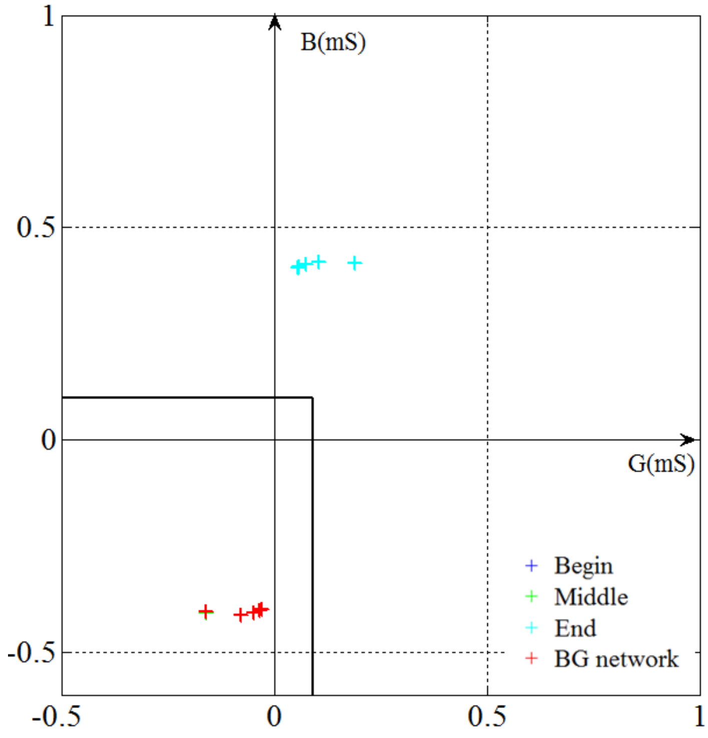


Figure 52. Admittance criterion in cabled network in case of one OHL in the BG network at the middle point of the feeder, when R_L was not connected.

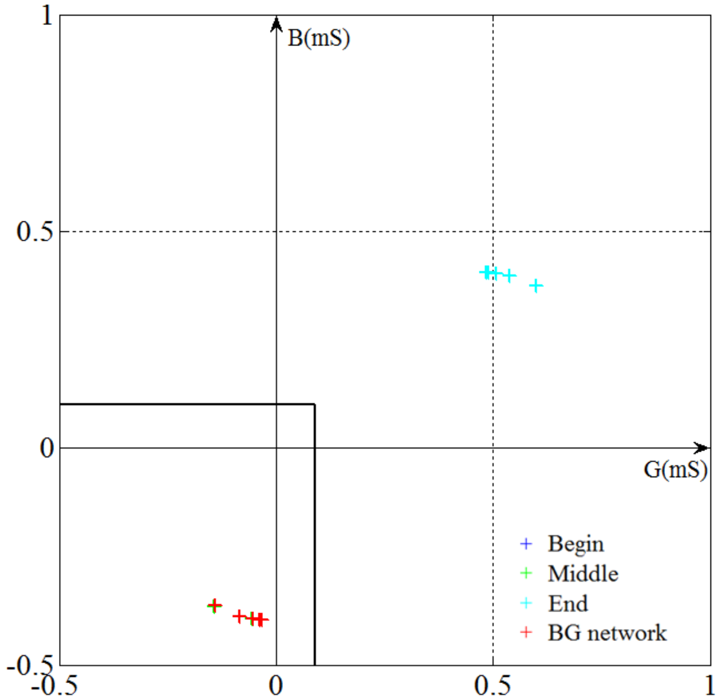


Figure 53. Admittance criterion in cabled network in case of one OHL in the BG network at the middle point of the feeder, when R_L was connected.

5.4 Ring-shaped network

Two different cases with phase angle criterion and admittance criterion were simulated at the beginning and at the middle of the protected ring. The simulation results can be found in Appendix 7. Even though the network model is rather simple setting reliable E/F protection is problematic. This is due to real component of the earth fault current divided into two parts. In practice, real networks are divided into smaller radial zones by breakers in case of faults emerge or it is used communication connection between relays, which help relays to detect the faulted part. Consequently, the above mentioned procedures facilitate earth fault protection to function correctly. (ABB 2011: 15–16.) Because the network topology was in this case rather different compared to traditional network topologies, the aim was only to study the behaviour of the earth fault quantities. Instead the settings from the case mixed radial network with recloser were used for illustrative purposes.

Relay located at the beginning of the protected ring

According to Fig. 54, where the phase angle criterion at the beginning of the protected ring is presented, only the closest forward faults (begin), could be detected. Other faults (60 km from the beginning equaled to middle, and 90 km from the beginning equaled to end) further along the ring were not detected. On the contrary, the admittance method could detect further faults (begin and middle) at the protected ring, including the faults at the end of the feeder (from 90 km from the beginning) according to Fig. 55. However, it was noticed the further the fault, the closer the value was to the conductance forward boundary line. Because the ring was divided in two protection zones, the feeder fault (end) should be detected at the middle point and thus, the conductance forward boundary line should be placed in Fig. 55 to cover also the feeder faults (end), so that they would be located in the non-operating zone. Consequently, it would need careful placing of the conductance forward boundary line or possibly also tilting the line.

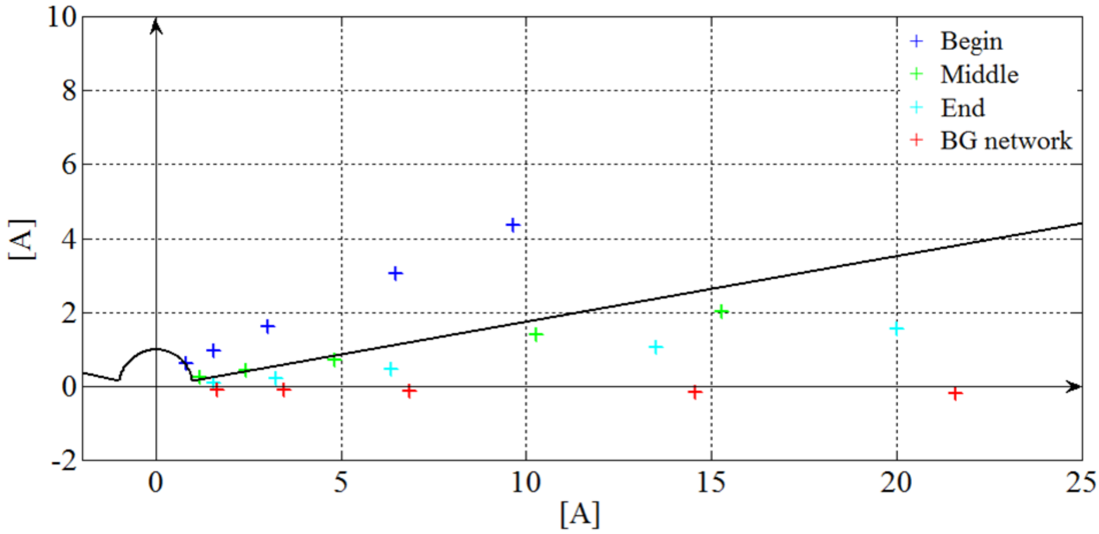


Figure 54. Phase angle criterion in ring-shaped network at the beginning of the protected ring.

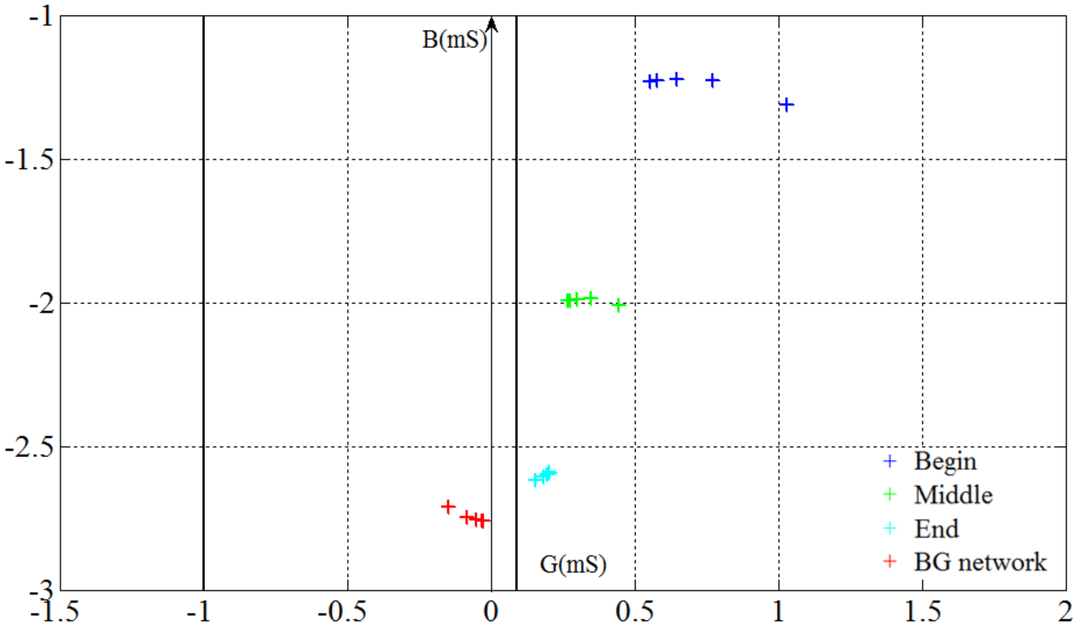


Figure 55. Admittance criterion in ring-shaped network at the beginning of the protected ring.

Relay located at the middle of the protected ring

Phase angle criterion studied at the middle of the protected ring, which is illustrated in Fig. 56, could detect only the forward faults (end). In case of reverse faults, they were located correctly in the non-operating area. Similarily, the admittance method, see Fig. 57, was capable to detect only forward faults (end). The admittance method measured the reverse faults (begin and end) at the protected ring, and they were located into the non-operating zone. The measured admittances of BG network faults were positive with respect to both real and imaginary axes, which would be challenging when placing sufficient boundaries to the *box*-characteristic considering these two directions to avoid false trippings.

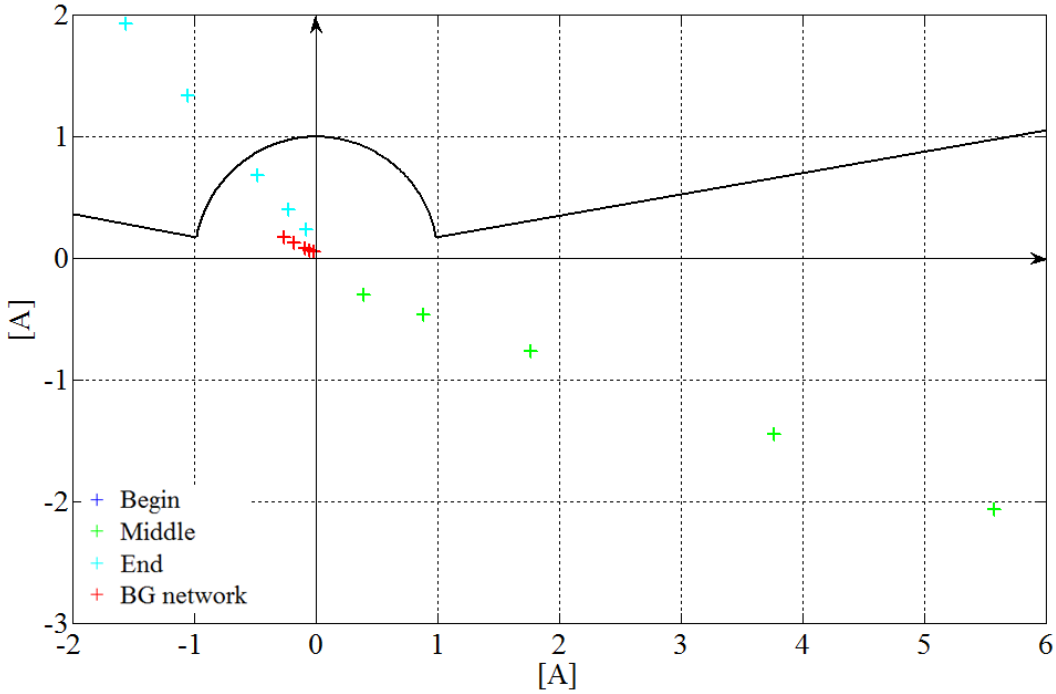


Figure 56. Phase angle criterion in ring-shaped network at the middle point of the protected ring.

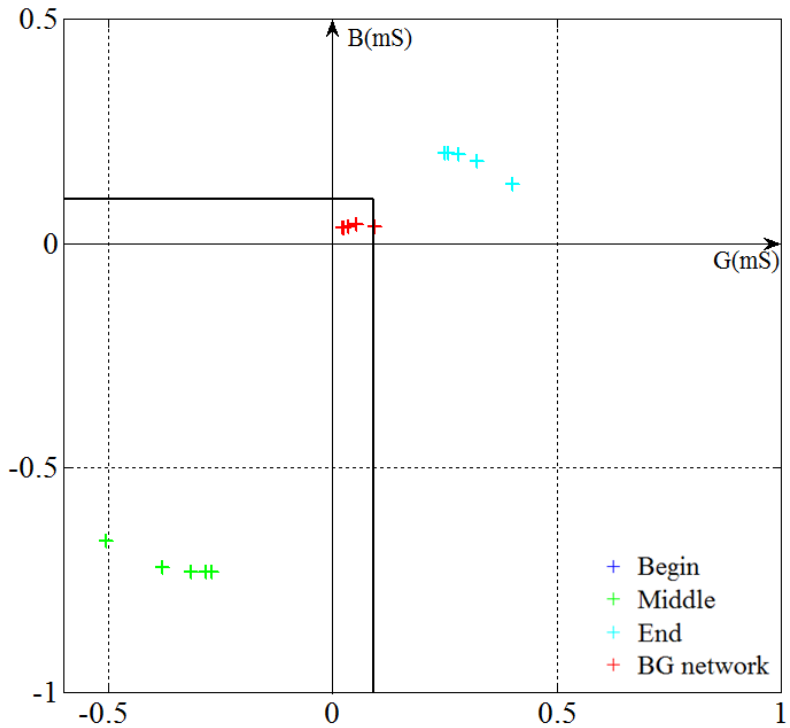


Figure 57. Admittance criterion in ring-shaped network at the middle point of the protected ring.

5.5 Error analysis

The effect of errors in measurements on E/F protection was analysed in one situation, where the BG network was the largest, and the parallel resistor was continuously connected. This case was chosen, because it responded a real network situation. The calculated phase angle error limits, which can be also found in Appendix 8, were added then into the same protection graphs with the original results for further analysis.

As it was mentioned earlier about errors in measurements, there are errors in current, voltage and phase angle measurements. However, the current and voltage errors are very small, hence only the phase angle measurement errors may have an impact on the functioning of the protection. Therefore, the error calculations were studied only assuming that the phase angle errors were apprx. ± 5°. In practice, the phase angle error can be assumed to be in real networks apprx. ± 3° according to Wahlroos (2014). Therefore, the error calculations presented here can be considered as worst case estimates. The results including errors are illustrated both with phase angle criterion and admittance criterion, see Fig. 58 and 59, where the original results are marked by crosses and calculated error limits by dots.

According to Fig. 58, where the calculated -5° phase angle errors in case of faults located at the protected feeder, are located more near the operating sector, because the phase angle is now smaller. On the other hand, when the fault is located in the BG network, the -5° phase angle errors turn the fault more clearly away from the operating sector, which is beneficial. Positive phase angle error is respectively beneficial in case of fault locating at the protected feeder, whereas the BG network fault might get closer to operating sector. It can be concluded that the calculated errors did not turn the feeder faults to the non-operating zone even the calculated errors represented the worst case estimates. In this situation it can be seen the reason why parallel resistor should be connected. The increased resisitive component of the residual current facilitates the protection to be selective by turning the current phasor more into the operating sector.

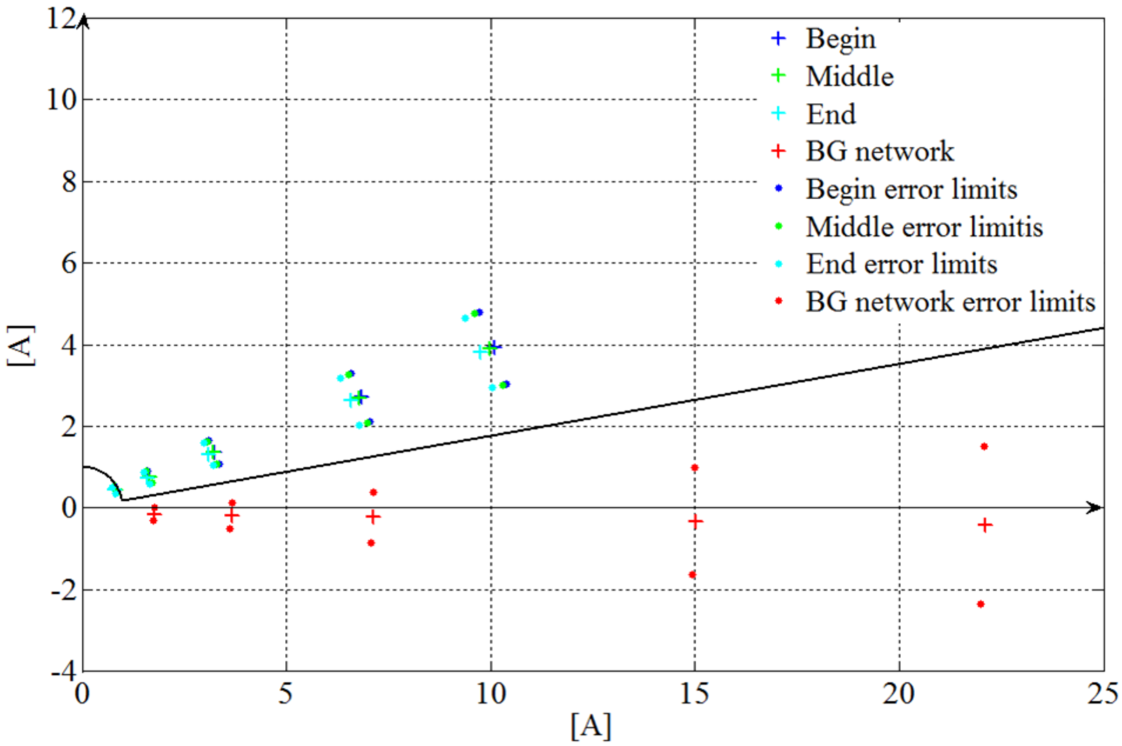


Figure 58. Error analysis of phase angle criterion.

Fig. 59 shows the admittance criterion in each fault place with varying fault resistances, where the calculated phase angle error limits (± 5°) are marked. It can be seen that the feeder faults were not affected substantially. Nonetheless, those faults are still detected if errors would arise. The negative-signed phase angle error could decrease the reliability of the fault detection in case of fault locating at the protected feeder if the conductance forward boundary would not be carefully set. Moreover, the positive phase angle error in the BG network faults might turn the calculated admittances falsely to operating area according to Fig. 59, where the calculated admittances with errors are exceeding the set conductance forward boundary. It has to be remembered that calculated error values represent the worst case values, and real errors can be assumed to be a bit smaller.

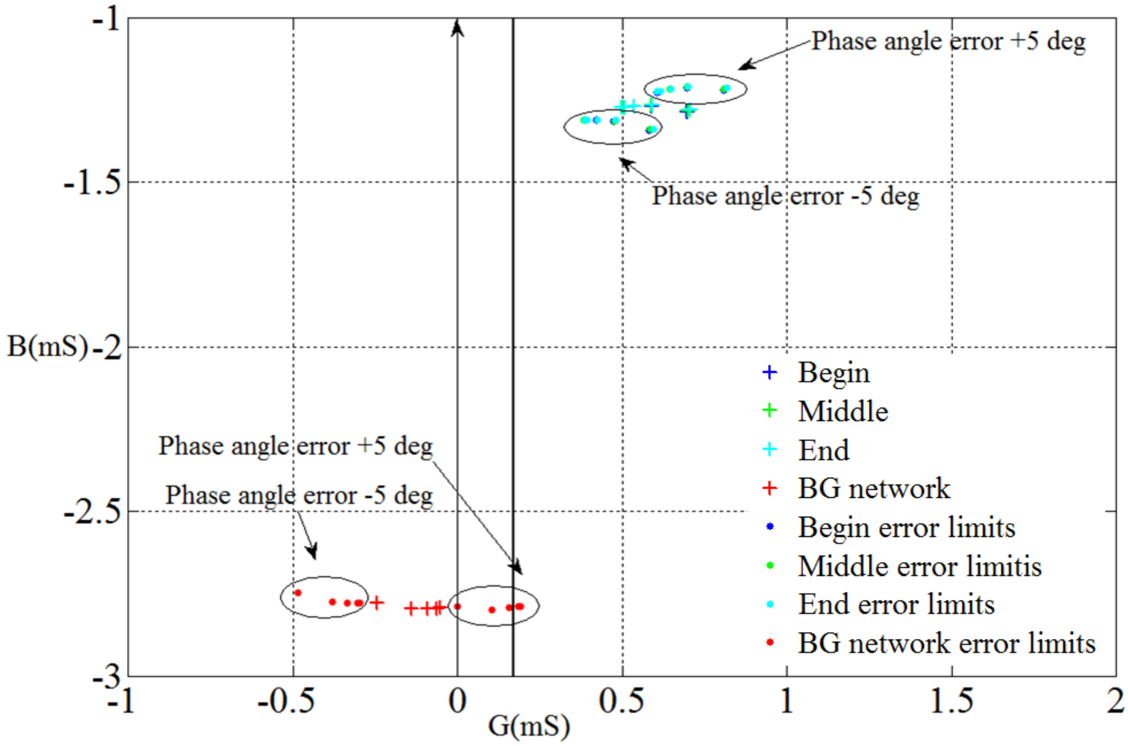


Figure 59. Error analysis of admittance criterion.

6 CONCLUSIONS AND FURTHER STUDIES

The aim of this thesis was to find out how earth fault protection should be arranged with defined fault scenarios in different MV distribution networks and what is the protection sensitivity that can be reached. The network model was studied with mixed and cabled structures using partly decentralized compensation. Moreover, the effects of phase angle errors in measurements on protection were studied in one case. The simulations were carried out by using PSCAD network modelling tool.

Earth fault protection was studied by using two different protection methods: traditional phase angle criterion and novel admittance criterion in four different MV distribution network simulation models. In cabled radial network with full BG network, i.e. consisting of all four feeders, the admittance method detected feeder faults up to 3000 Ω, whereas the phase angle criterion reached only up to 1000 Ω. When the BG network was reduced to contain only two OHLs, both methods were able to detect even the highest fault resistance feeder faults.

In case of mixed and cabled radial network with recloser, the protected feeder was now studied in addition at the beginning also at the middle point of protected feeder. It was noticed that most of the results corresponended between these two networks by earth fault protection sensitivity point of view. And by that, there were no significant differences either the protected feeder was mixed or totally cabled. According to results gained from full BG network situation, where earth fault protection was studied at the beginning of the feeder and the parallel resistor was connected, feeder faults with both methods were detected up to 5000 Ω. Even without the parallel resistor connection, admittance criterion achieved the same sensitivity, but it was interesting that phase angle criterion detected only the feeder faults, when fault resistance was 5000 Ω. With lower fault resistances the phase angles were not between ± 80°. In the same way behaved the results achieved from the middle point of the feeder, where the selective protection method detected now only forward feeder faults. In these simulations faults were located at the end of the protected feeder. The results can be assumed to be only theoretical, which would mean that earth fault protection is incapable of detecting these faults in real situation.

When there was only one OHL in the BG network and the parallel resistor was not connected, both methods were not able to detect feeder faults. But when the protected feeder contained only cable, admittance criterion detected only the feeder faults with 10 kΩ fault resistances. As a result, the protection is not able to detect the faults in real situation in this case. When studied at the middle of the protected feeder and without the parallel resistor connection, the fault at the end of the feeder was detected only when the fault resistance was 5000 Ω by phase angle criterion. This result can be also assumed to be only theoretical. The admittance method detected all the feeder end faults and similarily, when R_L was connected. When the parallel resistor was connected, phase angle criterion detected faults from 500 Ω up to 5000 Ω. When the BG network was containing only one or two OHLs, feeder faults were located near the boundary line of the operating sector in the phase angle criterion. It refers that the BG network became overcompensated. Therefore, it is recommended the tolerance range is not too narrow to avoid malfunctions.

Phase angle boundary settings with U_{oh} was set a little higher (7 %) in case of mixed and cabled radial networks with recloser than in cabled radial network (4 %) due to chosen compensation degree (0.95). The zero sequence voltage was calculated to be higher in mixed network with recloser than cabled network with recloser. It was set to equal in both cases in order to achieve more clear representation of the results. In the same way was done with I_h setting: 1 A in every situation despite the lower zero sequence current value of cabled radial network. However, it was noticed if the current threshold was set in that case e.g. to 0.2 A, the desired sensitivity would have been achieved. But in practice, this would not be reasonable, because the minimum current threshold value is 0.5 A within admittance criterion. It has to be remembered that such low values have to be measured by cable type CT, and at some point the smaller the current magnitude is the bigger is the effect of errors to measurement accuracy. Moreover, because there were two OHLs in the BG network, it can be assumed that the values would have been even smaller.

Earth fault protection was also studied by creating a protected, closed ring-shaped network model, which was rather special case compared to traditional network topologies. According to simulations, the results showed the admittance method could work with forward faults, when it was studied at the beginning of the ring, but the further the fault was, the closer it was located to conductance forward boundary line. Therefore, the settings should be very accurate to avoid false starts. Because the ring was divided into two protection zones, the further fault at the protected ring (90 km from the beginning) should not be detected at the beginning. This could be handled by setting the conductance forward boundary line accurately to cover the feeder fault into the non-operating zone. Consequently, it would be needed careful placing of the boundary line. When studied at the middle point of the ring, admittance method seems to achieve better sensitivity with forward fault than phase angle criterion. However, it cannot be stated that the created network model would respond exactly to the situation in reality, and there is not much of field test data or practical experience of this kind of network structure. Therefore, achieved results from these simulations can not be compared to measured real values, and further to be reliable. Therefore, the results can be assumed to be only rough estimates.

Partly decentralized compensation is studied yet fairly little, and experiences from it are all mainly theoretical inspections. By simulation results of the residual current magnitudes gained from the created network models, matched quite well for calculated residual current magnitudes in each case. It was noticed that according to derived formula for residual current magnitude, the amount of calculated residual current magnitude was reduced, when the protected feeder was totally cabled (≈ 1.5 A) compared to situation, when it contained OHL and cable (≈ 1.8 A). When compensation degree was lower (0.9), the protected feeder was totally cabled and the local coils were installed in every 10 km (first simulated situation), the magnitude of residual current (≈ 0.3 A) was in this case much smaller compared to above mentioned situations, where the coil density was 5 km and compensation degree was 0.95. Therefore, the derived formula can be assumed to be valid, because also the simulated results at the protected feeder, which can be found in Appendices 5 and 6, of the mixed and both cabled situations matched closely to these values despite the small variations due to fault locations.

Error analysis was carried out by choosing the typical MV distribution network situation. According to error analysis of phase angle criterion, there were no significant changes by fault detection point of view. In this situation, it can be noticed the relevance of the parallel resistor. Connection of the parallel resistor eliminates the effect of errors by increasing the resistive component and turning the residual current phasor even more to the operating sector. It has to be remembered that calculated errors were the worst case estimates. However, the error analysis of the admittance criterion showed that in theory some of the BG network faults may be located falsely in the operating sector and therefore cause maloperations. But, the calculated results of phase angle errors were a bit larger than in real situations, which would not probably impact on the funtioning of the protection. It is possible to avoid BG network faults to be located in the operating zone by setting the conductance forward boundary line with sufficient margin.

It can be concluded that admittance criterion is very promising method detecting earth faults even some cases without the parallel resistor connection. The *box*-shaped characteristic was utilized in this thesis and simulations showed that it was valid in these networks. Many other admittance characteristics can be chosen, but the decentralized compensation was considered in the *box*-characteristic, and it is valid if network would behave like isolated neutral networks. However, careful defining of the boundary lines with conductance and susceptance forward values is needed. The minimum current threshold should be considered. The U_{oh}-condition has to be also set above the healthy state zero sequence voltage both with admittance and phase angle criterion to avoid false starts. According to results achieved from these simulations, the other two boundaries in admittance criterion were meaningless. Therefore, admittance method could have been also implemented by setting only conductance and susceptance forward boundaries. It was noticed, especially with susceptance forward value, which was utlilized in this thesis according to chosen source that there was no additional explanation of the used susceptance forward value. Therefore, it can not be stated that the used value in this thesis is the right one.

If phase angle criterion is used for earth fault protection, parallel resistor should be connected. In these network models the desired sensitivity (5000 Ω fault resistance faults) with calculated settings applied, was mainly achieved. However, when the compensation degree was lower in cabled radial network, feeder faults were detected only up to 1000 Ω. The limiting factor was the magnitude of the residual current. It can be stated that the accurate threshold settings, quaranteed reliable earth fault protection in mixed and cabled radial networks with reclosers. But in order to define more generalized threshold settings, more simulations are definitely needed. It can be observed that accurate calculations for protection quantities, where are considered errors, are high important. However, more realiable results are gained, when the parallel resistor is connected; e.g. with phase angle criterion, the 500–2500 Ω fault resistance feeder faults can be detected.

In this thesis, the basic admittance criterion was used by dividing residual current phasor with zero sequence phasor. For further studies it would be interesting to study, how much better earth fault protection accuracy could be possible to achieve by using the delta-quantities-calculation, which was actually recommended to use with mixed networks. The novel cumulative admittance method would be also interesting to study thoroughly. It seems to be promising method by calculating the cumulative phasor sum, which stabilizes earth fault protection relevant phasors considerably. However, further analysis of these methods would require more complicated calculation schema than used in this thesis.

Only permanent single phase earth faults were studied in this thesis, because they are the most common faults in MV distribution networks. But in order to study and understand more intermittent faults in MV distrubution networks, they should be also considered in further studies. Especially, because it seems the general trend is going towards increased use of UGC, and the natural ageing of the existing cables will increase the probability of intermittent earth faults.

In this thesis only measurement blocks relevant to performance of earth fault protection were studied. It would have been interesting to study the network models also with earth fault relay model blocks. By that, starting of relay trippings and the operation time analysis of relays, which were not studied in this thesis, would be able to study in each case at least with traditional protection methods.

Zero sequence impedance of cable due to increased cable lengths is affected by many factors, but unfortunately there exist still many uncertainties related to it. In future, zero sequence impedance and related uncertainties should be considered and studied more thoroughly.

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APPENDICES

Appendix 1. Equation derivations

Residual current in compensated network

$$\underline{Y}_0 = \frac{1}{R_L} + j(3\omega(C - C_{Fd})) - \frac{1}{\omega L_{BG}})$$

$$\underline{I}_r = \underline{Y}_0\underline{U}_0$$

$$\underline{I}_r = (\frac{1}{R_L} + j(3\omega(C - C_{Fd}) - \frac{1}{\omega L_{BG}})\underline{U}_0$$

$$\underline{I}_r = \frac{1 + jR_L(3\omega(C - C_{Fd}) - \frac{1}{\omega L_{BG}})}{R_L}\underline{U}_v$$

$$\underline{I}_r = \frac{(-1 + jR_L(3\omega(C - C_{Fd}) - \frac{1}{\omega L_{BG}})}{R_L + R_f + jR_L R_f(3\omega C - \frac{1}{\omega L})}\underline{U}_v$$

Absolute value of residual current in compensated network

$$I_r = \left|\frac{(-1 + jR_L(3\omega(C - C_{Fd}) - \frac{1}{\omega L_{BG}})}{R_L + R_f + jR_L R_f(3\omega C - \frac{1}{\omega L})}\underline{U}_v\right| = \frac{\sqrt{1 + (R_L(3\omega(C - C_{Fd}) - \frac{1}{\omega L_{BG}}))^2}}{\sqrt{(R_f + R_L)^2 + (R_L R_f(3\omega C - \frac{1}{\omega L}))^2}}U_v$$

Appendix 2. Phase angle criterion settings

Cable

$X_C = \frac{1}{\omega C_{\text{cable}}} = 0.0119$ MΩ·km => $C_{\text{cable}} = \frac{1}{2 \cdot \pi \cdot 50 \cdot 0.0119} = 0.267487$ μF/km,

and it produces earth fault current:

$I_f = \omega C_{\text{cable}} U_v = 2 \cdot \pi \cdot 50 \cdot 0.267487^{-6} \cdot \sqrt{3} \cdot 20000 = 2.911009$ A/km ≈ 2.9 A/km.

OHL

$X_C = \frac{1}{\omega C_{\text{OHL}}} = 0.7267$ MΩ·km => $C_{\text{OHL}} = \frac{1}{2 \cdot \pi \cdot 50 \cdot 0.7267} = 0.004380$ μF/km,

and it produces earth fault current:

$I_f = \omega C_{\text{OHL}} U_v = 2 \cdot \pi \cdot 50 \cdot 0.004380^{-6} \cdot \sqrt{3} \cdot 20000 = 0.047668$ A/km ≈ 0.048 A/km.

MIXED RADIAL NETWORK WITH RECLOSER

Protected feeder consists of 30 km OHL and 30 km cable

$C = l_{\text{cable}} \cdot C_{\text{cable}} + l_{\text{OHL}} \cdot C_{\text{OHL}}$ (Total network)

= 110 km · 0.267487 μF/km + 110 km · 0.004380 μF/km = 29.905426 μF

$C_{\text{Fd}} = l_{\text{cable}} \cdot C_{\text{cable}} + l_{\text{OHL}} \cdot C_{\text{OHL}}$ (Protected feeder)

= 30 km · 0.267487 μF/km + 30 km · 0.004380 μF/km = 8.156025 μF

The value of total L:

$$L = \frac{1}{0.95 \cdot 3 \cdot \omega^2 C}$$

$$L = \frac{1}{0.95 \cdot 3 \cdot (2 \cdot \pi \cdot 50)^2 \cdot 29.905426^{-6}} = 0.118879 \text{ H}$$

$C_{BG} = l_{BGcable} \cdot C_{cable} + l_{BGOHL} \cdot C_{OHL}$ (The capacitance of the BG network, where is considered the centralized compensation)

$= (110 - 20)\ \text{km} \cdot 0.267487\ \mu\text{F/km} + (110 - 30)\ \text{km} \cdot 0.004380\ \mu\text{F/km} = 24.424273\ \mu\text{F}$

The BG network coil:

$$L_{BG} = \frac{1}{0.95 \cdot 3 \cdot \omega^2 C_{BG}}$$

$$L_{BG} = \frac{1}{0.95 \cdot 3 \cdot (2 \cdot \pi \cdot 50)^2 \cdot 24.424273^{-6}} = 0.145557\ \text{H}$$

$$I_r = \frac{\sqrt{1 + (R_L(3\omega(C_{BG}) - \frac{1}{\omega L_{BG}}))^2}}{\sqrt{(R_f + R_L)^2 + (R_f R_L(3\omega C - \frac{1}{\omega L}))^2}} U_v$$

$$= \frac{\sqrt{1 + (2309.4 \cdot (3 \cdot 2 \cdot \pi \cdot 50 \cdot (24.424273^{-6}) - \frac{1}{2 \cdot \pi \cdot 50 \cdot 0.145557}))^2}}{\sqrt{(2309.4 + 5000)^2 + (2309.4 \cdot 5000(3 \cdot 2 \cdot \pi \cdot 50 \cdot 29.905426^{-6} - \frac{1}{2 \cdot \pi \cdot 50 \cdot 0.118879}))^2}} \cdot \frac{20000}{\sqrt{3}}$$

$= 1.838277\text{A} \approx 1.8\ \text{A}$

$R_f = 5000\ \Omega$, $R_L = 2309.4\ \Omega$ (produce 5 A), the fault current:

$$U_0 = \frac{R_L}{\sqrt{(R_f + R_L)^2 + R_f^2 R_L^2 (3\omega C - \frac{1}{\omega L})^2}} \frac{E}{\sqrt{3}}$$

$U_0 =$

$$\frac{2309.4}{\sqrt{(2309.4 + 5000)^2 + 2309.4^2 \cdot 50000^2 (3 \cdot 2 \cdot \pi \cdot 50 \cdot 29.905426^{-6} - \frac{1}{2 \cdot \pi \cdot 50 \cdot 0.118879})^2}} \cdot \frac{20000}{\sqrt{3}}$$

$U_0 = 1494.853768\ \text{V}$ => 12.9 % of the phase to earth voltage

According to these calculations, relay settings can be chosen:

I_h = 1 A, U_{oh} = 7 % (808.29 V)

CABLED RADIAL NETWORK WITH RECLOSER

Protected feeder consists of 60 km cable

$C = l_{cable} \cdot C_{cable} + l_{OHL} \cdot C_{OHL}$

= 140 km · 0.267487 µF/km + 80 km · 0.004380 µF/km = 37.798638 µF

$C_{Fd} = l_{cable} \cdot C_{cable}$

= 60 km · 0.267487 µF/km = 13.374364 µF

The value of total L:

$$L = \frac{1}{0.95 \cdot 3 \cdot \omega^2 C}$$

$$L = \frac{1}{0.95 \cdot 3 \cdot (2 \cdot \pi \cdot 50)^2 \cdot 37.798638} = 0.094054 \text{ H}$$

C_{BG} = = (140 - 50) km · 0.267487 µF/km + 80 km · 0.004380 µF/km = 24.424273 µF

(The capacitance of the BG network, where is considered the centralized compensation)

The BG network coil:

$$L_{BG} = \frac{1}{0.95 \cdot 3 \cdot \omega^2 C_{BG}}$$

$$L_{BG} = \frac{1}{0.95 \cdot 3 \cdot (2 \cdot \pi \cdot 50)^2 \cdot 24.424273^{-6}} = 0.145557 \text{ H}$$

$$I_r = \frac{\sqrt{1 + \left(R_L\left(3\omega(C_{BG}) - \frac{1}{\omega L_{BG}}\right)\right)^2}}{\sqrt{(R_f + R_L)^2 + \left(R_f R_L\left(3\omega C - \frac{1}{\omega L}\right)\right)^2}} U_v$$

$$= \frac{\sqrt{1 + \left(2309.4\left(3 \cdot 2 \cdot \pi \cdot 50 \cdot (24.424273^{-6}) - \frac{1}{2 \cdot \pi \cdot 50 \cdot 0.145557}\right)\right)^2}}{\sqrt{(2309.4 + 5000)^2 + \left(2309.4 \cdot 5000 \cdot \left(3 \cdot 2 \cdot \pi \cdot 50 \cdot 37.798638^{-6} - \frac{1}{2 \cdot \pi \cdot 50 \cdot 0.094054}\right)\right)^2}} \cdot \frac{20000}{\sqrt{3}}$$

= 1.502439 A ≈ 1.5 A

$R_f = 5000\ \Omega$, $R_L = 2309.4\ \Omega$ (produce 5 A), the fault current:

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

$U_0 =$

$$\frac{2309.4}{\sqrt{(2309.4 + 5000)^2 + 2309.4^2 \cdot 50000^2 \cdot \left(3 \cdot 2 \cdot \pi \cdot 50 \cdot 37.798638^{-6} - \frac{1}{2 \cdot \pi \cdot 50 \cdot 0.094054}\right)^2}} \cdot \frac{20000}{\sqrt{3}}$$

U_0 = 1221.675174 V => 10,6 % of the phase to earth voltage

According to these calculations, relay settings can be chosen:

I_h = 1 A, U_{oh} = 7 % (808.29 V)

CABLED RADIAL NETWORK

C = 37.798638 µF

C_{Fd} = 16.049238 µF

The value of total L:

$$L = \frac{1}{0.9 \cdot 3 \cdot \omega^2 C}$$

$$L = \frac{1}{0.9 \cdot 3 \cdot (2 \cdot \pi \cdot 50)^2 \cdot 37.798638} = 0.099279 \text{ H}$$

C_{BG} = 24.424273 μF (the same as cabled radial network with recloser)

The BG network coil:

$$L_{BG} = \frac{1}{0.9 \cdot 3 \cdot \omega^2 C_{BG}}$$

$$L_{BG} = \frac{1}{0.9 \cdot 3 \cdot (2 \cdot \pi \cdot 50)^2 \cdot 24.424273^{-6}} = 0.153643 \text{ H}$$

$$I_r = \frac{\sqrt{1 + (R_L(3\omega(C_{BG}) - \frac{1}{\omega L_{BG}}))^2}}{\sqrt{(R_f + R_L)^2 + (R_f R_L(3\omega C - \frac{1}{\omega L}))^2}} U_v$$

$$= \frac{\sqrt{1 + (2309.4 \cdot (3 \cdot 2 \cdot \pi \cdot 50 \cdot (24.424273^{-6}) - \frac{1}{2 \cdot \pi \cdot 50 \cdot 0.153643}))^2}}{\sqrt{(2309.4+5000)^2 + (2309.4 \cdot 5000 \cdot (3 \cdot 2 \cdot \pi \cdot 50 \cdot 37.798638^{-6} - \frac{1}{2 \cdot \pi \cdot 50 \cdot 0.099279}))^2}} \cdot \frac{20000}{\sqrt{3}}$$

= 0.278063 A ≈ 0.3 A

R_f = 5000 Ω, R_L = 2309.4 Ω (produce 5 A), the fault current:

$$U_0 = \frac{R_L}{\sqrt{(R_f + R_L)^2 + R_f^2 R_L^2 (3\omega C - \frac{1}{\omega L})^2}} \frac{E}{\sqrt{3}}$$

U_0 =

$$\frac{2309.4}{\sqrt{(2309.4 + 5000)^2 + 2309.4^2 \cdot 50000^2 \cdot (3 \cdot 2 \cdot \pi \cdot 50 \cdot 37.798638^{-6} - \frac{1}{2 \cdot \pi \cdot 50 \cdot 0.099279})^2}} \cdot \frac{20000}{\sqrt{3}}$$

U_0 = 638.266232 V => 5.53 % of the phase to earth voltage

According to these calculations, relay settings can be chosen:

I_h = 1 A, U_{oh} = 4 % (461.88 V)

Appendix 3. Admittance boundary calculations

According to Appendix 2, cable produces earth fault current per phase 2.911009 A/km and OHL 0.047668 A/km.

MIXED NETWORK WITH RECLOSER

30 km cable: 30 km · 2.911009 A/km = 87.330928 A
30 km OHL: 30 km · 0.047668 A/km = 1.430068 A

20 km decentrally compensated: 20 km · 2.911009 A/km = 58.220195 A, and the inductive part: 0.95 · (58.667750 A + 1.430068 A) = 56.667750 A

Earth fault current of the protected feeder is:
(30 km cable + 30 km OHL) - the inductive part = (87.330928 + 1.430068) A - 56.667750 A = 32.092610 A

Earth fault current can be converted into admittance:

$$\underline{Y}_{\mathrm{Fdtot}} = \frac{32.092610}{20000/\sqrt{3}} \approx j2.779 \text{ mS}$$

A parallel resistor produces 5 A current and it can be converted into admittance:

$$G_{\mathrm{cc}} = \frac{5}{20000/\sqrt{3}} \approx 0.433 \text{ mS}$$

- ⇨ outside fault: $\underline{Y}_0 = -\underline{Y}_{\mathrm{Fdtot}} = -j2.779$ mS
- ⇨ inside fault: $\underline{Y}_0 = \underline{Y}_{\mathrm{Bgtot}} + \underline{Y}_{\mathrm{CC}} = (0.433 + jB)$ mS, B depends on compensation degree

The admittance boundaries with sufficient margins:

Conductance forward = 0.433 mS · 0.2 = 0.086602 ≈ 0.09 mS
Conductance reverse = -1.0 mS (range apprx. 0.5 · 2.779 – 1.2 · 0.433 = -1.38965…-0.64952)
Susceptance forward = 0.1 mS (from the manual)

Susceptance reverse = 1.5 · -2.779 mS = -4.16895 mS ≈ -4.17 mS (1.5 is the sufficient safety factor

CABLED NETWORK WITH RECLOSER

50 km cable: 60 km · 2.911009 A/km = 174.660585 A

50 km decentrally compensated: 50 km · 2.911009 A/km = 145.550488 A, and the inductive part: 0.95 · (145.550488 A) = 138.272963 A

An earth fault current of the protected feeder is:
60 km cable – the inductive part = 174.660585 - 138.272963 = 36.387622 A

Earth fault current can be converted into admittance:

$$\underline{Y}_{\mathrm{Fdtot}} = \frac{36.387622}{20000/\sqrt{3}} \approx j3.151260 \text{ mS}$$

A parallel resistor produces 5 A current and it can be converted into admittance:

$$G_{\mathrm{cc}} = \frac{5}{20000/\sqrt{3}} \approx 0.433 \text{ mS}$$

- ⇨ outside fault: $\underline{Y}_0 = -\underline{Y}_{\mathrm{Fdtot}} \approx -j3.151$ mS
- ⇨ inside fault: $\underline{Y}_0 = \underline{Y}_{\mathrm{Bgtot}} + \underline{Y}_{\mathrm{CC}} = (0.433 + jB)$ mS, B depends on compensation degree

The admittance boundaries with sufficient margins:

Conductance forward = 0.433 mS · 0.2 = 0.086602 ≈ 0.09 mS
Conductance reverse = -1.0 mS (range apprx. 0.5 · -3.151…1.2 · -0.433 = -1.38965…-0.51961)
Susceptance forward = 0.1 mS (from the manual)
Susceptance reverse = 1.5 · -3.151 mS = -4.726890 mS ≈ -4.73 mS (1.5 is the sufficient safety factor

CABLED RADIAL NETWORK

60 km cable: 60 km · 2.911009 A / km = 174.660585 A

50 km decentrally compensated: 50 km · 2.911009 A / km = 145.550488 A, and the inductive part: 0.9 · (145.550488 A) = 130.995439 A

An earth fault current of the protected feeder is:
60 km cable - the inductive part = 174.660585 A - 130.995439 A = 43.6651458 A

Earth fault current can be converted into admittance:

$$\underline{Y}_{\mathrm{Fdtot}} = \frac{43.665145}{20000/\sqrt{3}} \approx j3.781 \text{ mS}$$

A parallel resistor produces 5 A current and it can be converted into admittance:

$$G_{\mathrm{cc}} = \frac{5}{20000/\sqrt{3}} \approx 0.433 \text{ mS}$$

- ⇨ outside fault: $\underline{Y}_0 = -\underline{Y}_{\mathrm{Fdtot}} \approx -j3.781$ mS
- ⇨ inside fault: $\underline{Y}_0 = \underline{Y}_{\mathrm{Bgtot}} + \underline{Y}_{\mathrm{CC}} = (0.433 + jB)$ mS, B depends on compensation degree

The admittance boundaries with sufficient margins:

Conductance forward = 0.433 mS · 0.2 = 0.086602 ≈ 0.09 mS
Conductance reverse = -1.0 mS (range apprx. 0.5 · -3.781…1.2 · -0.433 = -1.89075…-0.51961)
Susceptance forward = 0.1 mS (from the manual)
Susceptance reverse = 1.5 · -3.781 mS = -5.67225 mS ≈ -5.67 mS (1.5 is the sufficient safety factor

Appendix 4. Matlab® scripts

The calculated results were transferred to Matlab®. Each fault place value consisted of two columns. In the first column, there were the magnitudes of the zero sequence current, and in the second column the scaled phase angles in radians in case of phase angle criterion. The created script, calculated now the real and imaginary parts, for each fault place with varying fault resistance (0–20 kΩ). In cabled radial network, there were three fault places compared to other situations. In the same way, the script calculated the real and the imaginary parts of the total admittance. Scaling was not necessary with admittance method. The boundaries were selected according to each network model calculation values from Appendices 2–3. Phase angle criterion script was modified partly by (Matlab® central 2011.) The erros analysis was excecuted in the same way, but now the script consisted in addition the original results, the calculated error limits; i.e. total amount of the columns was 24.

Phase angle criterion:

```
I=A(:,1).*cos(A(:,2));
ang=A(:,1).*sin(A(:,2));
plot(I,ang,'b+ ')
hold on;

I=A(:,3).*cos(A(:,4));
ang=A(:,3).*sin(A(:,4));
plot(I,ang,'g+ ')
hold on;

I=A(:,5).*cos(A(:,6));
ang=A(:,5).*sin(A(:,6));
plot(I,ang,'c+ ')
hold on;

I=A(:,7).*cos(A(:,8));
ang=A(:,7).*sin(A(:,8));
plot(I,ang,'r+ ')
hold on;

lineLength = 30;
angle = (10);
x(1) = cosd (10);
y(1) = sind (10);
x(2) = x(1) + lineLength * cosd(angle);
y(2) = y(1) + lineLength * sind(angle);
plot(x, y, 'k');
hold on;
lineLength = 30;
```

```
angle = (170);
x(1) = cosd (170);
y(1) = sind (170);
x(2) = -x(1)+ lineLength * cosd(angle);
y(2) = y(1) + lineLength * sind(angle);
hold on;
plot(x, y, 'k');
t = 10*pi/180: 0.01 : 170*pi/180;
r = 1;
a = r * cos(t);
b = r * sin(t);
plot(a, b, 'k');
axis equal;
hold on;
grid on;
```

Admittance criterion: (The example boundary settings are from mixed network)

```
I1=A(:,1).*cos(A(:,2));
ang1=A(:,1).*sin(A(:,2));
plot(I1,ang1,'b+ ')
hold on;

I2=A(:,3).*cos(A(:,4));
ang2=A(:,3).*sin(A(:,4));
plot(I2,ang2,'g+ ')
hold on;

I3=A(:,5).*cos(A(:,6));
ang3=A(:,5).*sin(A(:,6));
plot(I3,ang3,'c+ ')
hold on;

I3=A(:,7).*cos(A(:,8));
ang3=A(:,7).*sin(A(:,8));
plot(I3,ang3,'r+ ')
hold on;

plot([0.09 0.09],[-4.17 0.1],'k');
plot([-1 -1],[-4.17 0.1],'k');
plot([-1 0.09],[0.1 0.1],'k');
plot([-1 0.09],[-4.17 -4.17],'k');
axis equal;
grid on;
```

Appendix 5. Results of mixed radial network with recloser

				Mixed radial Part 10 km R off					
		BEGIN				MIDDLE			
Fault place	**Fault resistance (Ω)**	**U_0 Mag (V)**	**$3I_0$ Mag (A)**	**Phase Angle (deg)**	**Y_0 Mag (mS)**	**U_0 Mag (V)**	**$3I_0$ Mag (A)**	**Phase Angle (deg)**	**Y_0 Mag (mS)**
1	500	9006.414	11.482	-86.934	1.275	9014.863	0.302	-180.020	0.034
1	1000	6161.841	7.836	-86.557	1.272	6167.503	0.256	-175.408	0.042
1	2500	2819.354	3.568	-84.630	1.265	2821.734	0.190	-169.759	0.067
1	5000	1401.922	1.795	-78.783	1.281	1402.838	0.161	-171.214	0.115
1	10000	699.165	1.003	-70.127	1.434	699.324	0.145	-181.979	0.208
1	20000	699.165	1.003	-70.127	1.434	699.324	0.145	-181.979	0.208
3	500	8929.305	11.383	-86.925	1.275	8924.188	0.301	-179.964	0.034
3	1000	6107.245	7.765	-86.546	1.272	6103.866	0.255	-175.272	0.042
3	2500	2793.032	3.532	-84.610	1.265	2791.815	0.190	-169.517	0.068
3	5000	1387.336	1.774	-78.722	1.279	1387.302	0.160	-170.945	0.116
3	10000	690.920	0.991	-69.974	1.434	691.513	0.145	-181.782	0.210
3	20000	690.920	0.991	-69.974	1.434	691.513	0.145	-181.782	0.210
5	500	8731.253	11.128	-86.900	1.274	8726.259	13.308	86.793	1.525
5	1000	5937.345	7.546	-86.513	1.271	5934.067	9.076	86.486	1.530
5	2500	2707.967	3.420	-84.534	1.263	2706.794	4.178	84.700	1.543
5	5000	1343.748	1.717	-78.544	1.277	1343.727	2.104	78.762	1.565
5	10000	668.847	0.962	-69.682	1.438	669.439	1.024	66.916	1.529
5	20000	668.847	0.962	-69.682	1.438	669.439	1.024	66.916	1.529
9	500	9006.240	25.183	-91.043	2.796	9014.689	0.302	-180.020	0.034
9	1000	6161.720	17.251	-91.204	2.800	6167.382	0.256	-175.408	0.042
9	2500	2819.294	7.916	-91.831	2.808	2821.675	0.190	-169.759	0.068
9	5000	1401.890	3.940	-93.386	2.810	1402.806	0.161	-171.214	0.115
9	10000	699.148	1.933	-96.464	2.765	699.307	0.145	-181.979	0.208
9	20000	699.148	1.933	-96.464	2.765	699.307	0.145	-181.979	0.208
				Relay settings:					
			Admittance criterion		**Phase angle criterion**				
			U_{oh} = 810 V		U_{oh} = 810 V				
			I_h = 0.5 A		I_h = 1 A				

				Mixed radial Part 10 km R on					
		BEGIN				MIDDLE			
Fault place	**Fault resistance (Ω)**	**U_0 Mag (V)**	**$3I_0$ Mag (A)**	**Phase Angle (deg)**	**Y_0 Mag (mS)**	**U_0 Mag (V)**	**$3I_0$ Mag (A)**	**Phase Angle (deg)**	**Y_0 Mag (mS)**
1	500	7917.463	10.833	-68.693	1.368	7924.844	0.275	-183.495	0.035
1	1000	5372.360	7.362	-68.309	1.370	5377.234	0.235	-181.219	0.044
1	2500	2548.174	3.512	-67.136	1.378	2550.284	0.182	-178.736	0.071
1	5000	1308.104	1.829	-65.147	1.399	1308.999	0.157	-179.190	0.120
1	10000	639.154	0.935	-61.494	1.464	639.382	0.143	-184.145	0.224
1	20000	639.154	0.935	-61.494	1.464	639.382	0.143	-184.145	0.224
3	500	7840.047	10.727	-68.682	1.368	7845.454	0.274	-183.461	0.035
3	1000	5321.085	7.291	-68.293	1.370	5324.890	0.234	-181.114	0.044
3	2500	2524.192	3.478	-67.106	1.378	2526.204	0.182	-178.535	0.072
3	5000	1295.080	1.810	-65.088	1.398	1296.311	0.157	-178.944	0.121
3	10000	631.805	0.924	-61.365	1.463	632.628	0.143	-183.910	0.226
3	20000	631.805	0.924	-61.365	1.463	632.628	0.143	-183.910	0.226
5	500	7639.879	10.453	-68.650	1.368	7645.159	12.261	71.291	1.604
5	1000	5166.928	7.079	-68.249	1.370	5170.634	8.317	70.987	1.609
5	2500	2447.690	3.372	-67.021	1.378	2449.650	3.974	70.024	1.622
5	5000	1254.600	1.753	-64.927	1.398	1255.803	2.064	68.244	1.644
5	10000	610.471	0.894	-61.051	1.464	611.278	1.024	64.299	1.676
5	20000	610.471	0.894	-61.051	1.464	611.278	1.024	64.299	1.676
9	500	7917.304	22.122	-91.066	2.794	7924.684	0.275	-183.495	0.035
9	1000	5372.252	15.018	-91.250	2.795	5377.126	0.235	-181.219	0.044
9	2500	2548.120	7.131	-91.821	2.798	2550.231	0.182	-178.736	0.071
9	5000	1308.074	3.663	-92.830	2.800	1308.969	0.157	-179.190	0.120
9	10000	639.138	1.782	-94.991	2.788	639.366	0.143	-184.145	0.224
9	20000	639.138	1.782	-94.991	2.788	639.366	0.143	-184.145	0.224
				Relay settings:					
			Admittance criterion		**Phase angle criterion**				
			U_{oh} = 810 V		U_{oh} = 810 V				
			I_h = 0.5 A		I_h = 1 A				

				Mixed radial Part 10 km 1 OHL R off					
		BEGIN				MIDDLE			
Fault plac	**Fault resistance (Ω)**	**U_0 Mag (V)**	**$3I_0$ Mag (A)**	**Phase Angle (deg)**	**Y_0 Mag (mS)**	**U_0 Mag (V)**	**$3I_0$ Mag (A)**	**Phase Angle (deg)**	**Y_0 Mag (mS)**
1	500	10929.724	26.142	-89.136	2.392	10940.119	0.308	-185.747	0.028
1	1000	9999.983	23.912	-89.081	2.391	10009.437	0.303	-184.138	0.030
1	2500	7183.093	17.163	-88.911	2.389	7189.753	0.266	-180.809	0.037
1	5000	4409.623	10.528	-88.609	2.387	4413.563	0.217	-178.436	0.049
1	10000	2312.164	5.521	-87.942	2.388	2314.035	0.175	-179.581	0.076
1	20000	2312.164	5.521	-87.942	2.388	2314.035	0.175	-179.581	0.076
3	500	10832.890	25.911	-89.133	2.392	10840.447	0.306	-185.787	0.028
3	1000	9915.688	23.710	-89.078	2.391	9922.663	0.302	-184.131	0.030
3	2500	7125.020	17.024	-88.906	2.389	7130.163	0.266	-180.691	0.037
3	5000	4370.663	10.433	-88.601	2.387	4373.968	0.217	-178.208	0.050
3	10000	2287.107	5.460	-87.926	2.387	2289.031	0.175	-179.275	0.076
3	20000	2287.107	5.460	-87.926	2.387	2289.031	0.175	-179.275	0.076
5	500	10577.449	25.300	-89.123	2.392	10584.841	4.310	82.630	0.407
5	1000	9668.067	23.118	-89.066	2.391	9674.880	3.950	82.320	0.408
5	2500	6926.148	16.547	-88.891	2.389	6931.158	2.852	81.357	0.411
5	5000	4237.967	10.115	-88.576	2.387	4241.181	1.766	79.626	0.416
5	10000	2210.451	5.276	-87.876	2.387	2212.321	0.936	75.423	0.423
5	20000	2210.451	5.276	-87.876	2.387	2212.321	0.936	75.423	0.423
6	500	10929.501	30.530	-90.929	2.793	10939.896	0.308	-185.747	0.028
6	1000	9999.777	27.939	-90.974	2.794	10009.230	0.303	-184.138	0.030
6	2500	7182.943	20.082	-91.115	2.796	7189.602	0.266	-180.809	0.037
6	5000	4409.529	12.337	-91.366	2.798	4413.469	0.217	-178.436	0.049
6	10000	2312.114	6.467	-91.961	2.797	2313.985	0.175	-179.581	0.076
6	20000	2312.114	6.467	-91.961	2.797	2313.985	0.175	-179.581	0.076
				Relay settings:					
				Admittance criterion:	**Phase angle criterion:**				
				U_{oh} = 810 V	U_{oh} = 810 V				
				I_h = 0.5 A	I_h = 1 A				

				Mixed radial Part 10 km 1 OHL R on					
		BEGIN				MIDDLE			
Fault place	**Fault resistance (Ω)**	**U_0 Mag (V)**	**$3I_0$ Mag (A)**	**Phase Angle (deg)**	**Y_0 Mag (mS)**	**U_0 Mag (V)**	**$3I_0$ Mag (A)**	**Phase Angle (deg)**	**Y_0 Mag (mS)**
1	500	9099.412	22.193	-78.941	2.439	9108.012	0.269	-189.624	0.030
1	1000	7367.669	17.985	-78.868	2.441	7374.547	0.244	-191.290	0.033
1	2500	4548.547	11.135	-78.650	2.448	4552.631	0.200	-195.310	0.044
1	5000	2694.237	6.632	-78.300	2.462	2696.491	0.170	-200.457	0.063
1	10000	1433.126	3.577	-77.686	2.496	1434.144	0.148	-209.003	0.103
1	20000	1433.126	3.577	-77.686	2.496	1434.144	0.148	-209.003	0.103
3	500	9004.784	21.963	-78.936	2.439	9022.499	0.268	-189.658	0.030
3	1000	7294.532	17.807	-78.862	2.441	7308.970	0.243	-191.266	0.033
3	2500	4504.983	11.029	-78.641	2.448	4514.068	0.200	-195.166	0.044
3	5000	2667.282	6.566	-78.284	2.462	2672.833	0.169	-200.206	0.063
3	10000	1416.650	3.537	-77.653	2.496	1419.788	0.148	-208.684	0.104
3	20000	1416.650	3.537	-77.653	2.496	1419.788	0.148	-208.684	0.104
5	500	8756.052	21.358	-78.923	2.439	8773.293	5.517	39.806	0.629
5	1000	7086.896	17.302	-78.846	2.441	7100.939	4.479	39.494	0.631
5	2500	4371.565	10.703	-78.616	2.448	4380.395	2.787	38.522	0.636
5	5000	2584.688	6.364	-78.242	2.462	2590.081	1.669	36.791	0.644
5	10000	1368.903	3.420	-77.580	2.498	1371.951	0.901	32.923	0.657
5	20000	1368.903	3.420	-77.580	2.498	1371.951	0.901	32.923	0.657
6	500	9099.220	25.398	-90.953	2.791	9107.821	0.269	-189.624	0.030
6	1000	7367.514	20.553	-91.021	2.790	7374.392	0.244	-191.291	0.033
6	2500	4548.451	12.666	-91.228	2.785	4552.535	0.200	-195.311	0.044
6	5000	2694.179	7.475	-91.573	2.775	2696.433	0.170	-200.457	0.063
6	10000	1433.095	3.937	-92.240	2.747	1434.113	0.148	-209.004	0.103
6	20000	1433.095	3.937	-92.240	2.747	1434.113	0.148	-209.004	0.103
Relay settings:									
			Admittance criterion:		**Phase angle criterion:**				
			U_{oh} = 810 V		U_{oh} = 810 V				
			I_h = 0.5 A		I_h = 1 A				

Appendix 6. Results of cabled radial network with recloser

Cabled radial Part 10 km R off

		BEGIN				MIDDLE			
Fault place	**Fault resistance (Ω)**	**U_0 Mag (V)**	**$3I_0$ Mag (A)**	**Phase Angle (deg)**	**Y_0 Mag (mS)**	**U_0 Mag (V)**	**$3I_0$ Mag (A)**	**Phase Angle (deg)**	**Y_0 Mag (mS)**
1	500	8228.545	10.483	-86.840	1.274	8240.212	3.330	-95.203	0.404
1	1000	5239.158	6.654	-86.341	1.270	5246.453	2.149	-96.585	0.410
1	2500	2269.685	2.865	-83.039	1.262	2272.504	0.973	-102.613	0.428
1	5000	1113.711	1.452	-74.734	1.303	1114.637	0.515	-115.790	0.462
1	10000	567.181	0.873	-66.340	1.540	567.228	0.283	-138.339	0.499
1	20000	567.181	0.873	-66.340	1.540	567.228	0.283	-138.339	0.499
3	500	8181.439	10.421	-86.831	1.274	8176.788	3.306	-95.228	0.404
3	1000	5207.943	6.612	-86.333	1.270	5205.118	2.134	-96.610	0.410
3	2500	2254.134	2.842	-83.023	1.261	2253.377	0.967	-102.635	0.429
3	5000	1104.118	1.436	-74.645	1.300	1104.425	0.512	-115.834	0.464
3	10000	560.957	0.863	-66.105	1.539	561.718	0.282	-138.466	0.502
3	20000	560.957	0.863	-66.105	1.539	561.718	0.282	-138.466	0.502
5	500	8068.286	10.275	-86.817	1.274	8063.705	12.307	86.728	1.526
5	1000	5133.219	6.515	-86.313	1.269	5130.439	7.859	86.322	1.532
5	2500	2225.479	2.805	-82.971	1.260	2224.739	3.456	83.173	1.553
5	5000	1091.135	1.419	-74.554	1.301	1091.446	1.730	74.587	1.585
5	10000	554.565	0.855	-66.008	1.541	555.325	0.848	60.359	1.527
5	20000	554.565	0.855	-66.008	1.541	555.325	0.848	60.359	1.527
9	500	8228.383	26.328	-91.013	3.200	8240.049	3.330	-95.203	0.404
9	1000	5239.053	16.786	-91.201	3.204	5246.347	2.149	-96.585	0.410
9	2500	2269.636	7.297	-92.277	3.215	2272.455	0.973	-102.613	0.428
9	5000	1113.685	3.575	-95.017	3.210	1114.611	0.515	-115.790	0.462
9	10000	567.168	1.762	-99.442	3.106	567.215	0.283	-138.340	0.499
9	20000	567.168	1.762	-99.442	3.106	567.215	0.283	-138.340	0.499

Relay settings:

Admittance criterion:	**Phase angle criterion:**
U_{oh} = 810 V	U_{oh} = 810 V
I_h = 0.5 A	I_h = 1 A

Cabled radial Part 10 km R on

		BEGIN				MIDDLE			
Fault place	**Fault resistance (Ω)**	**U_0 Mag (V)**	**$3I_0$ Mag (A)**	**Phase Angle (deg)**	**Y_0 Mag (mS)**	**U_0 Mag (V)**	**$3I_0$ Mag (A)**	**Phase Angle (deg)**	**Y_0 Mag (mS)**
1	500	7379.141	10.095	-68.599	1.368	7389.559	2.971	-95.395	0.402
1	1000	4731.033	6.481	-68.116	1.370	4737.568	1.921	-96.945	0.406
1	2500	2133.556	2.941	-66.582	1.379	2136.291	0.890	-101.706	0.417
1	5000	1075.703	1.510	-63.928	1.403	1076.880	0.471	-109.806	0.438
1	10000	521.442	0.775	-59.234	1.486	521.791	0.254	-125.658	0.486
1	20000	521.442	0.775	-59.234	1.486	521.791	0.254	-125.658	0.486
3	500	7328.424	10.025	-68.585	1.368	7333.511	2.950	-95.425	0.402
3	1000	4699.913	6.437	-68.098	1.370	4703.317	1.909	-96.977	0.406
3	2500	2119.278	2.920	-66.547	1.378	2121.030	0.886	-101.745	0.418
3	5000	1067.459	1.496	-63.853	1.401	1068.554	0.469	-109.852	0.439
3	10000	516.179	0.766	-59.046	1.483	516.939	0.253	-125.711	0.490
3	20000	516.179	0.766	-59.046	1.483	516.939	0.253	-125.711	0.490
5	500	7222.976	9.880	-68.567	1.368	7227.996	11.603	71.245	1.605
5	1000	4633.196	6.345	-68.074	1.369	4636.556	7.473	70.889	1.612
5	2500	2092.348	2.882	-66.505	1.377	2094.082	3.415	69.689	1.631
5	5000	1054.326	1.477	-63.776	1.401	1055.411	1.755	67.423	1.662
5	10000	509.460	0.756	-58.894	1.484	510.215	0.873	62.575	1.712
5	20000	509.460	0.756	-58.894	1.484	510.215	0.873	62.575	1.712
9	500	7378.991	23.594	-91.034	3.197	7389.409	2.971	-95.395	0.402
9	1000	4730.936	15.139	-91.236	3.200	4737.472	1.921	-96.945	0.406
9	2500	2133.511	6.840	-91.884	3.206	2136.246	0.890	-101.707	0.417
9	5000	1075.679	3.454	-93.062	3.211	1076.856	0.471	-109.806	0.438
9	10000	521.429	1.670	-95.555	3.202	521.778	0.254	-125.659	0.486
9	20000	521.429	1.670	-95.555	3.202	521.778	0.254	-125.659	0.486
Relay settings:									
			Admittance criterion:		**Phase angle criterion:**				
			U_{oh} = 810 V		U_{oh} = 810 V				
			I_h = 0.5 A		I_h = 1 A				

Cabled radial Part 10 km 1 OHL R off									
		BEGIN				MIDDLE			
Fault place	**Fault resistance (Ω)**	**U_0 Mag (V)**	**$3I_0$ Mag (A)**	**Phase Angle (deg)**	**Y_0 Mag (mS)**	**U_0 Mag (V)**	**$3I_0$ Mag (A)**	**Phase Angle (deg)**	**Y_0 Mag (mS)**
1	500	10400.640	24.866	-89.087	2.391	10415.524	4.174	-94.435	0.401
1	1000	8532.760	20.385	-88.982	2.389	8544.879	3.442	-95.029	0.403
1	2500	4775.717	11.387	-88.652	2.384	4782.331	1.955	-96.886	0.409
1	5000	2529.796	6.016	-88.042	2.378	2533.065	1.061	-100.885	0.419
1	10000	1235.012	2.939	-86.655	2.380	1236.237	0.538	-111.625	0.436
1	20000	1235.012	2.939	-86.655	2.380	1236.237	0.538	-111.625	0.436
3	500	10343.816	24.729	-89.083	2.391	10351.079	4.149	-94.458	0.401
3	1000	8491.704	20.286	-88.978	2.389	8497.755	3.424	-95.050	0.403
3	2500	4750.976	11.326	-88.648	2.384	4754.521	1.946	-96.905	0.409
3	5000	2512.492	5.973	-88.035	2.377	2514.545	1.056	-100.903	0.420
3	10000	1222.439	2.907	-86.628	2.378	1223.681	0.536	-111.693	0.438
3	20000	1222.439	2.907	-86.628	2.378	1223.681	0.536	-111.693	0.438
5	500	10241.652	24.484	-89.078	2.391	10248.849	4.189	82.395	0.409
5	1000	8393.442	20.050	-88.972	2.389	8399.428	3.454	81.828	0.411
5	2500	4692.100	11.184	-88.639	2.384	4695.605	1.967	80.047	0.419
5	5000	2481.580	5.898	-88.021	2.377	2483.612	1.073	76.166	0.432
5	10000	1206.973	2.869	-86.596	2.377	1208.204	0.550	65.616	0.456
5	20000	1206.973	2.869	-86.596	2.377	1208.204	0.550	65.616	0.456
6	500	10400.424	33.246	-90.912	3.197	10415.307	4.174	-94.435	0.401
6	1000	8532.580	27.290	-90.989	3.198	8544.699	3.442	-95.029	0.403
6	2500	4775.615	15.297	-91.238	3.203	4782.230	1.955	-96.886	0.409
6	5000	2529.742	8.117	-91.875	3.209	2533.011	1.061	-100.885	0.419
6	10000	1234.986	3.951	-93.805	3.200	1236.211	0.538	-111.625	0.436
6	20000	1234.986	3.951	-93.805	3.200	1236.211	0.538	-111.625	0.436
Relay settings:									
			Admittance criterion:		**Phase angle criterion:**				
			U_{oh} = 810 V		U_{oh} = 810 V				
			I_h = 0.5 A		I_h = 1 A				

Cabled radial Part 10 km 1 OHL R on									
		BEGIN				MIDDLE			
Fault place	**Fault resistance (Ω)**	**U_0 Mag (V)**	**$3I_0$ Mag (A)**	**Phase Angle (deg)**	**Y_0 Mag (mS)**	**U_0 Mag (V)**	**$3I_0$ Mag (A)**	**Phase Angle (deg)**	**Y_0 Mag (mS)**
1	500	8797.198	21.450	-78.889	2.438	8809.734	3.512	-94.627	0.399
1	1000	6726.532	16.411	-78.763	2.440	6736.005	2.685	-95.413	0.399
1	2500	3709.568	9.070	-78.382	2.445	3714.600	1.480	-97.829	0.398
1	5000	2036.827	5.004	-77.742	2.457	2039.403	0.810	-102.049	0.397
1	10000	1030.352	2.569	-76.511	2.493	1031.447	0.403	-111.211	0.391
1	20000	1030.352	2.569	-76.511	2.493	1031.447	0.403	-111.211	0.391
3	500	8733.868	21.295	-78.883	2.438	8751.090	3.490	-94.654	0.399
3	1000	6682.540	16.303	-78.756	2.440	6695.829	2.670	-95.445	0.399
3	2500	3685.760	9.010	-78.369	2.445	3693.283	1.473	-97.874	0.399
3	5000	2021.774	4.966	-77.719	2.456	2026.089	0.806	-102.122	0.398
3	10000	1020.178	2.542	-76.458	2.492	1022.567	0.401	-111.365	0.393
3	20000	1020.178	2.542	-76.458	2.492	1022.567	0.401	-111.365	0.393
5	500	8630.686	21.044	-78.876	2.438	8647.711	5.457	39.795	0.631
5	1000	6600.328	16.102	-78.747	2.440	6613.459	4.201	39.452	0.635
5	2500	3640.832	8.900	-78.356	2.445	3648.268	2.363	38.377	0.648
5	5000	1997.102	4.905	-77.696	2.456	2001.369	1.337	36.435	0.668
5	10000	1006.863	2.509	-76.412	2.492	1009.225	0.713	31.996	0.707
5	20000	1006.863	2.509	-76.412	2.492	1009.225	0.713	31.996	0.707
6	500	8797.011	28.102	-90.933	3.194	8809.546	3.512	-94.627	0.399
6	1000	6726.389	21.484	-91.031	3.194	6735.862	2.685	-95.413	0.399
6	2500	3709.489	11.841	-91.331	3.192	3714.521	1.480	-97.829	0.398
6	5000	2036.784	6.490	-91.849	3.186	2039.359	0.810	-102.050	0.397
6	10000	1030.330	3.260	-92.921	3.164	1031.425	0.403	-111.212	0.391
6	20000	1030.330	3.260	-92.921	3.164	1031.425	0.403	-111.212	0.391
Relay settings:									
			Admittance criterion:		**Phase angle criterion:**				
			U_{oh} = 810 V		U_{oh} = 810 V				
			I_h = 0.5 A		I_h = 1 A				

Appendix 7. Results of ring-shaped network

Ring-shaped Part 10 km									
		BEGIN				MIDDLE			
Fault place	**Fault resistance (Ω)**	**U_0 Mag (V)**	**$3I_0$ Mag (A)**	**Phase Angle (deg)**	**Y_0 Mag (mS)**	**U_0 Mag (V)**	**$3I_0$ Mag (A)**	**Phase Angle (deg)**	**Y_0 Mag (mS)**
1	500	7831.120	10.585	-65.737	1.352	7837.571	0.317	57.573	0.040
1	1000	5282.706	7.172	-64.827	1.358	5286.881	0.229	54.921	0.043
1	2500	2482.047	3.432	-62.112	1.383	2483.729	0.129	47.909	0.052
1	5000	1261.326	1.828	-57.859	1.449	1261.892	0.086	38.176	0.068
1	10000	612.438	1.021	-51.857	1.667	612.341	0.062	21.998	0.102
1	20000	612.438	1.021	-51.857	1.667	612.341	0.062	21.998	0.102
3	500	7655.390	15.413	-82.401	2.013	7629.350	5.948	-110.280	0.780
3	1000	5157.882	10.380	-82.164	2.012	5140.476	4.031	-111.034	0.784
3	2500	2419.956	4.867	-81.421	2.011	2412.030	1.923	-113.404	0.797
3	5000	1227.036	2.475	-80.097	2.017	1223.304	0.998	-117.712	0.816
3	10000	593.320	1.222	-77.461	2.059	591.939	0.494	-127.297	0.835
3	20000	593.320	1.222	-77.461	2.059	591.939	0.494	-127.297	0.835
4	500	7719.206	20.061	-85.505	2.599	7724.943	2.484	39.153	0.322
4	1000	5206.849	13.541	-85.545	2.601	5210.751	1.704	38.189	0.327
4	2500	2445.254	6.373	-85.681	2.606	2447.123	0.841	35.196	0.344
4	5000	1241.049	3.244	-85.951	2.614	1242.011	0.461	29.870	0.371
4	10000	601.098	1.577	-86.625	2.624	601.530	0.254	18.289	0.422
4	20000	601.098	1.577	-86.625	2.624	601.530	0.254	18.289	0.422
9	500	7830.961	21.610	-90.508	2.760	7837.412	0.317	57.573	0.040
9	1000	5282.599	14.577	-90.635	2.759	5286.774	0.229	54.921	0.043
9	2500	2481.994	6.845	-91.031	2.758	2483.677	0.129	47.908	0.052
9	5000	1261.298	3.469	-91.730	2.751	1261.863	0.086	38.176	0.068
9	10000	612.423	1.664	-93.135	2.717	612.326	0.062	21.998	0.102
9	20000	612.423	1.664	-93.135	2.717	612.326	0.062	21.998	0.102

Appendix 8. Results of phase angle error calculations

Error calculations, phase angle error ± 5° (BEGIN)							
Fault place	**Fault resistance (Ω)**	**U_0 Mag (V)**	**$3I_0$ Mag (A)**	**Phase Angle (deg)**	**Phase Angle error (-5 °)**	**Phase Angle error (+5 °)**	**Y_0 Mag (mS)**
1	500	7917.463	10.833	-68.693	-73.693	-63.693	1.368
1	1000	5372.360	7.362	-68.309	-73.309	-63.309	1.370
1	2500	2548.174	3.512	-67.136	-72.136	-62.136	1.378
1	5000	1308.104	1.829	-65.147	-70.147	-60.147	1.399
1	10000	639.154	0.935	-61.494	-66.494	-56.494	1.464
1	20000	639.154	0.935	-61.494	-66.494	-56.494	1.464
3	500	7840.047	10.727	-68.682	-73.682	-63.682	1.368
3	1000	5321.085	7.291	-68.293	-73.293	-63.293	1.370
3	2500	2524.192	3.478	-67.106	-72.106	-62.106	1.378
3	5000	1295.080	1.810	-65.088	-70.088	-60.088	1.398
3	10000	631.805	0.924	-61.365	-66.365	-56.365	1.463
3	20000	631.805	0.924	-61.365	-66.365	-56.365	1.463
5	500	7639.879	10.453	-68.650	-73.650	-63.650	1.368
5	1000	5166.928	7.079	-68.249	-73.249	-63.249	1.370
5	2500	2447.690	3.372	-67.021	-72.021	-62.021	1.378
5	5000	1254.600	1.753	-64.927	-69.927	-59.927	1.398
5	10000	610.471	0.894	-61.051	-66.051	-56.051	1.464
5	20000	610.471	0.894	-61.051	-66.051	-56.051	1.464
9	500	7917.304	22.122	-91.066	-96.066	-86.066	2.794
9	1000	5372.252	15.018	-91.250	-96.250	-86.250	2.795
9	2500	2548.120	7.131	-91.821	-96.821	-86.821	2.798
9	5000	1308.074	3.663	-92.830	-97.830	-87.830	2.800
9	10000	639.138	1.782	-94.991	-99.991	-89.991	2.788
9	20000	639.138	1.782	-94.991	-99.991	-89.991	12.000