TAMPEREEN TEKNILLINEN YLIOPISTO
TAMPERE UNIVERSITY OF TECHNOLOGY

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EFFECTS OF INCREASED DISTRIBUTION NETWORK CABLING ON DISTRIBUTION MANAGEMENT AND NETWORK INFORMATION SYSTEMS

Master of Science Thesis

Examiner: Professor Pekka Verho
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ABSTRACT

Jukka Nokelainen: Effects of Increased Distribution Network Cabling on Distribution Management and Network Information Systems
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The tightening of requirements for the distribution networks' quality of supply obliges distribution system operators to make large investments in distribution networks. Medium voltage network cabling is one prominent method to improve the reliability of delivery. However, the cable characteristics are different from the characteristics of an overhead line. An underground cable produces significant amount of both reactive power and earth fault current. In order to keep the touch voltages in acceptable limits during an earth fault, in addition to centralized coils also distributed arc suppression coils are being increasingly used. Transferring reactive power causes losses and major cost are caused by the Fingrid's fee for inputting reactive power in main grid. The reactive power is being compensated by shunt reactors.

The objective of this thesis was to find the development needs to ABB MicroSCADA Pro DMS600 software in the aspect of medium voltage network cabling. Representatives of 4 distribution system operators were interviewed and both measurements and simulations were performed to find the needs for improvements. Also the feasibility of active voltage level management feature Volt-VAr Control for Finnish customers was discussed.

As an outcome of this thesis, several development needs were gathered. New devices such as shunt reactors and Dyn11+YN transformers need to be accurately modelled to enhance load flow calculation and to ease the network coding. The earth fault analysis method of present DMS600 version includes multiple simplifications that may cause inaccuracies in networks containing long cable feeders and multiple arc suppression coils. More accurate earth fault calculation method was presented to improve the accuracy of the earth fault analysis method. Needs for features and notices to support the distribution system operators in the planning and operation of distribution network consisting of distributed compensation coils were presented. For example visualizing the compensation degree of feeders could help the planning and operation of feeders containing distributed arc suppression coils. Also the analysing of multiple network plans that are in the area of same HV-MV substation should be possible. That way the growth of reactive power and earth fault current could be taken into consideration during network planning. Required theory and information for developing above mentioned improvements were gathered. However, future work is needed to implement features to the DMS600 software.

TIIVISTELMÄ

JUKKA NOKELAINEN: Jakeluverkon maakaapeloinnin vaikutukset käytöntuki- ja verkkotietojärjestelmiin
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Tiukentuvien jakeluverkon toimitusvarmuusvaatimusten takia jakeluverkkoyhtiöt joutuvat tekemään investointeja toimitusvarmuuden parantamiseksi. Keskijänniteverkon kaapelointi on tehokas ratkaisu näiden vaatimusten täyttämiseksi. Keskijännitekaapelin sähköiset ominaisuudet kuitenkin eroavat avojohtoverkon ominaisuuksista. Keskijännitekaapeli tuottaa huomattavan määrän loistehoa ja maasulkuvirtaa. Maasulun aikaisten kosketusjännitteiden pitämiseksi sallituissa rajoissa, jakeluverkkoyhtiöt käyttävät yhä enemmän keskitetyn sammutuskuristimen lisäksi hajautettuja sammutuskuristimia. Loistehon siirrosta jakeluverkossa aiheutuu häviöitä. Mikäli loistehoa siirretään liikaa kantaverkkoon päin, huomattavia kustannuksia voi aiheutua myös Fingridin loistehomaksusta. Loistehon kompensoimiseksi jakeluverkossa käytetään rinnakkaisreaktoreita.

Työn tavoitteena oli selvittää kehittämistarpeet ABB MicroSCADA Pro DMS600 tuotteeseen keskijänniteverkon kaapelointiin liittyvien asioiden kannalta. Kehittämistarpeiden kartoittamiseksi neljän jakeluverkkoyhtiön edustajia haastateltiin, tehtiin mittauksia todellisessa haja-asutusalueen keskijänniteverkossa ja suoritettiin simulointeja PSCAD ohjelmistolla. Yhtenä työn tavoitteena oli myös selvittää ABB MicroSCADA Pro DMS600 aktiiviseen jännitteen ja loistehon hallintaan tarkoitetun Volt-VAr Control –ominaisuuden hyödynnettävyyttä suomalaisissa jakeluverkkoyhtiöissä.

Työn tuloksena kerättiin useita kehittämistarpeita ABB MicroSCADA Pro DMS600 tuotteeseen. Uudet laitteet, kuten rinnakkaisreaktorit ja muuntajakuristimet tulee mallintaa verkkotieto- ja käytöntukijärjestelmässä tehonjakolaskennan tarkentamiseksi ja verkon koodauksen helpottamiseksi. Tämän hetkinen maasulkulaskentametodi sisältää myös yksinkertaistuksia, jotka voivat aiheuttaa epätarkkuutta verkoissa, joissa on pitkiä kaapelilähtöjä ja useita kompensointilaitteita. Maasulkulaskentojen parantamiseksi työssä esitettiin kehittyneempi laskentatapa maasulkujen mallintamiseksi. Myös ominaisuuksia hajautettuja kompensointilaitteita sisältävän jakeluverkon suunnittelun ja käytön helpottamiseksi tarvitaan. Lähdön kompensointiasteen visualisointi voisi helpottaa hajautettujen sammutuskuristimien käyttöä ja suunnittelua. Myös useiden saman aseman syöttämän verkon alueella tehtävien verkostosuunnitelmien samanaikainen analysointi tulee olla mahdollista, jotta suunnittelussa voidaan ottaa huomioon maasulkuvirran ja loistehon kasvun vaikutukset. Työssä kerättiin yllä mainittujen kehitystarpeiden toteuttamiseen tarvittava teoria, mutta työssä esitetyt ominaisuudet jäävät tulevaisuudessa toteutettaviksi.

PREFACE

This Master of Science Thesis was written for ABB Oy Power Systems, Network Management. The examiner of the thesis was Professor Pekka Verho from the Department of Electrical Engineering and the supervisor of the thesis was Lic. Tech Pentti Juuti from ABB Oy. I would like to thank both examiner and supervisor for guidance and advices during this work.

I am also grateful for my colleagues and superior for their support. Many thanks belongs to my superior M.Sc. Ilkka Nikander for useful comments, M.Sc. Kai Kinnunen for participating to the interviews and B. Eng. Antti Kostiainen for giving assistance in questions related to the performed measurements.

I would also like to thank the interviewed persons from the distribution network companies; Tero Salonen and Mika Marttila from Leppäkosken Sähkö Oy, Markku Pouttu and Arttu Ahonen from Koillis-Satakunnan Sähkö Oy, Tommi Lähdeaho from Elenia Oy and Timo Kiiski, Jussi Antikainen and Matti Pirskanen from Savon Voima Verkko Oy. Thank you for your time and comments.

Finally I want to express my deepest gratitude for my family for supporting me during my studies and whole life.

Tampere, 19th May 2015

Jukka Nokelainen

CONTENTS

SYMBOLS AND ABBREVIATIONS

SYMBOLS

B	Capacitive susceptance
C_0	Capacitance to earth
C_{0xkm}	The capacitance of a cable section
C_e	Capacitance to earth
C_j	Capacitance of faulted feeder
D_e	The equivalent penetration depth
E	Voltage between phase and earth in fault point just before an earth fault
f	Frequency
I_C	The capacitive earth fault current component
I_E	Current flowing to earth
I_{ef}	Earth fault current
I_f	Earth fault current
Ifc	The capacitive component of the fault current
Ifc2	The capacitive component of the fault current in case fault is in the end of the feeder
Ifr	The resistive component of the fault current
Ifr2	The resistive component of the fault current in case fault is in the end of the feeder
Iftot	The total fault current
Iftot_DMS	The total fault current calculated by DMS
Iftot2	The total fault current in case fault is in the end of the feeder
I_L	Current produced in a compensation coil
I_{on}	Nominal compensation capacity
I_R	The resistive earth fault current component
I_r	Residual current, the sum of phase currents, asymmetric current
I_{R0}	Current in coil’s parallel resistance
I_{res}	Residual current, the sum of phase currents, asymmetric current
I_{RL}	Current in coil resistance
I_0	Zero sequence current
k	Coefficient for the relation between touch and earthing voltages
L	Inductance
l	The cable length
L_{BG}	The inductance of the coils in background feeder
L_{Fd}	The inductance of the coils in studied feeder

L_{Local}	The inductance of distributed coil
n	The amount of distributed arc suppression coil
P	Active power
P_0	No-load losses
P_k	The copper losses of transformer
P_{loss}	Active power losses in a line
Q	Reactive power
Q_C	Reactive power generated by line susceptances
Q_{cap}	Reactive power generated by a capacitor
$Q_{L,line}$	Reactive power consumed by line series reactances
Q_N	Nominal reactive power output
Q_S	Reactive power window output limit
Q_{S1}	Reactive power window output limit
R	Resistance
r	Reduction factor
R/X	The resistance-reactance ratio of a coil
R_0	Coil's parallel neutral point resistance
R_{0l}	The zero sequence resistance of faulted feeder
R_{0la}	The zero sequence resistance of healthy feeder before the first cable-coil-module
R_{0T2}	The zero sequence resistance of zero point transformer
$r_{c'}$	The geometric mean radius of a conductor
R_c	the conductor resistance
R_e	Parallel connection of R_0 and R_L
R_{e1}	The earthing resistance of the grid at the beginning end of the cable
R_{e2}	The earthing resistance of the grid at the second end of the cable
R_f	Fault resistance
R_g	The ground resistance
R_L	Coil resistance
R_l	The positive sequence resistance of faulted feeder
R_m	Earthing resistance
R_n	The resistance in the neutral point
R_{nu}	The zero sequence resistance of distributed arc suppression coil
R_s	The sheath resistance
$r_{s'}$	The geometric mean radius of sheath
S	Apparent power
S_N	Apparent power of the largest generator
S_n	Nominal apparent power
$S_{R_{1\delta}}$	The rated reactive power per phase

$S_{R_{3\delta}}$	The rated three-phase reactive power
t_k	Peak usage time
U	Voltage
U_0	Zero sequence voltage
U0	Neutral point displacement voltage in case the fault is in the beginning of feeder
U02	Neutral point displacement voltage in case the fault is in the end of feeder
U0_DMS	Neutral point displacement voltage calculated by DMS
$U_{0mät}$	Zero sequence voltage that is measured by a relay
U_{ae}	The voltage phasor of phase voltage b during an earth fault in phase c
U_{an}	The voltage phasor of phase voltage a
U_{be}	The voltage phasor of phase voltage a during an earth fault in phase c
U_{bn}	The voltage phasor of phase voltage b
U_{cn}	The voltage phasor of phase voltage c
U_{coil}	Voltage over the each coil
U_k	Touch voltage
U_m	Earthing voltage
U_N	Nominal line voltage
U_{n0}	Neutral point displacement voltage during an earth fault in phase c
U_{ph}	Earthing voltage
U_s	Step voltage
U_{tp}	Touch voltage
V_0	Neutral point voltage
W_{Gen}	Net active power production
W_{Output}	Output active energy
V_p	Phase to earth voltage
X	Reactance
X_{0c}	The zero sequence capacitive reactance of faulted feeder
X_{0ca}	The zero sequence capacitive reactance of healthy feeder before the first cable-coil-module
$X_{0ckabel}$	The zero sequence capacitive reactance of cable in cable-coil module
X_{0l}	The zero sequence inductive reactance of faulted feeder
X_{0la}	The zero sequence inductive reactance of healthy feeder before the first cable-coil-module
X_{0T1}	The zero sequence reactance of primary transformer or zero point transformer
X_{0T2}	The zero sequence inductive reactance of zero point transformer

X_C	Capacitor reactance
X_c	The positive sequence capacitive reactance of faulted feeder
X_{ca}	The positive sequence capacitive reactance of healthy feeder
X_{Delta}	Reactance of a delta-connected shunt reactor
X_L	Coil reactance
X_l	The positive sequence reactance of faulted feeder
X_{Line}	The inductive reactance of a line
X_n	The reactance in the neutral point
X_{nu}	The zero sequence inductive reactance of distributed arc suppression coil
$X_{nät}$	The impedance of supply point
X_{shunt}	The shunt reactance of compensated line section
X_{T1}	The positive sequence impedance of primary substation
X_{Wye}	Reactance of a wye-connected shunt reactor
Y	Shunt admittance
Z	Series impedance
Z_0	Zero-sequence impedance
Z_{0a}	The total zero sequence impedance of healthy feeder
Z_1	Positive-sequence impedance
Z_2	Negative-sequence impedance
Z_c	Characteristic impedance
Z_n	The total impedance consisting of impedance of centralized coil and the zero sequence impedance of transformer
Z_{na}	Parallel connection of Zn and Z0a
Z_u	The zero sequence impedance of cable/distributed coil –module
ω	Angular speed
μ_0	The permeability of a free space
$3I_{0mät}$	Zero sequence current that is measured by a relay

ABBREVIATIONS

ABB	Asea Brown Boveri
AHX-W240	A medium voltage power cable
AMR	Automated meter reading
AVC relay	Automatic voltage control relay
CVC	Coordinated voltage control
CVR	Conservation voltage reduction
DER	Distributed energy resource
DG	Distributed generation
DMS	Distribution management system
DMS600	ABB MicroSCADA Pro DMS600
DMS600 NE	ABB MicroSCADA Pro DMS600 Network Editor

DMS600 WS	ABB MicroSCADA Pro DMS600 Workstation
DSO	Distribution system operator
HV	High voltage
LV	Low voltage
MV	Medium voltage
NIS	Network information system
OHL	Overhead line
OLTC	On load tap changer
LTC	load tap changer
PFC	Power factor correction
PSCAD	Power System Computer Aided Design, a simulation software
RMS	Root mean square
SCADA	Supervisory control and data acquisition
SFS	The Finnish Standards Association
SIL	Surge impedance loading
SQL	Structured query language
SVC	Static Var Compensator
TSO	Transmission system operator
VSR	Variable shunt reactor
VVC	Volt-VAr Control

FIGURES

1. INTRODUCTION

1.1 Background of the thesis

Wind, storms and snow loads have caused major disturbances to the power distribution network during recent years. Due to the long power grid disturbances, new law came into effect on 1st September 2013. According to new law, fault in the distribution network caused by storm or snow load cannot cause an interruption over 6 hours in town plan area and over 36 hours in the other area after year 2028. In addition to the new law distribution system operators (DSOs) are obligated to pay a legal compensation to their customers for interruptions over 12 hours.

Replacing overhead lines with underground cables is one way to improve the reliability of delivery because the underground cable is safe from storms and snow loads. However the cable characteristics are different from the characteristics of an overhead line. Replacing overhead lines with underground cables increases the production of earth fault current and reactive power. Especially in rural area networks consisting long cable sections earth fault analysis might cause new problems. In these networks the zero sequence series impedance of cables might reach a value that is not negligible. Zero sequence series impedance might cause resistive current component and problems detecting earth fault. In order to minimize these problems, DSOs are going to increase the use of distributed compensation.

Also due to the cable characteristics cable’s natural loading is higher than one in case of overhead line. Because of this cable more likely produces reactive power. Reactive power transportation causes losses and the voltage to rise. The Finnish transmission system operator Fingrid Oyj is attending to the reactive power balance to maintain voltage levels in sustainable level. In order to encourage DSOs to keep the reactive power transportation between main grid and distribution network at appropriate level, Fingrid inherits fees for exceeding reactive power limits. Reactive power fee and losses caused by reactive power transportation drives DSOs to pay more attention to reactive power in distribution network.

1.2 Research problem and objectives

Due to different characteristics of cabled network DSOs have to pay attention to new issues. Compensation methods that have been in the past rarely used will be more commonly used in the future. MicroSCADA Pro DMS600 network information system (NIS) and distribution management system (DMS) have to give accurate calculation results and support despite the network characteristics.

The objectives of this thesis are to investigate by measurements and simulations the DMS's ability to keep up with the calculation requirements caused by increased distribution network cabling and to find by interviews of Finnish DSOs the development needs to DMS600 software. It is also being investigated if the feature Volt-VAr Control is an effective solution in Finnish distribution networks to solve the problems related to reactive power transportation and voltage stability.

The thesis introduces relevant information to understand the theory of a single phase earth fault, reactive power control objectives and the compensation methods in distribution networks. Requirements from the aspect of NIS and DMS are presented and development needs and recommended methods to fulfill the requirements are presented.

1.3 Research methodology

Research methodology in this thesis is based on literature study, measurements, simulations and interviews with the representatives of DSOs. Earth fault and reactive power theory are presented based on literature. Measurement and PSCAD simulation results are presented and compared to DMS's estimation results. DSO's cabling objectives and requirements are presented based on interviews.

Measurements were done in medium voltage network of Savon Voima Verkko Oy in rural area feeder consisting of over 40 km line. Inspected feeder was mainly cable. Three Dyn11+YN coupled transformers were connected along the feeder to compensate the earth fault current and the reactive power generated by lines. Reactive power, voltages and currents were measured in the beginning of the feeder and in the MV-LV substations where Dyn11+YN coupled transformers were located. The measured quantities are compared to quantities calculated by DMS in different situations in order to investigate the accuracy of DMS's calculation.

PSCAD simulations were done to investigate the accuracy of DMS's earth fault calculations. The accuracy of DMS's calculations were studied in case of long cable feeder and in case of different earth fault compensation methods.

Representatives of three Finnish DSOs were interviewed during the spring 2015. Interviewed DSOs and their representatives were:

- Tero Salonen and Mika Marttila, Leppäkosken Sähkö Oy
- Markku Pouttu and Arttu Ahonen, Koillis-Satakunnan Sähkö Oy
- Tommi Lähdeaho, Elenia Oy
- Timo Kiiski, Jussi Antikainen and Matti Pirskanen, Savon Voima Verkko Oy

DSO’s cabling objectives, compensation strategies of earth fault current and reactive power as well as development needs to DMS and NIS were asked. Questionnaire that was in the basis for discussion is presented in Appendix 1.

1.4 Structure of the thesis

The thesis contains 10 Chapters. The theory of earth fault in medium voltage networks is presented in Chapter 2. Also problems due to increased medium voltage network cabling and the earth fault compensation methods are presented in Chapter 2.

Chapter 3 contains the theory of reactive power control. In this chapter the objectives of reactive power compensation and the theory of compensation devices are presented.

Chapter 4 contains theory of voltage control. The voltage control objectives, problems caused by distributed generation and control methods and control variables are presented in that chapter.

Network information system and distribution management system of the ABB MicroSCADA Pro DMS600 software are introduced with their functionalities in Chapter 5.

Field measurements and the comparison of measured and estimated results are presented in Chapter 6. Also development needs to DMS based on the measurements are introduced in this chapter.

Chapter 7 covers the comparison of earth fault analysis results of PSCAD model and DMS. Development needs based on analysis of that chapter are also presented.

Cabling objectives and compensation methods of interviewed DSOs are presented in Chapter 8. Interviewed DSO’s requirements and development ideas are also presented in that chapter. In the end of that chapter the feasibility of Volt-VAr Control feature to Finnish customers is discussed.

Chapter 9 contains results of the thesis. The proposed methods to fulfill the DSO’s requirements are presented. Conclusions are presented in Chapter 10.

2. EARTH FAULTS IN MEDIUM VOLTAGE NETWORKS

Earth fault is the most common fault type in medium voltage network, where almost half of the faults are earth faults. An earth fault occurs when one or several phases become galvanically connected to earth. An earth fault occurs if for example a tree falls over an overhead line or if an excavator scratches a cable. When the earth fault occurs a fault current starts to flow through the fault point causing danger to human. This is why the fault has to be isolated. In this section the theory of earth faults, detection methods and compensation methods are presented. Also the problems caused by the extended use of medium voltage cable are introduced.

2.1 Earth fault theory

The series impedance and shunt capacitance of the transmission lines are important factors that effect on the earth fault behavior of system. There are also components in the system whose only purpose is to control the earth fault behavior. The amount of fault current depends on the earthing of the system. The system earthing consist of the connections between transformer neutral point and earth. The connections influence the zero sequence equivalent impedance of the system and by that the unsymmetrical fault current. The fault current determines the voltage at the transformer neutral i.e. the neutral point displacement voltage.

System earthing needs to be designed to limit the earth fault current in order to avoid touch and step voltages. However the fault current and displacement voltages needs to be high enough to facilitate high-impedance earth fault detection. Different system earthing methods are

- Solidly earthed neutral point
- Neutral point earthing via impedance
- Isolated neutral point
- Neutral point earthed via a suppression coil

In addition the suppression coil earthing can be done centralized, distributed or with combination of these. In this sections latest two from the previous list is represented since those are the most commonly used system earthing methods in Finnish medium voltage networks.

2.1.1 Isolated network

In an isolated system there is no connection between the neutral points of network and earth. Thus isolated system is also called as an unearthed system. Since there is no connection between the neutral point and earth the only return path for an earth fault current is through the capacitances of each phase to earth. In isolated networks the earth fault current is often small and lower than load current, thereby it is unlikely to cause damage to lines, cables or other equipment. The voltage between faulted equipment and earth is small, which improves safety. Transients and power frequency over voltages can be higher than in resistance earthed systems. [1]

An earth fault in isolated system is represented in Figure 1. Before the fault, the voltage at the fault location equals the phase to earth voltage E. Because all the neutral points of the system are isolated from earth, the zero sequence impedance between any point of the system and earth appear as infinite. The series impedance of lines and equipment to the zero sequence current is essentially smaller than the shunt impedance represented by the earth capacitance of the lines and can thus be neglected. Equivalent Thevenin's circuit can be modeled as in Figure 2 where point c represents the neutral point of MV winding side of HV-MV transformer.

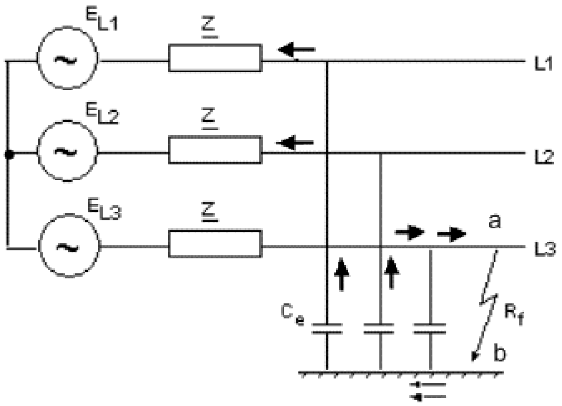

Figure 1. An earth fault in a network with an unearthed neutral [2]. Edited

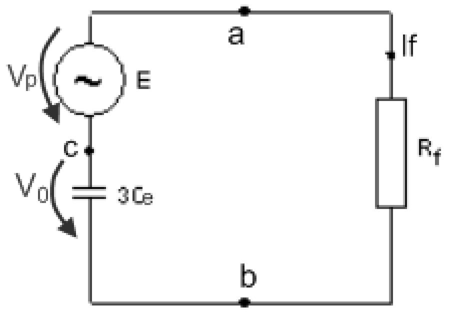

Figure 2. The equivalent circuits for the earth fault in a network with an unearthed neutral. C_e represents the capacitance between phase and earth [2] [3]. Edited

From the equivalent circuit the equations (1) and (2) for the maximum earth fault current I_f and the neutral point voltage V_0 can be calculated in terms of the phase-earth voltage E before the fault. In a solid earth fault the earth fault current is solely capacitive, but in case of non-solid earth fault there is both resistive and capacitive current components in earth fault current. In equation (1) I_R represents the resistive part and I_C represents the capacitive part of fault current. [4] [1].

$$I_f = I_R + jI_C = \frac{R_f(3\omega C_e)^2 E}{1+(R_f 3\omega C_e)^2} + j\frac{3\omega C_e E}{1+(R_f 3\omega C_e)^2} \tag{1}$$

$$\underline{V}_0 = \frac{1}{j3\omega C_e}(I_f) = \frac{1}{1+j3\omega C_e R_f}E \tag{2}$$

In case of an unsolid fault there is a voltage drop across the fault resistance R_f. Therefore the entire pre fault phase voltage is not applied across the system capacitance. Using equations (1) and (2) equations (3) and (4) can be derived for the ratio of neutral point voltage and phase voltage. [2]

$$\frac{V_0}{E} = \frac{1}{\sqrt{1+\left(3\omega C_\mathrm{e} R_f\right)^2}} \tag{3}$$

$$\frac{V_o}{E} = \frac{\frac{1}{j\omega C_0}}{\frac{1}{j\omega C_\mathrm{e}} + 3R_f} \tag{4}$$

Equation (4) states, that the highest value of neutral voltage is equal to the phase voltage. The highest value is reached when the fault resistance is zero and for higher resistances, the zero sequence voltage becomes smaller. In case of a solid earth fault the healthy phase to earth voltage increases to the value of healthy state phase to phase voltage. The maximum phase to phase voltage 1,05 $V_{phase\text{-}phase}$ is achieved when the fault resistance is about 37% of the impedance consisting of the network capacitances [2]. The phase and the magnitude of the neutral point voltage and the voltage across the fault resistance depends on the phase and magnitude of the earth fault current and the fault resistance. The behavior of voltages during and earth fault are represented in Figure 3.

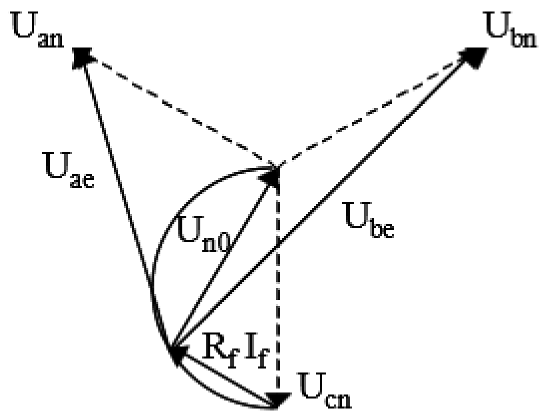

Figure 3. The voltage phasor diagram for an earth fault in an isolated neutral system [3]

In a normal conditions the phase to neutral voltages and the phase to earth voltages are basically the same but during an earth fault those are quite different. The neutral shift is equal to the zero sequence voltage. [2] Changes in neutral point displacement voltage and unsymmetrical currents can be used to detect earth fault in a system. Typically, over voltage relays are used to detect neutral point displacement voltage and directional residual over current relays are used for selective fault direction. Relay operation thresholds decide the sensitivity of earth fault detection. Since high impedance faults, which cause low fault currents and neutral point displacement voltages, are needed to detect, the relay needs to operate on low thresholds. These are, however, always natural unbalances in the system, which rise the neutral point displacement voltages and unsymmetrical currents, which can cause unwanted relay operations. [3]

Since earth fault current in isolated neutral system highly depend on the system capacitances, it might not be suitable earthing method in the networks with large amounts of cable, or in contrary in small networks consisting overhead lines. [3]

2.1.2 Compensated network

In large overhead or cable systems with isolated neutral the capacitance between phase and earth is so large that earth fault currents increases. In order to compensate the earth fault current inductive neutral point reactors, also called Petersen coils are installed between an arbitrary number of system neutral points and earth. The inductance of Petersen coil can be adjusted to match closely the network phase-earth capacitances depending on the system configuration. If the Petersen coil is tuned to be lower than the earth capacitance of the network the network is under compensated. This is the way that compensated networks are usually operated, because in case of overcompensation the detection of fault is unsure. [1] Earth fault current compensation can be done with centralized Petersen coil in HV-MV substation, or with distributed compensation coils along feeders.

In centralized compensation Petersen coil is installed in HV-MV substation. Centralized compensation coil is typically equipped with compensation controller, which keeps the compensation degree at given state. Compensation degree is the ratio of inductive current of compensation coil and total earth fault current generated in capacitances of the system. An earth fault situation in centrally compensated system is represented in Figure 4.

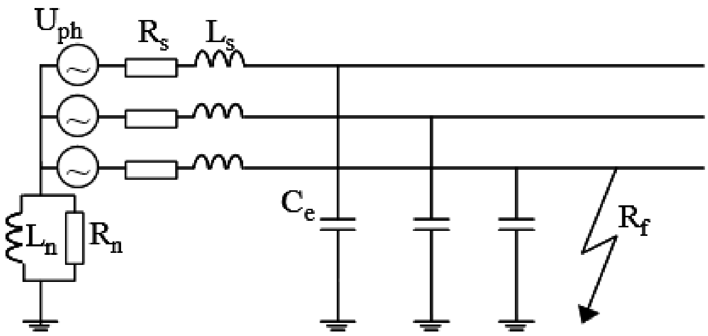

Figure 4. An earth fault in centrally compensated system [3]

The equivalent circuit for earth fault in centrally compensated system without line impedances is represented in Figure 5.

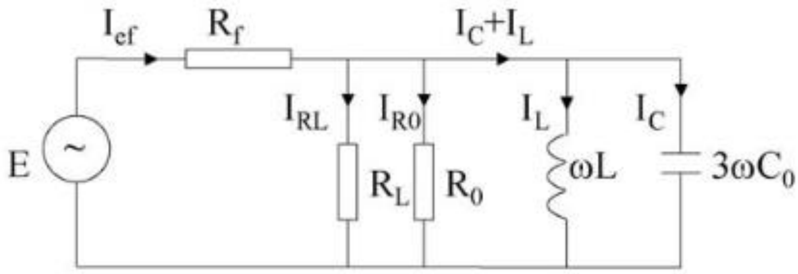

Figure 5. The equivalent circuit of earth fault in a centrally compensated system [4]

The earth fault current of compensated system is small, thus parallel resistance in compensation coil is used in order to facilitate earth fault detection. Resistive part of earth fault current is generated in parallel resistance R_o and in the series resistance R_L of the coil. L is the inductance of the compensation coil. In case of a solid earth fault the earth fault current is calculated as shown in equation (5). [4]

$$I_{ef} = I_{RL} + I_{R0} + I_L + I_c$$

$$I_{ef} = \frac{(R_L + R_o)E}{R_L \cdot R_o} + j \cdot \left(3\omega C_0 - \frac{1}{\omega \mathrm{L}}\right) E \tag{5}$$

In case of non-solid earth fault earth fault current reduces as given in equation (6).

$$I_{ef} = \frac{R_e(R_f R_e + 1) + R_f {X_e}^2 + jX_e}{(R_f R_e + 1)^2 + R_f {X_e}^2} \tag{6}$$

Where

$$R_e = \frac{R_L + R_0}{R_L \cdot R_o}$$

$$X_e = 3\omega C_0 - \frac{1}{\omega L}$$

Equation (7) gives the neutral displacement voltage, the voltage across the system's impedance to earth [4]

$$U_0 = \frac{I_{ef}}{\sqrt{\left(\frac{1}{R_e}\right)^2 + \left(3\omega C_0 - \frac{1}{\omega L}\right)^2}} \tag{7}$$

The current flowing through the Petersen coil has resistive and reactive component. The angle of the current can be derived from equation (5). There are however load current and system resistance neglected. [1] Selective detection of earth fault current is typically done with directional residual over current relays and voltage relays. Directional residual over current relays measure the resistive part of the earth fault current and voltage relays measure the neutral point displacement voltage. For fault detection to be successful system is kept slightly over or under compensated. It will keep the earth fault current low enough to enable arc fault self-extinction, and sufficient earth fault detection. [3]

2.2 Objectives of earth fault protection and compensation

Earth fault current that is flowing from phase to earth causes a voltage to earth in fault point. Typically an earth fault occurs in MV-LV substation. In that case earth fault current flows from line to earth through an air gap and the earthing of MV-LV substation. Earth fault current causes a voltage drop U_m over earthing resistance R_m. The relation of these is represented in equation (8).

$$U_m = I_f \cdot R_m \tag{8}$$

The earthing voltage $U_m$causes a touch voltage that might affect over a human or an animal. Usually the touch voltage U_{tp} is only part of the voltage to earth U_m. Finnish Standard Association defines the allowed relation between the earthing voltage and touch voltage for different installations. The relation is presented in equation (9) and the coefficient k for different installations is represented in Table 1.

$$U_m \leq k \cdot U_{tp} \tag{9}$$

Table 1. The allowed coefficients for different earthing conditions. [5]

k	*System conditions*
2	Ideal value
4	Bad earthing conditions. Voltage grading in every MV-LV substation and earthing of every LV-feeder is necessary
5	Bad earthing conditions, voltage grading in every MV-LV substation and own earthing for every customer point is necessary.

Dangerousness of the touch voltage depends on the time the voltage affects over a human body. Finnish Standard Association defines the allowed touch voltages in function of the fault time, which is represented in Figure 6.

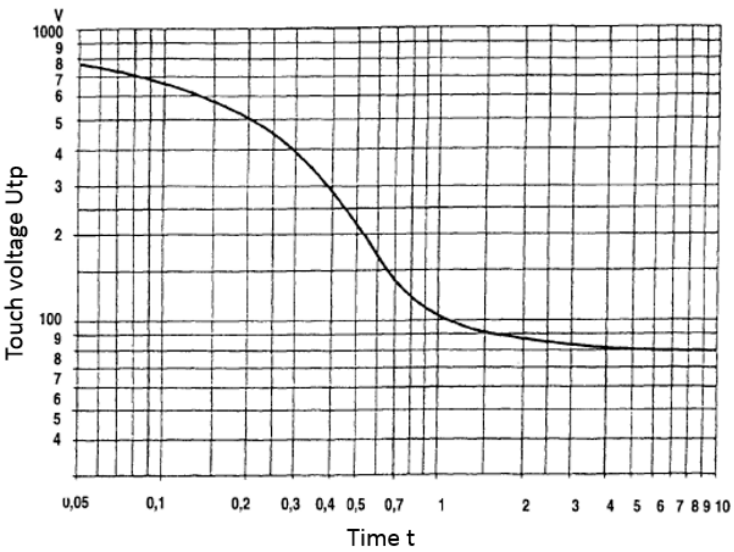

Figure 6. The allowed touch voltages in the function of fault time [6]

When calculating touch voltages it needs to be taken into account that part of the earth fault current flows in the other parts than the earthing resistance. For example in substations the earth fault current might also flow through an overhead earthing wire or through the metal sheath of cables. In these cases the earth fault current used in equation (8) is corrected with reduction factor r as represented in equation (10). [6]

$$I_E = r \cdot I_f \tag{10}$$

In which I_E is the current flowing to earth, r is reduction factor and I_f is earth fault current.

If for example feeders A, B and C consist of cables with different reduction factors r_A, r_B and r_C, the total earth fault current flowing to earth is calculated with equation (11).

$$I_E = r_A \cdot 3I_{0A} + r_B \cdot 3I_{0B} + r_C \cdot 3I_{0C} \quad (11)$$

In which $3I_{0A}$ is the earth fault current generated by feeder A, $3I_{0B}$ is the earth fault current generated by feeder B and $3I_{0C}$ is the earth fault current generated by feeder C. [6]

As can be seen from equation (8) and Figure 6. The only way to keep the touch voltages in acceptable limits is to reduce the earth fault current, fault time or earthing resistance. Since the earthing conditions in Finland are usually bad, the reduction of earthing resistance is expensive and operation time of earth fault relay needs to be as quick as possible to avoid too long fault time even though operation during earth fault is in principle possible due to the Dyn11 connected MV-LV transformers. Possible ways to decrease an earth fault current is to divide network into smaller pieces by multiple primary transformers or to use compensation coils for earth fault compensation. [5].

2.3 Earth fault detection methods

In an isolated neutral system the earth fault current is smaller than load current and thus the detection of earth fault cannot be utilized by use of over current relay. The possible indicators of earth fault are fundamental frequency neutral point displacement voltage, change in fundamental frequency phase voltage, fundamental frequency asymmetric current, harmonics in current or voltage and high frequency current changes. Detection with fault current harmonics is based on the fact that earth fault current contains 5 th harmonic. The high frequency current changes occurs during the first moments of earth fault. Basically the earth fault detection in substations is taken care of by directional relay which operates based on the measured asymmetric current I_r and measured asymmetric voltage between system neutral and earth. The asymmetrical current can be measured by the sum connection of current transformers or with cable type current transformer.

The current that relay sees during an earth fault is smaller than the total earth fault in fault point. This is because the current generated in faulted feeder is transmitted in both direction through the current measurement device. In Figure 7 an equivalent circuit of an isolated system is represented whose capacitances of two lines are separated. $3C_j$ represents the earth capacitance of faulted feeder.

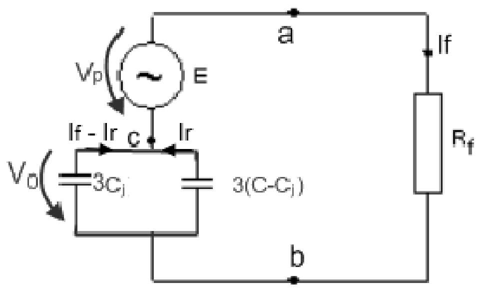

Figure 7. The equivalent circuit of an earth fault in isolated system. The capacitances of faulted feeder are separated. [1]

Since the same zero sequence voltage V_0 effects on both capacitances $3C_j$ and $3(C\text{-}C_j)$, it follows equation (12) for the residual current I_r that is seen by a relay during an earth fault. [5]

$$I_r = \frac{(C - C_j)}{C} I_f \tag{12}$$

For directional earth fault protection to detect the faulted feeder current I_r and voltage V_0 needs to exceed the defined limits and the angle between negative $\underline{V}_0$ and $\underline{I}_r$ have to be close to 90˚. Therefore the third operating condition of directional earth fault relay is an angle sector represented in equation (13). The suitable angle tolerance $\Delta\varphi$ depends in neutral isolated system on the system conductance and resistances of the lines. [5]

$$90^\circ - \Delta\varphi < \varphi < 90^\circ + \Delta\varphi \tag{13}$$

In which φ is the angle between $\underline{I}_r$ and $\underline{V}_0$, and $\Delta\varphi$ is the angle tolerance.

The single phase equivalent circuit of a system consisting of both distributed and centralized coils is presented in Figure 8. L_{BG} is the coil inductance located in background network (centralized and distributed coils) and L_{Fd} is the inductance of the coils located in the inspected feeder.

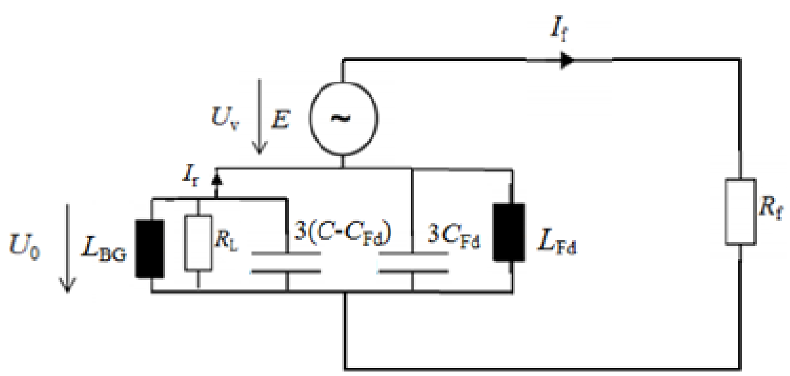

Figure 8. The single phase equivalent of an earth fault in centralized and distributed compensated system [7], modified from [5]

The absolute value of the residual current for the faulted feeder in system represented in Figure 8 can be calculated with equation (14) [7].

$$I_r = \frac{\sqrt{1 + (R_L(3\omega(C - C_{Fd}) - \frac{1}{\omega L_{BG}}))^2}}{\sqrt{(R_f + R_L)^2 + (R_f R_L(3\omega C - \frac{1}{\omega L}))^2}} \frac{U}{\sqrt{3}} \tag{14}$$

Where L is the total inductance of all coils in the network.

In compensated neutral system the $\underline{I}_r$ is mainly generated in the parallel resistance of the centralized coil and is thus mainly resistive. The parallel resistance of the coil can be configured to work differently in different systems depending on the desired purposes. Parallel resistance can be connected all the time or it can be connected only during an earth fault if the earth fault have not disappeared after small time delay. The parallel resistance increases the resistive earth fault current and it is thus easier for relays to detect earth fault selectively. In case of resonant earthed neutral system the directional over current relay is set to trip if the angle between current and voltage is maximum $\pm\Delta\varphi$. Since the system is often operated close to resonance, the angle φ might alternate significantly during earth fault and angle tolerance is thus usually set remarkably higher than in neutral isolated systems. [5]

In system where only distributed compensation coils is used the earth fault current is mainly reactive. Thus the earth fault detection can be utilized as in neutral isolated system. In this case the changes in switching state causes large changes in earth fault current generation of the feeder consisting of local coil, which causes problems in sensitive earth fault detection. Locations of the coils should be carefully selected to avoid the situation where local coils overcompensate the feeder and therefore the earth fault current produced by the feeder would become inductive. Protection settings might not been adjusted to take such an operation into account. [8]

The advantage of the traditional earth fault protection methods is that they are commonly known and the setting principles are familiar to protection engineers. The performance of the traditional protection methods is considered adequate, but there are some limitations especially systems with distributed coils, multiple types of fault resistance and intermittent earth faults. These kind of systems will be in use since the cabling increases but part of the lines remain overhead lines. Also one limitation of the traditional earth fault detection method is that relay settings must be changed if the compensation coil is disconnected, which complicates the daily operation of distribution network. [9] Recent studies indicates that admittance based protection would solve these problems, since its inherent immunity to fault resistance, good sensitivity and easy setting principles. [8]

2.4 Challenges in earth fault analysis due to extended cabling

Cabling of medium voltage network is not a new phenomenon since medium voltage cable is commonly used in urban area networks. In urban area networks the load density is high and therefore large wire cross-sections are used. Because the distance between MV-LV substations is small there are lots of earthing points in cable sheath. In addition there are lots of other earthing networks in cities. In case of rural area medium voltage networks the situation is quite different to urban area network. In rural area the load density is lower, which is why wire and sheath cross-sections are smaller and the cable sheath is earthed in only few points. Earthing conditions are worse than in urban areas. [10]

In case of urban area networks some assumptions in earth fault analysis can be used that doesn’t necessarily apply in rural cable network. In conventional earth fault analysis the total cable length determines the earth fault behavior of the system. It does not make any difference if the total length is made up by a few long or many short cables. The second assumption is that the earth fault current is solely capacitive and proportional to total cable length. Because the current is capacitive it can be totally compensated by use of a Petersen coil. The size of the coil can be dimensioned from cable data and its resistive losses are proportional to the inductive current generated in the coil. The third assumption is that the neutral point displacement voltage in a tuned system is determined exclusively by the neutral point resistance and fault resistance. The last assumption is that the fault location does not effect on the earth fault behavior of the system. [4]

2.4.1 Zero sequence impedance of cable

The zero sequence series impedance influences the earth fault behavior of systems consisting of long cable feeders. The zero sequence impedance of underground cable is determined by the zero sequence capacitance and series impedance. The zero sequence capacitance does not have as much uncertainties as zero sequence series impedance, which strongly depends on cable installations. Since zero sequence series impedance does not influence the earth fault behavior of conventional systems, it have not been interesting value and there are still many uncertainties in its calculation methods. The zero sequence impedance Z modeled by a pi-section and by a capacitance only is presented in Figure 10. The argument of the impedance is represented by δ.

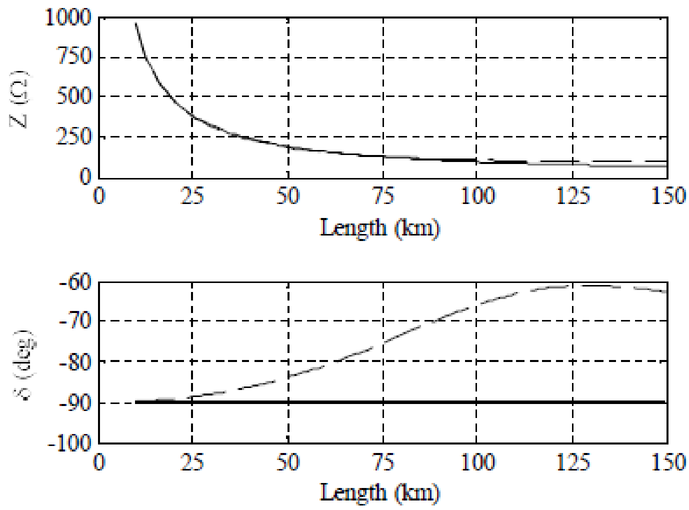

Figure 9. The magnitude and argument of the equivalent zero sequence impedance of cables modelled by pi-sections (dashed) and capacitances only (solid). [3]

As can be seen in Figure 10 the series impedance does not influence the absolute value of zero sequence impedance but does however effect on the argument. The argument of the impedance differs from the -90˚, which means the impedance consist of a resistive and reactive part. [3]

In Master of Science thesis of Hanna-Mari Pekkala [11] and Sami Vehmasvaara [12] the equation (15) is used for zero sequence in PSCAD simulations of cabled networks. The equation is developed by Gunnar Henning from ABB Power Technologies. [11]

$$Z_0 = l(R_c + 3\frac{j\omega\mu_0}{2\pi}\ln\frac{r_s}{\sqrt[3]{r_c' \cdot d'}}) + \frac{3lR_s(R_{e1} + R_{e2} + l(R_g + \frac{j\omega\mu_0}{2\pi}\ln\frac{D_e}{r_s'}))}{R_{e1} + R_{e2} + l(R_s + R_g + \frac{j\omega\mu_0}{2\pi}\ln\frac{D_e}{r_s'})} \quad (15)$$

In equation (15) constraints are the following:

- l is the cable length
- D_e is the equivalent penetration depth [m]
- r_c' is the geometric mean radius of a conductor
- R_c is the conductor resistance
- R_{e1} is the earthing resistance of the grid at the beginning end of the cable
- R_{e2} is the earthing resistance of the grid at the second end of the cable
- R_g is the earth 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 equation (16) and the earth resistance R_g can be calculated with equation (17).

$$659 \cdot \sqrt{\frac{\rho}{f}} \tag{16}$$

$$R_g = \frac{\omega \mu_0}{8} \tag{17}$$

Where f is the frequency [Hz] and ρ is the earth resistivity.

The equations above show that the impedance depends on the cable length and the earthing resistance in both ends of the cable. Usually in computing programs the zero sequence impedance is specified as Ω per kilometer. If these equations are used in these programs Ω/km value needs to be calculated for each line section separately. [3] According to studies initiated by Anders Vikman in Vattenfal Eldistribution AB, the effect of an earthing wire can be modelled simply by roughly halving the zero sequence resistance given by the equation. The zero sequence reactance should be multiplied by two. [11]

2.4.2 Influence of fault location

In case of long cable feeders series impedance of sequence networks become more dominant and cannot necessary be neglected. The zero sequence series impedance consist of a resistive and inductive part, and consequently the equivalent impedance has a resistive component that cannot be compensated by use of Petersen coil. Anna Guldbrand has shown in her thesis that zero sequence series impedance reaches non-negligible value in radial 30-40 km long cable feeders. Non-negligible value was reached even in shorter cable feeders consisting of shorter cables connected to several parallel feeders a distance from the feeding busbar. Sequence network models of earth fault at the end of the line are represented in Figure 10.

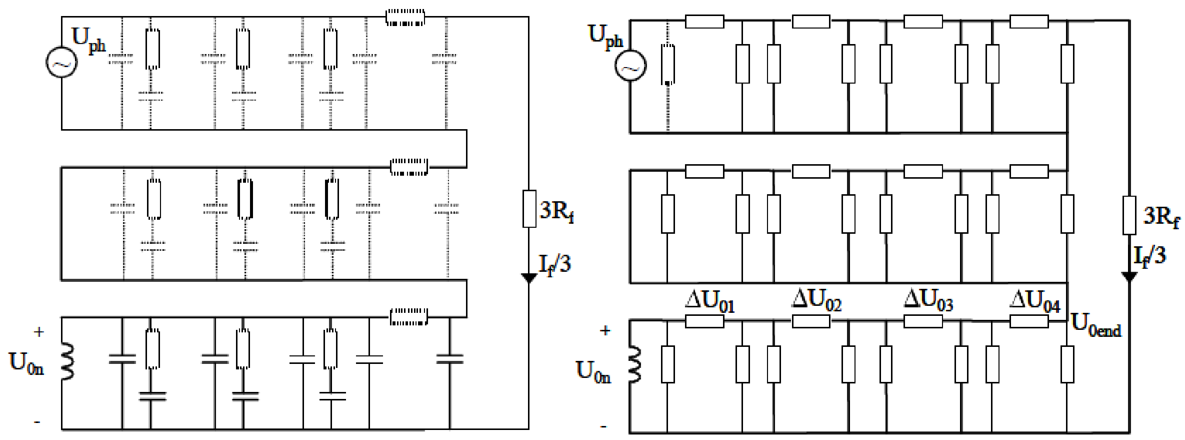

Figure 10. Sequence networks representing an earth fault at the end of the line with negligible (left) and non-negligible (right) series impedances of sequence networks [3]

In the left figure the series impedances of positive, negative and zero sequence networks are neglected as in conventional earth fault analysis. In right figure the series impedances are non-negligible, which causes voltage drop in sequence networks. Since the voltage drop has a real and imaginary part, the zero sequence voltage magnitude can either increase or decrease. In Figure 11 the neutral point displacement voltage and zero sequence voltage at fault location is presented during an end of line fault with different line lengths.

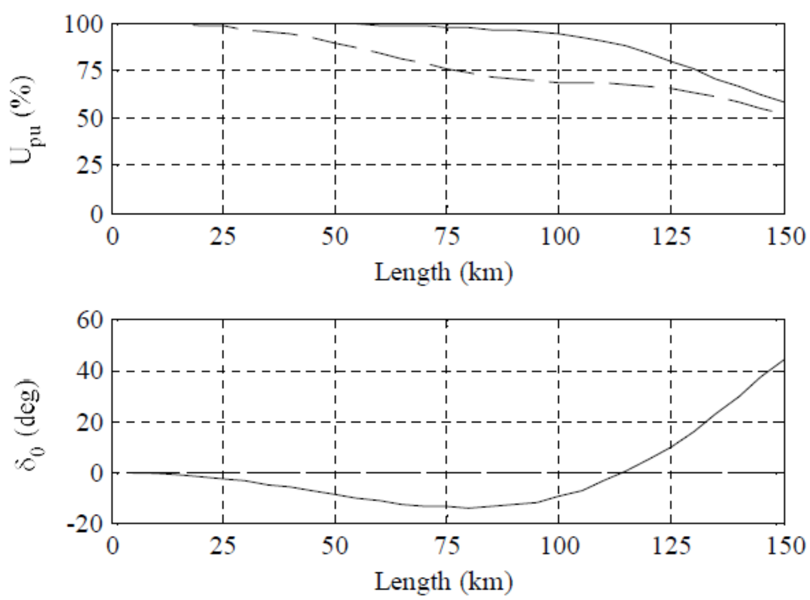

Figure 11. Neutral point displacement voltage (dashed) and zero sequence voltage at fault location (solid) during an end of line fault in resonance earthed system. Phase is related to the neutral point displacement voltage. [3]

Since there are voltage drops across the non-negligible series impedances of the faulted feeder, the amplitude and the phase of neutral point displacement voltage are different from that of the zero sequence voltage at the fault location. The voltage drop depends on the size and phase of zero sequence current but also the size and phase of equivalent zero sequence impedance and hence depends on the network structure and location of the fault. In addition, the voltage drops in positive and negative sequence networks influence the zero sequence voltage at the fault location. This causes that the zero sequence voltage at the fault point differs from the phase voltage, even if the fault impedance is negligible. [3]

Since the maximum earth fault current is considered as the worst case scenario, it is therefore consequential to find the fault location in which the earth fault current reaches its maximum value. Figure shows the earth fault current during busbar fault and end of line fault in resonance earthed system tuned for faults in busbar. I_R is the resistive earth fault current component and I_C is the capacitive earth fault current component.

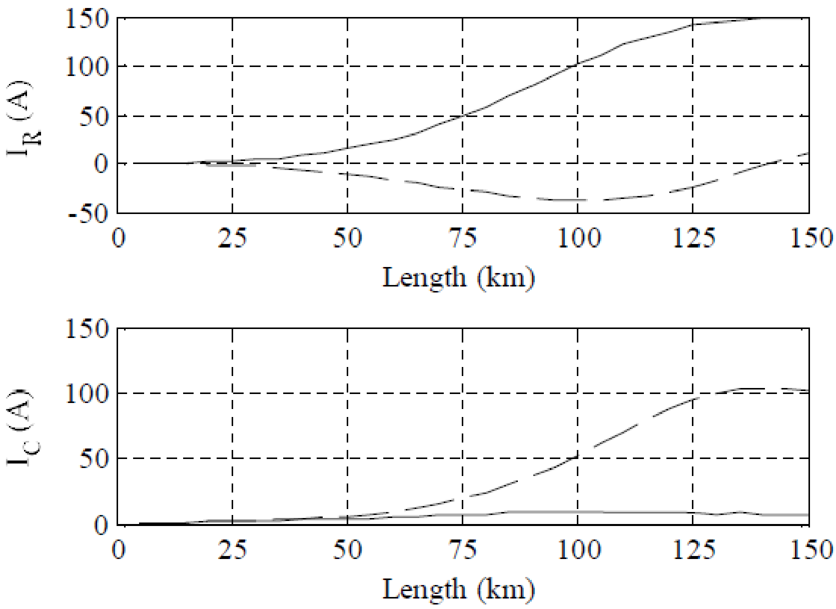

Figure 12. Fault currents at the fault location during solid busbar earth fault (solid) and solid earth fault at end of the line (dashed) in resonance earthed rural cable system with variable cable lengths [3]

The curves in Figure 12 shows that fault current during an end of line fault is smaller than fault current during busbar fault. This is because the positive and negative impedance contribute to the equivalent impedance, which limits the earth fault current. Even though the calculations show that the earth fault current is larger for faults in busbar than faults in end of line, it cannot be concluded that a fault on the busbar gives maximum earth fault current. The Petersen coil decreases the earth fault current but since it cannot be tuned to compensate same amount of earth fault current independently on fault location, the influence of earthing will vary depending on fault location. [3] As mentioned above the effect on fault location on the earth fault current and neutral point displacement voltage is due to series impedances of sequence networks. The effect of series impedances can be minimized by use of distributed compensation described in Section 2.5.2.

2.5 Earth fault current compensation

2.5.1 Centralized compensation

In Finnish networks the high voltage side of the primary transformer is earthed only in some particular points defined by Fingrid Oyj, but basically the transmission network is unearthed. As a result the earth fault in transmission network does not effect on the currents or voltages in the medium voltage network. Same applies in case of earth fault in medium voltage network: it does not effect on the primary side network of primary transformer. The primary transformers are mainly Yd coupled, which means that there is no neutral point in secondary side available. Therefore in order to connect an earthing device to neutral point of medium voltage network a neutral point needs to be created. This is usually done with earthing transformer, which usually is Znyn-coupled. The compensation coil is connected to neutral point of earthing transformer via disconnector that enables the disconnection of the coil during for example maintenance. The centralized Petersen coil is automatically adjustable. In Finland compensation degree is kept slightly under compensated, but for example in Sweden it is kept slightly overcompensated. Behind this practice is the idea that it is more likely for some network part to be disconnected from network, which changes the network closer to resonance point. [11]

2.5.2 Distributed compensation

Instead of one large controlled coil in the HV-MV substation it is possible to install small compensation devices around the system. Each of these devices comprises a star point transformer and Petersen coil without automatic control or transformer that consist of YN connected Petersen coil for earth fault current compensation and distribution transformer [10]. Distribution transformers with only earth fault current compensation capability are Zn(d)yn or Znzn0-coupled. These couplings give the magnetic balance to the transformer in case of an earth fault at LV-side of distribution transformer, which disables the earth fault current to be seen in MV-voltage side. [11] If these coils are properly located in individual feeders around the network, no additional automatically adjusted arc-suppression-coil is required. The disconnection of the compensation equipment when the associated feeder is isolated from the network keeps the compensation level at sustainable state regardless of the switching arrangements on the network. [1]

2.5.2.1 Effect of distributed compensation on earth fault current transportation

In system where series reactance can be neglected, equivalent circuit of earth fault in system with distributed compensation is equal to one in case of system with centralized compensation except that zero sequence network consists of multiple parallel inductances and possible resistances. Earth fault current and neutral point displacement voltage can be calculated with equations (6) and (7) presented in Section 2.1.2.

The distributed compensation is one solution to limit the resistive losses caused in transportation of reactive current and non-ideal neutral point reactors. In Figure 13 the sequence networks in case of earth fault in busbar is presented. In system presented in left side of the figure only centralized compensation coil is used. In the system presented in the right side of the figure combination of centralized and distributed compensation is used.

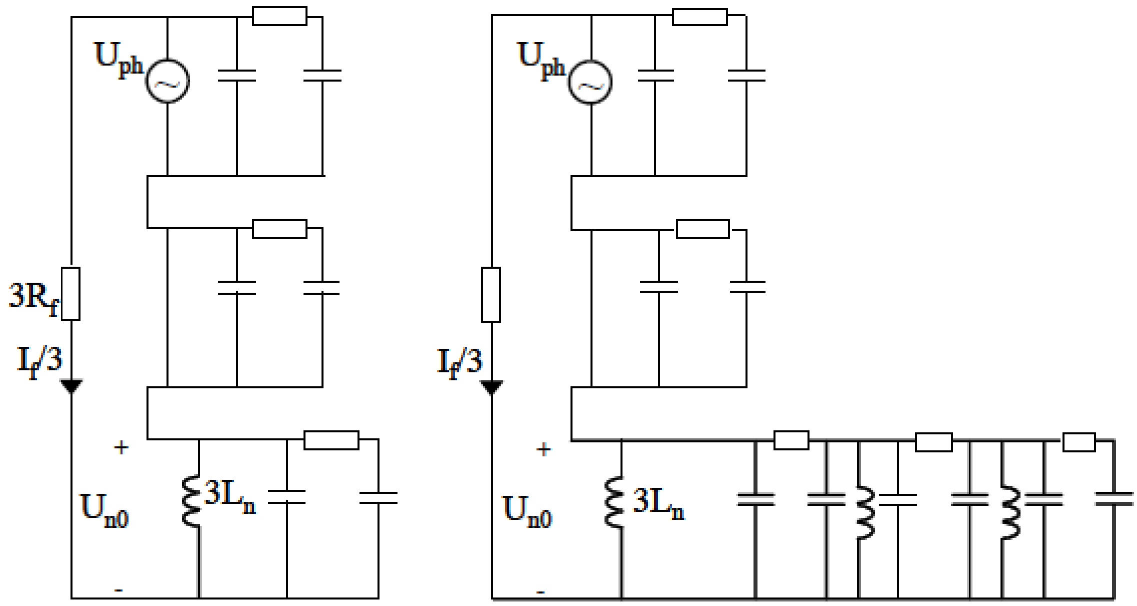

Figure 13. Earth fault at the busbar in single long cable system with centralized (left) and distributed compensation (right) [3]

If the cable is long and only centralized compensation is used the zero sequence series impedance is not negligible. If also distributed coils are used and those are dimensioned to compensate for the capacitive current generated in the system, and the distance between the coils is limited, the total shunt impedance is very large and the series impedance can therefore be neglected. [3]

2.5.2.2 Coil rating

The effect of arc suppression coils is based on the inductive earth fault current generated in the coil, which compensates the capacitive earth fault current. Distributed compensation coils are manually adjustable and there are coils of different sizes. ABB produces coils with compensation capacity of 3,5 - 5 A, 5 - 15 A and 15 - 25 A. [10] The rating of the coil can also made by the shunt impedances of the system. For the influence of series impedance of the system to be as small as possible, the equivalent zero sequence shunt impedance should be as large as possible. The shunt reactance of system can be calculated with equation (18).

$$X_{shunt} = \frac{\omega 3L_{local} \cdot \frac{1}{\omega C_{0xkm}}}{\frac{1}{\omega C_{0xkm}} - \omega 3L_{local}} \tag{18}$$

Where X_{shunt} is the shunt reactance of compensated line section, L_{local} is the inductance of distributed coil and C_{0xkm} is the equivalent capacitance of the cable section.

While the reactance of coil approaches the reactance of cable section the total shunt reactance approaches infinity. In reality the capacitance to earth is distributed and the shunt admittance is therefore finite. As the distance between coils increases, shunt admittance of the system decreases and resistive losses in zero sequence network increases. [4] In addition to resistive losses of in lines resistive losses are also generated in compensation coils. Resistive losses of compensation coils are approximately 2,5 % and therefore losses increases while the coil size increases. [10] The current provided by compensation coil can be calculated with equation (19).

$$I_L = \frac{U_0}{\sqrt{3}} \cdot \frac{1}{R_L + j\omega L} \tag{19}$$

Where U_0 is the zero sequence voltage affecting on distributed coil, R_L is the series resistance of the coil and L is the inductance of the coil.

2.5.2.3 Coil location

The location of distributed arc suppression coils effects on the resistive losses during earth fault. It is recommended in Licentiate thesis of Anna Guldbrand that 15 to 20 km of each cable feeders are compensated by centralized compensation coil and the rest of the feeders are compensated with local compensation coils.

In reference [13] J. Jaakkola and K. Kauhaniemi have been investigated the effect of density of distributed coil. In that paper the smallest variation in fault currents in different fault locations was reached in distributed compensated networks where distributed coils were placed in 5 km intervals. However, there was no big difference compared to situation where coils were placed in 10 km or 20 km intervals. Therefore it is probably cost efficient to install coils with 10 or 20 km intervals. In case of centralized and distributed coils it turned out to be good solution to compensate first 10 km of feeders with centralized compensation coil and the rest of the feeders with distributed coils with interval of 10 km. [13]

During a pilot project in Savon Voima Verkko Oy Dyn11+YN coupled distributed coils were installed in cabled rural distribution network. Esa Virtanen proposes that on the basis of experience in that project the optimum location of coils is about 10 km from each other’s, and that in mixed network 50 % of earth fault current should be compensated centrally and 50 % with distributed coils. [10]

2.6 Analysis method for compensated system equipped with distributed coils

In above sections it have been demonstrated that the assumptions of conventional earth fault analysis cannot be used in system consisting of long cable feeders. In addition to the series resistances of long feeders the increased amount of resistive losses in distributed coils and in zero point transformers causes inaccuracy to conventional analysis. Gunilla Brännman has developed a method in which the resistance of distributed coils and the zero sequence impedance of transformer are taken into consideration. The model is developed based on symmetrical components and is explained more detail in publication “Analysmodell för Impedansjordat System med Lokal Kompensering”. In this section the basics of the modeling method are presented. [14]

In conventional earth fault analysis only the shunt capacitances and shunt reactance of zero sequence network are taken into consideration. In this modeling method only impedances which have smaller effect than 1 % into total impedance are neglected. The positive sequence impedance is the impedance of network that participates the short circuit in the system. Negative sequence impedance is usually equal to positive sequence impedance in case of lines and transformers. Zero sequence impedance depends mainly on the earthing of the system. In order to present the idea of the method the sequence networks are created for system consisting of two feeders A and B. There is a centralized compensation coil in the neutral point of primary transformer and two distributed coils are placed in feeder B. Dyn coupled transformer in feeder A is a normal distribution transformer. The system is presented in Figure 14.

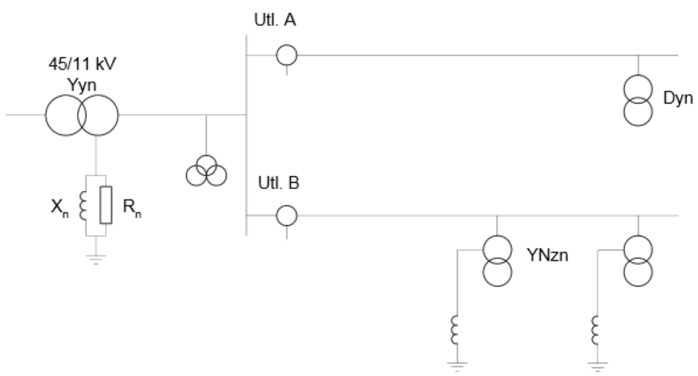

Figure 14. System consisting of two feeders. Earth fault occurs in feeder A. [14]

In case of a single phase earth fault on feeder A the equivalent positive and negative sequence impedances look like one presented in Figure 15. The positive sequence resistance of primary transformer and feeder B is in this case neglected. Every line sections are modelled with pi-section consisting of shunt capacitances and series impedance.

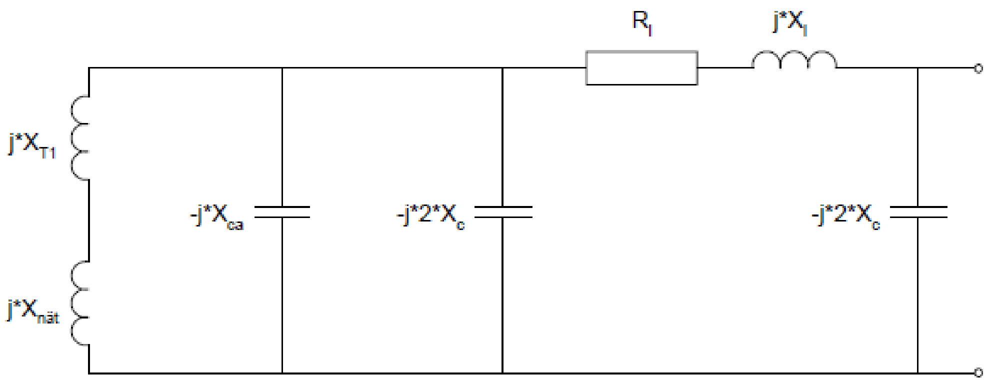

Figure 15. The equivalent circuit of positive and negative sequence networks in case of a single phase earth fault in feeder A [14]

In Figure 15 $X_{nät}$ is the impedance of supply point, X_{T1} is the positive sequence impedance of primary substation, X_{ca} is the positive sequence capacitive reactance of feeder B, X_c is the positive sequence capacitive reactance of feeder A, R_l is the positive sequence resistance of feeder A, X_l is the positive sequence reactance of feeder A.

The zero sequence impedance of the system can be calculated from equivalent circuit presented in Figure 16.

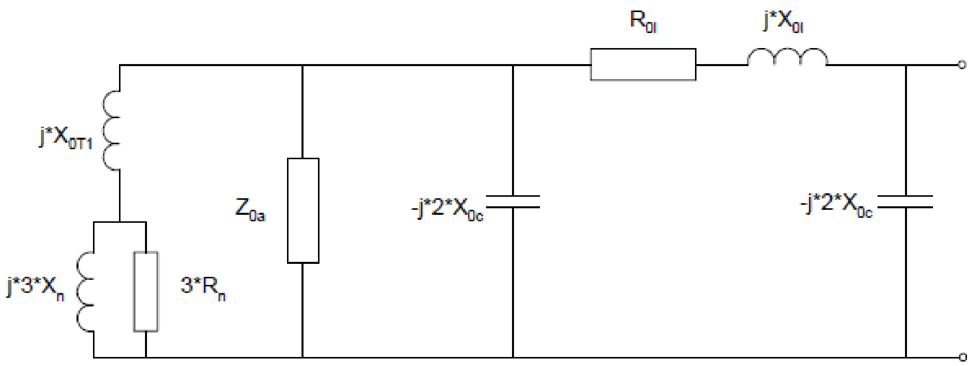

Figure 16. The equivalent circuit of zero sequence network in case of a single phase earth fault in feeder A [14]

In Figure 16 X_n is the reactance in the neutral point, R_n is the resistance in the neutral point, X_{0T1} is the zero sequence reactance of primary transformer or zero point transformer, Z_{0a} is the total zero sequence impedance of feeder B, X_{0c} is the zero sequence capacitive reactance of feeder A, R_{0l} is the zero sequence resistance of feeder A, X_{0l} is the zero sequence inductive reactance of feeder A.

The total zero sequence impedance of feeder B consists of modules, including locally compensated line sections and distributed coils, and pi-sections of lines that are not locally compensated. The impedance of feeder B is presented in Figure 17.

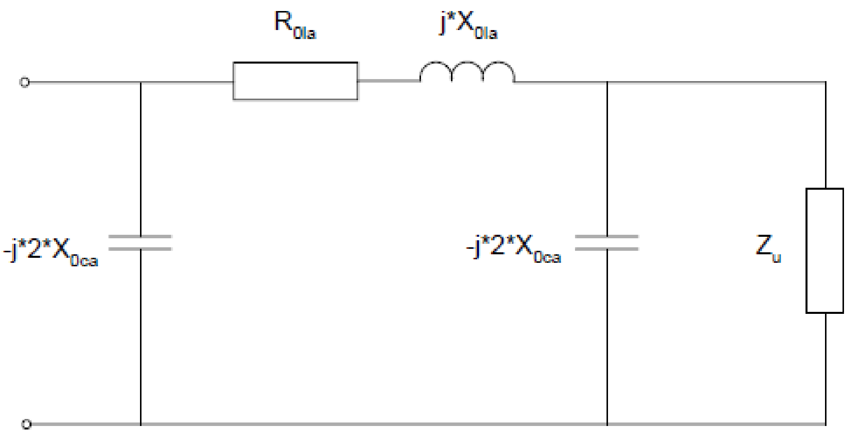

Figure 17. The equivalent circuit for the zero sequence impedance of feeder B. Corresponds Z_{0a} in Figure 16 [14]

In Figure 17 X_{0ca} is the zero sequence capacitive reactance of feeder B before the first cable/distributed coil –module, R_{0la} is the zero sequence resistance and X_{0la} is the zero sequence inductive reactance respectively. Z_u is the zero sequence impedance of cable/distributed coil –module which is presented more detail in Figure 18.

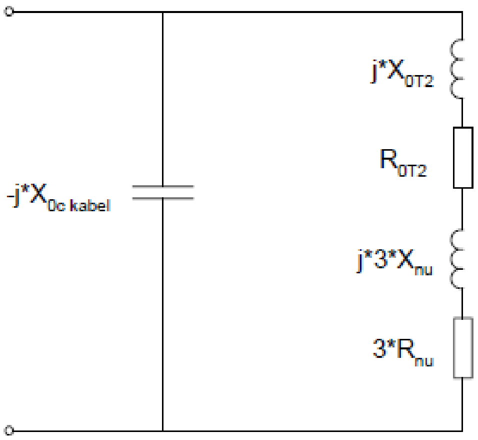

Figure 18. The equivalent circuit of the zero sequence impedance of the module consisting of distributed compensation coil and locally compensated line sections. Circuit corresponds Z_u in Figure 17 [14]

In Figure 18 $X_{0ckabel}$ is the zero sequence capacitive reactance of cable in cable-coil module, X_{0T2} is the zero sequence inductive reactance of zero point transformer, R_{0T2} is the zero sequence resistance of zero point transformer, X_{nu} is the zero sequence inductive reactance of distributed arc suppression coil and R_{nu} is the zero sequence resistance of distributed arc suppression coil. As can be seen in Figure 18 the series impedance of the locally compensated line section is neglected.

In systems that consists of multiple distributed arc suppression coils in the feeder, the total impedance of cable-coil modules is the inductance of parallel connection of those modules. In case the arc suppression coils are similar to each other the total impedance of n modules is Z_u/n.

Based on the theory of sequence network modeling, the voltage over the zero sequence impedance seen from fault place is calculated with equation (20) and the sum of phase currents in fault place is calculated with equation (21). In the equation positive and negative sequence impedances are assumed to be equal, E_1 is assumed to be equal to phase voltage U_{ph} and the fault impedance is assumed to be purely resistive.

$$U_0 = \frac{U_{ph} Z_0}{2Z_1 + Z_0 + 3R_f} \tag{20}$$

$$3I_0 = \frac{\sqrt{3}U}{2Z_1 + Z_0 + 3R_f} \tag{21}$$

Because the series impedances and shunt admittances of zero sequence impedance are not neglected, the displacement voltage seen by a protection relay is not equal to U_0 calculated in equation (20) and the sum current measured by relay is not equal to current calculated with equation (21). This issue can be seen in Figure 19. The $U_{0mät}$ and $3I_{0mät}$ are the quantities measured by the relay.

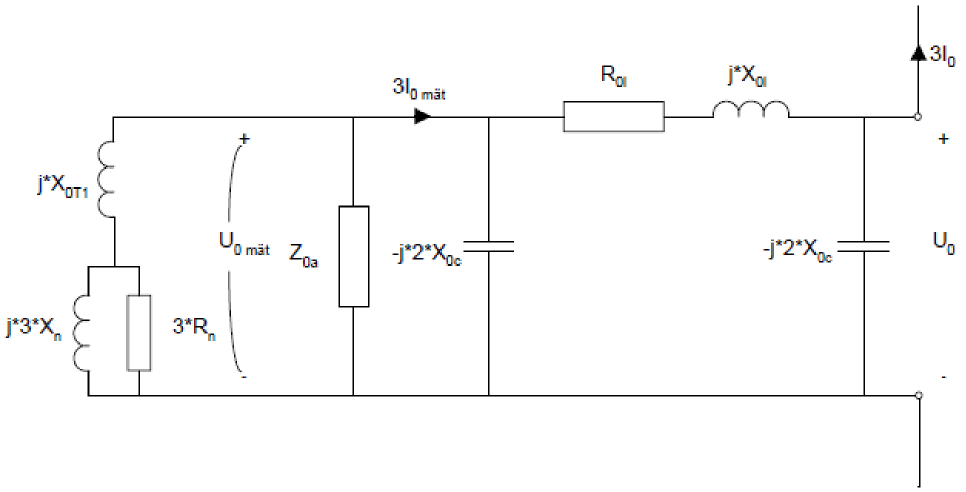

Figure 19. The equivalent circuit of zero sequence network [14]

The sum current measured by the relay can be calculated with equation (22) and the displacement voltage measured by the relay can be calculated with equation (23).

$$3I_{0\,\text{mät}} = I_{13} \frac{-2X_{0c} \cdot i}{-2X_{0c} \cdot i + Z_{na}} \tag{22}$$

$$U_{0\,\text{mät}} = \frac{U_0}{\frac{1}{Z_{na}} + \frac{1}{-2X_{0c} \cdot i} + Z_{na}} \tag{23}$$

In which

$$I_{13} = \ 3I_0 \frac{-2X_{0c} \cdot i}{-2X_{0c} \cdot i + Z_{02}}$$

$$Z_{02} = \ \frac{1}{\frac{1}{Z_{na}} + \frac{1}{-2X_{0c} \cdot i}} + R_{0l} + X_{0l} \cdot i$$

$$Z_{na} = \ \frac{1}{\frac{1}{Z_n} + \frac{1}{Z_{0a}}}$$

In the above equations Z_n is the total impedance consisting of impedance of centralized coil and the zero sequence impedance of transformer.

This method is more accurate way to model the earth fault behavior of system consisting distributed compensation coils and long cables. The effect of coil size, resistive losses and the series impedances of lines are now taken into consideration. It is however hard to accurately define the zero sequence parameters of lines and devices, which makes it hard to model the behavior of the systems accurately. [14]

3. REACTIVE POWER CONTROL

3.1 Objectives of reactive power compensation

Investments of distribution networks are expensive and the lifetimes of network components are long. That is why investments need to be carefully designed to make sure that resources are used effectively. When different network investment plans are compared both technical and economic issues need to be taken into consideration. In this section technical and economic factors that effects on reactive power compensation method are presented.

3.1.1 Power losses

Reactive power is the second component of electrical power. Some loads need reactive power but transferring reactive power causes unnecessary losses in power lines and transformers. Apparent power is the complex sum of reactive and active powers, which is why the excess of reactive power Q increases the demand of apparent power. According to Ohm’s law the power of electric circuit depends on voltage and current. Since the voltage of transmission network is kept constant the current has to grow to enable apparent power to increase. Growth of current causes active losses in lines. Active power losses P_{loss} of a line is calculated using equation (24).

$$P_{Loss} = 3I^2R \tag{24}$$

Where I is the phase current flowing in a transmission line and R is the series resistance of the line. Since the current of transmission line consist of reactive and active components, equation (24) can be derived into equation (25).

$$P_{loss} = \left(\frac{P}{U}\right)^2 R + \left(\frac{Q}{U}\right)^2 X \tag{25}$$

Where X is the series reactance of the transmission line and U is the voltage of the network in examined point. [15]

It can be seen in both equations above that reactive power noticeably effects on the losses of transmission line. As the reactive power increases the current in transmission line, it also reduces the transferring capacity of the line. Transferring capacity of cable is determined by thermal limits. Another concern is the load losses of primary transformer. The losses in primary transformer are also dependent on the apparent power flow.

3.1.2 Voltage rise

Voltage drop along the feeder depends on the line's impedances and the load current flowing through the line. In a single radial lightly loaded circuit homogenously distributed phase to earth capacitance feeds reactive power to circuit and the voltage drop is therefore having a negative value proportional to the square of circuit length. An inductive reactance of power line consumes reactive power and the shunt capacitances of the line generate it. The amount of generated reactive power is proportional to voltage of the line. The amount of consumed reactive power in the series inductive reactance is proportional to the current flowing through the line. The total reactive power generated by three phases can be calculated with equation (26).

$$Q_C = 3{U_{ph}}^2 B \tag{26}$$

Where U_{ph} is the phase voltage and B is the capacitive susceptance of the line. The total amount of reactive power consumed in three phases of power line can be calculated with equation (27).

$$Q_{L,line} = 3I^2 X_{Line} \tag{27}$$

Where I is the current flowing through the line and X_{Line} is the inductive series reactance of the line.

Power line is working on its natural loading if the generated and consumed reactive powers are equal. In this case the power line compensates itself, which means the power line takes no reactive power from elsewhere. Equations (26) and (27) can now set equal as in equation (28).

$$Q_C = Q_{L,line} \Leftrightarrow 3{U_{ph}}^2 B = 3I^2 X_L \Leftrightarrow \frac{{U_{ph}}^2}{I^2} = \frac{X_L}{B} = \frac{L}{C} = {Z_C}^2 \tag{28}$$

Where Z_C is the impedance of the load needed to operate power line on its natural loading. If both side of the equation is squared, it results equation (29).

$$Z_C = \sqrt{\frac{L}{C}} \tag{29}$$

With this load impedance, the power line operates on its natural loading. According to the theory of transmission lines the best transmission condition is achieved in case the impedance of the load equals to the characteristic impedance of the line. This means that Z_C can also be called the characteristic impedance. Z_C is actually a phasor with angle, but in case of lossless line equation (29) is valid and the voltage profile is flat through the line. The surge impedance loading (SIL) is amount of real power that is needed to operate power line in its natural loading. Surge impedance loading can be calculated with equation (30).

$$SIL = \frac{U^2}{Z_C} \tag{30}$$

Surge impedance loading is considerably higher for cables compared with overhead lines because the higher values of capacitance. In distribution network the SIL of the cable is approximately 10 times larger than the SIL of an overhead line [16]. At least in case of transmission network cables the current carrying capacity limits the transferred load before the natural loading is achieved. This is why cables are operated below its SIL and the cables are therefore generating reactive power [17] [16].

3.1.3 Reactive power fee

The power system in Finland consists of power plants, main grid, regional networks, distribution networks, and consumers of energy. Fingrid Oyj is the owner of main grid in Finland. Fingrid is responsible for operation supervision, operation planning, maintenance and development of the main grid and for electricity market development.

Fingrid is attending to the reactive power balance to maintain voltage levels in sustainable level. In order to encourage DSOs to keep the reactive power in limits, Fingrid inherits fees for exceeding reactive power limits. The use of reactive power is monitored preliminary at a regional level. Regions are created from customer's or customers' connection points which are close to each other electrically. When the reactive power limits of a regional monitoring area are exceeded and it disturbs the operation of the main grid, Fingrid has the right to invoice the owner of the connection point. [18]

The output limit of reactive power at the connection point is calculated using formulas (31). The formula that results higher value is chosen to be the output limit on the basis of the calculation.

$$\begin{gathered} Q_S = W_{out} \cdot \frac{0,16}{t_k} + 0,025 \cdot \frac{W_{prod}}{5000} \\ Q_S = W_{out} \cdot \frac{0,16}{t_k} + 0,1 \cdot S_N \end{gathered} \tag{31}$$

Where W_{out} is the output energy (MWh) at the connection point, W_{prod} is the net production (MWh) of the power plant at the connection point, S_N is the apparent power of largest generator at the connection point and t_k is the peak usage time, which is defined for different consumption type. Peak usage times for consumption types are following represented in Table 2.

Table 2. Peak usage times for consumption types [19]

t_k *(h)*	*Consumption type*
7000	Process industries
6000	Other industries
5000	Other consumption

If the largest generator is smaller than 10 MVA W_{prod}= 0 and S_N= 0. 0,1·S_N is however at most 30 MVAr. The input limit of reactive power at the connection point is calculated using the equation (32).

$$Q_{S1} = -0{,}25 \cdot Q_S \tag{32}$$

The reactive power fee consist of usage fee and energy fee. The reactive power fee is determined on the basis of the highest exceeding of the reactive power window in a month. Energy fee is 10 €/MVArh for all reactive power that is supplied or received in/from the area that is exceeding the reactive power window in the month. The reactive power window and the fees to be paid for exceeding the use of reactive power are presented in Figure 20. Fees are calculated using following equations (33), (34) and (35):

- If $P \leq Q_S$ / 0,16 and $Q > Q_S$

$$(Q - Q_S) \cdot 3000\ €/MVAr \tag{33}$$

- If $P \leq Q_S$ / 0,16 and $Q/P > 0{,}16$

$$(Q - 0{,}16 \cdot P) \cdot 3000\ €/MVAr \tag{34}$$

- If $|Q| > |Q_{S1}|$

$$(|Q| - |Q_{S1}|) \cdot 3000\ €/MVAr \tag{35}$$

Q is the reactive power in the high voltage side of connection point in the examination hour. If the reactive power measurement Q_M is in low voltage side $Q = Q_M - Q_L$ where Q_L is the calculated reactive power losses of transformers and branch lines at the connection point. P is measured average power of active power at the connection point during the examination hour.

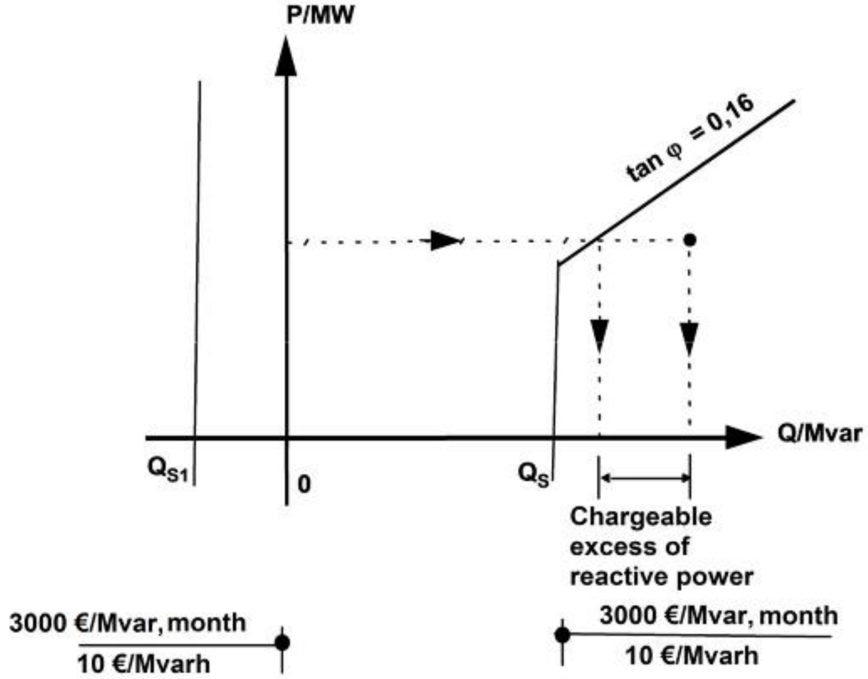

Figure 20. Reactive power window [19]

If the output or input of reactive power exceeds the reactive power window, the reason for exceeding shall be verified before potential invoicing. The exceeding of the window shall not be invoiced if the exceeding is caused by a fault or disturbance in the main grid. If the window have not been exceeded more than 10 hours per month and the output or input reactive power have not exceeded doubly the supply limit, no reactive power fees will be charged for that month. [19]

Reactive power fee contract is at the moment open to interpretation. Fees are not based on real expenses and it has been hard to reveal the source of exceeding reactive power window because there might have been multiple connection points of different DSOs in the same monitoring area. Because the extending use of cable in distribution network effects on reactive power generation, some changes are going to be made in main grid contract. In new contract that will be taking effective in beginning of 2016, reactive power fees are based on real expenses and connection points are going be monitored and charged separately. [20] Reactive power fees will be based on the expenses of investing costs of reactors, capacity that reactive power reserves and maintenance costs of compensators. Reactive energy fee will be based on the losses of compensators and the losses in the feeders caused by reactive power. Costs will also be checked annually. Any official numbers have not been published but in reference [21] new cost for exceeding reactive power fees have been suggested. Suggested fees are

- Reactive power consumption: 1000 €/MVAr, month
- Reactive power production: 1500 €/MVAr, month
- Reactive energy: 5 €/MVArh

Even though fees would be smaller than earlier, since reactive power window will be formed for every connection point, DSOs need to pay more attention on the monitoring of reactive power window to avoid reactive power fees.

3.2 Compensation devices

Preventing unnecessary reactive power flow in network is possible by generating reactive power where it is consumed, or on the contrary, consume reactive power where it is generated. In some countries feeder capacitors are commonly used to generate reactive power for purposes of lines and consumers but in Nordic countries these are rare. Capacitors are mainly located in substations to control reactive power flow through primary transformers to avoid reactive power charges from the transmission system operator (TSO). [22] Contrarily to overhead line network in cable network reactive power needs to be consumed to prevent unnecessary reactive power flow. Reactive power can be consumed with shunt reactors connected parallel to the lines.

3.2.1 Shunt capacitors

Shunt capacitors are used to compensate inductive reactive power. Capacitors are quite common in HV-MV substations that are feeding overhead lines. While cabling of distribution network increases the need for capacitors in substations decreases at least if the loads of substation are easily predictable and load profile is flat. HV shunt capacitor bank consists of multiple parallel and series connected standard sized capacitor banks. Capacitor banks are typically 20 – 50 MVAr in 110 kV networks and 1-5 MVAr in 20 kV networks. Reactive power generated by capacitor can be calculated with equation (36) [15].

$$Q_{cap} = \omega C U^2 = \left(\frac{U}{U_N}\right)^2 Q_N \qquad (36)$$

Where ω is the angular frequency, U_N is the nominal voltage of a capacitor, Q_N is the nominal reactive power of a capacitor and U is the voltage of the network.

As can be seen from equation (36) the reactive power generated by shunt capacitor fluctuates dramatically if voltage decreases. In case of a fault in power system feeder is separated from network. Thus the reactive power of system decreases and reactive power support is needed. While reactive power decreases also the voltage in network decreases. Thus also the reactive power generated by capacitor decreases. Above described scenario is why shunt capacitors poorly fit for reactive power support of power system while fault. [15]

3.2.2 Shunt reactors

Reactors are electrically the opposite of capacitors. Reactors are used to consume reactive power. Reactors can also be used to filter harmonics or to limit current. There are several possible connection choices for reactors used in reactive power compensation: delta-connection, unearthed wye-connection, earthed wye-connection and earthed wye connection with a neutral reactor. [23] The latter is used only in countries where one phase reclosing is used. The purpose of reactor between star point and earth is to compensate the secondary arc current flowing from healthy line to faulted line during earth fault that might prevent the successful reclosing [15].

Delta-connection and unearthed wye-connection can be transformed to each other with wye-delta transformation. These unearthed reactor connections affects only in reactive power of line while reactors with earthed star point compensates also the earth fault current of the system. The reactance of wye connected reactor can be calculated with equation (37) and the reactance of delta connected reactor can be calculated with equation (38).

$$X_{wye} = \frac{{U_N}^2}{S_{R_{3\delta}}} = \frac{{U_N}^2}{3 \cdot S_{R_{1\delta}}} \tag{37}$$

$$X_{delta} = 3 \cdot \frac{{U_N}^2}{S_{R_{3\delta}}} = \frac{{U_N}^2}{S_{R_{1\delta}}} \tag{38}$$

Where U_N is the nominal system voltage, $S_{R_{3\delta}}$ is the rated three-phase reactive power, $S_{R_{1\delta}}$ is the rated reactive power per phase. [23]

Reactive power consumed by shunt reactor can be calculated using equation (27), equation (39) or equation (40):

$$Q = \frac{3{U_{coil}}^2}{X_{ph}} \tag{39}$$

$$Q = \left(\frac{U}{U_N}\right)^2 Q_N \tag{40}$$

Where Q is the reactive power that shunt reactor consumes, U_{coil} is voltage over the each coil, X_{ph} is reactance of individual coil in shunt reactor, U is voltage over shunt reactor and U_N is rated voltage of shunt reactor and Q_N is rated power of reactor.

3.2.3 FACTS devices

In networks where consumption and generation are reasonably predictable and stable, fixed shunt capacitor banks or fixed shunt reactors are used. Reactive power compensation is then accomplished for a specific operation condition only. Mechanical switching of those units offers more flexibility in the system.

In the situation where loads change rapidly, for example in electric arc furnaces, rapid voltage changes can cause disturbances in lightning systems and in other power equipment. In such cases Static Var Compensation (SVC) installations are provided. SVC consists of thyristor controlled reactor in parallel to a fixed capacitor bank. It provides a fast controllable reactive load which responds very quickly to voltage changes. [24] Like an SVC, Static Compensator (STATCOM) instantly and continuously provides variable reactive power in response to voltage transients, supporting the stability of grid voltage. A small STATCOM can also be combined with switched passive elements to more economically have a controllable reactive power compensator. [25]

If very fast and dynamic response is not mandatory, a continuously Variable Shunt Reactor (VSR) may be optimal choice for reactive power compensation. VSRs are favored in networks with distributed generation whose may not always provide full control over their electrical output and in networks with strongly varying loads powered through long overhead lines or cables. As a part of the overall reactive compensation scheme, a continuously VSR may provide reactive power compensation and smooth steady state voltage control in response to the daily load cycle and possible changes in power generation. Because the consumed reactive power of VSRs is not fixed, it offers the ability to adapt to system topology changes. [26]

The adjustability of VSRs power output is obtained via variation of its inductance, which is achieved by adjusting the air gaps of its magnetic circuits. In order to apply the automatic control of the VSR an automatic control device is needed to control the motor drive unit for coil adjustment. For example Trench’s control device is used both in earth fault compensation controller and in VSR reactive power controller that allows remote operation of the VSR by means of digital inputs or via a substation automation and control system. [26]. The compensation ability of different compensation devices in function of voltage is presented in In Figure 21.

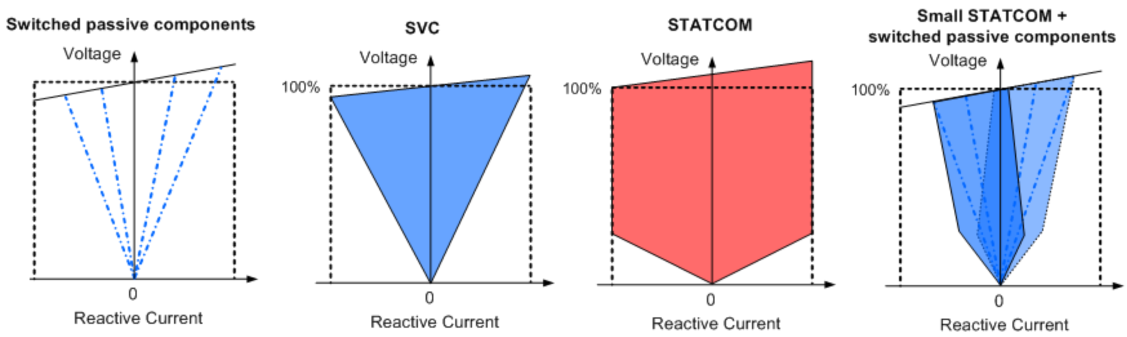

Figure 21 Reactive current versus the connected voltage of different reactive power compensation devices [24]

Reactive power of passive components is dependent on voltage and the reactance of the component, but reactive power of STATCOM and SVC have much larger ability to change the generated reactive power in different voltage conditions.

4. VOLTAGE CONTROL

4.1 Voltage control in a passive distribution networks

The distribution network voltage is kept at an acceptable level to avoid harmful effects to network components and customer devices. Customer equipment is designed for a particular voltage level and too large deviations from the nominal voltage can result in malfunction of the equipment. [1]

In order to maintain allowed voltage level in feeder consisting of consumption, the network is dimensioned and the voltage control is planned is such a way that the minimum customer supply voltage is near the lower limit of the permissible voltage range and the maximum customer supply voltage near the upper limit of the permissible voltage range. To achieve these requirements maximum and minimum loading conditions are examined. Voltage profile of a radial distribution feeder that contains only load is presented in Figure 22.

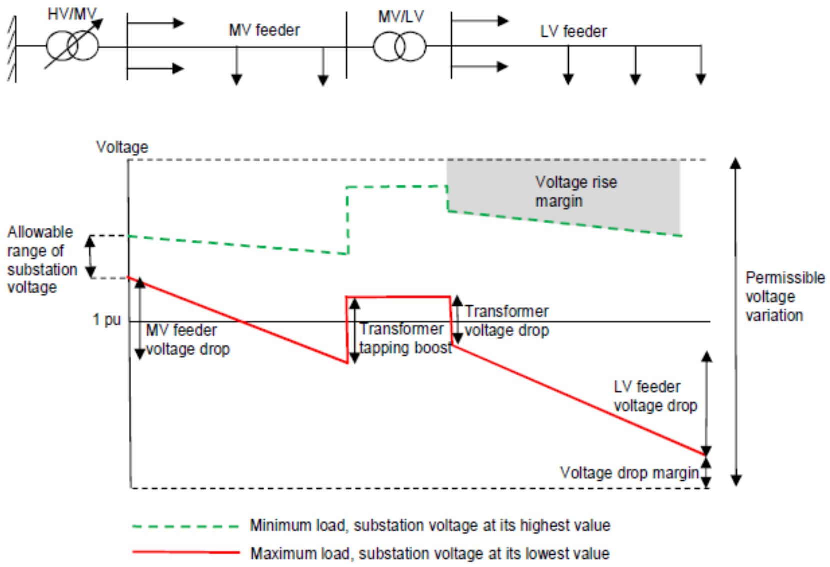

Figure 22. The voltage profile of radial feeder with only load [22] [1]

Usually only the HV-MV substation voltage is automatically controlled and the network is dimensioned so that all network voltages remain in acceptable level despite the changes in loading conditions. Other ways to effect on the voltage in the customer supply points are off-circuit taps of MV-LV transformers, feeder capacitors and line regulators. In Nordic countries feeder capacitors and line regulators are rare. In Nordic countries capacitors are usually connected to substations to avoid reactive power charges from the transmission system operator. [22]

The voltage level in substation is usually adjusted by AVC relay. At the simplest, the AVC relay aims to keep the substation voltage constant. The AVC relay compares the measured substation voltage and the reference voltage. If the reference voltage differs from measured voltage more than the AVC relay dead band, the delay counter is started. The delay counter remains active as long as the measured voltage remains outside the hysteresis limit of the AVC relay. The delay can use definite or inverse time characteristics. Modern AVC relays have a possibility to use line-drop compensation as standard. In line-drop compensation the substation voltage is not kept constant but it depends on the current flowing through the main transformer. The measured substation voltage V_{SS} is replaced with V_{SS} -(R+jX)*I, where (R+jX) is the line impedance between the substation and the load centre which voltage is wanted to kept constant. I is the current of main transformer. [22]

The MV-LV transformers of the have off-circuit taps that can be used to change the winding ratio of the transformers. To change the setting of these taps interruption of electricity supply is needed, which is why their position is decided at the planning stage and kept constant throughout the year. [22]

4.2 Distributed generation in a passive distribution network

In Figure 22 unidirectional power flows have been assumed when voltage control has been planned and, therefore, the margin to the feeder voltage upper limit is relatively small. When generation is connected to network, unidirectional power flow cannot be assumed and the voltage profile of the network can become quite different as presented in Figure 23.

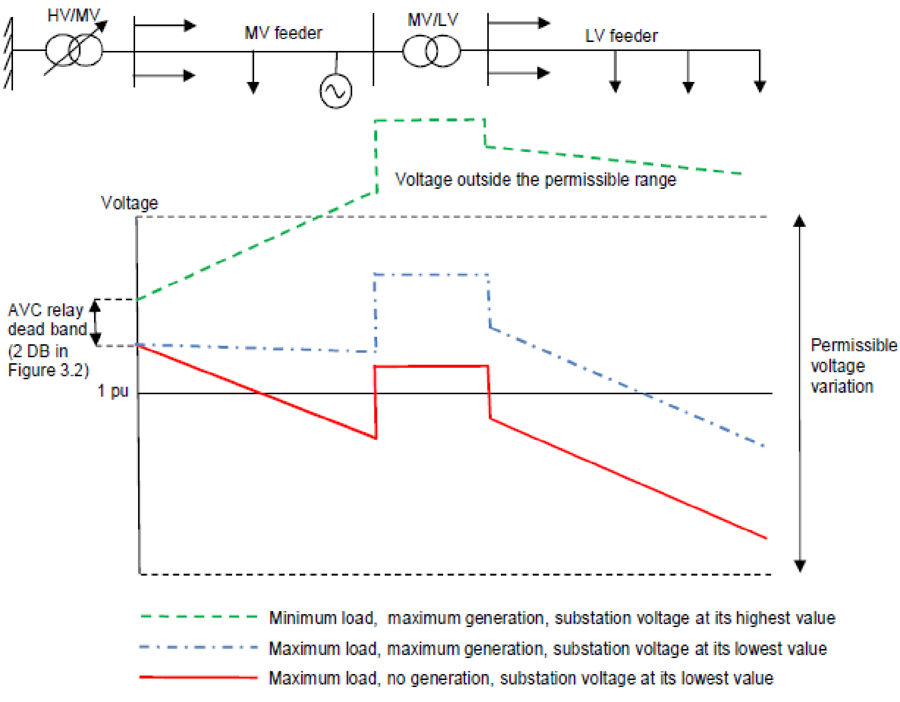

Figure 23. The voltage profile of a radial feeder when also generation is present [22].

When generation is connected on the MV-feeder, the feeder might have sections with both ascending and descending voltage profiles. In maximum loading conditions generation rises the voltage and hence improves the voltage. During minimum loading, maximum generation conditions, the maximum voltage exceeds the feeder voltage upper limit and the voltage performance of the feeder is not acceptable.

At the moment distributed generation (DG) is not allowed to participate in network control in any way. Two extreme loading conditions are considered and if voltage becomes excessive passive methods are used to lower the distribution network maximum voltage to an acceptable level. Usually conductor size is increased or generation is connected on a dedicated feeder. [22]

4.3 Active voltage level management

Voltage rise caused by DG is usually the factor that limits the hosting capacity for DG. The voltage rise can be reduced by decreasing line impedance, by controlling the real and reactive power flows in the network or by adjusting the substation voltage at some point along the feeder. Methods to decrease the maximum supply point voltage is listed in the following:

- Increasing conductor size
- Connecting generation on a dedicated feeder
- Adjusting the off-circuit taps of the MV-LV transformers
- Installing step voltage regulators on feeders
- Reducing substation voltage
- Allowing the generator to absorb reactive power
- Allowing the curtailment of generator real power
- Installing passive or active reactive power compensators on feeders
- Controlling the loads
- Installing energy storages and charging them when voltage rise needs to be mitigated

Coordinated voltage control (CVC) methods determine their control actions based on the state of the whole distribution network and controls the controllable resources to maintain voltages in acceptable limits. The CVC methods can determine their control actions based on control rules or use some kind of optimization algorithm. The import data can be directly measured or state estimation can be utilized. Coordinated voltage control methods could be categorized also based on the control variables they use in the control. The most common control variables are substation voltage and real and reactive powers of DG units. [22]

The optimizing algorithms can be categorized based on the objective function. Possible variables to be minimizes by CVC algorithm are network losses, DG real power curtailment, cost of reactive power control, cost of reactive and real power import from the transmission system, number or cost of tap changer operations and quantities related to voltage quality such as average voltage deviation and maximum voltage deviation. [22]

There are quite big difference in how easily different kinds of active resources can be taken into voltage control use. Production curtailment of DG units can be taken into use relatively easily if equipment needed for remote real power control already exists. However electricity distribution and production are unbundled and the DSO is not responsible for dispatching the DG units. Contracts needs to be made to allow the DSO to control real power of DG units. In case of load control, the equipment to control loads needs to be installed because no such equipment usually exists. Also contracts with customer needs to be done if customer owned resources are used. Also the behavior of the controlled loads needs to be taken into account in the control algorithm. If the controlled load is for example heating load, the temperature of the house needs to be taken into account and, hence load control can continue some limited time. [22] In contractual point of view the easiest way to voltage control is to use DSO owned resources such as tap changer of main transformer and reactive power compensation devices presented in Section 3.

5. MICROSCADA PRO DMS600

5.1 DMS600 Network Editor

DMS600 Network Editor (DMS600 NE) is the network information system (NIS) of MicroSCADA Pro DMS600 product portfolio. DMS600 NE is primarily used to model the distribution network into the network database and to make multiple administrative actions to whole DMS such as management of the integration between MicroSCADA and DMS600. Customer information from the CIS is imported to network database and is also available in DMS600 NE. Network data provides information for network analyses such as load flow with user defined loading level, fault current calculation and protection analysis calculations. [27] In addition to network editing DMS600 NE has also possibility to make network planning. Several extension modules for network asset management and maintenance and condition data collection is available. [28]

5.2 DMS600 Workstation

DMS600 Workstation is a distribution management system of MicroSCADA Pro DMS600 product portfolio. DMS is an intelligent decision support system for distribution network operation and management. DMS is an autonomous part of an integrated system which consists of distribution automation, SCADA, network database system, the geographical and the customer database and telephone answering machine. The DMS includes many intelligent and advanced applications useful for the control center operator to minimize the operation costs subject to the technical constraints. Such applications are maintaining of the switching state through the graphical user-interface, real time network monitoring and sophisticated network calculations based on optimization, short term load forecasting, switching planning, and fault management. [29]

The DMS integrates multiple external traditionally separately worked computer systems into one user interface. SCADA provides connections to the distribution automation systems such as relays, fault detectors, remote controlled circuit breakers and measurements offering real-time information from the process. The network database contains amount of detailed and versatile data on existing network, which can be used in state estimation. Maps offers information on roads and line sections. Customer database is used for modeling the loads and outage costs. Telephone answering machine is used to serve customers' trouble calls. [29]

The DMS offers real-time electrical state of distribution network and it can inform the operator of various abnormalities such as faults, voltage drops and over loadings, and offer proposal of necessary actions. Operator can study real time state of network or investigate network in simulation mode for example to check the adequacy of protection relay configuration in abnormal switching state or to make switching plans for future network repair work. [29]

5.3 Features

5.3.1 Earth fault analysis

In order to plan required earthing equipment and earth fault protection relay configuration DMS600 NE and WS provides a feature that calculates earth fault currents and neutral point displacement voltages in case of a solid and resistive single phase earth faults. Also the protection relay settings, relay configuration check and check of adequate earthing are listed in earth fault calculation result list. The earth fault calculation result list of DMS600 NE is presented in Figure 24. The same list aside from earthing check is available in DMS600 WS. Calculation results available in WS can be used to check if the relay settings are sufficient in current or simulated switching state.

SUBSTATION: HEINÄAHO

Isolated or decentralized compensation.

Fault resistance 500 ohm

********* Primary transformer 2_P_1 (Calculation voltage:20.0 kV) *********

FAULT RESISTANCE	EARTH FAULT CURRENT
0 OHM	12.7 A
500 OHM	11.1 A

Feeder	CONDUCTOR LENGTH IN TYPES				OTHER FAULT		OWN FAULT			SETTING					OPERATING			
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
NAME	TOT	OVERH	ISOL	GROUND	I0	Ires	I0	Ires	U0	U0	I0	P0	Q0	T	SU0	SI0	ST	
	km	km	km	km	A	A	A	A	kV	kV	A	kW	kVAr	s	%	%	%	
KURJENKYLÄ	62.9	58.2	4.7	0.1	3.6	3.1	9.1	8.0	10.1	1.2	2.0	0.0	0.0	0.4	876	399	0	*
AUTIO	8.8	4.6	1.9	2.4	8.8	7.7	3.9	3.4	10.1	1.2	2.0	0.0	0.0	0.4	876	172	0	*
ÄIJÄNNEVA	60.7	56.4	4.2	0.1	-0.1	-0.1	12.8	11.2	10.1	1.2	2.0	0.0	0.0	0.4	876	559	0	*
VIRRAT	9.3	7.7	1.5	0.1	0.8	0.7	11.9	10.4	10.1	1.2	2.0	0.0	0.0	0.4	876	521	0	*
RITARI	38.8	36.0	2.8	0.1	2.3	2.0	10.4	9.1	10.1	1.2	2.0	0.0	0.0	0.7	876	456	0	*

Feeder	GROUNDING RESISTANCE (OHM)		
	A	B	D
KURJENKYLÄ	93	248	62
AUTIO	93	248	62
ÄIJÄNNEVA	93	248	62
VIRRAT	93	248	62
RITARI	70	188	47

Note: Values of the columns 8 and 9 are calculated using Directional angle of the 0°.

Figure 24. The earth fault calculation results of resonant earthed substation Heinäaho.

Earth fault calculation results offer total earth fault current in case of solid and unsolid earth fault and more accurate information for each feeder. Results that are calculated separately for each feeder are the following:

- Total feeder length.
- Ratio of overhead line, isolated line and underground cable.

- Neutral point displacement voltage in substation.
- Residual current seen by protection relay in case the earth fault is in protected feeder.
- Residual current seen by protection relay in case the earth fault is in background feeder.

The total earth capacitance of all feeders is calculated by means of earth capacitance of conductors and conductor lengths of sections in feeders. The internal impedance of Thevenin's source is assumed to be formed merely of the network's earth capacitance. In Section 2.1 the equations of complex earth fault currents and neutral point displacement voltages are presented based on the Thevenin's theorem.

5.3.2 Load modeling

The simulation of different network configurations requires adequate models of loads at MV-LV substation level. In outage planning the forecast are needed for several days and in back-up connection planning even for months. Usually measurement data is available in primary substations or in switching substations but there are multiple load points in the network that needs to be estimated [30]. MicroSCADA Pro DMS600 uses loads curves or Velander formula to estimate loads. Velander formula is used to determine the maximum power of load point. It is also used if only annual energies of consumption points are available. If load curves are used each load point has a load curve based on the type of consumer. One load curve can represent any bounded area, for example an electrical company's network, a factory's or customer's electrical load. User can define different groups for different consumers, for example for agriculture, domestic customer, private services and 2-shift industry. [27] The total load profile of MV-LV substation derives from the sum of customer's load profiles. Similarly the load profile of feeder accumulates from the loads of MV-LV substations in it. In general, power of every load point and distribution transformer is calculated based on summed group energies and load curves of groups.

If the load flow calculation results is wanted to be accurate, it is remarkably important that load curves and annual energies are up to date. Since the AMR measurement and more intelligence devices have increased in networks it is possible to develop more accurate load curves. MicroSCADA Pro DMS600 have a load curve editor for that kind of purposes. User can define load- and deviation curves manually or create even more accurate load curves by importing measurement data. [27]

5.3.3 Load flow calculations

The purpose of load flow calculations is to offer voltage, current and power loss data of every section and node in network. Load flow calculation is done based on the network configuration, network data, load data and measurement data available from SCADA. In DMS600 WS and NE it is possible to study the voltages, loads and current of any line section and it is possible to calculate the load flow summary for any feeder. The user interface of line section's estimated data is presented in Figure 25 and load flow calculation results of feeder Oaks are presented in Figure 26.

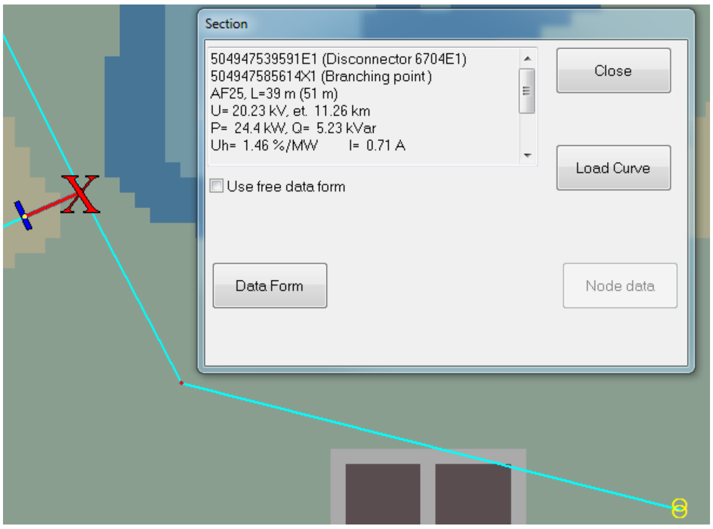

Figure 25. The electrical data of line section. U is the main voltage of node marked with X, et. is the distance from HV-MV substation to node, P and Q are the active and reactive powers, I is the current and Uh is the voltage rigidity.

SUBSTATION: RIVERS
FEEDER: 6 Oaks
Current situation:
Calculated utilization time of power = 3556 h Utilization time of losses = 2023 h
Apparent power = 1607.8 kVA Active power = 1549.5 kW Reactive power = 429.1 KVAr
Power losses = 1.6 kW Loss energy = 3.2 MWh/a
Cost of losses = 774 m.u.

		CONDUCTOR			LOAD					VOLTAGE				TRANSFORMER	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
			km		km	A	%	MW	kW/km	%	%	%/MW	kV	kW	kVAr
1 S	6 E	3743E3	0.01	MA185	0.01	48	17	1.55	0.5	0.00	0.00	0.0	20.50		
2 E	3743E3 X	2626	1.53	AA132	1.54	48	9	1.55	0.7	0.17	0.17	0.1	20.46		
3 X	2626 I		0.30	AA132	1.84	48	9	1.55	0.7	0.03	0.21	0.1	20.46		
4 I	E	3096E1	0.03	MA120	1.87	48	23	1.55	0.8	0.00	0.21	0.1	20.46		

Figure 26. The load flow summary of feeder Oaks in substation RIVERS.

The load flow calculation in radial network differs from calculation of a looped network. Only voltage that load flow calculation has as a parameter is a busbar voltage of HV-MV substation. That is why calculation has to be done iteratively. Basic idea of calculation sequence is following:

1. Calculation is started by assuming that all nodes has some voltage.
2. Based on the load model, load currents of all lines are calculated starting from the farthermost node in radial network.

3. Based on the load currents calculated in step 2 voltages of all nodes are calculated starting from root node of network.
4. The lowest calculated voltage is compared with lowest calculated voltage of previous calculation round or guess made in step 1. If the difference is smaller than 0,03 kV in MV network or smaller than 1 V in LV network calculation is stopped. Alternatively calculation is started from step 2 with voltages calculated in phase 3. [31]

MicroSCADA Pro DMS600 is often getting measurements from SCADA interface. Usually measurements are available from substations including voltage measurement of busbar and current measurements for each feeders. These measurements can be used for improved load estimation. In case the current or power measurements are available, loads can be fitted so that the total load will match to measurement. Same applies with active and reactive power measurements along the feeder. At the moment in version 4.4 FP1 HF1 voltage measurements can be utilized only if those are in HV-MV substation [32].

5.3.4 Volt-VAr Control

ABB has lately introduced a new feature in MicroSCADA Pro DMS600 for coordinated voltage control for medium voltage distribution systems. Volt and VAr control (VVC) is a technology to control the switching of capacitor banks and tap setting of load tap changer transformers and voltage regulators. This feature has two main modes of operation, one for power factor correction (PFC) and other for conservation voltage control (CVR) for demand reduction by lowering voltage level. In both modes voltage violation correction is used to maintain voltage within definable limits. VVC uses linear programming formulation solver to find the optimal switching operations [27].

The power factor correction mode is a technology to maintain the power factor at optimal state in varying loading conditions. Power factor correction is commonly taken as a way of reducing MW losses while it minimizes the reactive power flows. This algorithm calculates the optimal switching of capacitor banks in order to keep the reactive power of defined point at reasonable limit [27]. It is also possible to set a set point for active and reactive power output of distributed generation. Power factor correction mode also keeps voltages within definable limits. User can define the power factor of substation or power factor of single feeder head to be corrected. If the power factor of whole substation is corrected, the reactive power flowing through main transformer will stay at minimum while all controllable objects in network and in substation can be used. If the feeder wise control in used, the power factor of single feeder is corrected in spite of the reactive power flow through main transformer. [27]

Conservation voltage reduction mode control is used for demand reduction by lowering voltage level. Demand reduction can reduce the operation cost of a distribution company by reducing coincident peak capacity payment and defer distribution system capacity expansion [33]. The control objects of this mode are the tap changer of main transformer and voltage regulators within the feeder. Also capacitors can be used in order to compensate reactive power or adjust voltage.

6. FIELD MEASUREMENTS

In order to respond to the technical requirements of extendedly cabled medium voltage network, DSOs have been installing new equipment into medium voltage networks. Such equipment as distributed arc suppression coil with reactive power compensation is still quite rare in Finnish medium voltage networks. One objective of this thesis was to verify the ability of MicroSCADA Pro DMS600 to cope with new components and calculation requirements. The measurements made in Savon Voima Verkko Oy’s medium voltage network are presented in this section.

6.1 Test setup

Test subjects were 3 MV-LV substations with compensation coils and distribution transformers. The nominal apparent power of both distribution transformers and compensation coils were 200 kVAr. Reactors were wye connected and the star points were earthed. There was an isolating switch for disconnecting the compensation coil in the transformer machine. Further technical specification is presented in Appendices 2 and 3. Measurement data was gathered from relay units containing measuring instrument. Measurement devices were located in every MV feeder of the tested MV-LV substations and in HV-MV substation. Test objectives were the following

1. To verify the reactive power behavior of shunt reactor in function of voltage.
2. To survey the effects of distributed reactive power compensation units on total reactive power and voltage profile of feeder.
3. To compare the above-mentioned quantities into DMS estimations.

To examine these quantities tap changer of the main transformer was adjusted so that busbar voltage of the substation changed stepwise from a normal condition into about 21 kV. After couple of minutes voltage was changed to value of 20 kV. At last the voltage was adjusted to be 19 kV. All of these steps were repeated with and without compensation coils.

Tests were performed in substation Lapinlahti, which contains 2 primary transformer PT1 and PT2 both supplying 7 feeders. Test equipments were located at feeder Nerkoo which contained about 41 km of medium voltage network 22.8 km of it cable, 35 MV-LV substations and 180 customers at the occurring switching state. Location of studied MV-LV substations and positive direction of measured power flows are presented in Figure 27.

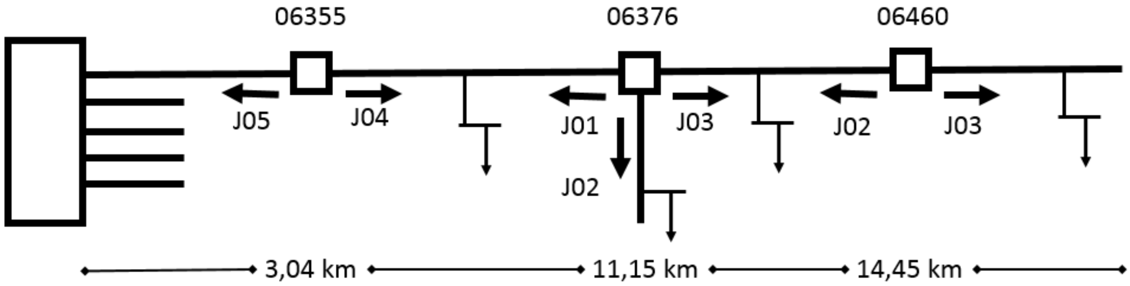

Figure 27 MV-LV substations containing measurement devices and shunt reactors (squares) and the positive direction of measured power flow in MV-LV substations (arrows). Small arrows represents loads along the feeder.

In addition to MV-LV substations presented the Figure 27 there were 32 other MV-LV substations along the inspected feeder. What needs to be noticed is that MV-LV substation 06355 was the first MV-LV substation in the studied feeder, and there were no LV-networks supplied via MV-LV substations 06355 and 06376.

Distributed shunt reactors had been placed so that the first shunt reactor in MV-LV substation 06355 was located 3,04 kilometers from the substation. Second shunt reactor in MV-LV substation 06376 was located 11,15 kilometers from the substation and the last shunt reactor in MV-LV substation 06460 was located 14,45 kilometers from the substation. Shunt reactor in 06376 was located at the branching point of trunk feeder. There is also a long line branch between shunt reactors 06376 and 06460 that explains why these shunt reactors were so close to each other.

6.2 Measurement results

6.2.1 Shunt reactor with earthed wye connection

The effect of voltage to the consumed reactive power of compensation coil was examined by calculating the net reactive power of MV-LV substation. The net reactive power is the sum of measured powers flowing out of the examined substation. Because there was no load in MV-LV substation 06355 during measurements the net powers of substation contains the losses of compensation coil and the no-load losses of distribution transformer. The reactive part of transformer’s no-load losses is much lower than the reactive losses of compensation coil. The total reactive power of the MV-LV substation 06355 during the stepwise voltage changes is presented in Figure 28.

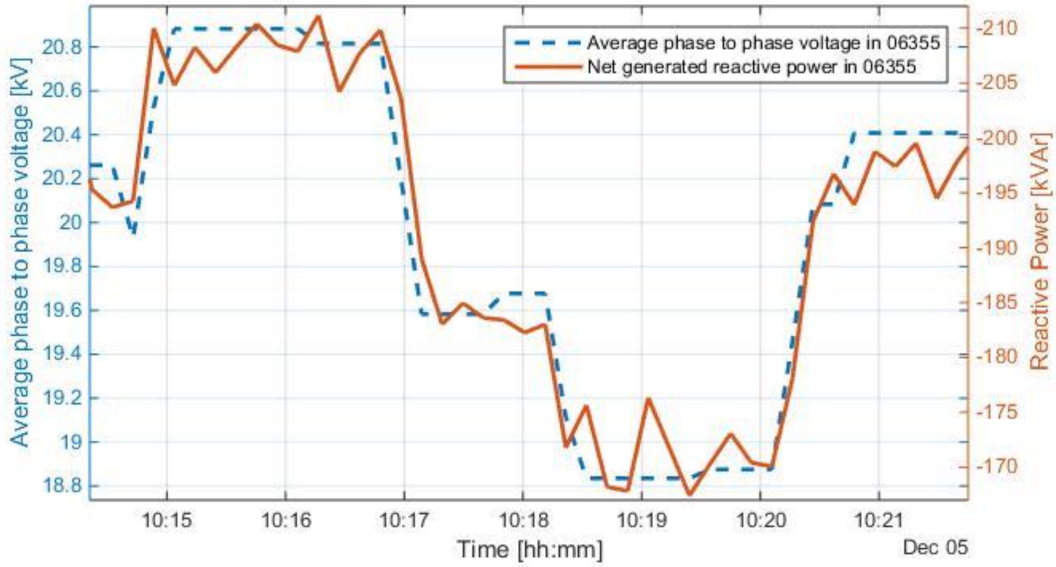

Figure 28 Net reactive power and calculated average phase to phase voltage in MV-LV substation 06355.

The phase to phase voltage in Figure 28 is calculated from the average value of the measured phase to earth voltages in MV-LV substation 06355. Each coil in wye connected shunt reactor consumes reactive power proportional to the voltage between phase and the star point of reactor. Therefore the total reactive power consumed by reactor can be calculated with an equation (39) in which the system voltage is the main voltage calculated from the average value of phase to earth voltages.

6.2.2 Effect of shunt reactors in load flow of feeder

Shunt reactors are used in medium voltage network to compensate the reactive power generated by medium voltage network cables. Measurements were done to examine the effects of distributed shunt reactors on medium voltage reactive power flow and current capacity in stable and in varied voltage conditions.

In Figure 29 the supplied reactive power and the current of the studied feeder are presented while the distributed shunt reactors are disconnected one by one. The upright dashed lines represent the moments when the shunt reactors were disconnected.

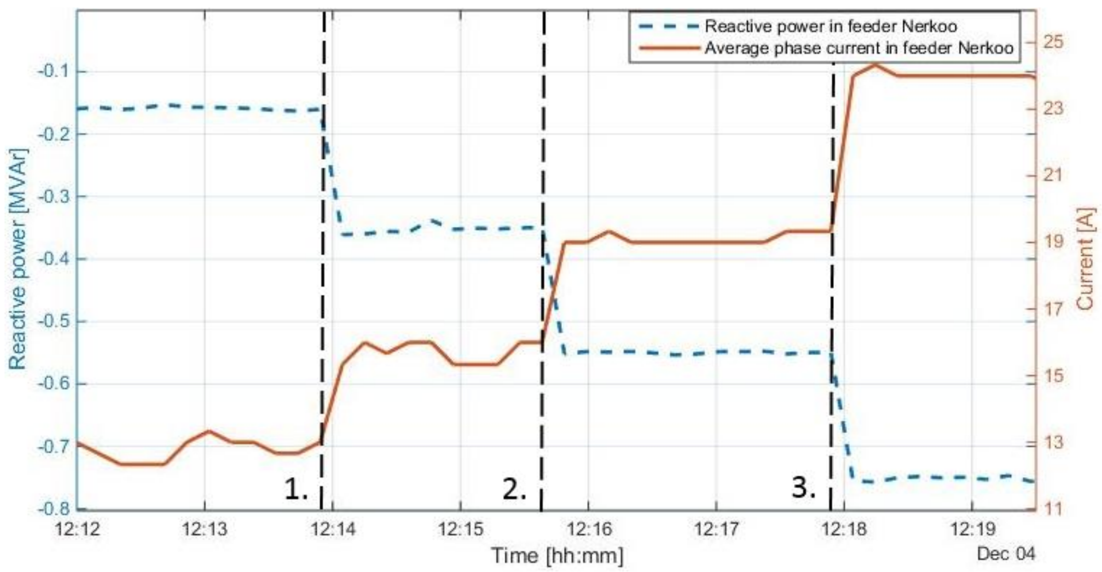

Figure 29. Supplied reactive power and the average phase current of the studied feeder while the distributed shunt reactors are disconnected.

It can be seen from Figure 29 that the distributed shunt reactors have notable effect on the reactive power and the current flowing in the feeder. When the shunt reactors were connected, the lines of the feeder were generating reactive power about 160 kVAr towards transmission network and the average phase current was about 13 amperes. After all three shunt reactors were disconnected, the feeder generated about 600 kVAr more reactive power towards the transmission network and the average phase current was almost doubled to 24 amperes. The growth of the current is an outcome of the increasing transmission of reactive power. The other feeders of substation Lapinlahti were consuming reactive power from 100 kVAr to -100 kVAr. While the distributed shunt reactors were disconnected, all the reactive power generated in feeder Nerkoo was flowing through the primary transformer PT2. The reactive power flow through primary transformer can also be prevented by installing a centralized compensation coil in substation. One benefit of the distributed reactive power compensation is that the current carrying capacity of line is not used for reactive power transportation.

The tap changer of primary transformer was controlled to investigate the effect of voltage change on the reactive power generation of the feeder. Supplied reactive power in the beginning of the inspected feeder and the voltage in the substation are presented in Figure 30 and Figure 31. In Figure 30 the shunt reactors are disconnected and in Figure 31 the shunt reactors are connected. In order to minimize the effect of load variations the measurements were done within a short period of time.

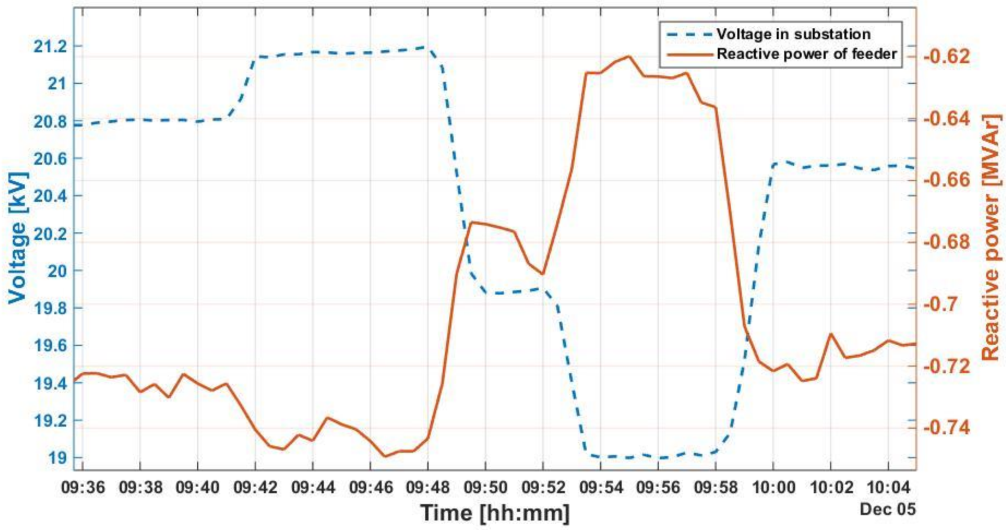

Figure 30. Reactive power and voltage in the beginning of feeder. Distributed shunt reactors are disconnected.

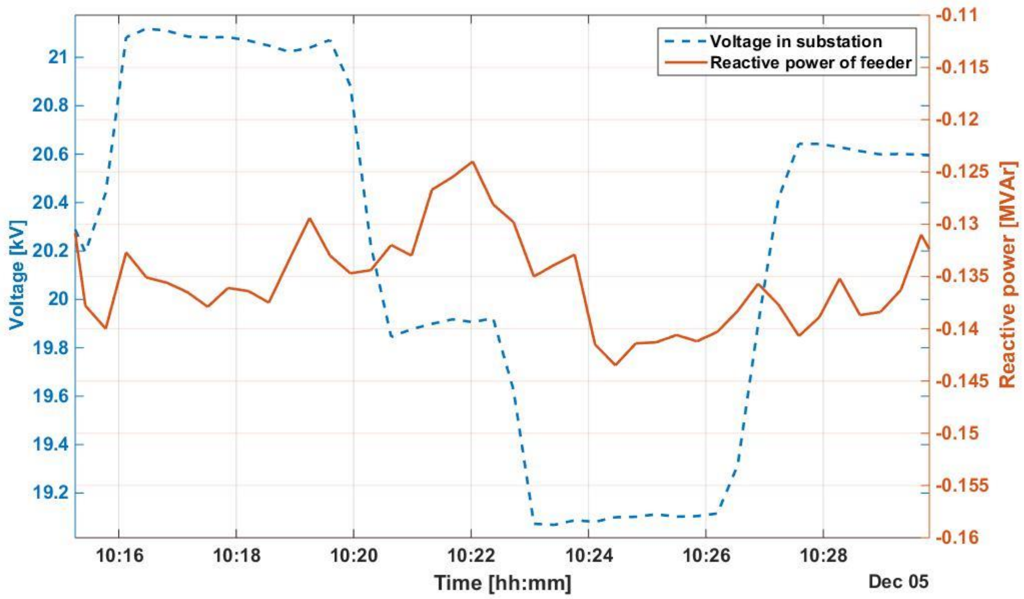

Figure 31. Reactive power and voltage in the beginning of feeder. Distributed shunt reactors are not connected.

It can be seen from figures that the variation in supplied reactive power is more dependent on voltage in system where distributed shunt reactors are not connected. In case the shunt reactors are connected there are no noticeable changes in reactive power while voltage is varied. This is caused by the fact that the reactive power generated by cable is compensated already in the distributed shunt reactors. If the shunt reactors are disconnected, the reactive power generated along the feeder is transported to the beginning of feeder.

6.3 Comparison of measurements and DMS600 calculations

6.3.1 Model of shunt reactors

Tested equipment with an earth fault current compensation capability and a reactive power compensation capability was modeled in MicroSCADA Pro DMS600 before the measurements. The model of the equipment consisting of a distribution transformer and a wye connected shunt reactor with earthed star point is presented in Figure 32.

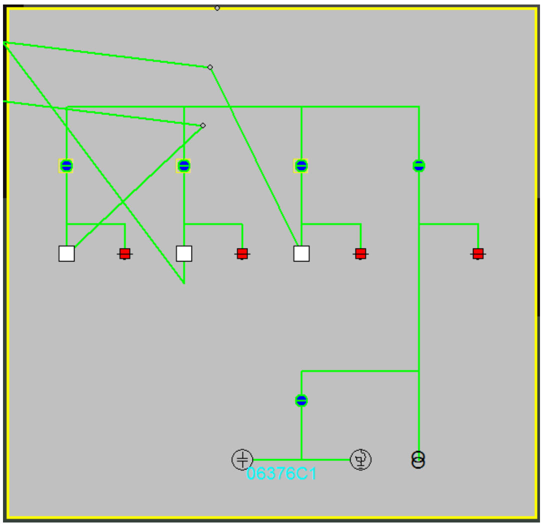

Figure 32. The model of a MV-LV substation consisting of a distribution transformer and a wye connected reactor with earthed star point.

Since there is no possibility in DMS600 to model a shunt reactor, a capacitor was coded to DMS600. The nominal reactive power of the capacitor was set to be negative to represent the consumption of reactive power. In order to model the coil's earth fault current compensation capability an arc suppression coil was coded to the MV-LV substation.

The active power consumed in MV-LV substation 06355 includes the losses of the shunt reactor and the losses of the distribution transformer. The LV-network of the transformer was disconnected so the losses of the transformer were formed merely by the no-load losses of the distribution transformer. The nominal losses of the shunt reactor are 7550 W and no-load losses of the distribution transformer are 405 W, so the losses are mainly generated in the shunt reactor. In order to verify the accuracy of the modeled equipment, calculated and measured reactive and active powers in case of different connection voltages are presented in Figure 33 and in Figure 34.

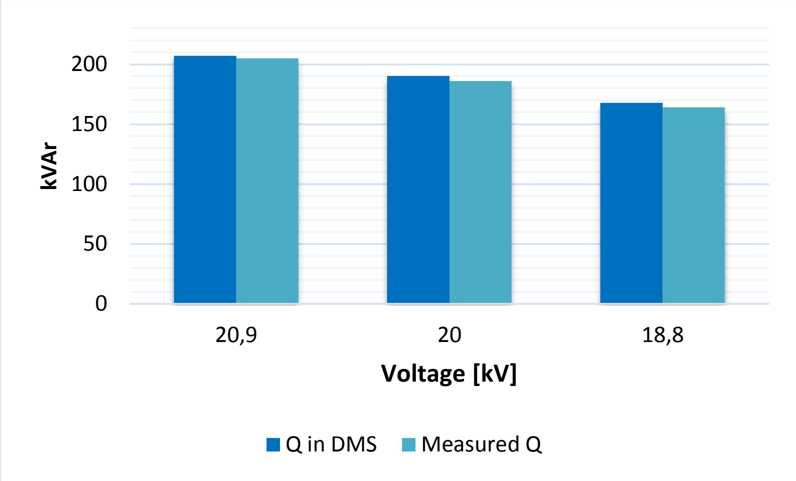

Figure 33. The measured and calculated reactive power values in case of three different voltages affecting over shunt reactor.

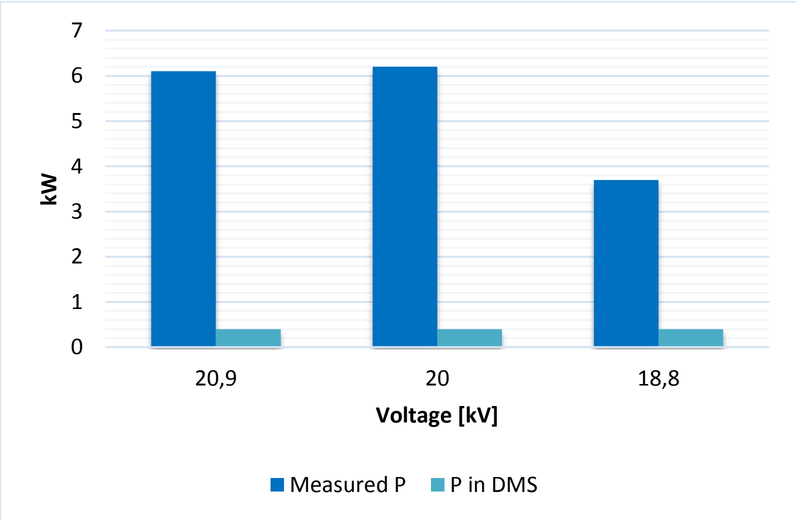

Figure 34. The measured and calculated active power values in case of three different voltages affecting over shunt reactors

It can be seen from Figure 33 that the reactive power is accurately calculated in DMS. In Figure 34 it is shown that the calculated active power remarkably differs from the measured active power. The differences between active powers is mainly due to the losses in shunt reactor. In DMS the reactor is modeled with an ideal capacitor, and the losses of the substation are constant no-load losses of the distribution transformer.

6.3.2 Effect of shunt reactors on voltages along feeder

In order to test the accuracy of state estimation, the measured voltages along the feeder are compared to voltages that are calculated based on estimated loadings. Measured powers along the feeder and in the beginning of the feeder can be used in the DMS's load estimation. Usually only measurements from the beginning of the feeder are used because there are no measurements available from the MV-LV substations. Measured voltages are compared to calculated voltages in two different situation. In the first case the loads are estimated based on the measured powers and the voltage in the beginning of feeder. In second case also measured powers from 3 MV-LV substations along the feeder are used in estimation. The measured voltages along the feeder are compared to calculated voltages during different voltage levels in substation with and without distributed shunt reactors. Results in case the shunt reactors were disconnected are presented in Figure 35. Results in case shunt reactors were connected are presented in Figure 36. In both figures the voltages of three MV-LV substation are presented in case of three voltage level. Clustered column "DMS" represents estimated voltages in case only measured P, Q and V values from substation were used. Clustered column "DMS2" represents calculated voltages in case also measured powers from the MV-LV substations were used. The measured powers from the MV-LV substations along the feeder that were used in estimation are presented in Appendix 4. Measured and estimated voltages are presented in Appendix 5. Estimation tests were done after the real measurements by adding the saved measurement values in each step into DMS-database. The SQL-queries that were used in setting of measurement values are presented in Appendices 6 and 7.

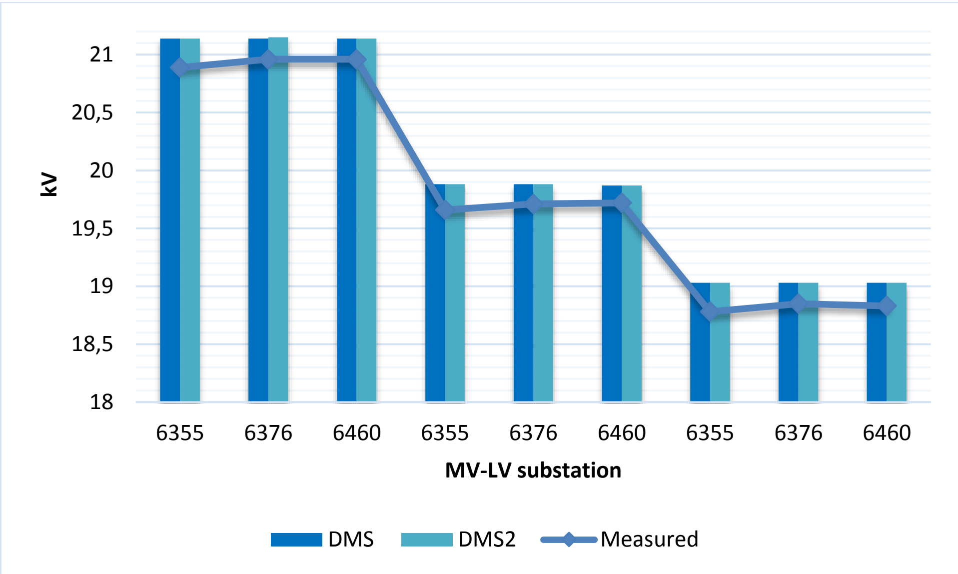

Figure 35. The measured and estimated voltages along inspected feeder in case of different tap changer positions. Shunt reactors are not connected.

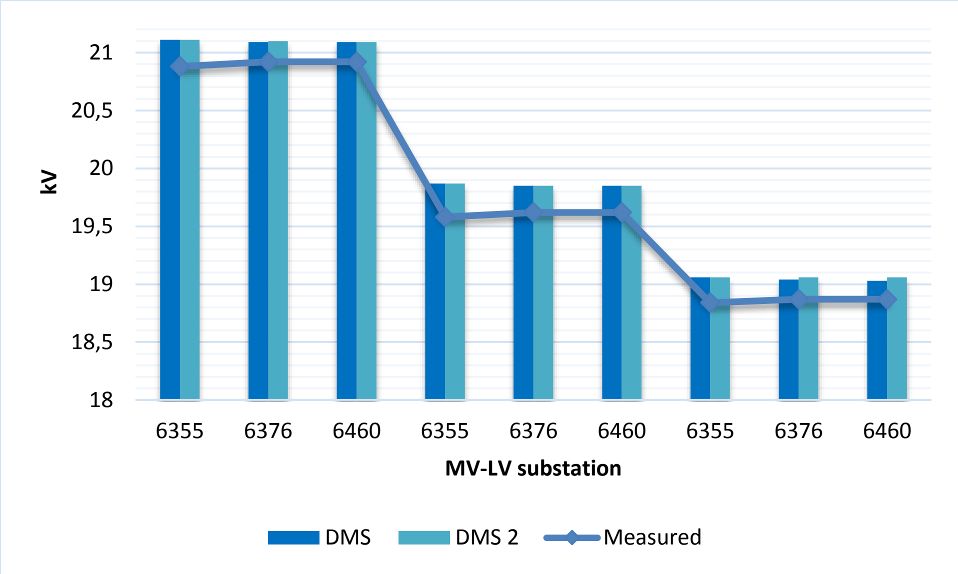

Figure 36. The measured and estimated voltages along inspected feeder in case of different tap changer positions. Shunt reactors are connected.

Calculated voltages are higher than measured voltages in every measurement points. The differences between measured and calculated voltages is in worse case about 200 V. The use of power measurements along the feeder seem not to make the voltage calculation more accurate in this system. The difference remains that big probably because of the other distribution transformers along the line branches without measurements. Also the fact that the load curves were in somewhat different state at the time the test was done than at the time measurements were done makes some error to the test results. The effect of load curves can be assumed small because there are no loads in inspected feeder that would have large variations in consumption.

However there was no load between the HV-MV substation and the MV-LV substation 06355 so it is expected that the voltage of that line section would be accurately calculated. In order to test the DMS's calculation method, the voltage difference occurring in that line section was also calculated with Matlab. The line section was modeled with one pi-section and the receiving end voltage was calculated with the measured sending end voltage and current. The used Matlab-script is presented in Appendix 8. Line parameters used in calculation are presented in Table 3.

Table 3. The parameters of the first line section.

Length [m]	Resistance [Ω/km]	Reactance [Ω/km]	Susceptance [μS/km]
3040	0,125	0,110	94,20

The measured receiving end voltage and voltage calculated with Matlab and DMS are presented in Figure 37. Only case that is above presented in Figure 35 is presented. Shunt reactors are disconnected.

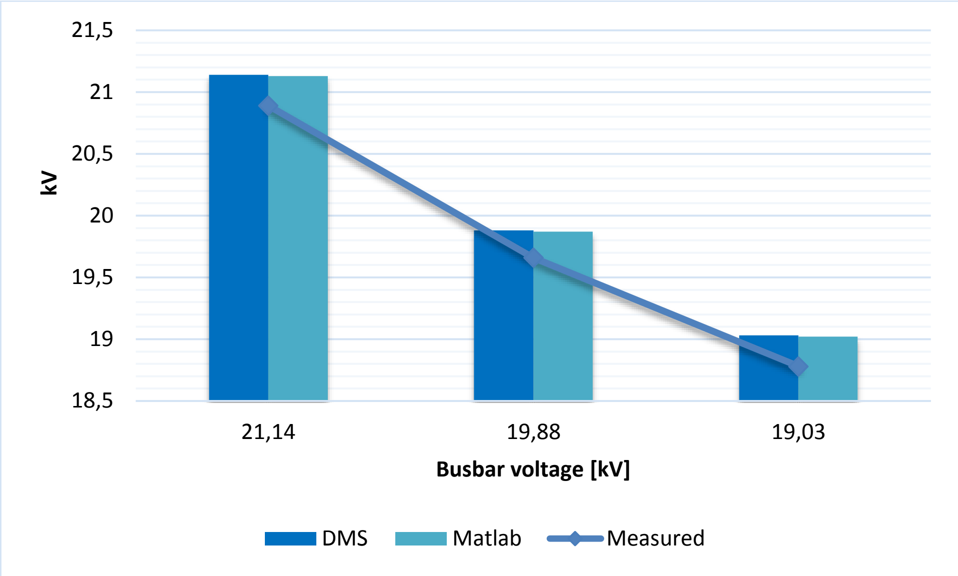

Figure 37. Voltages in 06355. Measured, Matlab (pi-section) and DMS600

It can be seen in Figure 37 that the results of DMS and Matlab pi-section does not differ from each other much. Therefore the differences between the measured and calculated voltages are caused from the improper calculating parameters rather than improper calculation method. The accuracy of voltage measure is ± 0,5 %, the accuracy of reactive power measure is ± 3 %, accuracy of active power measure is ± 1 % and accuracy of current measure is ± 5 % or 1 A [34]. The inaccuracies of measurement values explains part of the differences. One possible reason for differences between calculated and measured voltages might be that the resistance of cable is bigger than resistance used in calculation because there are multiple medium voltage cables close to each other. If the cable warm up it might cause the resistance of the cable to rise. On the basis of ohm's law the voltage drop is higher in lines with higher resistance.

6.4 Development needs to DMS600 based on measurements

As presented in Section 6.3.1 the model of shunt reactor used in pilot study models the reactive power of wye connected shunt reactor with sufficient accuracy. However the active power of shunt reactor is high and the reactor cannot be modeled as an ideal sink of reactive power. Thereby the active losses of shunt reactors needs to be taken into account. In order to make the coding of Dyn11+YN transformer easier, an own component for transformer is needed.

In Section 6.3.2 the measured and the calculated voltages were compared case of two different DMS configuration. It seems that P and Q measurements in 3 MV-LV substations along the feeder did not make the estimation of voltages more accurate but the power flow was divided more accurately between feeder branches. Differences between measured and calculated voltages are not, however, caused by false calculation but more likely caused by inaccuracies in measurements.

7. PSCAD SIMULATIONS

In this section simulations are performed to examine the present DMS version's ability to perform earth fault calculations in extensively cabled distribution network. Basically the accuracy of commonly used conventional earth fault analysis is compared to a more complex analysis method. Simulations are made with a simple network model consisting of shunt reactors and one type of cable. The cable that is used in simulations is AHX-W240. Line parameters are the same that have been used in pilot project of ABB Oy and Savon Voima Verkko Oy. Line parameters are presented in Table 4. Susceptance b have been calculated from the corresponding capacitive reactance values for DMS.

Table 4. AHX-W240 calculation parameters used in simulations

	R [mΩ/m]	*X_l [mΩ/m]*	*X_C [MΩ*m]*	*b [μs/km]*
Pos. sequence	0.139	0.116	10.6	94.340
Zero sequence	0.576	0.221	10.97	91.158

Centralized arc suppression coil is connected to a busbar via an earthing transformer whose calculation parameters for each winding are presented in Table 5. S_n is the nominal apparent power, X_l is the leakage resistance, P_0 is the leakage resistance and P_k is the copper losses of the transformer.

Table 5. The calculation parameters of the centralized coil's zero point transformer

U1/U2	**S_n [kVA]**	**X_l [pu]**	**P_0 [pu]**	**Pk [pu]**
6,83/6,83	300	0,078	0,0011	0,014

Distributed arc suppression coils are modeled as YN coupled coils. The calculation parameters of the shunt reactors are listed in Table 6. U_n is the nominal voltage, Q_n is the nominal compensated reactive power, I_{on} is the nominal compensated earth fault current and R/X is the resistance-reactance ratio of the coil.

Table 6. The calculation parameters of shunt reactor [Appendix 2]

U_n [kV]	**Q_n [kVAr]**	**I_{on} [A]**	**R/X [%]**
20,5	200	16,9	2,5

In earth fault analysis of DMS only the zero sequence susceptance of the line presented in Table 4 and the nominal compensation current of arc suppression coil presented in

Table 6 are used. The zero sequence capacitance is used in conventional earth fault analysis also in [1] p. 62. The calculation voltage in DMS's earth fault analysis is 20 kV so the tap changer in PSCAD model is adjusted to maintain voltage 20 kV in busbar during every network configuration.

7.1 Effect of long cable in earth fault current calculations

In order to study the DMS's ability to model earth faults in network consisting large amount of cable, simulations were made in networks containing different amount of cable. Modeled network contains 5 feeders. 4 of the feeders consists of 5 km AHX-W240 cable. In this simulation case the length of one studied feeder was varied from 5 to 35 km. There were no line branches in the studied feeder nor in the background network. Two simulation cases were studied in every network configuration. In first case a solid earth fault occurred in the beginning of the studied feeder and in second case a solid earth fault occurred in the farthermost node of the studied feeder. It is not, however, possible to define a fault point in DMS so only one situation case was calculated by DMS. In both cases only the centralized coil was used to compensate the earth fault current. The inductance of the centralized coil was adjusted to compensate 90 % of the earth fault in the busbar by using equation (41). The compensation current I_L of an arc suppression coil was set to be 90 % of the earth fault current that flows to the ground in case an earth fault occurred in the beginning of the studied feeder.

$$L = \frac{\frac{U_n}{\sqrt{3}}}{\omega I_L} \tag{41}$$

In the first case the fault occurred in the beginning of the studied feeder. The fault current in the fault place is presented in Figure 38. In figures Ifc is the capacitive part of the fault current, Ifr is the resistive part of the fault current, Iftot is the total fault current, Iftot_DMS is the total fault current calculated by DMS. Ifc2, Ifr2 and Iftot2 are the corresponding quantities in case the fault occurred in the end of the studied feeder. All simulation results are presented in detail in Appendix 9.

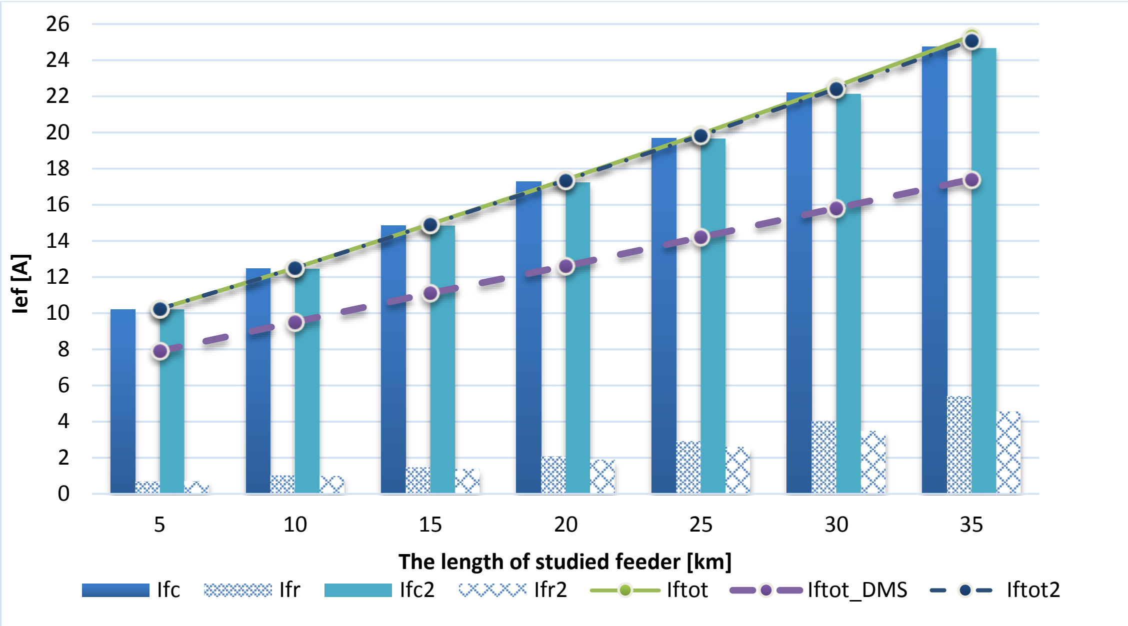

Figure 38. Fault current in fault place. Fault is in the beginning and in the end of the studied feeder. The length of studied feeder is varied.

As expected, the differences between the results of PSCAD and DMS simulations are bigger with longer lines. In case the studied feeder is 5 km long the earth fault current calculated by DMS is about 2 amperes lower than the earth fault current calculated by PSCAD. In case the studied feeder is 35 km long the difference between the results is about 8 amperes. Since the difference becomes larger with longer lines, it can be deduced that different line parameters are used in calculation in PSCAD and DMS. In PSCAD's calculation method both zero sequence and positive sequence parameters effect on the earth fault current. As explained in Section 7, the zero sequence susceptance was set to be the ground susceptance of the line in DMS. Other possible reason for differences is the losses in earthing transformer and other parts of sequence networks. Due to the losses the centralized coil does not produce the inductive current that it adjusted to produce based on equation (41). However, it needs to be noticed that in DMS user can define the compensated current for centralized coil. DMS's calculation method does not take stand on what inductance is needed to achieve that current.

It can also be seen that the resistive part of the fault current increases while the length of the feeder increases. This is caused by the resistive losses of lines, earthing transformer and arc suppression coil. The resistive part of earth fault current reaches maximum value of 5.41 A in case the feeder is 35 km long and the earth fault occurs in the beginning of the feeder. It can also be seen that the total fault current is about the same size independently of the fault place. However the reactive part and resistive part of the fault current are different in different fault places.

In Figure 39 the neutral point displacement voltages are presented. In PSCAD simulation the voltages are calculated from the sum of busbar voltages. In figure U0 is the neutral point displacement voltage in case the fault occurs in the beginning of feeder and U0_DMS is the neutral point displacement voltage calculated by DMS. Coefficient U02 is corresponding quantity in case the fault occurs in the end of studied feeder.

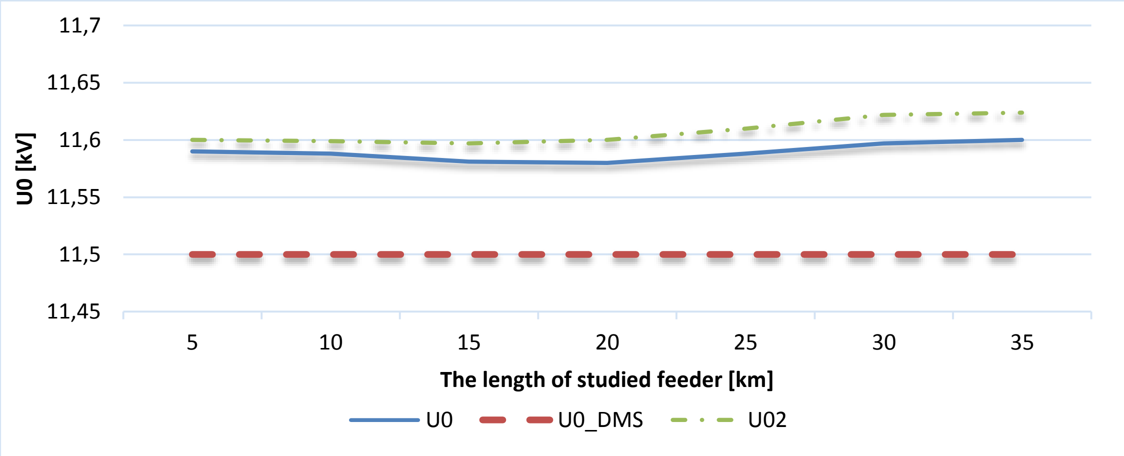

Figure 39. Neutral point displacement voltage. Fault is in the beginning and in the end of studied feeder. The length of studied feeder is varied. Centralized arc suppression coil is adjusted to keep compensation ratio in 90 % in case the fault occurs in the beginning of feeder.

Results indicates that the neutral point displacement voltage calculated by DMS is close to simulated, but the difference between results increases in case of longer lines. The voltage changes while the length of feeder is increased probably due to the bigger effect of series impedances.

The neutral point displacement voltage of this system is higher if the earth fault occurs in the end of the feeder. In multiple papers it have been claimed that the zero sequence series impedance causes the drop in neutral point displacement voltage if the fault occurs in the end of long cable feeder. In this simulation model for example the zero sequence resistance of cable is 0.576 Ω/km, which is very low compared to for example 2,52 Ω/km used in Master of Science thesis of Sami Vehmasvaara [12].

7.2 Effect of distributed compensation in earth fault calculations

In order to study the DMS’s ability to model the earth fault situation in case of different use cases of compensation coils, simulations were made with the same network model used in previous section. The length of the studied feeder is in this simulation case 35 km because this is, based on interviews, probably the longest cabled trunk line in Finnish distribution networks. In this case a solid earth fault occurred in the beginning of the studied feeder. In first simulation case the centralized compensation coil was set to maintain constant compensation degree and the amount of 16,9 A shunt reactors in the system was varied. In second simulation case the centralized compensation coil was not used but the amount of distributed shunt reactors was varied. In both cases the placing of the distributed coils was started from the end of the feeder and those were located in a way that each coil compensates the capacitive earth fault current that the cable around it generated. First 6 coils were placed into the studied feeder. After that coils were placed also in feeders in background feeders. Results of each simulation case is in detail presented in Appendix 9.

7.2.1 Combination of centralized and distributed compensation

Before the simulations the earth fault generated by inspected feeder was calculated by DMS in order to solve how many distributed coils could be installed on that feeder without the feeder to be overcompensated. The inspected feeder generates earth fault current 110,5 A so there could be maximum 110,5 A / 16,9 A = 6.5 local coils. Feeders in background network generates 15,8 A earth fault current, so those would be overcompensated if coil was installed in those feeders. The inductance of the centralized coil is determined by the earth fault current without any compensation. Earth fault current in case of solid earth fault in the beginning of inspected feeder in case of an isolated neutral system is 180,25 A based on PSCAD model and 173,7 A based on DMS model. The inductance L of centralized coil is calculated with equation (41), where U_n is the nominal main voltage, I_L is (180,25 A)*0,9-(n*16,9 A) in PSCAD and (173,7 A)*0,9-(n*16,9 A) in DMS. N is the number of distributed coils in network.

The effect of distributed coils on fault current and neutral point displacement voltages based on PSCAD simulations and DMS calculations are presented in Figure 40, and in Figure 41.

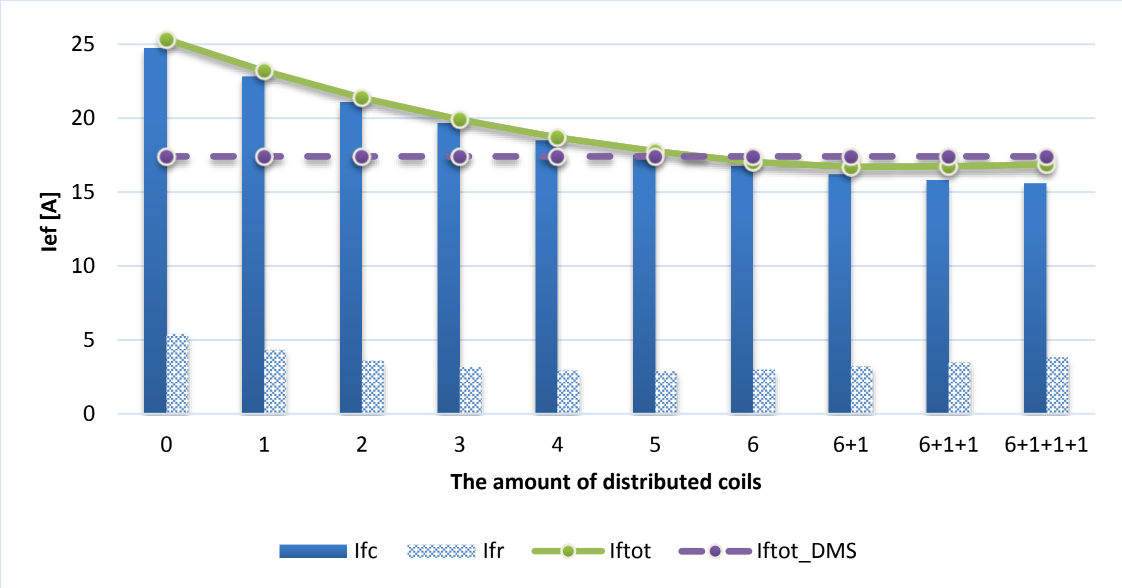

Figure 40. Earth fault current in fault point. Centralized coil is adjusted to keep the compensation degree in 90 % while the amount of distributed coils is varied.

In Figure 40 it can be seen that based on PSCAD simulations the earth fault current decreases while the amount of distributed coils is increased even though the centralized coil is adjusted to keep the compensation rate in a constant value. This is probably due to the smaller effect of system's series reactances when the amount of distributed coils is increased. Also the resistive current component degreases while coils are located in the faulted feeder because of this phenomena. Also the fact that the amount of earth fault current compensated by distributed coil is not always the nominal 16,9 A, effects on the differences between results of PSCAD and DMS. It needs to be noticed that in DMS user can define the compensated current for centralized coil. DMS's calculation method does not take stand on what inductance is needed to achieve that current. However, as expected, the earth fault coefficients go closer to the coefficients calculated based on assumptions while the amount of coils is increased.

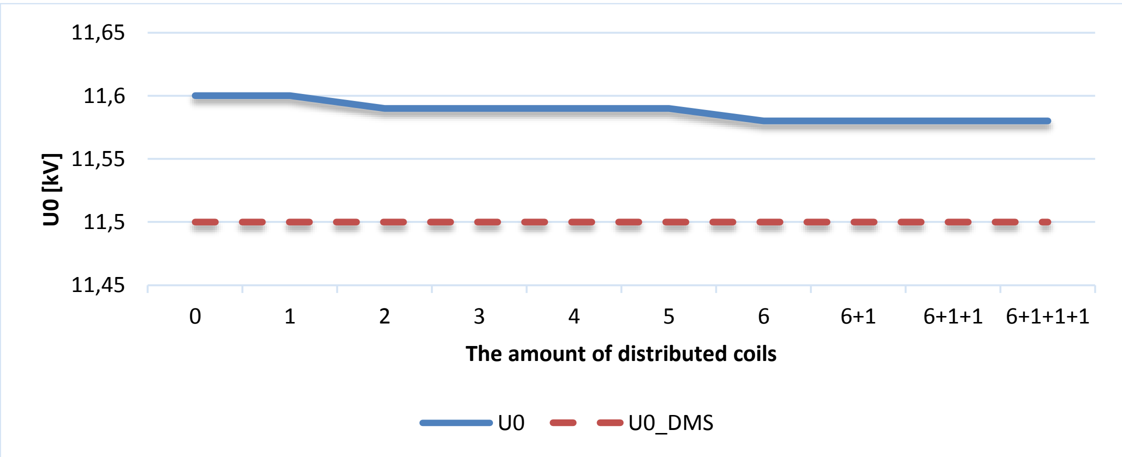

Figure 41. Neutral point displacement voltage. Centralized coil is adjusted to keep the compensation degree in 90 % while the amount of distributed coils is varied.

In Figure 41 it is shown that the increased amount of distributed coils decreases the neutral point displacement voltage. This is probably due to the smaller effect of system's series reactances when the amount of distributed coils is increased. Based on conventional earth fault analysis the neutral point displacement voltage is constant while the compensation degree is constant. The difference between results in this system is in worse case about 100 V and the minimum difference is about 80 V.

7.2.2 Distributed compensation

In second case only distributed compensation coils are used. The earth fault currents and neutral point displacement voltages are simulated in system where the amount of distributed coils is varied. First the studied feeder is almost completely compensated with the local coils and then one compensation coil is placed also in every feeder in background network. The results of simulations are presented in Figure 42 and in Figure 43.

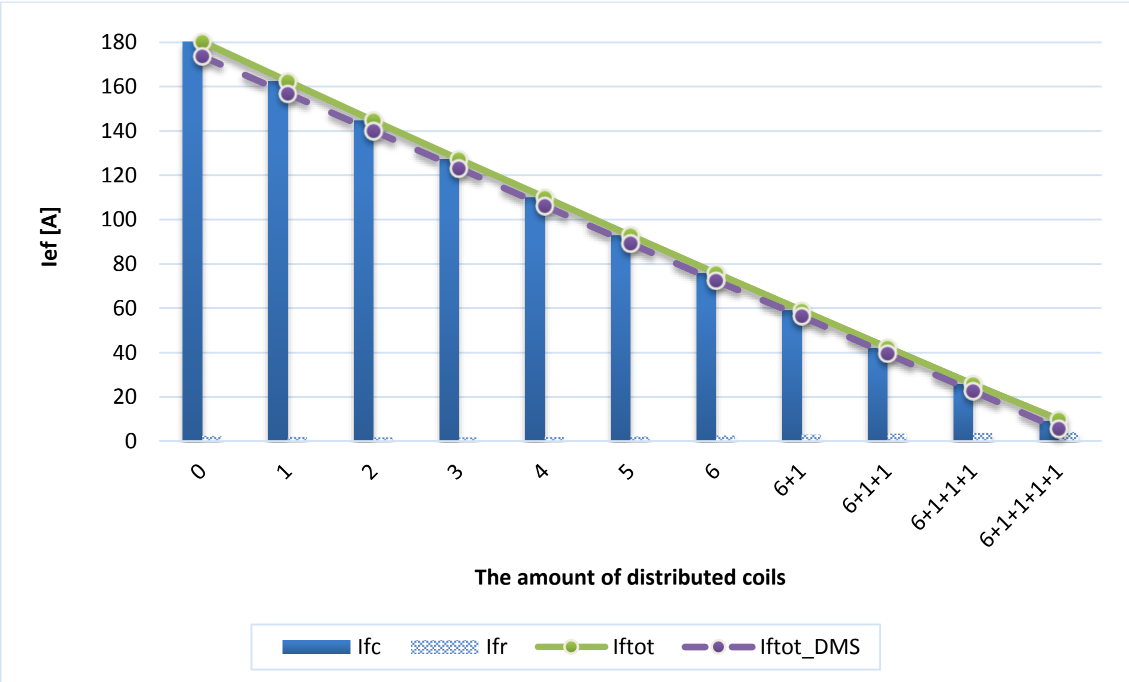

Figure 42. Earth fault current in fault place. Only distributed coils are used.

It can be seen in Figure 42 that the use of distributed coils decreases the amount of earth fault current. There is a small difference between results of PSCAD simulation and DMS, and the difference degreases while use of distributed coils increases. The difference between the results in worse case is 6,55 A and the minimum difference is 2,7 A. The difference between results degreases probably due to the degreasing effect of series impedances while the amount of distributed coils increases.

It can also be seen that the amount of resistive earth fault current starts to grow when the coils are installed in background network. In this case probably the total amount of resistive losses in zero sequence network begins to grow.

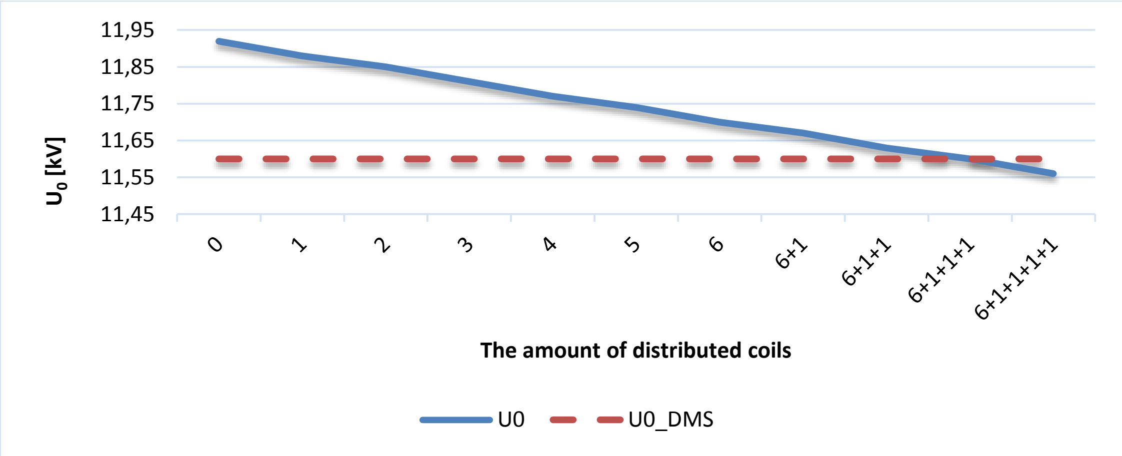

Figure 43. Neutral point displacement voltage. Only distributed coils are used.

Figure 43 shows that there is some difference in the results of the neutral point displacement voltages if only few distributed coils are used. The difference between the results is in worse case about 320 V. Not until the network is almost totally compensated a difference remains between the results. In that case also the PSCAD simulation model acts as conventional earth fault analysis assumes.

7.3 Development needs to DMS600 based on simulations

The earth fault results calculated with the PSCAD simulation model and with the DMS model have some differences. First of all the zero sequence capacitance was used in conventional earth fault analysis, that caused smaller earth fault currents than PSCAD model. Other differences between the results of PSCAD and DMS are caused by simplifications. These simplifications can be made when the earth fault related calculations are made in networks consisting multiple short cable feeders. As it have been presented in previous simulations the calculation results are not accurate in a network consisting long cable feeder. If the results remarkably differs from the values of the real system, false calculation results might cause larger touch voltages and difficulties in detecting earth faults. However there are inaccuracies and simplifications in the PSCAD model that is used in previous simulations. Especially the zero sequence impedance of cable is not known exactly. Therefore, the actual earth fault behavior of cables is not known precisely.

The biggest differences in the calculation results appear in a system with a long cable feeder where the distributed compensation coils are not used. The results would be more accurate if the positive sequence impedance and also the series impedance of zero sequence impedance was taken into account. Also the impedances of the earthing transformer and the resistance of the distributed coils needs to be taken into account to get more accurate results. It might also be useful for DMS user if the resistive and reactive parts of the earth fault current was presented in addition to the total current. In systems consisting of longer cables, whose zero sequence resistance is larger than the resistance used in the previous simulation model, the earth fault quantities might have different results in different fault places. In that case DMS should provide a feature for analyzing earth faults in different fault places.

8. INTERVIEWS

One objective of this thesis was to find the need for improvements in the aspect of medium voltage network cabling. Representatives of 4 distribution system operators were interviewed in order to discuss the problems that large scale medium voltage network cabling causes and to find the development needs to MicroSCADA Pro DMS600 to facilitate their work. In this chapter the DSOs' cabling objectives, compensation strategies and development ideas are presented. Also the feasibility of Volt-VAr Control for Finnish customers is discussed in this section.

8.1 Cabling objectives

In recent years increased long electricity distribution interruptions caused by storms and major weather events had the legislators and Energy Authority to consider tightening and amendment to Electricity Market Act and authority requirements. New Electricity Market Act was given in 9th August 2013 and it came into effect on 1st September 2013. The aim of the law is to improve the reliability of electricity distribution and to reduce the long interruptions caused by major weather events. According to the new law distribution network must be planned, built and maintained so that fault in the distribution networks caused by a storm or snow load doesn't cause an interruption for customers with maximum duration of six hours per occurrence in the town plan area and 36 hours per occurrence in other area. 100 % of DSO's customers must meet the requirements set in article at latest by 31st December 2028 including holiday houses. [28]

Cabling is one way to improve the reliability of distribution because cable is protected from storms and snow loads. In this section the interviewed DSO's cabling objectives and practices are presented.

8.1.1 Elenia Oy

Elenia Oy serves 415 000 customers in its operational area in Tavastia Proper, Päijänne-Tavastia, Tampere region, South Ostrobothnia and Northern Ostrobothnia. [35] Elenia Oy's distribution network consists of 23 000 km of medium voltage line and 40 000 km of low voltage line. [36] Already in 2009 Elenia Oy made a decision that all re-build lines will be constructed underground cable. [35] The cabling goal is to have cabling rate of 70 % in both medium voltage and in low voltage networks. At the moment the cabling rate of medium voltage network is 20 % and the cabling rate of low voltage network is 40 %. To achieve the cabling goal 900 km of medium voltage cable and 1000 km of low voltage cable is installed yearly at least in next years. [36]

Already before the new reliability requirements Elenia Oy studied the fault points saved in DMS to determine the cabling requirements for achieving proper reliability of delivery. The cabling goal 70 % + 70 % was set based on this study. The cabling is not, however, the only way to improve the reliability of delivery. For example automation is in big role since lots of overhead line remains in network. [36]

The main focus of cabling is at the moment in urban area and in rural area trunk cables since it have been proved to be the most cost efficient solution in low loaded rural area networks. Tomi Hakala have studied the issue in his Master of Science thesis, “Prioritization principles for the reinvestment plan of low loaded parts of the rural medium voltage network” [37]. The cabling of trunk cables in rural area network have proved to be a good solution also in practice since Elenia Oy have already cabled a few 30-40 km long trunk cables between rural area substations. Even though faults occur in line branches, those are disconnected from the trunk line and the delivery of the whole feeder is interrupted only a short time. During major storm the cabled trunk line is energized and the faulted branches can be fixed and restored one by one. [36]

8.1.2 Koillis-Satakunnan Sähkö Oy

Koillis-Satakunnan Sähkö Oy provides electricity distribution services in South Ostrobothnia, central Finland and in Tampere region. [38] Distribution network of Koillis-Satakunnan Sähkö Oy consists of 1600 km of medium voltage line and 2300 km of low voltage line. At the moment cabling rate is 3,7 % in medium voltage network and 26 % in low voltage network. [39]

Koillis-Satakunnan Sähkö Oy aims to have 100 % cabling rate in urban network areas to meet the reliability requirements. The total cabling of urban areas networks requires however only about 55 km of additional medium voltage network cabling. Cabling pace in medium network will be about 20 km per year in next two years, but after the urban are have been cabled, it will take a long time to achieve cabling rate of 10 % in medium voltage network. In a low voltage network cabling rate will be increased by 3 percentage unit every year until the cabling rate of 65 – 70 % is achieved. [39]

The main strategy of Koillis-Satakunnan Sähkö Oy for achieving the reliability requirements in rural area network is to move overhead lines close to road. This have been proved to be an efficient solution for avoiding trees falling to lines and for facilitating the clearing of the fault. Cabling of rural area medium voltage networks is not considered to be a good solution because of the following issues:

- Expenses in relation to supplied power
- Slow localization and reparation of a cable fault
- Lack of backup connections

- Soil conditions and waterways

The re-build low voltage network is however decided to build with an underground cable because the low voltage underground cable is usually even more profitable than overhead line. [39]

8.1.3 Leppäkosken Sähkö Oy

Leppäkosken Sähkö Oy operates distribution network in area of Ikaalinen, Jämijärvi, Kihniö, Parkano, Hämeenkyrö and Ylöjärvi. Distribution network consists of 1500 km of medium voltage line and 2800 km of low voltage line. At the moment 9,6 % of medium voltage network and 39 % of low voltage network is cabled. In order to enhance the reliability of delivery Leppäkosken Sähkö Oy pursuits a cabling rate of 40 % in the medium voltage network and cabling rate of 60 % in the low voltage network until year 2028. These goals are achieved by a cabling pace of 34 km per year in the medium voltage network and 45 km per year in the low voltage network. Leppäkosken Sähkö Oy have relatively short feeders compared to rural area networks. When the cabling goals are achieved the longest cabled feeders will consist of 20-30 km cable. The longest rural area feeder consists of 54 km of line, but it will not be cabled. [40]

At the moment 42 % of customers in urban area network and 13 % of customers in rural area network are connected in network that complies with the requirements of maximum interruption time of 6 h in urban area and 36 h in rural area. Underground cabling is not an automatic way to reconstruct an old network. Cable is used in places that it is cost efficient. Among cabling the other ways to improve the reliability of delivery are listed below.

- Maintaining of fault clearance organization
- Backup connections
- Moving overhead lines close to road
- Effective clearing of overhead line routes

There have never been an interruption of delivery in distribution network of Leppäkosken Sähkö Oy that have lasted over 36 h, which is why the effective fault clearance organization is in big role in their strategy. [40]

8.1.4 Savon Voima Verkko Oy

Savon Voima Verkko Oy operates distribution network in eastern Finland. Distribution network consists of about 25 500 km lines and electricity is delivered for over 113 000 consumption points. [41] At the moment there are 11 202 km of medium voltage line and 13 991,5 km of low voltage line in distribution network of Savon Voima Verkko Oy. 5,9 % of the medium voltage network and 27 % of the low voltage network is cabled. The goal is to cable 25 – 30 % of medium voltage network. In 2020 17 % of the medium voltage network will be cabled. Distribution network of Savon Voima Verkko Oy is mainly rural area network. There are 225 meters of lines per one customer in their distribution network, which is significantly more than in urban area networks having only about 20 meters of line per one customer. This is why it is not profitable to invest more in cable.

There will be long cabled feeders in rural area networks. The longest cabled feeder at the moment is the feeder Nerkoo, where the measurements of this thesis were done. The trunk line of Nerkoo is about 14,6 km long and there are lots of line branches.

8.2 Compensation strategies

Increased medium voltage network cabling give rise to earth fault current and reactive power generated in lines. In this section compensation strategies and future plans among these problems of interviewed utilities are presented.

8.2.1 Earth fault current

At the moment networks are used both unearthed and compensated, but the future trend in all interviewed distribution system operators is to have at least centralized arc suppression coil in every substation. Leppäkosken Sähkö Oy have recently installed a centralized compensation coil to all substations. Elenia Oy, Koillis-Satakunnan Sähkö Oy and Savon Voima Verkko Oy will install centralized compensation coil in all substations in near future. Also distributed compensation is already being used in parallel with centralized coil. The combination of centralized and distributed compensation coils is the future solution for the challenges of cable network within all interviewed DSOs' distribution networks. The benefits of this solution are listed below. [40] [39] [36] [42]

- Investing in distributed coils postpones the investing in larger centralized coil. In very large cabled network earth fault current might even be so large that centralized coil with sufficient capacity is not even available. [40] [36] [42]
- Distributed coils decreases the transportation of earth fault current and thus the resistive component of earth fault current. [40] [36] [42]
- Without centralized coil the earth fault current remains too high because the distributed coils cannot be dimensioned optimally for all switching states. [36]
- Without centralized compensation coil resonance circuit might appear that causes unwanted relay tripping. [36]

The increased use of distributed arc suppression coils is somewhat new approach to compensation of earth fault current and hereby causes new concerns to be taken care of in planning and operation of distribution network. The strategy of distributed coil dimensioning in Elenia Oy is that 80 % of earth fault current generated in line section between remote controlled switches is compensated locally, and rest of the earth fault current is compensated with centralized coil. This strategy is set to prevent the overcompensation of individual feeder in any switching state made by remote controlled switches. There remains however possibility of overcompensation if the state of manually operated switches is changed. [36] Overcompensation of feeders is the main concern also in other interviewed utilities. Leppäkosken Sähkö Oy and Savon Voima Verkko Oy are also willing to optimally dimension and place the distributed coil from the aspect of the earth fault current's resistive part. [40]

8.2.2 Reactive power

Increased cabling of medium voltage network increases the reactive power generated in low loaded network. All of the interviewed distribution system operators envisage that the increased cabling raises new requirements for the planning and for the operation of network. The main reason for adjusting reactive power is the reactive power window of Fingrid Oy, because expenses rise quickly if the window is exceeded. Especially if the reactive power of every HV-MV substation is started to monitor separately in the beginning of year 2016, the DSOs need to pay more attention to the reactive power consumption and generation. Since the generated reactive power might exceed the reactive power window during summer nights already in networks consisting of mainly overhead lines, the situation will be more severe in networks that consist of mainly cable.

At present time all of the interviewed utilities have capacitors in some of the HV-MV substations and in switching stations to support the voltage of weak overhead lines [36], to raise voltage during replacement of HV-MV substation [40] or to prevent the reactive power consumption from exceeding the consumption side of the reactive power window. [39]. While the amount of medium voltage cable increases the need for capacitors probably decreases in many situations and the demand for shunt reactor increases. Elenia Oy and Savon Voima Verkko have been testing a few distributed shunt reactors along long cable feeders. Representative of Elenia Oy told that the heating of distributed shunt reactors might cause problems and needs to be taken into consideration. The reactive power compensation strategy of Elenia Oy is that shunt reactors are installed in HV-MV substations and in switching stations because the centralized compensation is the most cost efficient way to compensate reactive power. The strategy is a result of Master science thesis of Sami Vehmasvaara "Compensation strategies in cabled rural networks". [36] Leppäkosken Sähkö Oy have not desided the final compensation strategy, but they see that it might be more cost effective in their network to compensate reactive power with distributed coils. Leppäkosken Sähkö Oy will probably use coils with compensation capabilities of both earth fault current and reactive power. [40] Also Savon Voima Verkko

Oy will use the disttibuted compensation method. The cabling rate of Koillis-Satakunnan Sähkö Oy will be so low that they unlikely invest in shunt reactors. [39]

In addition to shunt reactors and capacitors distribution system operators aim to minimize the transportation of reactive power by charging customers for noticeable consumption or generation of reactive power. Leppäkosken Sähkö Oy and Elenia Oy charges for the use of reactive power but Koillis-Satakunnan Sähkö Oy charges for both generation and consumption of reactive power. The reactive power charge have turned out to be an effective way to encourage customers to instal own compensation devices. [40] [39] [36]

Also distributed energy resources affect in the reactive power flow and in the voltage stability of distribution network. Interviewed DSOs have generation in their network. Koillis-Satakunnan Sähkö Oy has a few hydroelectric power plants of which reactive power generation is being controlled from the control room via SCADA. The reactive power generation of power plants are being controlled to keep the reactive power flow of the system inside the reactive power window. The power plants are however connected to HV-MV substation busbar or there are own feeders without consumpiton for the power plants. Above-mentioned arrangements make the protection analysis and the controlling of voltages in customer supply points easier. [39] Elenia Oy have no planning strategy for distributed generation. Representatives of Elenia Oy envision that the microgeneration connected to low voltage networks is distributed widely and the amount of power plants connected to medium voltage network will not increase since small power plants are not profitable. [36]

8.3 Customer requirements and ideas

In this section the customers' development ideas and needs are presented. The requirements are divided into earth fault current and reactive power –related sections and also the overheating of cable –related concern is introduced.

8.3.1 Earth fault current compensation

As it have been previously mentioned, the use of distributed arc suppression coils is going to increase and the replacement of centralized arc suppression coils is in many cases compulsory since the capacity of old coils is not sufficient. Customers requires tools for planning the optimal location and sizing of arc suppression coils. Also checks and notices made by DMS are required to help the operator in the risk analysis of different network configurations.

8.3.1.1 Calculation of earth fault current caused by multiple network plans

Since the capacities of the presently installed centralized arc suppression coils are not at the moment large enough to compensate the earth fault current of cabled networks, the coils needs to be replaced with bigger ones. [40] Also the strengthening of earthing is planned by the calculations of network information system. [36] Multiple network plans are performed in the same HV-MV substation area and all of them are affecting on the earth fault current of the network. A procedure now for deciding the correct time for coil replace is to separately execute earth fault calculation for each plan and then by hand calculate the total earth fault current in each phase of the cabling process. Network information system should provide a possibility for calculating an earth fault calculation for multiple network plans in the same time. [37] [36] Furthermore NIS could provide the calculation results in each phase of planned network construction process.

8.3.1.2 Calculations to prevent overcompensation of feeder

The placing and sizing of distributed arc suppression coils should be done in a way that an individual feeder stays under compensated in every switching state. This should be done to ensure the correct functioning of conventional earth fault relays. [40] [39] [36] [42] For example in Elenia Oy this requirement is being implemented so that arc suppression coils are being dimensioned to compensate 80 % of the earth fault current generated in the line between each remote controlled switches. The compensation degree of lines is being calculated by hand by dividing the inductive current of local coil with the generated earth fault current of particular line section. [36] Network information system should provide a compensation degree of each feeder in an earth fault results list. This information could also be visualized by colors in network window, which would ease the checking of compensation degree in multiple different network configurations. [36] [40]

8.3.1.3 Support for admittance protection

Some of the interviewed DSOs are willing to invest in a new technology in the area of network protection. For example Savon Voima Verkko Oy requires that the admittance protection would be supported in DMS. In present DMS version only older relay types are supported. DMS should provide a possibility to document relay configuration of the admittance relay and the configuration data should be used to check the performance of relay configuration. [42]

8.3.1.4 More detailed earth fault analysis

As have been presented in Section 2.5.2.1 the use of distributed arc suppression coils decreases the transportation of earth fault current and hence the resistive part of it. Also the neutral point displacement voltage and residual current seen by relay remains somewhat independent on fault location if the distributed coils are placed between optimal intervals. In Elenia Oy the more detailed protection analysis is not being done by the network planners by NIS, but in Leppäkosken Sähkö Oy MicroSCADA Pro DMS600 is being used also for earth fault relay configuration planning. [36] [40] Network information system should provide more detailed information about earth faults. For example resistive and reactive part of residual current and neutral point displacement voltage in case of different fault locations are needed for exact relay configuration and distributed coil placing [40].

8.3.1.5 Notices for operator

Compared to network consisting of mainly overhead lines, more attention needs to be paid in earth fault current issues in cabled networks. In extendedly cabled network the maximum earth fault current generated in feeders varies significantly during switching state changes. In addition, in systems where distributed compensation is used, new issues needs to be taken into consideration.

The increase of earth fault current raises a possibility that the capacity of an automatically controlled centralized coil is not large enough to compensate the earth fault current of a large network. Centralized coils have a controller which knows the current state of coil's reactance. This information is delivered to SCADA and an alarm is added to an alarm list if needed. However the alarm is not being noticed until the coil's state has reached the alarming value. This is why the capacity of compensation coil should be taken into consideration in switching planning mode and warn the switching planner if the maximum limit of compensation coil will be reached. In addition to the notices in switching planning mode, the operator should be warned if the earth fault current is larger than the maximum compensation capacity of the centralized coil in state monitoring mode. This way all information would be available in DMS even if the state of the compensation controller is not available in SCADA. [40] [36]

The use of distributed compensation coils needs to be taken into account also in operation of distribution network. Even though the location and size of distributed coils have been tried to be planned in a way that the feeder would not be overcompensated in any switching state, it is not always possible in a network consisting of multiple switching components. For example in Elenia Oy local compensation is sized to compensate 80 % of the earth fault current generated in lines between two remote-controlled switches. There are however manually-controlled disconnectors in network that may cause the overcompensation of the feeder. DMS should provide information about this kind of situation. Information should be available when switching sequence is planned and also in a state monitoring mode. With the help of information in switching planning the switching planner would be aware of the situation and may decide whether more complex switching sequence is necessary to avoid the overcompensation. In case the abnormal switching state lasts only a short amount of time the overcompensation does not necessarily cause any actions. In case that abnormal switching state will last a long time, further switching is needed. If the overcompensation situation is left in the network for example during major storm, it is important that the switching state will later be fixed to normal. Therefore DMS should provide for example coloring mode that highlights the feeders that are overcompensated. The same visualization could be used that is already described in Section 8.3.1.2. [36]

8.3.2 Reactive power

Extended use of medium voltage cable increases the reactive power generated in distribution network. In order to effectively plan the reactive power compensation and to handle the voltage and reactive power balance, adequate component models and load flow calculations in NIS and DMS are required. What also needs to be taken into consideration in network operation is that the reactive current generated by network might significantly vary if the switching state is changed. In this section requirements for NIS and DMS are presented to support the decision making of DSOs.

8.3.2.1 Modeling of components

The installation of a shunt reactor effects on the load flow of a network and needs to be therefore properly modeled. In addition to static reactors also automatically controlled reactors might be used in the near future [36]. Also a component consisting of distribution transformer and a star connected reactor with an earthable star point will be used in near future in the distribution networks of many DSOs. The latter one needs to be modeled with one component in order to have proper component reports and to avoid unnecessary network coding. What needs to be taken into consideration in the model of this component is that there is a possibility to disconnect the star point and earth. In this case the component operates as a shunt reactor but it does not compensate any earth fault current. The star point might be disconnected in case that cabling process have not been proceeded so far that earth fault current compensation is needed, but the required component is installed in advance [40].

8.3.2.2 Calculation of reactive power caused by multiple network plans

As it have already been explained in case of an earth fault current in Section 8.3.1.1, multiple plans in the MV network of the same HV-MV substation effects also on the reactive power generation of the whole network. A possibility to calculate the reactive power flow of multiple network plans is important because the reactive power flowing through primary transformer causes losses and might exceed the Ingrid's reactive power window. If the effect of multiple plans was calculated, the need for centralized shunt reactor would be easily evaluated in advance. However the generation of reactive power highly depends on the current loading situation, so there should be possibility to calculate the reactive power flow in case of different loadings. [36]

8.3.2.3 Notices for operator

In a network consisting of only overhead lines the major concern in network switching planning have been the voltage drop along the feeders. In case of an extendedly cabled network the voltage rise might be a bigger problem. Also the amount of reactive power transferred through the primary transformer needs to be observed more closely. DMS should provide information to avoid these problems. At the moment in some utilities the Ingrid’s power window is monitored in SCADA. If the reactive power limits were saved to DMS, it would be possible to warn the operator for the exceeding of reactive power window already during switching planning. [36]

8.3.3 Overheating of cable

The cooling time constant of a cable is larger than the cooling time constant of an overhead line, which means that cables cool down more slowly than overhead lines. This phenomena arouses a concern that the cable could heat up during the fault isolating process if multiple test switching are done with a fast sequence before the fault point is isolated. Representatives of PKS Sähkönsiirto Oy proposed that DMS should inform the network operator if there is a possibility of cable overheating. [43]

Also the concern aroused among interviewed representatives that the load current might reach the maximum allowed current in abnormal switching states. Measured currents should be used and an operator should be informed if the maximum loading current of line is reached. [42]

8.4 Feasibility of Volt-VAr Control for Finnish customers

One objective of this thesis was to discuss if the Volt-VAr Control feature of MicroSCADA Pro DMS600 is a considerable solution for the reactive power problems caused by the increased use of MV cable. The conclusions on this section are mainly based on interviews. VVC includes two different operation modes as presented in Section 5.3.4. In power factor correction mode capacitor banks, voltage regulators, on load tap changers and the outputs of power plants are being controlled to maintain the reactive power transportation at minimum state. Conservation voltage reduction can be used to minimize the capacity expansions of distribution system. Power factor correction mode might help the DSOs in the problems caused by the increasing reactive power generation.

Interviewed DSOs have few capacitors in their networks and the capacitors are being used only in exceptional situation. On the contrary the use of compensation coils will increase due to the MV cables and the reactive power window. Among interviewed DSOs Koillis-Satakunnan Sähkö Oy and Elenia Oy prefer the centralized coil to distributed coils. Other interviewed DSOs will probably use distributed compensation coils. In the aspect of VVC it is important to remember that for example Dyn11+YN transformers’ reactive output cannot be adjusted. Those cannot neither be disconnected because there is a normal distribution transformer also behind the transformer's disconnector. However, the centralized shunt reactors can be disconnected. If the use of passive centralized coils will increase, those could be controlled by VVC feature.

There are no voltage regulators in interviewed DSO's networks and tap changers cannot usually be used for reactive power control because it effects on the voltage of the whole network. Usually voltage is close to the minimum allowed level in some point of the network. Therefore, in addition to shunt reactors and capacitors, other possible control variables in the distribution networks of interviewed DSOs are the reactive power outputs of power plants. A small scale distributed generation is not considered a problem among interviewed DSOs but the reactive power outputs of larger generators in medium voltage networks are already controlled among some of the DSOs. The medium voltage power plants in the networks of interviewed DSOs are supplying power directly to HV-MV substations or those are connected to substation via own feeders. This is why the control of reactive power output is not that urgent compared to control in networks where consumption and generation are located in the same feeder. However, reactive power output is being controlled to maintain the reactive power flow between HV and MV networks in sustainable level. The use of VVC feature would facilitate the work of operators especially in systems containing multiple power plants.

Probably the biggest benefit of VVC would be achieved if the actions of VVC feature could be modelled already when a feeder for a new power plants is being planned. In that case there would not necessarily be need for a network that strong and expenses could be minimized. Therefore, NIS should provide a planning tools in which the active voltage control mode is taken into account. Development needs of NIS in the aspect of active voltage control methods have been further investigated in the Doctor of Science Thesis of Anna Kulmala: Active Voltage Control in Distribution Networks Including Distributed Energy Resources [22].

9. RESULTS

9.1 Developed solutions and methods

During the measurements, simulations and interviews multiple development needs for NIS and DMS were brought out. In this chapter the needed methods to achieve the requirements are proposed. At first the new devices and the methods to correctly model the devices' electrical phenomena are presented. After that the solutions to improve the calculation methods of present earth fault analysis feature are presented. At last the methods to develop a more accurate earth fault analysis feature, additional notices and visualizations are presented. Also the outline of the feature for multiple network plan calculations is presented.

9.1.1 New devices

In order to correctly model the earth fault behavior and the load flow of system, the components need to be correctly documented and modelled in DMS's network model. Until now the reactive power compensation have been implemented mainly with capacitors. Therefore there have not been a need for modeling reactors in DMS. Also the components used in earth fault current compensation have not been modelled in detail in DMS. In order to enhance earth fault calculation results, more detailed model of earth fault related components needs to be gathered.

9.1.1.1 Shunt reactor

Shunt reactor is used to compensate the reactive power that lines generate during low load situation. Shunt reactors can be star or delta coupled. The reactive power consumption of reactor depends on the reactance of coils and on the voltage over the coils. Even though the coupling of reactor effects on the power consumption as presented in Section 3.2.2, it is convenient in DMS to calculate the reactive power based on the nominal power and voltage of reactor as presented in equation (40). Based on measurements presented in Section 6.3.1 and interviews presented in Section 8.2, the active power losses of shunt reactors needs to be modelled also.

The connection voltage can be taken by the result of state estimation calculations but the nominal values of reactor needs to be gathered during network coding. It is already possible in present DMS version to code a shunt reactor in DMS network model, but the nominal values are not gathered. The values needed to model a shunt reactor are the following:

- Nominal voltage

- Nominal reactive power
- Active losses

The reactive power of reactor can be modelled using same equations and programming codes that are used in the model of capacitor, which can be seen by comparing equations (36) and (40). Only the direction of reactive power is different. The active power losses of reactor can be assumed to be constant which means that the reactor node acts as a constant active power load.

9.1.1.2 Dyn11+YN transformer

In addition to normal shunt reactors, the use of shunt reactors whose neutral point is earthed is going to increase in distribution networks. The advantages of this equipment are that it contributes to both reactive power and earth fault current compensation. Shunt reactor is built inside the same transformer machine with a normal distribution transformer. If the neutral point of a star connected reactor is not connected to earth, the reactor acts as a shunt reactor described in Section 9.1.1.1. If the neutral point is connected to earth, the device acts also as an arc suppression coil. Distribution transformer works as a normal MV-LV transformer independently from shunt reactor.

The workaround to model Dyn11+YN transformer in present DMS version is described in Section 6.3.1. However the coding of transformer in that way requires extra work from the network documenters. An individual component for this equipment is needed also to maintain the correct component report.

In DMS the Dyn11+YN transformer can be modelled by using the modules of shunt reactor described in Section 9.1.1.1, arc suppression coil and distribution transformer. The different modules of single equipment could be hided from user, or at least the shunt reactor should be visualized in parallel to distribution transformer. The proposed schema for MV-LV substation having Dyn11+YN transformer is presented in Figure 44. The schema should be automatically drawn based on the parameters given in the datasheet of transformer. The outline of transformer datasheet is presented in Figure 45.

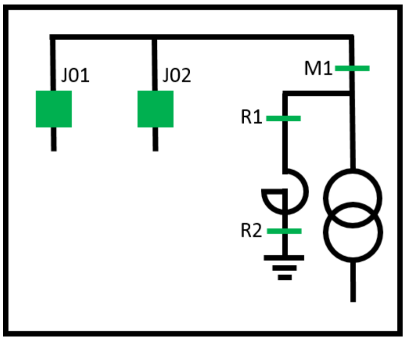

Figure 44. Proposed schema for MV-LV substation consisting of two MV disconnectors J01, J02, distribution transformer and shunt reactor. M1 is the transformer disconnector, R1 is the disconnector for reactor and R2 is the disconnector between Y coupled reactor and earth.

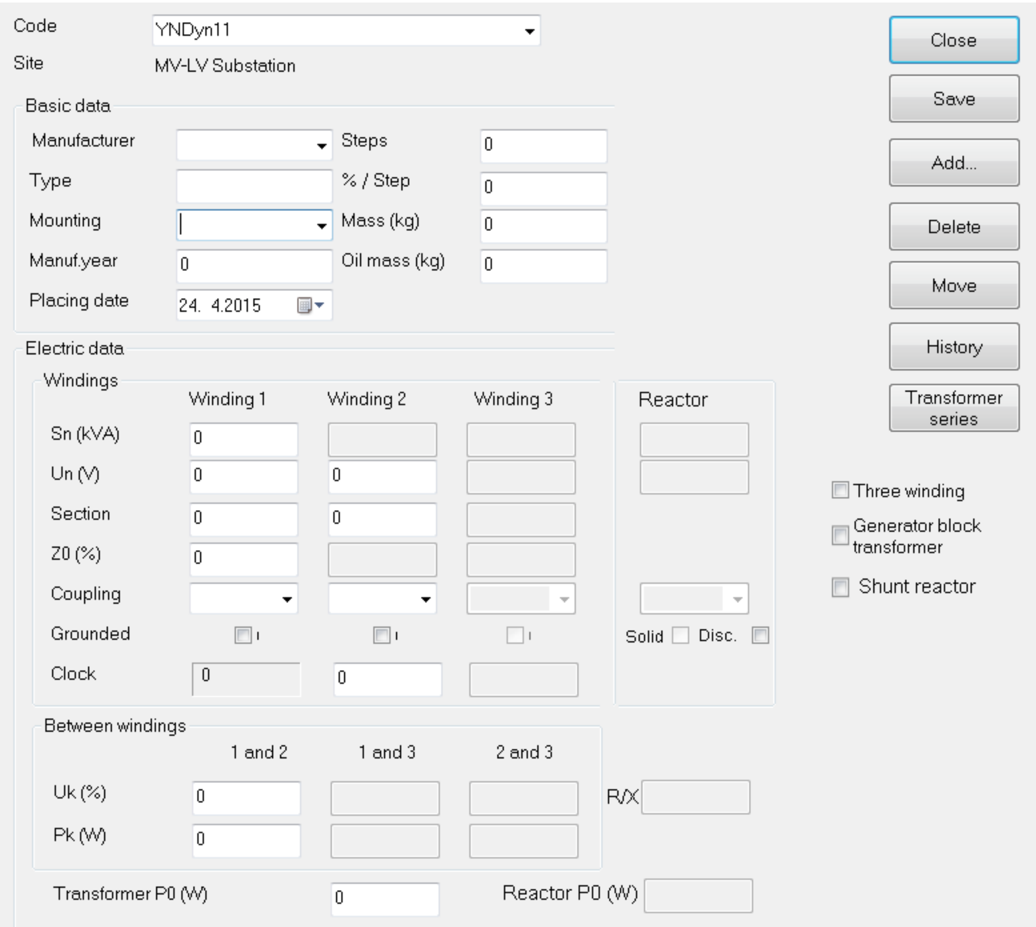

Figure 45. Transformer datasheet with a possibility to document shunt reactor

Shunt reactor is drawn in the substation schema if “Shunt reactor” is selected in the transformer’s datasheet. The disconnector R2 between neutral point and earth shown in Figure 44 is generated if “Disc.” is selected from datasheet. If “solid” is selected, the disconnector is not drawn. R/X value is the ratio of reactor’s resistance and reactance, which can be used in earth fault current calculations described in Section 9.1.6. If the disconnector R2 is open the shunt reactor consumes reactive power but does not effect on earth fault behavior of the system. If the disconnector R2 is closed, the shunt reactor consumes reactive power but also acts as an arc suppression coil during an earth fault.

9.1.1.3 Variable shunt reactor

The use of variable shunt reactors will not remarkably increase among interviewed DSOs, but the representative of Elenia said in interview that VSRs might be one possible solution to maintain reactive power balance in their network. If the prices of VSRs become down also other DSOs might begin to use these devices. VSR is automatically controlled by controller to keep the reactive power consumption at constant value almost independently from the voltage level. VSRs voltage dependency is discussed more in Section 3.2.3.

In DMS VSR could be modelled using the same data that was presented in Section 9.1.1.1. In addition to data used in the passive shunt reactor, also minimum and maximum reactive power limits needs to be documented. Also the configuration of VSR should be documented to predict the behavior of VSR during simulations and switching planning.

9.1.2 Earth fault calculation in case of mixed compensation

During simulations it was noticed that the present version of DMS600 cannot handle all of the needed earth fault current calculations of system consisting of both centralized and distributed compensation coils. At present the earth fault calculation list consist of a total earth fault current, a current generated by feeder and a residual current seen by relay in case the earth fault occurs in the inspected feeder. In the present DMS version the total earth fault current in fault place is calculated correctly, but the residual currents of faulted and healthy feeders are calculated in a wrong way .

The earth fault theory of conventional earth fault analysis in network consisting of centralized and distributed coils is presented in Section 2.3. The residual current of faulted feeder should be calculated with equation (14), which can be derived from Figure 8. Based on the same figure, the equation for residual current of healthy feeder should be calculated with equation (42). L_{Fd} represents the inductance of coils in studied feeder and L is the total inductance of the network.

$$I_r = \frac{\sqrt{1 + (R_L(3\omega C_{Fd} - \frac{1}{\omega L_{Fd}}))^2}}{\sqrt{(R_f + R_L)^2 + (R_f R_L(3\omega C - \frac{1}{\omega L}))^2}} \frac{U}{\sqrt{3}} \tag{42}$$

Applying these corrections the present conventional earth calculation feature would offer good approximation of important earth fault quantities in system where centralized and distributed compensation coils are used at the same time.

9.1.3 Visualization to prevent overcompensation of feeder

In order to support the network planner and operators in handling of distributed arc suppression coils, NIS and DMS should provide information from the compensation rate of feeders. As presented in Section 8.2.1 DSOs plan the location of distributed coils in a way that the individual feeder does not become overcompensated in any normal switching state. DMS should provide information in earth fault calculation list and in network view by colors. A proposed visualization concept for compensation degree is presented in Figure 46. In figure A the compensation rate is below 100 %. In figure B the feeder is overcompensated because only a short line section and a second distributed coil are connected to the feeder.

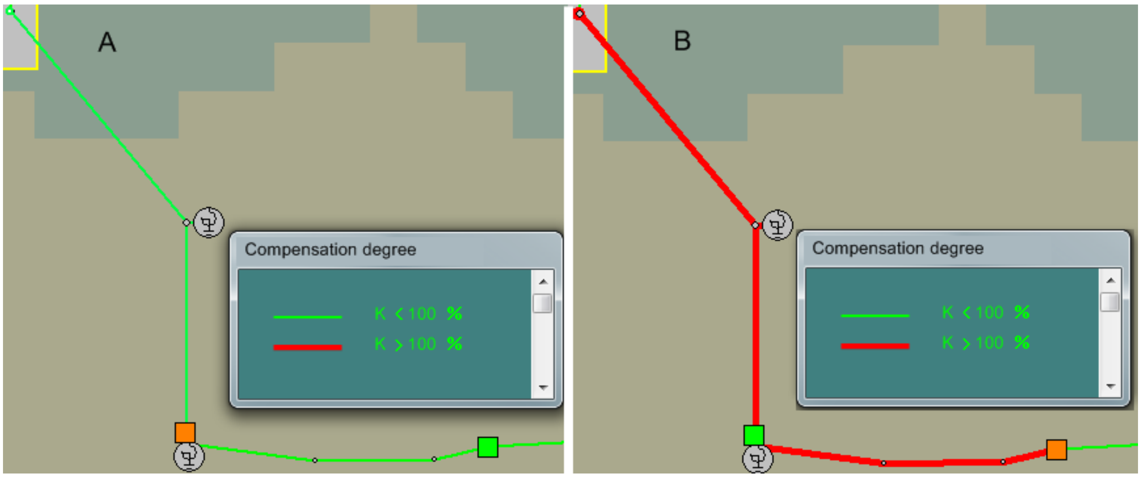

Figure 46. Visualization concept for the compensation degree of feeders. A: There is only one coil in the feeder. Feeder generates more earth fault current than local coil compensates -> K < 100 %. B: There are two coils in the short feeder -> K > 100 %.

With this visualization concept network planner could easily check that the feeder will not be overcompensated in any possible switching state. This visualization would also help network operator to prevent the overcompensation during switching operations and to correct the switching state for example after major storm.

In addition to visualization, the compensation capacity generated by distributed coils and centralized coils should be calculated in the earth fault calculation list. This way the compensation degree of feeders would be available in earth fault report and the capacity of centralized compensation coil would be easily monitored. The proposed earth fault result list with above mentioned corrections is presented in Figure 47.

Centralized compensation + Distributed compensation
Capacity: Centralized 180 A, Distributed 84,5 A, Total 264,5 A
Shunt resistance 2150 ohm
Automatic 95 %

********* Primary transformer TR (Calculation voltage:20.0 kV) *********

FAULT RESISTANCE EARTH FAULT CURRENT

Current state:	
500 OHM	11,2 A
0 OHM	34,0 A
Isolated:	
500 OHM	78,0 A
0 OHM	116 A

COMPENSATION CAPACITY USED:
Total: 43,8 %
Centralized: 17,5 %

Feeder	CONDUCTOR LENGTH IN TYPES						DISTR. COMP. DEGREE	OTHER FAULT		OWN FAULT		
NAME	TOT	Ovrh	CovO	OCbl	UGCbl	SMCbl	Ic/ILd	I0	Ires	I0	Ires	U0
	km	km	km	km	km	km	%	A	A	A	A	kV
Winchester	10.5	7.9	0.0	1.5	1.1	0.0	60	4.1	4.1	5.4	5.6	11.5
Wilbur	63.7	63.3	0.0	0.4	0.0	0.0	40	3.4	3.4	5.4	5.6	11.5
Roseburg	2.9	1.2	0.0	1.7	0.0	0.0	0	0.3	0.3	5.4	5.7	11.5
Cleveland	29.0	25.6	0.0	0.0	3.2	0.0	80	11.1	11.1	5.3	5.5	11.5
Oaks	2.4	1.8	0.0	0.0	0.5	0.0	0	1.9	1.9	5.4	5.7	11.5
Wardton	0.0	0.0	0.0	0.0	0.0	0.0	0	0.1	0.1	5.4	5.7	11.5

Figure 47. Proposed earth fault result list with an additional information. Figure is for demonstration use only. Results are not valid.

In case of a system presented in figure mixed compensation is used. The maximum compensation current of centralized compensation coil is 180 A, and the sum of nominal currents of distributed coils is 264,5 A. The centralized coil is set to keep compensation degree in 95 %. Earth fault currents are calculated in case of the present compensation equipment and in case of isolated system. From these results also a used compensation capacity is calculated. The total used compensation capacity is calculated with equation 100 % * (116 A / 264,5 A) = 43,8 % and the used capacity of centralized coil is calculated with equation 100 % * ((116 A – 84,5 A) / 180 A) = 17,5 %. Also a column “DISTR. COMP. DEGREE” have been added into the list of feeder’s results. It can be seen that for example 80 % of earth fault current generated by feeder Cleveland is compensated with distributed coils.

9.1.4 Notices and events

One main function of DMS is to give notices for user to prevent the operations that might cause for example unwanted relay tripping or danger. Both earth fault current and reactive power generation might change noticeably when the switching state of cabled network is changed. Already in present version of DMS multiple checks are done during switching planning mode. For example breaking capacity of circuit breakers is checked. The additional check that should be done during switching planning are the following:

- Capacity of centralized compensation coil
- Overcompensation of feeder
- Exceeding of reactive power window

Capacity of centralized compensation coil needs to be checked every time the amount of generated earth fault current changes. If the total earth fault current exceeds the maximum current of coil, a warning should be given. Also the distributed coils needs to be taken into account.

During switching planning overcompensation of feeders should be checked and noticed every time switching is done. Check should work in the same way than the visualization described in Section 9.1.3.

Exceeding of the reactive power window might cause expenses rather quickly. DMS should check if the reactive power transferred to transmission network is larger than a defined limit. The generated reactive power depends on the current loading situation and is thus difficult to accurately forecast. However, the forecasted loads and conductor data can be used to estimate the generated reactive power during the hour the switching is planned to be executed. In order to enable the described notice, reactive power limits for each connection points needs to be defined for example in the datasheet of feeding points in HV-MV substations.

9.1.5 Calculation of multiple plans

DSOs have multiple ongoing network plans, for example cabling projects, in the area of same HV-MV substation. Because the cabling significantly changes the reactive power and earth fault current generation, DSOs need to invest in shunt reactors and arc suppression coils. The need and size of investments depend on the total reactive power or earth fault current of HV-MV substation. It is possible in present DMS600 NE version to execute load flow and earth fault analysis only for one plan at the time. It should be possible to select network plans from the area of same HV-MV substation whose mutual reactive power and earth fault results would be calculated at the same time. The proposed calculation result list is presented in Figure 48.

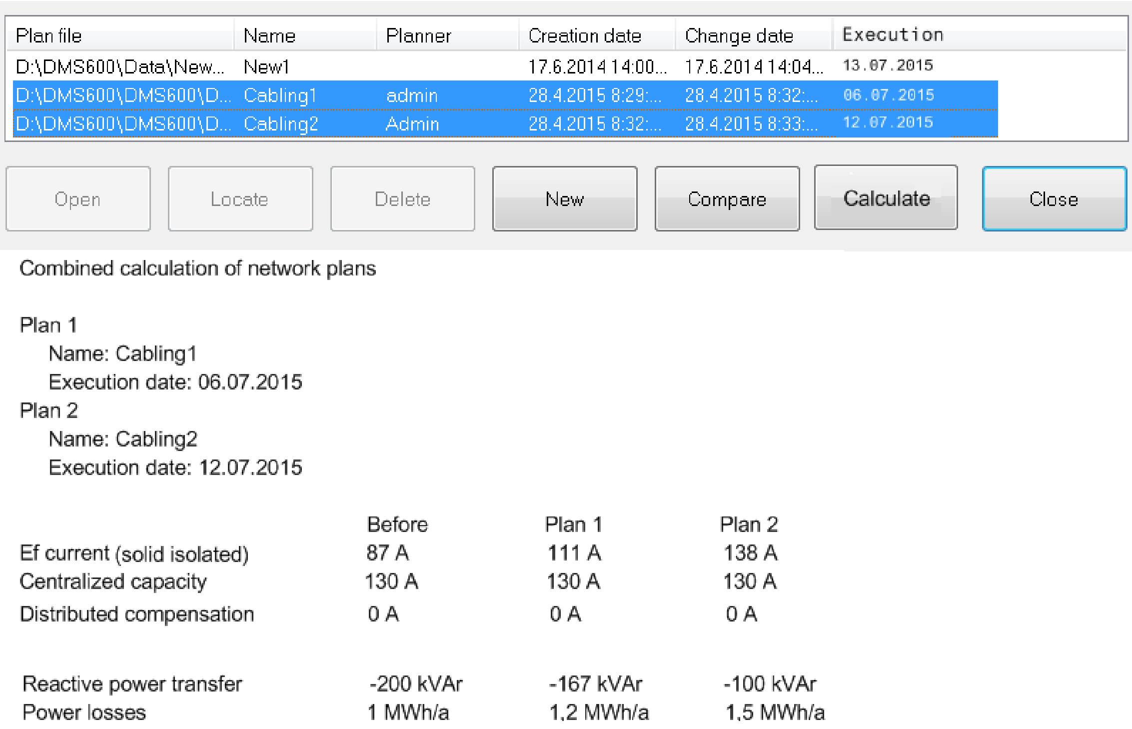

Figure 48. The example of the combined calculation results of multiple network plans

From the results presented in Figure 48 network planner can track the growth of an earth fault current, the amount of compensation capacity, the amount of reactive power and the power losses in network in different phases of network construction process. Also other information that is calculated already in present DMS version should be calculated for multiple plans.

9.1.6 Advanced earth fault protection analysis

It have been stated previously in Sections 2.4 and 7 that the conventional earth fault analysis with multiple assumptions might not be accurate enough to analyze the earth fault phenomena in networks consisting long cables or multiple distributed arc suppression coils. Many assumptions and simplifications are also made in DMS's earth fault analysis. The major assumptions that should be corrected are the following:

- Arc suppression coils are ideal
- Earthing transformers are not taken into account
- Equivalent circuit consists of only zero sequence capacitance, coil inductance and fault resistance

Due to these assumptions the zero sequence voltage is the same in the fault place and in HV-MV substations despite the fault place. Also the location of distributed coils does not effect on the earth fault behavior of the system. In order to make the earth fault analysis more accurate more information needs to be used in calculations. Arc suppression coils are usually connected to the tertiary winding of auxiliary transformer in substation. It should be possible to document the correct connection methods to DMS. This way the zero sequence impedance of the transformer could be used in earth fault analysis. Second option is to add the zero sequence impedance of whole earthing equipment in the datasheet of arc suppression coil. In latter case it should be taken into account that the zero sequence impedance of coils is multiplied by three in equivalent circuit, but the impedance of transformer is not multiplied. In addition to impedances of earthing equipment, more conductor data needs to be used. Already in present DMS version as well as positive sequence resistance and reactance also zero sequence resistance and zero sequence reactance are saved into database.

After the required data is saved into database, more accurate earth fault analysis feature can be applied. In advanced calculation method the sequence networks needs to be created and the zero sequence impedance of earthing transformer needs to be taken into account in calculation of neutral point displacement voltage. The theory of method is presented in Section 2.6. The main steps of analysis method in the aspect of DMS is presented in following:

1. User select the fault point and a fault impedance to be analyzed
2. Create the positive, negative and zero sequence impedances seen from the fault point as described in Section 2.6.
3. Calculate and show the fault current in fault point (equation (21)), residual currents of all feeders (equation (22)) and neutral point displacement voltage (equation (23)).

With the results of this analysis method DSOs can more accurately investigate the effect of long cable and the amount of arc suppression coils on relay configurations. Still inaccuracy remains in the zero sequence impedance of lines if user have not been saved the correct impedances into database. There are some equations that could be used in the calculation of zero sequence impedances, for example one presented in Section 2.4.1. One possibility is that DMS generates an approximation of zero sequence impedance for lines using equation (15). The earthing impedance data can be saved into DMS database so that data could be used in calculation of zero sequence impedance. However, the most effective method to solve the zero sequence impedance is to measure it [44]. If measurement values are used, user needs to document an own conductor type for each measured line section because the value of zero sequence impedance depends on installation type and earthing of sheath.

10. CONCLUSIONS

This thesis studied the development needs of ABB MicroSCADA Pro products portfolio's network information system and distribution management system from the aspect of medium voltage network cabling. Objectives of the thesis were to gather information about the problems that medium voltage cabling causes for DSOs and to examine the DMS's present ability to support users in these issues. Four DSOs were interviewed and measurements and simulations were made to find the development needs to software. Also the feasibility of Volt-VAr Control feature for Finnish DSOs was discussed.

Volt-VAr Control feature could facilitate network operators work because then operators would not need to control the reactive power output of power plants, capacitors and reactors to avoid the costs that are caused by reactive power transportation. However, there are not much capacitors nor power plants in interviewed DSOs' medium voltage networks. In addition, most of the DSOs are going to install shunt reactors that are not controllable. The biggest benefit of VVC would be achieved if the actions of VVC feature could be modelled already when a feeder for a new power plants is being planned. In that case there would not necessarily be need for a network that strong and expenses could be minimized. Therefore, NIS should provide a planning tools in which the active voltage control mode is taken into account.

Earth fault analysis and reactive power generation in case of a long rural area cable were the main issues that have been studied in this thesis. Most of the interviewed DSOs will increase the use of distributed earth fault current compensation and reactive power compensation devices. Combination of centralized and distributed arc suppression coils will be increasingly used because that way the phenomena caused by the series impedance of a long cable will be minimized. Other advantage of mixed compensation is that DSOs don't necessarily need to invest in very large centralized arc suppression coils. Because cables generate reactive power significantly more than overhead lines, also reactive power is being compensated to prevent losses and to prevent the exceeding of Fingrid's reactive power window. Some of the interviewed DSOs will use centralized shunt reactors and some of them will use distributed shunt reactors. Distributed shut reactors are usually easier to install and those prevent the voltage from rising along a long feeder.

DSOs require more accurate earth fault calculation results, support in both planning and handling of distributed arc suppression coils, accurate modeling of shunt reactors and arc suppression coils, possibility to handle the calculation results of multiple network plans and notices for operators to easier handle the reactive power and the capacity of centralized arc suppression coil during network operation. Also a feature for managing overheating of cable is proposed because cable cools down much slower compared to an overhead line.

Earth fault analysis method used in present DMS version could be improved in order to better fulfill the requirements needed in analysis of extensively cabled network. In the present DMS version earth fault calculations are based on conventional earth fault analysis, which contains certain assumptions. Equivalent circuit that is used in earth fault analysis consists of zero sequence capacitance of network, inductance of compensation coils and fault resistance. In a system consisting of a long cable also the zero sequence series impedance of lines and both the positive and negative sequence impedances of lines need to be taken into consideration. In a system consisting of multiple distributed coils also the total impedances of coils and earthing transformers need to be taken into account to accurately calculate the earth fault currents and neutral point displacement voltages.

In the present DMS version it is possible to use the measurement values of current, voltage, reactive power and active power to estimate the load flow in network. DMS's ability to estimate voltages along feeder was tested in distribution network of Savon Voima Verkko Oy. Powers, currents and voltages were measured from the beginning of the feeder and from the three MV-LV substations along the feeder. Measured and estimated voltages were compared in case of two different DMS configuration. In the first case only busbar voltage and powers measured in the beginning of the feeder were used in the estimation. In the second case also the measured powers from the MV-LV substations along the feeder were used. It seems that estimated voltages are somewhat higher than measured voltages. In the inspected system the use of measurements along the feeder did not make the voltage calculation much more accurate, but the loading between line branches were more accurately adjusted to match the measurements. The differences between the measured and calculated voltages are probably caused by the line branches, the inaccuracies of measurements and inadequate calculation parameters such as line resistance. The voltage drop was also studied with Matlab and same results were obtained.

After the development needs were gathered, solutions and methods were developed to meet the new requirements. Models for new devices such as shunt reactors and Dyn11+YN transformers are presented. Visualization for feeders' compensation degree is proposed. Requirements for notices and events that would help the user maintaining compensation degree and reactive power generation in acceptable limits are presented. Requirements for calculation of multiple network plans from the aspect of reactive power and earth fault current are presented. Finally the needed changes to software for developing a more detailed earth fault analysis feature was presented.

Several changes to DMS600's calculation functions are needed and more data needs to be saved into database. The additional data can be used for the more accurate modeling of shunt reactors and arc suppression coils during normal operating conditions and during earth faults.

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APPENDIX 1: QUESTIONNAIRE

Questions

General

- How large amount of distribution network is cabled in different voltage levels?
- What are the cabling goals in next 5-20 years?
- What are the reasons for these plans?
- How long cable feeders there will be in distribution network after the cabling goals have met?
- What kind of issues cabling have caused or will cause?

Earth faults

- What kind of earth fault current compensation methods will be in your network?
- What are the reasons for resulting in these methods?
- How the compensation devices effect on the protection methods used in network?
- What actions are made to keep the earth fault current and touch voltages in acceptable limits?

Reactive power

- What equipment will be used to keep the voltages and reactive powers in balance?
- What are the reasons for resulting in these solutions?
- What actions are made in network operation to keep the voltages and reactive power in acceptable limits?

Cable temperature rise

- How the overheating of line is prevented during fault isolation and experiment-switching?

Improvement needs

- Earth faults
- Reactive power
- Cable temperature rise

APPENDIX 2: THE DATASHEET OF A DYN11+YN TRANSFORMER

Tekninen erittely

13Q1922761 item 2		2013-09-24 MJ/JAT /rev E
Nimellisarvot		
Nimi		Kolmivaiheinen öljyeristeinen muuntaja-kuristin-yhdistelmälaite
Lajimerkki		CCMU 24 HA 400
Nimellisteho jakelumuuntaja	[kVA]	200
Nimellisjännite, ensiö	[V]	20500 ± 2 *2.5 %
Käämimateriaali, ensiö		Al
Käämien eristystaso, ensiö	[kV]	LI 125 AC 50
Läpivientien eristystaso, ensiö	[kV]	LI 125 AC 50
Nimellisjännite, toisio	[V]	410
Käämimateriaali, toisio		Al
Käämien eristystaso, toisio	[kV]	LI 24 AC 8
Läpivientien eristystaso, toisio	[kV]	LI 24 AC 8
Kytkentä		Dyn11
Rinnakkaiskuristin	[kVAr]	200
Nimellisjännite	[V]	20500
Maksimi jatkuva käyttöjännite	[V]	22000
Käämien eristystaso	[kV]	LI 125 AC 50
Käämimateriaali		Al
Nimellisvirta	[A]	5.6
Hajautettu sammutuskela	[A]	16.9 R/X < 2.5%
Taajuus	[Hz]	50
Kytkentä		YN
Jäähdytystapa		ONAN
Lämpenemä, huippuöljy/käämit	[K/K]	60/65 (3-vaihekäyttö) 60/100 (maasulku 15min)
Ympäristön lämpötila, max.	[°C]	40
Asennuskorkeus	[m]	1000

Takuuarvot toleransseineen		
Standardi		IEC60076 -1 ja IEC60076-6
Impedanssi Zk	[%]	4
Reaktanssi, X	[Ω/ph]	2101
Jakelumuuntaja Tyhjäkäyntihäviöt	[W]	405
Jakelumuuntajat Kuormitushäviöt	[W]	2345
Kuristimen häviöt 3-vaihekäytössä	[W]	7550
Alustavat mitat		
Pituus	[mm]	900
Leveys	[mm]	1516
Korkeus	[mm]	1360
Öljyn paino	[kg]	680
Kokonaispaino	[kg]	2050
Kuljetuspaino	[kg]	
Mittapiirustus		14 CCMU 24 H 32303
Muuntajan tyyppi		
Säiliön rakenne		Hermeettisesti suljettu aaltolevysäiliö
Öljyn tyyppi		Nynäs Nytro 10XN (IEC60296 class IIA)
Pintakäsittely		maalattu RAL7035 vaaleanharmaa, 120 µm

ABB

Tekninen erittely

standardin SFS-EN ISO 12944
ilmastorasitusluokka C3 mukaisesti

Vakio-osat

- nostosilmukat
- vetosilmukat
- tyhjennyslaite näytteenottomahdollisuudella
- maadoitusruuvit (2)
- arvokilpi

Varusteet

- Posliiniset läpiviennit ylä- ja alajänn.lepuolelle
- Ylipaineventtiili
- Suojalaite DGPT2
- Muuntajan väliottokytkin
- Kuristimen on/off-kytkin

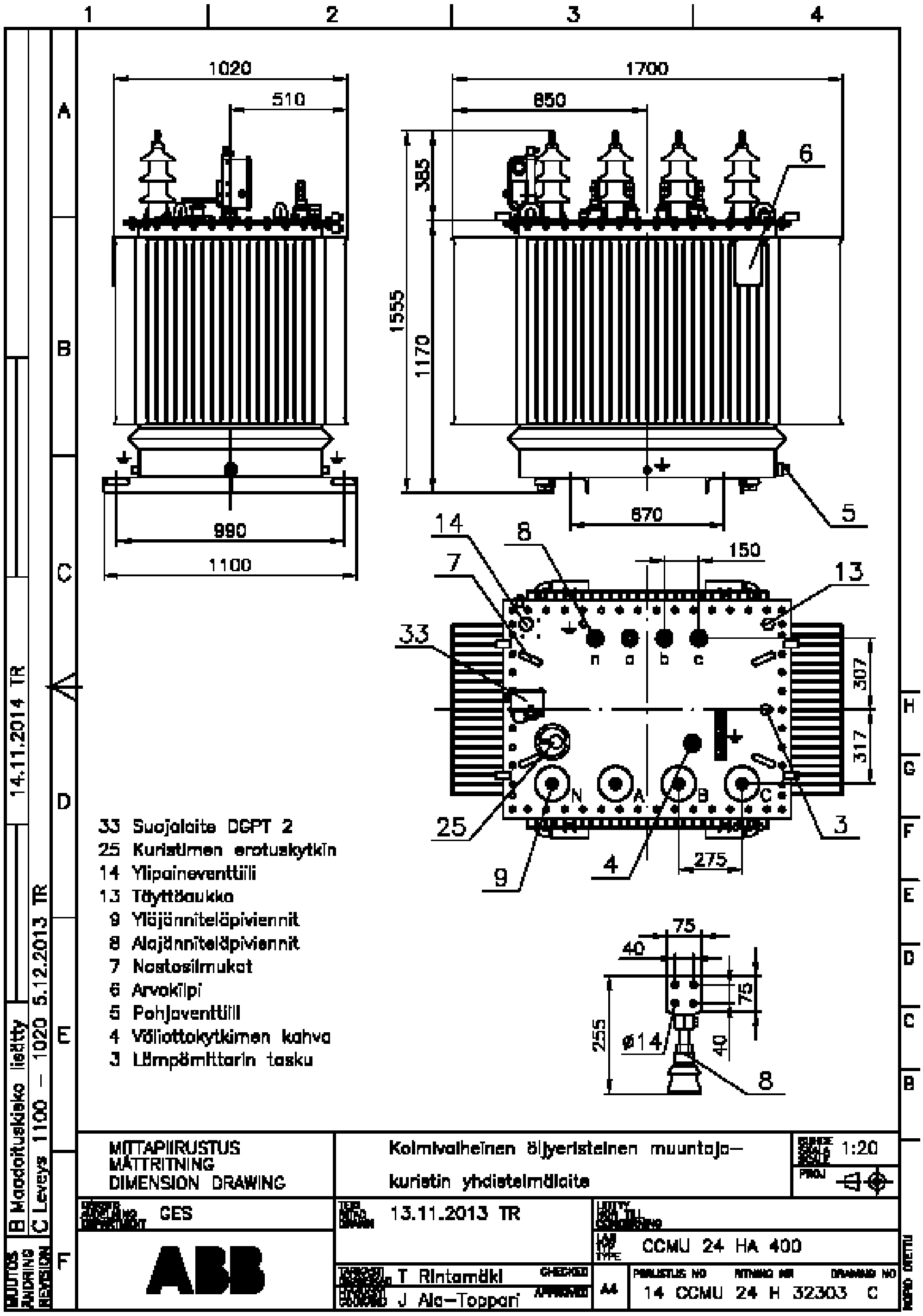
Rev B
Maasulku 15 min

Rev C
Käämimateriaalit Alumiini
Posliiniset läpiviennit ylä- ja alajänn.lepuolella

Rev D
Jakelumuuntajan säätöalue lisätty 20500 V ± 2 *2.5 %
Jakelumuuntajan Impedanssi lisätty Zk 4 %

Rev E
Öljyn paino päivitetty 600 kg => 680 kg
Kokonaispaino päivitetty 2050 kg => 2810 kg
Mittapiirustus numero lisätty

APPENDIX 3: THE DIMENSIONAL DRAWING OF A TRANSFORMER



APPENDIX 4: MEASURED POWERS ALONG FEEDER

	Asemamittaus				6355			
					J04		J05	
	I	U	P	Q	P	Q	P	Q
Connectednode		192690005	192712296		226211415		220358100	
Nodecode		523102058996F2	43921242F1		521103272108F1		521103274108F1	
scadacode		SLPL2J04:PAI52	SLPL2J14:PAI51	43921242F2	521103272108F1	521103272108F1_1	521103274108F1	521103274108F1_1
	24,67	21,14	485	-740	505	-612,6	-490,3	593,8
	23,3	19,88	454	-674	466,4	-570,7	-457,2	552,7
Reactors disconnected	23	19,03	434	-635	430,8	-531,3	-423,2	515,1
	13,67	21,12	475	-133	494,6	-205,9	-481	0
	14,33	19,88	464	-132	478,5	-189,7	-474,9	6,1
Reactors conencted	14	19,07	429	-135	418,3	-190,7	-415,3	22,9

	Asemamittaus				6376					
					J01		J02		J03	
	I	U	P	Q	P	Q	P	Q	P	Q
Connectednode		192690005	192712296		220096849		220096829		220096854	
Nodecode		523102058996F2	43921242F1		517103263449F1		517103265449F1		517103267449F1	
scadacode		SLPL2J04:PAI52	SLPL2J14:PAI51	43921242F2	517103263449F1	517103263449F1_1	517103265449F1	517103265449F1_1	517103267449F1	517103267449F1_1
	24,67	21,14	485	-740	-303,9	209,6	NULL	NULL	218,2	-109,2
	23,3	19,88	454	-674	-274,9	191,8	NULL	NULL	203,7	-101,4
Reactors disconnected	23	19,03	434	-635	-265,6	184,5	NULL	NULL	202,7	-98,3
	13,67	21,12	475	-133	-280,7	-186	NULL	NULL	212,8	82
	14,33	19,88	464	-132	-291,7	-165	NULL	NULL	201,3	62,8
Reactors conencted	14	19,07	429	-135	-258,5	-137,9	NULL	NULL	179,8	50,4

	Asemamittaus				6460			
					J02		J03	
	I	U	P	Q	P	Q	P	Q
Connectednode		192690005	192712296		221112110		221112135	
Nodecode		523102058996F2	43921242F1		516103461687F1		516103463687F1	
scadacode		SLPL2J04:PAI52	SLPL2J14:PAI51	43921242F2	516103461687F1	516103461687F1_1	516103463687F1	516103463687F1_1
	24,67	21,14	485	-740	NULL	NULL	50,1	-6,5
	23,3	19,88	454	-674	NULL	NULL	43,1	-5,3
Reactors disconnected	23	19,03	434	-635	NULL	NULL	38,5	-5,9
	13,67	21,12	475	-133	-58,2	-194,9	51,2	-8,2
	14,33	19,88	464	-132	-56,6	-171	44,8	-8,9
Reactors conencted	14	19,07	429	-135	-49,8	-157,8	41,7	c

APPENDIX 5: MEASURED AND ESTIMATED VOLTAGES

Table 7. Comparison of measured and estimated voltages along the feeder. Shunt reactors are disconnected. P, Q and BB voltage are corresponding quantities in the beginning of the feeder. Current is the current in the beginning of the feeder. Other powers used in load estimation are presented in Appendix 4.

P [kW]	*485*			*454*			*434*		
Q [kVAr]	-740			-674			-635		
BB voltage [kV]	21,14			19,88			19,03		
Fdr. voltage [kV]	**Measured**	**DMS**	**DMS 2**	**Measured**	**DMS**	**DMS 2**	**Measured**	**DMS**	**DMS 2**
06355	20.89	21,14	21,14	19,66	19,88	19,88	18,78	19,03	19,03
06376	20.96	21,14	21,15	19,71	19,88	19,88	18,85	19,03	19,03
06460	20.96	21,14	21,14	19,72	19,87	19,87	18,83	19,03	19,03
Current [A]	24.67	24,1	24,9	23.67	23,2	24,0	23.00	22,7	23,5

Table 8. Comparison of measured and estimated voltages along the feeder. Shunt reactors are connected. P, Q and BB voltage are corresponding quantities in the beginning of the feeder. Current is the current in the beginning of the feeder. Other powers used in load estimation are presented in Appendix 4.

P [kW]	475			464			429		
Q [kVAr]	-133			-132			-135		
Voltage [kV]	21,12			19.88			19.07		
Fdr. voltage [kV]	**Meas.**	**DMS**	**DMS 2**	**Meas.**	**DMS**	**DMS 2**	**Meas.**	**DMS**	**DMS 2**
06355	20.88	21,11	21,11	19,58	19,87	19,87	18,84	19,06	19,06
06376	20.92	21,09	21,10	19,62	19,85	19,85	18,87	19,04	19,06
06460	20.92	21,09	21,09	19,62	19,85	19,85	18,87	19,03	19,06
Current. [A]	13.67	13,4	13,8	14.33	14,1	14,9	14	14,6	13,2

APPENDIX 6: SQL QUERY FOR MEASUREVALUES

```
--Muristimet irti verkosta
Update  [SVV_OPERA_TESTI].[dbo].SwitchingComponent
set   StateE = '0',
      StateA = '0',
      StateB = '0',
      StateC = '0'
WHERE        (Switch LIKE '06460J01S1') OR
             (Switch LIKE '06355J01S1') OR
             (Switch LIKE '06376J01S1')

--Step 1:jannite 21 kV

--Asemasuureet
Update  [SVV_OPERA_TESTI].[dbo].measurevalues
set value = 21.14 where scadacode like 'SLPL2J04:PAI52'          --Kiskojan-
nite

Update  [SVV_OPERA_TESTI].[dbo].measurevalues              --Nerkoo patoteho
set value = '485' where scadacode like 'SLPL2J14:PAI51'

Update  [SVV_OPERA_TESTI].[dbo].measurevalues              --Nerkoo loisteho
set value = '-740' where scadacode like '43921242F2'


--Step 2: Jannite 20 kV

--Asemasuureet
Update  [SVV_OPERA_TESTI].[dbo].measurevalues
set value = '19.88' where scadacode like 'SLPL2J04:PAI52'        --Kiskojan-
nite

Update  [SVV_OPERA_TESTI].[dbo].measurevalues              --Nerkoo patoteho
set value = '454' where scadacode like 'SLPL2J14:PAI51'

Update  [SVV_OPERA_TESTI].[dbo].measurevalues              --Nerkoo loisteho
set value = '-674' where scadacode like '43921242F2'

--Step 3: Jannite 19 kV
--Asemasuureet
Update  [SVV_OPERA_TESTI].[dbo].measurevalues
set value = '19.03' where scadacode like 'SLPL2J04:PAI52'        --Kiskojan-
nite

Update  [SVV_OPERA_TESTI].[dbo].measurevalues              --Nerkoo patoteho
set value = '434' where scadacode like 'SLPL2J14:PAI51'

Update  [SVV_OPERA_TESTI].[dbo].measurevalues              --Nerkoo loisteho
set value = '-635' where scadacode like '43921242F2'



--Muristimet Kiinni verkossa

Update  [SVV_OPERA_TESTI].[dbo].SwitchingComponent
set   StateE = '1',
```

```
      StateA = '1',
      StateB = '1',
      StateC = '1'
WHERE         (Switch LIKE '06460J01S1') OR
              (Switch LIKE '06355J01S1') OR
              (Switch LIKE '06376J01S1')

--Step 1:jannite 21 kV

--Asemasuureet
Update  [SVV_OPERA_TESTI].[dbo].measurevalues
set value = '21.12' where scadacode like 'SLPL2J04:PAI52'        --Kiskojan-
nite

Update  [SVV_OPERA_TESTI].[dbo].measurevalues              --Nerkoo patoteho
set value = '475' where scadacode like 'SLPL2J14:PAI51'

Update  [SVV_OPERA_TESTI].[dbo].measurevalues              --Nerkoo loisteho
set value = '-133' where scadacode like '43921242F2'

--Step 2: Jannite 20 kV
--Asemasuureet
Update  [SVV_OPERA_TESTI].[dbo].measurevalues
set value = '19.88' where scadacode like 'SLPL2J04:PAI52'        --Kiskojan-
nite

Update  [SVV_OPERA_TESTI].[dbo].measurevalues              --Nerkoo patoteho
set value = '464' where scadacode like 'SLPL2J14:PAI51'

Update  [SVV_OPERA_TESTI].[dbo].measurevalues              --Nerkoo loisteho
set value = '-132' where scadacode like '43921242F2'

--Step 3: Jannite 19 kV
--Asemasuureet
Update  [SVV_OPERA_TESTI].[dbo].measurevalues
set value = '19.07' where scadacode like 'SLPL2J04:PAI52'        --Kiskojan-
nite

Update  [SVV_OPERA_TESTI].[dbo].measurevalues              --Nerkoo patoteho
set value = '429' where scadacode like 'SLPL2J14:PAI51'

Update  [SVV_OPERA_TESTI].[dbo].measurevalues              --Nerkoo loisteho
set value = '-135' where scadacode like '43921242F2'
```

APPENDIX 7: SQL QUERY FOR MEASUREMENTS ALONG FEEDER

```
--Muristimet irti verkosta
Update  [SVV_OPERA_TESTI2].[dbo].SwitchingComponent
set     StateE = '0',
        StateA = '0',
        StateB = '0',
        StateC = '0'
WHERE          (Switch LIKE '06460J01S1') OR
               (Switch LIKE '06355J01S1') OR
               (Switch LIKE '06376J01S1')

--Step 1:jannite 21 kV

--Asemasuureet
Update  [SVV_OPERA_TESTI2].[dbo].measurevalues
set value = 21.14 where scadacode like 'SLPL2J04:PAI52'          --Kiskojan-
nite

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues            --Nerkoo patoteho
set value = '485' where scadacode like 'SLPL2J14:PAI51'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues            --Nerkoo loisteho
set value = '-740' where scadacode like '43921242F2'

--06355
Update  [SVV_OPERA_TESTI2].[dbo].measurevalues
set value = '505' where scadacode like '521103272108F1'          --J04P

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues
set value = '-612.6' where scadacode like '521103272108F1_1'     --J04Q

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues            --J05P
set value = '-490.3' where scadacode like '521103274108F1'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues
set value = '593.8' where scadacode like '521103274108F1_1' --J05Q

--06376
Update  [SVV_OPERA_TESTI2].[dbo].measurevalues            --J01P
set value = '-303.9' where scadacode like '517103263449F1'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues            --J01Q
set value = '209.6' where scadacode like '517103263449F1_1'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues            --J02P
set value = NULL where scadacode like '517103265449F1'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues            --J02Q
set value = NULL where scadacode like '517103265449F1_1'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues            --J03P
set value = '218.2' where scadacode like '517103267449F1'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues            --J03Q
set value = '-109.2' where scadacode like '517103267449F1_1'
```

```
--06460
Update  [SVV_OPERA_TESTI2].[dbo].measurevalues           --J02P
set value = NULL where scadacode like '516103461687F1'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues           --J02Q
set value = NULL where scadacode like '516103461687F1_1'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues           --J03P
set value = '50.1' where scadacode like '516103463687F1'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues           --J03Q
set value = '-6.5' where scadacode like '516103463687F1_1'



--Step 2: Jannite 20 kV
--Asemasuureet
Update  [SVV_OPERA_TESTI2].[dbo].measurevalues
set value = '19.88' where scadacode like 'SLPL2J04:PAI52'        --Kiskojan-
nite

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues           --Nerkoo patoteho
set value = '454' where scadacode like 'SLPL2J14:PAI51'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues           --Nerkoo loisteho
set value = '-674' where scadacode like '43921242F2'

--06355
Update  [SVV_OPERA_TESTI2].[dbo].measurevalues
set value = '466.4' where scadacode like '521103272108F1'        --J04P

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues
set value = '-570.7' where scadacode like '521103272108F1_1'     --J04Q

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues           --J05P
set value = '-457.2' where scadacode like '521103274108F1'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues
set value = '552.7' where scadacode like '521103274108F1_1' --J05Q

--06376
Update  [SVV_OPERA_TESTI2].[dbo].measurevalues           --J01P
set value = '-274.9' where scadacode like '517103263449F1'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues           --J01Q
set value = '191.8' where scadacode like '517103263449F1_1'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues           --J02P
set value = NULL where scadacode like '517103265449F1'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues           --J02Q
set value = NULL where scadacode like '517103265449F1_1'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues           --J03P
set value = '203.7' where scadacode like '517103267449F1'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues           --J03Q
set value = '-101.4' where scadacode like '517103267449F1_1'
```

```
--06460
Update  [SVV_OPERA_TESTI2].[dbo].measurevalues             --J02P
set value = NULL where scadacode like '516103461687F1'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues             --J02Q
set value = NULL where scadacode like '516103461687F1_1'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues             --J03P
set value = '43.1' where scadacode like '516103463687F1'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues             --J03Q
set value = '-5.3' where scadacode like '516103463687F1_1'


--Step 3: Jannite 19 kV
--Asemasuureet
Update  [SVV_OPERA_TESTI2].[dbo].measurevalues
set value = '19.03' where scadacode like 'SLPL2J04:PAI52'        --Kiskojan-
nite

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues             --Nerkoo patoteho
set value = '434' where scadacode like 'SLPL2J14:PAI51'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues             --Nerkoo loisteho
set value = '-635' where scadacode like '43921242F2'

--06355
Update  [SVV_OPERA_TESTI2].[dbo].measurevalues
set value = '430' where scadacode like '521103272108F1'          --J04P

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues
set value = '-531.3' where scadacode like '521103272108F1_1'     --J04Q

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues             --J05P
set value = '-423.2' where scadacode like '521103274108F1'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues
set value = '515.1' where scadacode like '521103274108F1_1' --J05Q

--06376
Update  [SVV_OPERA_TESTI2].[dbo].measurevalues             --J01P
set value = '-265.6' where scadacode like '517103263449F1'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues             --J01Q
set value = '184.5' where scadacode like '517103263449F1_1'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues             --J02P
set value = NULL where scadacode like '517103265449F1'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues             --J02Q
set value = NULL where scadacode like '517103265449F1_1'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues             --J03P
set value = '202.7' where scadacode like '517103267449F1'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues             --J03Q
set value = '-98.3' where scadacode like '517103267449F1_1'
```

```sql
--06460
Update  [SVV_OPERA_TESTI2].[dbo].measurevalues            --J02P
set value = NULL where scadacode like '516103461687F1'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues            --J02Q
set value = NULL where scadacode like '516103461687F1_1'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues            --J03P
set value = '38.5' where scadacode like '516103463687F1'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues            --J03Q
set value = '-5.9' where scadacode like '516103463687F1_1'




--Muristimet Kiinni verkossa

Update  [SVV_OPERA_TESTI2].[dbo].SwitchingComponent
set   StateE = '1',
      StateA = '1',
      StateB = '1',
      StateC = '1'
WHERE         (Switch LIKE '06460J01S1') OR
              (Switch LIKE '06355J01S1') OR
              (Switch LIKE '06376J01S1')

--Step 1:jannite 21 kV

--Asemasuureet
Update  [SVV_OPERA_TESTI2].[dbo].measurevalues
set value = '21.12' where scadacode like 'SLPL2J04:PAI52'        --Kiskojan-
nite

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues            --Nerkoo patoteho
set value = '475' where scadacode like 'SLPL2J14:PAI51'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues            --Nerkoo loisteho
set value = '-133' where scadacode like '43921242F2'

--06355
Update  [SVV_OPERA_TESTI2].[dbo].measurevalues
set value = '494.6' where scadacode like '521103272108F1'        --J04P

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues
set value = '-205.9' where scadacode like '521103272108F1_1'     --J04Q

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues            --J05P
set value = '-481' where scadacode like '521103274108F1'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues
set value = '0' where scadacode like '521103274108F1_1'     --J05Q

--06376
Update  [SVV_OPERA_TESTI2].[dbo].measurevalues            --J01P
set value = '-280.7' where scadacode like '517103263449F1'
```

```sql
Update  [SVV_OPERA_TESTI2].[dbo].measurevalues                --J01Q
set value = '-186' where scadacode like '517103263449F1_1'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues                --J02P
set value = NULL where scadacode like '517103265449F1'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues                --J02Q
set value = NULL where scadacode like '517103265449F1_1'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues                --J03P
set value = '212.8' where scadacode like '517103267449F1'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues                --J03Q
set value = '82' where scadacode like '517103267449F1_1'

--06460
Update  [SVV_OPERA_TESTI2].[dbo].measurevalues                --J02P
set value = '-58.2' where scadacode like '516103461687F1'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues                --J02Q
set value = '-194.9' where scadacode like '516103461687F1_1'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues                --J03P
set value = '51.2' where scadacode like '516103463687F1'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues                --J03Q
set value = '-8.2' where scadacode like '516103463687F1_1'



--Step 2: Jannite 20 kV
--Asemasuureet
Update  [SVV_OPERA_TESTI2].[dbo].measurevalues
set value = '19.88' where scadacode like 'SLPL2J04:PAI52'        --Kiskojan-
nite

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues                --Nerkoo patoteho
set value = '464' where scadacode like 'SLPL2J14:PAI51'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues                --Nerkoo loisteho
set value = '-132' where scadacode like '43921242F2'

--06355
Update  [SVV_OPERA_TESTI2].[dbo].measurevalues
set value = '478.5' where scadacode like '521103272108F1'        --J04P

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues
set value = '-189.7' where scadacode like '521103272108F1_1'     --J04Q

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues                --J05P
set value = '-474.9' where scadacode like '521103274108F1'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues
set value = '6.1' where scadacode like '521103274108F1_1'   --J05Q

--06376
Update  [SVV_OPERA_TESTI2].[dbo].measurevalues                --J01P
set value = '-291.7' where scadacode like '517103263449F1'
```

```sql
Update  [SVV_OPERA_TESTI2].[dbo].measurevalues             --J01Q
set value = '-165' where scadacode like '517103263449F1_1'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues             --J02P
set value = NULL where scadacode like '517103265449F1'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues             --J02Q
set value = NULL where scadacode like '517103265449F1_1'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues             --J03P
set value = '201.3' where scadacode like '517103267449F1'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues             --J03Q
set value = '62.8' where scadacode like '517103267449F1_1'

--06460
Update  [SVV_OPERA_TESTI2].[dbo].measurevalues             --J02P
set value = '-56.6' where scadacode like '516103461687F1'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues             --J02Q
set value = '-171' where scadacode like '516103461687F1_1'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues             --J03P
set value = '44.8' where scadacode like '516103463687F1'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues             --J03Q
set value = '-8.9' where scadacode like '516103463687F1_1'


--Step 3: Jannite 19 kV
--Asemasuureet
Update  [SVV_OPERA_TESTI2].[dbo].measurevalues
set value = '19.07' where scadacode like 'SLPL2J04:PAI52'        --Kiskojan-
nite

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues             --Nerkoo patoteho
set value = '429' where scadacode like 'SLPL2J14:PAI51'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues             --Nerkoo loisteho
set value = '-135' where scadacode like '43921242F2'

--06355
Update  [SVV_OPERA_TESTI2].[dbo].measurevalues
set value = '418.3' where scadacode like '521103272108F1'        --J04P

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues
set value = '-190.9' where scadacode like '521103272108F1_1'     --J04Q

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues             --J05P
set value = '-415.3' where scadacode like '521103274108F1'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues
set value = '22.9' where scadacode like '521103274108F1_1'  --J05Q

--06376
Update  [SVV_OPERA_TESTI2].[dbo].measurevalues             --J01P
set value = '-258.5' where scadacode like '517103263449F1'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues             --J01Q
```

```
set value = '-137.9' where scadacode like '517103263449F1_1'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues            --J02P
set value = NULL where scadacode like '517103265449F1'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues            --J02Q
set value = NULL where scadacode like '517103265449F1_1'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues            --J03P
set value = '179.8' where scadacode like '517103267449F1'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues            --J03Q
set value = '50.4' where scadacode like '517103267449F1_1'

--06460
Update  [SVV_OPERA_TESTI2].[dbo].measurevalues            --J02P
set value = '-49.8' where scadacode like '516103461687F1'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues            --J02Q
set value = '-157.8' where scadacode like '516103461687F1_1'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues            --J03P
set value = '41.7' where scadacode like '516103463687F1'

Update  [SVV_OPERA_TESTI2].[dbo].measurevalues            --J03Q
set value = '-9.5' where scadacode like '516103463687F1_1'
```

APPENDIX 8: MATLAB CODE FOR PI-SECTION

```
syms Vr
syms Ir
%%AHX-W240
l=3.04 %km
x=0.11 %%ohmia/km
r=0.125 %%ohmia/km
c= 0.3 *10^(-6) %%mikrofaradia/km
b= 2*pi*c
X=x*l
R=r*l

B_s=b*l
Y=i*B_s
Z=R+i*X

A=1+(1/2)*Y*Z
D=1+(1/2)*Y*Z
B= Z
C= Y*(1+(1/4)*Y*Z)

Vs=19030
Is=23,00

M = ([A,B;C,D])
S = ([Vs;Is])
R = ([Vr;Ir])

ratk=solve (S == M*R)
abs(double(ratk.Vr))
abs(double)
```

APPENDIX 9: SIMULATION RESULTS

Table 9. Earth fault current and zero point displacement voltage calculated by PSCAD and DMS in different networks. Centralized coil is set to compensate 90 % of earth fault current. Fault occurs in the beginning of studied feeder

Line length	I_{fc}	I_{fr}	I_{ftot}	I_{ftot_DMS}	U_0	U_{0_DMS}
5	10,21	0,69	10,24	7,9	11,59	11,5
10	12,46	1,02	12,49	9,5	11,588	11,5
15	14,84	1,46	14,92	11,1	11,581	11,5
20	17,26	2,08	17,38	12,6	11,58	11,5
25	19,69	2,92	19,91	14,2	11,588	11,5
30	22,2	4,02	22,56	15,8	11,597	11,5
35	24,75	5,41	25,33	17,4	11,6	11,5

Table 10. Earth fault current and zero point displacement voltage calculated by PSCAD and DMS in different networks. Centralized coil is set to compensate 90 % of earth fault current. Fault occurs in the farthermost node of studied feeder's trunk line

Line length	I_{fc2}	I_{fr2}	I_{ftot2}	If_{tot_DMS2}	U_{02}	U_{0_DMS2}
5	10,21	0,7	10,23	7,9	11,6	11,5
10	12,46	0,98	12,49	9,5	11,599	11,5
15	14,84	1,37	14,9	11,1	11,597	11,5
20	17,24	1,89	17,34	12,6	11,6	11,5
25	19,65	2,59	19,82	14,2	11,61	11,5
30	22,13	3,48	22,41	15,8	11,622	11,5
35	24,66	4,56	25,08	17,4	11,624	11,5

Table 11. Earth fault current and zero point displacement voltage calculated by PSCAD and DMS in different networks. Centralized coil is set to keep the compensation degree in 90 %. Amount of 16,9 A distributed coils is varied

Local coils	I_{fc}	I_{fr}	I_{ftot}	If_{tot_DMS}	U_0	U_{0_DMS}
0	24,74	5,41	25,32	17,4	11,6	11,5
1	22,78	4,34	23,19	17,4	11,6	11,5
2	21,08	3,6	21,38	17,4	11,59	11,5
3	19,65	3,15	19,9	17,4	11,59	11,5
4	18,46	2,92	18,69	17,4	11,59	11,5
5	17,5	2,89	17,75	17,4	11,59	11,5
6	16,75	2,99	17,03	17,4	11,58	11,5
6+1	16,18	3,2	16,69	17,4	11,58	11,5
6+1+1	15,8	3,46	16,73	17,4	11,58	11,5
6+1+1+1	15,58	3,81	16,85	17,4	11,58	11,5

Table 12. Earth fault current and zero point displacement voltage calculated by PSCAD and DMS in different networks. Only distributed compensation is used. Amount of 16,9 A distributed coils is varied

Local coils	I_{fc}	I_{fr}	I_{ftot}	If_{tot_DMS}	U_0	U_{0_DMS}
0	180,23	2,54	180,25	173,7	11,92	11,6
1	162,33	2,01	162,34	156,8	11,88	11,6
2	144,72	1,77	144,73	140	11,85	11,6
3	127,22	1,75	127,23	123,1	11,81	11,6
4	109,95	1,93	109,97	106,2	11,77	11,6
5	92,84	2,23	92,87	89,3	11,74	11,6
6	75,87	2,61	75,91	72,4	11,7	11,6
6+1	58,99	3,02	59,06	56,4	11,67	11,6
6+1+1	42,2	3,43	42,34	39,5	11,63	11,6
6+1+1+1	25,52	3,83	25,81	22,6	11,6	11,6
6+1+1+1+1	8,94	4,23	9,89	5,7	11,56	11,6

APPENDIX 10: THE MODEL OF THE SIMULATED SYSTEM