TAMPERE UNIVERSITY OF TECHNOLOGY

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CHALLENGES IN EXTENSIVE CABLING OF THE RURAL AREA NETWORKS AND PROTECTION IN MIXED NETWORKS

Master of Science Thesis

Examiner: Professor Pekka Verho
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ABSTRACT

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Despite of the careful building and maintenance of the electricity network, faults like short-circuit and earth-faults take place from time to time. Majority of the faults customers experience in low voltage networks are caused by the faults in the medium voltage networks. Therefore minimizing faults in medium voltage networks contributes to the quality of delivery.

A way of improving the quality of delivery is to sectionalize the protection areas into smaller units with network reclosers. Reclosers include short-circuit and earth-fault protection and auto-reclosing functionalities. The best results are gained by placing the recloser so that the majority of the faults stay behind the device and the customers on the other side, so that they are not affected by the outage caused by the fault occurring behind the recloser. The quality of delivery indexes are improved by using reclosers.

After the great storms in the Nordic countries the network owners started to replace over-head line networks with underground cable. The cable characteristics, however, are very different from the characteristics of an over-head line. Cabling increases the capacitive earth-fault current for it may be considered as a cylindrical capacitor. Due to this, also the reactive power generation is increased in cabled networks.

Cable can be represented with a pi-section in which the series impedance consists of reactive and resistive parts. Because an underground cable has a zero sequence series impedance which is non-negligible on contrary to over-head line, cabling long feeders produces a resistive earth-fault current component. This cannot be compensated with the usage of a Petersen coil, which is used to compensate purely capacitive earth-fault current. Increase in earth-fault current may cause hazards for human safety because the earth-fault current can energize network equipment and thereby cause dangerous over-voltages. Therefore the contact voltages have to be limited also in terms of regulations.

The studies regarding earth-fault current behavior were carried out with a program namely Power System simulator for Engineering. The studies show that as the cabling increases, the zero sequence resistance becomes more dominating. When using only centralized compensation the zero sequence resistance produces resistive earth-fault current, which may cause dangerous over-voltages and causes voltage drops in zero sequence network. This may lead to difficulties in detecting high impedance earth-faults. The fault detection can be contributed with the usage of distributed compensation. The best results are gained by compensating first 10-15 kilometers centrally and the rest locally. The distributed Petersen coil should be dimensioned according to the produced earth-fault current in order to avoid over-compensation which may lead to false relay functions. The cable zero sequence impedance, however, is not an unambiguous matter. Therefore some field tests should be performed in the future in order to achieve even better knowledge regarding these issues.

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Viimeisten vuosikymmenten aikana asiakkaiden vaatimukset ovat kohdistuneet yhä enemmän sähkön laatuun. Enää ei riitä pelkästään se, että talous saadaan sähköistettyä, vaan nykyään sähkön on oltava häiriötöntä ja helposti ja nopeasti saatavilla. Tämän myötä kasvaa toimitusvarmuuden merkitys. Huolimatta siitä, että verkon rakentamiseen ja kunnossapitoon kiinnitetään yhä kasvavissa määrin huomiota, sähköverkko kokee aika ajoin vikoja. Suurin osa asiakkaiden kokemista vioista on peräisin keskijänniteverkon vioista. Vähentämällä vikojen vaikutusta keskijänniteverkossa on siis mahdollista vaikuttaa pienjänniteasiakkaiden kokemaan sähkön laatuun.

Keskijänniteverkon päävikatyypit ovat oikosulku ja maasulku. Verkossa sanotaan olevan oikosulku, kun kahden tai kolmen johtimen välillä on johtava yhteys. Riippuen siitä, kuinka monen vaiheen välillä eristysvika on, puhutaan kaksi- tai kolmevaiheisesta oikosulusta. Oikosulkuviat aiheutuvat usein esimerkiksi salamaniskuista tai verkon eristimien vioista.

Oikosulun aikaiset vikavirrat ovat usein hyvin suuria, ja oikosulkusuojauksen tarkoituksena onkin vikatilanteen aikana asiakkaiden turvallisuuden takaaminen ja verkon termisen ja dynaamisen kestoisuuden varmistaminen. Erityisesti epäsymmetriaa sisältävät oikosulut voivat vahingoittaa verkon laitteita, sillä nämä sisältävät vaimenevan tasavirtakomponentin. Tasavirtakomponentin vaikutuksesta esimerkiksi rautasydämiset virtamuuntajat kyllästyvät helposti, jonka seurauksena toisiopuolelle muunnettu virta saattaa sisältää säröä. Sähköverkon laitteet mitoitetaan usein suurimman alkuoikosulkuvirran mukaan.

Vattenfall Verkko Oy:llä oikosulkusuojaus toteutetaan useimmiten kaksiportaisena. Näistä hitaammalla portaalla laukaisuajat ovat usein hieman pitemmät ja virran havahtumisarvo muutamien satojen ampeerien luokkaa. Tämän porras mitoitetaan siten, että se havaitsee lähdön kaikki oikosulut – toisin sanoen virta-arvo asetellaan siten, että rele havaitsee lähdön loppupään kaksivaiheisen oikosulun. Toinen porras on usein nopeampi ja sen havahtumisvirrat ovat kiloampeerin luokkaa. Tämä porras takaa lähdön alkupään verkkolaitteiden ja johtojen termisen kestoisuuden. Jännitekuoppien vaikutuksen vähentämiseksi toinen porras on hyvä asetella ulottumaan mahdollisimman pitkälle verkkoon reunaehtojen puitteissa.

Kun johtolähdön yksi vaihe on kosketuksissa maahan joko suoraan tai jonkin johtavan osan kautta, verkossa sanotaan olevan maasulku. Maasulku voi olla joko yksivaiheinen, jolloin vain yksi vaihe on kosketuksissa maahan, tai kaksivaiheinen, jolloin johtolähdön kaksi vaihetta ovat kosketuksissa maahan ilman suoraa johtavaa yhteyttä toisiinsa. Tätä kutsutaan myös kaksoismaasuluksi. Maasulku voi olla myös katkeileva, jolloin se syttyy ja sammuu toistuvasti. Katkeilevat maasulut aiheutuvat usein kaapelin vikaantumisen tai vanhenemisen seurauksena.

Yksivaiheisen maasulun seurauksena viallisen vaiheen jännite laskee ja kahden terveen vaiheen jännite nousee. Tämä jännite-epäsymmetria näkyy nollajännitteen kasvuna. Nollajännite on vaihejännitteiden summa, joten terveessä ja symmetrisessä tilanteessa nollajännitteen arvo on lähellä nollaa. Jäykässä maasulussa verkon viallisen vaiheen jännite laskee lähes nollaan ja terveiden vaiheiden jännite kasvaa vikaa edeltäneen pääjännitteen suuruuteen. Samalla nollajännite kasvaa vikaa edeltäneen vaihejännitteen suuruuteen. Tämä sama jännite näkyy myös verkon laitteiden ja niiden maadoitettujen osien välillä. Jos ihminen on kosketuksissa tällaiseen verkon laitteeseen tai sen maadoitettuun osaan maasulun aikana, kokee hän osan tästä nollajännitteestä. Tätä kutsutaan kosketusjännitteeksi. Koska ihmiskeholla on oma ominaisimpedanssinsa, synnyttää kehon yli oleva jännite virran. Jopa matalatkin virrat ihmiskehon läpi voivat johtaa kuolemaan, sillä ne voivat aiheuttaa lihaskramppeja, joiden seurauksena henkilö ei pysty irrottamaan itseään jännitteiseksi tulleesta verkkolaitteen osasta.

Maasulkusuojauksen tarkoituksena on taata ihmisten turvallisuus verkon maasulkutilanteessa. Suunnattu maasulkusuojaus perustuu maasulkuvirran suuruuteen, nollajännitteen kasvuun ja näiden kahden väliseen vaihesiirtoon, joka maasta erotetussa verkossa on 90°. Virran ja jännitteen välinen vaihesiirto johtuu siitä, että maasulkuvirta on kapasitiivista, toisin sanoen virta kulkee 90° jännitteen edellä. Kun verkko on sammutettu, on virran ja jännitteen vaihesiirtokulma 0°.

Verkon sammutuksella tarkoitetaan kapasitiivisen maasulkuvirran kompensointia joko keskitetysti tai hajautetusti. Keskitetyllä kompensoinnilla tarkoitetaan tilannetta, jossa sähköaseman tähtipisteeseen kytketään kapasitiivista maasulkuvirtaa kompensoiva kuristin. Hajautetussa kompensoinnissa tällaisia kuristimia kytketään eri puolille verkkoa kompensoimaan tuotettua maasulkuvirtaa paikallisesti.

Sähkön toimitusvarmuutta voidaan parantaa muun muassa jakamalla lähtöjä useampiin suojausvyöhykkeisiin. Tähän tarkoitukseen voidaan käyttää verkkokatkaisijoita, jotka ovat verkkoon asennettavia katkaisulaitteita. Verkkokatkaisijat sisältävät samat suojausominaisuudet kuin itse lähtöjen kennot. Verkkokatkaisijan toimiva yksikkö on rele, jolle voidaan perustoiminnallisuuksien, eli ylivirta- ja maasulkusuojauksen lisäksi ohjelmoida jälleenkytkennät. Pikajälleenkytkennällä tarkoitetaan sähkönjakelun lyhyttä keskeytystä vikatilanteen poistamiseksi. Useimmiten jännitteetön aika on enintään 0,5s. Aikajälleenkytkennän jännitteetön aika on usein 1-3 minuuttia.

Verkkokatkaisijoita asentamalla voidaan parantaa toimitusvarmuusindeksejä, SAIDIa, SAIFIa ja MAIFIa. SAIDI tarkoittaa asiakkaiden vuodessa keskimäärin kokemaa keskeytysaikaa, SAIFI asiakkaiden keskimäärin vuodessa kokemia keskeytyksiä ja MAIFI asiakkaiden keskimäärin vuodessa kokemia lyhyitä keskeytyksiä, eli käytännössä pika- ja aikajälleenkytkentöjä. Parhaat tulokset saavutetaan asentamalla verkkokatkaisija verkkoon niin, että viat jäävät verkkokatkaisijan taakse ja suurin osa asiakkaista verkkokatkaisijan ja sähköaseman välille, jolloin asiakkaat eivät koe verkkokatkaisijan takana tapahtuvien vikojen aiheuttamia keskeytyksiä. Maaseutuverkoissa asiakkaat ovat usein kuitenkin jakaantuneet melko tasaisesti pitkin lähtöä, jolloin verkkokatkaisijalle voidaan löytää paras paikka laskemalla sen vaikutuksia toimitusvarmuusindekseihin eri kohdissa verkkoa.

Tässä työssä verkkokatkaisijan vaikutuksia tutkittiin Spillersbodan verkossa Ruotsissa. Verkosta haettiin kolme mahdollista paikkaa verkkokatkaisijalle, jonka jälkeen yhden verkkokatkaisijan vaikutuksia arvioitiin asiakastuntien ja keskeytysmäärien puitteissa. Tutkittavat toimitusvarmuusindeksit olivat SAIFI, SAIDI ja MAIFI. MAIFIin laskettiin mukaan vain aikajälleenkytkentä, sillä Vattenfall

Eldistributionin verkossa ei käytetä pikajälleenkytkentöjä. Johtopäätöksenä voitiin todeta, että verkkokatkaisijan asentaminen Spillersbodan verkkoon vähentäisi asiakkaiden kokemia vikoja merkittävästi.

Sähkön toimitusvarmuutta voidaan parantaa myös verkon kaapeloinnilla. Pohjoismaissa riehuneiden myrskyjen, Gudrunin, Pyryn ja Janikan jälkeen verkonhaltijat alkoivat korvata vanhaa ilmajohtoverkkoa maakaapelilla. Myrskyt osoittivat, että ilmajohtoverkkoon kytketyt asiakkaan kokivat paljon enemmän vikoja kuin maakaapeliverkkoon liitetyt asiakkaat. Kaapelin ominaisuudet poikkeavat kuitenkin hyvin paljon ilmajohdon ominaisuuksista. Kaapeli voidaan ajatella sylinterikondensaattorina, jonka vuoksi se kasvattaa verkon kapasitiivista virtaa. Piiriteoriassa kaapeli voidaan esittää pii-kytkennällä, jonka sarjaimpedanssi koostuu reaktiivisesta ja resistiivisestä osasta. Kaapelin nollaverkon sarjaimpedanssi, eli nollaimpedanssi, on paljon suurempi kuin ilmajohdolla. Sen vaikutus korostuu erityisesti pitkillä kaapeleilla, jotka tuottavat kapasitiivisen maasulkuvirran lisäksi myös resistiivisen virtakomponentin. Tätä resistiivistä virtakomponenttia ei voida kompensoida sammutuskuristimilla, jonka vuoksi se voi vikatilanteessa aiheuttaa vaaratilanteita ihmisille.

Kun maasulkuvirta kulkee kaapelin nollaimpedanssin läpi, aiheutuu nollaverkossa jännitehäviöitä, jotka näkyvät nollajännitteen eroina eri verkon osien välillä. Tämä on vastoin perinteisen maasulkuanalyysin oletuksia, jossa maasulkuvirta oletetaan puhtaasti kapasitiiviseksi ja verkon nollajännite yhtä suureksi joka puolella verkossa. Nollaverkossa tapahtuva jännitehäviö voi pitkillä kaapeleilla johtaa matalampaan nollapistejännitteeseen kiskossa, joka puolestaan vaikuttaa keskitetyn kompensoinnin tuottamaan induktiiviseen virtaan. Suuriohmisten vikojen tapauksessa kiskon alhainen nollajännite voi vaikeuttaa vikojen havaitsemista.

Maasulkuvirran käyttäytymistä tutkittiin Power System Simulator for Engineering ohjelmalla. Laskennan perustana oli malli, joka rakennettiin vastaamaan keskivertoa suomalaista maaseutuverkkoa. Alussa puhtaasti ilmajohtoa sisältävää verkkoa alettiin kaapeloida ja maasulkuvirran käyttäytymistä tarkasteltiin eri kaapelointiasteilla. Tarkastelut toistettiin myös siten, että verkon tähtipisteeseen lisättiin sammutuskuristin, joka viritettiin resonanssiin. Maasulkuvirran käyttäytymistä tutkittiin myös hajautetun kompensoinnin tapauksessa. Tarkasteluissa voitiin huomata, että resistiivinen virtakomponentti ei kasva lineaarisesti kaapelin pituuteen nähden, vaan pitkillä johdinpituuksilla kaapelin kapasitanssin vaikutus pieneni ja resistanssin vaikutus kasvoi. Näin ollen myös resistiivinen virta kasvoi suhteessa enemmän kaapelin pituuden kasvaessa. Koska resistiivinen virta johtui pääasiallisesti maasulkuvirran kulkeutumisesta pitkiä matkoja nollaverkon sarjaimpedanssien läpi, voitiin maasulkuvirran kulkeutumista vähentää kompensoimalla kapasitiivinen maasulkuvirta hajautetusti. Näin voitiin myös rajoittaa resistiivistä virtakomponenttia.

Hajautettujen kompensointilaitteiden nollaimpedanssitietoja oli vaikea saada, jonka vuoksi mallissa käytettiin hajautettuun maasulkuvirran kompensointiin ainoastaan 15A:n kelaa, jonka nollaimpedanssitiedot olivat saatavilla. Tämän kelatyypin todettiin tuottavan enemmän induktiivista virtaa kuin mallinnettu kaapelityyppi tuotti kapasitiivista, kun keloja liitettiin verkkoon yksi aina 5km kaapeliosuutta kohti. Tästä johtuen kaapeloitu johtolähtö ja koko mallinnettu verkko ylikompensoituivat. Johtopäätöksenä todettiin, että maasta erotetussa verkossa tällainen tilanne johtaisi virheelliseen releiden toimintaan, jolloin terve lähtö todennäköisesti irrotettaisiin verkosta, kun taas vikaantunut lähtö pysyisi kytkettynä. Tällaista tilannetta tulisi välttää, jotta suojauksella pystyttäisiin takaamaan asiakkaiden turvallisuus. Mikäli tällaisia keloja halutaan käyttää, olisi verkko syytä kompensoida vain osittain hajautetuilla kompensointilaitteilla. Yksi mahdollinen ratkaisu oli lisätä verkkoon yksi 15A kompensointikela aina noin 7:ä kaapelikilometriä kohti.

Kun ensimmäisen hajautettu kompensointikela kytkettiin malliverkkoon, todettiin resistiivisen maasulkuvirran kaksinkertaistuvan. Tämä johtui kompensointikelan nollaimpedanssista, joka on seurausta kelan maadoituksesta keskijännitepuolella. Kelan nollaimpedanssi aiheutti resistiivisen virtakomponentin, joka summautui kaapelin tuottamaan resistiiviseen virtaan. Koko verkon resistiivinen virta kasvoi aina siihen asti, kunnes 15 kilometriä verkkoa oli muutettu kaapeliksi, ja näistä jokaista 5km kohti oli asennettu yksi kompensointikela. Johtopäätöksenä todettiin, että kelan tyypistä riippuen noin 10–15 kilometriä asemalta tulisi hoitaa keskitetyllä kompensoinnilla. Tutkimuksissa huomattiin myös, että hajautetun kompensoinnin käyttäminen edisti suuriohmisten vikojen havaitsemista, joka kompensoimattomassa ja keskitetysti kompensoidussa verkossa olisi ollut lähes mahdotonta.

On kuitenkin muistettava, että kaapelin nollaimpedanssi ei ole yksiselitteinen asia. Maasulkuvirran käyttäytymiseen kaapeliverkossa vaikuttaa kaapelityypin lisäksi verkon topologia, maadoituspisteet, vikapaikka sekä jännitteenalenema myötäverkossa. Maasulkuvirtaa tulisi mitata kenttäkokeilla, jotta voidaan varmistua siitä, että tapa, jolla esimerkiksi Power System Simulator for Engineering laskee maasulkuvirtaa, on oikea.

Verkon laajamittainen kaapelointi kasvattaa myös reaktiivisen tehon tuottoa verkossa. Tutkimuksessa huomattiin, että koko esimerkkiverkon kaapelointi tuotti reaktiivista tehoa noin 4,5MVAr. Reaktiivinen teho olisi pyrittävä kompensoimaan paikallisesti jotta tehotasapaino valtakunnan verkossa voidaan säilyttää. Tämän vuoksi kaapeloitaessa laajoja verkkoja, tulisi reaktiivisen tehon tuotto ottaa huomioon. Reaktiivisen tehon tuottoa voidaan kontrolloida esimerkiksi induktiivisella rinnakkaiskompensoinnilla. Rajoittamalla reaktiivisen tehon tuottoa jakeluverkossa, voidaan myös kevyesti kuormitettujen lähtöjen loppupäiden jännitettä kontrolloida, jotka pyrkivät nousemaan kaapelin tuottaman reaktiivisen tehon vaikutuksesta.

PREFACE

This work was started in may 2009 commissioned by Vattenfall Verkko Oy and Vattenfall Eldistribution AB. As this was the first Nordic level master's thesis work done within Vattenfall, I had a great honor to be chosen to perform this work. First of all I want to thank Jouni Pylvänäinen for giving me this interesting subject and for choosing me to do this particular master's thesis. I also want to thank Pekka Verho, my examiner, for all the help given during this process.

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Hanna-Mari Pekkala

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ABBREVIATIONS AND NOTATION

C_0	Total capacitance to earth
C_{0f}	Capacitance per phase of the faulty feeder
$C_{0,i}$	The capacitance of a single feeder
d	The distance between conductors
D_e	The equivalent penetration depth
I_0	Zero sequence current
I_{0r}	Resistive earth-fault current seen at the bus bar
I_f	Earth-fault current
$\underline{I}_{fA}$	Earth-fault current phasor at point A in double earth-fault
$\underline{I}_{fB}$	Earth-fault current phasor at point B in double earth-fault
I_h	The current threshold value
I_{jC}	The capacitive earth-fault current component
I_k	The short-circuit component in double earth-fault
I_{k3}	Three phase short-circuit current
I_k'	Transient fault current
I_k''	Sub-transient fault current
$\underline{I}_R$	Receiving end current phasor
$\underline{I}_S$	Sending end current phasor
i_s	Maximum asymmetric short-circuit current value
I_r	The resistive earth-fault current component
$I>$	First over current protection stage
$I>>$	Second over current protection stage, momentary tripping
jX	Reactance
l	The cable length
$L_{0,I}$	Zero inductance of an individual feeder
n_j	The number of the customers who experience the interruptions i
N_s	The total amount of customers
R_0	Total network resistance in compensated network
$R_{0,I}$	The resistance of an individual feeder
r_c	The radius of the conductor
r_c'	The geometric mean radius of a conductor
R_g	The ground resistance
R_f	The fault resistance
R_e	Earthing resistance
R_{fA}	Fault resistance at point A in double earth-fault
R_{fB}	Fault resistance at point B in double earth-fault
R_m	Resistance to earth
R_s	The sheath resistance
r_s	The radius of the cable

r_s'	The geometric mean radius of sheath
t_{ij}	The time without electricity that customers *j* have to spend because of the interruptions *i*
$t1$	Time before the auto-reclosings
$t2$	Time after the high speed auto-reclosing
$t3$	Time before the final tripping
U	Phase-to-phase voltage
U_0	Neutral point displacement voltage
U_{0Z}	The zero sequence voltage
U_{1eq}	Equivalent phase-to-earth voltage
U_2	Phase-to-earth voltage in negative sequence network
U_3	Phase-to-earth voltage in positive sequence network
$\underline{U}_A$	Phase-to-earth voltage phasor in phase A
$\underline{U}_B$	Phase-to-earth voltage phasor in phase B
$\underline{U}_C$	Phase-to-earth voltage phasor in phase C
U_c	Declared supply voltage
$\underline{U}_{fA}$	Phase-to-earth voltage phasor at point A in double earth-fault
$\underline{U}_{fB}$	Phase-to-earth voltage phasor at point B in double earth-fault
U_{lvp}	Phase-to-phase voltage in low voltage side
U_m	Voltage-to-earth
U_{mvp}	Phase-to-phase voltage in medium voltage side
$\underline{U}_R$	Receiving end phase-to-earth voltage phasor
$\underline{U}_S$	Sending end phase-to-earth voltage phasor
U_{st}	The step voltage
U_{TP}	Contact voltage
U_v	Phase-to-earth voltage
$\underline{U}'_A$	Phase-to-earth voltage phasor in phase A during an earth-fault
$\underline{U}'_a$	Phasor of the voltage in phase A during a fault
$\underline{U}'_{a1}$	Positive sequence voltage during a fault, phase A
$\underline{U}'_{a2}$	Negative sequence voltage during a fault, phase A
$\underline{U}'_{a0}$	Zero sequence voltage during a fault, phase A
$\underline{U}'_B$	Phase-to-earth voltage phasor in phase B during an earth-fault
$\underline{U}'_b$	Phasor of the voltage in phase B during a fault
$\underline{U}'_{b1}$	Positive sequence voltage during a fault, phase B
$\underline{U}'_{b2}$	Negative sequence voltage during a fault, phase B
$\underline{U}'_{b0}$	Zero sequence voltage during a fault, phase B
$\underline{U}'_c$	Phasor of the voltage in phase C during a fault
$\underline{U}'_{c1}$	Positive sequence voltage during a fault, phase C

$\underline{U'}_{c2}$	Negative sequence voltage during a fault, phase C
$\underline{U'}_{c0}$	Zero sequence voltage during a fault, phase C
$Y_{0(i)}$	The admittance of a single feeder in zero sequence network
$Y_{0(n)}$	The admittance of *n* feeders in zero sequence network
$Y_{0,\pi}$	The corrected shunt admittance in zero sequence network
Y_{π}	The corrected shunt admittance
Z_f	The fault impedance
Z_{th}	The Thevenin’s impedance
Z_{T0}	Impedance of the neutral point equipment in zero sequence network
Z_{T1}	Impedance of the neutral point equipment in positive sequence network
Z_{T2}	Impedance of the neutral point equipment in negative sequence network
Z_{1eq}	Positive sequence network equivalent impedance
Z_{2eq}	Negative sequence network equivalent impedance
Z_{0eq}	Equivalent zero sequence network equivalent impedance
$Z_{0,eq(i)}$	The equivalent zero sequence impedance of a single feeder
$Z_{0,eq(n)}$	The equivalent zero sequence impedance of *n* feeders
$Z_{0(i)}$	The zero sequence impedance of a single feeder
$Z_{0(n)}$	The zero sequence impedance of *n* feeders
$Z_{0,\pi}$	The corrected zero sequence series impedance
Z_{π}	The corrected series impedance
μ_0	The permeability of a free space
ρ	The ground resistivity
φ	The relay tolerance
φ_0	Relay basic angle
$\Delta\varphi$	Phase shift between the voltage and the current phasors

AC	Alternating current
AXAL50	Medium voltage cable, conductor size 50mm^2
AXAL95	Medium voltage cable, conductor size 95mm^2
CAIDI	Customer Average Interruption Duration Index
CENELEC	The European Committee for Electrotechnical Standardization
COHL	Covered over-head line
DC	Direct current
EMC	Electromagnetic compatibility
EMV	Electricity Market Authority (Finland)
HD-637	Harmonization Document 637
HV	High voltage
IEC	The International Electrotechnical Commission

LV	Low voltage
MAIFI	Momentary Average Interruption Frequency Index
MV	Medium voltage
OHL	Over-head line
PEX	Cross-linked polyethylene
RNA/AM	Reliability based Network Analysis/ Asset Management
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SESKO ry	the Finnish Electrotechnical Standardization Committee
SFS	The Finnish Standards Association
TUKES	The Safety Technology Authority (Finland)
XLPE	Cross-linked polyethylene

1. INTRODUCTION

Vattenfall is Europe's fifth largest producer of electricity and the largest producer of heat. Vattenfall operates in the United Kingdom, Denmark, Germany, Poland, Netherlands, Sweden and Finland. The parent company, Vattenfall AB is owned by the Swedish state. This thesis work concentrates on Vattenfall's distribution network business in Finland and in Sweden. These will be referred to as the Nordic countries later in this study.

In Sweden the Vattenfall Eldistribution AB takes care of the electricity distribution within Vattenfall AB. Later in this study this will be referred to as Vattenfall Sweden. Vattenfall Eldistribution AB owns about 115 000 kilometers of electricity network and it has over 850 000 customers. In Finland the corresponding company is Vattenfall Verkko Oy which will be referred to as Vattenfall Finland later in this work. Vattenfall Verkko Oy has 386 000 customers and it owns over 60000 kilometers of electricity network.

In spite of the careful building and maintenance of the electricity network, faults take place from time to time. Most of the faults experienced in the low voltage (LV) network are caused by faults in the medium voltage (MV) network. Therefore minimizing the sources of the faults in MV networks contributes to the quality of delivery also within LV network customers.

The network experiences a short-circuit fault when for example a fallen branch creates a connection between two or three phase lines. An earth-fault occurs when just one phase line is in a conductive connection to earth or connected to a part which has a conductive connection to earth. Fault types will be introduced in more detail in Chapter 2. The great storms Janika and Pyry in Finland and Gudrun showed that customers connected to an over-head line (OHL) network experienced more outages during these storms than customers connected to a cabled network. As a result the network owners started to replace the OHL network with underground cable.

However, cable can be considered as a cylindrical capacitor which means a great increase in capacitive earth-fault current. Cable, as any other transmission line can be represented with a pi-section. In conventional earth-fault analysis the zero sequence series impedance of the pi-section is considered negligible. In rural areas the feeder lengths may be tens of kilometers, which means that the zero sequence series impedance has to be taken also into consideration also. As the zero sequence series impedance consists of reactive as well as resistive parts, it creates a resistive current component into the earth-fault current. Therefore, in addition to the increase in capacitive earth-fault current, the earth-fault current also contains a resistive part. This cannot be compensated with the usage of Petersen coils, which are used to decrease the capacitive earth-fault current. A rise in earth-fault current can be seen as risen touch voltages during an earth-fault. This may cause danger to people or animals if they get in touch with energized network equipment during an earth-fault. A distribution network company has a great responsibility to take care of customer safety by means of network protection. This is also regulated by law.

Extensive cabling also increases the production of reactive power. This may cause problems in cabled networks for example in a situation where the loads are fairly small in a long cabled feeder or when a large load is disconnected from the network. This will cause the voltage to rise at the end of the feeder, which may lead to breakdowns in weakened isolators or cause some network equipment to be damaged. In addition to this, the risen voltages may cause hazards for human safety. The reactive power flow from the distribution network to the high voltage (HV) network is endeavored to keep at zero. Therefore the reactive power should be compensated near the production. Extensive cabling may lead to a need to compensate the reactive power generation with shunt reactors. The cable characteristics and the influence of the extensive cabling will be discussed in Chapter 3.

Nowadays the customers will not be satisfied with electricity alone but they want high-quality and outage-free electricity. Cabling is a good solution but it is not always the most cost effective way of improving the quality of delivery. In principle, improving the quality of delivery indexes (SAIFI, SAIDI and MAIFI) means sectionalizing the feeder into smaller protection areas. This can be done with remote controllable reclosers, which are small protection units installed further in the network.

By using reclosers in OHL and mixed network the number of customers experiencing the outage, caused by the fault, may be reduced by sectionalizing the feeder. This will reduce the SAIFI, SAIDI and MAIFI figures and will, of course, contribute the customer satisfaction. The recloser has basically all the same functionalities as a simple feeder protection relay and with modern communications systems the recloser is easy to control from the operating center. The reclosers are introduced in Chapter 4 together with general protection principles. Chapter 4 also gives an insight to Finnish and Swedish distribution networks. Also the regulators and the regulations in both countries are introduced. When the study introduces some methods used in *Finland* or in *Sweden*, this refers to common practices used within *Vattenfall* in Finland and in Sweden.

The resistive earth-fault current is examined with a simulation program Power System Simulator for Engineering (PSS/E). The modeled network and the calculations are represented in Chapter 5. In Chapter 5 also the example network used in recloser calculation is introduced as well as the calculation methods. The results are introduced in Chapter 6. Based on the results the conclusions are presented in Chapter 7. Chapter 7 gives also recommendations for further study based on the knowledge achieved in this study.

2. FAULTS IN MEDIUM VOLTAGE NETWORKS

In recent decades, the importance of continuity of power supply has increased significantly. Customers will not be satisfied any more only when they get electricity but nowadays people in the energy industry talk about high-quality uninterrupted electricity. Earlier the quality of delivery was not considered as fault dependent but these days the interruption frequency and duration are important aspects of electricity distribution. Especially the distribution network has a significant role in electricity supply. It is estimated that over 90 per cent of the interruptions customers experience are because of different kinds of faults in the MV networks. [1] This chapter introduces first the theory needed for fault calculation and fault analysis. Second, the short-circuit faults and earth-faults are introduced. Protection related issues and protection practices within Vattenfall Distribution Nordic are discussed later in Chapter 4.

2.1. Fault theory

In spite of the careful building, faults take place in the distribution network from time to time. These are usually caused by weather conditions or faults in the network components. [2] The fault situations are seldom symmetrical which is why their handling and analysis require a specific theory. The network behaves differently during each fault, which is why also some mathematical methods are needed in order to receive accurate results. In the following sections the pi-section and the symmetrical components are introduced.

2.1.1. Pi-section

Normally, the loads per phase are assumed to be equal. Therefore transmission lines are analyzed on a per phase basis. A short transmission line can be represented with its series impedance alone. The shunt admittance is negligible, which means that the equivalent circuit is according to the one in Figure 2.1. This model is however accurate only for short transmission lines, which usually are defined as lines less than 100 km. In Figure 2.1 $\underline{U}_S$ and $\underline{U}_R$ are voltages in the sending (S) and in the receiving (R) end, $\underline{I}_S$ and $\underline{I}_R$ are currents in the sending and in the receiving end. $\underline{Z}$ is the line impedance, which consists of resistance R and reactance jX. [3]

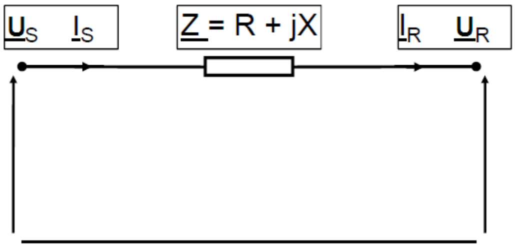


Figure 2.1 *The single-phase equivalent of a short transmission line [3]*

When the transmission line lengths are more than 100 km the model introduced above is not adequate. More accurate results are gained with the usage of pi-section. This model gives also more accurate calculation results for shorter transmission lines and cables, which is why it is used throughout this work. It must, however, be noticed that most of the calculation methods developed to analyze transmission lines are simplifications. Pi-section is illustrated in Figure 2.2. [3] In the pi-section the $\underline{Y}$ is the shunt admittance, which practically means the line capacitance to earth. [4]

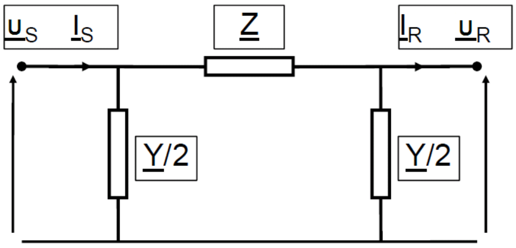


Figure 2.2 *The transmission line represented with a pi-section [3]*

When modeling long overhead lines (OHL) with pi-sections the correction factors must be used in order to model the line correctly. The behavior of the shunt capacitance and the series impedances are non-linear and the usage of correction factors compensates this non-linearity. The correction factors are frequency dependent and easy to calculate for a line examined on a fundamental frequency. If one does not wish to calculate and use correction factors, the model can as well be completed with several pi-connections representing the long line. The correction factors can be calculated according to equations (1) and (2). [4]

$$Z_\pi = Z\frac{\sinh G}{G} \tag{1}$$

$$Y_\pi = \frac{Y}{2} * \frac{\tanh\left(G/2\right)}{G/2} \tag{2}$$

Where

G is the line conductance
Y is the line admittance

Y_π is the corrected shunt admittance
Z is the line impedance
Z_π is the corrected series impedance

2.1.2. The symmetrical components

In normal operating conditions, the electricity network is almost symmetrical. This means that the load impedances and the transmission line impedances are the same in every phase and the phase voltages are equal with 120° phase shift to each other. Because of the symmetry, the network can be described with a single-phase equivalent, which simplifies the network analysis and calculation. If, for example, the current in one phase is calculated, it can be concluded that in normal operating conditions the currents in the two other phases are in the same magnitude with 120° phase-shift to each other. The symmetrical voltage phasors are illustrated in Figure 2.3. In the figure the terms $\underline{U}_A$, $\underline{U}_B$ and $\underline{U}_C$ represent the phase voltage phasors in phases A, B and C. [5]

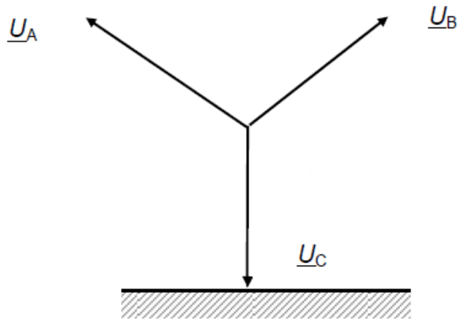


Figure 2.3 *Voltage phasors in normal operating conditions. [5]*

Some of the network faults, however, are not symmetrical and these kinds of faults cannot be described with single-phase equivalents. Asymmetric situations can be described with symmetrical components and sequence networks. Representing the network with symmetrical components is a mathematical method for network calculation where the phasor coordinates are transformed into sequence coordinates. This is shown in Figure 2.4. [4; 5]

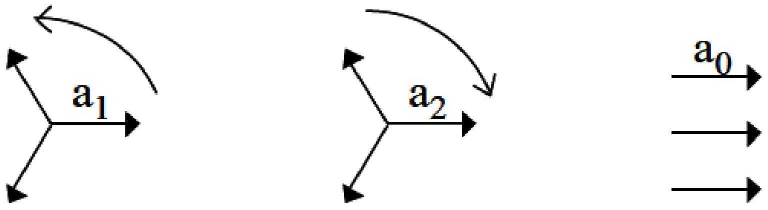


Figure 2.4 *Symmetrical components. Positive sequence network a_1, negative sequence network a_2 and the zero sequence network a_0. [4]*

The idea is that by connecting these sequence phasors, the phasor diagram of the fault can be represented. The asymmetrical phase voltages are thereby formed as a combination of three symmetrical networks. [3] Figure 2.5 shows how the sequence networks are connected when representing an asymmetric fault. In Figure 2.5 $\underline{U}'_{a1}$, $\underline{U}'_{b1}$ and $\underline{U}'_{c1}$ represent the positive sequence network, $\underline{U}'_{a2}$, $\underline{U}'_{b2}$ and $\underline{U}'_{c2}$ represent the negative sequence network and $\underline{U}'_{a0}$, $\underline{U}'_{b0}$ and $\underline{U}'_{c0}$ represent the zero sequence network. The sequence network phasors are drawn in different colors for clarification. Terms $\underline{U}'_{a}$, $\underline{U}'_{b}$ and $\underline{U}'_{c}$ represent the real phase voltage phasors during the fault. [3]

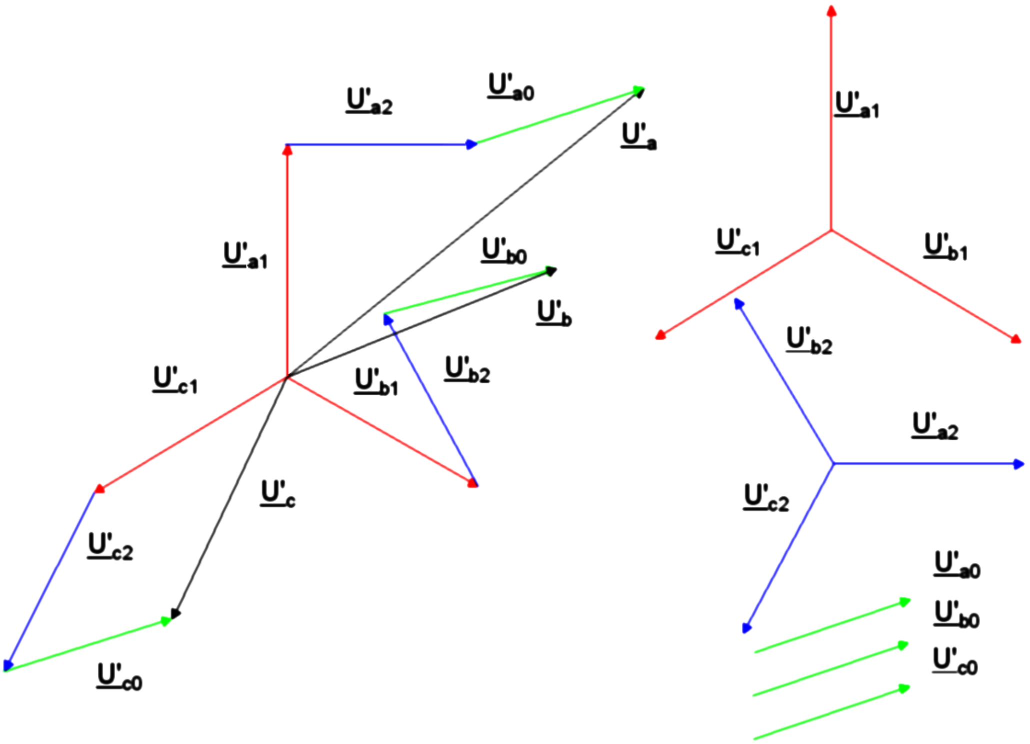


Figure 2.5 *The positive sequence network components (red), negative sequence network components (blue), zero sequence network components (green) and total phase voltage phasors (black) during an asymmetric fault. [3]*

So the three-phased network will be transformed into sequence networks. The sequence networks, on the other hand, can be represented with two-terminal equivalents. All the voltages, represented as U_{1eq}, are generated in the positive sequence network, and the two other networks contain only the equivalent impedances Z_{2eq} and Z_{0eq}. This is shown in Figure 2.6. In the figure U_1 is the phase-to-earth voltage in positive sequence network, U_2 is the phase-to-earth voltage in negative sequence network and U_0 is the phase-to-earth voltage in zero sequence network. Z_{1eq} is the equivalent impedance in positive sequence network. [4]

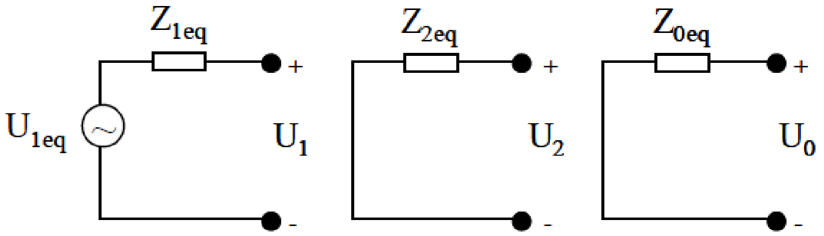


Figure 2.6 *Sequence networks represented as two-terminal equivalents. [4]*

By connecting these sequence network equivalents, the asymmetric fault can be represented as an equivalent coupling of the three sequence networks. This helps the analysis and calculation of the network's asymmetric situations and enables more accurate calculation results. This is illustrated in Figure 2.7 representing a single-phase earth-fault. [4]

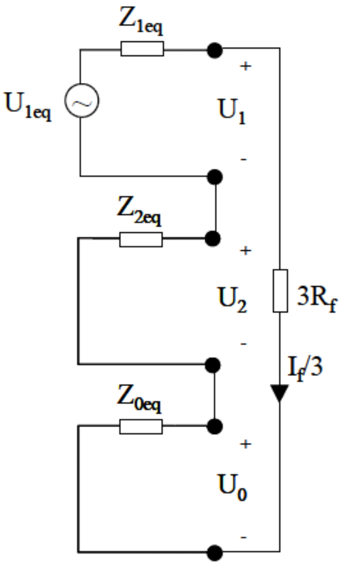


Figure 2.7 *Equivalent coupling of the sequence network equivalents in an earth-fault. [4]*

For three-phase short-circuit fault the single-phase equivalent mentioned earlier, can be used to simplify the calculation but for example with a single-phase earth-faults and two-phase short-circuit faults need to be analyzed with symmetrical components for those are asymmetric faults. Other asymmetrical network situations are cross-country faults, line breaks and asymmetrical loadings. [3; 4]

2.2. Short-circuit faults

A short-circuit fault occurs when two transmission lines have a conductive connection to each other for example through an arc. Short-circuit fault can be either two-phased or three-phased and it can also contain an earth connection. This section introduces the three-phase short-circuit faults. Two-phase short-circuit faults and their characteristics are introduced shortly in Section 2.2.3. The fault types are illustrated in Figure 2.8. [3]

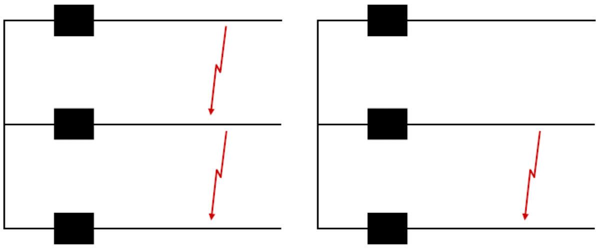


Figure 2.8 *A three-phase short-circuit fault (left) and a two-phased short-circuit fault (right). [3]*

These types of faults are usually caused by weather conditions and isolator faults. The fault current calculation is a significant part of the network planning, because the largest fault currents affect the dimensioning of the network equipment. Manufacturers usually give the highest short-circuit current value, which the devices will endure. Examples of these kinds of equipment are circuit-breakers and switching devices of other kind, which have to be able to break the fault current. [1; 3]

2.2.1. Short-circuit fault current

In order to choose the right components for the network and plan its protection, it is crucial to know the short-circuit current values of the network also with different topologies. The lowest short-circuit current value has to be known so that the protection can be planned to function properly. The relays or the fuses will not detect the fault, if the fault current is under the value needed to trip the relay or the fuse. This is, for example, why it is important in LV network planning to make sure that the short-circuit fault current at the customers' connection point is large enough, so that the main fuse at the connection point will function in case of a fault. The network components must also endure the largest short-circuit current values and therefore the short-circuit calculation is needed in the equipment dimensioning. [1; 3]

As stated in Section 2.1.2 the three-phase short-circuit fault is symmetrical. However, this is the case only when the fault occurs when the voltage reaches its peak value. Otherwise the three-phase short-circuit fault is asymmetrical. In this section the main focus is on the symmetrical faults, but later on when introducing the stages of the short-circuit fault current, the asymmetrical situation is also introduced. [5]

The three-phase short-circuit current can be calculated with the single-phase equivalent according to Thevenin's theorem. It is to be noticed that in this case the magnitude of the fault current is interesting and the phase-angle of the fault current is insignificant, whereas in for example earth-fault calculation the phase-angle is also important. This is why the following equation (3) does not necessarily need to be represented as phasors. [1]

$$I_{k3} = \frac{U_v}{Z_{th} + Z_f} \qquad (3)$$

Where

I_{k3} is the three-phase short-circuit current
U_v is the phase-to-earth voltage
Z_f is the fault impedance
Z_{th} is the Thevenin's impedance

In the equation, Thevenin's impedance Z_{th} represents the total network impedance seen from the fault point. This impedance also contains the impedance of the HV network. In addition to the impedance, there are also other factors that affect the short-circuit current. These are according to the equation (3) the network voltage, the fault type and the loading during the fault although this usually has a minor influence on the fault current. The short-circuit current also depends on the distance from the power station. The further the fault occurs, the smaller the fault current. The typical short-circuit fault current values in the Nordic distribution networks are 5-12kA in the 20kV bus bar. [1; 3]

2.2.2. The stages of the short-circuit fault

As stated earlier, the three-phase short-circuit fault is symmetrical, when it occurs at the time voltage reaches its peak value. When the fault occurs at any other point of the voltage curve, the fault becomes asymmetrical. These two cases are illustrated in Figures 2.9 and 2.10. The asymmetrical short-circuit fault includes current components that the symmetrical fault does not have, which is why it is important to introduce. [5]

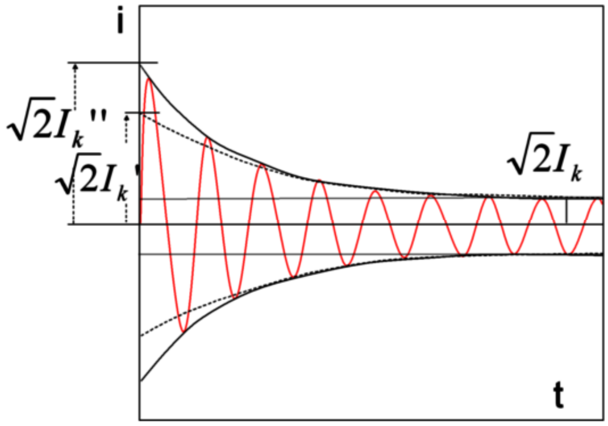


Figure 2.9 *The symmetrical short-circuit current [6]*

Figure 2.9 illustrates a symmetrical short-circuit fault. At the point, where the fault starts, the impedance of the network is at its minimum and the short-circuit current value is at its maximum. This current value in the beginning, the effective value of the sub-transient fault current I_k'', is influenced by the phase voltage value before the fault and the reactance of the synchronous machines, which are small in the beginning of the fault. During the fault, the AC-component of the current damps down to the steady state (effective) value I_k. This phenomenon is noticeable especially near large synchronous machines. The damping is due to the growing reactance of the machines, called transient reactance. The fault current induces into the windings of the machine. This slows down the changing of the magnetic flux in the machine, which again makes the reactance grow. The sub-transient value of the short-circuit current is therefore important to know especially nearby large synchronous machines. [1; 5; 7]

In other parts of the network, where the machines lie further away, the interesting value is the effective value of the transient current I_k'. Transmission lines, for example, are dimensioned to endure this fault current and the circuit-breakers must be capable of breaking this amount of fault current. Also the steady state fault current value is calculated, when calculating short-circuit current values in the distribution network. It is used for example to determine the thermal short-circuit durability of the transmission lines. [1; 6; 8]

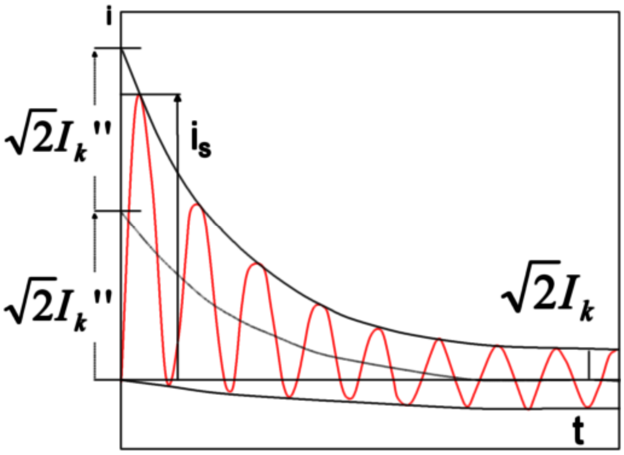


Figure 2.10 *An asymmetrical short-circuit fault [6]*

Unlike a symmetrical fault, an asymmetrical fault contains a damping DC-component in addition to the damping AC-component. The DC-component can easily damage network equipment. The iron core of the transformer, for example, reaches its saturation point easily. In, for example, a current transformer this means that the current is not repeated accurately to the secondary side and the waveform contains distortion like for instance crossover distortion. This is illustrated in Figure 2.11. The saturation of the current transformers may cause problems to the network protection as the relays use the information coming from the current transformers to detect the faults in the network. This is shown as prolonged tripping times. [5, 9]

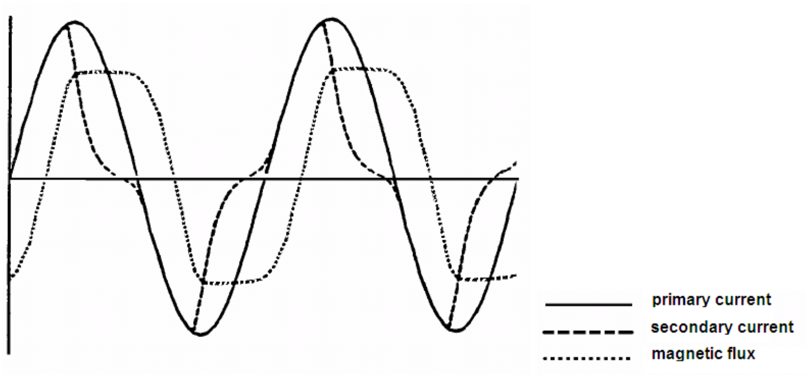


***Figure 2.11** The currents on the primary and the secondary side and the magnetic flux. [9]*

The short-circuit current has thermal effects on the network equipment but also dynamical effects. In Figure 2.10 the term i_s stands for the maximum asymmetric short-circuit current value. It can be written $i_s \approx 2{,}5 * I_k''$. This value determines the mechanical stress the network device experiences and is therefore used for example to determine the dynamical durability of the cables. [6; 8]

2.2.3. Supply voltage dips

Although a three-phased short-circuit faults cause large fault currents, there are also some other disadvantages caused by these types of faults. They also cause supply voltage dips. The standard EN-50160 defines a voltage dip as a "sudden reduction of the supply voltage to a value between 90 % and 1 % of the declared voltage U_c followed by a voltage recovery after a short period of time". In this definition U_c is the declared supply voltage, which usually is the same as the nominal voltage in the network. [1, 10]

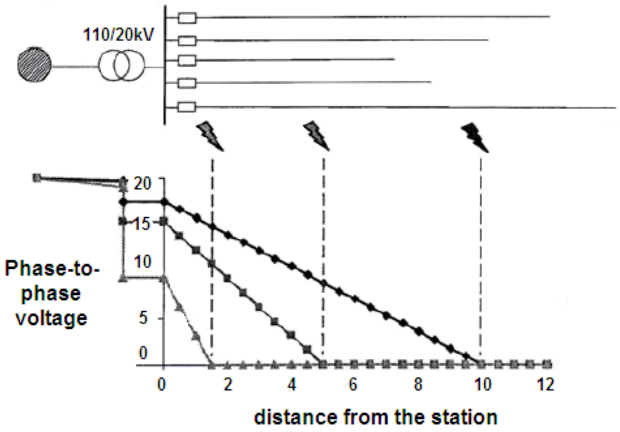


***Figure 2.12** The voltage at the power station during a three-phased short-circuit fault at varying distances from the station. [6]*

Figure 2.12 illustrates the voltage behavior during a short-circuit fault at varying distances from the station. The voltage drops at the fault point and in the network behind the fault point. This drop can also be seen in the bus bar. As the figure shows, the voltage dip in the bus bar is the largest when the fault occurs near the station. This reduction in voltage can be seen also in other feeders, which will of course affect the quality of delivery experienced by the customers. The network company has some possible methods to reduce the harm to customers caused by this fault, but they are not in the scope of this study. [1]

2.2.4. Two-phase short-circuit fault

Whereas the three-phase short-circuit fault near the bus bar causes the largest short-circuit current, the lowest short-circuit current is caused by a two-phase short-circuit fault at the end of the feeder. In a two-phase short-circuit fault two phase lines are connected to each other through some conducting material.

As the two-phase short-circuit fault is an asymmetric fault it can be modeled with using symmetrical components introduced in Section 2.1.2. A more simple way is to calculate the three-phase short-circuit fault current according to equation (3). Because the phase-to-phase voltage is applied over double impedance, the fault current in the two-phase short-circuit fault is $\sqrt{3}/2$ times the fault current in the three-phase short-circuit fault. [1, 11]

2.3. Earth-faults

Earth-fault is a fault in the distribution network in which a phase line is directly connected to earth or connected to a part, which has a conductive connection to earth. In Nordic distribution networks, which are normally either isolated from the earth or high impedance earthed, there is no low-impedance route that the fault current could pass through. So the fault circuit closes through the phase-to-earth capacitances of the surrounding network. This is represented in Figure 2.13. [11]

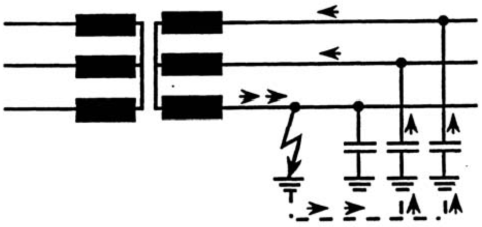


__Figure 2.13.__ Current flow in an isolated network during a single-phase earth-fault. [11]

Usually, an earth-fault is single-phased but it can also be two-phased in which two phase lines are connected to earth but without a short-circuit connection to each other. These are called double-faults. Also a two-phase short-circuit fault with a ground contact is possible. In this study the main focus is on the single-phase earth-fault. The double-faults are also introduced shortly. In Nordic countries the earth-faults are usually, along with the climatic factors, caused by animals, insulator faults and broken or fallen phase lines. [11]

2.3.1. Single-phase earth-fault

In normal operating conditions, the sum of the phases' charging currents through the earth capacitances is almost zero because of the network symmetry, which was discussed in Section 2.1.2. In a symmetric situation the voltages and currents cancel each other out. So there is no zero sequence voltage, which is a sum of phase-to-earth voltages. The same applies for the zero sequence current. Earth-fault, however, is an asymmetric fault because of the voltage drops in the faulty phase. This is shown in Figure 2.14 where the solid earth-fault is in the C-phase and the voltage $\underline{U}_C$ is zero. This, however, is purely a theoretic figure, because usually the fault contains some kind of fault resistance. In the figure $\underline{U}'_A$ is the voltage phasor of the voltage in the phase A during a fault and $\underline{U}'_B$ is the voltage phasor of the voltage in the phase B during a fault. $\underline{U}_0$ is the neutral point displacement voltage phasor. [5]

As seen in Figure 2.13 the charging currents of the healthy phases sum up to the damaged phase passing round the transformer core and to the fault point. From the fault point the sum current flows to the ground. This sum current flowing to the ground is called the earth-fault current I_f. [1; 12]

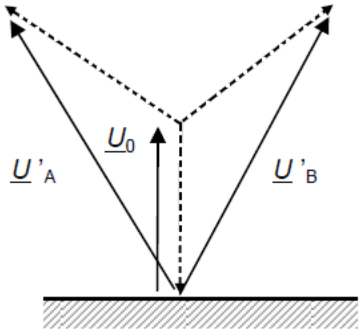


Figure 2.14 *Phase voltages phasors in an asymmetric situation. A solid earth-fault. [5]*

The magnitude of the earth-fault current depends on the total length of galvanic connected feeders. In the traditional urban networks the distance of the fault point from the power station is insignificant because the zero sequence series impedance can be neglected. The shunt capacitance is much larger than the series impedance, which is why in the conventional earth-fault analysis the series impedance has no effect on the earth-fault behavior. The situation changes as the length of the cabled feeders increase, but at this point it is convenient to assume the fault point to be insignificant. [1]

As the length of the networks increases, the earth-fault current increases also. For OHLs the capacitance is approximately 6nF/km per phase and produced earth-fault current 0.067A/km per phase in 20kV network. For ground cables, the magnitude of the earth-fault current depends also on the cable type. The capacitance is approximately 230-360nF/km per phase and the produced earth-fault current 2.70 - 4 A/km per phase in 20kV network. This means that as the cabling increases in rural area networks where the distances can grow up to tens of kilometers, the increase in fault currents has to be noticed. The network earthing method also affects the earth-fault current. These are discussed in Sections 2.3.2 and 2.3.3. [1]

The earth-fault current always encounters some kind of resistance. This resistance is called the resistance to earth R_m. As the current passes through this resistance, it causes a potential difference called voltage to earth U_m. This represents the voltage at the fault point compared with the actual earth potential, which is considered to be lying exceedingly far away. [11] The voltage value can be calculated from the equation (4). [1]

$$U_m = I_f * R_m \tag{4}$$

Where

U_m is the voltage to earth
I_f is the earth-fault current
R_m is the resistance to earth.

In Nordic countries, the specific conductivity of the soil is poor which means that the resistance that the earth-fault current encounters is large. According to the equation (4) voltage to earth can be limited by reducing resistance to earth R_m. This means increasing the network earthing by adding copper, or by decreasing the earth fault current I_f. Due to poor earthing conditions in Scandinavia, decreasing the resistance would become very expensive. This means that the earth-fault current has to be limited in order to limit the voltage to earth. This can be done by galvanic separation of the network into smaller parts, or earthing the network. [1] In practice the galvanic separation means building new main transformers for power stations or whole new power stations, which is not always the most cost-effective solution and therefore network earthing is widely used. How the network is earthed affects the zero sequence impedance, which again influences the earth-fault current. This way the earthing also affects the neutral point displacement voltage. [4]

In Nordic distribution networks there are two kinds of earthing methods mainly used – isolated, which means no earthing at all, and resonant earthed i.e. compensated, which means that the network is earthed through an inductive reactance. These both methods are represented in the following sections in case of a single-phase earth-fault. [1]

2.3.2. Earth-fault in isolated network

How the network behaves during an earth-fault depends on, in addition to the network impedances and capacitances, the earthing system of the network, which is a combination of all the equipment used to control the earth-fault. How the neutral point of the main transformer is earthed, determines the whole network earthing. In this section an isolated network is introduced, which means that the transformers neutral point is separated from the earth. [4]

In an isolated network, there is, theoretically, no conductive connection to earth. This is shown in Figure 2.15. As noted in Section 2.3.1 the earth-fault current I_f depends on the total length of the feeders, it is a sum of the healthy phases' charging currents and it flows from the healthy phases to the fault point, passing around the transformer core. [1] Large fault resistance R_f, which is the total resistance between the line and the earth, decreases the earth-fault current, which makes the earth-fault more difficult to detect. A large fault resistance occurs for example in a case where a tree is leaning on the phase line. Earth-fault current in the isolated network can be calculated with the equation (5). [12]

$$I_f = \frac{\sqrt{3}\omega C_0}{\sqrt{1+(3\omega C_0 R_f)^2}} * U \tag{5}$$

Where

I_f is the earth-fault current
C_0 is the total capacitance to earth
U is the phase-to-phase voltage
R_f is the resistance to earth

When analyzing theoretically a normal operating condition, the phase line capacitances and the voltages are symmetric and the sum of the charging currents is zero, because the charging currents cancel each other out. Thus there is no zero sequence current I_0, which means the current passing through a feeder's cell, and the neutral point displacement voltage, i.e. the zero sequence voltage U_0 are zero. In a real network there is always some small asymmetry, which causes small leakage currents and therefore the zero sequence current and neutral point displacement voltage are only almost zero. During the earth-fault the voltage of the faulty phase reduces, and the voltage of the healthy phases rises in respect to earth. This causes the neutral point displacement voltage to rise. It is to be noticed that neutral point displacement voltage means only the voltage between the networks neutral point and earth, whereas zero sequence voltage refers to the voltage in the other parts of the network. According to conventional earth-fault analysis the amount of the neutral point displacement voltage and zero sequence voltage is the same everywhere in the network. This will be discussed in Chapter 3. For now, only the term neutral point displacement voltage is used to indicate U_0.

The charging currents of the healthy phases have the same kind of behavior as the phase voltages during an earth-fault – current in the faulty phase decreases and currents in the healthy phases rise. [12] In a situation where the fault resistance R_f =0, called a solid earth-fault, the voltage of the faulty phase is zero, and voltage to earth in the healthy phases rise up to the magnitude of phase-to-phase voltage. The voltage at the neutral point rises to the magnitude of phase-to-earth voltage. [1] The neutral point displacement voltage can be calculated with the equation (6). [12]

$$U_0 = \frac{U/\sqrt{3}}{\sqrt{1+(3\omega C_0 R_f)^2}} \tag{6}$$

Where

U_0 is the neutral point displacement voltage

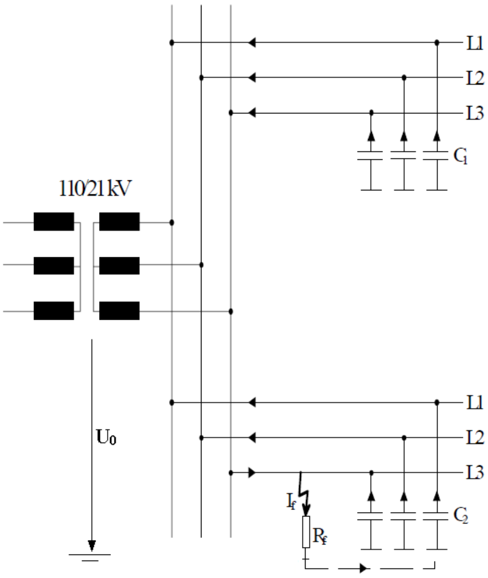


Figure 2.15 *Isolated network. I_f is the earth-fault current, R_f is the resistance to earth, U_0 is the neutral point displacement voltage. C_1 and C_2 represent the capacitances to earth. [11]*

When there is fault resistance, the total equivalent impedance is larger which decreases the magnitude of the earth-fault current and the neutral point displacement voltage. The current has a resistive part according to equation (7). [4] In Figure 2.16 the phasor diagram of earth-fault with fault resistance is represented. [5]

$$I_f = I_r + I_{jc} = \frac{R_f (3\omega C_0)^2 U}{1+(R_f 3\omega C_0)^2} + j\frac{3\omega C_0 U}{1+(R_f 3\omega C_0)^2} \tag{7}$$

Where

I_r is the resistive earth-fault current component

I_{jc} is the capacitive earth-fault current component

This means that the entire phase-to-earth voltage is not applied across the capacitance during an earth-fault. However, the neutral point displacement voltage, despite the fault resistance, differs from zero and the voltages on the healthy phases' may still exceed the pre-fault value. [4]

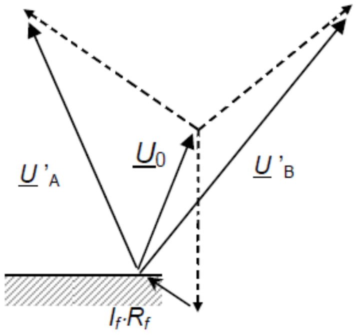


Figure 2.16 *The phasor diagram of an earth-fault with fault resistance* R_f. *[5]*

As noted earlier, the voltage in the faulty phase decreases during an earth-fault, whereas the voltages in the healthy phases increase. The sum of the charging currents is no longer zero, and thus I_0 is no longer zero. In the healthy lines the currents flow towards the power station. The current in the faulty phase flows from the power station towards the fault point. I_0 in the beginning of the feeder can be calculated with the equation (8). [12] Because of the direction - the charging current in the faulty phase is opposite to the sum current - I_0 does not include this part of the earth-fault current. Earth-fault current is capacitive, which means the current precedes the voltage and thus the protection in isolated networks is based on this phase-shift angle, which is 90° with pure capacitive current. [12]

$$I_0 = \frac{C_0 - C_{0f}}{C_0} * I_f \qquad (8)$$

Where

I_0 is the zero sequence current in the faulty phase

C_{0f} is the capacitance per phase of the faulty feeder

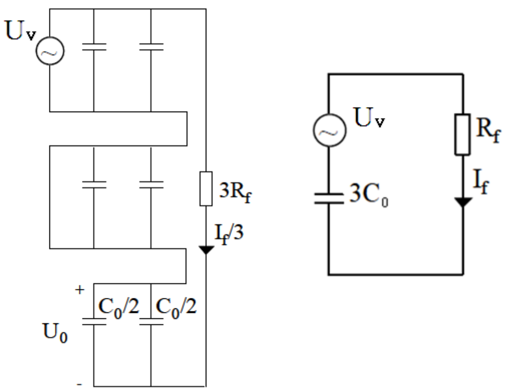


Figure 2.17 The series connection of the sequence networks (left) and The single-phase equivalent for earth-fault in an isolated network (right) where U_v is the phase-to-earth voltage. [4]

The single-phase equivalent of an earth-fault in the isolated network is shown in Figure 2.17 (right). The series impedance is small in comparison with the shunt capacitance of the network, and therefore it does not influence the earth-fault behavior and can be neglected. The series connection of sequence networks is also shown in Figure 2.17 (left). In the figure the phase lines are represented as pi-sections. The current and the neutral point displacement voltage equations represented above can be derived from the equivalent circuit or the sequence network equivalent. [4]

2.3.3. Earth-fault in a compensated network

The problem with an isolated network is that it can only be used when the network capacitance to earth is limited i.e. when the length of the network is limited. This is because of the increase in the capacitive earth-fault current respectively to the total length of the feeders. This capacitive earth-fault current can be compensated with inductive impedance brought to the network's neutral point. This reactor is also called the Petersen coil. [4]

The Petersen coil generates the compensating current. This inductive zero sequence current has an opposite phase-angle to the capacitive current generated by the network shunt capacitances and so they are directed oppositely and therefore cancel each other out. The earth-fault current stays small and the voltages stay at an acceptable level. Usually a resistance is connected in parallel with the Petersen coil to help the earth-fault detection. Compensation can either be centralized (Figure 2.18), which means that a reactor is connected between the main transformers neutral point and earth, or distributed (Figure 2.20), in which case smaller Petersen coils are connected to different parts of the network. [1; 4]

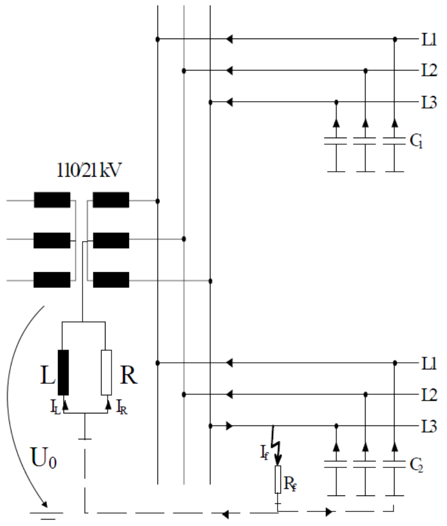


Figure 2.18 *Centrally compensated network. L represents the inductance of the compensation coil and R the resistance connected in parallel with the coil. [11]*

The series connection of the sequence networks is represented in Figure 2.19. The total earth-fault current can be calculated with the equation (9), which is derived from the equivalent. The derivations of the following equations are represented in Appendix 1. [4; 12]

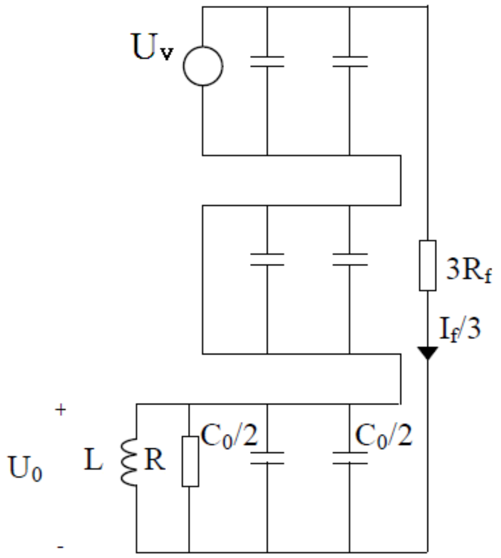


Figure 2.19 *Series equivalent of centrally compensated network. [4]*

$$I_f = \frac{\sqrt{1 + R_0^{\,2}\left(3\omega C_0 - \frac{1}{\omega L}\right)^2}}{\sqrt{\left(R_0 + R_f\right)^2 + R_0^{\,2} R_f^{\,2}\left(3\omega C_0 - \frac{1}{\omega L}\right)^2}} U_v \tag{9}$$

Where

L is the coil inductance
R_0 is the total network zero sequence resistance (neutral point resistance)
U_v is the phase-to-earth voltage

The neutral point displacement voltage can also be derived from the equivalent (Appendix 1) and can be calculated with the equation (10). [4; 12]

$$U_0 = \frac{1}{\sqrt{\left(\frac{1}{R_0}\right)^2 + j\left(3\omega C_0 - \frac{1}{\omega L}\right)^2}} I_f \qquad (10)$$

Because in a compensated system the earth-fault current is not capacitive, the relays are set to measure the active current component. The active current in the network is generated by the lines' impedances and the transformers' impedances but also the small leakage currents. Usually, this active current component is not large enough to facilitate the earth-fault detection and therefore the active current is magnified with a resistance connected in parallel with the Petersen coil. This will be discussed more later on. [4]

The Petersen coil tuning is made to correspond to the capacitive current generated by the network. When the inductive current generated by the Petersen coil is somewhat smaller than the capacitive current, the system is said to be under-compensated and the fault current has a small capacitive component.

On the other hand, when the Petersen coil is tuned to generate more inductive current than the network produces the capacitive current, the system is said to be over-compensated and the fault current has a small inductive component. Usually, the Petersen coil is not tuned to correspond to exactly the amount of capacitive current the network produces. This is because the system might reach its resonance frequency. This means that the capacitive reactance and inductive reactance are equal at some frequency. At this point the current generated by the inductance charges the capacitive network component, and as that component discharges, it produces an electric current which generates the magnetic field into the inductance and the phenomenon repeats itself as long as the resonance frequency is obtained. The resonance in the network causes harmonics, which can cause voltage distortion and the temperature's rising in the network equipment. Resonance can also cause over-voltages, which can, for example, lead to breakdowns in the insulating devices. [13] In Sweden the networks are slightly over-compensated and in Finland the networks are used slightly under-compensated. [4; 9] Usually the Petersen coil is adjusted to be 2-10 amperes under or over-compensated. [14]

The Petersen coil can be fixed or it can be equipped with a tapping switch, in which cases it must be disconnected from the live network for readjustment. It can also be quickly adjustable, which means that the tuning is made step-by-step by connecting capacitors to the auxiliary winding. In continuously re-adjustable reactors the tuning is made by changing the air gap in the reactor. In these latter two cases, the adjustments can be made without disconnecting the reactor from the network. At least a part of the compensation must be adjustable to correspond to the changing network topologies, but not necessarily all reactors. [9] Within Vattenfall the centralized compensation is automatically re-adjustable both in Sweden and in Finland, excluding some networks in Sweden.

Figure 2.20 shows the principle of the usage of distributed compensation. In the figure centralized compensation is bordered with the blue color and it is connected to the main transformer. The distributed compensation units are bordered with red and those are connected to the distribution transformer. The distributed Petersen coils are presented only with their inductance. In practice the coils also include a small resistance.

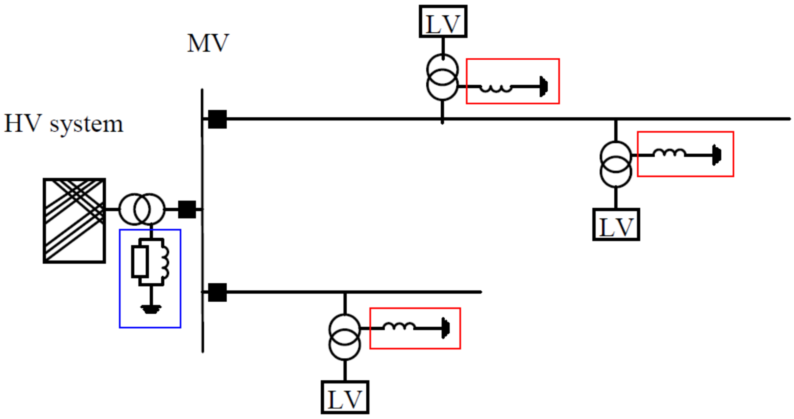


***Figure 2.20** Central and distributed compensation. [15]*

In the distributed compensation, several smaller Petersen coils are connected between the distribution transformers neutral point and earth. This is illustrated in Figure 2.21. The figure presents a Znzn0-coupled transformer with a Petersen coil connected to the MV-side's neutral point. In the figure U_{mvp} is the phase-to-phase voltage in the MV side and U_{lvp} is the phase-to-phase voltage in the LV side.

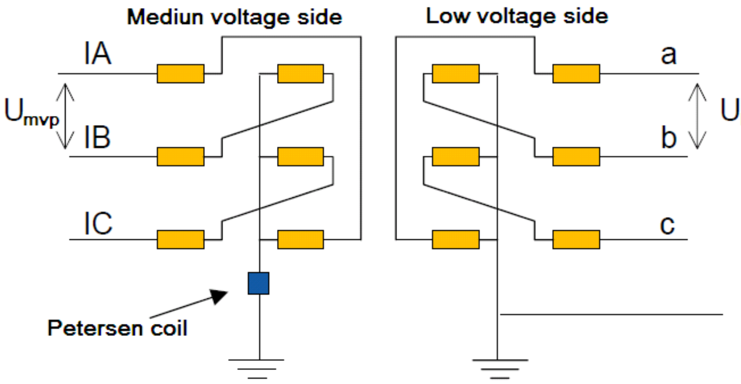


Figure 2.21 *Znzn0-coupled transformer used in distributed compensation. The figure illustrates the connection of the Petersen coil to the neutral point of the MV-side [16]*

With the usage of distributed compensation a part of the capacitive earth-fault current is compensated locally in the network, which decreases the earth-fault current flow through the impedance of the network. The advantages of this will be discussed in Chapter 4.

2.3.4. Arcing earth-faults

In this section two very much similar phenomena are introduced. An arcing earth-fault includes an arc discharging over for example a spark gap. The recovery voltage is discussed which determines, in addition to other factors, whether the arc will re-ignite or not. The other subject, namely intermittent earth-fault is a kind of a repetitious arcing earth-fault at the same fault point, which is mainly a problem in cabled networks. The intermittent earth-fault is discussed after the theory of the single arcing earth-fault is introduced.

A majority of earth-faults in OHL medium voltage networks include an arc discharge. These can cause a problem in isolated networks, but usually in compensated networks the arcs extinguish by themselves. Incorrectly, the common assumption usually is that this is because of the smaller earth-fault current, when in fact the extinction depends mainly on the steepness of the recovery voltage, the smaller earth-fault current and the peak value of the recovery voltage. [12]

When a low impedance earth-fault occurs in an isolated network, the voltage drops in the faulty phase as a result of an arc from the fault point to the earthed network part. This usually causes the circuit-breaker to function, or if the fault current is very small the arc may extinguish by itself at the first zero point of the sinusoidal current transient. After the fault the voltage at the zero sequence network is re-established and the faulty phase is re-energized. This causes a voltage transient which is called the recovery voltage. [17] Depending on the rise velocity of this recovery voltage, the arc may ignite again. Due to the first arc the air in the spark gap is ionized and because in isolated networks this rise velocity of the recovery voltage is steep, the arc re-ignites easily. In an ideal case the time delays of the relays would be long enough for the arc to extinguish again by itself, in which case it would not cause the relay to function. Usually, however, the voltages to earth are the limiting factor, and so the arc must be extinguished faster and thus it requires an automatic reclosing to extinct. Customers experience this as a short power cut and therefore it affects the experienced quality of delivery. [12; 18]

The rise velocity of the recovering voltage is determined by the network's neutral point impedance. In a compensated network the Petersen coil inductance and the parallel resistance slower the rise velocity. Therefore the voltage does not rise as steeply as in an isolated network. [17] So as the arc extinguishes in a compensated network, the recovery voltage does not cause a new arc. Also the longer relay time-delays in compensated networks contribute the self-extinction of arcs and therefore there are not as many reconnections in the compensated networks as in the isolated networks. However, the compensation degree must be over 75% before it affects positively to the amount of reconnections. [12; 19] In addition to a smaller earth-fault current and hence a lower voltage to earth, one of the main reasons distribution companies add centralized compensation into the network, is that the number of reconnections is reduced considerably, which also affects the interruption costs.

The reasons, which cause failures in the network, differ in cabled and in OHL network. In the OHL network the majority of the faults are caused by trees fallen on the phase lines usually due to bad weather conditions. The weather itself is the second largest cause of failures in the OHL network. [20] In general in the cabled networks there are much less failures than in the OHL network, but instead usually the duration of the interruption is longer, because locating the fault is much more difficult. [21] In cable networks the majority of the failures are caused by material failures i.e. ageing failures. Also a great deal of the faults in the cable network is caused by excavation work. Also the component ageing has great significance to load related failures, which are for example insulator failures due to overloads. In the cable network, the phenomenon described above, the arcing earth-fault, may evolve into an intermittent earth-fault, in which the breakdowns start to occur more frequently in the damaged cable, until the ignition frequency may be just a few milliseconds. [20, 22]

Intermittent earth-faults are a problem mainly in the compensated networks in cases where the isolation of the cable is weakened, for example as a result of damages done during the cable installation. [22] In these kind of damaged or weakened cable parts the dielectric characteristics are not enough to resist the electric field intensity and this leads to partial discharges. The voltage level where the arc ignites is called the starting voltage. The arc extinguishes as the current passes its zero point, but ignites again when the level of the starting voltage is reached again. This is because the arc generates a discharge channel into the isolation and the fault becomes permanent. It is to be noticed that these repetitious breakdowns occur in spite of the self-extinction of the arc. The arc extinguishes every time the fault occurs, but as the fault is permanent, the breakdowns are experienced repetitiously. [21]

Intermittent earth-faults are a problem because they are very hard to detect. The arc ignites with a certain voltage level and then extinguishes. As the ignition frequency can be just a few milliseconds, the relay has no time to function and it cannot detect a new fault for a certain time period. [21] Intermittent and arcing earth-faults also have another disadvantage partly due to these difficulties in detecting these faults. In the compensated network the neutral point displacement voltage caused by the fault, decreases more slowly than in the isolated network which is due to the neutral point impedance, which also caused the slower rise of the recovery voltage. The neutral point displacement voltage does not have time to damp because of the dense ignition frequency. When the arc extinguishes, the neutral point displacement voltage starts to drop, but as these breakdowns at the fault point occur more frequently and the neutral point displacement voltage decreases slowly, it has no time to reach zero. Therefore these kinds of repetitious faults can keep the neutral point displacement voltage up. At some point this voltage may reach the level at which the zero voltage relay at the bus bar awakes, and trips all the feeders. This causes outages for several customers, which affects the experienced quality of delivery. In addition to this, the protection does not function selectively. [12; 18; 21] The repetitious breakdowns can cause over-voltages to the healthy phases, which may damage the network devices or cause danger to customers. These over-voltages can also lead to another fault in some other network part. This kind of fault is called a double earth-fault and it is discussed more in Section 2.3.5. [17]

As noted earlier, the transmission lines can be considered as capacitors. With OHLs, the electrodes are the phase line and earth. With cables the capacitance is much larger than in the OHL and it lies between the cable phase line and the cable sheath. This is why in the cabled network the generation of the capacitive earth-fault current is much larger than in the OHL network. [14] Insulation and the cable sheath influence the most on the capacitance to earth. [21]

The charge of the phase-to-earth capacitances starts to unload as the phase gets in contact with earth and the voltage in the faulty phase start to fall towards the earth potential. This causes an oscillating current transient, called the discharge current transient. The frequency range of this transient is 500Hz – 2500Hz but it can reach values around 100 kHz. The discharge current transient damps in just a few milliseconds due to the damping effect of the network resistances and a possible arc discharge. [22]

As the voltage in the faulty phase drops, the voltages in the healthy phases increase. This causes a charge current transient, which usually reaches the frequency range 100Hz-800Hz. [17] The arcing earth-fault and the intermittent earth-fault cause the network's capacitances to charge and discharge repetitiously. The transient caused by this charging and discharging can be detected in the zero sequence current as a high frequency oscillation although the dominating part of the composite transient is the charge current transient. This oscillation can be applied to earth-fault detection in the newest relays. Although it has to be noticed that several other factors in addition to the network extensiveness affect the current transient, such as the fault point, load and the damping caused by the network impedances. [17]

2.3.5. Double earth-faults

Double earth-fault i.e. cross-country fault is a fault in which two different phase lines in the network have a conductive connection to earth, but without a short circuit connection to each other, which means they occur in different parts of the network. A single-phase earth-fault can spread into a double earth-fault because of the risen phase voltages, which can lead to a breakdown or cause an already faulted overvoltage protector to malfunction. Fault currents are usually large, and due to the poor conductivity of the Nordic soil, they go through well conductive routes, such as communications cables, and can therefore cause thermal damages to the cable. [1; 12]

When two phase lines get in touch with the earth, the earth-fault currents can be calculated with equations (11) and (12). [12] There is also a short-circuit component which goes between the fault places. Because of this short-circuit component (13) the earth-fault currents may be remarkably larger than in a single-phase earth-fault in cases where the fault resistance is small. [12]

$$\underline{I}_{fA} = \frac{\underline{U}_{fA} - \underline{U}_{fB} + j3\omega C_0 R_{fB} \underline{U}_{fA}}{R_{fA} + R_{fB} + j3\omega C_0 R_{fA} R_{fB}} \tag{11}$$

$$\underline{I}_{fB} = \frac{\underline{U}_{fB} - \underline{U}_{fA} + j3\omega C_0 R_{fA} \underline{U}_{fB}}{R_{fA} + R_{fB} + j3\omega C_0 R_{fA} R_{fB}} \tag{12}$$

$$\underline{I}_{k} = \frac{\underline{U}_{fA} - \underline{U}_{fB}}{R_{fA} + R_{fB} + j3\omega C_0 R_{fA} R_{fB}} \tag{13}$$

Where

$\underline{I}_{fA}$ is the earth-fault current at fault point A
$\underline{I}_{fB}$ is the earth-fault current at fault point B
$\underline{I}_{k}$ is the short-circuit current component
$\underline{U}_{fA}$ is the phase-to-earth voltage at point A
$\underline{U}_{fB}$ is the phase-to-earth voltage at point B
C_0 is the added capacitance of the whole network
R_{fA} is the fault resistance at point A
R_{fB} is the fault resistance at point B

Figure 2.22 illustrates a situation where two earth-faults occur in two different phase lines. The faults are in the phases S and R. In this case the earth-fault currents can be calculated with equations (11), (12) and (13).

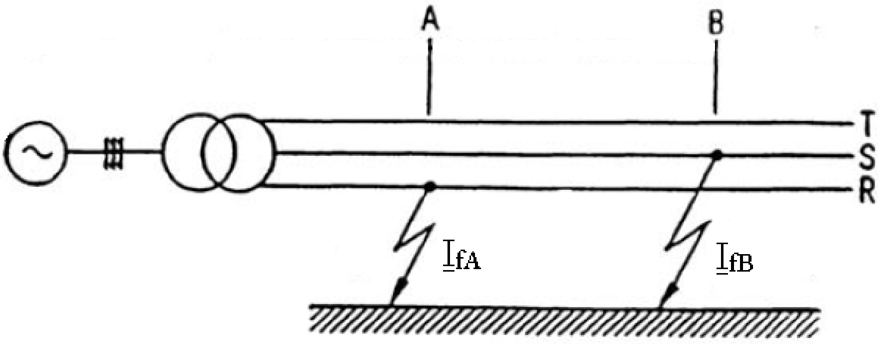


Figure 2.22 *The double earth-fault in which the earth-fault occurs in two different feeders. [11]*

When the fault resistances are unequal and the fault resistance at the other fault point is nearly zero, the earth-fault current is approximately the same as in single-phase earth-fault. The neutral point displacement voltage is the smallest when the fault resistances are equal. The neutral point displacement voltage can be calculated with the equation (14). [12]

$$\underline{U}_0 = \frac{-R_{fB}\underline{U}_{fA} - R_{fA}\underline{U}_{fB}}{R_{fA} + R_{fB} + j3\omega C_0 R_{fA} R_{fB}} \tag{14}$$

It should be noticed that these equations are valid only for faults with large fault resistance. Also other fault impedances in the fault circuit have to be included in the fault calculation if the fault resistance is small. Because the earth-fault current is larger, the fault is easier to detect, but it is also more dangerous. The fault can be detected by the over-current relays because of the short-circuit component although the earth-fault relays may be more sensitive to the fault. [12]

2.3.6. High impedance earth-faults

High-impedance earth-faults occur for example when a broken COHL falls or a tree leans against the phase line. In the former case, a line-fall itself is a fault in the OHL network because in this case the line stays energized and therefore may be dangerous for people or for animals. The fallen line also causes a single-phase earth-fault. When the feeder side of the line falls to earth, the fault resembles a normal single-phased earth-fault. When the load side of the line falls, whereas the feeder side of the line stays above the ground, the fault circuit must close through the load. Because the impedance the load represents is large, the earth-fault current and the neutral point displacement voltage become very small. This does not mean, however, that these kinds of faults should not be switched off. Like any other fault, in spite of the small fault current and small voltages, a high-impedance fault can also cause hazards for human safety and therefore must be detected and switched off. [1; 12]

2.3.7. Earth-fault location

Unlike for the detection of the short-circuit faults, there is no mathematical method for locating an earth-fault. In many cases customer reports help in locating the fault when, for example, a tree is leaning against the phase lines. In addition to this the only used methods for locating the earth-fault nowadays is simply to make experimental reconnections. Usually, this is time-consuming especially if the disconnectors are to be used manually. Usage of remote controllable disconnectors shortens the fault location time. Another disadvantage of experimental connections is that it causes several connections against the fault. This may lead to another fault because of the large connection transients and the risen phase-to-earth voltages in the healthy phases. Also customers experience several outages, which affect the quality of delivery.

Especially high impedance faults are very difficult to detect because the fault current is very small and it is difficult to distinguish from normal leakage currents caused by the natural asymmetries of the network. Faults that include a short-circuit fault in addition to earth contact can be located with numerical methods used in short-circuit fault cases, but just for earth-faults this kind of a numerical method does not exist. [2; 17]

A relatively sensitive fault indicator is the zero sequence relay which observes the changes in neutral point displacement voltage. It has to be noticed, however, that also changes in connection states influence the neutral point displacement voltage. This detection method can only be used as an alarming protection because the zero voltage relay is able to disconnect the whole station from the network if it trips. Also this protection is not capable of distinguishing the right, faulted feeder because it observes the whole stations neutral point displacement voltage, not just one precise feeder. [17]

Nowadays the usage of fault indicators is possible. The fault indicator gives an alarm when the fault current passes through it. Some indicators are even capable of detecting the direction of the fault, which helps the locating. Some indicators are based on the measurement of the magnetic fields caused by the zero sequence current. [17]

In Section 2.3.4 the earth-fault transients were introduced. Transient measurement is one of the promising new methods in earth-fault detection. In Sweden the experiences from transient measurement based fault indicators are good. In Finland within Vattenfall the intermittent earth-fault detection functionality is used as an alarming protection in the newest relays to help the detection of intermittent earth-faults. This measurement is based on comparing the zero sequence current peak values to the fundamental frequency values, and if these values exceed the fundamental values, the signals are processed to indicate the direction of the fault. [23]

2.4. Reliability of delivery

Reliability means that the system is able to perform the tasks, which it is designed for under stated conditions for a certain period of time. For electricity network the term reliability of delivery means the system’s ability to meet its supply function from the customer point of view. [1; 24] According to IEEE 1366 standard reliability of delivery can be described with key figures introduced below [25].

System Average Interruption Duration Index (SAIDI):

$$SAIDI = \frac{\sum_i \sum_j t_{ij}}{N_s} \tag{15}$$

System Average Interruption Frequency Index (SAIFI):

$$SAIFI = \frac{\sum_j n_j}{N_s} \tag{16}$$

Customer Average Interruption Duration Index (CAIDI):

$$CAIDI = \frac{\sum_i \sum_j t_{ij}}{\sum_j n_j} = \frac{SAIDI}{SAIFI} \tag{17}$$

Where

n_j is the number of the customers who experience the interruptions i
N_s is the total amount of customers
t_{ij} is the time without electricity that customers j have to spend because of the interruptions i

In these equations the momentary interruptions, i.e. outages lasting 3 minutes or less, are not taken into consideration. This is why the MAIFI figure is used to measure the short-term interruptions per customer. Along with SAIDI, the SAIFI figure and the short-term interruption figure are also nowadays of interest.

Momentary Average Interruption Frequency Index (MAIFI)

$$MAIFI = \frac{TotalNumberOfMomentaryInterruptions}{TotalNumberOfCustomers} \tag{18}$$

These figures are used for example when placing new remote control disconnectors to see the effect of the equipment. They will also be used later in this study when introducing the network reclosers and the effects they have on the network.

3. CHALLENGES IN EXTENSIVE RURAL AREA NETWORK CABLING

In the beginning of the 21st century, some furious storms raged in the Nordic countries causing a lot of damage. In November 2001 the storms Janika and Pyry hit Finland and as a result over 800 000 customers were left without electricity. Every fourth of these power failures lasted longer than five days. In January 2005 the storm Gudrun hit the Nordic and the most severe damages were caused in Sweden, where over 730 000 customers were left without electricity. The longest power cuts lasted over six weeks. Over 20 000km of distribution network was damaged during the Gudrun storm. [15; 26]

It is clear that in a modern society the lack of electricity hampers the every-day-life greatly. After the experiences caused by the storms Janika and Pyry the Finnish Government made an amendment in 2002 to change the Electricity Market Act so, that in a case of an interruption of system service longer than twelve (12) hours, the Finnish network service user is entitled to a standard compensation. The law to change the Electricity Market Act came in to force in 2003. The law with the same kind of content was passed by the Swedish parliament in December 2005. Obligated by law, in terms of the standard compensations for the customers, and because of the network service providers' experiences of these storms in the Nordic level, they started to replace great amounts of OHL with underground cable. The storms had shown that the underground cables were not nearly as much damaged during the storms as the OHLs. The pace in which the cabling of the rural network has taken place has increased considerably in the past few years. As the characteristics of an underground cable are very different from the characteristics of an OHL, the attention has to be paid to different matters in planning the distribution network. [15; 27] The cable can be considered as a cylindrical capacitor, and thus in the rural networks, where the line distances are relatively long compared to traditional urban network, the usage of an underground cable increases the capacitive earth-fault current considerably. [14] Though as such the earth-fault current may not cause any harm, it can energize some other power system parts. This can lead to hazardous situations if a person or an animal gets in touch with a live network part during an earth-fault. And because the ultimate demand of the distribution network is safety, using long cabled lines in rural networks needs a new kind of evaluation of the network. These features of an underground cable are discussed in the following sections. [4]

3.1. Long cables in rural areas

The storms in northern Europe showed that consumers in rural areas connected to an OHL network experienced a lot more power outages than consumers connected a to distribution network consisting of underground cables. The network owners started to replace the old OHLs with underground cable at an increasing pace. This will eventually lead to a whole new network topology in which the conventional earth-fault analysis cannot be applied. Whereas the traditional urban network consists of relatively short and cabled feeders and the traditional rural network of long OHLs, the new network contains long feeders built with cable. [4]

In Section 2.1.1 the model of a transmission line was introduced. In conventional earth-fault analysis, the dominating factor is the shunt admittance. This means that the series impedance may be neglected for its effects on the earth-fault current are insignificant. However, when the cables are long, the series impedance has to be taken into account. Neglecting the series impedance in case of long cabled feeders can lead to incorrect estimations of earth-fault currents and the neutral point displacement voltage rises caused by the earth-faults. [4]

In *urban networks* the feeders are relatively short and consist of cable. Therefore the network can be considered as a parallel coupling of the feeders, which all are represented as pi-sections. This is shown in Figure 3.1, which represents the positive, negative and the zero sequence networks of a compensated, urban network with four feeders. Z_{T1}, Z_{T2} and Z_{T0} represent the impedances of the neutral point equipment in positive, negative and zero sequence networks. [4]

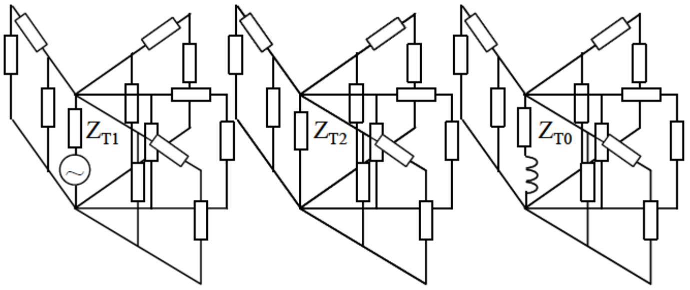


Figure 3.1 *Positive, negative and zero sequence networks of urban distribution network in which the feeders are connected in parallel.* Z_{T1}*,* Z_{T2} *and* Z_{T0} *represent the impedances of the neutral point equipment. [4]*

Now if the cable lengths are the same as in the above picture and they are represented as pi-sections, but are connected in series, the network would look like the one in Figure 3.2. This represents the *rural network* with one long feeder with the same total amount of cable as in Figure 3.1. Figure 3.2 shows the positive, negative and the zero sequence networks of the *rural network.* [4]

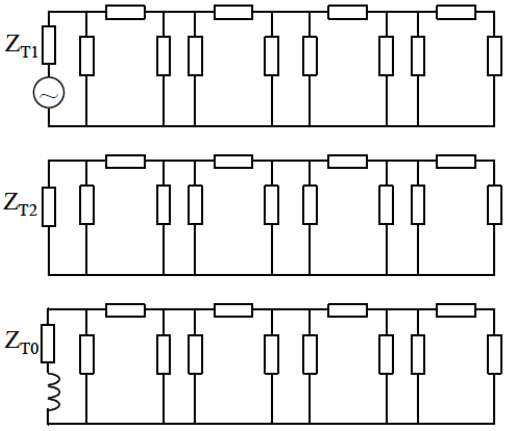


Figure 3.2 *Positive, negative and zero sequence networks of a rural distribution network with the same feeder lengths as in the previous picture, now connected in series.* Z_{T1}, Z_{T2} *and* Z_{T0} *represent the impedances of the neutral point equipment. [4]*

It is to be noticed that in the *urban network* the series impedances are coupled in parallel while in the *rural network* these same series impedances are connected in series. Therefore the series impedance is much larger than in the *urban network* and it has greater impact on the behavior of an earth-fault. [4]

3.1.1. The conventional earth-fault analysis

The conventional earth-fault analysis contains some assumptions. First, the earth-fault behavior is determined by the total cable length. It is therefore insignificant whether the network contains several short or just a few longer feeders. Second, the amount of earth-fault current is proportional to the total cable length. The earth-fault current is purely capacitive, which is based on the assumption that the dominating factor in the earth-fault is the shunt admittance i.e. the capacitance to earth. As introduced earlier, this is because the series impedance is insignificantly small in comparison with the shunt admittance and can therefore be neglected. This second assumption also includes the fact that the earth-fault current is possible to compensate with the usage of Petersen coil. The Petersen coil creates an inductive current to cancel the capacitive current out and the coil can be dimensioned according to the cable manufacturers' data of how much is the cables capacitance per kilometer. The coils resistive losses are only proportional to the inductive current generated by the coil. [4]

In Section 2.3.1 it was introduced that a line-to-ground fault in one phase causes the neutral point displacement voltage to rise. From this, a third assumption is made that in a system where the capacitive earth-fault current is compensated totally with a Petersen coil, the neutral point displacement voltage is determined solely by the fault resistance and the resistance of the Petersen coil. The last assumption is that neither the amount of the earth-fault current nor the neutral point displacement voltage is affected by the fault point i.e. the zero sequence voltage in the network has the same magnitude as the neutral point displacement voltage. [4].

3.1.2. The zero sequence impedance of a cable

The cable zero sequence impedance has been examined rather little because the conventional earth-fault analysis assumes the series impedance to be negligible. Though some manufacturers have published methods to calculate the cable zero sequence impedance, the whole concept is still associated with considerable uncertainties. In this section one of the calculation methods is introduced. This method was developed by Gunnar Henning from ABB Power Technologies. [4]

The cable zero sequence impedance is affected by many network parameters. In addition to cable properties also the earthing resistance in the ends of the cable length, the resistivity of ground, the possible usage of an earthing wire and the distance between an earthing wire and the cable, affect the zero sequence impedance. The impedance also varies as a function of cable length, as the influence of the earthing resistance decreases per cable length. [28]

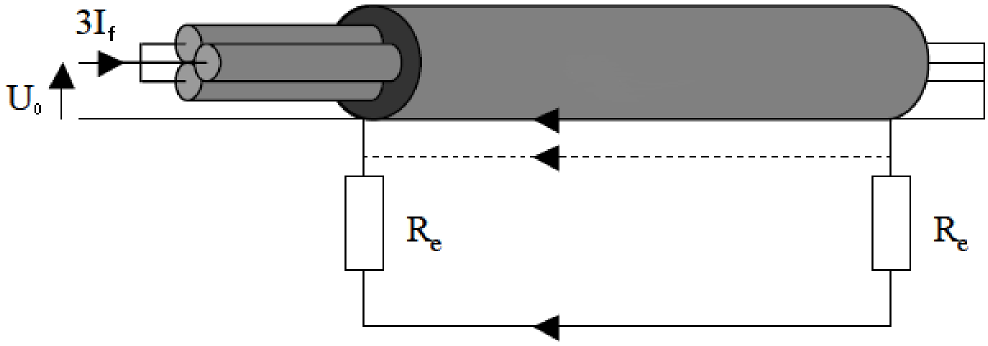


__Figure 3.3__ The model of the current returning paths in cabled network. Return path via earthing wire (dashed) and return path in earth and in cable sheath (solid lines) [28]

The coupling can be considered to form according to Figure 3.3. The current has a return path in the cable sheath and in earth. If an earthing wire is used, the current has a return path also in the wire as well. In the figure above the earthing wire is illustrated with a dashed line. The cable sheath is connected to earth via earthing resistance R_e. The voltage source in the sending end is connected between the phase lines and the return path. This end is also connected to earth via earthing resistance R_e. Each of these current circuits creates self and mutual impedances which influence the total zero sequence impedance of the cable. [28]

As mentioned earlier the cable characteristics also influence the zero sequence impedance of the cable. In Figure 3.4 the cable dimensions are introduced. In the figure r_s is the radius of the cable, r_c is the radius of the conductor and d is the distance between the conductors. [29]

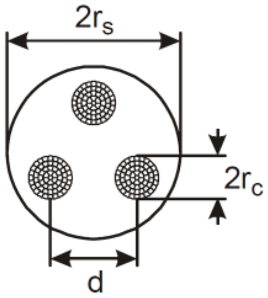


Figure 3.4 *The cable dimensions [Anders]*

In this study the cable zero sequence impedance is calculated with ABB formula (19) for high voltage cables developed by Gunnar Henning. In the formula it is assumed that the current return path is in sheath and in earth. [30]

According to studies initiated by Anders Vikman in Vattenfall Eldistribution AB, the affect of an earthing wire can be modeled simply by roughly halving the zero sequence resistance given by the ABB equation, whereas the zero sequence reactance should be multiplied by two. The cable zero sequence impedance is affected by many things and in order to calculate it with the knowledge achieved up to this point, some simplifications have to be made. Therefore it is convenient to assume the zero sequence resistance is to be half of the calculated value when using the earthing wire, according to Vikman's calculations. The studies were commissioned to the consult organization STRI AB and the calculations were made with the program MULTS.

$$Z_0 = l\left(R_c + 3\frac{j\omega\mu_0}{2\pi}\ln\frac{r_s}{\sqrt[3]{r_c'{*}d^2}}\right) + \frac{3lR_s\left[R_{e1} + R_{e2} + l\left(R_g + \frac{j\omega\mu_0}{2\pi}\ln\frac{D_e}{r_s'}\right)\right]}{R_{e1} + R_{e2} + l\left(R_s + R_g + \frac{j\omega\mu_0}{2\pi}\ln\frac{D_e}{r_s'}\right)} \tag{19}$$

Where

D_e is the equivalent penetration depth [m]
l is the cable length
r_c' is the geometric mean radius of a conductor
R_{e1} is the earthing resistance of the grid at the 1st end of the cable
R_{e2} is the earthing resistance of the grid at the 1st end of the cable
R_g is the ground resistance [Ω/m]
R_s is the sheath resistance
r_s' is the geometric mean radius of sheath
μ_0 is the permeability of a free space
ω is the angular velocity

The equivalent penetration depth can be calculated with Carson’s formula (20).

$$D_e = 659 * \sqrt{\frac{\rho}{f}} \tag{20}$$

The ground resistance R_g is calculated with the equation (21).

$$R_g = \frac{\omega \mu_0}{8} \tag{21}$$

Where

f is the frequency [Hz]
ρ is the ground resistivity [Ωm]

It is necessary to understand that the zero sequence impedance of a cable is not an unambiguous matter. The values might be different depending on which kind of presumptions are made. Though there are some models to evaluate and calculate the zero sequence impedance it has never been measured in real field tests. That is why it has not yet been confirmed whether the models with simplifications of a certain kind are truly valid in the zero sequence calculation. In real networks, for example, the cable might have earth connections also along the line. The line may not be earthed only at the distribution transformers but also for example in cable joints. This has an impact on the zero sequence impedance. The fact that the zero sequence impedance also reaches different values in terms of the cable length has to be taken into consideration. Some research has been done regarding this matter. The results show that for cables of certain lengths the zero sequence impedance varies very little which is why it can be approximated as constant depending only on the cable length. Yet this is not measured in a real network. In the lack of real measured data, the calculation has to be based on some simplifications and assumptions. With the knowledge achieved so far, calculations with these simplifications give fairly good results for understanding the behavior of an earth-fault in a cabled network. [4, 31]

3.1.3. Cable zero sequence impedance as a function of cable length

As shown in Section 3.1 the *rural network* has a different structure than the one applicable in conventional earth-fault analysis. Whereas in *urban network*s the feeders with a certain length are connected in parallel, in *rural network*s one feeder with the same total length consists of pi-sections connected in series. Anna Guldbrand from Lund University has examined the influence of the feeder length on the zero sequence impedance. For a 10kV network the results were as represented below in Figures 3.5 and 3.6. The figures show the influence of the feeder length on the absolute impedance value and the argument depending on how the line is modeled. It is to be noticed that the absolute value of the zero sequence impedance is not affected noticeably by the feeder length. However, the growth of the feeder length changes the impedance argument, which means that the angle of the impedance changes. This shows that earth-fault current also contains a resistive component in addition to the reactive component. This also proves that the conventional earth-fault analysis, which assumes the earth-fault current to be solely capacitive, is insufficient for analyzing networks containing long, cabled feeders. Although, in these studies have been made for the 10kV network, it is reasonable to assume that the same applies also for the 20kV networks. [4]

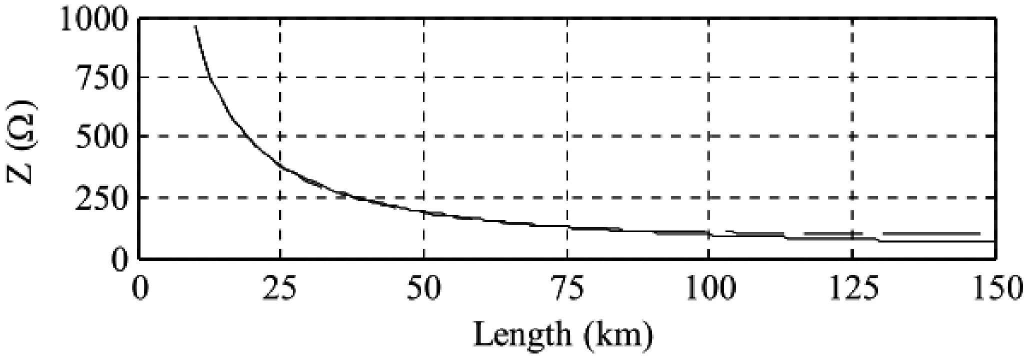


Figure 3.5 *Absolute value of the zero sequence impedance with varying cable lengths when cable modeled by pure capacitance (solid) and pi-sections (dashed). [4]*

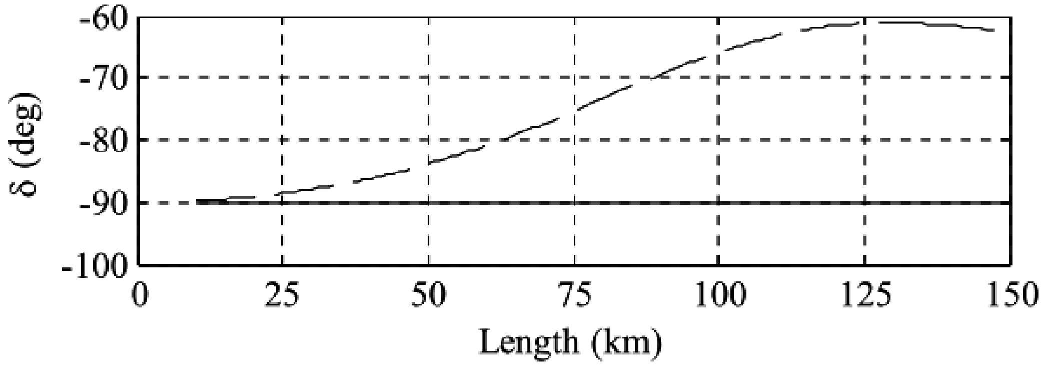


Figure 3.6 *Argument value of the zero sequence impedance with varying cable lengths when cable modeled by pure capacitance (solid) and pi-sections (dashed). [4]*

As explained in Section 2.1.1 the reactive impedances behave non-linearly depending on the feeder length and the electrical characteristics of the phase line material. Correction factors are used to compensate the non-linear behavior. Since the cable characteristics differ from the OHL characteristics, the non-linear behavior of the shunt capacitance and the series inductance also influence the earth-fault behavior. In Figures 3.7 and 3.8 this influence is illustrated as a function of feeder length. [4]

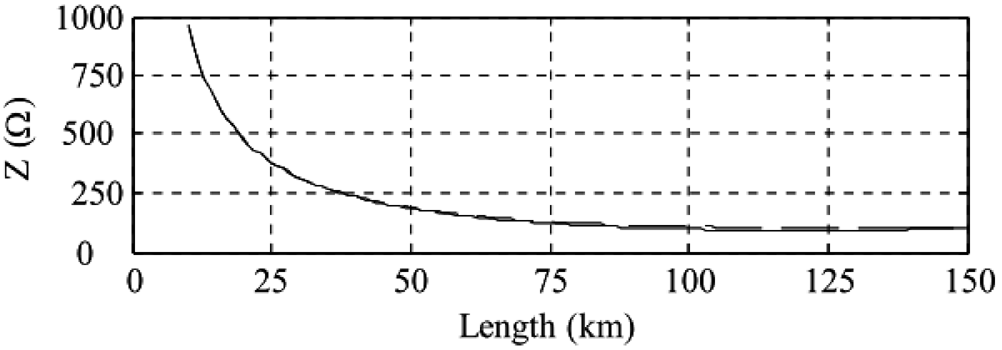


Figure 3.7 Absolute value of the zero sequence impedance with varying cable lengths when cable modeled by pi-sections with (solid) and without (dashed) correction factors. [4]

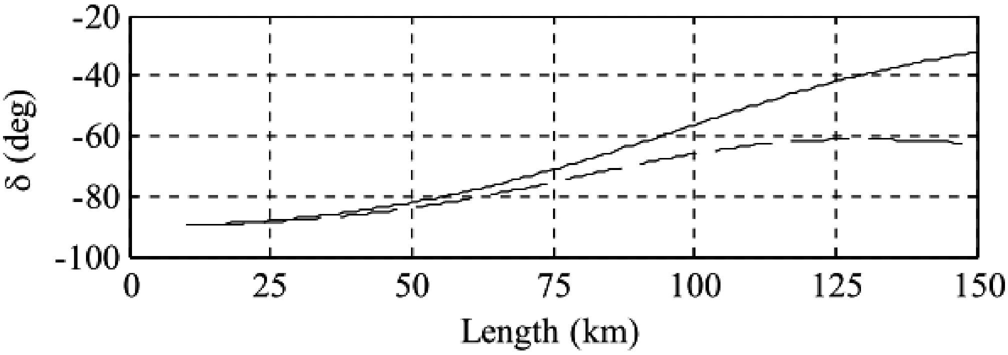


Figure 3.8 Argument value of the zero sequence impedance with varying cable lengths when cable modeled by pi-sections with (solid) and without (dashed) correction factors. [4]

As can be seen from Figure 3.7, the correction factor influence on the absolute value of the zero sequence impedance is insignificant. On the other hand, the correction factors influence the impedance argument as seen in Figure 3.8. According to the figures it can be stated that the usage of correction factors is not necessary with cable lengths under 40 kilometers. Another method to compensate this non-linearity is to model the transmission line with several pi-sections. [4]

3.1.4. Sequence network coupling – a bus bar fault

When examining an earth-fault in a bus bar of an urban system, it can be noticed that the total impedance of the network is smaller than the impedance of an individual cable. This is shown in the equations below. The impedance of a short individual cable consists of two considerably large shunt capacitances and one relatively small series impedance as shown in the equation (22). When *n* short cables are connected in series as in urban systems, the equivalent impedance is one *n*th part of the total impedance, which is shown in the equation (23). Therefore both series impedance and the shunt capacitances are one *n*th part of the impedances and admittances of an individual cable. This is represented also in Figure 3.9. [4]

$$Z_{0,eq(i)} = \left(\frac{1}{Y_{0,\pi}} + Z_{0,\pi}\right) // \frac{1}{Y_{0,\pi}} = \left(\frac{2}{j\omega C_{0,i}} + R_{0,i} + j\omega L_{0,i}\right) // \frac{2}{j\omega C_{0,i}} \quad (22)$$

$$Z_{0,eq(n)} = \frac{Z_{0,eq(i)}}{n} = \frac{1}{n}\left(\frac{2}{j\omega C_{0,i}} + R_{0,i} + j\omega L_{0,i}\right) // \frac{1}{n}\frac{2}{j\omega C_{0,i}} \quad (23)$$

Where

$C_{0,i}$ is the capacitance of a single feeder
$L_{0,i}$ is the inductance of a single feeder
$R_{0,i}$ is the resistance of a single feeder
$Y_{0,\pi}$ is the corrected shunt admittance in zero sequence network
$Z_{0,eq(i)}$ is the equivalent zero sequence impedance of a single feeder
$Z_{0,eq(n)}$ is the equivalent zero sequence impedance of *n* feeders
$Z_{0,\pi}$ is the corrected zero sequence series impedance

If the length of an individual feeder is limited, which is the case when talking about *urban network*s, the zero sequence series impedance is negligible in comparison with the shunt capacitance. This is because the relation between the zero sequence series impedance and shunt admittance is equal to the relation of an individual feeder. Moreover when the zero sequence series impedance is negligible, it causes no voltage drops in the zero sequence network. Therefore the zero sequence voltage is the same throughout the network i.e. the neutral point displacement voltage in the networks neutral point and the zero sequence voltage in the other parts of the network are the same. The positive and the negative sequence networks can be neglected. [4]

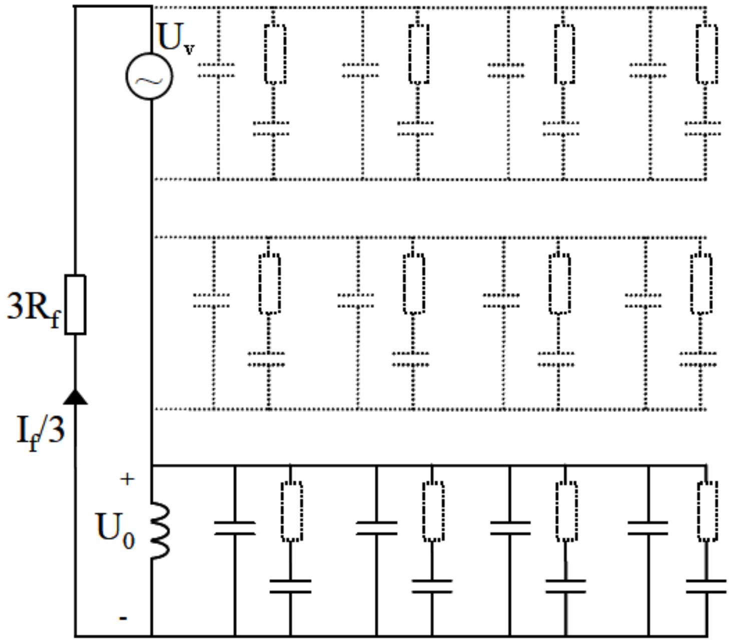


Figure 3.9 *The coupling of the urban network during a bus bar earth-fault.* I_f *is the earth-fault current,* R_f *is the fault resistance,* U_0 *is the neutral point displacement voltage and* U_v *is the phase-to-earth-voltage. [4]*

However, this is not the case when the feeder length is not limited. A single long radial can be considered as a series connection of pi-sections as introduced in the beginning of Section 3.1. As the pi-sections are connected in series, the zero sequence series impedances are connected in series according to the equation (24), unlike in an *urban network*. The total zero sequence series impedance is therefore *n* times the zero sequence series impedance of a single pi-section. The shunt admittance is one *n*th part of the shunt admittance of a single pi-section. This is shown in the equation (25). The series impedance and the shunt admittance can be modeled by using the correction factors or by using several pi-sections. The positive and the negative sequence networks can be neglected. [4]

$$Z_{0,eq(i+1)} = \left[\left(Z_{0,eq(i)} \, // \, \frac{2}{j\omega C_{0,i}} \right) + R_{0,i} + j\omega L_{0,i} \right] // \, \frac{2}{j\omega C_{0,i}} \tag{24}$$

$$\begin{aligned} Z_{0(n)} &\approx nZ_{0(i)} \\ \frac{1}{Y_{0(n)}} &\approx \frac{1}{nY_{0(i)}} \end{aligned} \tag{25}$$

Where

$Y_{0(i)}$ is the admittance of a single feeder in zero sequence network

$Y_{0(n)}$ is the admittance of n feeders in zero sequence network
$Z_{0(i)}$ is the zero sequence impedance of a single feeder
$Z_{0(n)}$ is the zero sequence impedance of n feeders

According to the equation (25), the shunt capacitance decreases as the length of the cable increases, whereas the zero sequence series impedance increases. Therefore the zero sequence series impedance is not necessarily negligible. The non-negligible series impedance causes a resistive component to the earth-fault current which cannot be compensated with the usage of Petersen coil. The zero sequence current also causes voltage drops over the non-negligible zero sequence series impedances. Therefore the zero sequence voltage is not the same throughout the network. During a solid earth fault at the bus bar the neutral point displacement voltage is in the magnitude of the pre-fault phase-to-earth voltage. Because of the zero sequence voltage drops in the network, the zero sequence voltage at the end of a single radial feeder may vary depending on the network structure. The zero sequence voltage at the end of the feeder, and the phase angle as a function of feeder length are represented in Figures 3.10 and 3.11. The figures are also for the 10kV network examined by Anna Guldbrand, but it is to be assumed that the same kind of behavior can be discovered in the 20kV networks. [4]

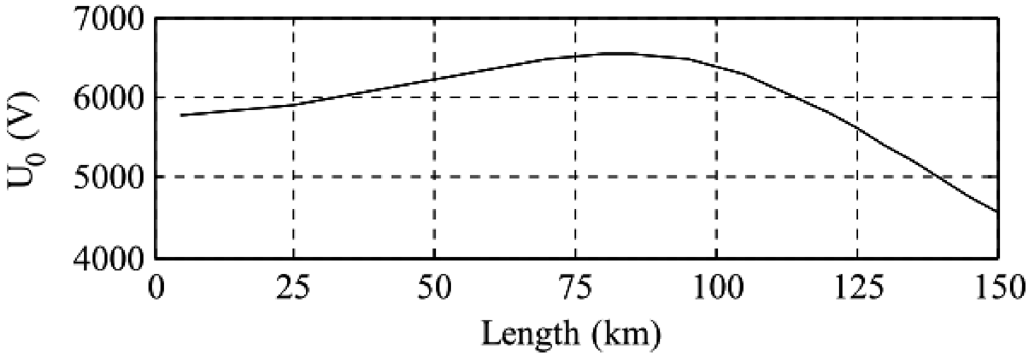


Figure 3.10 *The zero sequence voltage at the end of the feeder during a bus bar fault, in respect to feeder length. [4]*

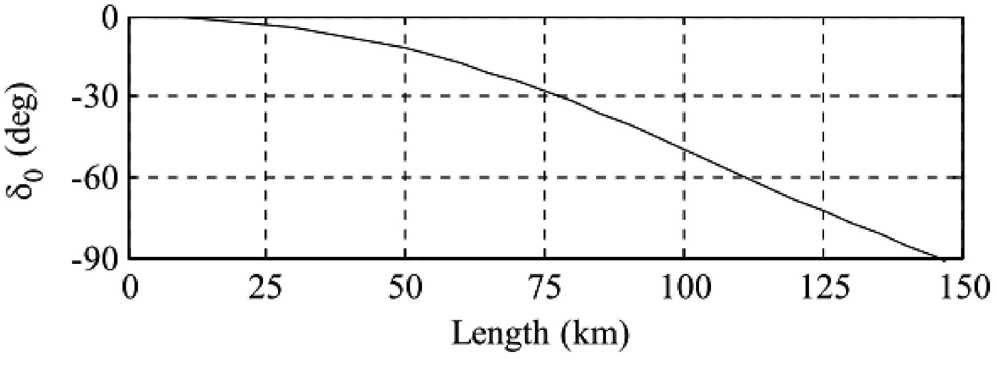


Figure 3.11 *The phase-angle of the zero sequence voltage in respect to cable length. [4]*

It is to be noticed that because the voltage drop has a real as well as imaginary part (the cable zero sequence series impedance consists of resistive and reactive parts), the voltage at the end of the feeder may not necessarily be smaller at the end of the feeder but may also be slightly larger than in the bus bar. [4]

3.1.5. Sequence network coupling – an end of the line fault

When the fault is at the end of the feeder in an urban system, the equivalent coupling of the sequence networks is like in Figure 3.12. The series impedance is negligible and the positive and the negative sequence networks can be neglected. The fault location does not influence the earth-fault behavior, because the equivalent impedance is purely capacitive and there are no voltage drops along the feeder. The situation is similar to the bus bar fault case in an *urban network.* [4]

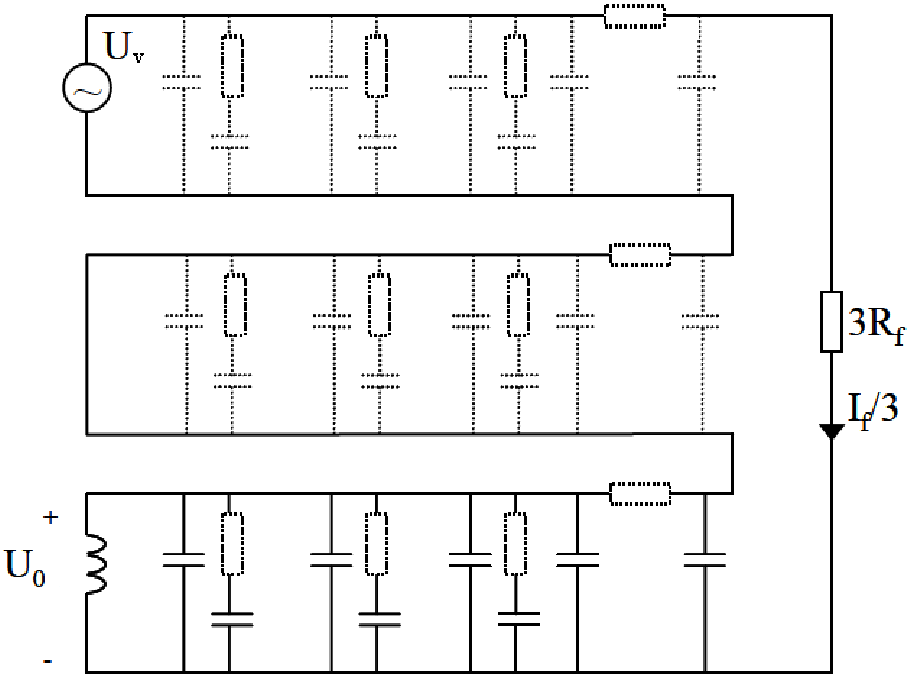


Figure 3.12 *The coupling of the sequence network when the fault is at the end of the feeder in urban network. [4]*

If the fault is at the end of the line in a *rural network*, the equivalent coupling of the sequence networks is like the one presented in Figure 3.13. As can be seen from the figure also the positive and the negative sequence networks are connected to the zero sequence network unlike in the case in which the fault was at the bus bar. From this follows that the voltage drops in the positive and in the negative sequence networks influence the zero sequence voltage at the fault point. This means that the zero sequence voltage at the fault point differs from the pre-fault phase-to-earth voltage value. As the zero sequence series impedance is non-negligible, the voltage drops also over the zero sequence series impedances. Therefore the neutral point displacement voltage differs from the zero sequence voltage at the fault point. The voltage drop over the zero sequence series impedances depends on the magnitude of the zero sequence current and the phase-angle of the current in addition to the magnitude of the equivalent zero sequence series impedances. Therefore also the network topology and the fault location affect the earth-fault behavior. [4]

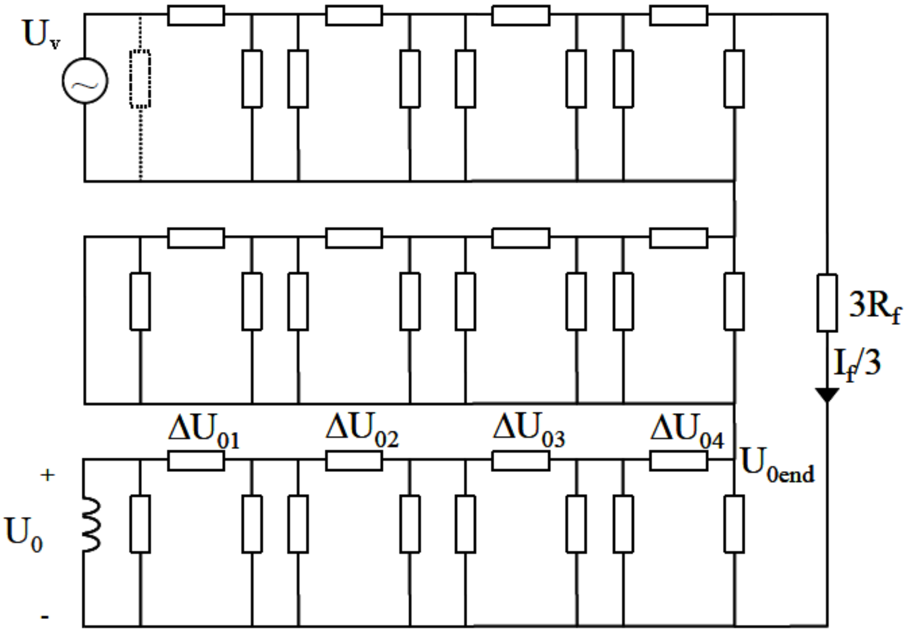


Figure 3.13 *The coupling of the sequence networks when the fault is at the end of the feeder in a rural area network. [4]*

The compensative current is produced at the bus bar by the centralized Petersen coil. The magnitude of the inductive current generated by the coil is determined by the neutral point displacement voltage, which according to the conventional earth-fault analysis is determined by the fault resistance and the neutral point resistance only in a tuned system. This leads to an assumption that the Petersen coil can be dimensioned according to the known earth-fault current produced by the cable and the only resistive losses are due to the neutral point resistance and the Petersen coil losses, which again are proportional to the generated inductive current. [4]

From the previous examples it can be noticed that the earth-fault current is not solely capacitive and the zero sequence voltage varies in rural area networks depending on the feeder length and the network structure. Therefore the Petersen coil cannot be dimensioned without taking the fault location into consideration. If the coil is dimensioned using the conventional assumptions, the capacitive and the inductive current may not correspond as planned. Additionally if the coil is dimensioned to correspond to a fault in the bus bar, the earth-fault current is compensated differently if the fault is somewhere else in the network. [4]

During an earth-fault at the end of a long, radial feeder the positive and the negative sequence networks affect the earth-fault behavior. The fault current is smaller when the fault is at the end of the feeder, and the voltage drops over the series impedances in positive and in negative sequence networks reduce the voltage at the fault point. From this follows that as the cable length increases, the voltage at the fault point decreases. Now as the zero sequence voltage also drops over the non-negligible zero sequence series impedances, the neutral point displacement voltage may be considerably smaller than the zero sequence voltage in the fault point especially with cables that have a large resistance. This may lead to difficulties in detecting high impedance earth-faults because the real neutral point displacement voltage at the bus bar, from where the relay gets the information, is smaller than the expected voltage. When the system consists of a branched feeder the effects on the earth-fault behavior are somewhat similar to the effects in the case of a radial feeder, but less severe. [4] It must, however, be kept in mind that all these features represented in this section depend on the cable characteristics.

During a bus bar fault, the load has no influence on the earth-fault behavior. This means that the positive and the negative sequence networks are negligible. During the end of the line fault, however, the positive and the negative sequence networks are connected to the zero sequence. The level on which the load influences the earth-fault depends on the load size and the phase of the load impedance, the fault impedance and the system structure as well as the neutral point equipment impedance. The larger the current is in the positive sequence network the larger the voltage drop across the positive sequence network series impedances. From this follows that the zero sequence voltage at the fault point is smaller and the fault current is also affected. If the fault impedance is large, the earth-fault current will not be largely affected by the load. The earth-fault current may also vary depending on the cable characteristics and the network structure. [4]

It is to be noticed, that the assumption used in conventional earth-fault analysis cannot be applied when the network consists of long underground cables. The earth-fault behavior in *rural network*s differs from that of a system with several short feeders, and that is why the new analysis is needed. In addition to these factors which change tremendously the conventional earth-fault analysis, one critical observation has to be made – the resistive earth-fault current cannot be compensated with the usage of Petersen coils. This may cause danger to humans and to animals. Why the earth-fault current is dangerous to people, is discussed in Section 3.2.

3.1.6. Resonance in rural area networks

It is also convenient to discuss resonance. In compensated networks the coils are rarely perfectly tuned to match the capacitive current produced by the shunt capacitance of the network. This is because in perfectly tuned systems there is a danger of reaching the resonance frequency. This would lead to an increased neutral point displacement voltage during normal operating conditions. [32]

In traditional OHL networks the feeder lengths, in which the fundamental frequency resonance is reached, are extremely long. That is why the fundamental frequency resonance in OHL networks is rarely of practical interest. The resonance length is determined by the line characteristics, and as the cable characteristics are very different from the characteristics of an OHL, the resonance lengths are therefore different from those of the OHLs'. [4]

Although the fundamental frequency resonance in cabled network is achieved with considerably shorter feeder lengths, it is not of practical interest because the lengths are still fairly long. The resonance in harmonic frequencies, however, is an issue worth considering. Because of the charging and discharging characteristics of the cable and the Petersen coil, the cabled and compensated networks experience harmonics more frequently than the OHL network. Studies made by Anna Guldbrand from Lund University showed that in 10kV networks the 300Hz resonance is achieved only with cable lengths of 20-30km while in traditional OHL lines the resonance length is 200km. In these cases, the lines are considered lossy, which also affects the resonance length. According to an estimation considering the line as lossless when defining the resonance length may lead to errors of 60% in case of a cabled network. [4]

3.2. Growth of the earth-fault current

From the network operator point of view switching off the earth fault is not critical. This is because in the network, earth-fault can be seen as a voltage reduction in the faulty phase and as a voltage rise in the healthy phases. Although there is asymmetry in the network, the phase-to-phase voltages, as well as the load currents, in the secondary side of the low voltage transformers stay normal due to the delta-star –connection. Therefore the fault is not necessarily noticed by regular customers. The fault current may also be small enough not to damage the equipment. [1] Anyhow, the rise in voltage to earth can cause dangerous situations if a person or an animal gets in contact with the energized network parts. These are the network parts, which in normal operating conditions are earthed, but which become energized as the risen zero sequence voltage is applied over the network components and the normally earthed parts.

The voltage a person experiences is a part of the voltage to earth and is called the contact voltage U_{TP}. [5] A rise in voltage to earth in medium voltage networks is reflected as a rise of contact voltage even in the low voltage network and can therefore cause danger to regular customers. [1] According to IEC-standards 95% of the population has a body impedance of 1050Ω assuming the contact areas are large and the voltage applied over person's body over 1000V. The body impedance, however, is non-linear. As the applied voltage is 100V, 95% of the population has a body impedance of 3125Ω. [4]

The voltage to earth, the contact voltage and step voltages are represented in Figure 3.14. The line V represents the potential rise close to the energized network part. The figure shows how the voltage is applied through the human body when touching or standing near the energized network part. When, for example, standing near an earthing electrode, the potential difference between persons' feet may cause an electric shock. This is called the step voltage $U_{st}i$, and it is caused by the varying earth potential near the electrode. [5]

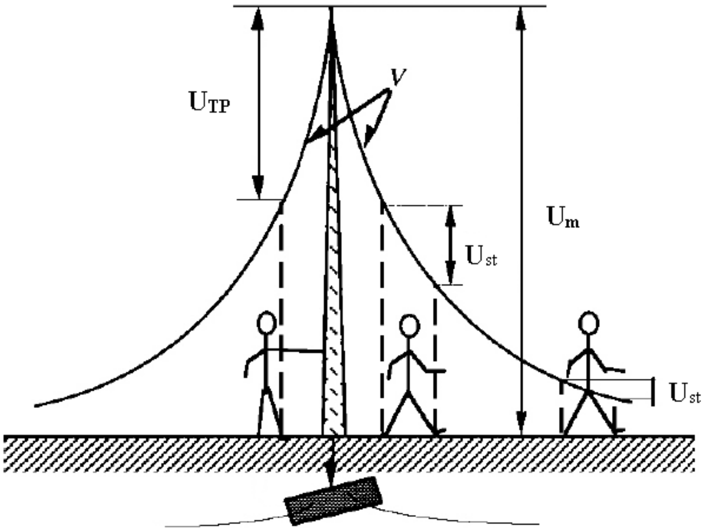


Figure 3.14 *The potential rise near the energized network part.* U_{st} *is the step voltage,* U_{TP} *is the contact voltage and* U_m *the total voltage to earth. [5]*

When there is an earth-fault in the network, the voltage is applied from the network neutral point to the ground. This voltage depends on the fault resistance and also on the fault point and the network structure as was presented in previous sections. It is crucial to disconnect the faulted network part as soon as possible, because the voltage applied from the energized network point to ground may cause danger to people or animals. When a person gets in touch with a live network part, a voltage is applied over the person's body. Because of the specific impedance of the human body, this voltage will create a current, which can cause severe consequences to the person. Even a 5mA to 10mA current through human body can cause muscular cramps, which can lead to the person's incapability to loosen oneself from the energized equipment. Depending on the duration of the current the consequences can be very dangerous. With a current rate from 20mA to 40mA a person will experience respiratory problems, and depending on the duration of the exposure, even a 50mA current can lead to a ventricular fibrillation and to asystole. [4] Therefore it is important to be able to detect the earth-faults and to disconnect them quickly.

3.3. Growth of the reactive power

As introduced earlier, the cable can be represented with a pi-section in which the shunt admittance represents the capacitance to earth. Therefore the cable can be considered as a capacitor, which generates capacitive power. Because the capacitance in the cable is much larger than in OHL, the generation of the reactive power is much larger in the cabled network. [14; 33]

As the cabling increases in the rural distribution network, it has to be noticed that the generation of the reactive power increases also. This is due to the capacitive characteristics of the cable. As the cable can be considered as a capacitor, the current it produces is capacitive and the power is therefore reactive. This reactive power influences the voltages in the distribution network but also in the overlying network though usually the network manager aims to keep the reactive power transfer over the main transformer at zero. Therefore it is common to limit the reactive power locally in the distribution network. According to Elforsk report "Nätkonsekvenser vid kablifiering av luftledningnät" a 260km long cabled 24kV network could generate 8Mvar of reactive power when operating with no-load. The losses would be about 0,16MW. When the load is connected, the reactive power flow through the transformer drops. Even though in the Nordic network the feeder lengths may not reach these values, this shows that the reactive power needs to be controlled when the cabling increases extensively. With long cabled networks one solution could be shunt reactors to limit the exchange of the reactive power between the distribution network and the regional network. [33]

The transfer of the reactive power causes losses, which are in proportion to the feeder length. Naturally it is therefore not profitable to transfer reactive power over long distances. This can be limited with the right placing of the shunt reactors, which will also reduce the reactive power surplus in the overlying, regional network. The total losses can be calculated when the total loads are known, but for example in a situation where the load is strongly inductive, the losses are much smaller because the cable produces the reactive power which the load consumes. When this kind of inductive load disconnects from the network, the reactive power surplus increases and therefore the losses increase and the voltage level may be influenced in the distribution network. In addition to shunt reactors, the losses and the reactive power surplus can be limited by using 24kV network cable in a 12kV network, because it has a lower capacitance to earth values than 12kV cable. [33] However this is possible only in Sweden, because in Finland the distribution network operates in 20kV. This is discussed more in Chapter 4.

As noted earlier the usage of cable influences the voltage level. This is illustrated in Figure 3.15. [33] In the figure the beginning of the feeder is OHL and the rest of the feeder is cabled. When the feeder operates in no-load or the load is very small, the voltage in the end of the feeder rises.

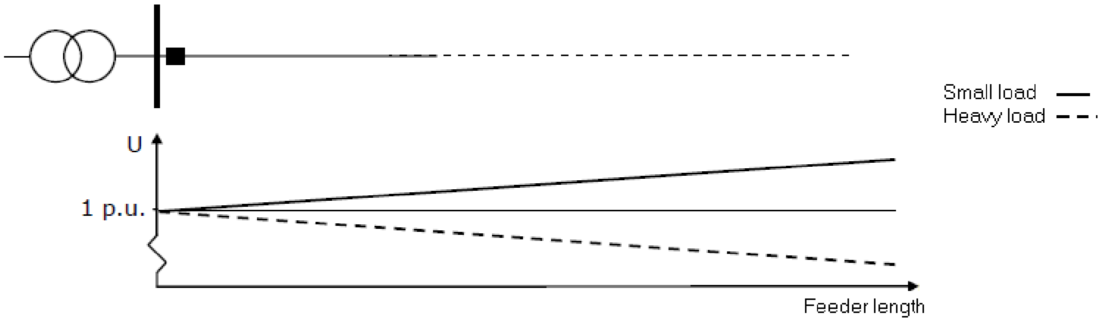


__Figure 3.15__ Voltage rise due to the small loading in the partly cabled feeder. [33]

According to the Elforsk report, the largest voltage rise at the end of the feeder is reached when one third of the feeder near the station is OHL and two thirds are cabled out in the network. This is because of the generation of the capacitive power in the cables and the reactance of the OHL. This voltage rise in the distribution network may also influence the voltage levels on low voltage side, which may cause danger to customers. The voltage level is normally controlled at the station with on-load tap-changer and automatic voltage regulators. However, the equipment has their own adjustment ranges and the voltages have to be limited also in the network so that the voltage regulators are able to adjust to their own range. This way the operating voltage across the network could be maintained at the wanted level. The voltage rise due to the extensive cabling is examined in Section 6.3. [33]

In Sweden the reactive power generation may also cause problems in 10kV networks where relatively small transformers are used. When the network is almost purely cabled, it produces more reactive power than the transformer can handle. Therefore limiting the reactive power generation is important in the future, as the cabling increases. [31]

4. MEDIUM VOLTAGE NETWORKS IN FINLAND AND IN SWEDEN

Both the Swedish and Finnish power systems are part of the Nordic power system together with eastern Denmark and Norway. The Nordic power system is connected to the European power system and power systems in Estonia and Russia with direct current connections. In July 2009 eight European Union countries around the Baltic Sea signed a Memorandum of Understanding, which promotes the integration of the electricity markets around the Baltic Sea. The integration aims at improving the energy supply security in Baltic countries and integrating the Baltic energy markets in stages into the Nordic electricity markets, which requires the development of the Baltic transmission systems to correspond to Nordic transmission systems. The electricity market integration will clarify the roles of the system operators in the Baltic area, promote the cross-border electricity trade and to create a balanced system covering the whole Baltic area. [5; 34]

The structure of the Nordic power system is the same everywhere in the Nordic countries: the system consists of power plants, the main grid, regional networks, distribution networks and consumers. The main grids are owned and maintained by national companies, in Finland Fingrid Oyj and in Sweden Svenska Kraftnät. These are called the system operators. Fingrid Oyj was founded in 1996 and it owns the 400kV and 220kV transmission systems and some of the 110kV network. The rest of the 110kV network is owned by the local energy companies. In Sweden the corresponding company, Svenska Kraftnät was founded in 1994 and it owns the 400kV and 220kV systems. Even some of the 220kV systems are owned by local energy companies like for example in the Stockholm area Fortum Abp. The task of a system operator in addition to maintenance, operation and development of the transmission network is to take care of cross-border connections, assure the technical functioning of the main grid and maintain the network power balance. [3; 35]

In Finland the used voltage levels are 400kV, 220kV, and 110kV in the main grid and in the regional network. In Sweden in addition to 400kV and 220kV systems there are 130kV, 70kV, 45kV and even 30kV regional networks. The distribution networks in Finland consist solely of 20kV network whereas in Sweden the used voltage levels in distribution networks are 20kV and 10kV. Even 6kV is used in some part of Sweden. The low voltage level in both countries is 0,4kV.

4.1. Regulators in the Nordic

At this point it might be useful to take a quick look at the regulators both in Finland and in Sweden. The regulations concerning network protection are presented in Section 4.2. The European Union gives indicative regulations, directives, which have to be included in the national legislation in every EU-country. In the electricity industry the most important directives are the Low Voltage Directive and the EMC-Directive, which is concerned with the electromagnetic compatibility of the electric equipment. [36]

The worldwide standards in electricity and electronic industry come from the International Electrotechnical Commission (IEC) in which both Finland and Sweden are full members. These standards are the basis of the national regulations. International standards are not mandatory standards but more of a suggestive type of standards. On the European level the standardization is made by the European Committee for Electrotechnical Standardization (CENELEC). It works closely with IEC and the EN- and HD- standards are mostly made based on the IEC-standards. In CENELEC the member countries are represented by the national standardization organizations. The representative of Finland is the Finnish Electrotechnical Standardization Committee (SESKO Ry) and the representative of Sweden is SEK Svensk Elstandard. SESKO Ry is a member of Finnish Standards Association (SFS), which brings the international and European-wide standards into the Finnish legislation. The validation of the Swedish standards is made by SEK Svenska Elstandard (SEK). [37; 38]

The security with electricity-related work is supervised only at the national level. In Finland the supervision is made by the Safety Technology Authority (TUKES Ry) which is an agency working on the administrative sector of the Ministry of Employment and the Economy. It supervises and promotes technical safety culture and the surveillance reaches from product safety supervision into the surveillance of the safety of electricity installations. The corresponding agency in Sweden is the Swedish national electrical safety board (Elsäkerhetsverket), which works under the Ministry of Enterprise, Energy and Communications. [36, 39]

The electricity markets are also supervised. In Finland this is done by the Electricity Market Authority (EMV), which works under the Ministry of Employment and the Economy. The corresponding authority in Sweden is the Swedish Energy Market Inspectorate (Energimarknadsinspektionen), which works under the Ministry of Enterprise, Energy and Communications. [40; 41]

4.2. Legislation

Network owners have a great responsibility to protect their customers from dangerous over-voltages both in normal operating conditions and in fault situations. One of the fundamental aspects of network building is therefore to limit the access of unauthorized personnel into the area or space that contains high voltage facilities and to limit the consequences of network faults. Network companies are also obligated by law to ensure the customers' safety. Swedish Elsäkerhetsverket refers to this as good electrical safety practice. [42]

In Sweden the obligating regulation for high voltage installations is ELSÄK-FS 2008:1. The corresponding regulation in Finland is SFS-6001. Both regulations define the high voltage as over 1kV in alternating current (AC) and over 1,5kV in direct current (DC). Requirements concerning high voltage DC facilities are stated in different documents and are not in the scope of this thesis work. [42; 43]

For short-circuit faults the regulations do not give any specific demand. SFS-6001 states that the installations must be planned, constructed and assembled in a way that they endure all mechanical and thermal stress caused by a short-circuit fault. The installations must also be protected with automatic equipment, which switch off the short-circuit faults between phases. SFS-6001 defines the short-circuit standard duration time as 1s. Other recommendable values are 0,5 and 0,3 seconds in which the equipment should switch off the fault. ELSÄK-FS 2008:1 does not define any values for short-circuit duration but otherwise speaks about good electrical safety practice, which among other aspects includes the demands of using and constructing high voltage systems in a way that they do not cause hazards for human or animal safety during a fault or normal operation. It also states that faults in the circuit should not damage the network equipment. ELSÄK-FS 2008:1 also refers to these aspects when defining the fundamental principles of electrical safety. [42; 43]

For earth-faults regulations give more detailed requirements. This is because an earth-fault in high voltage networks can create dangerous voltages even to the LV network, which thereby may lead to damages in LV equipment and danger for customers. This is also where the Swedish and Finnish restrictions differ from each other. The SFS-6001 gives the limiting contact voltage values respective to the duration of the fault current, whereas the Swedish ELSÄK-FS 2008:1 gives exact values for the whole voltage to earth. Figure 4.1 illustrates the Finnish requirements. [42; 43]

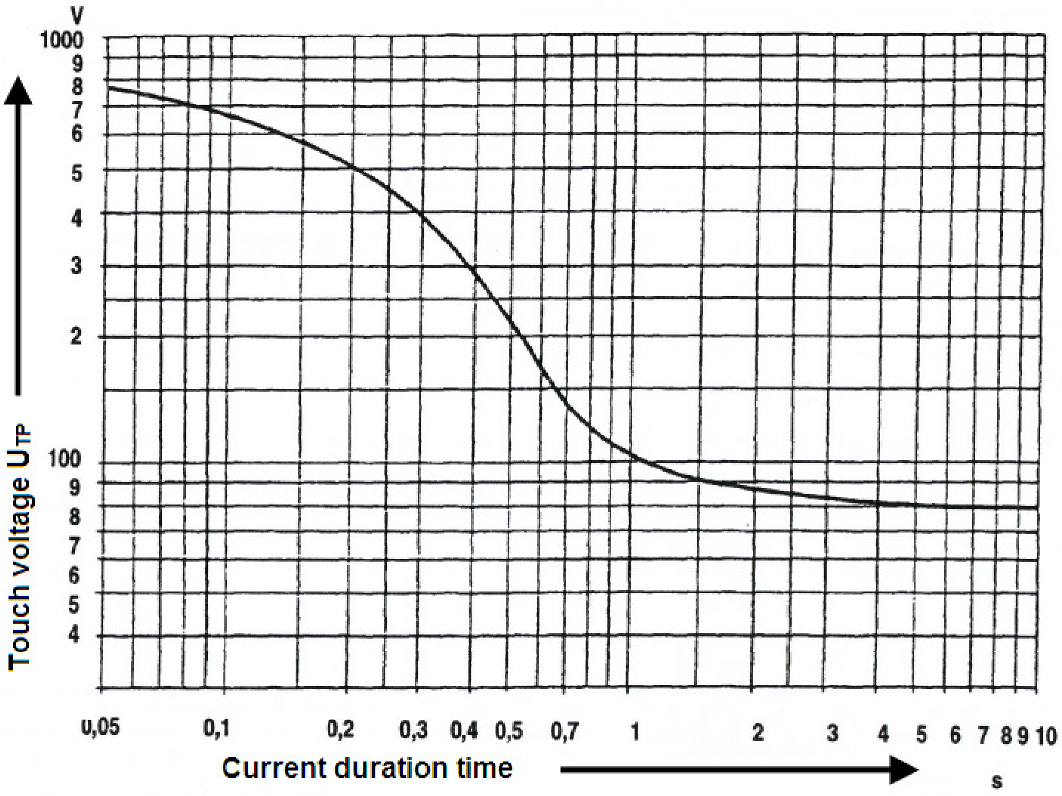


Figure 4.1 *The touch voltage respective to the current duration time [43]*

The practical planning is therefore based on contact voltage values, which have to be limited according to the curve above. The standard SFS-6001 recommends that the earth-fault should be switched off automatically. The HV system and LV system can have a common earthing if the contact voltages in LV networks are limited according to Figure 4.1 and if the potential rise (stressing over-voltage) at the neutral point of the LV system does not exceed allowed values. [43]

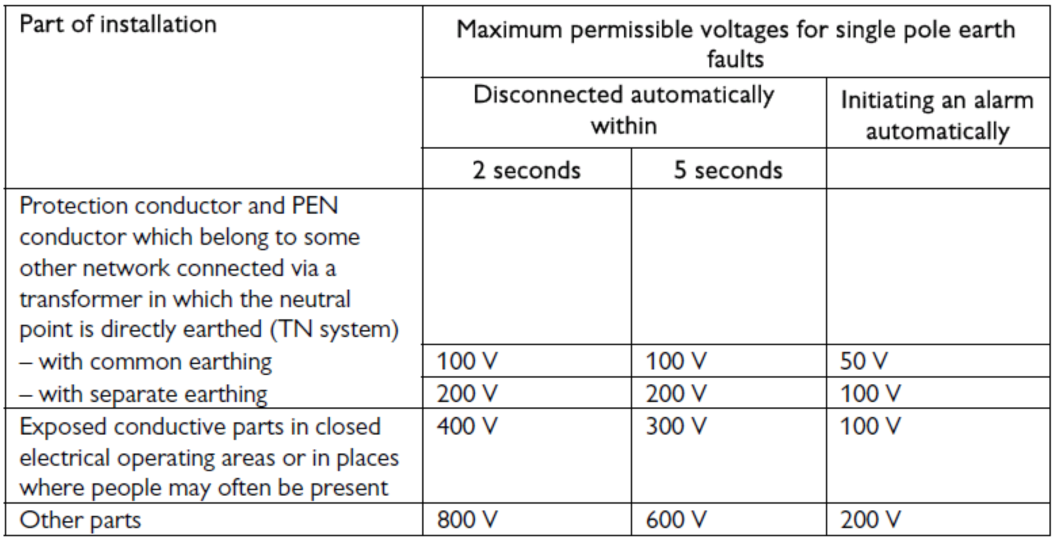
The HV and the LV systems may also be separately earthed. In this case, the HV network earthing must be connected to a universal earthing system. If not connected, the LV system is recommended to have a common grounding, and the prerequisites for TN-systems listed below must be fulfilled. In TN-systems, one point in the network, usually the distribution transformer's neutral point is earthed and all the live network parts are connected to this point via a protective conductor. [43, 44]

- If the LV system is earthed only at the feeding point, for example a transformer, the value of the voltage to earth value may not exceed the touch voltage values given in Figure 4.1. $U_m \leq U_{TP}$.
- If the protective conductor or the PEN-conductor is earthed at several points in the network, the voltage to earth value may be two times the maximum touch voltage value given in Figure 4.1. $U_m \leq 2U_{TP}$.

- If every branch in the LV network is earthed, the voltage to earth value may be four times the maximum touch voltage value given in Figure 4.1. $U_m \leq 4U_{TP}$.

These demands are based on the Harmonization Document 637 (HD-637) made by CENELEC but they are applied for Finnish conditions. The recommendable period of time to check the voltage to earth values is six years. [43]

For LV networks the Swedish legislation regarding electrical safety states that all systems shall be built as TN-systems. The ELSÄK-FS 2008:1 has requirements about the phase-to-earth voltage, whereas the Finnish law limits the voltage a person may experience. The requirements are illustrated in Figure 4.2. [42] The ELSÄK-FS 2008:1 also states that in non-solid earthed HV-systems a single- or double earth-fault should be switched off automatically, excluding HV-systems under 25kV, which do not include any OHL. In these cases the earth-fault protection may be only automatically alarming. [ELSÄK]



Part of installation	Maximum permissible voltages for single pole earth faults		
	Disconnected automatically within		Initiating an alarm automatically
	2 seconds	5 seconds	
Protection conductor and PEN conductor which belong to some other network connected via a transformer in which the neutral point is directly earthed (TN system)			
– with common earthing	100 V	100 V	50 V
– with separate earthing	200 V	200 V	100 V
Exposed conductive parts in closed electrical operating areas or in places where people may often be present	400 V	300 V	100 V
Other parts	800 V	600 V	200 V

Figure 4.2 *The Swedish requirements for the phase-to-earth voltage during an earth-fault. [42]*

ELSÄK-FS 2008:1 states, that in non-solidly earthed networks, which include strengthened OHL, coated OHL or over-head cable without sheath or contact protection, the earth-fault protection should be as sensitive as possible. Faults with fault resistance values up to 5000Ω shall be detected. If the network includes some other type of OHL than listed in the previous sentence, the earth-fault protection should detect faults with resistance values up to 3000Ω. In an area that does not have a detailed plan, this type of network may contain a few spans of coated OHL without having the requirement of fault detection up to 5000Ω. [42] SFS-6001 does not include any requirements for earth-fault protection sensitivity. There are, however, recommendations made by the Finnish Electricity Association (SENER Ry), which state that the earth-fault protection must function up to 500Ω in fault resistance value when the earth-fault occurs in a network part with no protective grounding. It is also recommendable, that the earth-fault protection would operate during higher fault resistance values than 500Ω. For coated OHLs the publication states that the earth-faults with fault protection should function with the highest sensibility that is possible to achieve regarding the limitations set by the protection equipment. [45]

4.3. Network compensation

The distribution networks in Sweden are almost entirely compensated. In Finland the compensation has also increased for two reasons. First of all the compensation helps an arcing earth-fault to extinguish by itself as was presented in Section 2.3.4. Therefore the breakers may not need to function and the network does not experience a power cut. This improves the quality of delivery from the customers' point of view. Second, the increasing cabling will increase the capacitive earth-fault current, which has to be compensated. Large earth-fault currents may lead to dangerous overvoltages in energized network parts. This section represents the compensation in Finland and in Sweden.

4.3.1. Centralized compensation

The major difference influencing the compensation and the network protection is the earthing type of the network. Although the basic structure and the construction principles are quite similar in Finland and in Sweden, the voltage level and the network earthing type separates these networks from each other. The network earthing not only influence the neutral point equipment but it also has a major effect on how the earth-fault current passes through the zero sequence.

In Finnish networks the upper side of the main transformer, the 110kV side, is earthed only in some particular points defined by Fingrid Oyj, so basically the upper network can be considered as isolated. This means that the earth-fault current has no route to drift from the upper side to the distribution side in case of an earth-fault in the 110kV network, and vice versa. The transformers are Yd-coupled, which means that the distribution side is delta-coupled with no neutral point and isolated from earth. Therefore in order to be able to connect a neutral point device to the transformer the neutral point has to be created. This is done with a separate transformer, which usually is Znyn-coupled. The compensation unit is connected to this neutral point transformer's primary side via a disconnector. This makes it possible to disconnect the coil from the network if the coil for example is damaged for some reason. The secondary side is for the LV distribution at the station. Because the neutral point is made with a separate transformer, the earth-fault current cannot access the main transformer, which would raise other problems as will be introduced below. Figure 4.3 represents the neural point device used in Finland. On the right is the Petersen coil and on the left the neutral point transformer. Between the neutral point devices is the disconnector.

Figure 4.3 *An earthing transformer (left) and the Petersen coil (right). Between the neutral point devices a disconnector.*

In Sweden the main transformers are usually Ynyn-coupled. There is, however, a small difference between the 130kV network and the 70kV and 40kV network. 70kV and 40kV network are separated in zero sequence wise whereas in 130kV network the zero sequence current can flow from the distribution side to the upper voltage side. This causes the earth-fault current to behave little differently. [31]

When an earth-fault occurs in 70kV network (upper voltage network separated zero sequence wise) the zero sequence current starts to flow. The zero sequence current has a route to the transformer because the distribution side of the main transformer is earthed. As the zero sequence current enters the transformer, it creates a zero sequence flux. Because the upper voltage side has no connection to the zero sequence, the magnetic balance is not gained. In order to gain the balanced again, the transformer would have to increase the flux on the upper voltage side, which would create a current also to the upper voltage side. This current could cause the upper side earth-fault protection devices to function causing a false disconnection. [31]

As there is no magnetic balance, the zero sequence flux exits the transformer core and closes trough the transformer tank. This warms the tank up creating active losses. These losses add up to the resistive current created by the zero sequence series impedance of the cable, and the total resistive current flow in the network increases. As introduced earlier, the resistive earth-fault current cannot be compensated which is why it may endanger customer safety. [31]

When the zero sequence flux created by the zero sequence current warms the tank causing active losses, the zero sequence impedance of the transformer seen from the distribution network, is large. In extensively cabled networks, where the zero sequence currents are large, the voltage drop over the transformers zero sequence impedance may be as high as 10%. Now when a large Petersen coil is connected to the transformers neutral point, the voltage drop is also over the Petersen coil. As the coil creates an inductive current in respect with the neutral point voltage, and as there is a significant voltage drop over the neutral point, the Petersen coil is not able to produce the amount of inductive current, for which it has been dimensioned. This leads to a situation where the capacitive current is not compensated as planned, which may also endanger customers, as the actual earth-fault current flowing in the network is larger than expected. [31]

The phenomena described above can be controlled by installing a stabilizing winding into the transformer. This is usually a delta winding, which creates the magnetic balance in case of a zero sequence current entering the transformer. By using a stabilizing winding in networks, in which the upper voltage network is separated from the distribution network side in zero sequence wise, the false relay functions in upper voltage side may be avoided. Also the resistive current flow in the network is restricted and the compensating devices function as planned. [31]

The situation is different, if the networks are connected in zero sequence wise, as the 130kV network in Sweden. In this case, as an earth-fault occurs in the network and the zero sequence current enters the transformer, the magnetic balance is maintained and the zero sequence flux does not exit the transformer core. As the flux is not closing trough the tank, the tank is not warmed up and the active losses are not created. Also the zero sequence impedance of the transformer, seen from the distribution network is small and there is no significant voltage drop over the neutral point. However, an earth-fault in 130kV network may cause dangerous voltage rise in compensated distribution network. This is because in case of an earth-fault in 130kV network, the zero sequence network in 130kV side and in 20kV side are connected. The capacitance of the distribution network, the transformer inductance and the Petersen coil inductance create a series resonance circuit, which may cause the voltages in distribution network to rise dangerously high. This is, however, usually prevented by the fast functioning of the primary side protection. [31]

All these things have to be taken into consideration when planning the network and dimensioning the neutral point equipment. The coil size is restricted by the rated current of the transformer if the transformer does not include a stabilizing winding. Also the resistive current due to the transformer tank warming has to be taken into consideration as well as the voltage drop over the neutral point. These are mainly the reasons why in Sweden the whole earth-fault phenomenon is studied more thoroughly than in Finland.

In both countries, the Petersen coils are automatically adjustable. In Sweden the network is operated approximately 2-10A over-compensated. [14] Behind this practice is the idea that it is more likely for some network part to disconnect from the network, which may lead to the network to reach its resonance point. In Finland the network is operated slightly under compensated.

4.3.2. Distributed compensation

In order to avoid the increase of the resistive current component during an earth-fault, distributed compensation is needed. The Petersen coil is usually located in the distribution transformer’s primary side. This was illustrated in Section 2.3.3 in Figure 2.21. The amount of inductive current created in the coil is fixed. It is recommended that the distribution transformers would be Zn(d)yn-coupled (in which delta is a stabilizing winding) or Znzn0-coupled. These couplings give the magnetic balance to the transformer in case of an earth-fault at LV side, which means that the earth-fault current does not pass to the primary side causing the possibility for the protection to function erroneously in the upper voltage side. These types of transformers have also a low zero sequence impedance, which is desirable for the LV transformers because the zero sequence impedance also contributes to the resistive zero sequence current. It has also been examined whether the Petersen coil in the distribution transformers could be used as a shunt reactor. In this case, the device would produce inductive power to the network during normal operating conditions and thus compensate the capacitive power produced by the cables, but it would also function as a Petersen coil, compensating the earth-fault current. This possibility has been examined in recent years, but as yet there are no commercial products. [46]

4.4. Network protection

It is necessary to protect customers from dangerous over-voltages and to prevent the damages in the network equipment. Network companies are obligated by the standards to meet the certain reliability and quality demands in network protection, which also assures that the network stays stable during and after faults. Among other things, protection should be selective, which means that only the smallest possible part of the network is disconnected. The whole system should be protected, which in some cases requires overlapping protection areas. Section 4.4.1 shortly introduces the short-circuit protection and Section 4.4.2 the earth-fault protection. [2]

4.4.1. Short-circuit protection

The main purpose of the short-circuit protection is to ensure safety. In addition to this one of the aims is to prevent network equipment from being damaged in case of a short-circuit fault where the fault currents are large and contain transients that can stress the equipment. It is important to assure the thermal and dynamical durability of the equipment in order to prevent malfunction. Short-circuit protection also disconnects the faulty network part from the network and ensures the safety of the network users and the customers. [1]

The short-circuit protection is usually executed with over-current relays which usually have two or three tripping steps. One is called the momentary tripping that functions with a large short-circuit current and faster than the other steps. This ensures that the equipment near the station will not experience too large short-circuit currents. The momentary tripping is also used with the station main breaker to protect the bus bar. The other protection steps are usually slower and they function with a lower current value. The lowest value the relay needs to detect is the two-phase short-circuit value in the furthest end of the network the station feeds. [1]

The automatic reclosings (auto-reclosing) are used to solve the faults in the OHL network. A reconnection means that the breaker is automatically closed after the breaker has disconnected the faulty network part. According to the Finnish fault statistics from 2008 in the rural network, 58% of the faults were cleared with a high-speed auto-reclosings and 21% with delayed auto-reclosings.

In the high-speed auto-reclosing the network part is non-energized for less than 0,5s after which the breaker is steered to close in order to restore the electricity. If the fault does not disappear, the relay trips again and steers the breaker to open. The system stays non-energized from one to three minutes depending on the relay settings after which the electricity is again restored. If the fault still remains, the relay trips a third time but this time the fault is permanent and needs locating and repairing. [1; 2; 47] The reconnections are rarely used in networks consisting mainly of cable, because in these networks a cable fault is usually a permanent fault. In these cases the reclosings may stress the network and therefore may cause more severe damages to the cable. Sometimes the usage of high-speed auto-reclosing hampers the customers' devices and therefore in some feeders only the delayed auto-reclosing is used. Some industrial facilities, for example, can endure the longer outage whereas the shorter outages may damage the equipment.

The network may contain more than one protection stage. This is for example the case if there is one 20kV feeding and there is a switching station in the network. Another example is a network with one 20kV feeding and a 20kV/10kV station in the network or a network may contains for example a recloser, which forms one extra protection stage in the network. This will be discussed more in Section 4.5. Of course also the upper voltage network must be taken into consideration when planning the short circuit protection. But, when examining only the distribution network, in order to gain a selective functioning, the current threshold values in the 20kV feeder protection must be set higher than in, for example, the switching substation. Also the tripping times must be set higher. This is because if a short-circuit fault occurs further in the network behind the switching station or the 20kV/10kV station, it is desirable for the protection device in that station to operate first. This is called selectivity, when the protection disconnects a smallest possible amount of the network, as the fault occurs. When the networks contain several protection stages, the tripping times can grow unacceptably long, which may be dangerous. With modern, numerical relays, the time delay between two protection stages is around 150ms, if one wants the network protection to function selectively. [2]

4.4.2. Earth-fault protection

As noted in Section 2.1.2 the earth-fault current in isolated networks is capacitive which means that the current is approximately 90° ahead the voltage. Therefore the directional feeder protection is based on the measurement of zero sequence current and neutral point displacement voltage at the neutral point, and the phase-angle φ between them. Zero sequence current can be measured with a sum connection of current transformers or by using a cable type current transformer. The neutral point displacement voltage at is usually measured from the delta-connection of the voltage transformers' secondary windings. [1]

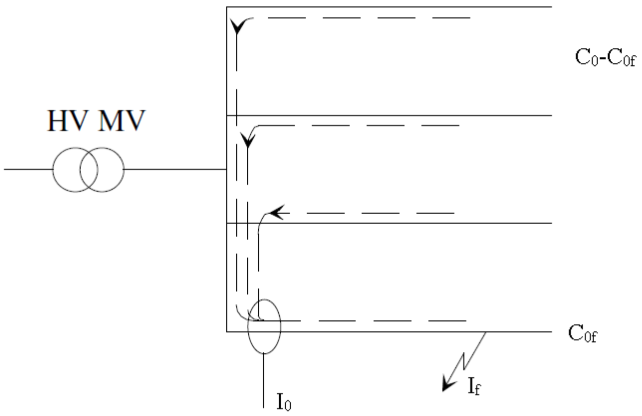


Figure 4.4 *The current flow in the earth-fault. [48]*

The protection has to be selective, which means that the relay has to be able to function only when a fault occurs and only in its own target area. As shown in Figure 4.4 the fault current flows from the power station to the fault point. On the contrary in the healthy phases, the fault current flows towards the power station, which means that the phase-angle between the zero sequence current and the neutral point displacement voltage in the healthy phase is opposite to the phase-angle in the faulted phase. This will be demonstrated in Chapter 6. So the relay, in addition to observing the zero sequence current and voltage, observes the angle between them, which according to Figure 4.5 is $90° - \Delta\varphi < \varphi < 90° + \Delta\varphi$. [1] In the figure U_0 represents the neutral point displacement voltage, I_0 is the zero sequence current, $\Delta\varphi$ is the angle between them, φ_0 is the basic angle and φ the tolerance. The tripping happens when the angle is in the represented tripping area marked with red. [12]

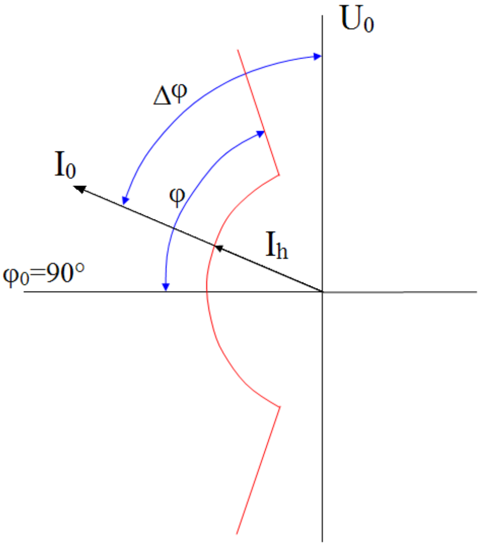


***Figure 4.5** The phasor of the earth-fault current in an isolated network*

The threshold value should be set so that the zero sequence current, which is close to zero in normal operating situation, would not cause the relay to function. The relay should awake after the threshold values have been reached, and after a specific time-delay, presuming that the relay is still awakened, it gives a signal to the circuit-breaker to function. As a result the customers experience a high-speed automatic re-closing or a delayed auto re-closing which means a short interruption in electricity. [12]

As in isolated networks, the directional earth-fault protection is implemented with phase comparator relays also in compensated networks. In case of a compensated network the zero sequence current is not ahead of the voltage because of the compensation, and therefore the protection has to be based on a different phase-shift than in isolated networks. [1]

In compensated networks the protection is accordingly based on the active current component with the phase-shift $\varphi_0 \pm \Delta\varphi$. This current is normally caused by resistances of the phase lines and resistive leakage current of the network. Usually an extra resistance is used in parallel with the Petersen coil. The idea of this resistance is to magnify the active current component of the fault current so that the relay is able to detect the fault and function. [1] The resistance can be continuously connected, or connectable in earth-fault situations. [12]

When the earth-fault current flows through the Petersen coil as an inductive current it compensates the capacitive current the lines produce. Thus the phase-angle of the earth-fault current and the zero sequence voltage is 0°. As a result, the relay awakes when certain threshold values of the zero sequence current and the neutral point displacement voltage have been exceeded, and when the angle between them is $0° - \Delta\varphi < \varphi < 0° + \Delta\varphi$. [1] The phasor diagram is presented in Figure 4.6. It is good to keep in mind that in practice the neutral point displacement voltage phase-angle is adjusted to zero with, for example, different kind of measurement transformer earthings. Rarely the neutral point displacement voltage phase-angle corresponds to zero naturally.

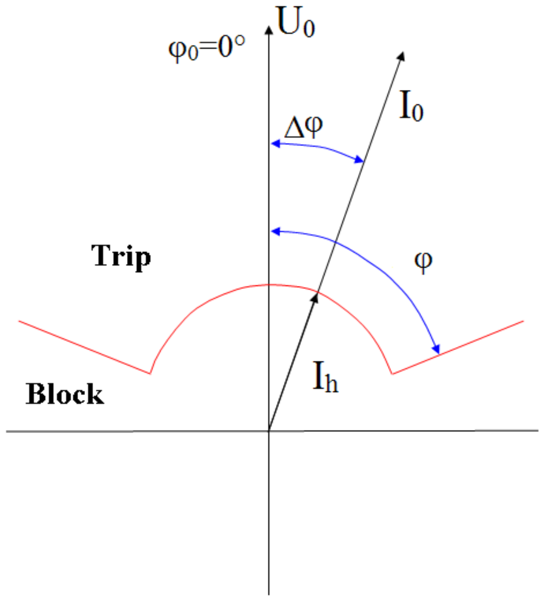


Figure 4.6 Phasor of the earth-fault current in compensated network.

In addition to observing earth-faults occurring at the bus bar, the zero voltage relay is used to backup the feeder protection. This relay observes only the neutral point displacement voltage. The relay has a larger threshold value than the feeder relays. In Finland in compensated networks the value is usually around 60% of the normal phase-to-earth voltage. In isolated network the value is much smaller, around 30%. This device also protects the bus bar from an earth-fault. The relay either disconnects the 20kV feeders from the network or the whole 110kV feeding. This is of course a problem because either all of the feeders or the whole station is disconnected from the network all at once. This might become an issue in networks where the probability of intermittent earth-faults has increased i.e. cabled and compensated networks as explained in Section 2.3.4. The number of outages caused by this relay can be decreased by setting the feeder protection also to observe the neutral point displacement voltage, in addition to normal directional earth-fault protection. Usually the threshold values are the same, but the tripping times are slightly different. This means that as the feeder protection relays have awakened because of the risen neutral point displacement voltage, and waited for a certain time delay, they start to disconnect feeders in the priority order instead of disconnecting all at once. If the fault does not disappear, the zero voltage relay trips the MV feeding. Usually, however, the stepping makes this move unnecessary. As the feeder relays disconnect one or two feeders, the network becomes unbalanced i.e. over-compensated or even more over-compensated in the Swedish networks which are already used as over-compensated. This is one point contributing to the network usage as slightly over-compensated, like in Sweden. When moving further away from the resonance point the neutral point displacement voltage drops and the zero voltage relay returns to its normal state. This gives the feeder relays an opportunity to detect the fault and function selectively. Also the operators have time to notice the intermittent earth-fault and start to work to find the faulty feeder. One of the actions used in Finland is to disconnect the Petersen coil from the network and to change the relay settings to correspond to the isolated network. As the network is now used as isolated the neutral point displacement voltage is not kept up by the compensation and the fault current becomes larger and therefore it may be detected by the normal feeder relays. [32]

Also some relay types contain a functionality of wide-angle protection. This means that the relay observes the zero sequence current and the neutral point displacement voltage as introduced earlier, but the tripping area is from $90 - \Delta\varphi < \varphi < \varphi_0 + \Delta\varphi$. Therefore this type of protection can be used both in isolated networks and in compensated networks. Also some of the older relays do not have a function to change the protection angle when, for example, the Petersen coil has to be disconnected from the network and the protection angle needs to be changed to correspond to that of an isolated network. In these cases it is sometimes necessary to use the wide-angle protection. The newest relays also usually contain some kind of transient detecting algorithm, but there is still very little experience whether the algorithms really work. This, however, is a very promising field and also extremely needed in the future, because along with the increasing cabling the intermittent earth-faults will increase.

In Finland the protection is based on these two different protection angles and all the newer relays include both of these settings - the settings and protection angles for the isolated network and the settings for the compensated network. This is beneficial for example in situations in which the Petersen coil is disconnected from the network. The newest relays are automatically adjusted to correspond to the new situation. As explained in Section 4.3.1 the Petersen coil is connected via a disconnector. This disconnector gives the relays a signal, if it functions and separates the coil from the network. The relays automatically change the settings and protection angles to be able to detect the earth-fault in an isolated network. In some older systems the opening of the disconnector automatically changes the protection angles but the settings have to be changed from the control center. Although in cases where the coil disconnector is steered to open from the control center, the system automatically sends a signal to the relays to change also the tripping settings.

In Sweden the network is entirely compensated except for a few older networks. The protection is based on the resistive current component. In cases where the Petersen coil for some reason is disconnected from the network, the zero voltage relay is the only usable back up protection device. This may lead to broad electricity interruptions as the zero voltage relays may trip the whole station from the network in case of an earth-fault.

4.5. Reclosers

One way of improving the distribution network protection and the quality of delivery is to sectionalize the protection areas into smaller units. In practice this means adding some coupling devices into the network so that the area experiencing a fault in the network is minimized. As a result also the number of customers experiencing the outage is minimized. Sectionalizing the network with reclosers has a major affect on SAIFI and MAIFI figures. It also improves the SAIDI figure but not that remarkably. [49]

When talking about network reclosers the usual impression is that it is some kind of a new technique. The truth is, however, that these techniques were used already in the 70s. Back then reclosers were discovered to be disadvantageous and they were removed from the network. The largest reason for this was the lack of telecommunications networks. Also the equipment was hard to use and to maintain, and because of the old relay techniques in the feeding substation the selectivity was very difficult to achieve. Nowadays the network companies have multiple ways to communicate with network devices. Also the recloser techniques have developed since the 70s, which has lead to a resurgence of the reclosers. [50]

4.5.1. Recloser structure

A recloser is a network device, which contains basically the same functions as the feeder cells in the substation. The intelligent unit of a recloser is a relay, which includes the basic functions like over-current protection and the earth-fault protection. It can also be programmed to perform high-speed and delayed auto-reclosings. In case of a fault, the recloser, if adjusted to be selective, operates before the feeder breaker and thereby limits the fault effects. This reduces the number of customers experiencing the fault.

Nowadays the reclosers are vacuum reclosers whereas in the 70s the substance used for the arc extinguishing was mineral oil. A vacuum has a very good isolating characteristic and the maintenance of a vacuum recloser is much easier than that of an oil recloser. Also the environmental influence is much smaller. [50] The new recloser mechanisms are operated with magnetic actuators instead of mechanical. This prolongs the operating life of the reclosers and increases the amount of possible full load operations greatly, because the actuator does not include mechanical and thus deteriorating parts. [51] Figure 4.7 illustrates one type of recloser.

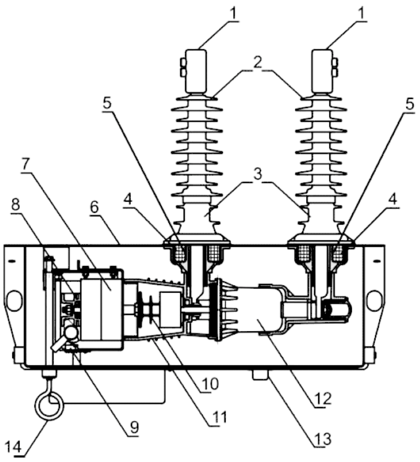


Figure 4.7 *Recloser structure [51]*

1. Bushing conductor
2. Silicone Rubbing Bushing Boot
3. Polymer Bushing
4. Rogowski Coil Current Sensor
5. Capacitively Coupled Voltage Sensor
6. Stainless Steel Tank
7. Magnetic Actuator
8. Opening Spring
9. Auxiliary Switches
10. Insulated Drive Rod
11. Polycarbonate Housing
12. Vacuum Interrupter
13. Ceramic Breather
14. Mechanical Trip Ring

The recloser can be installed in three different ways as illustrated in Figure 4.8. In order to have a visible disconnection point the recloser must be installed near a disconnector. In the first case (a) the recloser is installed to the same pole with the disconnector. This can be done if the pole is fairly new and in good condition. If the pole, where the sectionalizing point is planned, is old, the solution is to set up a shorter pole next to the sectionalizing point to which the recloser is installed. It can be installed in the feeding side as in option (b) or after the disconnector like in option (c). The former installation type (b) is usually used when there is a whole disconnecting station after the recloser. The remote terminal unit is placed in the lower part of the pole for it to be reachable. [52]

It is, however, good to notice, that it is not cost effective to install a recloser next to a remote controllable disconnector. This is because together these will not produce any more added value to the network company than they would do by themselves.

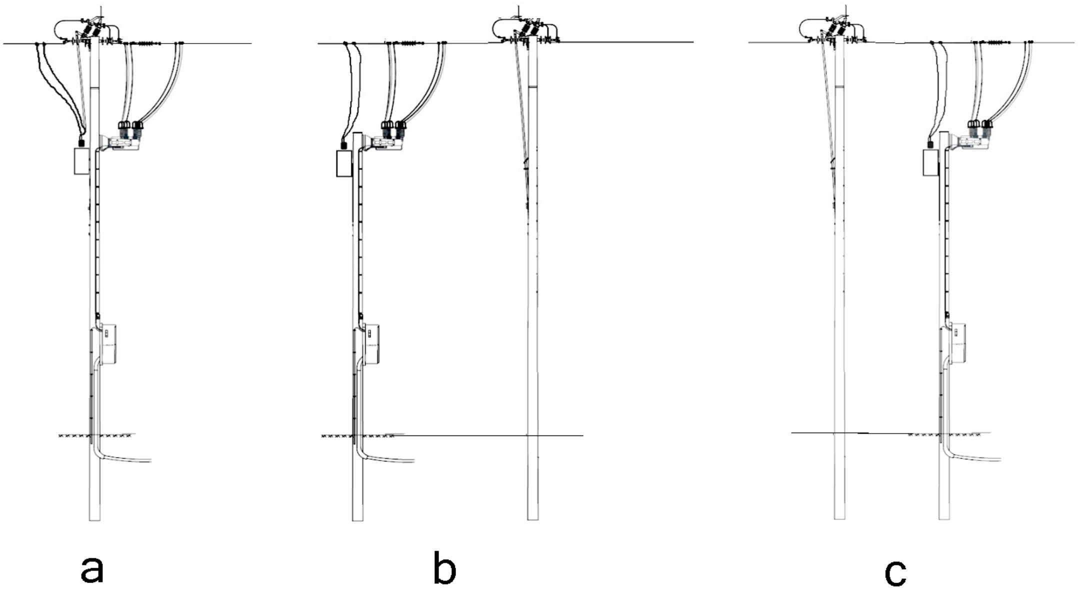


***Figure 4.8** Three different types of installing the recloser [52]*

Figure 4.9 illustrates some parts of the whole reclosing system. In the pole is the main operating device whereas the terminal unit is placed near the ground. The terminal unit includes the relay and the remote control device of the recloser. The protection of the recloser is directional, which means that it needs both voltage and current censors as represented in Figure 4.9. They lie on the top of the recloser where also the surge arresters are placed. In some cases where there is no low voltage distribution nearby, the LV transformer is placed in the pole together with the recloser itself. If there is a low voltage transformer near the sectionalizing point, the electricity is taken from there to the operating unit. Between the jumpers there is usually a bypass switch or an insulator over which bypass jumpers are connected. This way the recloser can be bypassed if the device is for example damaged and needs to be repaired. The voltage and the current sensors as well as the surge arresters include animal protection.

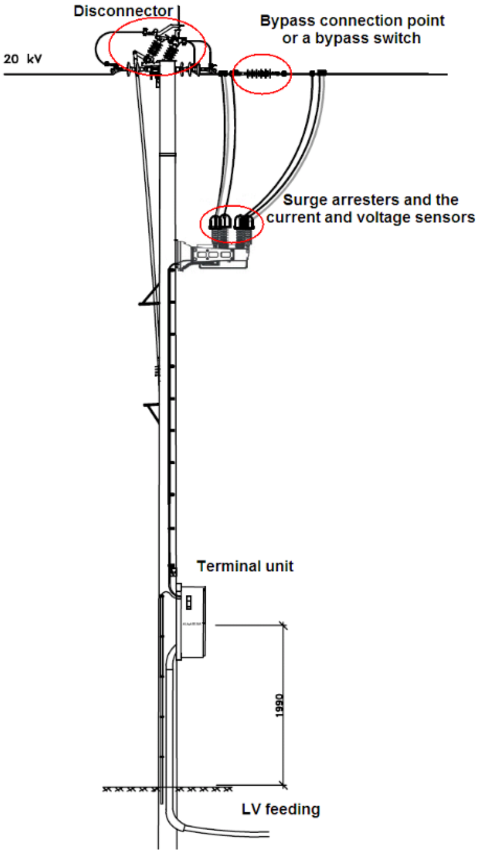


Figure 4.9 *Disconnector parts [52]*

In Vattenfall Finland the network contains altogether close to a hundred reclosers by the end of the year 2009. The experiences are very good and Vattenfall is going to install more network reclosers in the year 2010. The first reclosers were installed in 2006 when Vattenfall Finland started systematically investing in the reliability of delivery. Now that the company has a few years of experience from the usage of reclosers the demands for the suppliers are also very specific, taking telecommunications into consideration as well.

4.5.2. Recloser placement

Important in the recloser placing is to know the fault places and the customers affected by the faults. One recloser divides the feeder into two separate protection zones, which means that the customers, who are situated before the recloser, will not be affected by the fault occurring at the end of the feeder. Therefore one good policy is to protect for example industrial customers whose processes may be severely interrupted by the faults or auto-reclosings generated by a fault. Vattenfall Eldistribution in Sweden has given up the usage of high-speed reclosings after studies, which showed that so short outages were more harmful for the delicate processes than a delayed reconnection. [53]

If the faults and the customers are equally spread out in the feeder, the theoretical improvement in SAIDI and SAIFI is 25% when placing the recloser in the centre of the feeder. This method can be used when there are not any clearly noticeable fault places or electricity consumption concentrations. Theoretically, the best results are achieved when the faults occur at the end of the feeder and the customers are mainly located at the beginning of the feeder. This is however rarely the case in rural area networks.

Vattenfall Verkko Oy uses reliability based network calculation as a tool in recloser placement planning. It is based on the average failure rate, mean time to repair and the outage costs for the customer. The reliability calculation gives as a result the reliability of delivery characteristics introduced in Section 2.4 and also the average interruption costs for the network company. [53]

The development of the reliability calculation started in the 80s. Back then the main focus was on the evaluation of the benefits gained with the usage of remote controllable disconnectors. The new generation's reliability calculation was developed in the national LuoVa-project in the years 2002-2005. LuoVa was a project in which 11 Finnish network companies, 3 software companies and two research institutions participated. The type of calculation that was created in the LuoVa-project includes failure rates based on the usage and the condition information. Vattenfall Verkko continued testing this pilot together with the software company Tekla Oyj. This co-operation produced a commercial product called Xpower RNA/AM. [54]

Xpower is a network information system developed by Tekla Oyj. RNA/AM (Reliability based Network Analysis/ Asset Management) is a tool that allows the network planner to analyze the reliability of an existing or planned network. RNA takes into consideration the mechanical and the electrical state of the network, environmental factors like vegetation around the OHLs, operation and maintenance costs and outage costs for the customer and the network company. There are over 200 parameters that Vattenfall Verkko keeps up-to-date by sharpening and modifying the parameters when found necessary. Vattenfall Verkko Oy has very good experiences with the usage of RNA/AM and for example all the planning concerning remote controllable disconnectors and network reclosers are made with Xpower RNA/AM. [54; 55]

5. RESEARCH METHODS AND THE EXAMPLE NETWORKS

The applied part of this work is basically divided into two parts. The first part covers the rural area network cabling and the earth-fault behavior. The usage of distributed compensation in Finnish rural area networks is examined by means of a network model built with a simulation program presented in the next section. The model is built to correspond to an average Finnish rural area network. In the beginning the model consists of purely OHL network. The simulations are carried out by replacing the OHL with underground cable step by step and adding also the distributed compensation in to the network. The earth-fault behavior is examined, as the amount of cable increases in the network. Also the production of reactive power and the voltage rise in the end of the feeder are studied.

In the second part the reclosers are of interest. In these studies the recloser placement is considered and one example network from the Swedish archipelago is introduced. In this part it is examined how the reclosers' placement affects the SAIDI, SAIFI and MAIFI figures in respect with the total amount of faults per year. The recloser placement is studied in three different points in the network and these situations are compared with the situation when the network contains no reclosers.

5.1. Rural area network cabling

As stated earlier, the zero sequence impedance is not an unambiguous matter and therefore some simplifications have to be made. It is, however, important to keep this in mind when interpreting the modeling results. The conclusions have to be drawn within the validity range of these simplifications. In this study the calculations are carried out to treat the fundamental frequency only. Therefore the results are also valid only for the fundamental frequency. Though cabled networks are associated with transients because of the cable characteristics and the Petersen coil, these simulations are left outside of this work.

The analysis is performed with a simulation program, namely Power System Simulator for Engineering (PSS/E). PSS/E is a program mainly used for simulation, analysis and performance of the transmission network. It can, however be applied also to distribution network calculation. PSS/E is a program capable of performing both steady-state analysis and dynamic simulations. Examples of these are power flow analysis, power flow optimization, fault analysis for balanced and unbalanced faults and transient and stability analysis. In this study only power flow and fault analysis are applied. PSS/E is capable of introducing the zero sequence impedance in unbalanced fault calculation which is why it is an excellent program for protection coordination work.

5.1.1. Line parameters

The OHL zero sequence impedances are calculated with one of PSS/Es utilities, Line Properties Calculator (LineProp) which calculates parameters for OHL in the distribution and in the transmission network. LineProp requires as input parameters the pole height, spacing and sag of the OHL network. These values from an average Finnish rural area network are introduced in Table 5.1. The pole height is the distance from ground to the pole top and the spacing means the distance between conductors – the outermost conductors are 1,1 meters away from the conductor in the middle. The conductors are placed in the same horizontal level.

Specifications of the phase conductors are also required in LineProp calculation. These are introduced in Table 5.2. From these values the LineProp calculates the line's electrical parameters which can be used in fault and power flow calculation. In the network model the OHL type *Raven63* is used for the trunk lines and *Swan25* for branches. In Table 5.2 R_{ac} means the typical line resistance with alternating current, X_l means the line inductance and the term X_c refers to the line capacitance. *Amps* means the maximum loading current the line will endure.

Table 5.1.

OHL network	
Pole height (m)	9
Spacing (m)	+/- 1,1
Sag (m)	0,8

Table 5.2.

OHL				
	R_{ac} (Ω/km)	**X_l (Ω/km)**	**X_c (Ω/km)**	**Amps**
Swan25	1,35150	0,44930	0,21760	130,00
Raven63	0,53560	0,38590	0,19540	230,00

As the OHL is started replacing with underground cable, two kinds of cables are used - *AXAL-TT95* (AXAL95) as a trunk line cable and *AXAL-TT50* (AXAL50) in branches. Cables types are chosen to correspond to an average rural area network. The cable has three conductors placed as the conductors in Figure 3.3 in Section 3.1.2. The conductors are made of aluminum, the insulation is cross-linked polyethylene (abbreviated PEX or XLPE) and the cable sheath is made of black polyethylene. The cable parameters are introduced in Table 5.3. The abbreviations used in the Table 5.3

refer to Figure 3.4 introduced in Section 3.1.2. The positive and the zero sequence data of the conductors are introduced in Table 5.4.

Table 5.3.

Cable							
	$2r_c$ (mm)	**d (mm)**	**$2r_s$ (mm)**	**R_c (Ω/km)**	**R_s (Ω/km)**	**C_0 (μF/km)**	**L(mH/km)**
3x50/25	7,8	19,5	48	0,641	1,2	0,16	0,37
3x95/25	11,2	22,7	55	0,32	1,2	0,19	0,34

Table 5.4.

Conductor						
	R_1(Ω/km)	**X_1(Ω/km)**	**B_1(μS/km)**	**R_0(Ω/km)**	**X_0(Ω/km)**	**B_0(μS/km)**
Swan25	1,351000	0,469556	2,895714	1,498453	2,000771	1,287256
Raven63	0,534900	0,416756	3,139157	0,682353	1,947971	1,333076
3x50/25	0,641000	0,116239	50,265482	3,958279	0,168642	50,265482
3x95/25	0,320000	0,106814	59,690260	3,637264	0,152318	59,690260

In Table 5.4 the terms R_1, X_1 and B_1 refer to the positive sequence parameters and R_0, X_0 and B_0 represent the zero sequence parameters. The cable's zero sequence impedance is calculated with equation (19) introduced in Section 3.1.2. The term B stands for line susceptance, which means the line's capacitance to earth. Susceptance is reciprocal of the line capacitive reactance. X is the line inductance. The values given in Table 5.4 are calculated with equations (26) and (27) introduced below.

$$X_1 = j\omega L = j2\pi f L \tag{26}$$

$$B_1 = j\omega C_0 = j2\pi f C_0 \tag{27}$$

Other values used when calculating the zero sequence impedance of the cables are listed below.

- Permeability $\mu_0=4\pi*10^{-7}$
- $\omega=2\pi f$
- Frequency f=50Hz
- Ground resistivity ρ=2500Ωm
- Earthing resistance $R_{e1}=R_{e2}$=7Ω

As can be noticed from Table 5.4 the cables capacitance to earth is much larger than in OHL. This is why underground cable produces more capacitive earth-fault current than the OHL. It can also be seen that the inductance of the OHL is larger than the inductance of a cable whereas the zero sequence resistance of the cable is much larger.

Throughout this study the cables are assumed to be earthed only in the distribution transformers. Earthing wire is not used.

5.1.2. Modeled network

The Finnish rural area network consists of fairly long medium voltage feeders and several small consumption points. Because the main issue in this study is not to model the rural area network's electricity consumption but to examine the earth-fault current and the reactive power produced by the underground cable, the aim is not to model the network exactly as it is in real life. The model used throughout this study is a roughly simplified model of the Finnish rural area network. The model is illustrated in Figure 5.1.

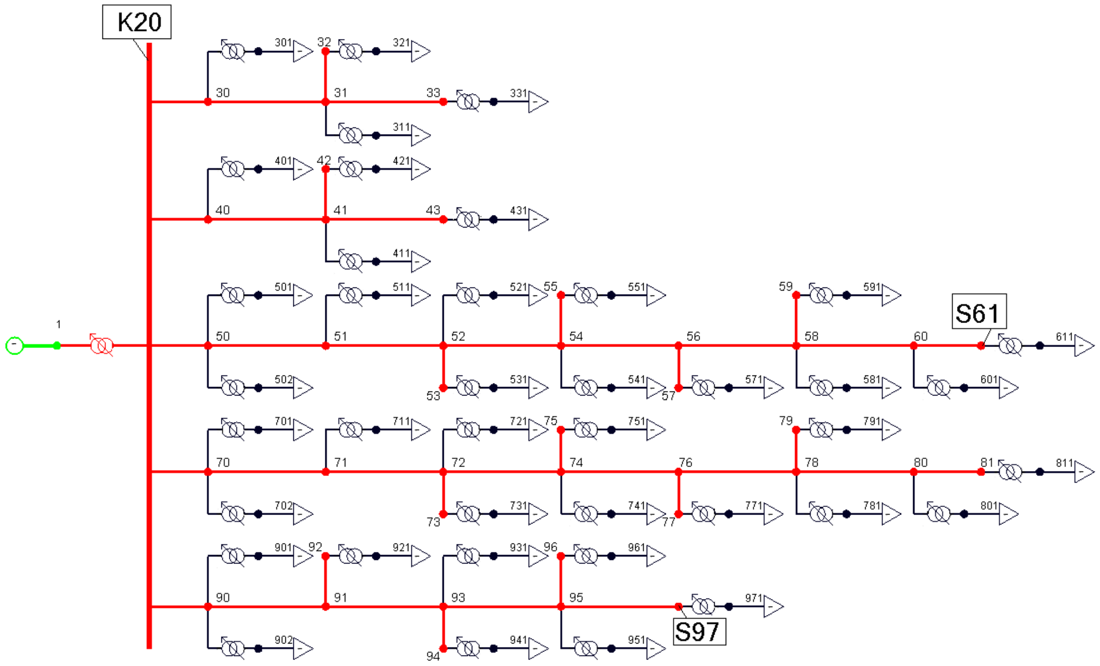


Figure 5.1 *Modeled network*

The network parameters are listed below. The network is fed from one point which is connected to high voltage network (110kV). In the network model the background network is represented with a generator. The main transformer is considered to be Yd-coupled, which means that the network is connected to a star in the HV side and to a delta in the MV side. There are no ground connections. The distribution transformers are Dyn-coupled, which means that the low voltage side has also a ground connection. This will not, however, affect the earth-fault behavior in the MV side. The transformer sizes are chosen to correspond to those used in average Finnish rural area networks.

- Main transformer 16MVA
- Five feeders, total network length 200km.

- Distribution transformers 100kVA/15A
- Loads 50kW,10kVAr
- Short-circuit effect of the 110kV network is 600MVA

In this study, the distributed compensation is executed with 100kVA transformers which produce 15A of compensative current. This type of transformer is used, because it was the only transformer with zero sequence impedance data available.

The base values are calculated as shown below

- Base power S_b=100MVA, base voltage U_b=20,6kV
- Base impedance $Z_b = \frac{U_b^2}{S_b} = \frac{(20600V)^2}{100000000VA} = 4{,}2436\Omega$

The fault resistances are entered as per unit values, which can be calculated by dividing the fault resistance with the basic impedance. PSS/E accepts no decimals when entering the fault resistance, which is why the values are rounded up:

- solid earth fault = 1pu
- 5kΩ: $r_{5k\Omega} = \frac{R_{5k\Omega}}{Z_b} = \frac{5000\Omega}{4{,}2436\Omega} \approx 1178pu$
- 10kΩ: $r_{10k\Omega} = \frac{R_{10k\Omega}}{Z_b} = \frac{10000\Omega}{4{,}2436\Omega} \approx 2537pu$

Usually, in Finnish rural area networks one or two feeders feed urban areas and from one to four feeders feed the rural areas. The feeder lengths may grow up to tens of kilometers because the country side may be very sparsely inhabited here and there. In this network model the feeder lengths are chosen to correspond to an average rural area network. The feeder lengths are listed in Table 5.5.

Table 5.5.

Feeder	
	length (km)
L1	20
L2	20
L3	60
L4	60
L5	40

As stated in Section 3.1.5 the earth-fault behavior in branched feeders is somewhat similar to that of a single radial feeder but less severe. Therefore the model used in this work is built as branched. Real rural area networks are usually much more branched than illustrated in this model and therefore using purely radial feeders would lead to incorrect conclusions. The loadings are rough estimations.

Table 5.6.

Transformer data		
	Main transformer	**Distribution transformer**
Losses (W)	85300	2000
Short-circuit impedance (%)	10,2	4
Apparent power (MVA)	16	0,1
U_{n1}(kV)/U_{n2}(kV)	110/20,6	20,6/0,4
R_{ground}(Ω)	2140	13,1
X_{ground} (Ω)	-	845
R_{zero} (Ω)	4,054	19,4
X_{zero} (Ω)	9,7439	16,3

Table 5.6 presents the transformer data. It is to be noticed that the resistance and reactance values represented in this table are also entered to PSS/E as per unit values. The short-circuit impedance values are taken from the network information system Xpower and are represented as percent values. The nominal voltage used throughout these calculations is 20,6kV. The R_{ground} in the case of the main transformer means the resistance which is in parallel with the compensation coil. The voltage over the resistance is U_r=500V and when corrected to correspond to the voltage level of 20,6kV. This is also illustrated in Figure 5.2:

$$R_{ground} = \left(\frac{U_{n2}/\sqrt{3}}{U_r}\right)^2 * R = \left(\frac{20600V/\sqrt{3}}{500V}\right)^2 * 3{,}780\Omega \approx 2140\Omega$$

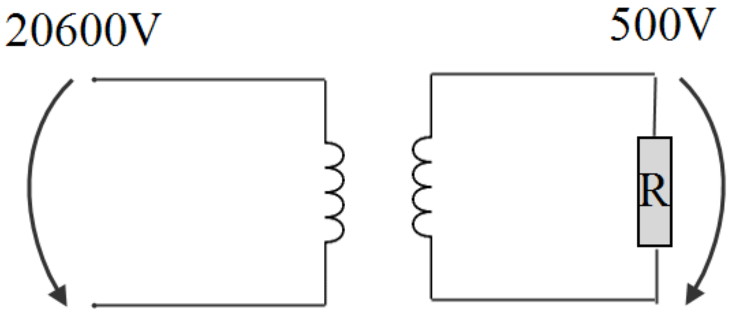


Figure 5.2 *Neutral point resistance corrected to correspond to the voltage level of 20,6kV*

In case of the main transformer the X_{ground} means the centralized Petersen coil's inductive reactance which is tuned to correspond to the produced capacitive current. In the case of the distribution transformer R_{ground} and X_{ground} refer to the distributed Petersen coil's resistance and reactance. R_{zero} and X_{zero} refer to the zero sequence impedance of the Petersen coil. In the case of the main transformer this data is the zero sequence data of the earthing transformer. This data is used because the main transformer has no conductive connection to earth because it is Yd-coupled as told earlier. In case of the distribution transformer this is the zero sequence data of the Zn(d)yn11-coupled transformer. Vattenfall uses nowadays Znzn0-coupled transformers but because of the difficulties in finding the zero sequence data for this type of transformer the data for Zn(d)yn-coupled transformer is used. The magnitude of Znzn0-coupled transformer is very much similar to that of a Zn(d)yn-coupled transformer.

5.1.3. Performed calculations

First the network consists purely of OHL. By replacing some parts with underground cable and comparing the effects of centralized and distributed compensation to a non-compensated situation and to the original state it is possible to see the influences of cabling to the earth-fault current. Also the produced reactive power is examined. The cabling takes place in the feeder L3. This way it is possible to examine also the effects of a long feeder on the earth-fault current. The faults are placed to the bus bar K20 (K20), and to the end of the feeders L3 to bus S61 and to the end of the feeder L5 to bus S97, as presented in Figure 5.1. The higher impedance earth-faults are examined only in case of an end of the line faults because it is of interest to examine the fault detection capability in these cases. The examined faults are solid earth-fault, 5kΩ earth-fault and 10kΩ earth-fault. These are chosen because within Vattenfall the protection is adjusted to detect faults up to 5kΩ and, if possible in terms of the network properties and the fault detection, the sensitivity is aimed to reach 10kΩ.

First the cabled place is examined. An OHL feeder usually contains some parts of newer OHL which has a longer life expectancy than the older OHL built in the 1960s. Therefore a common solution is to cable in smaller parts, not necessarily from the beginning of the feeder but the cabling may take place also in the central part or at the end of the feeder. Therefore it is of interest to examine whether this type of cabling in smaller pieces affects the earth-fault behavior. The studies are made regarding the cabling of the feeder L3 and the cabling is made in five kilometer parts. The affects are examined up to 15 kilometers at this point and the results are introduced in Section 6.1.1.

Second, the earth-fault current behavior is examined when the whole trunk line is cabled. This is compared with a situation where the capacitive earth-fault current is compensated with the usage of a centralized Petersen coil and with the usage of distributed Petersen coils. The aim is to show how the earth-fault current behavior changes, as compensation is introduced. These results are introduced in Section 6.1.2. From the network protection point of view, this section also illustrates, why the distributed compensation should not be done how it is done in this Section, for it causes the protection to function falsely. This is due to the over-compensating, distributed Petersen coil, but in the absence of the zero sequence data for other transformer types, this coil had to be used.

The results of the high impedance fault calculation are presented in Section 6.1.3. Because Section 6.1.2 introduced a way the distributed compensation should not be executed, the aim in Section 6.1.4 is to give an example, how the distributed compensation could be executed so that it using 15A coils will not cause the protection to function falsely. Section 6.1.4 represents the calculation results for partially compensated network.

Third, a combination of compensation methods is introduced. The aim is to find an ideal solution to compensate the modeled network by means of centralized and distributed compensation. These results are presented in Section 6.1.5 in case of a totally cabled network. The final research deals with the reactive power production of the cable and the voltage rise at the end of the feeder due to the reactive power production. The aim is just to compare the situation in which the network is purely OHL network and when the OHLs are replaced with underground cable. The idea is to show that the need for some kind of power compensation devices for the reactive power compensation increases tremendously as the cabling takes place. The results are presented in Section 6.2 (the reactive power generation) and 6.3 (the voltage rise).

5.2. Recloser placement

After the storm Gudrun in 2005 the Swedish network operators started to replace the old OHL with underground cable. During the past few years the pace with which the cabling has taken place has slowed down and the attention has been paid to other methods of improving the quality of delivery. In rural area networks, for example, cabling the network may not always be the most cost-effective solution because the customer amounts are fairly small and the distances may grow up to tens of kilometers. Vattenfall Sweden started to invest in remote controllable disconnectors and now the reclosers are also of interest.

The recloser placement is studied with an example network from eastern Sweden. The network lies in Norrtälje and from this particular network one problematic feeder is examined. The example network is a 10kV network with over thousand customers. In the studies the aim is to show how adding a recloser to the network affects the reliability of delivery. The network environment, i.e. whether the transmission lines go through forests or fields, is not taken into consideration.

Because of inadequate fault statistics, the feeder is simply divided into parts which all have been given a percentage value for the number of faults that occur in that particular section during one year. The percentage values are based on the experience and to 8 faults occurring years 2005-2009 that could be located. The study should be considered as a directional study, for in the absence of inclusive fault statistic any absolute calculation results would be difficult to introduce. The calculations are performed with Microsoft Office Excel.

The total number of customers and how the customers are spread on the feeder is illustrated in Figure 5.3. The total amount of customers is 1029 and in the figure the amounts are given as the amount between two disconnectors. The disconnectors are also shown in Figure 5.3. An open disconnector is indicated with two parallel lines and a closed disconnector with one. The cabled feeder parts are presented as dashed lines and the solid line refers to OHL. The Spillersboda 10kV network is colored with red and the backup feeding 10kV transmission lines are black. The green color indicates the 20kV medium voltage line which feeds the 10kV network and the purple color indicates the 70kV network. The power stations are marked with a black rectangle.

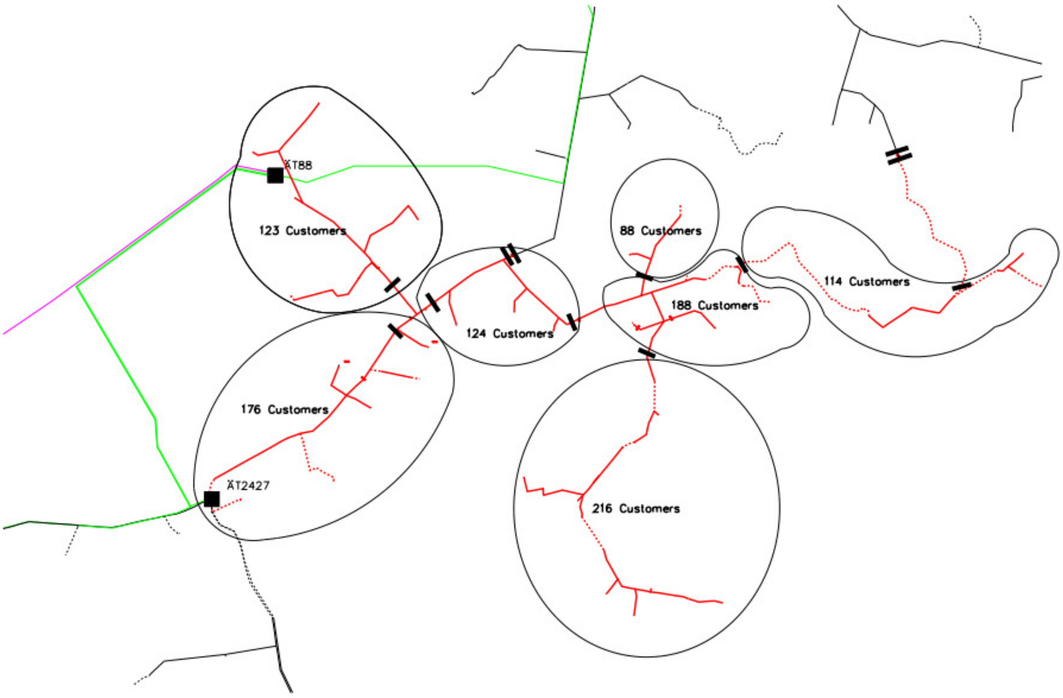


Figure 5.3 *Spillersboda –network*

When defining the possible recloser places it is good to remember a few things. It is rarely reasonable to place the recloser in front of a cabled network. This is because the faults in cabled networks are rarely of the kind of faults which the recloser could clear. As mentioned in Section 2.3.4, the common factors causing the faults in cabled networks are material failures and the possible harm done during the excavation work. In addition to this, if the auto-reclosing is used with the recloser, it strains the cable if the cable is already damaged. This means, for example, that the isolation is damaged and when the cable experiences several reclosings, it may lead to even more severe damages.

Another thing to remember is that the more the recloser can spare customers from experiencing the fault, the more beneficial it is from the customer point of view. Therefore it is rarely reasonable to place the recloser near the power station in which case a great deal of the customers would lie behind the recloser. The situation is different if in the beginning of the feeder there is for example an industrial plant which must be protected from a fault occurring further in the network. Also placing the recloser very far in the network with a fairly small area to be sectionalized is not reasonable, unless the part, which the recloser separates from the rest of the network, is very problematic.

As told earlier in this study the feeder is divided into parts which all have their own fault percentages. This is represented in Figure 5.4. The figure also introduces the possible recloser places in the network and the backup feeding points. There are three places that are going to be examined, which are chosen according to the following criteria:

- There must be a disconnector in order to have a clearance between open contacts.
- The place must lie neither too far in the network nor too close to the power station.
- The part which the feeder sectionalizes should not consist mainly of cable

The average fault clearance time in this area is around one hour, i.e. the time it takes to limit the fault to a smallest possible area and to restore electricity to some parts of the network. The average fault repairing time is two hours.

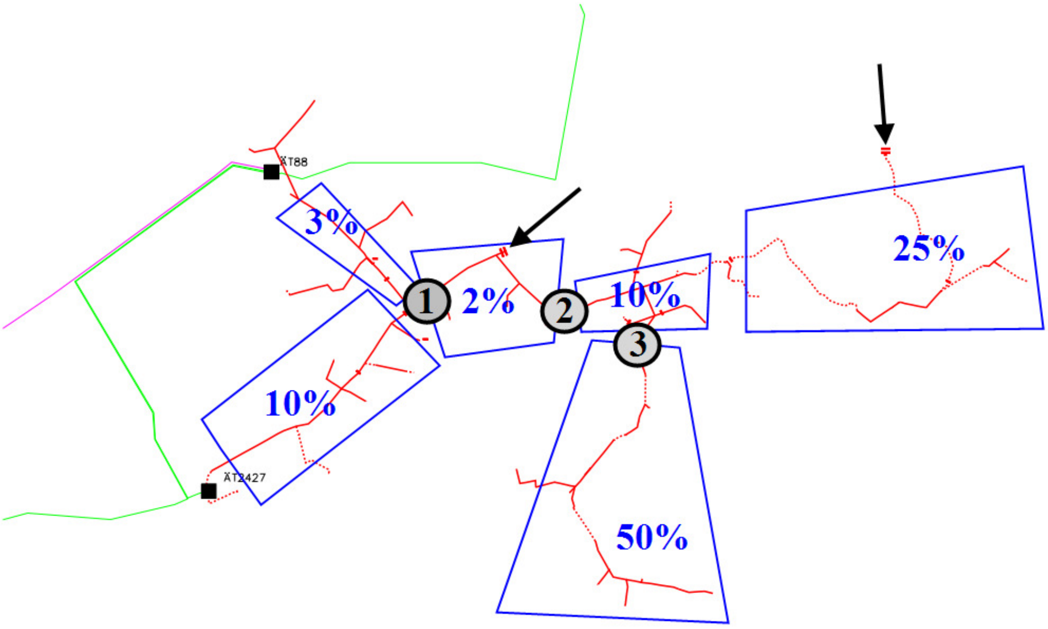


Figure 5.4 *Spillersboda network with recloser places and fault percentages*

In Section 6.4 the results are represented regarding this network calculation. The results contain SAIFI, MAIFI and SAIDI figures and the total number of customer hours. The calculations are performed with an Excel-sheet, which is presented in Appendix 7. In the Excel-sheet the number of faults can be entered as well as the number of high-speed auto-reclosings, delayed auto-reclosings and the average fault clearance and reparation time. Section 6.4 also gives an example of the reclosers protection settings and how the feeder relay protection should be set so that the selectivity is ensured.

6. RESULTS

6.1. Rural area network cabling

Throughout the modeling the faults are considered to occur in the bus bar, at bus S61 and at bus S97. The earth-fault currents are calculated in case of a solid earth-fault (4,2436Ω), 5kΩ earth-fault and a 10kΩ earth-fault. The higher impedance earth-faults are considered to occur only in the buses S61 and S97. This is because the fault detection capability in case of a high impedance fault further in the network is of interest. In the following tables the total earth-fault current is marked with I_f as it has been marked throughout this study and the earth-fault current the relay sees as I_0. In the appendixes the total earth-fault current is marked with *3I0* as the PSS/E gives it. In the appendixes this notation is kept in order to represent the values as given by PSS/E. This way one can repeat the calculations if needed and the results would be gained in the same form. In order to clarify the difference between the neutral point displacement voltage and the zero sequence voltage, the neutral point displacement voltage is marked with U_0 and the zero sequence voltage as U_{0Z}.

It is to be noticed that the phase-angles given by PSS/E are presented in respect with the phase-angle zero. The phase-shift $\Delta\varphi$ is calculated from the voltage and current phase-angles. It is also good to keep in mind that PSS/E gives the current values with accuracy of one decimal and zero sequence voltage values in accuracy of three decimals. This may in some cases cause minor deviation in calculation results. PSS/E represents the conductors as pi-sections, so the correction factors need not to be used.

Table 6.1

Solid earth-fault at bus S97				
VOLTAGE	U_0	φ_{U0}		
	11,996	178,12		
CURRENTS	I_0	φ_{I0}	$\Delta\varphi$	I_{0r}
TO GEN	0	0	178,12	0,0000000
TO L1	1	-91,88	270	0,0000000
TO L2	1	-91,88	270	0,0000000
TO L3	2,8	-91,92	270,04	0,0019548
TO L4	2,9	-91,92	270,04	0,0020246
TO L5	7,6	88,09	90,03	-0,0039794

In Table 6.1 the PSS/E calculation results are shown when a solid earth-fault occurs at the end of the feeder L5 in isolated network. The purpose of this table is to demonstrate the flow of the earth-fault current in the network. In this case the network consists of pure OHL. The current values are represented as seen from the bus bar. U_0 is the neutral point displacement. φ_{U0} is the phase-angle of the neutral point displacement voltage and I_0 is the earth-fault current at the bus bar, φ_{I0} is the phase-angle of the earth-fault current in respect with angle zero. $\Delta\varphi = \varphi_{U0} - \varphi_{I0}$ and it represents the phase-shift between the zero sequence current and the neutral point displacement voltage. I_{0r} is the resistive current component at the bus bar, which is calculated with the following equation (28).

$$I_{0r} = I_0 * \cos(\Delta\varphi) \tag{28}$$

As a solid earth-fault occurs at the end of feeder L5, the phase-to-earth voltage at the faulty feeder is reduced close to zero. The voltages at the healthy phases rise almost to the magnitude of phase-to-phase voltage. This gives rise to the zero sequence voltage. The earth-fault current flows from the healthy feeders towards the bus bar, which can be seen from Table 6.1 when the phase-shift of the fault currents from the healthy feeders is 270°. It can be noticed that the short OHL feeders L1 and L2 produce only a small amount of earth-fault current, and the produced resistive current is zero. Feeders L3 and L4 are the longest (60km each) and produce more earth-fault current. The zero sequence impedance was also calculated for OHLs as explained in Section 5.1.1 which shows as a minor resistive component. As can be noticed, the resistive current produced by a fairly long OHL is very small and can therefore be neglected. This is in accordance with the conventional earth-fault analysis.

The earth-fault current flows from the bus bar towards the fault point at the end of the feeder L5. This shows as a phase-shift of 90,03°. The phase shift is illustrated below in Figure 6.1. The figure shows how the total, the capacitive and the resistive currents are directed in comparison with the phase-angle of the neutral point displacement voltage. The current magnitudes in the figure are imaginative. In real networks the resistive component can be adjusted to be in phase with the neutral point displacement voltage by connecting the measurement transformers poles contrariwise, and the resulting vector is as represented earlier in Figure 4.6.

The resistive current component is the sum of the resistive currents produced by the feeders L3 and L4. However, these current values represented in Table 6.1 do not include the earth-fault current produced along the faulty feeder itself. The current coming from the transformer (TO GEN) is zero, for the transformer has no conductive connection to ground.

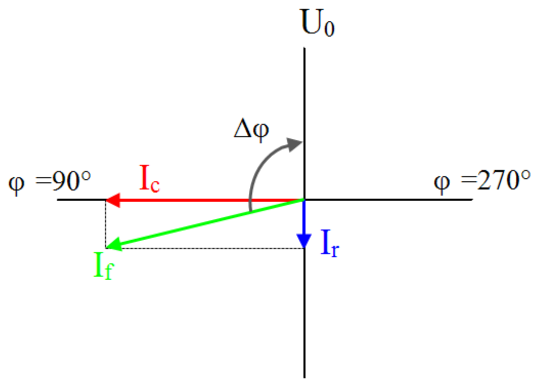


Figure 6.1. *An illustration of the current components in case of a solid earth-fault at the end of the feeder L5.*

Table 6.2 introduces the total earth-fault currents and *Δφ* as a solid earth-fault, 5kΩ and 10kΩ earth-faults occur in buses K20, S61 and S97. The network is pure OHL. The fault currents are introduced as seen from the fault point. It can be seen that the total earth-fault current is rather small in pure OHL network. From Table 6.2 it can be calculated that the average earth-fault current produced by OHL is 0,047A/km according to the model. Appendix 2 introduces the PSS/E calculation results for purely OH network.

Table 6.2

Total I_f and Δφ at the fault point

	K20		**S61**		**S97**	
	I_f (A)	**Δφ (°)**	**I_f (A)**	**Δφ (°)**	**I_f (A)**	**Δφ (°)**
solid	9,4	90,03	9,4	90,32	9,5	90,24
5kΩ	-	-	2,3	90,32	2,3	90,24
10kΩ	-	-	1,2	90,32	1,2	90,24

It can be noticed, that the phase-shift *Δφ* is a little larger when the fault is at the end of some feeder. This is because the values are measured from the fault point, and therefore the current includes also the earth-fault current which is produced along the faulty feeder, on contrary to the values represented in Table 6.1. The small resistive current causes the phase-angle to turn, which is why the phase-shift is different in different fault locations. The change in the phase-shift is very small and the resistive current is negligible. It can be noticed that the earth-fault currents are almost the same regardless of the fault point. Therefore it can be stated, that in OHL network the fault point is insignificant.

Table 6.3

Total I_0 and $\Delta\varphi$ at the bus bar						
	K20		**S61**		**S97**	
	I_0 (A)	**$\Delta\varphi$ (°)**	**I_0 (A)**	**$\Delta\varphi$ (°)**	**I_0 (A)**	**$\Delta\varphi$ (°)**
solid	9,4	90,03	6,6	90,03	7,6	90,03
5kΩ	-	-	1,6	90,03	1,8	90,04
10kΩ	-	-	0,8	90,03	0,9	90,03

Table 6.3 introduces the earth-fault currents as seen from the bus bar. The current values are the values that the protection relay sees. This value does not include that part of earth-fault current which is produced along the faulty feeder. This is why the current values are smaller in cases, where the fault occurs at the end of some feeder. When the fault occurs at bus S97 the earth-fault current at the bus bar is larger than in the case where the fault is at bus S61. This is because the feeder L3 is 20km longer than the feeder L5. Thus as the fault occurs at bus S61, the network producing the earth-fault current is 20km shorter in total length. The rest of the earth-fault current is produced along the faulty feeder itself. It can be noticed that the phase-shift between the neutral point displacement voltage and the earth-fault current is the same regardless of the fault point and fault resistance.

Table 6.4 introduces the voltages when the fault occurs in buses K20, S61 and S97. The voltages are given as seen from the bus bar (U_0) and as seen at the fault point (U_{0Z}). It can be noticed that the neutral point displacement voltage and the zero sequence voltage at the fault point vary a little bit. This is because of the voltage drop in positive sequence network. As stated in the theory, the zero sequence voltage rises to the magnitude of the pre-fault phase-to-earth voltage value. As the voltage drops over the networks resistances and over the loads, the phase-to-earth voltage at the end of the line is smaller than in the bus bar. Therefore also the zero sequence voltage is a bit smaller. The zero sequence network has no significant influence on the earth-fault behavior.

Table 6.4

U_0 and U_{0Z} (V)					
	K20	**S61**		**S97**	
		U_0	**U_{0Z}**	**U_0**	**U_{0Z}**
solid	11,891	11,99	11,783	11,996	11,859
5kΩ	-	2,868	2,818	2,893	2,859
10kΩ	-	1,468	1,443	1,48	1,463

As explained in Section 4.4.2 the directional earth-fault relay trips, as the zero sequence current, the zero sequence voltage and the angle between these two exceed the threshold values. The modern relays are able to detect even lower zero sequence current than 1A, but due to the natural asymmetry of the network and the minor error caused by the measurement transformers, it is rarely practical to use such low threshold values. Usually the relays are set to detect faults in the magnitude of 1-2A and voltages of 3-5% of the phase-to-earth voltage in isolated networks. In compensated networks the zero sequence voltage threshold value is set higher, because the zero sequence voltage in compensated networks is higher than in isolated networks. This will be explained more thoroughly later on.

In isolated networks the relays are able to detect zero sequence voltages of approximately (3-5%):

$$U_v = \frac{U}{\sqrt{3}} = \frac{20600V}{\sqrt{3}} = 11893{,}42V \approx 11900V$$

$$U_{relay} = 0{,}03 * 11900V = 357V$$

or

$$U_{relay} = 0{,}05 * 11900V = 595V$$

From Table 6.3 and 6.4 it can be seen that the fault currents in case of higher impedance faults are very small and in case of the 10kΩ fault the relays would not probably be able to detect the fault. The neutral point displacement voltage value exceeds the threshold value, but also the earth-fault current threshold value must be exceeded in order to the relay to perform the tripping.

6.1.1. Starting the cabling

Cabling the whole feeder at once is rarely a profitable solution. Furthermore, in old OHL networks there usually are some parts which are at the end of their life cycle and which have to be replaced. And because Vattenfall Finland has made a strategic decision not to build any more new OHLs, the replacement of the old OHL is done with underground cable. Vattenfall Sweden also has cabling as their first option, but also coated OHL is still used. Nevertheless, if the replacement of the old OHL part is done with underground cable, it may lead to situations where cable parts of only approximately 5-15 km are situated in different parts of the network. This is why it is of interest to study whether the cable placement affects the earth-fault current behavior. The PSS/E calculation results regarding the influence of the cabled place can be found in Appendix 3.

In this section the earth-fault current is studied as the cabling is started in an isolated network at the beginning of the feeder, from the centre of the feeder and at the end of the line. Only the trunk line is cabled and the used cable type is AXAL95. The higher impedance earth-faults are not treated in this section for it is of interest to examine, whether the cabled place has some kinds of effects on the earth-fault current behavior.

Table 6.5 introduces the earth-fault current the cabled network part produces i.e. the current that the feeder L3 produces and the total amount of earth-fault current in the network and the phase-shift $\Delta\varphi$. I_0 refers to the total earth-fault current at the bus bar produced by feeder L3, I_{0r} to the resistive part of the earth-fault current seen at the bus bar.

Table 6.5

Solid earth-fault at the bus bar							
		produced by L3			**Total I_0**		
Cabled		**I_0 (A)**	**$\Delta\varphi$ (°)**	**I_{0r} (A)**	**I_0 (A)**	**$\Delta\varphi$ (°)**	**I_{0r} (A)**
0 km		2,8	90,05	-0,0024435	9,4	90,03	-0,0049218
5km	beginning of the feeder	13,3	90,15	-0,0348193	19,8	90,11	-0,0380132
	in the middle	13,4	90,31	-0,0725006	20,0	90,22	-0,0767943
	end of the feeder	13,5	90,50	-0,1178082	20,1	90,34	-0,1192751
10km	beginning of the feeder	23,8	90,49	-0,2035378	30,4	90,39	-0,2069246
	in the middle	24,2	90,82	-0,3463313	30,8	90,65	-0,3494074
	end of the feeder	24,6	91,11	-0,4765498	31,2	90,88	-0,4791788
15km	beginning of the feeder	34,3	91,03	-0,6165742	40,9	90,87	-0,6210166
	in the middle	35,3	91,53	-0,9425229	41,9	91,29	-0,9432882
	end of the feeder	35,9	91,84	-1,1526965	42,5	91,55	-1,1495954

By comparing the results it can be noticed that almost all of the earth-fault current is produced by the cabled feeder L3. The rest of the earth-fault current is from the OHL feeders but as seen from Table 6.5 these have a minor influence on the total amount of the earth-fault current. It can also be noticed that whether the cabling is started from the end or from the beginning of the feeder, the influence on the resistive earth-fault current component is fairly small. The largest resistive currents are in cases in which the cabling is started from the end of the feeder. This is because the greatest part of the earth-fault current is produced at the end of the feeder. And the larger the earth-fault current is, the larger the influence of the zero sequence impedance. Now that a great amount of the total earth-fault current must flow through the phase lines zero sequence series impedances, it produces the resistive current. This is why the resistive current is larger, as the cabling is done further in the network. This can be also seen from the changes in $\Delta\varphi$.

From Table 6.5 it can be calculated that the increase in earth-fault current due to the cabling of 5km of feeder length is approximately 10 -11A/5km depending on the cabled amount and place. According to the manufacturer's data, AXAL95 produces 2,50A earth-fault current at the rated voltage, which is 24kV. From Table 6.4 it can be calculated that with the voltage used in this study (20,6kV) the cable produces ~2.1A/km. It must be noticed that the produced earth-fault current is not a fixed value because of the resistive earth-fault current produced in the cables' series impedances. It is also good to keep in mind, that in this case only one feeder is partly cabled. If the network contains several long feeders with 5-15 kilometers of cable in each of these, the influence would be larger than in this particular case. This means that, if 15km of one feeder is cabled, the resistive current is around 1,15A. If another 15km is cabled at the end of another long feeder, which also adds its influence on the earth-fault behavior, the result would be different. The total earth-fault current would be larger and it is reasonable to assume that the resistive current component would also be larger. The effects of the resistive current component are demonstrated in the following, very simplified example:

Section 3.2 introduced the human body's impedances. It was also introduced in Section 5.1.1 that the used earthing resistance used in this study is 7Ω. If it is assumed that a network contains 5 fairly long feeders and in each of these feeders the last 15 kilometers are cabled, and the network would be compensated so that the produced capacitive and inductive current would cancel each other out completely. One 15km cable part would produce approximately 1,15A of resistive earth-fault current and therefore the total resistive earth-fault current would be approximately 5,75A. It can be calculated with equation (4) introduced in Section 2.3.1 that when using the earthing resistance of 7Ω, the voltage to earth would be

$$U_m = I_r * R_m = 5{,}75A * 7\Omega = 40{,}25V \text{ .}$$

As represented in Section 3.2 a part of the voltage to earth, namely contact voltage, is experienced by a person touching the energized equipment. As the voltage is <100V, the impedance of the human body can be assumed to be Z_{body}=3125Ω. The maximum current passing through a person's body would be

$$I_{\max} = \frac{U_m}{Z_{body}} = \frac{40{,}25V}{3125\Omega} = 0{,}01288A \approx 13mA$$

Though this is just the worst case scenario in a network which would contain several long feeders and realistically a person would experience only a part of the voltage to earth, it was stated in Section 3.2 that a 5-10mA current passing through the human body may cause incapability to control ones muscles and to let go of energized equipment. This kind of situation lasting long enough may cause severe injuries. Therefore the increase in resistive current should not be ignored when cabling fairly short pieces but in several parts of the network.

Table 6.6 introduces the earth-fault currents as a solid earth-fault occurs at bus S61 in an isolated network. The results are represented as seen from the bus bar (I_0 and I_{0r}) and as seen from the fault point (I_f and I_r). It can be noticed that when observing the earth-fault currents at the bus bar, the total I_0 does not change that much. This is because the cabled feeder L3 also has the fault at the end of the line. Therefore the relays at the bus bar see only the earth-fault current that comes from the healthy feeders, and this current amount does not include the part of the fault current, which is produced along the faulty feeder.

In Table 6.6 it can be noticed that as 5km has been cabled in the middle of the feeder, the resistive current is 0,0023736A. This is due to the slightly smaller phase-shift of 90,02°, whereas in other cases the phase shift is 90,03°. This is probably due to the up rounding of the PSS/E, which may cause some calculation error. The same can be seen from the case in which 10km has been cabled at the beginning of the feeder.

When looking at Table 6.5 which introduced the earth-fault currents as the fault occurred at the bus bar, it can be noticed that in this case the earth-fault current increased, as the cabling was done further in the network. This was due to the increase in the resistive current component. Now, when looking at Table 6.6, it can be seen that the earth-fault current decreases, as the cabling is done further in the network. This phenomenon was discussed in Section 3.1.5 which introduced the sequence network coupling in case of an earth-fault at the end of a cabled line. It was explained, that in case of an end of the line fault, the positive and the negative sequence network are also connected to the zero sequence network, which affects the earth-fault current behavior. When the fault is at the end of the partly cabled feeder L3, the voltage drops over the positive and the negative sequence networks. Therefore also the voltage at the fault point is a bit lower, and as the earth-fault current is directly proportional to the voltage according to equations represented earlier in this study, the produced earth-fault current is also smaller. Also the resistive current decreases as the cabling is done further in the network. This can also be seen as changes in the phase-shift between the voltage phase-angle and the current phase-angle.

Table 6.6

Solid earth-fault at bus S61							
		At the bus bar			**At the fault point**		
Cabled		**I_0 (A)**	**$\Delta\varphi$ (°)**	**I_{0r} (A)**	**I_f (A)**	**$\Delta\varphi$ (°)**	**I_r (A)**
0 km		6,6	90,03	-0,0034558	9,4	90,32	-0,0524992
5km	beginning of the feeder	6,8	90,03	-0,0035605	20,5	90,92	-0,3291550
	in the middle	6,8	90,02	-0,0023736	20,3	90,72	-0,2550906
	end of the feeder	6,7	90,03	-0,0035081	20,0	90,44	-0,1535875
10km	beginning of the feeder	7,0	90,02	-0,0024435	32,1	91,64	-0,9186857
	in the middle	6,9	90,03	-0,0036128	31,5	91,25	-0,6871689
	end of the feeder	6,8	90,03	-0,0035605	30,8	90,87	-0,4676605
15km	beginning of the feeder	7,1	90,03	-0,0037176	43,8	92,47	-1,8876171
	in the middle	6,9	90,03	-0,0036128	42,6	91,90	-1,4124106
	end of the feeder	6,8	90,03	-0,0035605	41,7	91,52	-1,1061297

Table 6.7 introduces the earth-fault currents as the fault occurs at the end of the feeder L5 at bus S97 in an isolated network. It can be noticed that on contrary to previous case, here the earth-fault current increases as the cabling is done further in the network. This case represented in Table 6.7 is almost similar to the one in which the fault was at the bus bar. As the cabling is done in feeder L3 and the fault occurs at the end of feeder L5, all the earth-fault current flows to the feeder L5, and therefore the earth-fault current there is much larger.

Whereas in the previous case the phase-shift decreased and therefore also the resistive current decreased as the cabling moved further to the network, now the phase-shift between the neutral point displacement voltage angle and the earth-fault current angle at the bus bar increases. Thereby also the resistive current increases. As explained in the case of a bus bar fault, the resistive current is larger as the cabling is done at the end of the feeder, because the fault current must travel a longer distance through the network's zero sequence series impedances. In some cases this influences also the neutral point displacement voltage, and it may be smaller at the bus bar than the zero sequence voltage at the fault point. This is because of the voltage drop in the zero sequence network over the zero sequence series impedances.

Table 6.7

Solid earth-fault at bus S97							
		At the bus bar			**At the fault point**		
Cabled		**I_0 (A)**	**Δφ (°)**	**I_{0r} (A)**	**I_f (A)**	**Δφ (°)**	**I_r (A)**
0 km		7,6	90,03	-0,0039794	9,5	90,24	-0,0397934
5km	beginning of the feeder	18,5	90,11	-0,0355174	20,4	90,61	-0,2171847
	in the middle	18,7	90,24	-0,0783301	20,5	90,73	-0,2611815
	end of the feeder	18,8	90,38	-0,1246854	20,7	90,87	-0,3143043
10km	beginning of the feeder	30,0	90,41	-0,2146737	31,9	91,21	-0,6736296
	in the middle	30,5	90,69	-0,3672957	32,4	91,49	-0,8424802
	end of the feeder	30,9	90,94	-0,5069256	32,8	91,75	-1,0016632
15km	beginning of the feeder	41,9	90,91	-0,6654486	43,9	92,04	-1,5627168
	in the middle	43,0	91,35	-1,0130699	45,0	92,52	-1,9785653
	end of the feeder	43,7	91,63	-1,2430478	45,7	92,82	-2,2483676

Now if the same kind of simplified analysis was made as in the case of a solid earth-fault at the bus bar, and each 15km cable part at the end of a feeder produced 2,25A of resistive earth-fault current according to Table 6.7, the total resistive earth-fault current would be:

$$I_r = 2{,}25A * 5 = 11{,}25A$$

The maximum voltage to earth with a 7Ω earthing resistance would be:

$$U_m = I_r * R_m = 11{,}25A * 7\Omega = 78{,}75V$$

The current flowing through a human body with body impedance of 3125Ω would be:

$$I_{\max} = \frac{U_m}{Z_{body}} = \frac{78{,}75V}{3125\Omega} = 0{,}0252A \approx 25{,}2mA$$

This amount of current may cause respiratory problems in addition to the incapability of letting go of the energized equipment.

Table 6.8 introduces the zero sequence voltages as a solid earth-fault occurs in buses S61 and S97 in an isolated network. U_0 is the neutral point displacement voltage at the bus bar and U_{0Z} is the zero sequence voltage at the faulty bus.

Table 6.8

Voltages during a solid earth-fault at buses S61 and S97					
		at bus S61		at bus S97	
		U_0	U_{0Z}	U_0	U_{0Z}
pure OHL		11,99	11,783	11,996	11,859
5km cabled	beginning of the feeder	12,369	11,931	12,278	11,964
	in the middle	12,268	11,941	12,28	11,964
	end of the feeder	12,137	11,955	12,283	11,965
10km cabled	beginning of the feeder	12,657	12,051	12,565	12,067
	in the middle	12,45	12,071	12,573	12,068
	end of the feeder	12,25	12,091	12,582	12,07
15km cabled	beginning of the feeder	12,843	12,142	12,854	12,166
	in the middle	12,528	12,172	12,873	12,169
	end of the feeder	12,327	12,192	12,885	12,171

When examining the earth-fault current values in the case of an earth-fault at bus S61, it was explained that the current traveling through the zero sequence series impedances may cause the neutral point displacement voltage to be lower than the zero sequence voltage at the faulty bus. However, when examining the results represented in Table 6.8, it can be noticed that the neutral point displacement voltage is actually higher at the bus bar than at the fault point, though the fault occurs at the end of the cabled feeder. This is probably because the largest part of the feeder is OHL, which does not have large zero sequence series impedance. Therefore the voltage does not drop in the zero sequence network. The voltage at the fault point is lower because of the voltage drop in the positive and the negative sequence networks, as explained in case of a bus bar fault. The situation is different in the case of a fault at bus S97 in isolated network, because as explained earlier, all of the earth-fault current coming from the network and especially from the cabled feeder L3 flows towards feeder L5.

6.1.2. Trunk line cabling

In Finland it is very common that in rural area networks the trunk line is cabled first. At some point the aim is to have a completely cabled network but usually the primary task is the trunk line cabling and the branches are cabled later. By this is possible to increase the reliability of delivery much more than by cabling the branches. In this section the results are represented regarding the L3 trunk line cabling. The behavior of the earth-fault current is examined in the case of a non-compensated network, centrally compensated network and regarding a network that is compensated with distributed Petersen coils. The cabling is started from the end of the line. The aim of this section is to demonstrate, why using distributed compensation is a good solution regarding the network protection. It will be discovered, that compensating the feeder with 15A

Petersen coils turns the earth-fault current into inductive. To avoid this situation, the solution of partially compensating the network is introduced in Section 6.1.4.

Although in real networks the centralized Petersen coils are not perfectly tuned to correspond to the capacitive earth-fault current, in this study the network is examined in resonance. Within Vattenfall Finland the network is used as 5% under-compensated. However, this kind of compensation degree would have been difficult to perform exactly with PSS/E which is why in this work the network is managed as perfectly tuned. As explained in Section 3.1.2, the unambiguousness of the zero sequence impedance of the cable leads to the need of some simplifications in order to analyze the earth-fault current behavior in cabled network, which is why treating the network as perfectly tuned is considered adequate in terms of this study.

The network is tuned to correspond to 10kΩ fault at the bus bar. This is because within Vattenfall Finland the aim is to be able to detect faults up to 10kΩ fault resistance. Table 6.9 represents the coils reactance when the network is tuned to correspond to 10kΩ and to 20kΩ faults. It can be noticed that whether the tuning is made according to 10kΩ earth-fault at the bus bar or according to 20kΩ earth-fault at the bus bar, the reactance in both cases is almost the same. Throughout this study the network will be used as tuned according to 10kΩ.

Table 6.9

Network tuning - the coil reactance (Ω)								
	5km	**10km**	**15km**	**20km**	**25km**	**30km**	**35km**	**40km**
10kΩ	590	381	281	222	185	160	142	129
20kΩ	600	380	281	222	185	160	142	129

The tuning is made simply by changing the reactance value of the coil and calculating the neutral point displacement voltage with PSS/E. The neutral point resistance value is given in Table 5.6 in Section 5.1.2. The curve that the neutral point displacement voltage draws as a function of the coil reactance is represented in Figure 6.2. This curve represents a situation where the network contains 5km of cable. The tuning is made to correspond to a 10kΩ fault at the bus bar. The resonance point is found at the peak value of the neutral point displacement voltage, which is in this figure represented with an arrow. This figure demonstrates how the coil is tuned. The calculations are repeated as the situation changes i.e. as the amount of cable in the network changes.

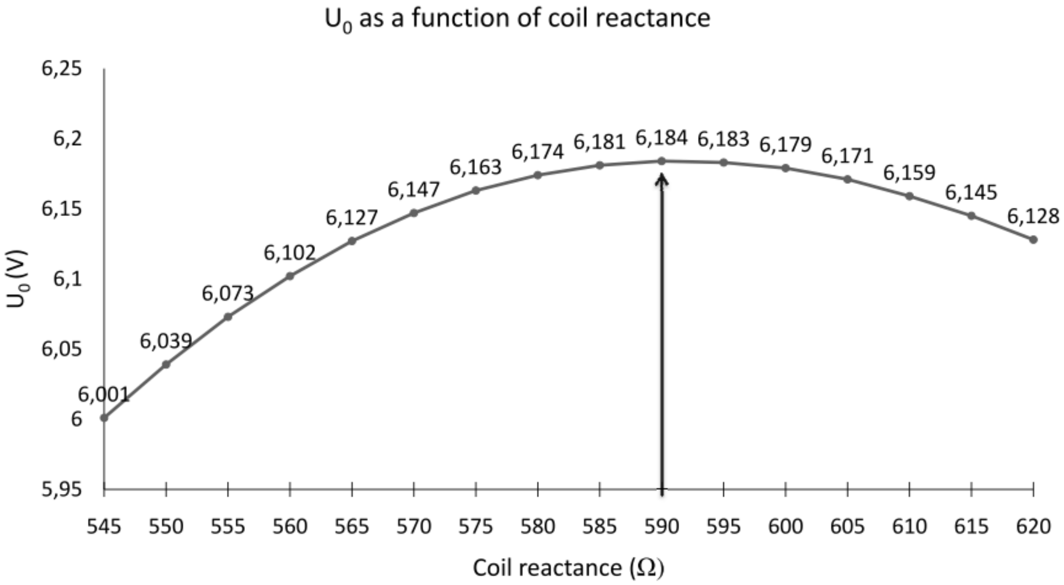


***Figure 6.2** The neutral point displacement voltage as a function of Petersen coils reactance during a 10kΩ fault at the bus bar.*

In these calculations the cabling is started at the end of the feeder. This is because as Section 6.1.1 introduced, the largest resistive current is in the situation where the cabling is started at the end of the feeder. The cabling takes place in 5km pieces and as an outcome the whole trunk line is cabled, i.e. 40km of the feeder L3 is cabled. The PSS/E calculation results can be found from Appendix 4.

Figure 6.3 represents the total I_f produced by the cabled feeder L3 in respect to the cabled amount. The values are as in a case where a solid earth-fault occurs at the bus bar. The produced earth-fault current is studied in a case where the network has no compensating devices and when the network is compensated centrally and with distributed Petersen coils. 0km means the situation where the network is purely OHL. In this case the network is studied only without compensation.

It is to be noticed that even though Figure 6.3 shows that the I_0, produced by the L3 in a centrally compensated situation, grows along with the non-compensated situation, this is not the total I_0 in the whole network. The compensative current is produced at the neutral point, when the fault circuit closes trough the neutral point equipment. Therefore the compensation is not seen in this figure which illustrates only the earth-fault current production in L3. In the next figure also the effects of the centralized compensation are seen.

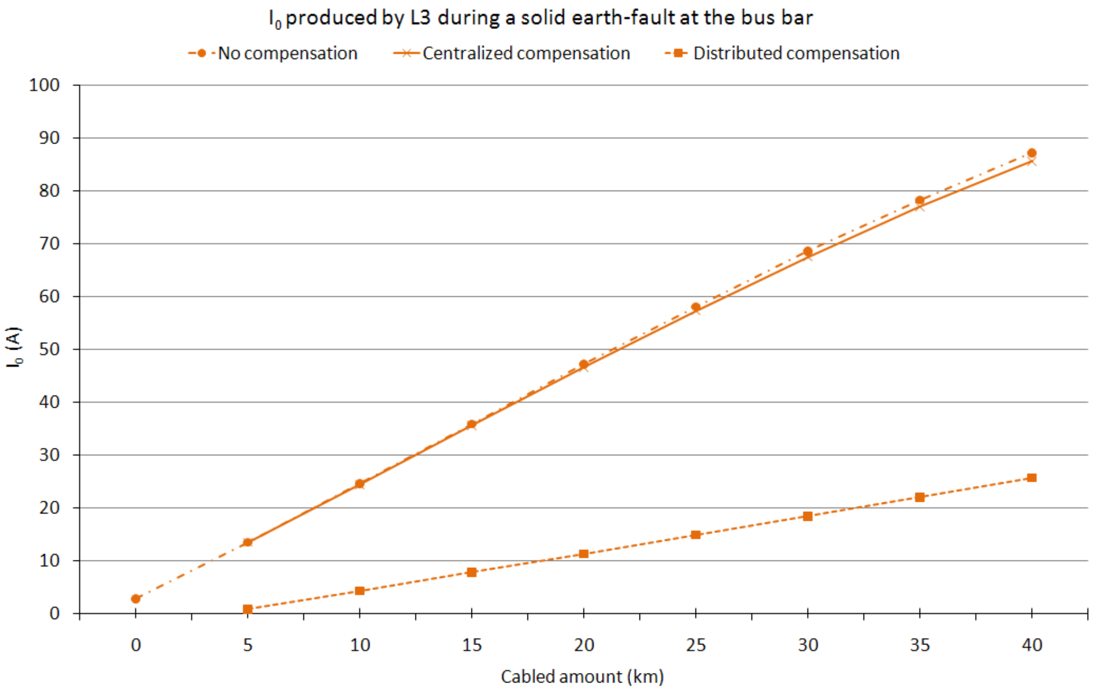


Figure 6.3 *The total I_0 produced by L3 during a solid earth-fault at the bus bar*

From Figure 6.3 it can be noticed that the production of earth-fault current is linear. The same pattern can be noticed from Figure 6.4 which introduces the total earth-fault current in the whole network as a solid earth-fault occurs at the bus bar. Also in this case the network is studied with no compensation, with centralized and with distributed compensation.

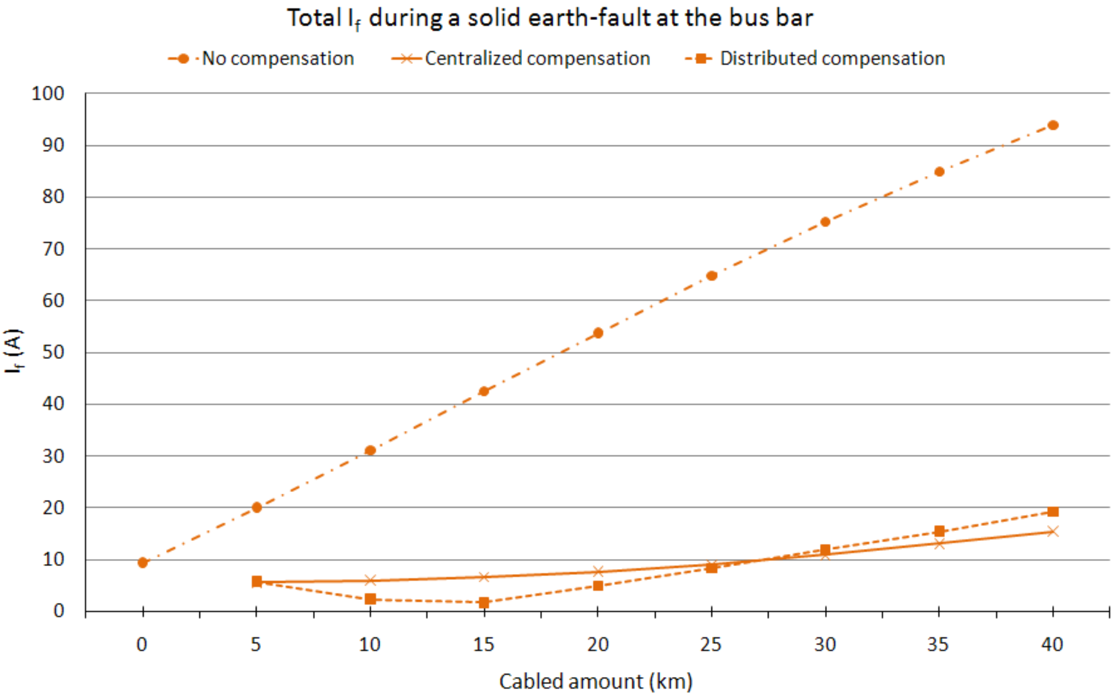


Figure 6.4 *Total I_f during a solid earth-fault at the bus bar*

In Figure 6.4 also the effects of centralized compensation are seen. When this is compared to the previous figure it can be noticed that due to the centralized compensation the total earth-fault current decreased remarkably. It can be seen that in this case the amount of earth-fault current does not increase linearly.

It can also be noticed from Figure 6.4 that the earth-fault current behaves quite strangely when the distributed compensation is introduced. This is because as stated in Section 6.1.1 the underground cable used in this work produces ~2,1A/km. From that follows that a 5km part of cable produces around 10,5A earth-fault current. In this study the distributed compensation devices produce 15A of compensative current and as one compensating unit is added per five kilometers of cable, this leads to over compensation. Therefore at first the total I_0 at the bus bar is capacitive and as the distributed compensation is introduced, the earth-fault current starts to decrease until the whole earth-fault current becomes inductive, i.e. the amount of earth-fault current amount starts to increase again. Inductive current has a phase-angle opposite to the capacitive current. The earth-fault current becomes inductive. This will be discussed more later on.

Figure 6.5 introduces the resistive current component which the feeder L3 produces during a solid earth-fault at the bus bar. The diagrams are given as they are in a non-compensated situation, in a centrally compensated situation and in the case in which the compensation is executed with distributed Petersen coils.

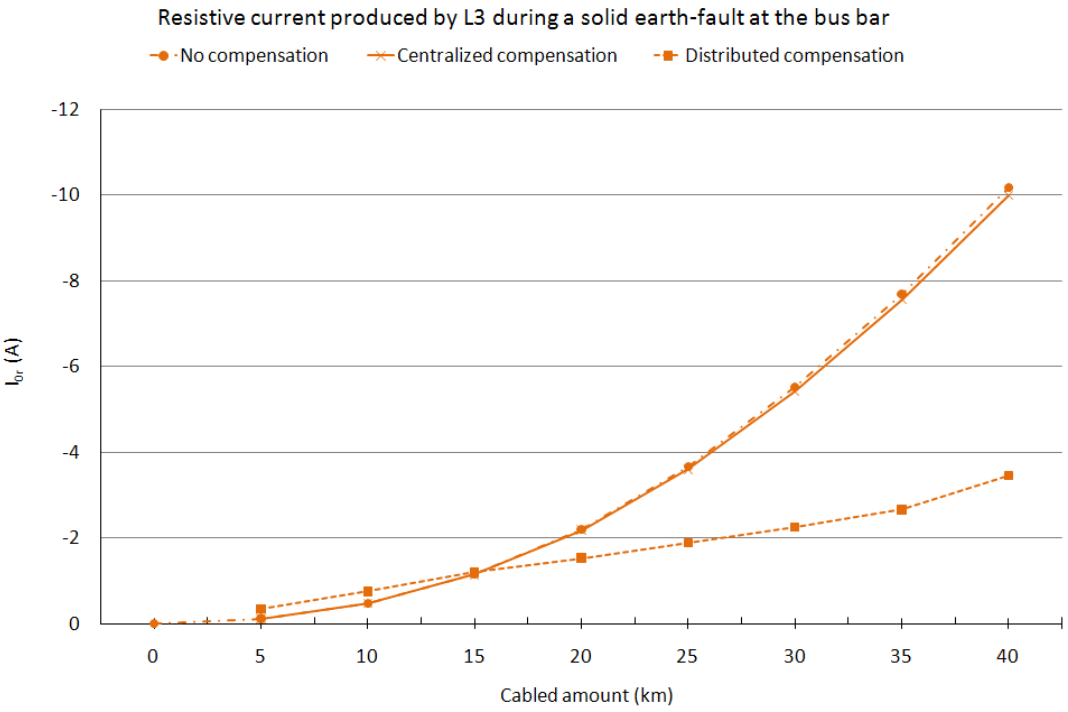


Figure 6.5 *The resistive current component produced by L3 during a solid earth-fault at the bus bar*

It can be noticed that the amount of resistive current does not increase linearly. As explained earlier, also this figure introduces only the current produced by L3 and therefore the line diagrams regarding resistive current in non-compensated and in centrally compensated networks are almost the same.

It can also be seen that the resistive current component with distributed compensation is a bit larger than in the case of non-compensated and centrally compensated networks, when 5-15 kilometers is cabled. This is because a distributed Petersen coil is in Zn(d)yn coupled. This means that the transformer has a connection to earth in the MV as well as in the LV side. When examining only the MV side, the connection to earth in means that the transformer has a zero sequence impedance, which consists of reactive and resistive parts. This resistance produces a small resistive current which is added to the resistive earth-fault current component produced by the cable's zero sequence series impedance. From Figure 6.5 it can be seen that the resistive current is doubled as the first distributed Petersen coil is introduced. As the cabling increases, the less the Petersen coil's zero sequence impedance affects the resistive earth-fault current. This is because the resistive current produced by the cable increases non-linearly and the influence of the minor Petersen coil zero sequence impedance becomes negligible. Figure 6.6 shows this even more clearly. In this figure the total resistive currents in the network are introduced in case of a non-compensated, centrally compensated and distributed compensated network.

It can be noticed that the resistive current in case of a centralized compensation is much larger than in case of a non-compensated network and distributed compensation. This is due to the neutral point resistance which was introduced in Section 5.1.2. Therefore the resistive current in this case is larger than in other cases.

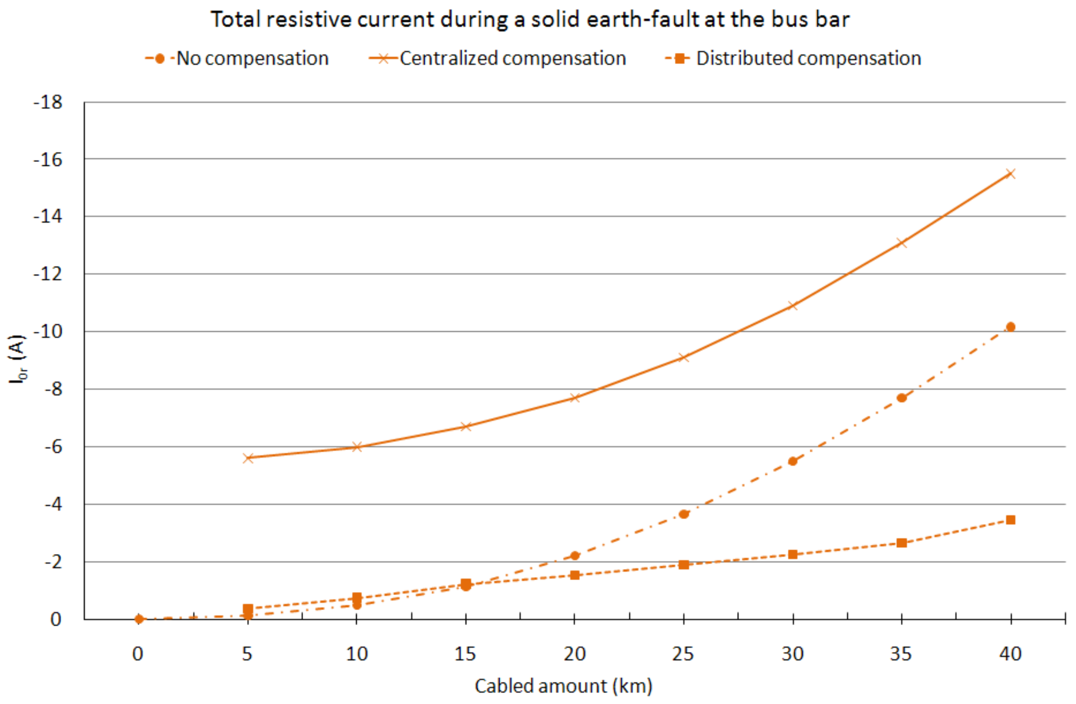


Figure 6.6 *Total resistive current during a solid earth-fault at the bus bar*

The figure is slightly misleading because the resistance is not usually connected all the time. In the networks in which the neutral point displacement voltage is naturally high in normal operating conditions, the resistance is continuously connected to lower the neutral point displacement voltage. When the fault is detected i.e. when a rise in neutral point displacement voltage or in zero sequence current is detected, the resistance is disconnected so that the earth-fault would have time to extinguish by itself and thereby it would not cause a short interruption (if auto-reclosings are used) or a permanent outage. After a certain time delay, if the relay is still awakened i.e. the fault is not cleared, the resistance is reconnected to amplify the earth-fault current in order to help the fault detection. In the network where the neutral point displacement voltage is small, the resistance is not connected. When the relay detects a rise in the neutral point displacement voltage or in the zero sequence current but tripping does not happen, the resistance is connected in order to help the fault detection.

Also from Figure 6.6 it is possible to see that as the first 5-15 kilometers are cabled and the distributed compensation is introduced, the produced resistive current is larger than in non-compensated situation. It was already explained in the preceding that this is due to the distributed Petersen coil’s zero sequence impedance. This is illustrated further in Figure 6.7. This figure demonstrates the increase in earth-fault current in respect to every added 5km in non-compensated networks and when using distributed compensation. Figure 6.7 is to be interpreted so that the number of cabled parts means how many times the 5km part has been added. The number 8 means that the whole trunk line is cabled i.e. 8*5km=40km.

In the figure the bar chart illustrates, how much resistive current increases as the cabling increases in a non-compensated situation. When the first 5km are cabled, the increase in resistive current is 0,11435A as compared to pure OHL network. As the second 5km are cabled, the increase in resistive current is 0,35990A in comparison with the situation where only 5km were cabled. It can be noticed, that as the cabling increases in the network, the more it has an effect on the earth-fault current. This confirms the non-linear behavior of the resistive earth-fault current. If the cable produced a fixed amount of resistive earth-fault current per kilometer, the bar charts would stay at the same level all the time. But as the resistive earth-fault current has more of an exponentially growing nature (as shown in Figures 6.5 and 6.6), every added cable length produces more earth-fault current than the previous one.

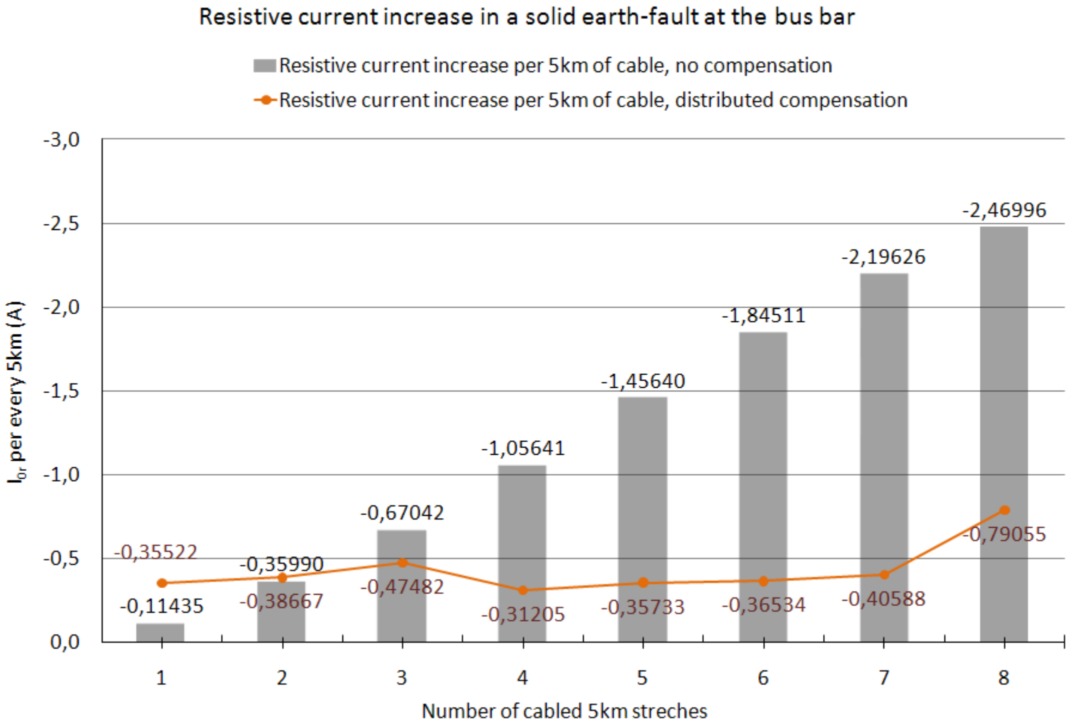


Figure 6.7 *The increase in resistive current component in respect with every added 5km during a solid earth fault at the bus bar*

Figure 6.7 also illustrates how the distributed compensation adds a small part to the total resistive current (solid line). As the first 5km is cabled and the first distributed Petersen coil is introduced, the produced resistive current is over three times larger than in the case where the network was non-compensated. It can be calculated that a single distributed Petersen coil increases the resistive current

$$I_{coil} = 0{,}35522A - 0{,}11435A = 0{,}24087A \tag{36}$$

As the cabling increases, the effect of the resistive current produced by the distributed Petersen coil decreases in comparison with the growing resistive current produced by the cable. The resistive current produced by the Petersen coil stays the same, but the influence is negligible compared to the cables resistive current. However, the fact that the distributed Petersen coil increases the total amount of the resistive current should not be ignored. If a network contained several long feeders in which cabling takes place and the distributed compensation is introduced, the effects on the total resistive earth-fault current would be much larger than in this case, where only one feeder is partially cabled.

Table 6.10

Voltages during a solid earth-fault at the bus bar						
	No compensation		Centralized compensation		Distributed compensation	
cabled (km)	U_0	U_{0Z}	U_0	U_{0Z}	U_0	U_{0Z}
5	11,923	12,205	11,853	12,134	11,89	11,84
10	11,955	12,419	11,861	12,321	11,889	11,771
15	11,986	12,563	11,867	12,438	11,888	11,722
20	12,016	12,627	11,871	12,476	11,888	11,698
25	12,042	12,609	11,874	12,434	11,888	11,693
30	12,066	12,507	11,876	12,311	11,887	11,707
35	12,086	12,325	11,876	12,11	11,886	11,74
40	12,103	12,066	11,875	11,839	11,884	11,784

According to Anna Guldbrand's studies introduced in Section 3.1.4, during a solid earth-fault at the bur bar, the zero sequence voltage at the end of the feeder increases in respect with cabled length. Table 6.10 introduces the neutral point displacement voltages and the zero sequence voltages as the network is not compensated and the cabling is introduced, and also the same voltages when the compensation is added to the network. U_0 represents the neutral point displacement voltage at the bus bar and U_{0Z} represents the zero sequence voltage at bus S61. This is also illustrated in Figure 6.8

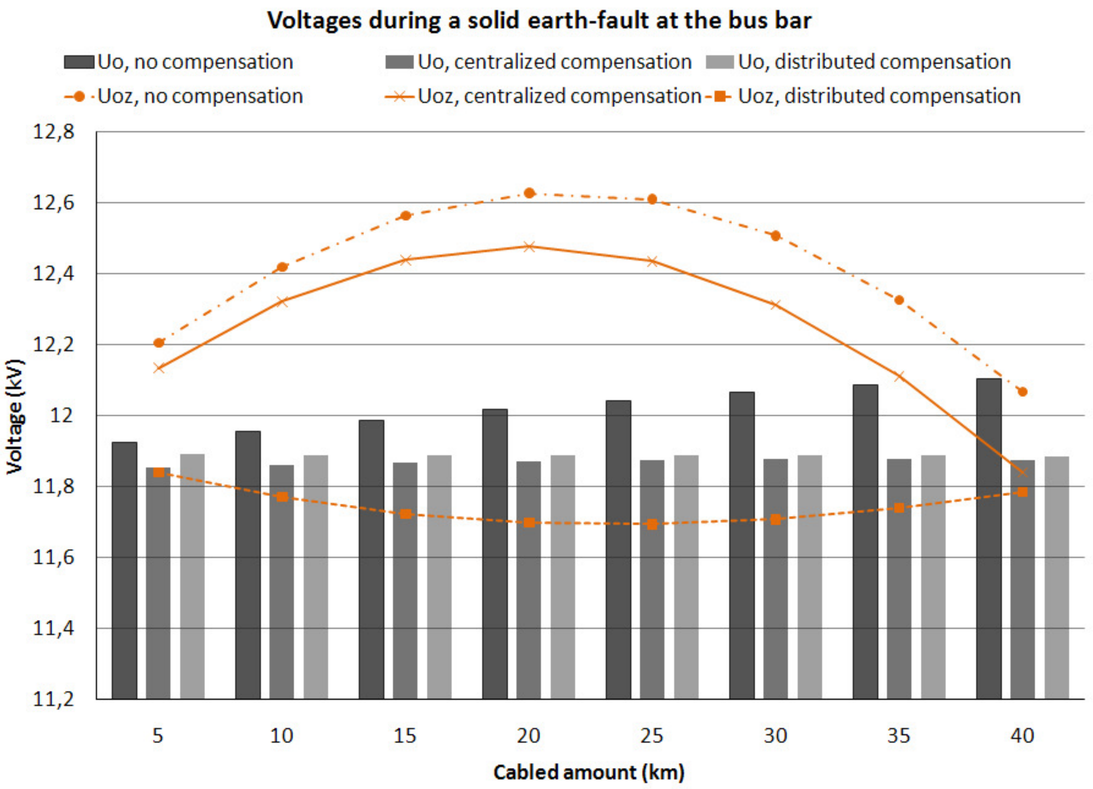


Figure 6.8 *Voltages during a solid earth-fault at the bus bar*

It can be noticed, that the voltage starts to increase, but after a certain cabled length it starts to decrease again. This is due to the resonance. As the capacitance of the network equals the inductance, the network is in resonance. This causes the zero sequence voltages to rise until they reach their peak, after which the voltage starts to decrease again. The behavior differs from the behavior in Anna Guldbrand's research represented in Section. This is due to the fact, that this modeled network includes some reactance due to the OHLs, which is why the network will pass its resonance point eventually. In Anna Guldbrand's research only a single feeder was examined. Also the earth-fault current behavior is influenced by the various features of the network, for example the cable type, the network topology etc.

Despite of the networks resonance point, it can be seen, that the zero sequence voltage at the end of the cabled feeder is higher than the neutral point displacement as also Anna Guldbrand stated in her study. Using the distributed compensation, the voltage at the end of the cabled feeder can be limited.

Figure 6.9 represents the total earth-fault currents as the fault occurs at bus S61. The values are as seen from the bus bar (dark grey lines) and as seen from the fault point (orange lines).

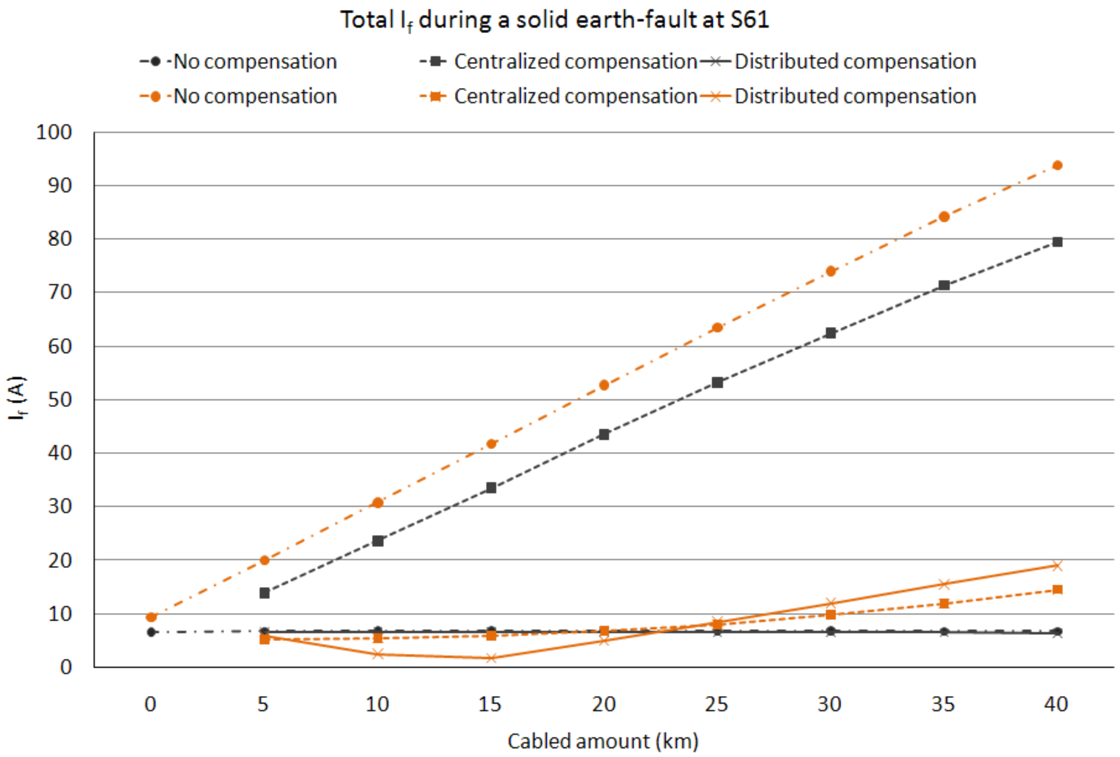


Figure 6.9 *The total I_f as a solid earth-fault occurs at bus S61examined from the bus bar (dark grey) and at the fault point (orange)*

It can be noticed that when looking at the values from the bus bar in the case of a centralized compensation, the earth-fault current increases almost linearly whereas in the case of a non-compensated network and network compensated with distributed Petersen coils the currents seem to stay the same. This is because the values are examined from the bus bar i.e. the earth-fault current seen there does not include the current part which is produced along the feeder. The OHL network produces almost the same amount of earth-fault current which is seen here. The reason why the earth-fault current increases linearly in the case of a centralized compensation is that the inductive current increases which shows at the bus bar.

When looking at the values from the fault point, it can be noticed, that the fault current curve makes a dip. This indicates that the earth-fault current turns into inductive. Therefore the amount of earth-fault current increases, as the cabling increases, because a new Petersen coil is introduced when adding 5km more cable, which over-compensates the network even further. The changes in the phase-shift are illustrated in Figure 6.10.

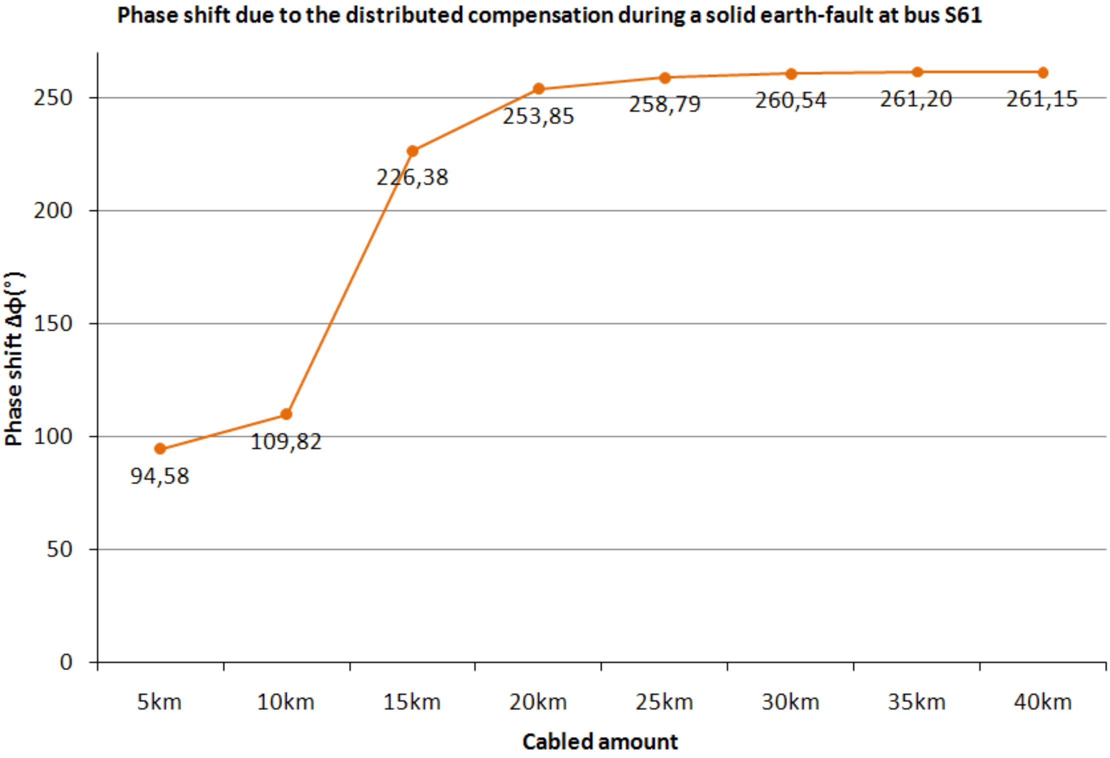


Figure 6.10 *Phase shift during a solid earth-fault at bus S61, the values are as seen from the fault point*

It can be seen clearly that the earth-fault current turns into inductive and therefore the phase shift between the zero sequence voltage and the earth-fault current is almost 270°. In this type of case, where the fault is at the end of the cabled line L3, the over-compensation does not cause any problems unless the feeder is so over-compensated that it cancels out the capacitive current coming from the healthy feeders in which case the earth-fault current would start to flow in the opposite direction and it would cause false relay functions.

Figure 6.11 introduces the total earth-fault current values as a solid earth-fault occurs at the end of the feeder L5, at bus S97. The values are given as seen from the bus bar (dark grey) and as seen at the fault point (orange).

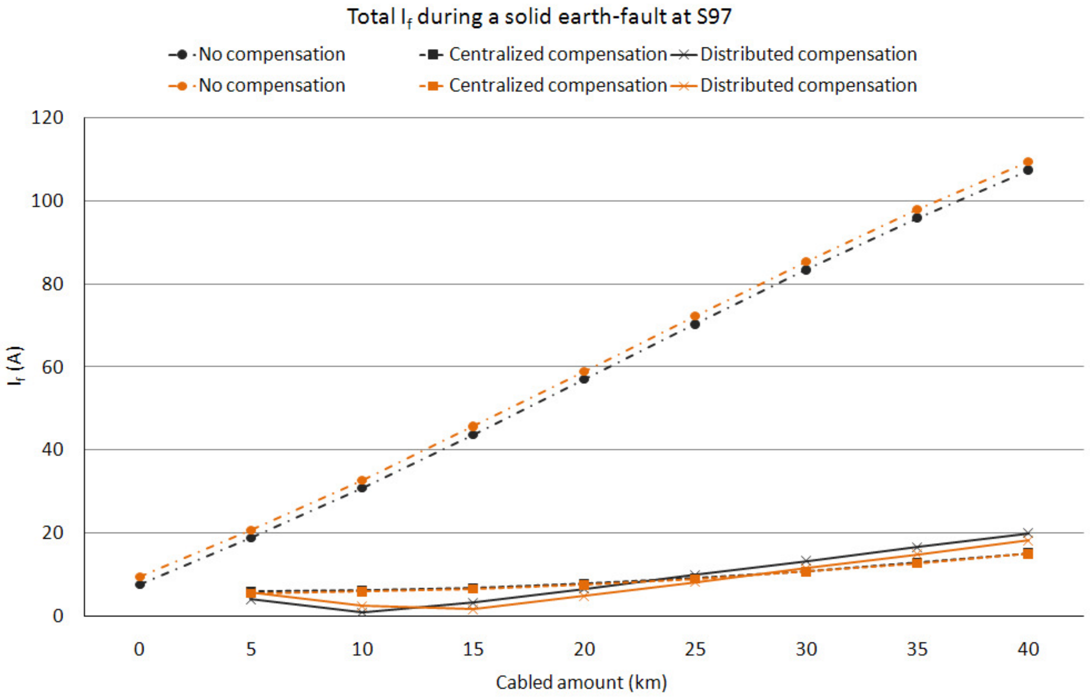


Figure 6.11 *Total I_f as a solid earth-fault occurs at bus S97*

From Figure 6.11 it can be seen that as the fault occurs at bus S97, the fault current value is almost the same whether one looks at the bus bar or at the fault point. This is because the largest part of the earth-fault current is produced along the feeder L3, and from there it flows towards the bus bar.

The total I_f is almost the same at the bus bar in the case of centralized compensation and distributed compensation, the difference is that the earth-fault current turn into inductive after 10km of cabling. This is illustrated further in Figure 6.12.

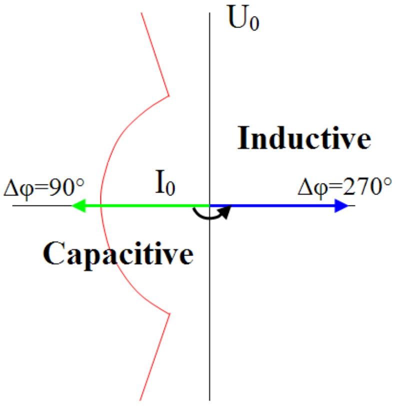


Figure 6.12 *Phasor diagram of the capacitive and inductive currents*

Figure 6.12 shows the current phasors as the earth-fault current is first capacitive and then it turns into inductive. In Section 4.4.2 it was explained, that in isolated network the protection is based on the capacitive current component i.e. the phase-shift between the neutral point displacement voltage and the zero sequence current is 90°. Now when the current component turns 180° into inductive, as illustrated in Figure 6.10, the phasor is not in the relay tripping area which is indicated with a red line. This would lead to a situation where the faulty feeder stays connected. And if the inductive current is large enough it could cause some healthy feeder to be disconnected in which case the protection would not function selectively.

It is good, however, to understand that if one uses protection which is based on the resistive current measurement, it does not cause any harm if a feeder gets over-compensated. This is because the resistive current is in phase with U_0 and even though the current angle turned into inductive, according to the phasor diagram, the earth-fault current phasor would just shift from the capacitive side to the inductive side along the x-axis, and therefore the phasor would still be in the relay tripping area. This is illustrated in Figure 6.13.

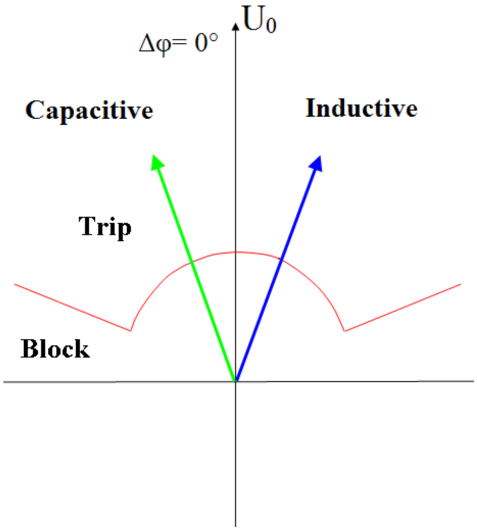


Figure 6.13 *The current vectors in compensated network*

Figure 6.14 introduces the neutral point currents as the faults occur at buses S61 and S97. The resistive currents, which are produced by the neutral point resistance, are marked as bar charts. The inductive current generated by the centralized Petersen coil is illustrated with line diagrams.

It can be seen that the resistive current stays quite constant regardless of the cabled amount, whereas the inductive current changes in respect with the cabled amount. This is because the coil is tuned to correspond to the capacitive earth-fault current generated in the network i.e. the capacitive current which is generated by the underground cable. It can be seen that in the case of a solid earth-fault at bus S97 the compensative current is a bit larger than in the case of a solid earth-fault at bus S61. This is because the earth-fault current is at its largest when the whole trunk line of feeder L3 is cabled and as the fault occurs in the end of the feeder L5.

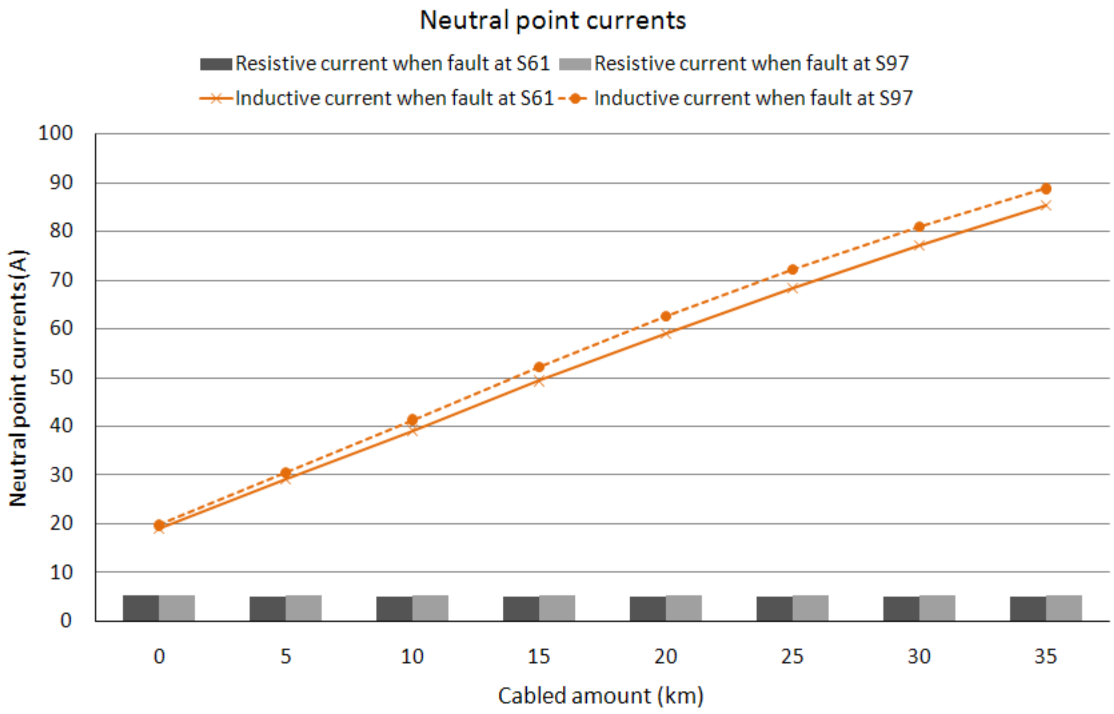


Figure 6.14 *Neutral point currents during a solid earth-fault at buses S61 and S97*

The resistive current coming from the neutral point stays the same. This is the amount the neutral point resistance creates. The resistive current changes a little bit because as shown in Figure 5.2 the resistance is connected in parallel with the centralized Petersen coil, and the voltage which is applied over the Petersen coil influences the voltage applied over the neutral point resistance. The change can be noticed from the PSS/E calculation results in Appendix 4, but since the change is so small, it cannot be seen in this figure.

6.1.3. Higher impedance earth-faults

The higher impedance earth-faults are examined only at buses S61 and S97. The values are studied as seen from the bus bar because the fault detection capability is of interest as the cabling increases. Figure 6.15 introduces the earth-fault currents and the neutral point displacement voltages as a 5kΩ fault occurs at bus S61. In the figure the bar charts represent the neutral point displacement voltages and the line diagrams represent the earth fault currents seen from the bus bar.

It can be seen that when the network is not compensated, the earth-fault current and the neutral point displacement voltage decrease as the cabling increases. This leads to a situation where the relays are not capable of detecting the faults occurring further in the network. As the centralized compensation is introduced, the neutral point displacement voltage stays higher thereby contributing to the earth-fault detection. It can be seen that the neutral point displacement voltage first grows, and then decreases again. This is because the network passes the resonance point. In practice this situation is avoided by adjusting the centralized Petersen coil a little above or below the resonance point. The studies are made with perfectly tuned system for it would have been difficult to create certain percentage under-compensation with PSS/E and as explained earlier, some simplifications have to be made because of the uncertainties included with the new earth-fault analysis. The conclusions are drawn within these simplifications, and those are assumed to give guidelines accurate enough regarding the new type of analysis.

The reason why the neutral point displacement voltage is larger in centrally compensated networks during a higher impedance earth-fault is that as the network is perfectly tuned, the neutral point inductance cancels the lines' capacitances out. So basically the voltage is divided only between the fault resistance and the neutral point resistance. In non-compensated networks there exists also voltage drop over the lines capacitances. This voltage drop becomes very small, however, as the fault resistance becomes dominating. This shows as small zero sequence voltages in case of a higher impedance earth-fault in non-compensated network.

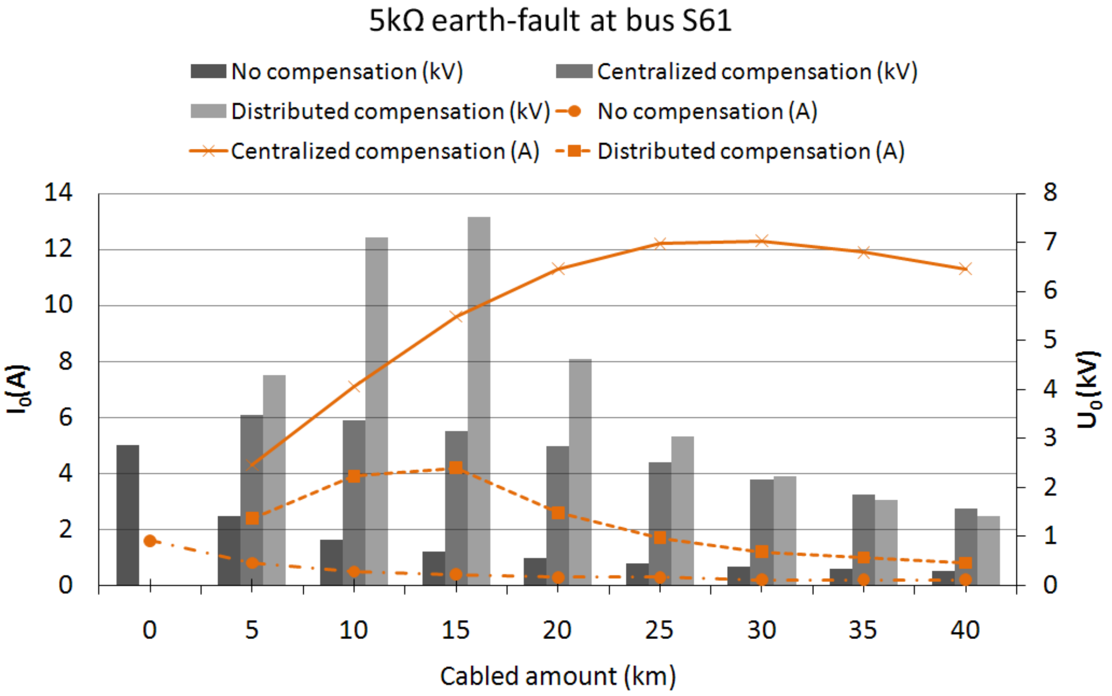


Figure 6.15 *Earth-fault currents and the neutral point displacement voltages during a 5kΩ earth-fault at bus S61*

In case of the distributed compensation it can be noticed that again the current becomes inductive after a certain cabled length. This shows as an increase and then as a decrease in the earth-fault current after which the earth-fault current decreases steadily. In Section 6.1.3 it is examined how it affects the earth-fault current, if the feeder is only partially compensated with distributed Petersen coils. It can be noticed that also in the case of distributed compensation the neutral point displacement voltage stays higher.

Figure 6.16 introduces the earth-fault currents and the neutral point displacement voltages as a 5kΩ fault occurs at bus S97. In the figure the bar charts represent the neutral point displacement voltages and the line diagrams represent the earth fault currents as seen in the bus bar.

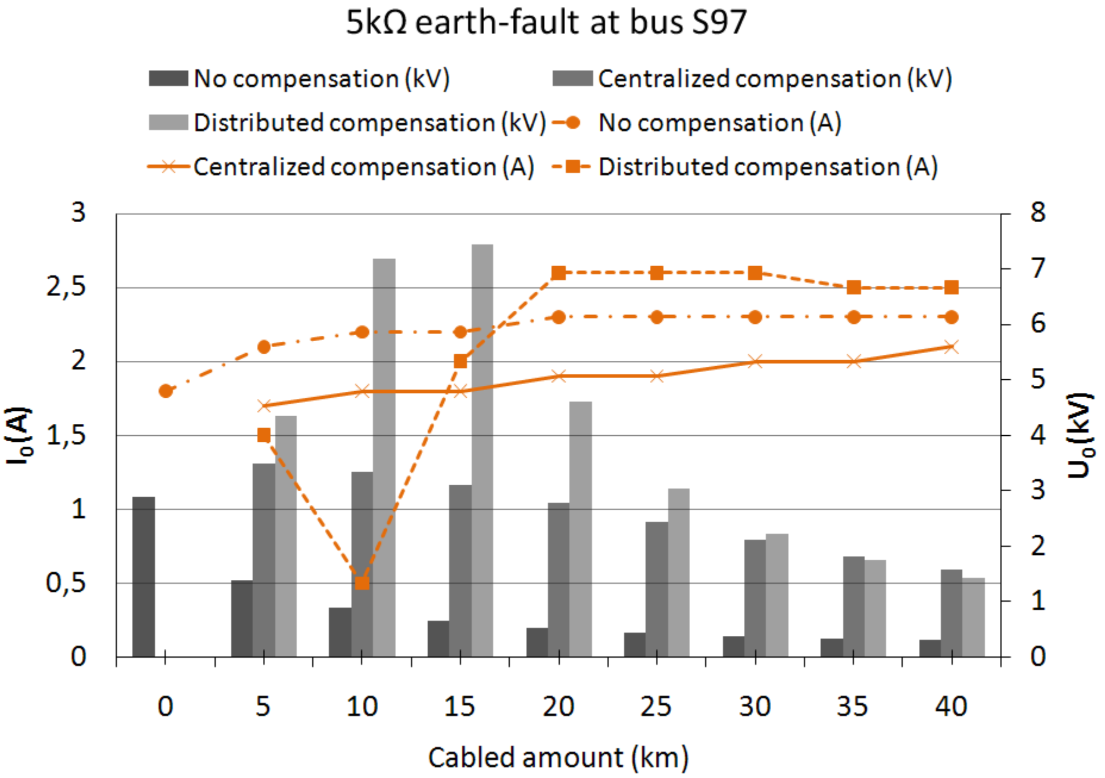


Figure 6.16 *Earth-fault currents and the neutral point displacement voltages during a 5kΩ earth-fault at bus S97*

Also in this case the neutral point displacement voltage is higher when compensated centrally. In this case the earth-fault current behaves differently when distributed Petersen coils are used. This is because the fault current flows in the other direction than in the previous case, when the fault was at the cabled feeder. Also in this figure it can be seen that the earth-fault current turns inductive. The earth-fault current has a steep dip, which indicates that the current turns from capacitive into inductive. It can also be noticed, that the neutral point displacement voltage behaves differently when distributed compensation is used. The voltage first grows and then starts to decrease again. This indicates that the inductive current by which the feeder is over-compensated exceeds the capacitive current which the rest of the network creates, i.e. the resonance point is reached. This shows as a high neutral point displacement voltage. High voltages may endanger people and cause isolators to break which is why this kind of situation should be avoided.

Figure 6.17 represents the situation where a 10kΩ fault occurs at the end of the cabled feeder L3. It can be seen that if the network is not compensated, the fault currents are extremely small and the faults containing 10kΩ fault resistance would not be detected. Also the neutral point displacement voltages are small.

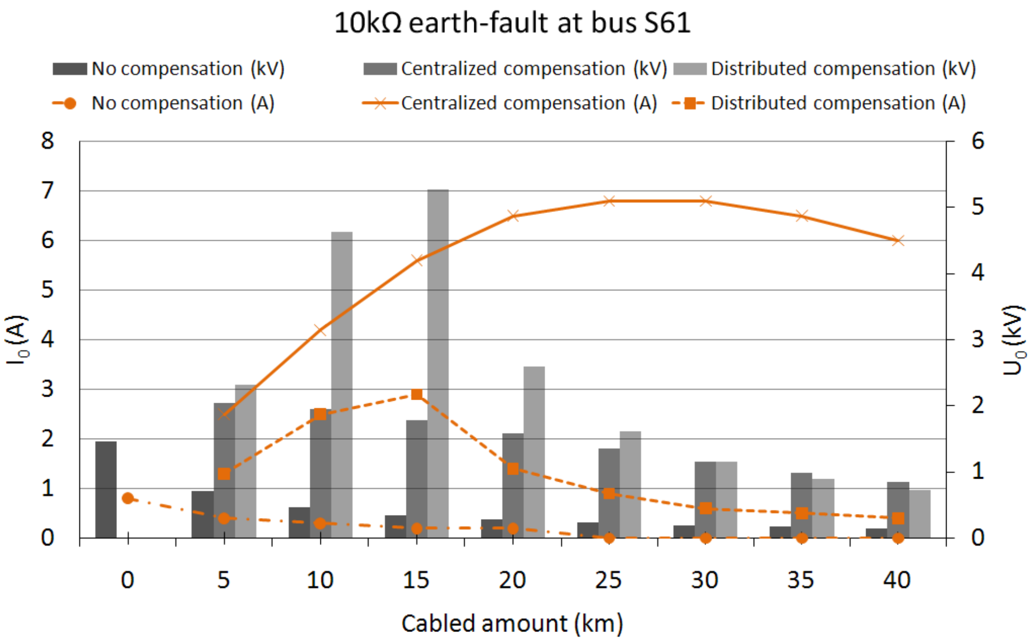


Figure 6.17 *Earth-fault currents and the neutral point displacement voltages during a 10kΩ earth-fault at bus S61*

When the compensation is introduced, the earth-fault current increases along with the neutral point displacement voltage. The reason why the earth-fault current in centrally compensated networks is much larger is partly due to the neutral point resistance. The earth-fault current starts to decrease after 30km has been cabled.

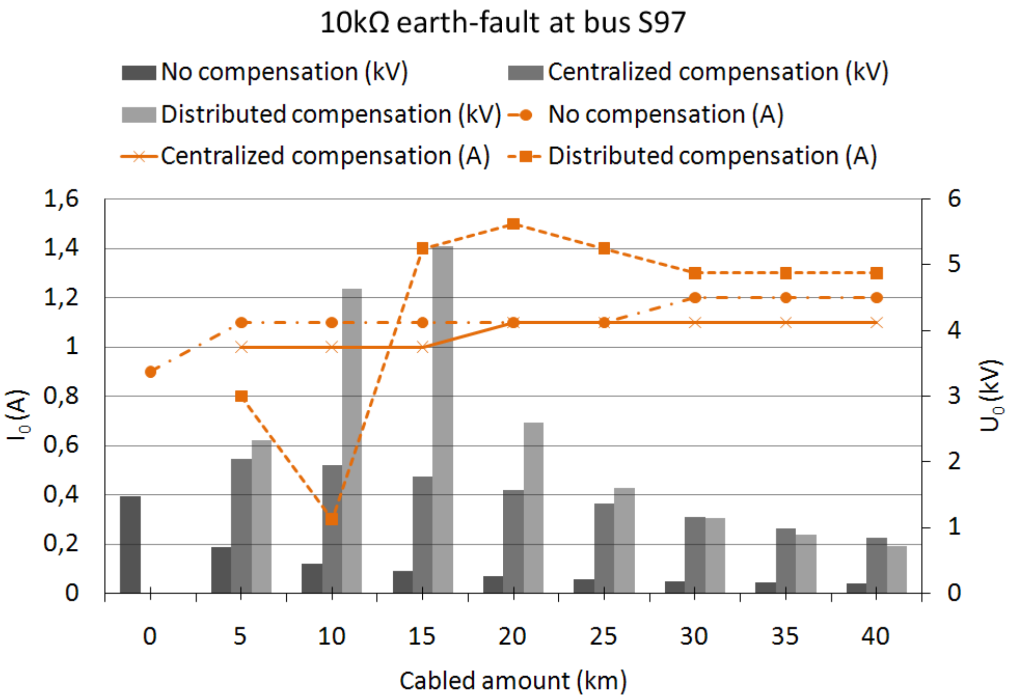


Figure 6.18 *Earth-fault currents and the neutral point displacement voltages during a 10kΩ earth-fault at bus S97*

Figure 6.18 introduces the earth-fault currents when a 10kΩ fault occurs at the end of the feeder L5. The network behaves basically the same way as in the 5kΩ earth-fault, which is why it is not necessary to explain the behavior again.

6.1.4. Partial compensation

As was discovered in Section 6.1.2, compensating the cabled trunk line with distributed Petersen coils every 5km makes the feeder over-compensated. This causes the protection to function falsely which may lead to tripping of the healthy feeders as the faulty feeder stays connected. This is not desirable which is why it may be of interest to examine the earth-fault behavior also when the network is only partially compensated with distributed Petersen coils.

Tables 6.11 and 6.12 introduce a situation where a solid earth-fault occurs at the bus bar in a network which is compensated with distributed Petersen coils. Table 6.11 introduces the values which are produced by the cabled feeder L3. The values are given in a case of a totally compensated network (coil every 5km) and in partially compensated network, in which the coils are placed every 5,7km (40km/7 coils). Also one example is introduced in which the distributed Petersen coils are placed every 6,7km (40km / 6 coils).

Table 6.11

Solid earth-fault at the bus bar, values from feeder L3							
	compensation				partial compensation		
cabled	I_0 (A)	$\Delta\varphi$ (°)	I_{0r} (A)	cabled	I_0 (A)	$\Delta\varphi$ (°)	I_{0r} (A)
5km	0,8	244,29	-0,3470531	5km, no coil	13,5	90,5	-0,1178082
10km	4,3	259,93	-0,7518602	10km + 1coil	9,8	92,44	-0,4172170
15km	7,8	261,21	-1,1919442	15km + 2coils	6,2	97,21	-0,7781396
20km	11,3	262,23	-1,5277238	20km + 3coils	2,9	114,99	-1,2251342
25km	14,9	262,72	-1,8881036	25km + 4coils	1,8	212,17	-1,5236497
30km	18,4	262,96	-2,2551452	30km + 5coils	4,9	246,98	-1,9161569
35km	22	263,06	-2,6582575	35km + 6coils	8,4	253,83	-2,3393014
40km	25,7	262,29	-3,4478900	40km + 7coils	11,9	256,42	-2,7941536
40km				40km + 6coils	3,4	134,34	-2,3763102

It can be noticed that the feeder stays under-compensated for the first 20km. After that the feeder becomes over-compensated again which would lead to a false relay functions. The last row represents the earth-fault current value as the whole trunk line is cabled but the compensation has been started after the first 10km of cabling. It can be noticed that this way the earth-fault current value stays as wanted and the relays should function correctly. It must be kept in mind, that these results are only valid for isolated networks. In compensated networks the protection angle is $\varphi_0 \pm \Delta\varphi$. This means that the protection works on both sides of the 0-angle and therefore it is not hazardous if the earth-fault current angle is pivoted to the minus side.

Table 6.12

Solid earth-fault at the bus bar							
	compensation				partial compensation		
cabled	I_0(A)	$\Delta\varphi$ (°)	I_{0r} (A)	cabled	I_0 (A)	$\Delta\varphi$ (°)	I_{0r} (A)
5km	5,8	93,56	-0,3601438	5km, no coil	20,1	90,34	-0,1192751
10km	2,4	108,13	-0,7468178	10km + 1coil	16,4	91,47	-0,4207178
15km	1,7	224,06	-1,2216403	15km + 2coils	12,8	93,51	-0,7836511
20km	4,9	251,76	-1,5336904	20km + 3coils	9,3	97,5	-1,2138936
25km	8,4	256,99	-1,8910173	25km + 4coils	5,8	105,39	-1,5392495
30km	11,9	259,07	-2,2563539	30km + 5coils	2,8	132,64	-1,8966912
35km	15,5	260,11	-2,6622360	35km + 6coils	2,7	211,78	-2,2952068
40km	19,2	259,64	-3,4527828	40km + 7coils	5,7	240,67	-2,7920823
				40km + 6coils	9,3	104,6	-2,3442450

Table 6.12 introduces the total earth-fault current values as the feeder L3 is compensated totally and partially. It can be seen that the total earth-fault current phase angle stays normal though feeder L3 is over-compensated. It still does not change the fact that when the cabling increases and more distributed Petersen coils are placed to the network, the angle of the total earth-fault current also changes into the wrong direction and the total earth-fault current becomes inductive. This can be avoided if the first 10km is left without compensation.

The result would be the same if one cabled feeder would be studied. The trunk line cabling was chosen because it is very common to start the trunk line cabling first. In case of a totally cabled feeder L3 it is reasonable to assume that the network would become even more over-compensated if the distributed Petersen coils were placed every 5km, because the smaller cable AXAL50 used in branches produces even less earth-fault current than AXAL95.

6.1.5. Totally cabled network

It is also of interest to study the earth-fault behavior as the network is totally cabled. This is because at some point in the future the aim is to have only cabled networks even in rural areas. Table 6.13 represents the total earth-fault current as the network is totally cabled. The earth-fault current behavior is also examined as the earth-fault current is compensated with the usage of distributed and centralized Petersen coils.

Table 6.13

Solid earth-fault at the bus bar			
	I_0 (A)	$\Delta\varphi$ (°)	I_{0r} (A)
no compensation	430,6	97,41	-55,5339110
distributed compensation	152,4	-98,11	-21,4996809
first 5km not compensated	85,4	-102,28	-18,1636679
first 10km not compensated	20,8	222,02	-15,4525532
first 15km not compensated	59	102,7	-12,9709261
centralized + distributed	18,5	180,4	-18,4995492

It can be noticed that when the network is totally cabled the produced earth-fault current is considerable. This alone is a forcing factor to use compensation of some kind. Also the amount of resistive current is significant. First the network is compensated with distributed Petersen coils placed every 5km. As was seen before and can be seen from this table, placing the coils every 5km over-compensates the network. The amount of resistive current is reduced but instead the earth-fault current has become inductive. When the first 5km of every feeder are left without compensation the inductive earth-fault current is reduced but the network is still over-compensated. This is also the case when the first 10km are left without any kind of compensation. The current angle turns into the right direction when the first 15km are left without compensation. In this case, however, the total amount of earth-fault current is quite large. The last row in Table 6.13 represents the situation where the network is partly compensated with distributed Petersen coils and partly with centralized Petersen coil. In this case the first 15km are left without distributed Petersen coils for it is the only situation in which the earth-fault current is not inductive. The rest of the capacitive earth-fault current is compensated with centralized Petersen coil. The coil is tuned to correspond to 10kΩ earth-fault at the bus bar.

It can be noticed that the total earth-fault current is at minimum when the compensation is executed as a combination of centralized and distributed compensation. In this situation, however, the resistive current is larger than in the case where the first 15km would just have been left without compensation. This is, however, partly due to the neutral point resistance which is connected in parallel with the centralized Petersen coil. Table 6.14 introduces the current generated at the neutral point.

Table 6.14

Current generated in the neutral point device		
	I_r	I_l
centralized + distributed	5,6313108	57,022613

The resistive current is 5,63A and the inductive current generated by the centralized Petersen coil is 57,02A. The study was not performed in the cabled network with compensating only with a centralized Petersen coil because Vattenfall Finland does not use such large coils that the whole produced capacitive current could have been compensated. Also in cases in which the network became over-compensated with the distributed Petersen coils, the centralized compensation was not introduced.

Table 6.15 introduces the zero sequence current, the phase shift and the resistive current values seen from the fault point, as a solid earth-fault occurs at bus S61 in totally cabled network. The different compensation combinations are compared. Table 6.16 on the other hand introduces the zero sequence current, the phase shift and the resistive earth-fault current seen from the fault point, as a solid earth-fault occurs at bus S97 in totally cabled network.

Table 6.15

Solid earth-fault at bus S61			
	I_f (A)	$\Delta\varphi$ (°)	I_r (A)
no compensation	213,7	138,22	-159,3579317
distributed compensation	119,4	-118,54	-57,0459976
first 5km not compensated	76,4	-110,23	-26,4183213
first 10km not compensated	19,9	228,47	-13,1939410
first 15km not compensated	54,6	122,99	-29,7292987
centralized + distributed	17,4	188,33	-17,2164312

Table 6.16

Solid earth-fault at bus S97			
	I_f	$\Delta\varphi$ (°)	I_r
no compensation	266	132,13	-178,4367966
distributed compensation	131,5	-112,52	-50,3652764
first 5km not compensated	79,2	-108,46	-25,0780879
first 10km not compensated	20,1	224,71	-14,2846016
first 15km not compensated	56,9	113,63	-22,8071578
centralized + distributed	17,7	183,42	-17,6684775

It can be noticed that in both cases the total earth-fault current as well as the resistive current flow in the network can be best limited with the combination of centralized and distributed compensation.

6.2. Reactive power generation

In the future also the production of the reactive power has to be considered. When the network is large and almost entirely cabled, the cable may produce too much reactive power for the transformer to handle. This may lead to a transformer overloading and even before that point the transformer will not function efficiently because of the reactive power transfer to the upper voltage side. This is mainly a problem in Swedish 10kV networks in which relatively small transformers are used, for example 4MVA. Overall, when the cabling increases the reactive power drifting to the transmission network increases also which may lead to reactive power unbalances even in the main grid. This can be avoided with the capacitive power compensation by shunt reactors.

When considering cabled network, many things have to be taken into consideration as can be seen from the previous section. One must realize that the cable produces resistive earth-fault current along with the capacitive current that the resistive current production leads to fault detection incapability and also that the compensation might function differently than expected. Among all of these issues, a cable produces reactive power, because a cable can be considered as a capacitor, as explained in the theory.

Usually the reactive power flow in the network is towards the consumption. Industrial facilities usually take reactive power from the network, thus they are said to be inductive loads. However, these types of consumers usually take care of their own compensation, which is why the power flowing to the large, industrial customer, is almost purely active power when seen from the network.

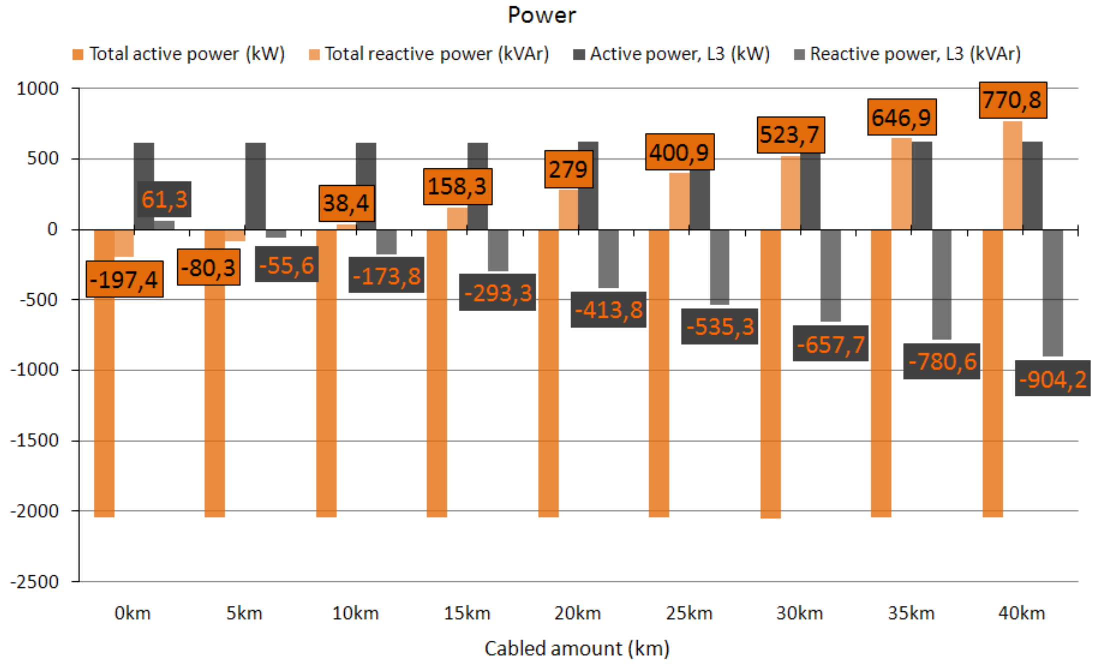


Figure 6.19 *Active and reactive power flow in the network*

This is demonstrated in Figure 6.19 which represents the reactive power changes as the trunk line of the feeder L3 is cabled. In the figure only reactive power values are represented, two other bars represent the active power flow in the network. As can be noticed, the active power flow does not actually change significantly.

In the beginning when the network is pure OHL, the total reactive power is flowing from the upper network to the medium voltage network which shows as a minus signed value. When the OHL is started to be replaced with cable, the reactive power production in the network increases. As the whole network is cabled, the produced reactive power is according to Appendix 7:

$$Q = 4497{,}3kVAr \approx 4{,}5MVAr \qquad (37)$$

It is possible, that if the network was small, for example a 10kV network in Sweden, which could have a 4MVA main transformer, all the transformer could do, would be to take care of the reactive power transfer to the upper voltage side, and there would be no room to take care of the active power transfer. The transformer could also be overloaded by all of the reactive power production.

6.3. Voltage rise in extensively cabled networks

As explained in Section 3.3 the generation of the reactive power also influences the voltages in the network. A figure was introduced of a situation where the loads in the network are small i.e. the loads are not consuming as much inductive power as the cable produces capacitive. This reactive power surplus leads to a voltage rise in the end of the feeders.

The voltage behavior is studied in a situation where the trunk line is cabled starting from the end of the feeder, analogically to previous studies. The voltage is measures at the bus bar and at the end of the line. This is illustrated in Figure 6.20 and the calculation results are represented in Table 6.17. The voltages are studied as the loads are those defined in Section 5.1.2 i.e. 50kW and 10kVAr, and when the loads are half of the defined loads, i.e. 25kW and 5kVAr.

Table 6.17

Voltages during normal loading and decreased loading				
	50kW + 10kVAr		25kW + 5kVAr	
cabled	Voltage at K20	Voltage at S61	Voltage at K20	Voltage at S61
5	20,574	20,304	20,586	20,515
10	20,589	20,391	20,602	20,599
15	20,605	20,464	20,618	20,665
20	20,621	20,518	20,634	20,71
25	20,637	20,558	20,65	20,736
30	20,653	20,582	20,666	20,743
35	20,669	20,589	20,682	20,731
40	20,685	20,58	20,698	20,7

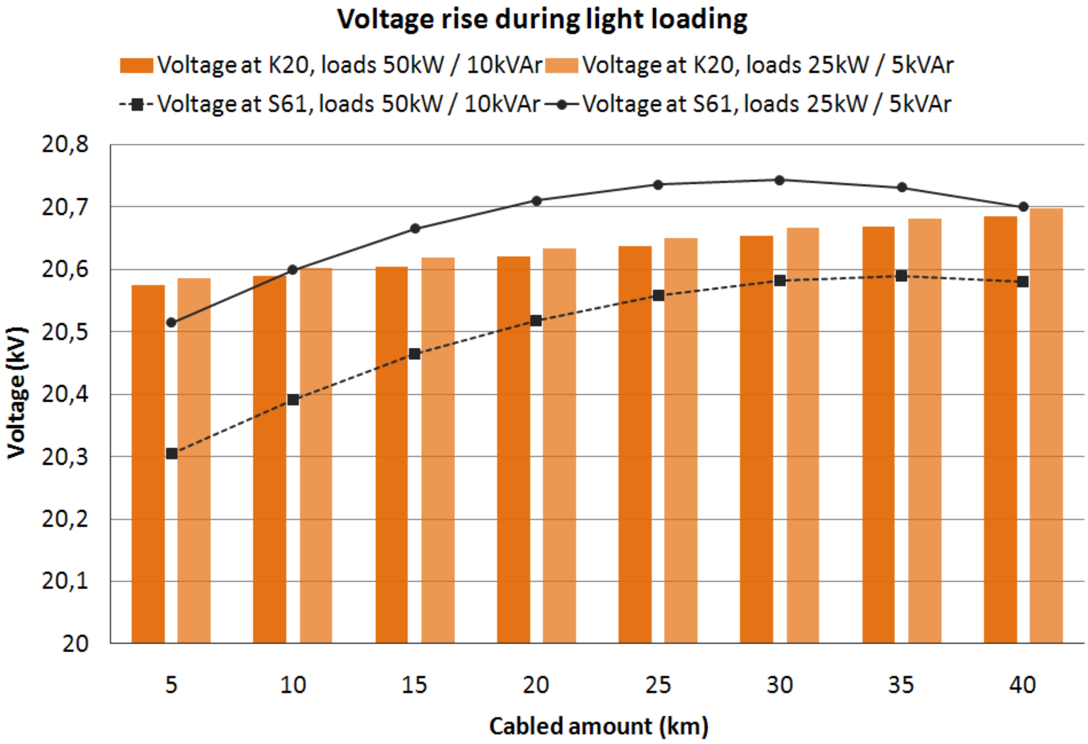


Figure 6.20 *The voltage rise at the end of the feeder during light load.*

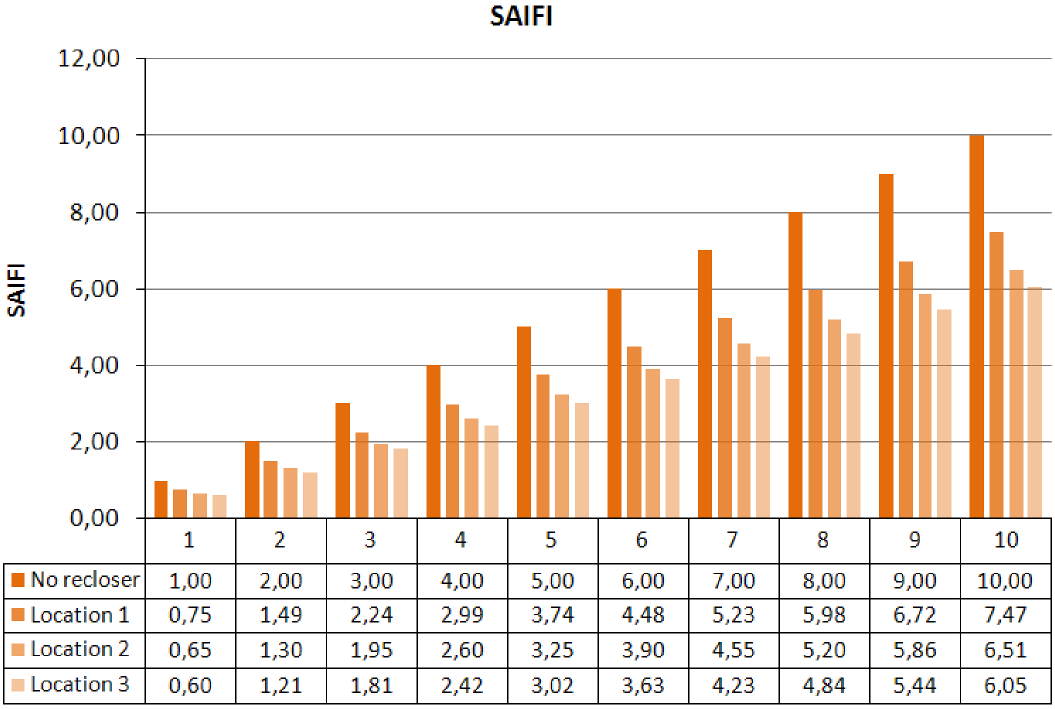
From the figure it can be seen, that when the loads are 50kW + 10kVAr, the voltage drops towards the end of the line, which is normally the case. This happens because of the transmission lines' series resistance. A current flowing through the resistance causes a voltage drop, which shows as a decreased voltage at the end of the line.

However, as the network is cabled, it produces capacitive reactive power, which is usually consumed by the loads. As the loads decrease to 25kW + 5kVAr, the capacitive power surplus lifts the voltage at the end of the feeder. According to the figure, the voltage is at its largest when little less than 30km is cabled. This is in accordance with the Elforks report introduced in Section 3.3, which stated, that the voltage is at its highest when one third of the feeder near the station is OHL and two thirds are cabled. This risen voltage may damage the network components if they are not designed to endure such voltage.

6.4. Recloser placement

In this section the results of recloser placement are introduced. As mentioned above in Section 5.2 the studied figures are SAIFI, SAIDI, MAIFI and the total customer hours. Based on these studies, the most suitable place for a recloser is chosen. The calculation blanket created with Microsoft Office Excel is introduced in Appendix 8.

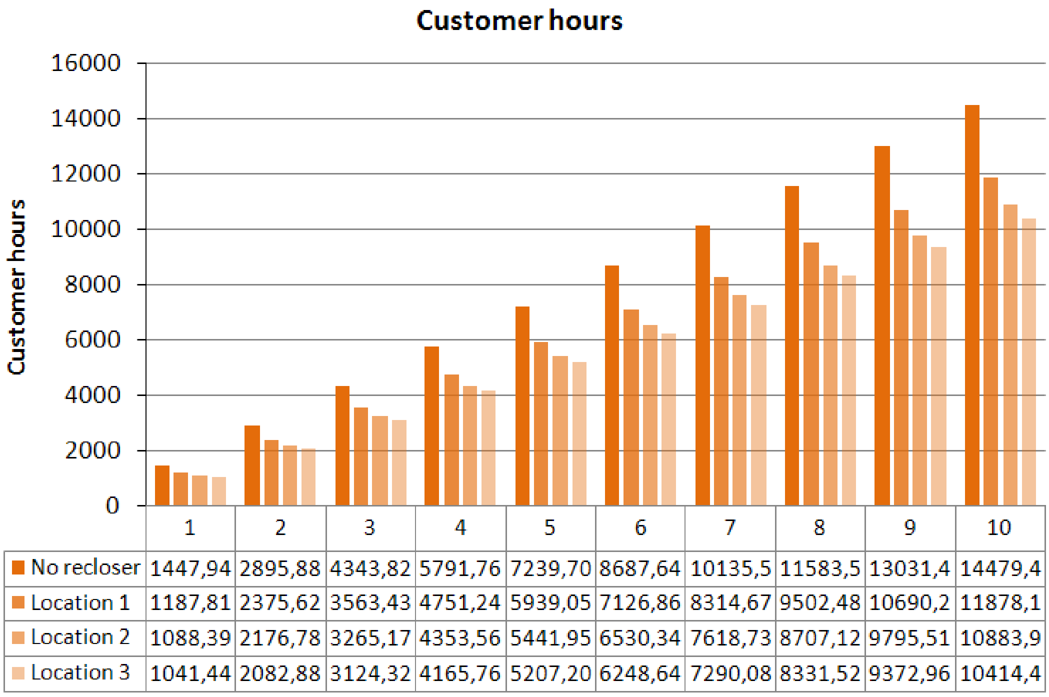
The SAIFI figure is represented in Figure 6.18. It can be noticed that based on SAIFI calculation, the best place for the recloser would be location 3. The calculation results are shown also in the figure.



	1	2	3	4	5	6	7	8	9	10
■ No recloser	1,00	2,00	3,00	4,00	5,00	6,00	7,00	8,00	9,00	10,00
■ Location 1	0,75	1,49	2,24	2,99	3,74	4,48	5,23	5,98	6,72	7,47
■ Location 2	0,65	1,30	1,95	2,60	3,25	3,90	4,55	5,20	5,86	6,51
■ Location 3	0,60	1,21	1,81	2,42	3,02	3,63	4,23	4,84	5,44	6,05

Figure 6.18 *Spillersboda –network, SAIFI*

SAIFI is used to describe the average interruptions per customer. In Figure 6.18 the possible recloser locations are numbered as in Figure 5.3 in Section 5.2. The calculation is performed with equation (16) introduced in Section 2.4. It can be noticed that the Location 3 is the best place for the recloser by looking at the SAIFI-figure. That particular area behind the Location 3 causes 50% of all the faults that occur in the feeder. It can be calculated that when introducing the recloser in Location 3 the SAIFI is reduced approximately 40%.

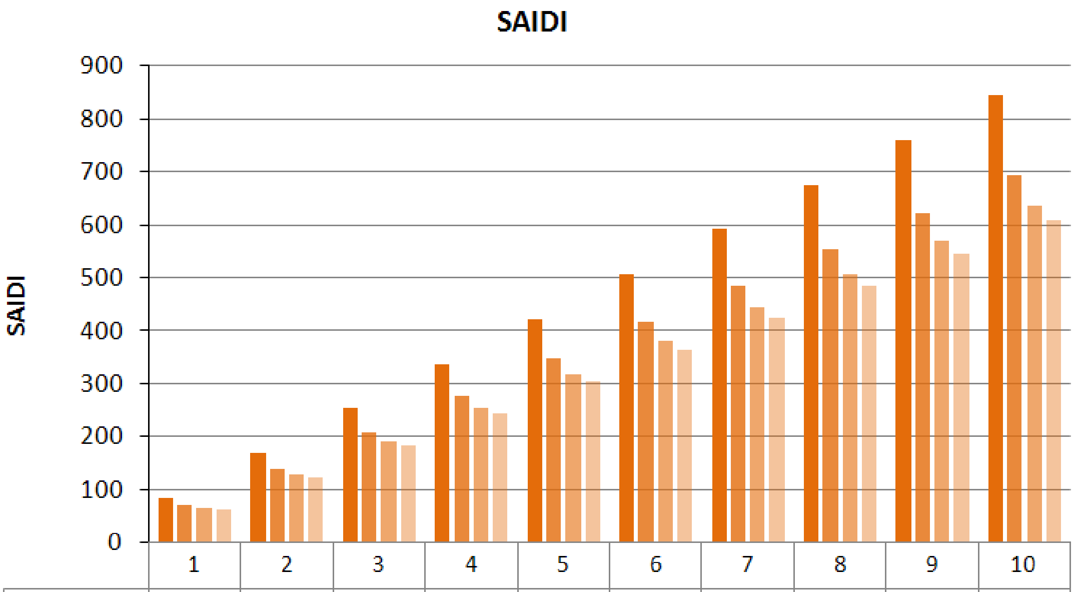


	1	2	3	4	5	6	7	8	9	10
■ No recloser	1447,94	2895,88	4343,82	5791,76	7239,70	8687,64	10135,5	11583,5	13031,4	14479,4
■ Location 1	1187,81	2375,62	3563,43	4751,24	5939,05	7126,86	8314,67	9502,48	10690,2	11878,1
■ Location 2	1088,39	2176,78	3265,17	4353,56	5441,95	6530,34	7618,73	8707,12	9795,51	10883,9
■ Location 3	1041,44	2082,88	3124,32	4165,76	5207,20	6248,64	7290,08	8331,52	9372,96	10414,4

Figure 6.19 *Spillersboda –network, Customer hours*

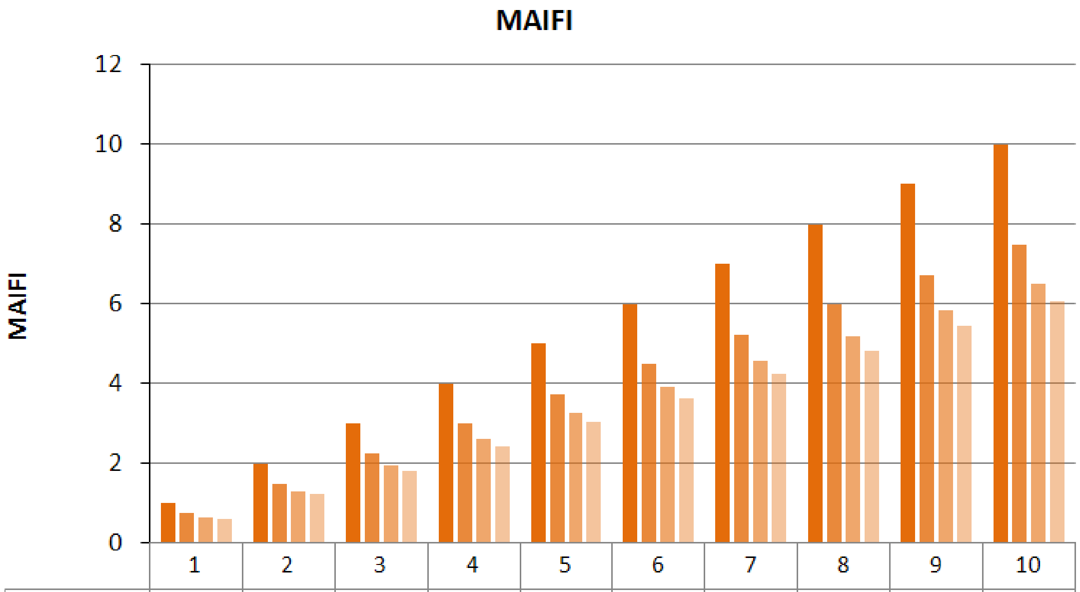
In Figure 6.19 the customer hours are introduced. A customer hour is a figure used to describe the total duration of outages per year experienced by the customers in that particular feeder. It can be calculated by multiplying the amount of customers who experience the outage by the outage duration time. The value is usually given per one year. From Figure 6.19 it can be noticed that the amount of customer hours is reduced almost 30% as the recloser is placed in Location 3.

SAIDI is used to describe the average interruption duration time per customer. The calculation results are represented in Figure 6.20. It can be seen that again the Location 3 would be the best place to install the recloser. It can be calculated that the SAIDI figure is reduced almost 30% as the recloser is placed in Location 3. This would be very beneficial from the customer's point of view as well as from the network owner's point of view because Vattenfall Sweden aims to reduce the SAIDI figure remarkably in the next few years.



	1	2	3	4	5	6	7	8	9	10
No recloser	84,43	168,86	253,28	337,71	422,14	506,57	591,00	675,42	759,85	844,28
Location 1	69,26	138,52	207,78	277,04	346,30	415,56	484,82	554,08	623,34	692,60
Location 2	63,46	126,93	190,39	253,85	317,31	380,78	444,24	507,70	571,17	634,63
Location 3	60,73	121,45	182,18	242,90	303,63	364,35	425,08	485,80	546,53	607,25

Figure 6.20 *Spillersboda –network, SAIDI*



	1	2	3	4	5	6	7	8	9	10
No recloser	1,00	2,00	3,00	4,00	5,00	6,00	7,00	8,00	9,00	10,00
Location 1	0,75	1,49	2,24	2,99	3,74	4,48	5,23	5,98	6,72	7,47
Location 2	0,65	1,30	1,95	2,60	3,25	3,90	4,55	5,20	5,86	6,51
Location 3	0,60	1,21	1,81	2,42	3,02	3,63	4,23	4,84	5,44	6,05

Figure 6.21 *Spillersboda -network, MAIFI*

As introduced earlier, MAIFI is the momentary interruption index. In Sweden the used delayed auto-reclosing time is 30 seconds and the high-speed auto-reclosing is not used. Figure 6.21 represents the calculation results for the MAIFI-figure. It can be seen that again Location 3 is the best solution for the recloser. MAIFI is reduced by almost 40%.

When looking at the results, it can be noticed that the best results are gained by placing the recloser so that it reduces the number of customers experiencing the faults, i.e. it is wise to place the recloser so that most of the faults stay behind the recloser and most of the customers on the other side. It is also not the most beneficial to install the recloser very close to the feeding substation. It can also be seen, that the reduction in all of the reliability of delivery indexes is remarkable if a recloser is placed in the network. It can also be noticed, that the recloser has a larger influence on the SAIFI and MAIFI figures than the duration indexes. This is because a recloser may not shorten the fault clearance time, rather it limits the fault's influence in the network. It also does not shorten the time it takes to repair the fault, if compared to a remote controllable disconnector installed to the same place.

One important issue when considering the placement of a recloser into the network is the selectivity of the protection. The recloser is not useful if it does not function selectively with the feeder protection, because the aim of using a recloser is to reduce the amount of customers experiencing the fault, and if the recloser is not selective with the feeder relay, every time a fault occurs the tripping is made from the station and no benefits are gained.

In an ideal case the recloser is selective both current wise and tripping time wise. The protection must still fulfill the basic requirements, for example that the smallest short circuit current value has to be detected and the first protection stage must not trip because of the loading current. In the protection planning it is also good to take into consideration the transient phenomena in the network, for example when a feeder containing a transformer is connected to the network, it causes a current transient which might be considerably higher than the normal loading current.

Table 6.14 introduces an example of the protection. t_1 is the time before the auto-reclosings, t_2 is the time between the high-speed auto-reclosing and the time-delayed auto-reclosing (if high-speed auto-reclosing is used) and t_3 is the time before the final tripping. $I>$ is the threshold value of the first protection stage and $I>>$ the threshold value of the momentary protection stage.

The $I>$ should not trip from loading current and it should also have an adequate safety margin so that every two-phase fault at the end of the line is detected i.e. the smallest two-phased short-circuit current should be large enough compared to the threshold value of $I>$. The times should not be too short so that the relay does not trip from transients, nor should they be too long because the lines will not endure thermally short-circuit currents lasting a long time. $I>>$ protects the feeder from larger over currents and it reduces the influence of supply voltage drops in other feeders, if a three-phased short-circuit fault occurs in a feeder it protects. It should not reach over the recloser, for the $I>>$ in the recloser is impossible to plan to be selective with the protection in the feeder. It would require prolonging of the *I*>> tripping times at the feeder relay which would endanger the lines' durability. The recloser protections threshold value is set lower than the feeder protection's but the criteria explained earlier is also taken into consideration. The faults in which the short-circuit currents are large are taken care of by the feeder protection. The tripping times are also set selectively with the feeder protection. A time delay of 0,15s between the protection stages is usually enough with modern relays.

Table 6.14

Short-circuit protection

	I>(A)	*t1*	*t2*	*t3*	*I>>(A)*	*t1*	*t2*	*t3*
Feeder relay	250	0,3	0,3	0,3	1700	0,15	0,15	0,15
Recloser	150	0,15	0,15	0,15	-	-	-	-

Directional earth-fault protection

	IoDir>>(A)	*t1*	*t2*	*t3*	*Uo(%)*
Feeder relay	2	0,7	0,7	0,7	10
Recloser	1	0,5	0,5	0,5	10

As stated in the theory, in compensated networks the earth-fault current tripping times may be longer because it gives the earth-fault current time to extinguish by itself. The zero sequence voltage is also higher because the zero sequence voltage in compensated network is higher as shown in previous sections. The recloser is set to be selective with the feeder protection relay also with earth-fault protection. In some cases, if it is impossible for the recloser protection to detect fault currents of 1A, it is also acceptable to set the earth-fault current threshold value to match the feeder protection relay value. As stated earlier, the amount of earth-fault current amount changes if the network topology is changed, so usually it is enough to be time selective with the feeder protection.

It should be kept in mind that the example shown above is just a demonstration of how selectivity is gained with the recloser. These relay settings are not from any actual network but are used to give a fairly good understanding, of how the settings should be set.

7. CONCLUSIONS

7.1. Conclusions

This thesis introduced first the theory related to network faults after which the most common fault types were introduced. It was explained, why in an increasingly cabled network the conventional earth-fault analysis cannot be applied to increasingly cabled networks and the cables' zero sequence impedance was introduced, followed by examples from Anna Guldbrand's licentiate thesis Also the distribution networks both in Finland and in Sweden were introduced and the compensation and protection methods in both countries were discussed. This was followed by a short introduction to the research executed in this study.

Though the basic structure of the electricity network in Finland and in Sweden is the same, there are still some differences. First of all, in Sweden there are multiple voltage levels, which has to be taken into consideration when for example planning the protection of the network. Also the network star point handling is different, which affects for example the earth-fault analysis.

In order to examine the rural area network cabling and the influence of the long cabled feeder, a network model was created to correspond to an average Finnish rural area network. Based on the calculations introduced and explained in Chapter 6 it can be stated that according to Anna Guldbrand's studies and the theory regarding the earth-fault analysis represented in Chapter 3, taking the zero sequence impedance into consideration really affects the earth-fault current behavior. It must be kept in mind that the zero sequence impedance is not an unambiguous matter, and because this subject has been studied fairly little, it is very difficult to predict how well the model used for simulating the earth-fault behavior in rural area networks really corresponds to a real network. After all, the zero sequence impedance is affected by many of the network features, for example the cable type, network topology, loading current and the nature of the load itself and of course the ground's resistivity and how frequently the cable is earthed along the cable route.

The influence of the zero sequence network was clearly noticeable in the studies performed in Section 6.1.1 which examined the influence of the cabled place in the network. As represented in the theory, the earth-fault current included a small resistive current component when the cable was introduced. The influence was examined as 15km of OHL network was replaced with underground cable in the beginning of the feeder, in the middle of the feeder and at the end of the feeder. It can be stated, that the placement of the cabling has no significant influence on the earth-fault current behavior. It must, however, be kept in mind, that if the network contains several long feeders which all contain cable, the effect of the zero sequence series impedance is larger than in a network, which contains only a few kilometers of cable. As 15km of cable may produce over 2A of resistive earth-fault current, having several 15km parts of cable in different points in the network may cause dangerous voltages, as the resistive current cannot be compensated.

As introduced in Chapter 3, a large earth-fault current can endanger customers because it creates a potential difference between the energized equipment and earth. When this voltage is applied trough human's body, which has a specific impedance that resists the current flow, it creates a current. Even a current in the magnitude of 5-10mA can be lethal, for it can cause muscular cramps, which lead to incapability to loosen oneself from the energized equipment.

Although cable parts around 5-15km do not by themselves cause pure resistive current so much that it could be dangerous to people, but if the network consists of several short cable parts, the resulting earth-fault current should be considered as hazardous. It must be remembered, that in this study the network earthing was considered to be fixed at all distribution transformers. In real network the earthing values usually change very much depending on the conformation of the soil. In real networks the earthing values are also usually a bit larger than the ones used in this work. Anyhow it can be recommended, that if the network contains long cabled parts especially in the ends of long OHLs the resistive current production would be examined more thoroughly.

It is good also to consider the special cases of earth-faults, for example double fault i.e. a cross-country fault. Although these are not modeled in this study, it is still reasonable to assume, that if a double earth-fault occurs, the earth-fault currents may be higher than in case of a single-phase earth-fault, and therefore also the resistive current may be larger during a double earth-fault.

Studies also concerned the trunk line cabling, in which the earth-fault phenomenon was examined by means of non-compensated and centrally compensated network. The trunk line cabling was also modeled with distributed Petersen coils. The trunk line was cabled, for sometimes the reliability of delivery is increased more by cabling the trunk line first. The aim is, of course, to have a totally cabled network at some point, but as the reliability of delivery indexes can be improved remarkably by cabling the trunk line, this usually is the priority.

The aim of this study was to show the benefits of the distributed compensation. Despite of the fact that the network was used as perfectly tuned and the Petersen coils produced a larger inductive current than the modeled cable type, Sections 6.1.2 and 6.1.3 showed that using distributed compensation the affects of the zero sequence series impedance of the cable can be decreased. The earth-faults were studied at buses K20, S61 and S97 and in addition to solid earth-fault, also high impedance earth-fault were studied.

It can be stated, based on the analysis performed in this study the cable's zero sequence series impedance has a non linear influence on the earth-fault current behavior. Therefore, as the cabling increases, the resistive current component becomes more dominating depending of course on the cable length and the network structure. The resistive current becomes a problem if it grows too high for it cannot be compensated. By using distributed compensation the resistive current increase in the network can be limited. This is because the resistive current component is due to the earth-fault current flow through the cables' non-negligible zero sequence series impedances. If the earth-fault current is compensated locally, the resistive current can be limited as smaller earth-fault current flows through the zero sequence series impedances. One thing that could also endanger customer safety and cause failures in the network components is the voltage rise at the end of the cabled feeder during a bus bar fault. This was also examined by Anna Guldbrand in her licentiate thesis, and the results gained from this particular study are in accordance with Anna Guldbrand's studies. Though it is good to keep in mind, that the network topology in this study differed from that of Anna Guldbrand's, which is why exactly the same kind of results are not gained. The studies showed that by using the distributed compensation also the zero sequence voltage at the end of the cabled feeder can be limited which ensures the customer safety.

By using the distributed compensation also the neutral point displacement voltage is kept higher in case of a high impedance earth-fault. This helps the earth-fault detection in extensively cabled network which contributes the network safety. Though the fault currents during a high impedance earth-fault are fairly small, they still create a potential difference between an energized network component and earth, which may endanger human safety, if the voltage is applied through a person's body.

It was also noticed, that if the distributed Petersen coils are dimensioned too large and not to correspond to the capacitive current produced by the cable, the network becomes over-compensated. This is not an ideal situation, because as the earth-fault current angle turns 180° into inductive, the feeder relays are not capable of distinguish the faulty feeder from the healthy ones. Also, if the inductive current is larger than the capacitive current produced by the whole network (for example in a case where the network if small and the coils oversized) the earth-fault protection may function falsely and a healthy feeder could be disconnected instead of the real faulty feeder.

Because over-compensating a feeder is not an ideal case, the distributed compensation was also studied as partial. This meant that if in previous case a coil was installed with every 5km of cable, now the coils where installed every 5,7km and every 6,7 km. It was noticed, that if one would want to compensate the whole feeder with distributed Petersen coils, the coils should be installed every 6,7km at least. This does not cause the feeder to become over-compensated.

It was also noticed, that when adding the first distributed Petersen coils into the network, the resistive current became larger. This was due to the zero sequence impedance of the Petersen coil. From this it could be concluded, that maybe leaving some part of the network non-compensated or compensating partly with centralized Petersen coil, could be a one good solution. This was examined in case of a totally cabled network

As a conclusion it can be stated, that using the distributed compensation the resistive current in the network can be limited and the earth-fault detection can be contributed. Based on this, it can be recommended, that the distributed compensation would be used. It is, however, important to dimension the distributed Petersen coils according to the network to avoid the over-compensation. For this purpose for example adjustable Petersen coils could be one solution. This way the coil could be dimensioned according to the needed compensation.

It has not yet been defined, what would be an ideal solution for the compensation. Previously it was introduced that the Petersen coil had a zero sequence impedance of its own. Therefore compensating the network only with using distributed Petersen coils, perhaps would not be ideal. This was examined with a totally cabled network. It could be noticed, that both the total earth-fault current and the resistive earth-fault current could be limited the most by using both centralized and distributed compensation. Based on these studies, it can be recommended, that 10-15 kilometers from the power station would be compensated centrally, which would also give the opportunity to readjust the compensation as the network topology changes. The rest of the network would be compensated with distributed Petersen coils, by which the resistive current component can be limited.

What comes to the network protection, it is clear that cabling changes the way the network must be protected. The increase in resistive current component has to be taken into consideration, and in extensive cabled networks, where there is resistive current despite of the distributed compensation, one possible solution would be to shorten the earth-fault tripping times. This would, however, affect the quality of delivery, for in compensated networks the earth-faults would not have enough time to extinguish by themselves, and would thereby cause the relay to start the auto-reclosing functions. Customers would experience these as short power cuts, which would affect the experienced quality of delivery.

It can also be stated, that in order to detect the higher impedance earth-fault the need of distributed compensation is obvious in extensively cabled networks, in which the voltage drop over the zero sequence series impedances causes the neutral point displacement voltage to be remarkably lower than for example the zero sequence voltage at the fault point. Not only ignoring this voltage drop would mislead the network company to assume that the voltage also in other parts of the network would be as low as in the bus bar, but the relays would not be able to detect the fault. When combining these two issues, the relays would not clear the fault and at the same time the zero sequence voltage at the network may be considerably high compared to the neutral point displacement voltage. This would, of course, endanger the customer safety.

As introduced earlier, cable also produces reactive power which also contributes the voltage rise in the end of the feeder during light loading. This was also examined in Chapter 6. In the resulting situation, where the whole trunk line was cabled, the reactive power produced in the medium voltage network and thereby also transferred into the upper voltage side was 770kVAr. As the whole network was cabled, the produced reactive power was ~4,5MVAr. It is clear, that this amount cannot be transferred into the upper voltage side. If the medium voltage networks in Sweden or in Finland contained lots of cable, the reactive power transferred to the upper voltage side could disturb the power balance in the main grid. This can be avoided by compensating the reactive power production in the medium voltage side. This can be done with a shunt reactor, and one of the newest applications is a combined compensation device, in which the Petersen coil compensates the capacitive earth-fault current but also would functions as a shunt reactor producing balancing power to the network. It can be recommended, that as the networks become more and more cabled, also the reactive power production has to be taken into consideration.

It was also noticed, that the voltage in the end of the feeder rose higher than the voltage at the bus bar during a lighter loading. This was due to the reactive power surplus. The voltages were at highest when one third near the station was OHL and two third cabled further in the network. The voltage rise should be avoided, for it can cause failures in the network components. This can also be limited with the usage of shunt reactors. It is recommendable, that as the cabling increases in the rural area network, the network companies would take these phenomena into consideration.

As introduced earlier, the aim of the distribution network companies is to deliver high quality electricity, which basically means no outages and no interruptions. One device used to improve the reliability of delivery is a network recloser. This device was shortly introduced in Chapter 4. As an example network was used a 10kV network from Sweden. The network contains lots of customers, and lots of faults, which is why it is an excellent example to demonstrate the effects of a single installed recloser.

The recloser was tested in three different locations, and the SAIFI, SAIDI, MAIFI and customer hour results were compared to a situation, in which the network had no recloser. It was noticed, that with a right placement of the recloser in terms of the introduced criteria, the quality of delivery indexes could be improved by 30-40%. It therefore is recommended, that the possibility of installing a recloser should be considered. It is to be kept in mind, that a recloser is an extra protection stage in the network, which is why planning the short-circuit and earth-fault protection for the recloser has to be done carefully. The tripping times cannot grow too high, and the selectivity must be considered in order to obtain the best results from the usage of reclosers.

7.2. Further study

Because the cable zero sequence impedance has not been studied very thoroughly, there are no guarantees, that the way the resistive currents are calculated with PSS/E, is correct. Therefore the zero sequence impedance should be studied more in order to achieve the knowledge needed to verify that this is the correct way to model earth-fault behavior. Some field tests are definitely needed in order to achieve better knowledge, which factors influence the real, measured resistive current and how much.

Based on these studies executed in this thesis work, it is clear that the cabling influences the earth-fault analysis. Introducing the zero sequence network is not possible in the network information systems used within Vattenfall. It should be studied, if the information systems used at the moment could also perform analysis in the zero sequence. It could also be considered, if the PSS/E could be used as an analyzing tool in extensive cabling projects. As the cabling increases, there must be tools with what the affects of the extensive cabling can be analyzed. The network companies must be able to control the production of the resistive earth-fault current, for it may endanger customer safety.

It must also be remembered, that cabled networks contains lots of fault related transients. Although some manufacturers have some kinds of transient detection functionalities, they are not widely used or in some cases do not function as planned. Therefore it could be of interest to study more the network transients, and to start implementing the existing transient functionalities more. Also the analysis performed in this study, should also be repeated with other frequencies than 50Hz.

As the cabling increases in rural areas and as the generation of the resistive earth-fault current increases, the need for wider earthings should be considered. As mentioned earlier, the usage of an extra earthing wire halves the zero sequence impedance of the cable, thereby lowering also the production of the resistive current. In the future, when the cabled networks grow larger, this option should be considered in order to ensure the customers' safety.

As for the reactive power production, it is clear that reactive power should not be transferred into upper voltage network, because it may cause power unbalance. The reactive power should be compensated locally in the medium voltage network. If the networks are small and thereby also the main transformers are fairly small, using some kinds of compensative devices in the network contributes the proper functioning of the main transformers. The transformer may become overloaded if the reactive power production is large. The options of taking care of this reactive power compensation should be studied further.

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APPENDIX

APPENDIX 1 – EQUATION DERIVATIONS FROM THE NETWORK EQUIVALENTS

Earth-fault current in compensated network:

$$\underline{I}_f = \frac{\underline{U}_v}{R_0 \parallel j\left(3\omega C_0 - \frac{1}{\omega L}\right) + R_f} = \frac{\underline{U}_v}{\dfrac{jR_0\left(3\omega C_0 - \frac{1}{\omega L}\right)}{R_0 + j\left(3\omega C_0 - \frac{1}{\omega L}\right)} + R_f} = \frac{\underline{U}_v}{\dfrac{R_0}{1 + jR_0\left(3\omega C_0 - \frac{1}{\omega L}\right)} + R_f}$$

Derivation of the absolute value:

$$I_f = \left| \frac{\underline{U}_v}{\dfrac{R_0}{1 + jR_0\left(3\omega C_0 - \frac{1}{\omega L}\right)} + R_f} \right| = \left| \frac{1 + jR_0\left(3\omega C_0 - \frac{1}{\omega L}\right)}{\left(R_0 + R_f\right) + jR_0 R_f\left(3\omega C_0 - \frac{1}{\omega L}\right)} \underline{U}_v \right|$$

$$= \frac{\sqrt{1 + R_0^{\,2}\left(3\omega C_0 - \frac{1}{\omega L}\right)^2}}{\sqrt{\left(R_0 + R_f\right)^2 + R_0^{\,2} R_f^{\,2}\left(3\omega C_0 - \frac{1}{\omega L}\right)^2}} U_v$$

Zero sequence voltage in compensated network:

$$\underline{U}_0 = \frac{-\underline{I}_f}{R_o \parallel j\left(3\omega C_0 - \frac{1}{\omega L}\right)} = -\frac{R_0}{1 + jR_0\left(3\omega C_0 - \frac{1}{\omega L}\right)} \underline{I}_f = -\frac{1}{\frac{1}{R_0} + j\left(3\omega C_0 - \frac{1}{\omega L}\right)} \underline{I}_f$$

Derivation of the absolute value:

$$U_0 = \left| \frac{1}{\frac{1}{R_0} + j\left(3\omega C_0 - \frac{1}{\omega L}\right)} \underline{I}_f \right| = \frac{1}{\sqrt{\left(\frac{1}{R_0}\right)^2 + j\left(3\omega C_0 - \frac{1}{\omega L}\right)^2}} I_f$$

APPENDIX 2 – PURE OHL NETWORK

EARTH-FAULT AT THE BUS BAR	**SOLID EARTH-FAULT**				
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		11,891	179,06		
	CURRENTS	**/3I0/**	**AN(3I0)**		
	FROM GEN	0	0	179,1	0
	FROM L1	0,9	89,05	90,01	-0,00015708
	FROM L2	0,9	89,05	90,01	-0,00015708
	FROM L3	2,8	89,01	90,05	-0,002443461
	FROM L4	2,8	89,01	90,05	-0,002443461
	FROM L5	1,9	89,04	90,02	-0,000663225
	SUM	9,4	89,03	90,03	-0,004921828

EARTH-FAULT AT BUS S61	**SOLID EARTH-FAULT**					**5KΩ EARTH-FAULT**				**10KΩ EARTH-FAULT**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		11,783	177,75			2,818	102,77			1,443	95,97		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	SUM	9,4	87,43	90,32	-0,052499231	2,3	12,45	90,32	-0,012845557	1,2	5,65	90,32	-0,006702029
	VALUES AT THE BUS BAR					**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		11,99	177,4			2,868	102,42			1,468	95,62		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	TO GEN	0	0	177,4	0	0	0	102,4	0	0	0	95,62	0
	TO L1	1	-92,61	270	0,000174533	0,2	-167,6	270	3,49066E-05	0	0	95,62	0
	TO L2	1	-92,61	270	0,000174533	0,2	-167,6	270	3,49066E-05	0	0	95,62	0
	TO L3	6,6	87,37	90,03	-0,003455752	1,6	12,39	90,03	-0,000837758	0,8	5,59	90,03	-0,000418879
	TO L4	2,9	-92,65	270,1	0,002530727	0,7	-167,6	270,1	0,000610865	0,3	-174,43	270,1	0,000261799
	TO L5	1,9	-92,62	270	0,000663225	0,4	-167,6	270	0,000139626	0,2	-174,4	270	6,98132E-05

EARTH-FAULT AT BUS S97	**SOLID EARTH-FAULT**					**5KΩ EARTH-FAULT**				**10KΩ EARTH-FAULT**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		11,859	178,36			2,859	103,16			1,463	96,3		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	SUM	9,5	88,12	90,24	-0,039793391	2,3	12,92	90,24	-0,009634189	1,2	6,06	90,24	-0,005026534
	VALUES AT THE BUS BAR					**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		11,996	178,12			2,893	102,93			1,48	96,06		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	TO GEN	0	0	178,1	0	0	0	102,9	0	0	0	96,06	0
	TO L1	1	-91,88	270	-1,83772E-16	0,2	-167,1	270	3,49066E-05	0	0	96,06	0
	TO L2	1	-91,88	270	-1,83772E-16	0,2	-167,1	270	3,49066E-05	0	0	96,06	0
	TO L3	2,8	-91,92	270	0,001954769	0,7	-167,1	270,1	0,000610865	0,3	-173,98	270	0,000209439
	TO L4	2,9	-91,92	270	0,002024582	0,7	-167,1	270,1	0,000610865	0,4	-173,98	270	0,000279253
	TO L5	7,6	88,09	90,03	-0,003979351	1,8	12,89	90,04	-0,001256637	0,9	6,03	90,03	-0,000471239

APPENDIX 3 – INFLUENCE OF THE CABLED PLACE

Cabling from the beginning of L3

EARTH-FAULT AT THE BUS BAR	SOLID EARTH-FAULT												
	5KM					10KM				15KM			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		11,92	178,84			11,955	178,61			11,986	178,38		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	FROM GEN	0	0	178,84	0,0000000	0	0	178,61	0,0000000	0	0	178,38	0,0000000
	FROM L1	0,9	88,83	90,01	-0,0001571	0,9	88,61	90	0,0000000	1	88,38	90	0,0000000
	FROM L2	0,9	88,83	90,01	-0,0001571	0,9	88,61	90	0,0000000	1	88,38	90	0,0000000
	FROM L3	13,3	88,69	90,15	-0,0348193	23,8	88,12	90,49	-0,2035378	34,3	87,35	91,03	-0,6165742
	FROM L4	2,8	88,79	90,05	-0,0024435	2,8	88,57	90,04	-0,0019548	2,8	88,34	90,04	-0,0019548
	FROM L5	1,9	88,82	90,02	-0,0006632	1,9	88,59	90,02	-0,0006632	1,9	88,36	90,02	-0,0006632
	SUM	19,8	88,73	90,11	-0,0380132	30,4	88,22	90,39	-0,2069246	40,9	87,51	90,87	-0,6210166

EARTH-FAULT AT BUS S61	SOLID EARTH-FAULT												
	5KM					10KM				15KM			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		11,93	176,91			12,051	176,05			12,142	175,21		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	SUM	20,5	85,99	90,92	-0,3291550	32,1	84,41	91,64	-0,9186857	43,8	82,74	92,47	-1,8876171
	VALUES AT THE BUS BAR					VALUES AT THE BUS BAR				VALUES AT THE BUS BAR			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		12,37	175,82			12,657	174			12,843	172,01		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	TO GEN	0	0	175,82	0,0000000	0	0	174	0,0000000	0	0	172,01	0,0000000
	TO L1	1	-94,19	270,01	0,0001745	1	-96	270	0,0000000	1	-98	270,01	0,0001745
	TO L2	1	-94,19	270,01	0,0001745	1	-96	270	0,0000000	1	-98	270,01	0,0001745
	TO L3	6,8	85,79	90,03	-0,0035605	7	83,98	90,02	-0,0024435	7,1	81,98	90,03	-0,0037176
	TO L4	2,9	-94,23	270,05	0,0025307	3	-96,04	270,04	0,0020944	3,1	-98,04	270,05	0,0027053
	TO L5	1,9	-94,2	270,02	0,0006632	2	-96,02	270,02	0,0006981	2	-98,01	270,02	0,0006981

EARTH-FAULT AT BUS S97	SOLID EARTH-FAULT												
	5KM					10KM				15KM			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		11,96	177,64			12,067	176,88			12,166	176,07		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	SUM	20,4	87,03	90,61	-0,2171847	31,9	85,67	91,21	-0,6736296	43,9	84,03	92,04	-1,5627168
	VALUES AT THE BUS BAR					VALUES AT THE BUS BAR				VALUES AT THE BUS BAR			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		12,28	177,11			12,565	176,03			12,854	174,87		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	TO GEN	0	0	177,11	0,0000000	0	0	176,03	0,0000000	0	0	174,87	0,0000000
	TO L1	1	-92,9	270,01	0,0001745	1	-93,97	270	0,0000000	1	-95,13	270	0,0000000
	TO L2	1	-92,9	270,01	0,0001745	1	-93,97	270	0,0000000	1	-95,13	270	0,0000000
	TO L3	13,6	-93,03	270,14	0,0332310	25	-94,46	270,49	0,2138002	36,8	-96,16	271,03	0,6615140
	TO L4	2,9	-92,94	270,05	0,0025307	3	-94,02	270,05	0,0026180	3,1	-95,17	270,04	0,0021642
	TO L5	18,5	87	90,11	-0,0355174	30	85,62	90,41	-0,2146737	41,9	83,96	90,91	-0,6654486

	5KΩ EARTH-FAULT												
EARTH-FAULT AT BUS S61	5KM					10KM				15KM			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		1,34	96,11			0,875	94,58			0,648	94,32		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	SUM	2,3	5,19	90,92	-0,0369296	2,3	2,94	91,64	-0,0658248	2,3	1,85	92,47	-0,0991214
	VALUES AT THE BUS BAR					VALUES AT THE BUS BAR				VALUES AT THE BUS BAR			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		1,39	95,01			0,919	92,53			0,685	91,12		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	TO GEN	0	0	95,01	0,0000000	0	0	92,53	0,0000000	0	0	91,12	0,0000000
	TO L1	0	0	95,01	0,0000000	0	0	92,53	0,0000000	0	0	91,12	0,0000000
	TO L2	0	0	95,01	0,0000000	0	0	92,53	0,0000000	0	0	91,12	0,0000000
	TO L3	0,8	4,99	90,02	-0,0002793	0,5	2,5	90,03	-0,0002618	0,4	1,09	90,03	-0,0002094
	TO L4	0,3	-175,03	270	0,0002094	0,2	-177,51	270	0,0001396	0,2	-178,93	270,1	0,0001745
	TO L5	0,2	-175,01	270	0,0000698	0	0	92,53	0,0000000	0	0	91,12	0,0000000

	5KΩ EARTH-FAULT												
EARTH-FAULT AT BUS S97	5KM					10KM				15KM			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		1,37	96,14			0,888	94,39			0,652	94,07		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	SUM	2,3	5,53	90,61	-0,0244865	2,3	3,18	91,21	-0,0485689	2,3	2,02	92,05	-0,0822747
	VALUES AT THE BUS BAR					VALUES AT THE BUS BAR				VALUES AT THE BUS BAR			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		1,41	95,61			0,924	93,54			0,688	92,87		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	TO GEN	0	0	95,61	0,0000000	0	0	93,54	0,0000000	0	0	92,87	0,0000000
	TO L1	0	0	95,61	0,0000000	0	0	93,54	0,0000000	0	0	92,87	0,0000000
	TO L2	0	0	95,61	0,0000000	0	0	93,54	0,0000000	0	0	92,87	0,0000000
	TO L3	1,6	-174,53	270,1	0,0039095	1,8	-176,95	270,5	0,0153936	2	-178,17	271	0,0363009
	TO L4	0,3	-174,43	270	0,0002094	0,2	-176,51	270,1	0,0001745	0,2	-177,18	270,1	0,0001745
	TO L5	2,1	5,5	90,11	-0,0040317	2,2	3,13	90,41	-0,0157427	2,2	1,96	90,91	-0,0349400

	10KΩ EARTH-FAULT												
EARTH-FAULT AT BUS S61	5KM	5KM				10KM				15KM			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		0,68	92,89			0,439	92,51			0,325	92,81		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	SUM	1,2	1,97	90,92	-0,0192676	1,2	0,87	91,64	-0,0343434	1,2	0,34	92,47	-0,0517155
	VALUES AT THE BUS BAR					VALUES AT THE BUS BAR				VALUES AT THE BUS BAR			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		0,7	91,8			0,461	90,46			0,344	89,6		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	TO GEN	0	0	91,8	0,0000000	0	0	90,46	0,0000000	0	0	89,6	0,0000000
	TO L1	0	0	91,8	0,0000000	0	0	90,46	0,0000000	0	0	89,6	0,0000000
	TO L2	0	0	91,8	0,0000000	0	0	90,46	0,0000000	0	0	89,6	0,0000000
	TO L3	0,4	1,77	90,03	-0,0002094	0,3	0,44	90,02	-0,0001047	0,2	-0,42	90,02	-0,0000698
	TO L4	0,2	-178,25	270,1	0,0001745	0	0	90,46	0,0000000	0	0	89,6	0,0000000
	TO L5	0	0	91,8	0,0000000	0	0	90,46	0,0000000	0	0	89,6	0,0000000

	10KΩ EARTH-FAULT												
EARTH-FAULT AT BUS S97	5KM	5KM				10KM				15KM			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		0,69	92,87			0,445	92,29			0,327	92,54		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	SUM	1,2	2,27	90,6	-0,0125661	1,2	1,08	91,21	-0,0253403	1,2	0,5	92,04	-0,0427166
	VALUES AT THE BUS BAR					VALUES AT THE BUS BAR				VALUES AT THE BUS BAR			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		0,71	92,34			0,464	91,44			0,345	91,34		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	TO GEN	0	0	92,34	0,0000000	0	0	91,44	0,0000000	0	0	91,34	0,0000000
	TO L1	0	0	92,34	0,0000000	0	0	91,44	0,0000000	0	0	91,34	0,0000000
	TO L2	0	0	92,34	0,0000000	0	0	91,44	0,0000000	0	0	91,34	0,0000000
	TO L3	0,8	-177,8	270,1	0,0019548	0,9	-179,05	270,5	0,0076968	1	-179,69	271	0,0179759
	TO L4	0,2	-177,7	270	0,0001396	0	0	91,44	0,0000000	0	0	91,34	0,0000000
	TO L5	1,1	2,23	90,11	-0,0021118	1,1	1,03	90,41	-0,0078714	1,1	0,43	90,91	-0,0174700

Cabling from the middle of the feeder L3

	SOLID EARTH-FAULT												
EARTH-FAULT AT THE BUS BAR	**5KM**					**10KM**				**15KM**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		11,92	178,83			11,96	178,6			11,99	178,36		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	FROM GEN	0	0	178,8	0,0000000	0	0	178,6	0,0000000	0	0	178,4	0,0000000
	FROM L1	0,9	88,83	90	0,0000000	0,9	88,59	90,01	-0,0001571	1	88,35	90,01	-0,0001745
	FROM L2	0,9	88,83	90	0,0000000	0,9	88,59	90,01	-0,0001571	1	88,35	90,01	-0,0001745
	FROM L3	13,4	88,52	90,31	-0,0725006	24,2	87,78	90,82	-0,3463313	35,3	86,83	91,53	-0,9425229
	FROM L4	2,8	88,79	90,04	-0,0019548	2,8	88,55	90,05	-0,0024435	2,8	88,31	90,05	-0,0024435
	FROM L5	1,9	88,81	90,02	-0,0006632	1,9	88,58	90,02	-0,0006632	1,9	88,34	90,02	-0,0006632
	SUM	20	88,61	90,22	-0,0767943	30,8	87,95	90,65	-0,3494074	41,9	87,07	91,29	-0,9432882

	SOLID EARTH-FAULT												
	5KM					**10KM**				**15KM**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		11,94	176,75			12,07	175,75			12,17	174,78		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	SUM	20,3	86,03	90,72	-0,2550906	31,5	84,5	91,25	-0,6871689	42,6	82,88	91,9	-1,4124106
EARTH-FAULT AT BUS S61	**VALUES AT THE BUS BAR**					**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		12,27	175,82			12,45	174,04			12,53	172,1		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	TO GEN	0	0	175,8	0,0000000	0	0	174	0,0000000	0	0	172,1	0,0000000
	TO L1	1	-94,18	270	0,0000000	1	-95,96	270	0,0000000	1	-97,91	270	0,0001745
	TO L2	1	-94,18	270	0,0000000	1	-95,96	270	0,0000000	1	-97,91	270	0,0001745
	TO L3	6,8	85,8	90,02	-0,0023736	6,9	84,01	90,03	-0,0036128	6,9	82,07	90,03	-0,0036128
	TO L4	2,9	-94,22	270	0,0020246	3	-96	270	0,0020944	3	-97,95	270,1	0,0026180
	TO L5	1,9	-94,2	270	0,0006632	1,9	-95,98	270	0,0006632	2	-97,92	270	0,0006981

	SOLID EARTH-FAULT												
	5KM					**10KM**				**15KM**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		11,96	177,63			12,07	176,84			12,17	175,98		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	SUM	20,5	86,9	90,73	-0,2611815	32,4	85,35	91,49	-0,8424802	45	83,46	92,52	-1,9785653
EARTH-FAULT AT BUS S97	**VALUES AT THE BUS BAR**					**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		12,28	177,09			12,57	175,97			12,87	174,73		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	TO GEN	0	0	177,1	0,0000000	0	0	176	0,0000000	0	0	174,7	0,0000000
	TO L1	1	-92,91	270	0,0000000	1	-94,04	270	0,0001745	1	-95,28	270	0,0001745
	TO L2	1	-92,91	270	0,0000000	1	-94,04	270	0,0001745	1	-95,28	270	0,0001745
	TO L3	13,8	-93,23	270,3	0,0770733	25,5	-94,85	270,8	0,3649359	37,9	-96,8	271,5	1,0119438
	TO L4	2,9	-92,96	270,1	0,0025307	3	-94,08	270,1	0,0026180	3,1	-95,32	270,1	0,0027053
	TO L5	18,7	86,85	90,24	-0,0783301	30,5	85,28	90,69	-0,3672957	43	83,38	91,35	-1,0130699

EARTH-FAULT AT BUS S61	5KΩ EARTH-FAULT												
	5KM					10KM				15KM			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		1,361	95,8			0,895	93,93			0,67	93,31		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	SUM	2,3	5,09	90,71	-0,0285005	2,3	2,67	91,26	-0,0505756	2,3	1,42	91,89	-0,0758557
	VALUES AT THE BUS BAR					VALUES AT THE BUS BAR				VALUES AT THE BUS BAR			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		1,398	94,88			0,923	92,22			0,69	90,63		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	TO GEN	0	0	94,88	0,0000000	0	0	92,22	0,0000000	0	0	90,63	0,0000000
	TO L1	0	0	94,88	0,0000000	0	0	92,22	0,0000000	0	0	90,63	0,0000000
	TO L2	0	0	94,88	0,0000000	0	0	92,22	0,0000000	0	0	90,63	0,0000000
	TO L3	0,8	4,85	90,03	-0,0004189	0,5	2,19	90,03	-0,0002618	0,4	0,6	90,03	-0,0002094
	TO L4	0,3	-175,17	270,1	0,0002618	0,2	-177,83	270,1	0,0001745	0,2	-179,42	270,1	0,0001745
	TO L5	0,2	-175,14	270	0,0000698	0	0	92,22	0,0000000	0	0	90,63	0,0000000

EARTH-FAULT AT BUS S97	5KΩ EARTH-FAULT												
	5KM					10KM				15KM			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		1,359	96,22			0,874	94,61			0,636	94,46		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	SUM	2,3	5,49	90,73	-0,0293033	2,3	3,11	91,5	-0,0602070	2,3	1,95	92,51	-0,1007256
	VALUES AT THE BUS BAR					VALUES AT THE BUS BAR				VALUES AT THE BUS BAR			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		1,395	95,68			0,91	93,73			0,672	93,21		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	TO GEN	0	0	95,68	0,0000000	0	0	93,73	0,0000000	0	0	93,21	0,0000000
	TO L1	0	0	95,68	0,0000000	0	0	93,73	0,0000000	0	0	93,21	0,0000000
	TO L2	0	0	95,68	0,0000000	0	0	93,73	0,0000000	0	0	93,21	0,0000000
	TO L3	1,6	-174,64	270,3	0,0089360	1,8	-177,09	270,8	0,0257602	2	-178,32	271,5	0,0534007
	TO L4	0,3	-174,37	270,1	0,0002618	0,2	-176,32	270,1	0,0001745	0,2	-176,84	270,1	0,0001745
	TO L5	2,1	5,44	90,24	-0,0087964	2,2	3,04	90,69	-0,0264935	2,2	1,86	91,35	-0,0518315

EARTH-FAULT AT BUS S61	10KΩ EARTH-FAULT												
	5KM					10KM				15KM			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		0,685	92,55			0,449	91,81			0,336	91,75		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	SUM	1,2	1,83	90,72	-0,0150792	1,2	0,56	91,25	-0,0261779	1,2	-0,15	91,9	-0,0397862
	VALUES AT THE BUS BAR					VALUES AT THE BUS BAR				VALUES AT THE BUS BAR			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		0,704	91,62			0,463	90,11			0,346	89,06		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	TO GEN	0	0	91,62	0,0000000	0	0	90,11	0,0000000	0	0	89,06	0,0000000
	TO L1	0	0	91,62	0,0000000	0	0	90,11	0,0000000	0	0	89,06	0,0000000
	TO L2	0	0	91,62	0,0000000	0	0	90,11	0,0000000	0	0	89,06	0,0000000
	TO L3	0,4	1,6	90,02	-0,0001396	0,3	0,08	90,03	-0,0001571	0,2	-0,96	90,02	-0,0000698
	TO L4	0,2	-178,42	270	0,0001396	0	0	90,11	0,0000000	0	0	89,06	0,0000000
	TO L5	0	0	91,62	0,0000000	0	0	90,11	0,0000000	0	0	89,06	0,0000000

EARTH-FAULT AT BUS S97	10KΩ EARTH-FAULT												
	5KM					10KM				15KM			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		0,684	92,97			0,438	92,54			0,319	92,98		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	SUM	1,2	2,24	90,73	-0,0152887	1,2	1,04	91,5	-0,0314123	1,2	0,46	92,52	-0,0527617
	VALUES AT THE BUS BAR					VALUES AT THE BUS BAR				VALUES AT THE BUS BAR			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		0,702	92,44			0,457	91,67			0,337	91,72		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	TO GEN	0	0	92,44	0,0000000	0	0	91,67	0,0000000	0	0	91,72	0,0000000
	TO L1	0	0	92,44	0,0000000	0	0	91,67	0,0000000	0	0	91,72	0,0000000
	TO L2	0	0	92,44	0,0000000	0	0	91,67	0,0000000	0	0	91,72	0,0000000
	TO L3	0,8	-177,88	270,3	0,0044680	0,9	-179,15	270,8	0,0128801	1	-179,81	271,5	0,0267004
	TO L4	0,2	-177,61	270,1	0,0001745	0	0	91,67	0,0000000	0	0	91,72	0,0000000
	TO L5	1,1	2,19	90,25	-0,0047996	1,1	0,98	90,69	-0,0132467	1,1	0,37	91,35	-0,0259157

Cabling from the end of the feeder L3

	SOLID EARTH-FAULT												
EARTH-FAULT AT THE BUS BAR	5KM					10KM				15KM			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		11,92	178,83			11,96	178,59			11,986	178,34		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	FROM GEN	0	0	178,8	0	0	0	178,6	0	0	0	178,3	0
	FROM L1	0,9	88,82	90,01	-0,00015708	0,9	88,58	90,01	-0,00015708	1	88,34	90	6,12574E-17
	FROM L2	0,9	88,82	90,01	-0,00015708	0,9	88,58	90,01	-0,00015708	1	88,34	90	6,12574E-17
	FROM L3	13,5	88,33	90,5	-0,117808229	24,6	87,48	91,11	-0,476549795	35,9	86,5	91,84	-1,152696535
	FROM L4	2,8	88,78	90,05	-0,002443461	2,8	88,54	90,05	-0,002443461	2,9	88,3	90,04	-0,002024582
	FROM L5	1,9	88,81	90,02	-0,000663225	1,9	88,57	90,02	-0,000663225	1,9	88,32	90,02	-0,000663225
	SUM	20,1	88,49	90,34	-0,119275101	31,2	87,71	90,88	-0,47917876	42,5	86,79	91,55	-1,149595412

	SOLID EARTH-FAULT												
EARTH-FAULT AT BUS S61	5KM					10KM				15KM			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		11,96	176,54			12,09	175,45			12,192	174,49		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	SUM	20	86,1	90,44	-0,153587465	30,8	84,58	90,87	-0,467660455	41,7	82,97	91,52	-1,106129736
	VALUES AT THE BUS BAR					VALUES AT THE BUS BAR				VALUES AT THE BUS BAR			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		12,14	175,82			12,25	174,05			12,327	172,12		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	TO GEN	0	0	175,8	0	0	0	174,1	0	0	0	172,1	0
	TO L1	1	-94,19	270	0,000174533	1	-95,96	270	0,000174533	1	-97,88	270	-1,83772E-16
	TO L2	1	-94,19	270	0,000174533	1	-95,96	270	0,000174533	1	-97,88	270	-1,83772E-16
	TO L3	6,7	85,79	90,03	-0,003508112	6,8	84,02	90,03	-0,003560472	6,8	82,09	90,03	-0,003560472
	TO L4	2,9	-94,23	270,1	0,002530727	2,9	-96	270,1	0,002530727	2,9	-97,92	270	0,002024582
	TO L5	1,9	-94,2	270	0,000663225	1,9	-95,97	270	0,000663225	1,9	-97,9	270	0,000663225

	SOLID EARTH-FAULT												
EARTH-FAULT AT BUS S97	5KM					10KM				15KM			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		11,97	177,62			12,07	176,8			12,171	175,92		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	SUM	20,7	86,75	90,87	-0,314304267	32,8	85,05	91,75	-1,001663233	45,7	83,1	92,82	-2,248367608
	VALUES AT THE BUS BAR					VALUES AT THE BUS BAR				VALUES AT THE BUS BAR			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		12,28	177,07			12,58	175,91			12,885	174,63		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	TO GEN	0	0	177,1	0	0	0	175,9	0	0	0	174,6	0
	TO L1	1	-92,94	270	0,000174533	1	-94,1	270	0,000174533	1	-95,37	270	-1,83772E-16
	TO L2	1	-92,94	270	0,000174533	1	-94,1	270	0,000174533	1	-95,37	270	-1,83772E-16
	TO L3	13,9	-93,43	270,5	0,121298843	25,9	-95,2	271,1	0,50173332	38,6	-97,21	271,8	1,239389589
	TO L4	2,9	-92,98	270,1	0,002530727	3	-94,14	270,1	0,002617994	3,1	-95,41	270	0,002164208
	TO L5	18,8	86,69	90,38	-0,124685408	30,9	84,97	90,94	-0,506925593	43,7	83	91,63	-1,243047789

EARTH-FAULT AT BUS S61	5KΩ EARTH-FAULT												
	5KM					10KM				15KM			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		1,386	95,41			0,918	93,29			0,686	92,66		
	CURRENT	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	SUM	2,3	4,97	90,44	-0,017662558	2,3	2,42	90,87	-0,034922696	2,4	1,14	91,52	-0,063662143
	VALUES AT THE BUS BAR					VALUES AT THE BUS BAR				VALUES AT THE BUS BAR			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		1,407	94,68			0,93	91,89			0,694	90,29		
	CURRENT	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	TO GEN	0	0	94,68	0	0	0	91,89	0	0	0	90,29	0
	TO L1	0	0	94,68	0	0	0	91,89	0	0	0	90,29	0
	TO L2	0	0	94,68	0	0	0	91,89	0	0	0	90,29	0
	TO L3	0,8	4,65	90,03	-0,000418879	0,5	1,87	90,02	-0,000174533	0,4	0,26	90,03	-0,00020944
	TO L4	0,3	-175,36	270	0,000209439	0,2	-178,15	270	0,000139626	0,2	-179,76	270,1	0,000174533
	TO L5	0,2	-175,34	270	6,98132E-05	0	0	91,89	0	0	0	90,29	0

EARTH-FAULT AT BUS S97	5KΩ EARTH-FAULT												
	5KM					10KM				15KM			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		1,349	96,3			0,861	94,8			0,626	94,71		
	CURRENT	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	SUM	2,3	5,43	90,87	-0,034922696	2,3	3,05	91,75	-0,07023858	2,3	1,89	92,82	-0,113156357
	VALUES AT THE BUS BAR					VALUES AT THE BUS BAR				VALUES AT THE BUS BAR			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		1,384	95,75			0,898	93,9			0,662	93,43		
	CURRENT	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	TO GEN	0	0	95,75	0	0	0	93,9	0	0	0	93,43	0
	TO L1	0	0	95,75	0	0	0	93,9	0	0	0	93,43	0
	TO L2	0	0	95,75	0	0	0	93,9	0	0	0	93,43	0
	TO L3	1,6	-174,75	270,5	0,013962457	1,9	-177,21	271,1	0,036806691	2	-178,41	271,8	0,064217077
	TO L4	0,3	-174,3	270,1	0,000261799	0,2	-176,14	270	0,000139626	0,2	-176,62	270,1	0,000174533
	TO L5	2,1	5,37	90,38	-0,013927625	2,2	2,97	90,93	-0,035707868	2,2	1,8	91,63	-0,062579065

EARTH-FAULT AT BUS S61	10KΩ EARTH-FAULT												
	5KM					10KM				15KM			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		0,698	92,1			0,461	91,13			0,344	91,05		
	CURRENT	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	SUM	1,2	1,66	90,44	-0,009215248	1,2	0,26	90,87	-0,018220537	1,2	-0,47	91,52	-0,031831072
	VALUES AT THE BUS BAR					VALUES AT THE BUS BAR				VALUES AT THE BUS BAR			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		0,708	91,37			0,467	89,73			0,348	88,69		
	CURRENT	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	TO GEN	0	0	91,37	0	0	0	89,73	0	0	0	88,69	0
	TO L1	0	0	91,37	0	0	0	89,73	0	0	0	88,69	0
	TO L2	0	0	91,37	0	0	0	89,73	0	0	0	88,69	0
	TO L3	0,4	1,34	90,03	-0,00020944	0,3	-0,3	90,03	-0,00015708	0,2	-1,34	90,03	-0,00010472
	TO L4	0,2	-178,68	270,1	0,000174533	0	0	89,73	0	0	0	88,69	0
	TO L5	0	0	91,37	0	0	0	89,73	0	0	0	88,69	0

EARTH-FAULT AT BUS S97	10KΩ EARTH-FAULT												
	5KM					10KM				15KM			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		0,678	93,08			0,432	92,76			0,314	93,25		
	CURRENT	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	SUM	1,2	2,22	90,86	-0,018011122	1,2	1,01	91,75	-0,036646216	1,2	0,43	92,82	-0,059038099
	VALUES AT THE BUS BAR					VALUES AT THE BUS BAR				VALUES AT THE BUS BAR			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		0,696	92,53			0,45	91,87			0,332	91,96		
	CURRENT	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	TO GEN	0	0	92,53	0	0	0	91,87	0	0	0	91,96	0
	TO L1	0	0	92,53	0	0	0	91,87	0	0	0	91,96	0
	TO L2	0	0	92,53	0	0	0	91,87	0	0	0	91,96	0
	TO L3	0,8	-177,97	270,5	0,006981228	0,9	-179,24	271,1	0,017434749	1	-179,88	271,8	0,032108539
	TO L4	0,2	-177,51	270	0,000139626	0	0	91,87	0	0	0	91,96	0
	TO L5	1,1	2,16	90,37	-0,007103441	1,1	0,93	90,94	-0,018045895	1,1	0,33	91,63	-0,031289532

APPENDIX 4 – TRUNK LINE CABLING

PSS/E results, no compensation

EARTH-FAULT AT THE BUS BAR	SOLID EARTH-FAULT												
		5km				10km				15km			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		11,923	178,83			11,955	178,59			11,986	178,34		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	FROM GEN	0	0	178,83	0,0000000	0	0	178,59	0,0000000	0	0	178,34	0,0000000
	FROM L1	0,9	88,82	90,01	-0,0001571	0,9	88,58	90,01	-0,0001571	1	88,34	90,00	0,0000000
	FROM L2	0,9	88,82	90,01	-0,0001571	0,9	88,58	90,01	-0,0001571	1	88,34	90,00	0,0000000
	FROM L3	13,5	88,33	90,50	-0,1178082	24,6	87,48	91,11	-0,4765498	35,9	86,5	91,84	-1,1526965
	FROM L4	2,8	88,78	90,05	-0,0024435	2,8	88,54	90,05	-0,0024435	2,9	88,3	90,04	-0,0020246
	FROM L5	1,9	88,81	90,02	-0,0006632	1,9	88,57	90,02	-0,0006632	1,9	88,32	90,02	-0,0006632
	SUM	20,1	88,49	90,34	-0,1192751	31,2	87,71	90,88	-0,4791788	42,5	86,79	91,55	-1,1495954

EARTH-FAULT AT THE BUS BAR	SOLID EARTH-FAULT												
		20km				25km				30km			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		12,016	178,09			12,042	177,85			12,066	177,61		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	FROM GEN	0	0	178,09	0,0000000	0	0	177,85	0,0000000	0	0	177,61	0,0000000
	FROM L1	1	88,09	90,00	0,0000000	1	87,84	90,01	-0,0001745	1	87,6	90,01	-0,0001745
	FROM L2	1	88,09	90,00	0,0000000	1	87,84	90,01	-0,0001745	1	87,6	90,01	-0,0001745
	FROM L3	47,2	85,42	92,67	-2,1987377	58,1	84,24	93,61	-3,6582495	68,6	83	94,61	-5,5135805
	FROM L4	2,9	88,05	90,04	-0,0020246	2,9	87,8	90,05	-0,0025307	2,9	87,56	90,05	-0,0025307
	FROM L5	1,9	88,07	90,02	-0,0006632	1,9	87,83	90,02	-0,0006632	1,9	87,59	90,02	-0,0006632
	SUM	53,8	85,74	92,35	-2,2060011	64,8	84,61	93,24	-3,6624010	75,2	83,41	94,20	-5,5075124

EARTH-FAULT AT THE BUS BAR	SOLID EARTH-FAULT								
		35km				40km			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		12,086	177,38			12,103	177,17		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	FROM GEN	0	0	177,38	0,0000000	0	0	177,17	0,0000000
	FROM L1	1	87,37	90,01	-0,0001745	1	87,17	90,00	0,0000000
	FROM L2	1	87,37	90,01	-0,0001745	1	87,17	90,00	0,0000000
	FROM L3	78,3	81,74	95,64	-7,6951420	87,2	80,47	96,70	-10,1736883
	FROM L4	2,9	87,33	90,05	-0,0025307	2,9	87,12	90,05	-0,0025307
	FROM L5	1,9	87,36	90,02	-0,0006632	1,9	87,15	90,02	-0,0006632
	SUM	85	82,18	95,20	-7,7037693	93,9	80,95	96,22	-10,1737245

EARTH-FAULT AT BUS S61	SOLID EARTH-FAULT												
		5km				10km				15km			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		11,955	176,54			12,091	175,45			12,192	174,49		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	SUM	20	86,1	90,44	-0,1535875	30,8	84,58	90,87	-0,4676605	41,7	82,97	91,52	-1,1061297
	VALUES AT THE BUS BAR					VALUES AT THE BUS BAR				VALUES AT THE BUS BAR			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		12,137	175,82			12,25	174,05			12,327	172,12		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	TO GEN	0	0	175,82	0,0000000	0	0	174,05	0,0000000	0	0	172,12	0,0000000
	TO L1	1	-94,19	270,01	0,0001745	1	-95,96	270,01	0,0001745	1	-97,88	270,00	0,0000000
	TO L2	1	-94,19	270,01	0,0001745	1	-95,96	270,01	0,0001745	1	-97,88	270,00	0,0000000
	TO L3	6,7	85,79	90,03	-0,0035081	6,8	84,02	90,03	-0,0035605	6,8	82,09	90,03	-0,0035605
	TO L4	2,9	-94,23	270,05	0,0025307	2,9	-96	270,05	0,0025307	2,9	-97,92	270,04	0,0020246
	TO L5	1,9	-94,2	270,02	0,0006632	1,9	-95,97	270,02	0,0006632	1,9	-97,9	270,02	0,0006632

EARTH-FAULT AT BUS S61	SOLID EARTH-FAULT												
		20km				**25km**				**30km**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		12,253	173,67			12,275	173,01			12,26	172,53		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	SUM	52,7	81,3	92,37	-2,1792772	63,5	79,59	93,42	-3,7880812	74	77,87	94,66	-6,0119601
	VALUES AT THE BUS BAR					**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**			
		/V0/	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
	VOLTAGE	12,363	170,04			12,357	167,84			12,305	165,52		
		/3I0/	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	CURRENTS	0	0	170,04	0,0000000	0	0	167,84	0,0000000	0	0	165,52	0,0000000
	SUM	1	-99,96	270,00	0,0000000	1	-102,17	270,01	0,0001745	1	-104,48	270,00	0,0000000
	TO L2	1	-99,96	270,00	0,0000000	1	-102,17	270,01	0,0001745	1	-104,48	270,00	0,0000000
	TO L3	6,8	80,02	90,02	-0,0023736	6,8	77,81	90,03	-0,0035605	6,8	75,49	90,03	-0,0035605
	TO L4	2,9	-100	270,04	0,0020246	2,9	-102,21	270,05	0,0025307	2,9	-104,53	270,05	0,0025307
	TO L5	1,9	-99,98	270,02	0,0006632	1,9	-102,18	270,02	0,0006632	1,9	-104,5	270,02	0,0006632

EARTH-FAULT AT BUS S61	SOLID EARTH-FAULT								
		35km				**40km**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		12,205	172,24			12,115	172,15		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	SUM	84,2	76,14	96,10	-8,9474348	93,8	74,43	97,72	-12,6003506
	VALUES AT THE BUS BAR					**VALUES AT THE BUS BAR**			
		/V0/	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
	VOLTAGE	12,203	163,09			12,05	160,58		
		/3I0/	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	CURRENTS	0	0	163,09	0,0000000	0	0	160,58	0,0000000
	SUM	1	-106,91	270,00	0,0000000	1	-109,42	270,00	0,0000000
	TO L2	1	-106,91	270,00	0,0000000	1	-109,42	270,00	0,0000000
	TO L3	6,7	73,07	90,02	-0,0023387	6,7	70,56	90,02	-0,0023387
	TO L4	2,9	-106,95	270,04	0,0020246	2,9	-109,46	270,04	0,0020246
	TO L5	1,9	-106,93	270,02	0,0006632	1,9	-109,44	270,02	0,0006632

EARTH-FAULT AT BUS S97	SOLID EARTH-FAULT												
		5km				**10km**				**15km**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		11,965	177,62			12,07	176,8			12,171	175,92		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	SUM	20,7	86,75	90,87	-0,3143043	32,8	85,05	91,75	-1,0016632	45,7	83,1	92,82	-2,2483676
	VALUES AT THE BUS BAR					**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		12,283	177,07			12,582	175,91			12,885	174,63		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	TO GEN	0	0	177,07	0,0000000	0	0	175,91	0,0000000	0	0	174,63	0,0000000
	TO L1	1	-92,94	270,01	0,0001745	1	-94,1	270,01	0,0001745	1	-95,37	270,00	0,0000000
	TO L2	1	-92,94	270,01	0,0001745	1	-94,1	270,01	0,0001745	1	-95,37	270,00	0,0000000
	TO L3	13,9	-93,43	270,50	0,1212988	25,9	-95,2	271,11	0,5017333	38,6	-97,21	271,84	1,2393896
	TO L4	2,9	-92,98	270,05	0,0025307	3	-94,14	270,05	0,0026180	3,1	-95,41	270,04	0,0021642
	TO L5	18,8	86,69	90,38	-0,1246854	30,9	84,97	90,94	-0,5069256	43,7	83	91,63	-1,2430478

EARTH-FAULT AT BUS S97	SOLID EARTH-FAULT												
		20km				**25km**				**30km**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		12,263	174,99			12,342	174,02			12,404	173,04		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	SUM	58,9	80,94	94,05	-4,1599295	72,3	78,62	95,40	-6,8040311	85,4	76,19	96,85	-10,1856963
	VALUES AT THE BUS BAR					**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		13,183	173,27			13,465	171,83			13,721	170,36		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	TO GEN	0	0	173,27	0,0000000	0	0	171,83	0,0000000	0	0	170,36	0,0000000
	TO L1	1	-96,74	270,01	0,0001745	1,1	-98,17	270,00	0,0000000	1,1	-99,65	270,01	0,0001920
	TO L2	1	-96,74	270,01	0,0001745	1,1	-98,17	270,00	0,0000000	1,1	-99,65	270,01	0,0001920
	TO L3	51,7	-99,41	272,68	2,4173767	65	-101,77	273,60	4,0813838	78	-104,24	274,60	6,2555161
	TO L4	3,1	-96,78	270,05	0,0027053	3,2	-98,22	270,05	0,0027925	3,3	-99,69	270,05	0,0028798
	TO L5	57	80,83	92,44	-2,4266703	70,3	78,5	93,33	-4,0834985	83,4	76,06	94,30	-6,2532258

EARTH-FAULT AT BUS S97	SOLID EARTH-FAULT								
		35km				**40km**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		12,448	172,08			12,473	171,18		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	SUM	97,9	73,72	98,36	-14,2339111	109,4	71,28	99,90	-18,8090436
	VALUES AT THE BUS BAR					**VALUES AT THE BUS BAR**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		13,944	168,89			14,128	167,48		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	TO GEN	0	0	168,89	0,0000000	0	0	167,48	0,0000000
	TO L1	1,1	-101,11	270,00	0,0000000	1,1	-102,53	270,01	0,0001920
	TO L2	1,1	-101,11	270,00	0,0000000	1,1	-102,53	270,01	0,0001920
	TO L3	90,4	-106,75	275,64	8,8843019	101,8	-109,22	276,70	11,8770810
	TO L4	3,3	-101,15	270,04	0,0023038	3,4	-102,57	270,05	0,0029671
	TO L5	95,9	73,58	95,31	-8,8750053	107,4	71,12	96,36	-11,8972483

EARTH-FAULT AT BUS S61	5KΩ EARTH-FAULT												
		5km				**10km**				**15km**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		1,386	95,41			0,918	93,29			0,686	92,66		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	SUM	2,3	4,97	90,44	-0,0176626	2,3	2,42	90,87	-0,0349227	2,4	1,14	91,52	-0,0636621
	VALUES AT THE BUS BAR					**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**			
	VOLTAGE	**/V0/**	**AN(V0)**		**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**		**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**		**3I0*COS(Δφ)**
		1,407	94,68			0,93	91,89			0,694	90,29		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	TO GEN	0	0	94,68	0,0000000	0	0	91,89	0,0000000	0	0	90,29	0,0000000
	TO L1	0	0	94,68	0,0000000	0	0	91,89	0,0000000	0	0	90,29	0,0000000
	TO L2	0	0	94,68	0,0000000	0	0	91,89	0,0000000	0	0	90,29	0,0000000
	TO L3	0,8	4,65	90,03	-0,0004189	0,5	1,87	90,02	-0,0001745	0,4	0,26	90,03	-0,0002094
	TO L4	0,3	-175,36	270,04	0,0002094	0,2	-178,15	270,04	0,0001396	0,2	-179,76	270,05	0,0001745
	TO L5	0,2	-175,34	270,02	0,0000698	0	0	91,89	0,0000000	0	0	90,29	0,0000000

EARTH-FAULT AT BUS S61	5KΩ EARTH-FAULT												
		20km				**25km**				**30km**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		0,548	92,76			0,457	93,36			0,392	94,38		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	SUM	2,4	0,39	92,37	-0,0992460	2,4	-0,06	93,42	-0,1431716	2,4	-0,29	94,67	-0,1954000
	VALUES AT THE BUS BAR					**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**			
	VOLTAGE	**/V0/**	**AN(V0)**		**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		0,553	89,13			0,46	88,19			0,393	87,36		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	TO GEN	0	0	89,13	0,0000000	0	0	88,19	0,0000000	0	0	87,36	0,0000000
	TO L1	0	0	89,13	0,0000000	0	0	88,19	0,0000000	0	0	87,36	0,0000000
	TO L2	0	0	89,13	0,0000000	0	0	88,19	0,0000000	0	0	87,36	0,0000000
	TO L3	0,3	-0,89	90,02	-0,0001047	0,3	-1,84	90,03	-0,0001571	0,2	-2,66	90,02	-0,0000698
	TO L4	0	0	89,13	0,0000000	0	0	88,19	0,0000000	0	0	87,36	0,0000000
	TO L5	0	0	89,13	0,0000000	0	0	88,19	0,0000000	0	0	87,36	0,0000000

EARTH-FAULT AT BUS S61	5KΩ EARTH-FAULT								
		35km				**40km**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		0,343	95,73			0,305	97,41		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	SUM	2,4	-0,37	96,10	-0,2550338	2,4	-0,32	97,73	-0,3228121
	VALUES AT THE BUS BAR					**VALUES AT THE BUS BAR**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		0,343	86,59			0,304	85,84		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	TO GEN	0	0	86,59	0,0000000	0	0	85,84	0,0000000
	TO L1	0	0	86,59	0,0000000	0	0	85,84	0,0000000
	TO L2	0	0	86,59	0,0000000	0	0	85,84	0,0000000
	TO L3	0,2	-3,44	90,03	-0,0001047	0,2	-4,19	90,03	-0,0001047
	TO L4	0	0	86,59	0,0000000	0	0	85,84	0,0000000
	TO L5	0	0	86,59	0,0000000	0	0	85,84	0,0000000

EARTH-FAULT AT BUS S97	**5KΩ EARTH-FAULT**												
		5km				**10km**				**15km**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		1,349	96,3			0,861	94,8			0,626	94,71		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	SUM	2,3	5,43	90,87	-0,0349227	2,3	3,05	91,75	-0,0702386	2,3	1,89	92,82	-0,1131564
	VALUES AT THE BUS BAR					**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		1,384	95,75			0,898	93,9			0,662	93,43		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	TO GEN	0	0	95,75	0,0000000	0	0	93,90	0,0000000	0	0	93,43	0,0000000
	TO L1	0	0	95,75	0,0000000	0	0	93,90	0,0000000	0	0	93,43	0,0000000
	TO L2	0	0	95,75	0,0000000	0	0	93,90	0,0000000	0	0	93,43	0,0000000
	TO L3	1,6	-174,75	270,50	0,0139625	1,9	-177,21	271,11	0,0368067	2	-178,41	271,84	0,0642171
	TO L4	0,3	-174,3	270,05	0,0002618	0,2	-176,14	270,04	0,0001396	0,2	-176,62	270,05	0,0001745
	TO L5	2,1	5,37	90,38	-0,0139276	2,2	2,97	90,93	-0,0357079	2,2	1,8	91,63	-0,0625791

EARTH-FAULT AT BUS S97	**5KΩ EARTH-FAULT**												
		20km				**25km**				**30km**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		0,489	95,27			0,401	96,19			0,342	97,35		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	SUM	2,3	1,22	94,05	-0,1624421	2,4	0,79	95,40	-0,2258600	2,4	0,5	96,85	-0,2862491
	VALUES AT THE BUS BAR					**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		0,526	93,55			0,438	94			0,378	94,67		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	TO GEN	0	0	93,55	0,0000000	0	0	94,00	0,0000000	0	0	94,67	0,0000000
	TO L1	0	0	93,55	0,0000000	0	0	94,00	0,0000000	0	0	94,67	0,0000000
	TO L2	0	0	93,55	0,0000000	0	0	94,00	0,0000000	0	0	94,67	0,0000000
	TO L3	2,1	-179,13	272,68	0,0981913	2,1	-179,6	273,60	0,1318601	2,1	-179,93	274,60	0,1684177
	TO L4	0	0	93,55	0,0000000	0	0	94,00	0,0000000	0	0	94,67	0,0000000
	TO L5	2,3	1,11	92,44	-0,0979183	2,3	0,67	93,33	-0,1335995	2,3	0,36	94,31	-0,1728514

EARTH-FAULT AT BUS S97	**5KΩ EARTH-FAULT**								
		35km				**40km**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		0,299	98,65			0,269	100,03		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	SUM	2,4	0,29	98,36	-0,3489416	2,4	0,13	99,90	-0,4126298
	VALUES AT THE BUS BAR					**VALUES AT THE BUS BAR**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		0,335	95,46			0,304	96,33		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	TO GEN	0	0	95,46	0,0000000	0	0	96,33	0,0000000
	TO L1	0	0	95,46	0,0000000	0	0	96,33	0,0000000
	TO L2	0	0	95,46	0,0000000	0	0	96,33	0,0000000
	TO L3	2,2	179,82	-84,36	0,2162109	2,2	179,63	-83,30	0,2566756
	TO L4	0	0	95,46	0,0000000	0	0	96,33	0,0000000
	TO L5	2,3	0,14	95,32	-0,2132518	2,3	-0,02	96,35	-0,2543838

EARTH-FAULT AT BUS S61	**10KΩ EARTH-FAULT**												
		5km				**10km**				**15km**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		0,698	92,1			0,461	91,13			0,344	91,05		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	SUM	1,2	1,66	90,44	-0,0092152	1,2	0,26	90,87	-0,0182205	1,2	-0,47	91,52	-0,0318311
	VALUES AT THE BUS BAR					**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		0,708	91,37			0,467	89,73			0,348	88,69		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	TO GEN	0	0	91,37	0,0000000	0	0	89,73	0,0000000	0	0	88,69	0,0000000
	TO L1	0	0	91,37	0,0000000	0	0	89,73	0,0000000	0	0	88,69	0,0000000
	TO L2	0	0	91,37	0,0000000	0	0	89,73	0,0000000	0	0	88,69	0,0000000
	TO L3	0,4	1,34	90,03	-0,0002094	0,3	-0,3	90,03	-0,0001571	0,2	-1,34	90,03	-0,0001047
	TO L4	0,2	-178,68	270,05	0,0001745	0	0	89,73	0,0000000	0	0	88,69	0,0000000
	TO L5	0	0	91,37	0,0000000	0	0	89,73	0,0000000	0	0	88,69	0,0000000

EARTH-FAULT AT BUS S61	10KΩ EARTH-FAULT												
		20km				25km				30km			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		0,275	91,48			0,229	92,31			0,196	93,48		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	SUM	1,2	-0,89	92,37	-0,0496230	1,2	-1,11	93,42	-0,0715858	1,2	-1,19	94,67	-0,0977000
	VALUES AT THE BUS BAR					VALUES AT THE BUS BAR				VALUES AT THE BUS BAR			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		0,277	87,86			0,23	87,14			0,197	86,46		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	TO GEN	0	0	87,86	0,0000000	0	0	87,14	0,0000000	0	0	86,46	0,0000000
	TO L1	0	0	87,86	0,0000000	0	0	87,14	0,0000000	0	0	86,46	0,0000000
	TO L2	0	0	87,86	0,0000000	0	0	87,14	0,0000000	0	0	86,46	0,0000000
	TO L3	0,2	-2,17	90,03	-0,0001047	0	0	87,14	0,0000000	0	0	86,46	0,0000000
	TO L4	0	0	87,86	0,0000000	0	0	87,14	0,0000000	0	0	86,46	0,0000000
	TO L5	0	0	87,86	0,0000000	0	0	87,14	0,0000000	0	0	86,46	0,0000000

EARTH-FAULT AT BUS S61	10KΩ EARTH-FAULT								
		35km				40km			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		0,172	94,95			0,153	96,71		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	SUM	1,2	-1,15	96,10	-0,1275169	1,2	-1,01	97,72	-0,1611985
	VALUES AT THE BUS BAR					VALUES AT THE BUS BAR			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		0,172	85,8			0,152	85,14		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	TO GEN	0	0	85,80	0,0000000	0	0	85,14	0,0000000
	TO L1	0	0	85,80	0,0000000	0	0	85,14	0,0000000
	TO L2	0	0	85,80	0,0000000	0	0	85,14	0,0000000
	TO L3	0	0	85,80	0,0000000	0	0	85,14	0,0000000
	TO L4	0	0	85,80	0,0000000	0	0	85,14	0,0000000
	TO L5	0	0	85,80	0,0000000	0	0	85,14	0,0000000

EARTH-FAULT AT BUS S97	10KΩ EARTH-FAULT												
		5km				10km				15km			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		0,678	93,08			0,432	92,76			0,314	93,25		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	SUM	1,2	2,22	90,86	-0,0180111	1,2	1,01	91,75	-0,0366462	1,2	0,43	92,82	-0,0590381
	VALUES AT THE BUS BAR					VALUES AT THE BUS BAR				VALUES AT THE BUS BAR			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		0,696	92,53			0,45	91,87			0,332	91,96		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	TO GEN	0	0	92,53	0,0000000	0	0	91,87	0,0000000	0	0	91,96	0,0000000
	TO L1	0	0	92,53	0,0000000	0	0	91,87	0,0000000	0	0	91,96	0,0000000
	TO L2	0	0	92,53	0,0000000	0	0	91,87	0,0000000	0	0	91,96	0,0000000
	TO L3	0,8	-177,97	270,50	0,0069812	0,9	-179,24	271,11	0,0174347	1	-179,88	271,84	0,0321085
	TO L4	0,2	-177,51	270,04	0,0001396	0	0	91,87	0,0000000	0	0	91,96	0,0000000
	TO L5	1,1	2,16	90,37	-0,0071034	1,1	0,93	90,94	-0,0180459	1,1	0,33	91,63	-0,0312895

EARTH-FAULT AT BUS S97	10KΩ EARTH-FAULT												
		20km				25km				30km			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		0,245	94,14			0,201	95,27			0,171	96,58		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	SUM	1,2	0,1	94,04	-0,0845435	1,2	-0,12	95,39	-0,1127215	1,2	-0,27	96,85	-0,1431245
	VALUES AT THE BUS BAR					VALUES AT THE BUS BAR				VALUES AT THE BUS BAR			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		0,263	92,42			0,219	93,09			0,189	93,9		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	TO GEN	0	0	92,42	0,0000000	0	0	93,09	0,0000000	0	0	93,90	0,0000000
	TO L1	0	0	92,42	0,0000000	0	0	93,09	0,0000000	0	0	93,90	0,0000000
	TO L2	0	0	92,42	0,0000000	0	0	93,09	0,0000000	0	0	93,90	0,0000000
	TO L3	1	179,74	-87,32	0,0467578	1,1	179,48	-86,39	0,0692612	1,1	179,3	-85,40	0,0882188
	TO L4	0	0	92,42	0,0000000	0	0	93,09	0,0000000	0	0	93,90	0,0000000
	TO L5	1,1	-0,02	92,44	-0,0468305	1,1	-0,24	93,33	-0,0638954	1,2	-0,4	94,30	-0,0899745

EARTH-FAULT AT BUS S97	**10KΩ EARTH-FAULT**								
		35km				**40km**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		0,15	97,99			0,135	99,44		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	SUM	1,2	-0,38	98,37	-0,1746780	1,2	-0,45	99,89	-0,2061086
	VALUES AT THE BUS BAR					**VALUES AT THE BUS BAR**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		0,168	94,8			0,152	95,74		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	TO GEN	0	0	94,80	0,0000000	0	0	95,74	0,0000000
	TO L1	0	0	94,80	0,0000000	0	0	95,74	0,0000000
	TO L2	0	0	94,80	0,0000000	0	0	95,74	0,0000000
	TO L3	1,1	179,16	-84,36	0,1081054	1,1	179,04	-83,30	0,1283378
	TO L4	0	0	94,80	0,0000000	0	0	95,74	0,0000000
	TO L5	1,2	-0,52	95,32	-0,1112618	1,2	-0,61	96,35	-0,1327220

	SOLID EARTH-FAULT										
EARTH-FAULT AT THE BUS BAR		**5km**					**10km**				
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**I_L**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**I_L**
		11,853	179,2				11,861	179,19			
	CURRENTS	**/3I0/**	**AN(3I0)**				**/3I0/**	**AN(3I0)**			
	FROM GEN	20,8	-75,41	254,61	-5,5200672	20,0541481	31,5	-80,73	259,92	-5,5132264	31,0137765
	FROM L1	0,9	89,19	90,01	-0,0001571		0,9	89,18	90,01	-0,0001571	
	FROM L2	0,9	89,19	90,01	-0,0001571		0,9	89,18	90,01	-0,0001571	
	FROM L3	13,5	88,7	90,50	-0,1178082		24,4	88,08	91,11	-0,4726754	
	FROM L4	2,8	89,15	90,05	-0,0024435		2,8	89,14	90,05	-0,0024435	
	FROM L5	1,9	89,18	90,02	-0,0006632		1,9	89,17	90,02	-0,0006632	
	SUM	5,6	-1,33	180,53	-5,5997604		6	-1,39	180,58	-5,9996926	

	SOLID EARTH-FAULT										
EARTH-FAULT AT THE BUS BAR		**15km**					**20km**				
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**I_L**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**I_L**
		11,867	179,18				11,871	179,17			
	CURRENTS	**/3I0/**	**AN(3I0)**				**/3I0/**	**AN(3I0)**			
	FROM GEN	42,5	-83,35	262,53	-5,5252998	42,1393054	53,5	-84,92	264,09	-5,5086887	53,2156401
	FROM L1	0,9	89,17	90,01	-0,0001571		0,9	89,16	90,01	-0,0001571	
	FROM L2	0,9	89,17	90,01	-0,0001571		0,9	89,16	90,01	-0,0001571	
	FROM L3	35,6	87,34	91,84	-1,1430640		46,6	86,49	92,68	-2,1789121	
	FROM L4	2,8	89,13	90,05	-0,0024435		2,8	89,12	90,05	-0,0024435	
	FROM L5	1,9	89,16	90,02	-0,0006632		1,9	89,15	90,02	-0,0006632	
	SUM	6,7	-0,76	179,94	-6,6999963		7,7	-1,98	181,15	-7,6984491	

	SOLID EARTH-FAULT										
EARTH-FAULT AT THE BUS BAR		**25km**					**30km**				
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**I_L**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**I_L**
		11,874	179,15				11,876	179,12			
	CURRENTS	**/3I0/**	**AN(3I0)**				**/3I0/**	**AN(3I0)**			
	FROM GEN	64,1	-85,92	265,07	-5,5086640	63,8628579	74	-86,61	265,73	-5,5097878	73,7945949
	FROM L1	0,9	89,14	90,01	-0,0001571		0,9	89,12	90,00	0,0000000	
	FROM L2	0,9	89,14	90,01	-0,0001571		0,9	89,12	90,00	0,0000000	
	FROM L3	57,3	85,55	93,60	-3,5978968		67,5	84,52	94,60	-5,4134274	
	FROM L4	2,8	89,1	90,05	-0,0024435		2,8	89,08	90,04	-0,0019548	
	FROM L5	1,9	89,13	90,02	-0,0006632		1,9	89,1	90,02	-0,0006632	
	SUM	9,1	-1,56	180,71	-9,0993013		10,9	-0,66	179,78	-10,8999196	

	SOLID EARTH-FAULT										
EARTH-FAULT AT THE BUS BAR		**35km**					**40km**				
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**I_L**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**I_L**
		11,876	179,1				11,875	179,07			
	CURRENTS	**/3I0/**	**AN(3I0)**				**/3I0/**	**AN(3I0)**			
	FROM GEN	83,3	-87,11	266,21	-5,5061092	83,1178246	91,6	-87,48	266,55	-5,5122571	91,4339927
	FROM L1	0,9	89,09	90,01	-0,0001571		0,9	89,06	90,01	-0,0001571	
	FROM L2	0,9	89,09	90,01	-0,0001571		0,9	89,06	90,01	-0,0001571	
	FROM L3	77	83,46	95,64	-7,5673810		85,6	82,37	96,70	-9,9870151	
	FROM L4	2,8	89,05	90,05	-0,0024435		2,8	89,02	90,05	-0,0024435	
	FROM L5	1,9	89,08	90,02	-0,0006632		1,9	89,05	90,02	-0,0006632	
	SUM	13,1	-0,6	179,70	-13,0998204		15,5	-0,37	179,44	-15,4992597	

	SOLID EARTH-FAULT										
EARTH-FAULT AT BUS S61		**5km**					**10km**				
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**		**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	
		11,628	178				11,68	177,78			
	CURRENTS	**/3I0/**	**AN(3I0)**				**/3I0/**	**AN(3I0)**			
	SUM	5,2	-1,87	179,87	-5,1999866		5,4	-0,55	178,33	-5,3977064	
	VALUES AT THE BUS BAR						**VALUES AT THE BUS BAR**				
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**I_L**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**I_L**
		11,286	178,03				11,143	178,62			
	CURRENTS	**/3I0/**	**AN(3I0)**				**/3I0/**	**AN(3I0)**			
	TO GEN	19,8	103,42	74,61	5,2546794	19,0900064	29,6	98,7	79,92	5,1806825	29,1431043
	TO L1	0,9	-91,98	270,01	0,0001571		0,9	-91,38	270,00	0,0000000	
	TO L2	0,9	-91,98	270,01	0,0001571		0,9	-91,38	270,00	0,0000000	
	TO L3	13,9	-69,72	247,75	-5,2632158		23,6	-78,67	257,29	-5,1923885	
	TO L4	2,7	-92,02	270,05	0,0023562		2,6	-91,42	270,04	0,0018151	
	TO L5	1,8	-91,99	270,02	0,0006283		1,7	-91,4	270,02	0,0005934	

	SOLID EARTH-FAULT										
EARTH-FAULT AT BUS S61		**15km**					**20km**				
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**		**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	
		11,72	177,6				11,744	177,49			
	CURRENTS	**/3I0/**	**AN(3I0)**				**/3I0/**	**AN(3I0)**			
	SUM	5,9	1,92	175,68	-5,8832375		6,8	3	174,49	-6,7685803	
	VALUES AT THE BUS BAR						**VALUES AT THE BUS BAR**				
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**I_L**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**I_L**
		11,048	179,45				10,988	-179,45			
	CURRENTS	**/3I0/**	**AN(3I0)**				**/3I0/**	**AN(3I0)**			
	TO GEN	39,5	96,92	82,53	5,1352787	39,1647662	49,6	96,46	-275,91	5,1071207	49,3363691
	TO L1	0,9	-90,55	270,00	0,0000000		0,9	-89,46	-89,99	0,0001571	
	TO L2	0,9	-90,55	270,00	0,0000000		0,9	-89,46	-89,99	0,0001571	
	TO L3	33,5	-81,72	261,17	-5,1423589		43,5	-82,71	-96,74	-5,1053372	
	TO L4	2,6	-90,59	270,04	0,0018151		2,6	-89,5	-89,95	0,0022689	
	TO L5	1,7	-90,57	270,02	0,0005934		1,7	-89,47	-89,98	0,0005934	

EARTH-FAULT AT BUS S61	**SOLID EARTH-FAULT**																				
		25km					**30km**					**35km**					**40km**				
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**		**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**		**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**		**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	
		11,757	177,44				11,76	177,44				11,749	177,51				11,728	177,65			
	CURRENTS	**/3I0/**	**AN(3I0)**				**/3I0/**	**AN(3I0)**				**/3I0/**	**AN(3I0)**				/3I0/	AN(3I0)			
	SUM	8	6,12	171,32	-7,9083730		9,8	10,07	167,37	-9,5628636		11,9	13,51	164,00	-11,4390142		14,5	17,38	160,27	-13,6487617	
	VALUES AT THE BUS BAR						**VALUES AT THE BUS BAR**					**VALUES AT THE BUS BAR**					**VALUES AT THE BUS BAR**				
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**I_L**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**I_L**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**I_L**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**I_L**
		10,97	-178,16				10,988	-176,69				11,027	-175,04				11,088	-173,25			
	CURRENTS	**/3I0/**	**AN(3I0)**				**/3I0/**	**AN(3I0)**				**/3I0/**	**AN(3I0)**				**/3I0/**	**AN(3I0)**			
	TO GEN	59,2	96,77	-274,93	5,0875649	58,9809858	68,5	97,57	-274,26	5,0883541	68,3107506	77,3	98,76	-273,80	5,1229725	77,1300535	85,5	100,2	-273,45	5,1451745	85,3450478
	TO L1	0,9	-88,17	-89,99	0,0001571		0,9	-86,7	-89,99	0,0001571		0,9	-85,04	-90,00	0,0000000		0,9	-83,26	-89,99	0,0001571	
	TO L2	0,9	-88,17	-89,99	0,0001571		0,9	-86,7	-89,99	0,0001571		0,9	-85,04	-90,00	0,0000000		0,9	-83,26	-89,99	0,0001571	
	TO L3	53,2	-82,67	-95,49	-5,0897516		62,4	-82,01	-94,68	-5,0912542		71,3	-80,92	-94,12	-5,1225922		79,4	-79,54	-93,71	-5,1376942	
	TO L4	2,6	-88,21	-89,95	0,0022689		2,6	-86,74	-89,95	0,0022689		2,6	-85,08	-89,96	0,0018151		2,6	-83,3	-89,95	0,0022689	
	TO L5	1,7	-88,18	-89,98	0,0005934		1,7	-86,71	-89,98	0,0005934		1,7	-85,06	-89,98	0,0005934		1,7	-83,27	-89,98	0,0005934	
EARTH-FAULT AT BUS S97	**SOLID EARTH-FAULT**																				
		5km					**10km**					**15km**					**20km**				
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**		**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**		**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**		**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	
		11,709	178,73				11,713	178,71				11,714	178,68				11,709	178,64			
	CURRENTS	**/3I0/**	**AN(3I0)**				**/3I0/**	**AN(3I0)**				**/3I0/**	**AN(3I0)**				**/3I0/**	**AN(3I0)**			
	SUM	5,5	-2,18	180,91	-5,4993063		5,9	-2,28	180,99	-5,8991193		6,5	-1,72	180,40	-6,4998416		7,5	-3,05	181,69	-7,4967377	
	VALUES AT THE BUS BAR						**VALUES AT THE BUS BAR**					**VALUES AT THE BUS BAR**					**VALUES AT THE BUS BAR**				
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**I_L**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**I_L**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**I_L**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**I_L**
		11,66	178,32				11,663	178,27				11,661	178,19				11,647	178,08			
	CURRENTS	**/3I0/**	**AN(3I0)**				**/3I0/**	**AN(3I0)**				**/3I0/**	**AN(3I0)**				**/3I0/**	**AN(3I0)**			
	TO GEN	20,5	103,71	74,61	5,4404509	19,7649056	31	98,35	79,92	5,4257148	30,5214944	41,7	95,65	82,54	5,4140779	41,3470405	52,5	93,99	84,09	5,4057225	52,2209552
	TO L1	0,9	-91,69	270,01	0,0001571		0,9	-91,73	270,00	0,0000000		0,9	-91,82	270,01	0,0001571		0,9	-91,93	270,01	0,0001571	
	TO L2	0,9	-91,69	270,01	0,0001571		0,9	-91,73	270,00	0,0000000		0,9	-91,82	270,01	0,0001571		0,9	-91,93	270,01	0,0001571	
	TO L3	13,2	-92,18	270,50	0,1151903		24	-92,84	271,11	0,4649266		34,9	-93,66	271,85	1,1266760		45,7	-94,6	272,68	2,1368301	
	TO L4	2,8	-91,73	270,05	0,0024435		2,8	-91,77	270,04	0,0019548		2,8	-91,86	270,05	0,0024435		2,8	-91,97	270,05	0,0024435	
	TO L5	5,9	-20,34	198,66	-5,5898599		6,2	-19,45	197,72	-5,9058428		6,8	-17,32	195,51	-6,5523698		7,8	-16,58	194,66	-7,5460685	
EARTH-FAULT AT BUS S97	**SOLID EARTH-FAULT**																				
		25km					**30km**					**35km**					**40km**				
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**		**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**		**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**		**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	
		11,7	178,58				11,686	178,49				11,668	178,4				11,646	178,3			
	CURRENTS	**/3I0/**	**AN(3I0)**				**/3I0/**	**AN(3I0)**				**/3I0/**	**AN(3I0)**				/3I0/	AN(3I0)			
	SUM	8,9	-2,78	181,36	-8,8974929		10,7	-2,08	180,57	-10,6994705		12,7	-2,26	180,66	-12,6991574		15	-2,29	180,59	-14,9992047	
	VALUES AT THE BUS BAR						**VALUES AT THE BUS BAR**					**VALUES AT THE BUS BAR**					**VALUES AT THE BUS BAR**				
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**I_L**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**I_L**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**I_L**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**I_L**
		11,63	177,9				11,609	177,67				11,579	177,41				11,545	177,12			
	CURRENTS	**/3I0/**	**AN(3I0)**				**/3I0/**	**AN(3I0)**				**/3I0/**	**AN(3I0)**				**/3I0/**	**AN(3I0)**			
	TO GEN	62,8	92,83	85,07	5,3969439	62,5676673	72,4	91,94	85,73	5,3906572	72,1990361	81,2	91,21	86,20	5,3814407	81,0214792	89	90,57	86,55	5,3557957	88,8387047
	TO L1	0,9	-92,11	270,01	0,0001571		0,9	-92,34	270,01	0,0001571		0,9	-92,59	270,00	0,0000000		0,9	-92,88	270,00	0,0000000	
	TO L2	0,9	-92,11	270,01	0,0001571		0,9	-92,34	270,01	0,0001571		0,9	-92,59	270,00	0,0000000		0,9	-92,88	270,00	0,0000000	
	TO L3	56,1	-95,7	273,60	3,5225481		66	-96,93	274,60	5,2931290		75,1	-98,23	275,64	7,3806534		83,2	-99,58	276,70	9,7070053	
	TO L4	2,8	-92,15	270,05	0,0024435		2,8	-92,38	270,05	0,0024435		2,8	-92,63	270,04	0,0019548		2,7	-92,92	270,04	0,0018850	
	TO L5	9,1	-14,29	192,19	-8,8948201		10,8	-11,76	189,43	-10,6540543		12,9	-10,38	187,79	-12,7809525		15,2	-9,16	186,28	-15,1087878	

EARTH-FAULT AT BUS S61

5KΩ EARTH-FAULT

	5km				
VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	
	3,592	178,13			
CURRENTS	/3I0/	AN(3I0)			
SUM	1,6	-1,74	179,87	-1,5999959	
VALUES AT THE BUS BAR					
VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	I_L
	3,487	178,15			
CURRENTS	/3I0/	AN(3I0)			
TO GEN	6,1	103,55	74,60	1,6198923	5,8809820
TO L1	0,3	-91,85	270,00	0,0000000	
TO L2	0,3	-91,85	270,00	0,0000000	
TO L3	4,3	-69,6	247,75	-1,6281891	
TO L4	0,8	-91,89	270,04	0,0005585	
TO L5	0,5	-91,87	270,02	0,0001745	

	10km				
VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	
	3,539	176,82			
CURRENTS	/3I0/	AN(3I0)			
SUM	1,6	-1,51	178,33	-1,5993204	
VALUES AT THE BUS BAR					
VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	I_L
	3,376	177,67			
CURRENTS	/3I0/	AN(3I0)			
TO GEN	9	97,74	79,93	1,5736610	8,8613538
TO L1	0,3	-92,34	270,01	0,0000524	
TO L2	0,3	-92,34	270,01	0,0000524	
TO L3	7,1	-79,63	257,30	-1,5609081	
TO L4	0,8	-92,38	270,05	0,0006981	
TO L5	0,5	-92,35	270,02	0,0001745	

	15km				
VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	
	3,349	174,74			
CURRENTS	/3I0/	AN(3I0)			
SUM	1,7	-0,94	175,68	-1,6951701	
VALUES AT THE BUS BAR					
VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	I_L
	3,157	176,6			
CURRENTS	/3I0/	AN(3I0)			
TO GEN	11,3	94,06	82,54	1,4671242	11,2043539
TO L1	0,3	-93,41	270,01	0,0000524	
TO L2	0,3	-93,41	270,01	0,0000524	
TO L3	9,6	-84,57	261,17	-1,4736312	
TO L4	0,8	-93,45	270,05	0,0006981	
TO L5	0,5	-93,42	270,02	0,0001745	

	20km				
VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	
	3,047	173,67			
CURRENTS	/3I0/	AN(3I0)			
SUM	1,8	-0,82	174,49	-1,7916830	
VALUES AT THE BUS BAR					
VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	I_L
	2,851	176,72			
CURRENTS	/3I0/	AN(3I0)			
TO GEN	12,9	92,64	84,08	1,3305027	12,8312027
TO L1	0,2	-93,28	270,00	0,0000000	
TO L2	0,2	-93,28	270,00	0,0000000	
TO L3	11,3	-86,54	263,26	-1,3262140	
TO L4	0,7	-93,32	270,04	0,0004887	
TO L5	0,4	-93,3	270,02	0,0001396	

EARTH-FAULT AT BUS S61

5KΩ EARTH-FAULT

	25km				
VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	
	2,686	171,04			
CURRENTS	/3I0/	AN(3I0)			
SUM	1,8	-0,28	171,32	-1,7793839	
VALUES AT THE BUS BAR					
VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	I_L
	2,506	175,44			
CURRENTS	/3I0/	AN(3I0)			
TO GEN	13,5	90,37	85,07	1,1601711	13,4500559
TO L1	0,2	-94,57	270,01	0,0000349	
TO L2	0,2	-94,57	270,01	0,0000349	
TO L3	12,2	-89,06	264,50	-1,1693182	
TO L4	0,6	-94,61	270,05	0,0005236	
TO L5	0,4	-94,58	270,02	0,0001396	

	30km				
VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	
	2,314	167,65			
CURRENTS	/3I0/	AN(3I0)			
SUM	1,9	0,28	167,37	-1,8540246	
VALUES AT THE BUS BAR					
VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	I_L
	2,162	173,52			
CURRENTS	/3I0/	AN(3I0)			
TO GEN	13,5	87,79	85,73	1,0051640	13,4625275
TO L1	0,2	-96,49	270,01	0,0000349	
TO L2	0,2	-96,49	270,01	0,0000349	
TO L3	12,3	-91,79	265,31	-1,0057041	
TO L4	0,5	-96,53	270,05	0,0004363	
TO L5	0,3	-96,5	270,02	0,0001047	

	35km				
VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	
	1,967	164,61			
CURRENTS	/3I0/	AN(3I0)			
SUM	2	0,61	164,00	-1,9225234	
VALUES AT THE BUS BAR					
VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	I_L
	1,846	172,07			
CURRENTS	/3I0/	AN(3I0)			
TO GEN	12,9	85,86	86,21	0,8526868	12,8717880
TO L1	0	0	172,07	0,0000000	
TO L2	0	0	172,07	0,0000000	
TO L3	11,9	-93,81	265,88	-0,8549628	
TO L4	0,4	-97,98	270,05	0,0003491	
TO L5	0,3	-97,95	270,02	0,0001047	

	40km				
VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	
	1,663	161,21			
CURRENTS	/3I0/	AN(3I0)			
SUM	2,1	0,94	160,27	-1,9767172	
VALUES AT THE BUS BAR					
VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	I_L
	1,572	170,31			
CURRENTS	/3I0/	AN(3I0)			
TO GEN	12,1	83,76	86,55	0,7281475	12,0780711
TO L1	0	0	170,31	0,0000000	
TO L2	0	0	170,31	0,0000000	
TO L3	11,3	-95,97	266,28	-0,7331513	
TO L4	0,4	-99,74	270,05	0,0003491	
TO L5	0,2	-99,71	270,02	0,0000698	

EARTH-FAULT AT BUS S97

5KΩ EARTH-FAULT

	5km				
VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	
	3,495	179,53			
CURRENTS	/3I0/	AN(3I0)			
SUM	1,7	-1,37	180,90	-1,6997903	
VALUES AT THE BUS BAR					
VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	I_L
	3,481	179,12			
CURRENTS	/3I0/	AN(3I0)			
TO GEN	6,1	104,52	74,60	1,6198923	5,8809820
TO L1	0,3	-90,88	270,00	0,0000000	
TO L2	0,3	-90,88	270,00	0,0000000	
TO L3	4	-91,38	270,50	0,0349061	
TO L4	0,8	-90,92	270,04	0,0005585	
TO L5	1,7	-19,54	198,66	-1,6106376	

	10km				
VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	
	3,352	179,6			
CURRENTS	/3I0/	AN(3I0)			
SUM	1,7	-1,39	180,99	-1,6997462	
VALUES AT THE BUS BAR					
VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	I_L
	3,338	179,16			
CURRENTS	/3I0/	AN(3I0)			
TO GEN	8,9	99,24	79,92	1,5577052	8,7626226
TO L1	0,3	-90,84	270,00	0,0000000	
TO L2	0,3	-90,84	270,00	0,0000000	
TO L3	6,9	-91,95	271,11	0,1336664	
TO L4	0,8	-90,88	270,04	0,0005585	
TO L5	1,8	-18,56	197,72	-1,7145995	

	15km				
VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	
	3,11	179,18			
CURRENTS	/3I0/	AN(3I0)			
SUM	1,7	-1,22	180,40	-1,6999586	
VALUES AT THE BUS BAR					
VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	I_L
	3,096	178,69			
CURRENTS	/3I0/	AN(3I0)			
TO GEN	11,1	96,16	82,53	1,4430783	11,0057951
TO L1	0,2	-91,32	270,01	0,0000349	
TO L2	0,2	-91,32	270,01	0,0000349	
TO L3	9,3	-93,15	271,84	0,2986094	
TO L4	0,7	-91,36	270,05	0,0006109	
TO L5	1,8	-16,82	195,51	-1,7344508	

	20km				
VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	
	2,796	-179,83			
CURRENTS	/3I0/	AN(3I0)			
SUM	1,8	-1,52	-178,31	-1,7992170	
VALUES AT THE BUS BAR					
VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	I_L
	2,781	179,61			
CURRENTS	/3I0/	AN(3I0)			
TO GEN	12,5	95,52	84,09	1,2870768	12,4335608
TO L1	0,2	-90,4	270,01	0,0000349	
TO L2	0,2	-90,4	270,01	0,0000349	
TO L3	10,9	-93,07	272,68	0,5096597	
TO L4	0,7	-90,44	270,05	0,0006109	
TO L5	1,9	-15,05	194,66	-1,8381449	

EARTH-FAULT AT BUS S97	**5KΩ EARTH-FAULT**																				
		25km					**30km**					**35km**					**40km**				
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**		**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**		**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**		**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	
		2,454	179,96				2,123	179,35				1,831	179,43				1,587	179,38			
	CURRENTS	**/3I0/**	**AN(3I0)**				**/3I0/**	**AN(3I0)**				**/3I0/**	**AN(3I0)**				**/3I0/**	**AN(3I0)**			
	SUM	1,9	-1,41	181,37	-1,8994569		1,9	-1,23	180,58	-1,8999027		2	-1,23	180,66	-1,9998673		2	-1,21	180,59	-1,9998940	
	VALUES AT THE BUS BAR						**VALUES AT THE BUS BAR**					**VALUES AT THE BUS BAR**					**VALUES AT THE BUS BAR**				
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**I_L**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**I_L**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**I_L**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**I_L**
		2,439	179,28				2,109	178,52				1,817	178,44				1,573	178,2			
	CURRENTS	**/3I0/**	**AN(3I0)**				**/3I0/**	**AN(3I0)**				**/3I0/**	**AN(3I0)**				**/3I0/**	**AN(3I0)**			
	TO GEN	13,2	94,21	85,07	1,1343895	13,1511657	13,1	92,79	85,73	0,9753814	13,0636377	12,7	92,23	86,21	0,8394668	12,6722254	12,1	91,64	86,56	0,7260395	12,0781980
	TO L1	0,2	-90,73	270,01	0,0000349		0,2	-91,48	270,00	0,0000000		0	0	178,44	0,0000000		0	0	178,20	0,0000000	
	TO L2	0,2	-90,73	270,01	0,0000349		0,2	-91,48	270,00	0,0000000		0	0	178,44	0,0000000		0	0	178,20	0,0000000	
	TO L3	11,8	-94,33	273,61	0,7429835		12	-96,08	274,60	0,9623871		11,8	-97,2	275,64	1,1596766		11,3	-98,5	276,70	1,3183793	
	TO L4	0,6	-90,77	270,05	0,0005236		0,5	-91,52	270,04	0,0003491		0,4	-91,61	270,05	0,0003491		0,4	-91,85	270,05	0,0003491	
	TO L5	1,9	-12,92	192,20	-1,8570902		2	-10,91	189,43	-1,9729730		2	-9,35	187,79	-1,9815430		2,1	-8,08	186,28	-2,0873983	
EARTH-FAULT AT BUS S61	**10KΩ EARTH-FAULT**																				
		5km					**10km**					**15km**					**20km**				
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**		**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**		**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**		**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	
		2,123	178,15				2,084	176,65				1,951	174,27				1,749	173,1			
	CURRENTS	**/3I0/**	**AN(3I0)**				**/3I0/**	**AN(3I0)**				**/3I0/**	**AN(3I0)**				**/3I0/**	**AN(3I0)**			
	SUM	1	-1,72	179,87	-0,9999974		1	-1,68	178,33	-0,9995753		1	-1,41	175,68	-0,9971589		1	-1,39	174,49	-0,9953795	
	VALUES AT THE BUS BAR						**VALUES AT THE BUS BAR**					**VALUES AT THE BUS BAR**					**VALUES AT THE BUS BAR**				
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**I_L**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**I_L**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**I_L**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**I_L**
		2,06	178,18				1,988	177,5				1,84	176,12				1,636	176,15			
	CURRENTS	**/3I0/**	**AN(3I0)**				**/3I0/**	**AN(3I0)**				**/3I0/**	**AN(3I0)**				**/3I0/**	**AN(3I0)**			
	TO GEN	3,6	103,57	74,61	0,9553962	3,4709103	5,3	97,57	79,93	0,9267115	5,2183528	6,6	93,59	82,53	0,8580466	6,5439863	7,4	92,06	84,09	0,7619495	7,3606680
	TO L1	0,2	-91,83	270,01	0,0000349		0,2	-92,51	270,01	0,0000349		0	0	176,12	0,0000000		0	0	176,15	0,0000000	
	TO L2	0,2	-91,83	270,01	0,0000349		0,2	-92,51	270,01	0,0000349		0	0	176,12	0,0000000		0	0	176,15	0,0000000	
	TO L3	2,5	-69,57	247,75	-0,9466215		4,2	-79,8	257,30	-0,9233541		5,6	-85,05	261,17	-0,8596182		6,5	-87,11	263,26	-0,7628665	
	TO L4	0,5	-91,87	270,05	0,0004363		0,5	-92,55	270,05	0,0004363		0,4	-93,93	270,05	0,0003491		0,4	-93,89	270,04	0,0002793	
	TO L5	0,3	-91,84	270,02	0,0001047		0,3	-92,52	270,02	0,0001047		0,3	-93,9	270,02	0,0001047		0,3	-93,87	270,02	0,0001047	
EARTH-FAULT AT BUS S61	**10KΩ EARTH-FAULT**																				
		25km					**30km**					**35km**					**40km**				
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**		**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**		**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**		**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	
		1,514	170,21				1,28	166,59				1,07	163,45				0,891	159,97			
	CURRENTS	**/3I0/**	**AN(3I0)**				**/3I0/**	**AN(3I0)**				**/3I0/**	**AN(3I0)**				**/3I0/**	**AN(3I0)**			
	SUM	1	-1,1	171,31	-0,9885203		1,1	-0,78	167,37	-1,0733826		1,1	-0,55	164,00	-1,0573879		1,1	-0,29	160,26	-1,0353585	
	VALUES AT THE BUS BAR						**VALUES AT THE BUS BAR**					**VALUES AT THE BUS BAR**					**VALUES AT THE BUS BAR**				
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**I_L**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**I_L**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**I_L**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**I_L**
		1,412	174,62				1,196	172,46				1,004	170,9				0,843	169,08			
	CURRENTS	**/3I0/**	**AN(3I0)**				**/3I0/**	**AN(3I0)**				**/3I0/**	**AN(3I0)**				**/3I0/**	**AN(3I0)**			
	TO GEN	7,6	89,55	85,07	0,6531333	7,5718833	7,5	86,73	85,73	0,5584244	7,4791819	7	84,69	86,21	0,4626983	6,9846911	6,5	82,52	86,56	0,3900212	6,4882882
	TO L1	0	0	174,62	0,0000000		0	0	172,46	0,0000000		0	0	170,90	0,0000000		0	0	169,08	0,0000000	
	TO L2	0	0	174,62	0,0000000		0	0	172,46	0,0000000		0	0	170,90	0,0000000		0	0	169,08	0,0000000	
	TO L3	6,8	-89,89	264,51	-0,6505697		6,8	-92,86	265,32	-0,5548162		6,5	-94,98	265,88	-0,4669965		6	-97,21	266,29	-0,3882389	
	TO L4	0,3	-95,43	270,05	0,0002618		0,3	-97,59	270,05	0,0002618		0,2	-99,14	270,04	0,0001396		0,2	-100,97	270,05	0,0001745	
	TO L5	0,2	-95,4	270,02	0,0000698		0,2	-97,56	270,02	0,0000698		0,2	-99,12	270,02	0,0000698		0	0	169,08	0,0000000	

EARTH-FAULT AT BUS S97	10KΩ EARTH-FAULT										
		5km					**10km**				
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**		**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	
		2,053	179,68				1,955	179,75			
	CURRENTS	**/3I0/**	**AN(3I0)**				**/3I0/**	**AN(3I0)**			
	SUM	1	-1,23	180,91	-0,9998739		1	-1,24	180,99	-0,9998507	
	VALUES AT THE BUS BAR						**VALUES AT THE BUS BAR**				
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**I_L**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**I_L**
		2,044	179,26				1,946	179,31			
	CURRENTS	**/3I0/**	**AN(3I0)**				**/3I0/**	**AN(3I0)**			
	TO GEN	3,6	104,66	74,60	0,9560020	3,4707435	5,2	99,39	79,92	0,9101199	5,1197345
	TO L1	0,2	-90,74	270,00	0,0000000		0,2	-90,69	270,00	0,0000000	
	TO L2	0,2	-90,74	270,00	0,0000000		0,2	-90,69	270,00	0,0000000	
	TO L3	2,3	-91,24	270,50	0,0200710		4	-91,8	271,11	0,0774878	
	TO L4	0,5	-90,78	270,04	0,0003491		0,5	-90,73	270,04	0,0003491	
	TO L5	1	-19,39	198,65	-0,9474897		1	-18,41	197,72	-0,9525553	

EARTH-FAULT AT BUS S97	10KΩ EARTH-FAULT										
		15km					**20km**				
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**		**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	
		1,792	179,26				1,586	-179,62			
	CURRENTS	**/3I0/**	**AN(3I0)**				**/3I0/**	**AN(3I0)**			
	SUM	1	-1,14	180,40	-0,9999756		1	-1,31	-178,31	-0,9995650	
		VALUES AT THE BUS BAR					**VALUES AT THE BUS BAR**				
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**I_L**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**I_L**
		1,783	178,77				1,578	179,81			
	CURRENTS	**/3I0/**	**AN(3I0)**				**/3I0/**	**AN(3I0)**			
	TO GEN	6,4	96,23	82,54	0,8309376	6,3458288	7,1	95,72	84,09	0,7310596	7,0622625
	TO L1	0	0	178,77	0,0000000		0	0	179,81	0,0000000	
	TO L2	0	0	178,77	0,0000000		0	0	179,81	0,0000000	
	TO L3	5,3	-93,07	271,84	0,1701753		6,2	-92,86	272,67	0,2888172	
	TO L4	0,4	-91,28	270,05	0,0003491		0,4	-90,23	270,04	0,0002793	
	TO L5	1	-16,74	195,51	-0,9635838		1,1	-14,84	194,65	-1,0642377	

EARTH-FAULT AT BUS S97	10KΩ EARTH-FAULT										
		25km					**30km**				
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**		**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	
		1,369	-179,88				1,167	179,43			
	CURRENTS	**/3I0/**	**AN(3I0)**				**/3I0/**	**AN(3I0)**			
	SUM	1	-1,24	-178,64	-0,9997183		1,1	-1,15	180,58	-1,0999436	
	VALUES AT THE BUS BAR						**VALUES AT THE BUS BAR**				
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**I_L**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**I_L**
		1,361	179,44				1,159	178,61			
	CURRENTS	**/3I0/**	**AN(3I0)**				**/3I0/**	**AN(3I0)**			
	TO GEN	7,4	94,37	85,07	0,6359456	7,3726232	7,2	92,88	85,73	0,5360875	7,1800146
	TO L1	0	0	179,44	0,0000000		0	0	178,61	0,0000000	
	TO L2	0	0	179,44	0,0000000		0	0	178,61	0,0000000	
	TO L3	6,6	-94,17	273,61	0,4155671		6,6	-96	274,61	0,5304611	
	TO L4	0,3	-90,61	270,05	0,0002618		0,3	-91,44	270,05	0,0002618	
	TO L5	1,1	-12,75	192,19	-1,0751980		1,1	-10,82	189,43	-1,0851352	

EARTH-FAULT AT BUS S97	10KΩ EARTH-FAULT										
		35km					**40km**				
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**		**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	
		0,993	179,52				0,851	179,46			
	CURRENTS	**/3I0/**	**AN(3I0)**				**/3I0/**	**AN(3I0)**			
	SUM	1,1	-1,15	180,67	-1,0999248		1,1	-1,13	180,59	-1,0999417	
		VALUES AT THE BUS BAR					**VALUES AT THE BUS BAR**				
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**I_L**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**I_L**
		0,985	178,53				0,843	178,28			
	CURRENTS	**/3I0/**	**AN(3I0)**				**/3I0/**	**AN(3I0)**			
	TO GEN	6,9	92,32	86,21	0,4560883	6,8849098	6,5	91,72	86,56	0,3900212	6,4882882
	TO L1	0	0	178,53	0,0000000		0	0	178,28	0,0000000	
	TO L2	0	0	178,53	0,0000000		0	0	178,28	0,0000000	
	TO L3	6,4	-97,11	275,64	0,6289771		6,1	-98,42	276,70	0,7116915	
	TO L4	0,2	-91,52	270,05	0,0001745		0,2	-91,77	270,05	0,0001745	
	TO L5	1,1	-9,26	187,79	-1,0898487		1,1	-8	186,28	-1,0933991	

EARTH-FAULT AT THE BUS BAR	**SOLID EARTH-FAULT**																
		5km				**10km**				**15km**				**20km**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		11,89	179,13			11,889	179,2			11,888	179,26			11,888	179,33		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	FROM GEN	0	0	179,13	0,0000000	0	0	179,20	0,0000000	0	0	179,26	0,0000000	0	0	179,33	0,0000000
	FROM L1	0,9	89,12	90,01	-0,0001571	0,9	89,19	90,01	-0,0001571	0,9	89,26	90,00	0,0000000	0,9	89,32	90,01	-0,0001571
	FROM L2	0,9	89,12	90,01	-0,0001571	0,9	89,19	90,01	-0,0001571	0,9	89,26	90,00	0,0000000	0,9	89,32	90,01	-0,0001571
	FROM L3	0,8	-65,16	244,29	-0,3470531	4,3	-80,73	259,93	-0,7518602	7,8	-81,95	261,21	-1,1919442	11,3	-82,9	262,23	-1,5277238
	FROM L4	2,8	89,08	90,05	-0,0024435	2,8	89,15	90,05	-0,0024435	2,8	89,22	90,04	-0,0019548	2,8	89,28	90,05	-0,0024435
	FROM L5	1,9	89,11	90,02	-0,0006632	1,9	89,18	90,02	-0,0006632	1,9	89,24	90,02	-0,0006632	1,9	89,31	90,02	-0,0006632
	SUM	5,8	85,57	93,56	-0,3601438	2,4	71,07	108,13	-0,7468178	1,7	-44,8	224,06	-1,2216403	4,9	-72,43	251,76	-1,5336904

EARTH-FAULT AT THE BUS BAR	**SOLID EARTH-FAULT**																
		25km				**30km**				**35km**				**40km**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		11,888	179,4			11,887	179,47			11,886	179,54			11,884	179,6		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	FROM GEN	0	0	179,40	0,0000000	0	0	179,47	0,0000000	0	0	179,54	0,0000000	0	0	179,60	0,0000000
	FROM L1	0,9	89,39	90,01	-0,0001571	0,9	89,46	90,01	-0,0001571	0,9	89,53	90,01	-0,0001571	0,9	89,59	90,01	-0,0001571
	FROM L2	0,9	89,39	90,01	-0,0001571	0,9	89,46	90,01	-0,0001571	0,9	89,53	90,01	-0,0001571	0,9	89,59	90,01	-0,0001571
	FROM L3	14,9	-83,32	262,72	-1,8881036	18,4	-83,49	262,96	-2,2551452	22	-83,52	263,06	-2,6582575	25,7	-82,69	262,29	-3,4478900
	FROM L4	2,8	89,35	90,05	-0,0024435	2,8	89,42	90,05	-0,0024435	2,8	89,49	90,05	-0,0024435	2,8	89,55	90,05	-0,0024435
	FROM L5	1,9	89,38	90,02	-0,0006632	1,9	89,45	90,02	-0,0006632	1,9	89,52	90,02	-0,0006632	1,9	89,58	90,02	-0,0006632
	SUM	8,4	-77,59	256,99	-1,8910173	11,9	-79,6	259,07	-2,2563539	15,5	-80,57	260,11	-2,6622360	19,2	-80,04	259,64	-3,4527828

EARTH-FAULT AT BUS S61	**SOLID EARTH-FAULT**																
		5km				**10km**				**15km**				**20km**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		11,784	177,77			11,784	177,84			11,783	177,97			11,781	178,15		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	SUM	5,9	83,19	94,58	-0,4711208	2,5	68,02	109,82	-0,8476658	1,7	-48,41	226,38	-1,1727829	5	-75,7	253,85	-1,3907649
	VALUES AT THE BUS BAR					**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		11,964	177,04			11,933	176,85			11,901	176,83			11,863	177,38		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	TO GEN	0	0	177,04	0,0000000	0	0	176,85	0,0000000	0	0	176,83	0,0000000	0	0	177,38	0,0000000
	TO L1	0,9	-92,96	270,00	0,0000000	0,9	-93,16	270,01	0,0001571	0,9	-93,18	270,01	0,0001571	0,9	-92,62	270,00	0,0000000
	TO L2	0,9	-92,96	270,00	0,0000000	0,9	-93,16	270,01	0,0001571	0,9	-93,18	270,01	0,0001571	0,9	-92,62	270,00	0,0000000
	TO L3	6,6	87,01	90,03	-0,0034558	6,6	86,82	90,03	-0,0034558	6,6	86,8	90,03	-0,0034558	6,6	87,36	90,02	-0,0023038
	TO L4	2,8	-93	270,04	0,0019548	2,8	-93,2	270,05	0,0024435	2,8	-93,22	270,05	0,0024435	2,8	-92,66	270,04	0,0019548
	TO L5	1,9	-92,98	270,02	0,0006632	1,9	-93,17	270,02	0,0006632	1,9	-93,19	270,02	0,0006632	1,9	-92,64	270,02	0,0006632

EARTH-FAULT AT BUS S61	**SOLID EARTH-FAULT**																
		25km				**30km**				**35km**				**40km**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		11,777	178,38			11,771	178,67			11,761	179			11,748	179,39		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	SUM	8,5	-80,41	258,79	-1,6524472	12	-81,87	260,54	-1,9723081	15,5	-82,2	261,20	-2,3712805	19	-81,76	261,15	-2,9231152
	VALUES AT THE BUS BAR					**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		11,821	178,11			11,775	179			11,722	-179,96			11,664	-179,16		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	TO GEN	0	0	178,11	0,0000000	0	0	179,00	0,0000000	0	0	-179,96	0,0000000	0	0	-179,16	0,0000000
	TO L1	0,9	-91,9	270,01	0,0001571	0,9	-91,01	270,01	0,0001571	0,9	-89,96	-90,00	0,0000000	0,9	-89,17	-89,99	0,0001571
	TO L2	0,9	-91,9	270,01	0,0001571	0,9	-91,01	270,01	0,0001571	0,9	-89,96	-90,00	0,0000000	0,9	-89,17	-89,99	0,0001571
	TO L3	6,5	88,08	90,03	-0,0034034	6,5	88,97	90,03	-0,0034034	6,5	90,02	-269,98	-0,0022689	6,4	90,81	-269,97	-0,0033510
	TO L4	2,8	-91,94	270,05	0,0024435	2,8	-91,05	270,05	0,0024435	2,8	-90	-89,96	0,0019548	2,8	-89,21	-89,95	0,0024435
	TO L5	1,8	-91,91	270,02	0,0006283	1,8	-91,02	270,02	0,0006283	1,8	-89,98	-89,98	0,0006283	1,8	-89,18	-89,98	0,0006283
EARTH-FAULT AT BUS S97	**SOLID EARTH-FAULT**																
		5km				**10km**				**15km**				**20km**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		11,831	178,58			11,803	178,78			11,776	178,99			11,749	179,19		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	SUM	5,8	84,88	93,70	-0,3742874	2,4	70,59	108,19	-0,7492059	1,6	-45,08	224,07	-1,1495849	4,8	-72,51	251,70	-1,5071638
	VALUES AT THE BUS BAR					**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		11,908	178,41			11,82	178,69			11,734	178,95			11,651	179,22		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	TO GEN	0	0	178,41	0,0000000	0	0	178,69	0,0000000	0	0	178,95	0,0000000	0	0	179,22	0,0000000
	TO L1	0,9	-91,59	270,00	0,0000000	0,9	-91,32	270,01	0,0001571	0,9	-91,05	270,00	0,0000000	0,9	-90,78	270,00	0,0000000
	TO L2	0,9	-91,59	270,00	0,0000000	0,9	-91,32	270,01	0,0001571	0,9	-91,05	270,00	0,0000000	0,9	-90,78	270,00	0,0000000
	TO L3	0,8	114,13	64,28	0,3471789	4,3	98,77	79,92	0,7525992	7,7	97,74	81,21	1,1766628	11,1	96,99	82,23	1,5006845
	TO L4	2,8	-91,63	270,04	0,0019548	2,8	-91,36	270,05	0,0024435	2,8	-91,1	270,05	0,0024435	2,8	-90,82	270,04	0,0019548
	TO L5	4	83,2	95,21	-0,3632256	0,9	29,89	148,80	-0,7698278	3,2	-69,41	248,36	-1,1800754	6,6	-77,53	256,75	-1,5127226
EARTH-FAULT AT BUS S97	**SOLID EARTH-FAULT**																
		25km				**30km**				**35km**				**40km**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		11,723	179,39			11,696	179,59			11,669	179,78			11,638	179,96		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	SUM	8,1	-77,47	256,86	-1,8413828	11,5	-79,29	258,88	-2,2179416	14,9	-80,07	259,85	-2,6257644	18,2	-79,39	259,35	-3,3635248
	VALUES AT THE BUS BAR					**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		11,568	179,49			11,485	179,75			11,401	-179,99			11,313	-179,77		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	TO GEN	0	0	179,49	0,0000000	0	0	179,75	0,0000000	0	0	-179,99	0,0000000	0	0	-179,77	0,0000000
	TO L1	0,9	-90,51	270,00	0,0000000	0,9	-90,25	270,00	0,0000000	0,9	-89,99	-90,00	0,0000000	0,9	-89,78	-89,99	0,0001571
	TO L2	0,9	-90,51	270,00	0,0000000	0,9	-90,25	270,00	0,0000000	0,9	-89,99	-90,00	0,0000000	0,9	-89,78	-89,99	0,0001571
	TO L3	14,5	96,77	82,72	1,8374163	17,8	96,8	82,95	2,1846911	21,1	96,96	-276,95	2,5531662	24,4	97,94	-277,71	3,2734831
	TO L4	2,8	-90,56	270,05	0,0024435	2,7	-90,29	270,04	0,0018850	2,7	-90,03	-89,96	0,0018850	2,7	-89,82	-89,95	0,0023562
	TO L5	9,9	-79,86	259,35	-1,8296096	13,3	-80,79	260,54	-2,1859748	16,6	-81,15	-98,84	-2,5510168	20	-80,33	-99,44	-3,2802936

EARTH-FAULT AT BUS S61	**5KΩ EARTH-FAULT**																
		5km				**10km**				**15km**				**20km**			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		4,229	113,83			7,016	141,9			7,451	-162,92			4,592	-130,27		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	SUM	2,1	19,26	94,57	-0,1673217	1,5	32,08	109,82	-0,5085995	1,1	-29,3	-133,62	-0,7588595	1,9	-24,11	-106,16	-0,5288092
	VALUES AT THE BUS BAR					**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		4,293	113,11			7,105	140,91			7,526	-164,06			4,624	-131,04		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	TO GEN	0	0	113,11	0,0000000	0	0	140,91	0,0000000	0	0	-164,06	0,0000000	0	0	-131,04	0,0000000
	TO L1	0,3	-156,9	270,01	0,0000524	0,6	-129,09	270,00	0,0000000	0,6	-74,07	-89,99	0,0001047	0,4	-41,04	-90,00	0,0000000
	TO L2	0,3	-156,9	270,01	0,0000524	0,6	-129,09	270,00	0,0000000	0,6	-74,07	-89,99	0,0001047	0,4	-41,04	-90,00	0,0000000
	TO L3	2,4	23,08	90,03	-0,0012566	3,9	50,88	90,03	-0,0020420	4,2	105,91	-269,97	-0,0021991	2,6	138,94	-269,98	-0,0009076
	TO L4	1	-156,94	270,05	0,0008727	1,7	-129,14	270,05	0,0014835	1,8	-74,11	-89,95	0,0015708	1,1	-41,08	-89,96	0,0007679
	TO L5	0,7	-156,91	270,02	0,0002443	1,1	-129,11	270,02	0,0003840	1,2	-74,08	-89,98	0,0004189	0,7	-41,06	-89,98	0,0002443
EARTH-FAULT AT BUS S61	**5KΩ EARTH-FAULT**																
		25km				**30km**				**35km**				**40km**			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		3,024	-117,93			2,217	-112,23			1,742	-109,13			1,431	-107,46		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	SUM	2,2	-16,73	-101,20	-0,4273156	2,3	-12,77	-99,46	-0,3780257	2,3	-10,34	-98,79	-0,3514707	2,3	-8,61	-98,85	-0,3538508
	VALUES AT THE BUS BAR					**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		3,036	-118,2			2,218	-111,9			1,736	-108,09			1,42	-106		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	TO GEN	0	0	-118,20	0,0000000	0	0	-111,90	0,0000000	0	0	-108,09	0,0000000	0	0	-106,00	0,0000000
	TO L1	0,2	-28,21	-89,99	0,0000349	0,2	-21,91	-89,99	0,0000349	0	0	-108,09	0,0000000	0	0	-106,00	0,0000000
	TO L2	0,2	-28,21	-89,99	0,0000349	0,2	-21,91	-89,99	0,0000349	0	0	-108,09	0,0000000	0	0	-106,00	0,0000000
	TO L3	1,7	151,77	-269,97	-0,0008901	1,2	158,07	-269,97	-0,0006283	1	161,88	-269,97	-0,0005236	0,8	163,97	-269,97	-0,0004189
	TO L4	0,7	-28,25	-89,95	0,0006109	0,5	-21,95	-89,95	0,0004363	0,4	-18,13	-89,96	0,0002793	0,3	-16,05	-89,95	0,0002618
	TO L5	0,5	-28,23	-89,97	0,0002618	0,3	-21,92	-89,98	0,0001047	0,3	-18,11	-89,98	0,0001047	0,2	-16,02	-89,98	0,0000698
EARTH-FAULT AT BUS S97	**5KΩ EARTH-FAULT**																
		5km				**10km**				**15km**				**20km**			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		4,327	114,06			7,184	142,44			7,472	-163,14			4,642	-131,34		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	SUM	2,1	20,36	93,70	-0,1355178	1,5	34,25	108,19	-0,4682537	1	-27,21	-135,93	-0,7184906	1,9	-23,04	-108,30	-0,5965857
	VALUES AT THE BUS BAR					**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		4,355	113,9			7,194	142,35			7,445	-163,18			4,603	-131,31		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	TO GEN	0	0	113,90	0,0000000	0	0	142,35	0,0000000	0	0	-163,18	0,0000000	0	0	-131,31	0,0000000
	TO L1	0,3	-156,11	270,01	0,0000524	0,6	-127,66	270,01	0,0001047	0,6	-73,18	-90,00	0,0000000	0,4	-41,32	-89,99	0,0000698
	TO L2	0,3	-156,11	270,01	0,0000524	0,6	-127,66	270,01	0,0001047	0,6	-73,18	-90,00	0,0000000	0,4	-41,32	-89,99	0,0000698
	TO L3	0,3	49,61	64,29	0,1301449	2,6	62,42	79,93	0,4546132	4,9	115,61	-278,79	0,7487854	4,4	146,46	-277,77	0,5948659
	TO L4	1	-156,15	270,05	0,0008727	1,7	-127,7	270,05	0,0014835	1,8	-73,22	-89,96	0,0012566	1,1	-41,36	-89,95	0,0009599
	TO L5	1,5	18,68	95,22	-0,1364703	0,5	-6,45	148,80	-0,4276821	2	-51,54	-111,64	-0,7375471	2,6	-28,06	-103,25	-0,5959210

EARTH-FAULT AT BUS S97	**5KΩ EARTH-FAULT**																
		25km				**30km**				**35km**				**40km**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		3,083	-118,99			2,27	-113,12			1,785	-109,83			1,464	-108,77		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	SUM	2,1	-15,85	-103,14	-0,4773956	2,2	-11,99	-101,13	-0,4246786	2,3	-9,68	-100,15	-0,4053193	2,3	-8,12	-100,65	-0,4250608
	VALUES AT THE BUS BAR					**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		3,042	-118,89			2,228	-112,95			1,744	-109,6			1,423	-108,51		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	TO GEN	0	0	-118,89	0,0000000	0	0	-112,95	0,0000000	0	0	-109,60	0,0000000	0	0	-108,51	0,0000000
	TO L1	0,2	-28,89	-90,00	0,0000000	0,2	-22,96	-89,99	0,0000349	0	0	-109,60	0,0000000	0	0	-108,51	0,0000000
	TO L2	0,2	-28,89	-90,00	0,0000000	0,2	-22,96	-89,99	0,0000349	0	0	-109,60	0,0000000	0	0	-108,51	0,0000000
	TO L3	3,8	158,39	-277,28	0,4815298	3,5	164,09	-277,04	0,4289678	3,2	167,35	-276,95	0,3872100	3,1	169,21	-277,72	0,4164295
	TO L4	0,7	-28,93	-89,96	0,0004887	0,5	-23	-89,95	0,0004363	0,4	-19,65	-89,95	0,0003491	0,3	-18,55	-89,96	0,0002094
	TO L5	2,6	-18,23	-100,66	-0,4809495	2,6	-13,49	-99,46	-0,4273334	2,5	-10,76	-98,84	-0,3841893	2,5	-9,06	-99,45	-0,4104671
EARTH-FAULT AT BUS S61	**10KΩ EARTH-FAULT**																
		5km				**10km**				**15km**				**20km**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		2,259	103,9			4,501	128,93			5,253	-154,51			2,572	-120,41		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	SUM	1,1	9,32	94,58	-0,0878361	0,9	19,11	109,82	-0,3051597	0,8	-20,89	-133,62	-0,5518978	1,1	-14,25	-106,16	-0,3061527
	VALUES AT THE BUS BAR					**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		2,294	103,17			4,558	127,93			5,306	-155,65			2,59	-121,17		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	TO GEN	0	0	103,17	0,0000000	0	0	127,93	0,0000000	0	0	-155,65	0,0000000	0	0	-121,17	0,0000000
	TO L1	0,2	-166,83	270,00	0,0000000	0,4	-142,07	270,00	0,0000000	0,4	-65,66	-89,99	0,0000698	0,2	-31,17	-90,00	0,0000000
	TO L2	0,2	-166,83	270,00	0,0000000	0,4	-142,07	270,00	0,0000000	0,4	-65,66	-89,99	0,0000698	0,2	-31,17	-90,00	0,0000000
	TO L3	1,3	13,14	90,03	-0,0006807	2,5	37,91	90,02	-0,0008727	2,9	114,32	-269,97	-0,0015184	1,4	148,8	-269,97	-0,0007330
	TO L4	0,5	-166,88	270,05	0,0004363	1,1	-142,11	270,04	0,0007679	1,3	-65,7	-89,95	0,0011345	0,6	-31,22	-89,95	0,0005236
	TO L5	0,4	-166,85	270,02	0,0001396	0,7	-142,09	270,02	0,0002443	0,8	-65,67	-89,98	0,0002793	0,4	-31,19	-89,98	0,0001396
EARTH-FAULT AT BUS S61	**10KΩ EARTH-FAULT**																
		25km				**30km**				**35km**				**40km**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		1,59	-110,97			1,141	-107,03			0,888	-105,01			0,726	-104,06		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	SUM	1,1	-9,76	-101,21	-0,2138461	1,2	-7,57	-99,46	-0,1972308	1,2	-6,21	-98,80	-0,1835830	1,2	-5,21	-98,85	-0,1846178
	VALUES AT THE BUS BAR					**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		1,596	-111,24			1,142	-106,7			0,885	-103,96			0,721	-102,61		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	TO GEN	0	0	-111,24	0,0000000	0	0	-106,70	0,0000000	0	0	-103,96	0,0000000	0	0	-102,61	0,0000000
	TO L1	0	0	-111,24	0,0000000	0	0	-106,70	0,0000000	0	0	-103,96	0,0000000	0	0	-102,61	0,0000000
	TO L2	0	0	-111,24	0,0000000	0	0	-106,70	0,0000000	0	0	-103,96	0,0000000	0	0	-102,61	0,0000000
	TO L3	0,9	158,73	-269,97	-0,0004712	0,6	163,28	-269,98	-0,0002094	0,5	166,01	-269,97	-0,0002618	0,4	167,37	-269,98	-0,0001396
	TO L4	0,4	-21,29	-89,95	0,0003491	0,3	-16,74	-89,96	0,0002094	0,2	-14,01	-89,95	0,0001745	0,2	-12,65	-89,96	0,0001396
	TO L5	0,2	-21,26	-89,98	0,0000698	0,2	-16,72	-89,98	0,0000698	0	0	-103,96	0,0000000	0	0	-102,61	0,0000000

	10KΩ EARTH-FAULT																
		5km				**10km**				**15km**				**20km**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		2,309	103,89			4,625	128,99			5,298	-155,19			2,622	-121,56		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	SUM	1,1	10,2	93,69	-0,0707940	0,9	20,8	108,19	-0,2809522	0,7	-19,26	-135,93	-0,5029434	1,1	-13,26	-108,30	-0,3453917
EARTH-FAULT AT BUS S97	**VALUES AT THE BUS BAR**					**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		2,324	103,73			4,632	128,9			5,279	-155,23			2,6	-121,53		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	TO GEN	0	0	103,73	0,0000000	0	0	128,90	0,0000000	0	0	-155,23	0,0000000	0	0	-121,53	0,0000000
	TO L1	0,2	-166,28	270,01	0,0000349	0,4	-141,11	270,01	0,0000698	0,4	-65,23	-90,00	0,0000000	0,2	-31,53	-90,00	0,0000000
	TO L2	0,2	-166,28	270,01	0,0000349	0,4	-141,11	270,01	0,0000698	0,4	-65,23	-90,00	0,0000000	0,2	-31,53	-90,00	0,0000000
	TO L3	0,2	39,44	64,29	0,0867633	1,7	48,97	79,93	0,2972471	3,5	123,56	-278,79	0,5348467	2,5	156,24	-277,77	0,3379920
	TO L4	0,6	-166,32	270,05	0,0005236	1,1	-141,15	270,05	0,0009599	1,3	-65,28	-89,95	0,0011345	0,6	-31,57	-89,96	0,0004189
	TO L5	0,8	8,51	95,22	-0,0727842	0,3	-19,9	148,80	-0,2566093	1,4	-43,59	-111,64	-0,5162830	1,5	-18,28	-103,25	-0,3438006

	10KΩ EARTH-FAULT																
		25km				**30km**				**35km**				**40km**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		1,631	-111,95			1,173	-107,8			0,913	-105,6			0,745	-105,29		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	SUM	1,1	-8,81	-103,14	-0,2500643	1,2	-6,68	-101,12	-0,2314374	1,2	-5,45	-100,15	-0,2114710	1,2	-4,64	-100,65	-0,2217709
EARTH-FAULT AT BUS S97	**VALUES AT THE BUS BAR**					**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		1,609	-111,85			1,152	-107,63			0,892	-105,37			0,724	-105,02		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	TO GEN	0	0	-111,85	0,0000000	0	0	-107,63	0,0000000	0	0	-105,37	0,0000000	0	0	-105,02	0,0000000
	TO L1	0	0	-111,85	0,0000000	0	0	-107,63	0,0000000	0	0	-105,37	0,0000000	0	0	-105,02	0,0000000
	TO L2	0	0	-111,85	0,0000000	0	0	-107,63	0,0000000	0	0	-105,37	0,0000000	0	0	-105,02	0,0000000
	TO L3	2	165,44	-277,29	0,2537830	1,8	169,41	-277,04	0,2206120	1,7	171,58	-276,95	0,2057053	1,6	172,69	-277,71	0,2146546
	TO L4	0,4	-21,89	-89,96	0,0002793	0,3	-17,68	-89,95	0,0002618	0,2	-15,41	-89,96	0,0001396	0,2	-15,07	-89,95	0,0001745
	TO L5	1,4	-11,19	-100,66	-0,2589728	1,3	-8,17	-99,46	-0,2136667	1,3	-6,53	-98,84	-0,1997784	1,3	-5,58	-99,44	-0,2132191

Voltages at the end of the feeder during a solid earth-fault at the bus bar

NO COMPENSATION																
	5km		**10km**		**15km**		**20km**		**25km**		**30km**		**35km**		**40km**	
VOLTAGE	**/V0/**	**AN(V0)**	**/V0/**	**AN(V0)**	**/V0/**	**AN(V0)**	**/V0/**	**AN(V0)**	**/V0/**	**AN(V0)**	**/V0/**	**AN(V0)**	**/V0/**	**AN(V0)**	**/V0/**	**AN(V0)**
	12,205	178,2	12,419	177,18	12,563	175,94	12,627	174,49	12,609	172,86	12,507	171,06	12,325	169,13	12,066	167,1
CENTRALIZED COMPENSATION																
	5km		**10km**		**15km**		**20km**		**25km**		**30km**		**35km**		**40km**	
VOLTAGE	**/V0/**	**AN(V0)**	**/V0/**	**AN(V0)**	**/V0/**	**AN(V0)**	**/V0/**	**AN(V0)**	**/V0/**	**AN(V0)**	**/V0/**	**AN(V0)**	**/V0/**	**AN(V0)**	**/V0/**	**AN(V0)**
	12,134	178,57	12,321	177,78	12,438	176,77	12,476	175,57	12,434	174,16	12,311	172,58	12,11	170,85	11,839	169
DISTRIBUTED COMPENSATION																
	5km		**10km**		**15km**		**20km**		**25km**		**30km**		**35km**		**40km**	
VOLTAGE	**/V0/**	**AN(V0)**	**/V0/**	**AN(V0)**	**/V0/**	**AN(V0)**	**/V0/**	**AN(V0)**	**/V0/**	**AN(V0)**	**/V0/**	**AN(V0)**	**/V0/**	**AN(V0)**	**/V0/**	**AN(V0)**
	11,84	179,42	11,771	179,9	11,722	-179,56	11,698	-179,35	11,693	-179,07	11,707	-178,73	11,74	-178,32	11,784	-177,44

APPENDIX 5 – TRUNK LINE CABLING, PARTIAL COMPENSATION

	SOLID EARTH-FAULT																
		10km + 1 coil				**15km + 2 coils**				**20km +3 coils**				**25km + 4 coils**			
EARTH-FAULT AT THE BUS BAR	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		11,922	178,9			11,922	178,97			11,921	179,04			11,921	179,11		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	FROM GEN	0	0	178,90	0,0000000	0	0	178,97	0,0000000	0	0	179,04	0,0000000	0	0	179,11	0,0000000
	FROM L1	0,9	88,9	90,00	0,0000000	0,9	88,97	90,00	0,0000000	0,9	89,04	90,00	0,0000000	0,9	89,11	90,00	0,0000000
	FROM L2	0,9	88,9	90,00	0,0000000	0,9	88,97	90,00	0,0000000	0,9	89,04	90,00	0,0000000	0,9	89,11	90,00	0,0000000
	FROM L3	9,8	86,46	92,44	-0,4172170	6,2	81,76	97,21	-0,7781396	2,9	64,05	114,99	-1,2251342	1,8	-33,06	212,17	-1,5236497
	FROM L4	2,8	88,86	90,04	-0,0019548	2,8	88,93	90,04	-0,0019548	2,8	89	90,04	-0,0019548	2,8	89,07	90,04	-0,0019548
	FROM L5	1,9	88,88	90,02	-0,0006632	1,9	88,95	90,02	-0,0006632	1,9	89,02	90,02	-0,0006632	1,9	89,09	90,02	-0,0006632
	SUM	16,4	87,43	91,47	-0,4207178	12,8	85,46	93,51	-0,7836511	9,3	81,54	97,50	-1,2138936	5,8	73,72	105,39	-1,5392495

	SOLID EARTH-FAULT																
		30km + 5 coils				**35km + 6 coils**				**40km + 7 coils**				**40km + 6 coils**			
EARTH-FAULT AT THE BUS BAR	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		11,92	179,18			11,92	179,25			11,919	179,32			11,953	179,03		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	FROM GEN	0	0	179,18	0,0000000	0	0	179,25	0,0000000	0	0	179,32	0,0000000	0	0	179,03	0,0000000
	FROM L1	0,9	89,17	90,01	-0,0001571	0,9	89,24	90,01	-0,0001571	0,9	89,31	90,01	-0,0001571	0,9	89,02	90,01	-0,0001571
	FROM L2	0,9	89,17	90,01	-0,0001571	0,9	89,24	90,01	-0,0001571	0,9	89,31	90,01	-0,0001571	0,9	89,02	90,01	-0,0001571
	FROM L3	4,9	-67,8	246,98	-1,9161569	8,4	-74,58	253,83	-2,3393014	11,9	-77,1	256,42	-2,7941536	3,4	44,69	134,34	-2,3763102
	FROM L4	2,8	89,13	90,05	-0,0024435	2,8	89,2	90,05	-0,0024435	2,8	89,27	90,05	-0,0024435	2,8	88,98	90,05	-0,0024435
	FROM L5	1,9	89,16	90,02	-0,0006632	1,9	89,23	90,02	-0,0006632	1,9	89,3	90,02	-0,0006632	1,9	89,01	90,02	-0,0006632
	SUM	2,8	46,54	132,64	-1,8966912	2,7	-32,53	211,78	-2,2952068	5,7	-61,35	240,67	-2,7920823	9,3	74,43	104,60	-2,3442450

EARTH-FAULT AT BUS S61	SOLID EARTH-FAULT																
		10km + 1 coil				15km + 2 coils				20km +3 coils				25km + 4 coils			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		11,936	176,65			11,918	176,82			11,899	177,05			11,884	177,35		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	SUM	16,4	83,91	92,74	-0,7839823	12,8	80,93	95,89	-1,3135223	9,3	76,11	100,94	-1,7649627	5,9	68,33	109,02	-1,9227993
	VALUES AT THE BUS BAR					VALUES AT THE BUS BAR				VALUES AT THE BUS BAR				VALUES AT THE BUS BAR			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		12,092	175,25			12,046	174,87			11,996	174,66			11,948	175,04		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	TO GEN	0	0	175,25	0,0000000	0	0	174,87	0,0000000	0	0	174,66	0,0000000	0	0	175,04	0,0000000
	TO L1	1	-94,75	270,00	0,0000000	1	-95,14	270,01	0,0001745	1	-95,35	270,01	0,0001745	0,9	-94,97	270,01	0,0001571
	TO L2	1	-94,75	270,00	0,0000000	1	-95,14	270,01	0,0001745	1	-95,35	270,01	0,0001745	0,9	-94,97	270,01	0,0001571
	TO L3	6,7	85,22	90,03	-0,0035081	6,7	84,84	90,03	-0,0035081	6,6	84,63	90,03	-0,0034558	6,6	85,01	90,03	-0,0034558
	TO L4	2,9	-94,8	270,05	0,0025307	2,9	-95,18	270,05	0,0025307	2,9	-95,39	270,05	0,0025307	2,8	-95,01	270,05	0,0024435
	TO L5	1,9	-94,77	270,02	0,0006632	1,9	-95,15	270,02	0,0006632	1,9	-95,36	270,02	0,0006632	1,9	-94,98	270,02	0,0006632

EARTH-FAULT AT BUS S61	SOLID EARTH-FAULT																
		30km + 5 coils				35km + 6 coils				40km + 7 coils				40km + 6 coils			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		11,867	177,7			11,847	178,1			11,825	178,55			11,882	177,66		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	SUM	2,8	41,29	136,41	-2,0280182	2,7	-37,56	215,66	-2,1937249	5,7	-66,06	244,61	-2,4440316	9,3	66,67	110,99	-3,3313065
	VALUES AT THE BUS BAR					VALUES AT THE BUS BAR				VALUES AT THE BUS BAR				VALUES AT THE BUS BAR			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		11,898	175,59			11,842	176,29			11,782	177,16			11,851	173,42		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	TO GEN	0	0	175,59	0,0000000	0	0	176,29	0,0000000	0	0	177,16	0,0000000	0	0	173,42	0,0000000
	TO L1	0,9	-94,42	270,01	0,0001571	0,9	-93,71	270,00	0,0000000	0,9	-92,85	270,01	0,0001571	0,9	-96,59	270,01	0,0001571
	TO L2	0,9	-94,42	270,01	0,0001571	0,9	-93,71	270,00	0,0000000	0,9	-92,85	270,01	0,0001571	0,9	-96,59	270,01	0,0001571
	TO L3	6,6	85,56	90,03	-0,0034558	6,5	86,26	90,03	-0,0034034	6,5	87,13	90,03	-0,0034034	6,6	83,39	90,03	-0,0034558
	TO L4	2,8	-94,46	270,05	0,0024435	2,8	-93,76	270,05	0,0024435	2,8	-92,89	270,05	0,0024435	2,8	-96,63	270,05	0,0024435
	TO L5	1,9	-94,43	270,02	0,0006632	1,9	-93,73	270,02	0,0006632	1,8	-92,86	270,02	0,0006283	1,9	-96,6	270,02	0,0006632

EARTH-FAULT AT BUS S97	SOLID EARTH-FAULT																
		10km + 1 coil				15km + 2 coils				20km +3 coils				25km + 4 coils			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		11,935	177,86			11,906	178,09			11,877	178,31			11,85	178,53		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	SUM	16,7	85,95	91,91	-0,5566046	12,9	84,21	93,88	-0,8729047	9,3	80,51	97,80	-1,2621548	5,8	72,92	105,61	-1,5607099
	VALUES AT THE BUS BAR					VALUES AT THE BUS BAR				VALUES AT THE BUS BAR				VALUES AT THE BUS BAR			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		12,188	177,4			12,095	177,7			12,004	177,99			11,916	178,28		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	TO GEN	0	0	177,40	0,0000000	0	0	177,70	0,0000000	0	0	177,99	0,0000000	0	0	178,28	0,0000000
	TO L1	1	-92,61	270,01	0,0001745	1	-92,3	270,00	0,0000000	1	-92,02	270,01	0,0001745	0,9	-91,72	270,00	0,0000000
	TO L2	1	-92,61	270,01	0,0001745	1	-92,3	270,00	0,0000000	1	-92,02	270,01	0,0001745	0,9	-91,72	270,00	0,0000000
	TO L3	10	-95,04	272,44	0,4257316	6,3	-99,51	277,21	0,7906902	2,9	-117	294,99	1,2251342	1,8	146,11	32,17	1,5236497
	TO L4	2,9	-92,65	270,05	0,0025307	2,9	-92,34	270,04	0,0020246	2,9	-92,06	270,05	0,0025307	2,8	-91,76	270,04	0,0019548
	TO L5	14,9	85,74	91,66	-0,4316293	11,1	83,59	94,11	-0,7955540	7,5	78,61	99,38	-1,2223618	4,1	65,9	112,38	-1,5610653

	SOLID EARTH-FAULT																
		30km + 5 coils				35km + 6 coils				40km + 7 coils				40km + 6 coils			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		11,823	178,74			11,795	178,95			11,768	179,15			11,898	178,27		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	SUM	2,8	45,95	132,79	-1,9020771	2,7	-32,92	211,87	-2,2929703	5,6	-61,55	240,70	-2,7405417	9,3	73,29	104,98	-2,4038813
EARTH-FAULT AT BUS S97	VALUES AT THE BUS BAR					VALUES AT THE BUS BAR				VALUES AT THE BUS BAR				VALUES AT THE BUS BAR			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		11,829	178,56			11,743	178,83			11,657	179,09			12,014	177,87		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	TO GEN	0	0	178,56	0,0000000	0	0	178,83	0,0000000	0	0	179,09	0,0000000	0	0	177,87	0,0000000
	TO L1	0,9	-91,44	270,00	0,0000000	0,9	-91,17	270,00	0,0000000	0,9	-90,91	270,00	0,0000000	1	-92,14	270,01	0,0001745
	TO L2	0,9	-91,44	270,00	0,0000000	0,9	-91,17	270,00	0,0000000	0,9	-90,91	270,00	0,0000000	1	-92,14	270,01	0,0001745
	TO L3	4,9	111,59	66,97	1,9169439	8,2	105	73,83	2,2836037	11,6	102,68	76,41	2,7256807	3,4	-136,47	314,34	2,3763102
	TO L4	2,8	-91,48	270,04	0,0019548	2,8	-91,21	270,04	0,0019548	2,8	-90,95	270,04	0,0019548	2,9	-92,18	270,05	0,0025307
	TO L5	1,9	5,08	173,48	-1,8877113	4	-55,99	234,82	-2,3045882	7,2	-68,67	247,76	-2,7251069	7,5	69,68	108,19	-2,3412683

	5KΩ EARTH-FAULT																
		10km + 1 coil				15km + 2 coils				20km +3 coils				25km + 4 coils			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		1,68	98,89			2,114	103,96			2,801	112,11			4,017	125,43		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	SUM	2,3	6,15	92,74	-0,1099487	2,3	8,06	95,90	-0,2364228	2,2	11,16	100,95	-0,4178950	2	16,41	109,02	-0,6517964
EARTH-FAULT AT BUS S61	VALUES AT THE BUS BAR					VALUES AT THE BUS BAR				VALUES AT THE BUS BAR				VALUES AT THE BUS BAR			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		1,702	97,49			2,137	102			2,824	109,71			4,038	123,12		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	TO GEN	0	0	97,49	0,0000000	0	0	102,00	0,0000000	0	0	109,71	0,0000000	0	0	123,12	0,0000000
	TO L1	0	0	97,49	0,0000000	0,2	-168	270,00	0,0000000	0,2	-160,3	270,01	0,0000349	0,3	-146,88	270,00	0,0000000
	TO L2	0	0	97,49	0,0000000	0,2	-168	270,00	0,0000000	0,2	-160,3	270,01	0,0000349	0,3	-146,88	270,00	0,0000000
	TO L3	0,9	7,46	90,03	-0,0004712	1,2	11,98	90,02	-0,0004189	1,6	19,68	90,03	-0,0008378	2,2	33,09	90,03	-0,0011519
	TO L4	0,4	-172,56	270,05	0,0003491	0,5	-168,04	270,04	0,0003491	0,7	-160,34	270,05	0,0006109	1	-146,92	270,04	0,0006981
	TO L5	0,3	-172,53	270,02	0,0001047	0,3	-168,02	270,02	0,0001047	0,4	-160,31	270,02	0,0001396	0,6	-146,9	270,02	0,0002094

	5KΩ EARTH-FAULT																
		30km + 5 coils				35km + 6 coils				40km + 7 coils				40km + 6 coils			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		5,809	153,97			5,771	-162,77			3,986	-134,8			2,716	121,54		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	SUM	1,4	17,55	136,42	-1,0141776	1,3	-18,42	-144,35	-1,0563702	1,9	-19,41	-115,39	-0,8146772	2,1	10,55	110,99	-0,7522305
EARTH-FAULT AT BUS S61	VALUES AT THE BUS BAR					VALUES AT THE BUS BAR				VALUES AT THE BUS BAR				VALUES AT THE BUS BAR			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		5,824	151,85			5,769	-164,58			3,971	-136,18			2,709	117,3		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	TO GEN	0	0	151,85	0,0000000	0	0	-164,58	0,0000000	0	0	-136,18	0,0000000	0	0	117,30	0,0000000
	TO L1	0,5	-118,15	270,00	0,0000000	0,5	-74,58	-90,00	0,0000000	0,3	-46,19	-89,99	0,0000524	0,2	-152,71	270,01	0,0000349
	TO L2	0,5	-118,15	270,00	0,0000000	0,5	-74,58	-90,00	0,0000000	0,3	-46,19	-89,99	0,0000524	0,2	-152,71	270,01	0,0000349
	TO L3	3,2	61,83	90,02	-0,0011170	3,2	105,4	-269,98	-0,0011170	2,2	133,79	-269,97	-0,0011519	1,5	27,27	90,03	-0,0007854
	TO L4	1,4	-118,19	270,04	0,0009774	1,4	-74,62	-89,96	0,0009774	0,9	-46,23	-89,95	0,0007854	0,6	-152,75	270,05	0,0005236
	TO L5	0,9	-118,17	270,02	0,0003142	0,9	-74,6	-89,98	0,0003142	0,6	-46,2	-89,98	0,0002094	0,4	-152,72	270,02	0,0001396

	5KΩ EARTH-FAULT																
		10km + 1 coil				**15km + 2 coils**				**20km +3 coils**				**25km + 4 coils**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		1,654	98,83			2,107	103			2,827	110,38			4,088	123,94		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	SUM	2,3	6,92	91,91	-0,0766581	2,3	9,12	93,88	-0,1556342	2,2	12,58	97,80	-0,2985743	2	18,32	105,62	-0,5385120
EARTH-FAULT AT BUS S97	**VALUES AT THE BUS BAR**					**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		1,689	98,37			2,14	102,61			2,857	110,06			4,111	123,69		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	TO GEN	0	0	98,37	0,0000000	0	0	102,61	0,0000000	0	0	110,06	0,0000000	0	0	123,69	0,0000000
	TO L1	0	0	98,37	0,0000000	0,2	-167,39	270,00	0,0000000	0,2	-159,95	270,01	0,0000349	0,3	-146,32	270,01	0,0000524
	TO L2	0	0	98,37	0,0000000	0,2	-167,39	270,00	0,0000000	0,2	-159,95	270,01	0,0000349	0,3	-146,32	270,01	0,0000524
	TO L3	1,4	-174,07	272,44	0,0596024	1,1	-174,61	277,22	0,1382475	0,7	175,07	-65,01	0,2957221	0,6	91,52	32,17	0,5078832
	TO L4	0,4	-171,68	270,05	0,0003491	0,5	-167,44	270,05	0,0004363	0,7	-159,99	270,05	0,0006109	1	-146,36	270,05	0,0008727
	TO L5	2,1	6,71	91,66	-0,0608337	2	8,5	94,11	-0,1433431	1,8	10,67	99,39	-0,2936768	1,4	11,3	112,39	-0,5332726

	5KΩ EARTH-FAULT																
		30km + 5 coils				**35km + 6 coils**				**40km + 7 coils**				**40km + 6 coils**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		5,896	153,14			5,734	-164,05			3,954	-137,36			2,757	116,82		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	SUM	1,4	20,35	132,79	-0,9510385	1,3	-15,92	-148,13	-1,1040227	1,9	-18,05	-119,31	-0,9301158	2,2	11,85	104,97	-0,5682892
EARTH-FAULT AT BUS S97	**VALUES AT THE BUS BAR**					**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		5,9	152,96			5,708	-164,17			3,917	-137,41			2,784	116,42		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	TO GEN	0	0	152,96	0,0000000	0	0	-164,17	0,0000000	0	0	-137,41	0,0000000	0	0	116,42	0,0000000
	TO L1	0,5	-117,05	270,01	0,0000873	0,5	-74,17	-90,00	0,0000000	0,3	-47,42	-89,99	0,0000524	0,2	-153,59	270,01	0,0000349
	TO L2	0,5	-117,05	270,01	0,0000873	0,5	-74,17	-90,00	0,0000000	0,3	-47,42	-89,99	0,0000524	0,2	-153,59	270,01	0,0000349
	TO L3	2,4	85,98	66,98	0,9385258	4	122	-286,17	1,1139530	3,9	146,18	-283,59	0,9163926	0,8	162,08	-45,66	0,5591318
	TO L4	1,4	-117,09	270,05	0,0012217	1,4	-74,21	-89,96	0,0009774	0,9	-47,46	-89,95	0,0007854	0,7	-153,63	270,05	0,0006109
	TO L5	1	-20,53	173,49	-0,9935521	1,9	-38,99	-125,18	-1,0946794	2,4	-25,17	-112,24	-0,9083690	1,7	8,23	108,19	-0,5306875

	10KΩ EARTH-FAULT																
		10km + 1 coil				**15km + 2 coils**				**20km +3 coils**				**25km + 4 coils**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		0,85	94,89			1,08	98,98			1,463	105,7			2,216	116,98		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	SUM	1,2	2,15	92,74	-0,0573646	1,2	3,08	95,90	-0,1233510	1,1	4,75	100,95	-0,2089475	1,1	7,96	109,02	-0,3584880
EARTH-FAULT AT BUS S61	**VALUES AT THE BUS BAR**					**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		0,861	93,49			1,092	97,03			1,475	103,3			2,228	114,67		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	TO GEN	0	0	93,49	0,0000000	0	0	97,03	0,0000000	0	0	103,30	0,0000000	0	0	114,67	0,0000000
	TO L1	0	0	93,49	0,0000000	0	0	97,03	0,0000000	0	0	103,30	0,0000000	0,2	-155,34	270,01	0,0000349
	TO L2	0	0	93,49	0,0000000	0	0	97,03	0,0000000	0	0	103,30	0,0000000	0,2	-155,34	270,01	0,0000349
	TO L3	0,5	3,46	90,03	-0,0002618	0,6	7	90,03	-0,0003142	0,8	13,27	90,03	-0,0004189	1,2	24,64	90,03	-0,0006283
	TO L4	0,2	-176,56	270,05	0,0001745	0,3	-173,02	270,05	0,0002618	0,4	-166,75	270,05	0,0003491	0,5	-155,38	270,05	0,0004363
	TO L5	0	0	93,49	0,0000000	0,2	-172,99	270,02	0,0000698	0,2	-166,72	270,02	0,0000698	0,3	-155,35	270,02	0,0001047

EARTH-FAULT AT BUS S61	**10KΩ EARTH-FAULT**																
		30km + 5 coils				**35km + 6 coils**				**40km + 7 coils**				**40km + 6 coils**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		3,711	146,72			3,726	-156,84			2,23	-126,9			1,442	115,75		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	SUM	0,9	10,31	136,41	-0,6518630	0,9	-12,5	-144,34	-0,7312416	1,1	-11,51	-115,39	-0,4716552	1,1	4,76	110,99	-0,3940255
	VALUES AT THE BUS BAR					**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		3,721	144,61			3,724	-158,65			2,222	-128,29			1,438	111,5		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	TO GEN	0	0	144,61	0,0000000	0	0	-158,65	0,0000000	0	0	-128,29	0,0000000	0	0	111,50	0,0000000
	TO L1	0,3	-125,4	270,01	0,0000524	0,3	-68,66	-89,99	0,0000524	0,2	-38,29	-90,00	0,0000000	0	0	111,50	0,0000000
	TO L2	0,3	-125,4	270,01	0,0000524	0,3	-68,66	-89,99	0,0000524	0,2	-38,29	-90,00	0,0000000	0	0	111,50	0,0000000
	TO L3	2,1	54,58	90,03	-0,0010996	2,1	111,32	-269,97	-0,0010996	1,2	141,69	-269,98	-0,0004189	0,8	21,48	90,02	-0,0002793
	TO L4	0,9	-125,44	270,05	0,0007854	0,9	-68,7	-89,95	0,0007854	0,5	-38,33	-89,96	0,0003491	0,3	-158,54	270,04	0,0002094
	TO L5	0,6	-125,41	270,02	0,0002094	0,6	-68,67	-89,98	0,0002094	0,3	-38,31	-89,98	0,0001047	0,2	-158,52	270,02	0,0000698

EARTH-FAULT AT BUS S97	**10KΩ EARTH-FAULT**																
		10km + 1 coil				**15km + 2 coils**				**20km +3 coils**				**25km + 4 coils**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		0,835	94,88			1,073	98			1,469	103,79			2,242	115,05		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	SUM	1,2	2,97	91,91	-0,0399955	1,2	4,12	93,88	-0,0812004	1,2	5,99	97,80	-0,1628587	1,1	9,44	105,61	-0,2959967
	VALUES AT THE BUS BAR					**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		0,853	94,42			1,09	97,61			1,484	103,47			2,255	114,8		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	TO GEN	0	0	94,42	0,0000000	0	0	97,61	0,0000000	0	0	103,47	0,0000000	0	0	114,80	0,0000000
	TO L1	0	0	94,42	0,0000000	0	0	97,61	0,0000000	0	0	103,47	0,0000000	0,2	-155,2	270,00	0,0000000
	TO L2	0	0	94,42	0,0000000	0	0	97,61	0,0000000	0	0	103,47	0,0000000	0,2	-155,2	270,00	0,0000000
	TO L3	0,7	-178,02	272,44	0,0298012	0,6	-179,61	277,22	0,0754077	0,4	168,47	-65,00	0,1690473	0,3	82,63	32,17	0,2539416
	TO L4	0,2	-175,63	270,05	0,0001745	0,3	-172,44	270,05	0,0002618	0,4	-166,58	270,05	0,0003491	0,5	-155,24	270,04	0,0003491
	TO L5	1	2,76	91,66	-0,0289684	1	3,49	94,12	-0,0718456	0,9	4,08	99,39	-0,1468384	0,8	2,42	112,38	-0,3045981

EARTH-FAULT AT BUS S97	**10KΩ EARTH-FAULT**																
		30km + 5 coils				**35km + 6 coils**				**40km + 7 coils**				**40km + 6 coils**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		3,765	145,21			3,717	-158,76			2,231	-129,85			1,449	110,67		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	SUM	0,9	12,42	132,79	-0,6113819	0,9	-10,62	-148,14	-0,7644064	1,1	-10,54	-119,31	-0,5384881	1,1	5,69	104,98	-0,2843300
	VALUES AT THE BUS BAR					**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		3,767	145,04			3,7	-158,87			2,21	-129,9			1,464	110,27		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	TO GEN	0	0	145,04	0,0000000	0	0	-158,87	0,0000000	0	0	-129,90	0,0000000	0	0	110,27	0,0000000
	TO L1	0,3	-124,97	270,01	0,0000524	0,3	-68,88	-89,99	0,0000524	0,2	-39,91	-89,99	0,0000349	0	0	110,27	0,0000000
	TO L2	0,3	-124,97	270,01	0,0000524	0,3	-68,88	-89,99	0,0000524	0,2	-39,91	-89,99	0,0000349	0	0	110,27	0,0000000
	TO L3	1,5	78,06	66,98	0,5865786	2,6	127,3	-286,17	0,7240695	2,2	153,69	-283,59	0,5169394	0,4	155,93	-45,66	0,2795659
	TO L4	0,9	-125,01	270,05	0,0007854	0,9	-68,92	-89,95	0,0007854	0,5	-39,95	-89,95	0,0004363	0,3	-159,78	270,05	0,0002618
	TO L5	0,6	-28,45	173,49	-0,5961312	1,3	-33,7	-125,17	-0,7488057	1,4	-17,66	-112,24	-0,5298819	0,9	2,07	108,20	-0,2811014

APPENDIX 6 – TOTALLY CABLED NETWORK

	SOLID EARTH-FAULT												
		No compensation				**Distributed compensation (1 coil per 5km of cable)**				**5km from the station uncompensated**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
EARTH-FAULT AT THE BUS BAR		12,81	169,74			11,752	-177,96			11,936	-179,31		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	FROM GEN	0	0	169,74	0,0000000	0	0	-177,96	0,0000000	0	0	-179,31	0,0000000
	FROM L1	44,1	78,36	91,38	-1,0620698	14,8	-81,36	-96,60	-1,7010698	1,6	-38	-141,31	-1,2488632
	FROM L2	44,1	78,36	91,38	-1,0620698	14,8	-81,36	-96,60	-1,7010698	1,6	-38	-141,31	-1,2488632
	FROM L3	128,6	69,29	100,45	-23,3251342	45,7	-79,13	-98,83	-7,0150985	32,6	-78,38	-100,93	-6,1812720
	FROM L4	128,6	69,29	100,45	-23,3251342	45,7	-79,13	-98,83	-7,0150985	32,6	-78,38	-100,93	-6,1812720
	FROM L5	86,3	75,22	94,52	-6,8010511	31,2	-80,52	-97,44	-4,0400219	17,8	-78,43	-100,88	-3,3597974
	SUM	430,6	72,33	97,41	-55,5339110	152,4	-79,85	-98,11	-21,4996809	85,4	-77,03	-102,28	-18,1636679

	SOLID EARTH-FAULT													
		10km from the station uncompensated				**15km from the station uncompensated**				**15km with centralized compensation**				
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**I_L**
EARTH-FAULT AT THE BUS BAR		12,115	179,29			12,291	177,85			12,134	178,98			
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			
	FROM GEN	0	0	179,29	0,0000000	0	0	177,85	0,0000000	57,3	-85,38	264,36	-5,6313108	57,0226125
	FROM L1	13,2	85,92	93,37	-0,7759447	27,8	86,43	91,42	-0,6889156	27,5	87,55	91,43	-0,6862795	
	FROM L2	13,2	85,92	93,37	-0,7759447	27,8	86,43	91,42	-0,6889156	27,5	87,55	91,43	-0,6862795	
	FROM L3	19,2	-74	253,29	-5,5205316	6,4	-45,61	223,46	-4,6454704	6,3	-44,49	223,47	-4,5721286	
	FROM L4	19,2	-74	253,29	-5,5205316	6,4	-45,61	223,46	-4,6454704	6,3	-44,49	223,47	-4,5721286	
	FROM L5	4,6	-52,12	231,41	-2,8692187	11	75,63	102,22	-2,3283256	10,8	76,75	102,23	-2,2878346	
	SUM	20,8	-42,73	222,02	-15,4525532	59	75,15	102,70	-12,9709261	18,5	-1,42	180,40	-18,4995492	

	SOLID EARTH-FAULT												
		No compensation				**Distributed compensation (1 coil per 5km of cable)**				**5km from the station uncompensated**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		10,53	165,21			10,865	-177,08			11,454	-178,4		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	SUM	213,7	26,99	138,22	-159,3579317	119,4	-58,54	-118,54	-57,0459976	76,4	-68,17	-110,23	-26,4183213
EARTH-FAULT AT BUS S61	**VALUES AT THE BUS BAR**					**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		6,281	109,81			9,063	-150,98			10,506	-165,19		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	TO GEN	0	0	109,81	0,0000000	0	0	-150,98	0,0000000	0	0	-165,19	0,0000000
	TO L1	21,6	-161,57	271,38	0,5201974	11,4	125,62	-276,60	1,3102835	1,4	156,12	-321,31	1,0927553
	TO L2	21,6	-161,57	271,38	0,5201974	11,4	125,62	-276,60	1,3102835	1,4	156,12	-321,31	1,0927553
	TO L3	148,2	13,69	96,12	-15,7997731	82,2	-53,18	-97,80	-11,1558201	46,5	-62,08	-103,11	-10,5471902
	TO L4	63	-170,64	280,45	11,4267765	35,3	127,84	-278,82	5,4125767	28,7	115,74	-280,93	5,4417946
	TO L5	42,3	-164,72	274,53	3,3408992	24,1	126,45	-277,43	3,1164871	15,7	115,69	-280,88	2,9634168

	SOLID EARTH-FAULT													
		10km from the station uncompensated				**15km from the station uncompensated**				**15km with centralized compensation**				
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	
		11,939	178,43			12,006	174,31			11,95	177,58			
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			
	SUM	19,9	-50,04	228,47	-13,1939410	54,6	51,32	122,99	-29,7292987	17,4	-10,75	188,33	-17,2164312	
EARTH-FAULT AT BUS S61	**VALUES AT THE BUS BAR**					**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**				
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**I_L**
		11,416	176,84			11,219	158,06			11,267	173,7			
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			
	TO GEN	0	0	176,84	0,0000000	0	0	158,06	0,0000000	53,2	89,34	84,36	5,2283723	52,9424605
	TO L1	12,5	-96,54	273,38	0,7369740	25,4	-113,36	271,42	0,6294409	25,5	-97,73	271,43	0,6363682	
	TO L2	12,5	-96,54	273,38	0,7369740	25,4	-113,36	271,42	0,6294409	25,5	-97,73	271,43	0,6363682	
	TO L3	10,3	20,99	155,85	-9,3985182	57,1	60,4	97,66	-7,6111054	13,5	10,58	163,12	-12,9183525	
	TO L4	18,1	103,55	73,29	5,2042511	5,8	114,6	43,46	4,2099576	5,9	130,23	43,47	4,2818347	
	TO L5	4,3	125,42	51,42	2,6815091	10	-124,16	282,22	2,1166597	10	-108,53	282,23	2,1183654	

EARTH-FAULT AT BUS S97	**SOLID EARTH-FAULT**												
		No compensation				**Distributed compensation (1 coil per 5km of cable)**				**5km from the station uncompensated**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		10,969	166,03			11,173	-176,79			11,632	-178,43		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	SUM	266	33,9	132,13	-178,4367966	131,5	-64,27	-112,52	-50,3652764	79,2	-69,97	-108,46	-25,0780879
	VALUES AT THE BUS BAR					**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		7,916	125,07			10,066	-159,26			10,988	-169,53		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	TO GEN	0	0	125,07	0,0000000	0	0	-159,26	0,0000000	0	0	-169,53	0,0000000
	TO L1	27,2	-146,32	271,39	0,6598094	12,7	117,34	-276,60	1,4597018	1,4	151,77	-321,30	1,0926026
	TO L2	27,2	-146,32	271,39	0,6598094	12,7	117,34	-276,60	1,4597018	1,4	151,77	-321,30	1,0926026
	TO L3	79,4	-155,38	280,45	14,4013659	39,2	119,57	-278,83	6,0173274	30	111,4	-280,93	5,6882871
	TO L4	79,4	-155,38	280,45	14,4013659	39,2	119,57	-278,83	6,0173274	30	111,4	-280,93	5,6882871
	TO L5	212,9	26,93	98,14	-30,1450144	103,8	-60,98	-98,28	-14,9483192	62,3	-66,89	-102,64	-13,6327668

EARTH-FAULT AT BUS S97	**SOLID EARTH-FAULT**													
		10km from the station uncompensated				**15km from the station uncompensated**				**15km with centralized compensation**				
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	
		12,003	178,98			12,175	175,77			12,023	178,31			
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			
	SUM	20,1	-45,73	224,71	-14,2846016	56,9	62,14	113,63	-22,8071578	17,7	-5,11	183,42	-17,6684775	
	VALUES AT THE BUS BAR					**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**				
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**I_L**
		11,618	178,61			11,781	166,33			11,55	176,78			
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			
	TO GEN	0	0	178,61	0,0000000	0	0	166,33	0,0000000	54,5	92,42	84,36	5,3561333	54,2361672
	TO L1	12,7	-94,77	273,38	0,7487656	26,7	-105,1	271,43	0,6663150	26,2	-94,65	271,43	0,6538372	
	TO L2	12,7	-94,77	273,38	0,7487656	26,7	-105,1	271,43	0,6663150	26,2	-94,65	271,43	0,6538372	
	TO L3	18,4	105,31	73,30	5,2874336	6,1	122,86	43,47	4,4269816	6	133,31	43,47	4,3544082	
	TO L4	18,4	105,31	73,30	5,2874336	6,1	122,86	43,47	4,4269816	6	133,31	43,47	4,3544082	
	TO L5	15,6	-40,79	219,40	-12,0546437	46,1	63,52	102,81	-10,2212316	18,4	-36,75	213,53	-15,3381795	

EARTH-FAULT AT BUS S61	5KΩ EARTH-FAULT												
		No compensation				Distributed compensation (1 coil per 5km of cable)				5km from the station uncompensated			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		0,119	136,37			0,22	-121,67			0,361	-114,05		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	SUM	2,4	-1,86	138,23	-1,7899797	2,4	-3,14	-118,53	-1,1462852	2,4	-3,82	-110,23	-0,8298949
	VALUES AT THE BUS BAR					VALUES AT THE BUS BAR				VALUES AT THE BUS BAR			
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)
		0,071	80,97			0,183	-95,58			0,331	-100,84		
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)		
	TO GEN	0	0	80,97	0,0000000	0	0	-95,58	0,0000000	0	0	-100,84	0,0000000
	TO L1	0,2	169,58	-88,61	0,0048515	0,2	-178,98	83,40	0,0229874	0	0	-100,84	0,0000000
	TO L2	0,2	169,58	-88,61	0,0048515	0,2	-178,98	83,40	0,0229874	0	0	-100,84	0,0000000
	TO L3	1,7	-15,16	96,13	-0,1815340	1,7	2,22	-97,80	-0,2307165	1,5	2,27	-103,11	-0,3402319
	TO L4	0,7	160,52	-79,55	0,1269642	0,7	-176,75	81,17	0,1074523	0,9	-179,91	79,07	0,1706486
	TO L5	0,5	166,44	-85,47	0,0394905	0,5	-178,14	82,56	0,0647439	0,5	-179,96	79,12	0,0943763

EARTH-FAULT AT BUS S61	5KΩ EARTH-FAULT													
		10km from the station uncompensated				15km from the station uncompensated				15km with centralized compensation				
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	
		1,349	-138,51			0,522	122,82			1,474	-174,9			
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)			
	SUM	2,2	-6,98	-131,53	-1,4586266	2,4	-0,17	122,99	-1,3067824	2,1	-3,23	-171,67	-2,0778451	
	VALUES AT THE BUS BAR					VALUES AT THE BUS BAR				VALUES AT THE BUS BAR				
	VOLTAGE	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	/V0/	AN(V0)	Δφ	3I0*COS(Δφ)	I_L
		1,289	-140,1			0,488	106,58			1,39	-178,78			
	CURRENTS	/3I0/	AN(3I0)			/3I0/	AN(3I0)			/3I0/	AN(3I0)			
	TO GEN	0	0	-140,10	0,0000000	0	0	106,58	0,0000000	6,6	96,86	-275,64	0,6486327	6,5680496
	TO L1	1,4	-53,47	-86,63	0,0822972	1,1	-164,85	271,43	0,0274512	3,1	-90,21	-88,57	0,0773624	
	TO L2	1,4	-53,47	-86,63	0,0822972	1,1	-164,85	271,43	0,0274512	3,1	-90,21	-88,57	0,0773624	
	TO L3	1,2	64,06	-204,16	-1,0948873	2,5	8,91	97,67	-0,3336682	1,7	18,1	-196,88	-1,6267555	
	TO L4	2	146,61	-286,71	0,5750554	0,3	63,11	43,47	0,2177204	0,7	137,75	-316,53	0,5080143	
	TO L5	0,5	168,49	-308,59	0,3118716	0,4	-175,65	282,23	0,0847346	1,2	-101,01	-77,77	0,2542038	

EARTH-FAULT AT BUS S97	**5KΩ EARTH-FAULT**												
		No compensation				**Distributed compensation (1 coil per 5km of cable)**				**5km from the station uncompensated**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		0,1	131,03			0,206	-114,85			0,355	-111,49		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	SUM	2,4	-1,1	132,13	-1,6099561	2,4	-2,34	-112,51	-0,9188272	2,4	-3,02	-108,47	-0,7603394
	VALUES AT THE BUS BAR					**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		0,072	90,07			0,185	-97,33			0,335	-102,59		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	TO GEN	0	0	90,07	0,0000000	0	0	-97,33	0,0000000	0	0	-102,59	0,0000000
	TO L1	0,2	178,69	-88,62	0,0048166	0,2	179,27	-276,60	0,0229874	0	0	-102,59	0,0000000
	TO L2	0,2	178,69	-88,62	0,0048166	0,2	179,27	-276,60	0,0229874	0	0	-102,59	0,0000000
	TO L3	0,7	169,62	-79,55	0,1269642	0,7	-178,5	81,17	0,1074523	0,9	178,34	-280,93	0,1706486
	TO L4	0,7	169,62	-79,55	0,1269642	0,7	-178,5	81,17	0,1074523	0,9	178,34	-280,93	0,1706486
	TO L5	1,9	-8,07	98,14	-0,2690255	1,9	0,95	-98,28	-0,2736205	1,9	0,06	-102,65	-0,4160901

EARTH-FAULT AT BUS S97	**5KΩ EARTH-FAULT**													
		10km from the station uncompensated				**15km from the station uncompensated**				**15km with centralized compensation**				
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	
		1,34	-141,17			0,513	114,4			1,462	-178,42			
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			
	SUM	2,2	-5,87	-135,30	-1,5637588	2,4	0,76	113,64	-0,9623728	2,1	-1,85	-176,57	-2,0962381	
	VALUES AT THE BUS BAR					**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**				
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**I_L**
		1,297	-141,54			0,496	104,95			1,404	-179,96			
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			
	TO GEN	0	0	-141,54	0,0000000	0	0	104,95	0,0000000	6,6	95,69	-275,65	0,6497790	6,5679363
	TO L1	1,4	-54,92	-86,62	0,0825411	1,1	-166,47	271,42	0,0272593	3,2	-91,39	-88,57	0,0798580	
	TO L2	1,4	-54,92	-86,62	0,0825411	1,1	-166,47	271,42	0,0272593	3,2	-91,39	-88,57	0,0798580	
	TO L3	2,1	145,17	-286,71	0,6038081	0,3	61,49	43,46	0,2177564	0,7	136,57	-316,53	0,5080143	
	TO L4	2,1	145,17	-286,71	0,6038081	0,3	61,49	43,46	0,2177564	0,7	136,57	-316,53	0,5080143	
	TO L5	1,7	-0,94	-140,60	-1,3136471	1,9	2,15	102,80	-0,4209421	2,2	-33,49	-146,47	-1,8339128	

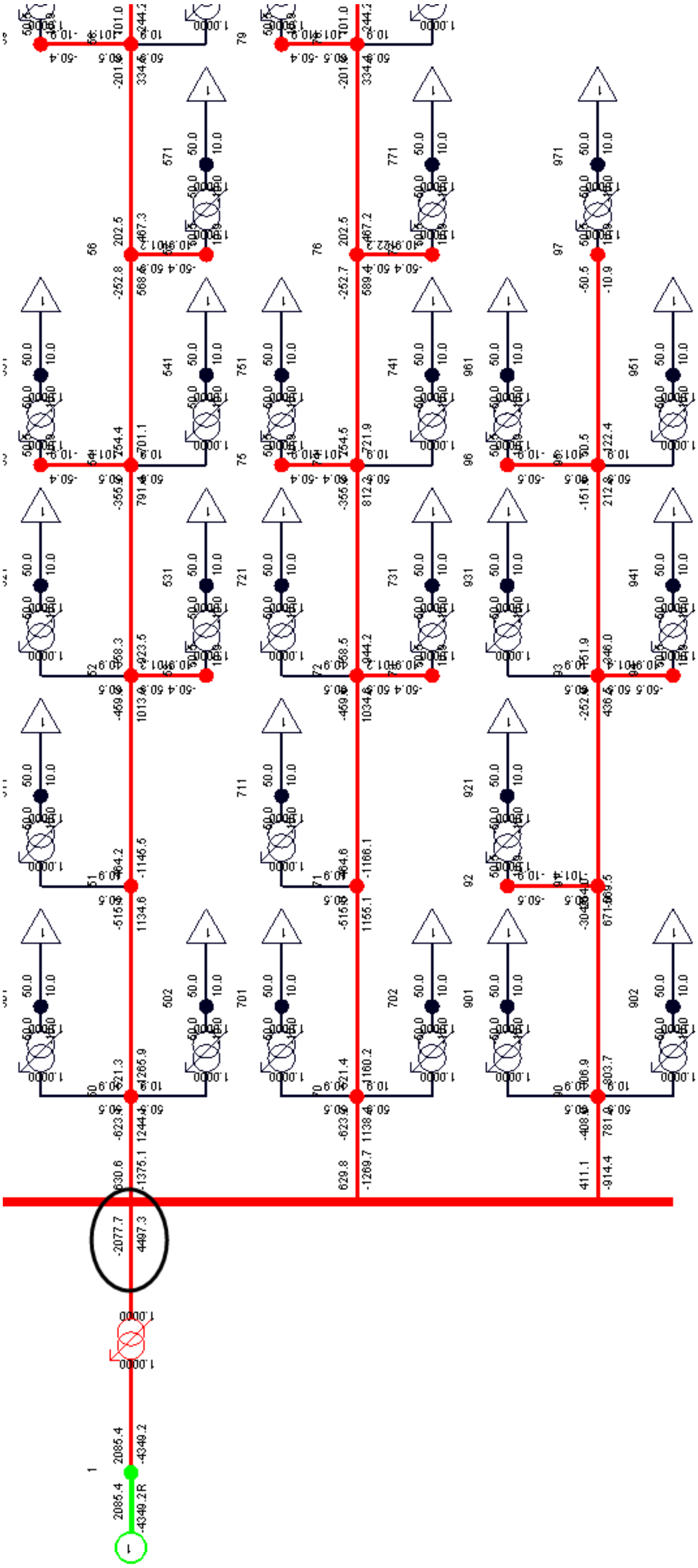
	10KΩ EARTH-FAULT												
		No compensation				**Distributed compensation (1 coil per 5km of cable)**				**5km from the station uncompensated**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		0,06	136,21			0,11	-121,19			0,182	-113,23		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	SUM	1,2	-2,01	138,22	-0,8948503	1,2	-2,66	-118,53	-0,5731426	1,2	-3	-110,23	-0,4149475
EARTH-FAULT AT BUS S61	**VALUES AT THE BUS BAR**					**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		0,036	80,81			0,092	-95,1			0,167	-100,02		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	TO GEN	0	0	80,81	0,0000000	0	0	-95,10	0,0000000	0	0	-100,02	0,0000000
	TO L1	0	0	80,81	0,0000000	0	0	-95,10	0,0000000	0	0	-100,02	0,0000000
	TO L2	0	0	80,81	0,0000000	0	0	-95,10	0,0000000	0	0	-100,02	0,0000000
	TO L3	0,8	-15,32	96,13	-0,0854278	0,8	2,7	-97,80	-0,1085725	0,7	3,09	-103,11	-0,1587749
	TO L4	0,4	160,36	-79,55	0,0725510	0,4	-176,27	81,17	0,0614013	0,5	-179,09	79,07	0,0948048
	TO L5	0,2	166,28	-85,47	0,0157962	0,2	-177,66	82,56	0,0258976	0,2	-179,14	79,12	0,0377505

	10KΩ EARTH-FAULT													
		10km from the station uncompensated				**15km from the station uncompensated**				**15km with centralized compensation**				
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	
		0,702	-136,2			0,264	121,84			0,784	-174,41			
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			
	SUM	1,2	-4,67	-131,53	-0,7956145	1,2	-1,16	123,00	-0,6535668	1,1	-2,73	-171,68	-1,0884229	
EARTH-FAULT AT BUS S61	**VALUES AT THE BUS BAR**					**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**				
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	I_L
		0,671	-137,79			0,247	105,59			0,74	-178,29			
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			
	TO GEN	0	0	-137,79	0,0000000	0	0	105,59	0,0000000	3,5	97,36	-275,65	0,3445798	3,4829965
	TO L1	0,7	-51,17	-86,62	0,0412705	0,6	-165,84	271,43	0,0149734	1,7	-89,71	-88,58	0,0421279	
	TO L2	0,7	-51,17	-86,62	0,0412705	0,6	-165,84	271,43	0,0149734	1,7	-89,71	-88,58	0,0421279	
	TO L3	0,6	66,36	-204,15	-0,5474865	1,3	7,92	97,67	-0,1735075	0,9	18,59	-196,88	-0,8612235	
	TO L4	1,1	148,92	-286,71	0,3162805	0	0	105,59	0,0000000	0,4	138,25	-316,54	0,2903419	
	TO L5	0,3	170,79	-308,58	0,1870820	0,2	-176,64	282,23	0,0423673	0,7	-100,51	-77,78	0,1481662	

EARTH-FAULT AT BUS S97	10KΩ EARTH-FAULT												
		No compensation				**Distributed compensation (1 coil per 5km of cable)**				**5km from the station uncompensated**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		0,05	130,88			0,103	-114,39			0,178	-110,68		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	SUM	1,2	-1,25	132,13	-0,8049780	1,2	-1,87	-112,52	-0,4596071	1,2	-2,22	-108,46	-0,3799710
	VALUES AT THE BUS BAR					**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**			
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**
		0,036	89,92			0,093	-96,86			0,168	-101,78		
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**		
	TO GEN	0	0	89,92	0,0000000	0	0	-96,86	0,0000000	0	0	-101,78	0,0000000
	TO L1	0	0	89,92	0,0000000	0	0	-96,86	0,0000000	0	0	-101,78	0,0000000
	TO L2	0	0	89,92	0,0000000	0	0	-96,86	0,0000000	0	0	-101,78	0,0000000
	TO L3	0,4	169,47	-79,55	0,0725510	0,4	-178,03	81,17	0,0614013	0,5	179,15	-280,93	0,0948048
	TO L4	0,4	169,47	-79,55	0,0725510	0,4	-178,03	81,17	0,0614013	0,5	179,15	-280,93	0,0948048
	TO L5	1	-8,22	98,14	-0,1415924	1	1,42	-98,28	-0,1440108	1	0,87	-102,65	-0,2189948

EARTH-FAULT AT BUS S97	10KΩ EARTH-FAULT													
		10km from the station uncompensated				**15km from the station uncompensated**				**15km with centralized compensation**				
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	
		0,699	-139,03			0,259	113,33			0,777	-178,21			
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			
	SUM	1,2	-3,73	-135,30	-0,8529594	1,2	-0,31	113,64	-0,4811864	1,1	-1,64	-176,57	-1,0980295	
	VALUES AT THE BUS BAR					**VALUES AT THE BUS BAR**				**VALUES AT THE BUS BAR**				
	VOLTAGE	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**/V0/**	**AN(V0)**	**Δφ**	**3I0*COS(Δφ)**	**I_L**
		0,676	-139,4			0,25	103,88			0,747	-179,75			
	CURRENTS	**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			**/3I0/**	**AN(3I0)**			
	TO GEN	0	0	-139,40	0,0000000	0	0	103,88	0,0000000	3,5	95,9	-275,65	0,3445798	3,4829965
	TO L1	0,7	-52,77	-86,63	0,0411486	0,6	-167,54	271,42	0,0148687	1,7	-91,17	-88,58	0,0421279	
	TO L2	0,7	-52,77	-86,63	0,0411486	0,6	-167,54	271,42	0,0148687	1,7	-91,17	-88,58	0,0421279	
	TO L3	1,1	147,31	-286,71	0,3162805	0	0	103,88	0,0000000	0,4	136,79	-316,54	0,2903419	
	TO L4	1,1	147,31	-286,71	0,3162805	0	0	103,88	0,0000000	0,4	136,79	-316,54	0,2903419	
	TO L5	0,9	1,21	-140,61	-0,6955599	1	1,08	102,80	-0,2215485	1,2	-33,28	-146,47	-1,0003161	

APPENDIX 7 – POWER FLOW IN TOTALLY CABLED NETWORK



APPENDIX 8 – THE RECLOSER STUDY

Customers, total	1029
Faults / a	1
High-speed AR / a	0
Delayed AR / a	3
Fault clearance time (min)	60
Fault repairing time (min)	120

No recloser		**Location 1**		**Location 2**		**Location 3**	
Customers x Faults	1029	Customers x Faults	768,87	Customers x Faults	669,45	Customers x Faults	622,5
Customers x High-speed AR	0	Customers x High-speed AR	0	Customers x High-speed AR	0	Customers x High-speed AR	0
Customers x Delayed AR	3087	Customers x Delayed AR	2306,61	Customers x Delayed AR	2008,35	Customers x Delayed AR	1867,5
Customer hours	1447,94	Customer hours	1187,81	Customer hours	1088,39	Customer hours	1041,44
		reduction (cust x faults)	260,13	reduction (cust x faults)	359,55	reduction (cust x faults)	406,5
		reduction(cust x high-speed AR)	0	reduction(cust x high-speed AR)	0	reduction(cust x high-speed AR)	0
		reduction (cust x delayed AR)	780,39	reduction (cust x delayed AR)	1078,65	reduction (cust x delayed AR)	1219,5
		reduction (customer hours)	260,13	reduction (customer hours)	359,55	reduction (customer hours)	406,5
SAIFI	1	SAIFI	0,747201166	SAIFI	0,65058309	SAIFI	0,604956268
SAIDI	84,42798834	SAIDI	69,26005831	SAIDI	63,46297376	SAIDI	60,72536443
MAIFI	3	MAIFI	2,241603499	MAIFI	1,951749271	MAIFI	1,814868805
		reduction (SAIFI)	0,252798834	reduction (SAIFI)	0,34941691	reduction (SAIFI)	0,395043732
		reduction (SAIDI)	15,16793003	reduction (SAIDI)	20,96501458	reduction (SAIDI)	23,70262391
		reduction (MAIFI)	0,758396501	reduction (MAIFI)	1,048250729	reduction (MAIFI)	1,185131195