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FACULTY OF TECHNOLOGY
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ELECTRICAL ENGINEERING

MASTER'S THESIS

TECHNO-ECONOMIC FEASIBILITY OF NOVEL ON-LINE CONDITION MONITORING METHODS IN LOW VOLTAGE DISTRIBUTION NETWORKS

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Abstract

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Techno-Economic Feasibility of Novel On-Line Condition Monitoring Methods in Low Voltage Distribution Networks

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Keywords: low voltage, distribution network, cable, fault, condition monitoring

The focus in this thesis is to study both technical and economical possibilities of novel on-line condition monitoring techniques in underground low voltage distribution cable networks.

This thesis consists of literature study about fault progression mechanisms in modern low voltage cables, laboratory measurements to determine the base and restrictions of novel on-line condition monitoring methods, and economic evaluation, based on fault statistics and information gathered from Finnish distribution system operators.

This thesis is closely related to master’s thesis “*Channel Estimation and On-line Diagnosis of LV Distribution Cabling*”, which focuses more on the actual condition monitoring methods and signal theory behind them.

Tiivistelmä

Lappeenrannan teknillinen yliopisto
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Arto Ylä-Outinen
Uudentyyppisten on-line kunnonvalvontamenetelmien teknis-taloudelliset käyttömahdollisuudet pienjännitteisissä jakeluverkoissa

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Tämän työn tavoitteena on tutkia uudentyyppisten on-line kunnonvalvontamenetelmien teknis-taloudellista soveltuvuutta pienjännitteisiin maakaapelijakeluverkkoihin.

Työ koostuu pienjännitteisten maakaapeleiden vikaantumismekanismeja käsittelevästä kirjallisuustutkimuksesta, uudentyyppisten kunnonvalvontamenetelmien mahdollisuuksien määrittämisestä laboratoriomittauksin, sekä menetelmien soveltamisen taloudellisesta arvioinnista. Taloudellinen arviointi perustuu suomalaisilta jakeluverkkoyhtiöiltä saatuihin vikatilastoihin ja haastatteluihin koskien käytössä olevia viankorjausmenetelmiä ja -käytäntöjä.

Tämä työ liittyy läheisesti diplomityöhön “*Channel Estimation and On-line Diagnosis of LV Distribution Cabling*”, jossa uudentyyppisiä kunnonvalvontamenetelmiä tarkastellaan tarkemmin signaalinkäsittelyn näkökulmasta.

This work was carried out in the Smart Grids and Energy Markets (SGEM) research program coordinated by CLEEN Ltd. with funding from the Finnish Funding Agency for Technology and Innovation, Tekes.

Tämä työ on tehty Smart Grids and Energy Markets (SGEM) tutkimusprojektin yhteydessä, jota koordinoi CLEEN Oy ja rahoittaa Teknologian ja innovaatioiden kehittämiskeskus Tekes.

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Abbreviations and symbols

AC	alternating current
AMCMK	PVC insulated aluminum 1 kV power cable with concentric copper conductor and PVC sheath
AMR	automatic meter reading
AN	annuity
AXMK	XLPE insulated aluminum 1 kV power cable with PVC sheath
CIS	customer information system
DC	direct current
DMS	distribution management system
DSO	distribution system operator
EMA	Energy Market Authority
GENELEC	European Committee for Electrotechnical Standardization
HCC	harm caused to the customers
HDPE	high-density polyethylene
HV	high voltage
HVDC	high voltage direct current
IEC	International Electrotechnical Commission
LDPE	low-density polyethylene
LV	low voltage
LVDC	low voltage direct current
MV	medium voltage
NIS	network information system
OCM	on-line condition monitoring
OIP	oil-impregnated paper
PD	partial discharge
PE	polyethylene
PLC	power line communication
PVC	polyvinyl chloride
QMS	quality management system
RH	relative humidity

SCADA	supervisory control and data acquisition
SGEM	Smart Grids and Energy Markets
TDR	time domain reflectometry
TSR	transient recording system
UV	ultraviolet
WTA	willingness to accept
WTP	willingness to pay
XLPE	cross-linked polyethylene

List of symbols

A	outage cost parameter	€ / kW
B	outage cost parameter	€ / kWh
c	unit cost	€ / h
f	fault rate	1 / km, a
I	investment	€
l	length	km
n	evaluation period	a
P	real power	kW
p	interest rate	%
t	time	h

Subscripts

e	equipment
f	fault
l	labor
pi	planned interruption
r	repair

1 Introduction

This thesis is a part of nationwide Smart Grids and Energy Markets (SGEM) research. Thesis is closely related to master's thesis "*Channel Estimation and On-line Diagnosis of LV Distribution Cabling*". In this thesis, the novel on-line condition measurement (OCM) techniques for low voltage (LV) underground cable network are evaluated from distribution system operators (DSO) point of view. Thesis consists of literature study of fault mechanisms in LV underground cable network, laboratory measurements and techno-economic evaluation, based on statistics provided by Finnish DSOs.

1.1 Background and purpose of the research

Traditional concept of electric power system consists of centralized generation, power transmission and distribution systems and passive loads. Electricity is generated in large generating plants and transmitted via transmission network, substations and distribution network to the end customers. Distribution network consists of medium voltage (MV) network, usually rated 10 or 20 kV, and 400 V LV networks, fed by MV network through secondary substations. Power flows straightforwardly from higher voltage level to lower and thus, significance of LV networks is much lower than MV networks because a fault in MV network affects much larger group of customers. LV networks are also known to be more reliable compared to MV networks due lower dielectric stress. Therefore, lots of studies have been made to increase reliability of MV networks but very little research have been done to increase reliability of LV networks.

Smart grid is a broad future network concept which includes active loads, energy storages, distributed generation and communication between different network components. Smart grid allows the consumers to participate in energy markets by adjusting the consumption according to the current price of electricity, as well as selling the surplus energy they produce by solar panels or by small scale wind turbines. Electric vehicles can be used as energy storages, feeding the energy to the network when power demand is high. Distributed generation, energy storages, communication and intelligent control system allow independent local microgrids to maintain supply in the case of an interruption in feeding MV network occurs.

Overall, the importance of LV networks will most probably raise in the future. Novel techniques, such as low voltage direct current (LVDC), will increase power transmission capacity of present LV networks. Not only the power transmitted to the customers will raise, but also the power transmitted from the customers, as the customer-owned distributed generation and energy storages will become more common. This will increase the power transmission within LV networks. Therefore, demand of reliability of LV networks will most probably increase as the impact of faults increase.

1.2 Objectives

Purpose of this thesis is to determine techno-economical potential of novel OCM techniques in LV distribution network. Failure mechanisms and causes of failures in LV underground cable network are also studied, based on both literature study and practical experiences from Finnish DSOs.

High frequency signal injection techniques are tested in laboratory environment to determine the types and severities of defects that could possibly be detected with such condition monitoring techniques. The effect of insulation material is tested by performing the tests with two different LV cables; cross-linked polyethylene (XLPE) insulated AXMK and polyvinylchloride (PVC) insulated AMCMK. Branches and joints are added to determine the functionality of measurement techniques in more complex network topologies.

Economic potential of OCM system is determined by assessing the potential cost savings it generates through decreasing the number of unexpected faults annually. Evaluation is based on fault statistics and information gathered from Finnish DSOs.

2 LV distribution

Electricity distribution networks connect the end customers to the transmission network. Distribution network consists of primary HV/MV substations, MV network, secondary MV/LV substations and LV networks. At primary substations HV, used in longer distance power transmission, is transformed to MV and fed to the MV network. Distribution transformers inside secondary substations transform MV to LV, and feed the LV networks, where the most of end customers are connected to. In Finnish distribution system, the most commonly used voltage in LV networks is 3-phase 230/400 VAC. Also 690 V and 1 kV phase-to-phase low voltages are used in some special cases, the former is usually used in factories and latter in some distribution networks. (Lakervi & Partanen, 2009)

Structure of LV network, amount of power transferred, and maximum transmission distances vary considerably by region. In urban areas, LV networks are often built interconnected but used radially. In rural areas, networks are built radial without any back-up connections. Underground cables are used in urban areas, whereas rural LV networks are often built using overhead cables. The power transferred through a single cable can be more than 100 kW in urban LV network. In rural areas, the peak transmission power is normally considerably lower and quite often only few kWs. The maximum transmission distance vary from hundreds of meters in urban areas, to over a kilometer in rural areas. Figure 2.1. illustrates the typical rural and urban LV networks. (Lakervi & Partanen 2009)

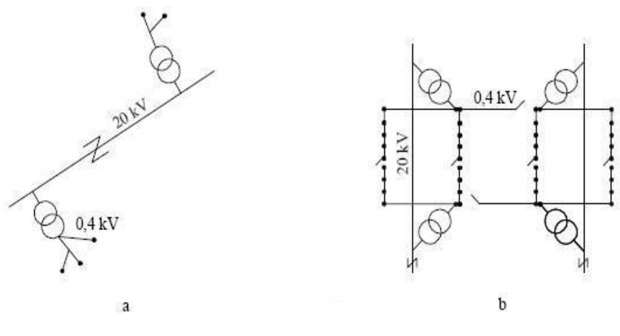

Figure 2.1. Typical a) rural and b) urban LV network. The black dots represent customers connected to the network. (Lakervi & Partanen, 2009).

2.1 Low voltage power cables

Main components of a modern thermoplastic insulated underground LV cable are conductors, insulation, possible concentric conductor and outer protective sheath. Different components of an AMCMK –underground cable are presented in Figure 2.2.

Figure 2.2. Concentric AMCMK 1 kV cable, where 1) is outer protective sheath, 2) concentric conductor, 3) polypropene bands, 4) phase insulation, 5) aluminum conductors. (Modified from Draka, 2011).

Manufacturing and usage of LV cables are regulated by international and national standards. In Finland, SESKO compiles the national SFS –standards, based on European and world wide standards compiled by GENELEC and IEC. SESKO also cooperatives with IEC and GENELEC in preparation of international electrotechnical standards.

Standards applied to LV underground cables are divided by insulation material used. SFS 4879 is for XLPE insulated cables and SFS 4880 for PVC insulated cables. These standards strictly define cables mechanical properties, electrical properties and testing methods. The most comprehensive type testing is done when a new cable type is introduced. There are also random sample tests done to a complete cable, or components taken from complete cable, and routine tests done to every cable manufactured. (SFS-4879, 2008, SFS-4880, 2008)

SFS 4879 defines structure and sizing of cables with aluminum or copper conductors and XLPE insulation. Insulation should be made from cross-linked polyethylene and it's thickness should vary between 0,7 - 2,8 mm, according to cross-sectional area of conductors. The highest operating temperature allowed is

90 °C. Thickness of outer sheath, usually made from PVC- or PE- based thermoplastic, should be 1,8 - 3,1 mm. (SFS-4879, 2008)

SFS 4880 defines structure, sizing and testing of cables with PVC insulation and -sheath. Extruded insulation thickness should vary between 1,0 - 1,6 mm, according to cross-sectional area of conductors. The highest operating temperature allowed is 70 °C. Thickness of outer PVC- sheath should be 1,8 - 3,2 mm. (SFS-4880, 2008)

Routine tests consist of conductor tests, spark tests and high-voltage test with 3 kV AC for 5 min, or 10 kV DC for 15 min. During the type testing, cable is immersed to water of 70 °C, and insulation resistance is then measured. Cable is left under the water for 1 h, followed by voltage test with 4 kV AC for 4 h. (SFS-4880, 2008)

Some cables have concentric conductor running between outer sheath and insulation, which is made from copper wires. Concentric conductor is connected to the earth potential and it provides protection against electric shock, in case the cable sheath and insulation has been penetrated, for example, with metallic shovel. Fault current then flows from phase conductor to the concentric conductor, instead of flowing through the person holding the shovel. (Suntila, 2009)

White polypropene tapes are used for keeping the individual wires together during the manufacturing process. They also isolate the main insulation material from the hot thermoplastic when the cable sheath is being extruded. Tapes also help the cable to withstand the forces caused by high current short circuits. Concentric cables have two layers of polypropene tapes, one on each side of the concentric conductor. (Suntila, 2009)

Conductors are usually made from annealed aluminum strands. Conductors are round shaped with small cross-sectional areas, usually under 25 mm^2, and sector shaped with larger cross-sectional areas. Cross-sectional area of conductors, together with insulation material used, define the maximum continuous and fault currents allowed through the cable. (SFS-4879, 2008, SFS-4880, 2008)

The most common cable types used in Finnish underground LV distribution cable network are PVC- and XLPE –insulated aluminum cables. The main properties of these cables are presented in Table 2.1.

Table 2.1. The main properties of the AXMK and AMCMK LV cables.

National type code	AXMK	AMCMK
Sheath material	PVC	PVC
Insulation material	XLPE	PVC
Conductor material	aluminium	aluminium
Number of conductors	4	3 + 1
Concentric conductor	-	copper strings

In this thesis, cables presented in Table 2.1 will be called by their national type codes; AXMK and AMCMK.

There are also cables with two separate sheath layers, for example, Draka AMCMK-HD with inner PVC- and outer PE -sheaths (Draka, 2011). These double sheathed cables are designed especially for rough environments and to be installed using a cable plough. By using different materials in different sheaths, advantages of both materials can be utilized. Downside of double sheathed cables is price. For example, 95 mm^2 double sheathed XLPE insulated cable is about 20 % more expensive than single sheathed version (Pavo, 2011).

2.1.1 LV cable accessories

Cable accessories are needed to join cables to an another cable or to a device, such as a fuse base or a transformer pole. Connection between conductor and a cable joint or a lug can be done by bolting or by crimping. Joints are protected using heat-shrink tubes or resin casts. LV cable termination using lugs and heat-shrink tubes is presented in Figure 2.3 and bolted LV cable joint in Figure 2.4.

Figure 2.3. LV cable termination using lugs and heat-shrink tubes. (Ensto, 2011)

Figure 2.4. Bolted LV cable joint. Bolted connections will be protected with smaller heat-shrink tubes, while larger tube serves as a sheath to whole joint area. (Ensto, 2011)

Joints can be placed in distribution cabinets, vertical plastic tubes or directly under the ground. Joints which are located directly under the ground without any external protection are exposed to ground moisture and other ageing factors. Ingress of moisture, for example, can cause corrosion and lead to high impedance contacts, which can eventually cause a cable fault as the insulation around the joint overheats.

2.2 LVDC

The European Low Voltage Directive (LVD, 2006) defines the limits for the LV levels in public distribution system. It limits the low voltage to 1000 VAC and to 1500 VDC. Therefore, by using the DC instead of AC, more power can be transferred using the same cables than the conventional 230/400 VAC technique. A basic concept of low voltage direct current (LVDC) distribution is presented in Figure 2.5. (Partanen et al. 2010)

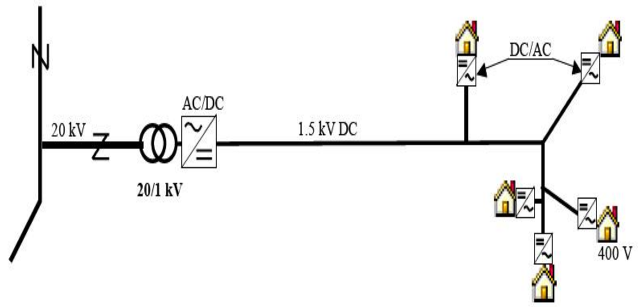

Figure 2.5. A basic concept of LVDC distribution. (Kaipia et al. 2006)

20 kV AC is transformed to 1 kV AC using a 20/1 kV transformer. The LV AC is then rectified to 1,5 kV DC by using a AC/DC converter. The power is then transmitted to DC/AC inverters, located next to each end user. DC/AC inverters are responsible for providing 230/400 V AC for the customers. (Partanen et al. 2010)

LVDC distribution system can be built either unipolar or bipolar. Unipolar system has one voltage level. Bipolar system consists of two unipolar systems connected in series. The bipolar LVDC system with possible customer connection options is presented Figure 2.6. (Partanen et al. 2010)

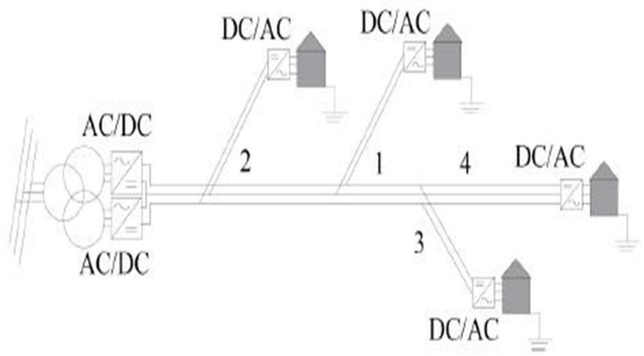

Figure 2.6. Different customer connection options in bipolar LVDC system. (Partanen et al 2010)

In the bipolar system, customers can be connected to DC network in four ways: 1) between a positive pole, 2) between a negative pole, 3) between positive and negative poles and 4) between positive and negative poles with neutral connection (Partanen et al. 2010).

By using higher voltage than traditional 400 V AC system, more power can be transmitted using the same LV cables and within the same voltage drop limits. In addition, the voltage drop in DC network have no direct effect on customers AC voltage levels, because the customer voltage can be conditioned with inverters. Therefore, higher voltage drop can be accepted in DC network, and even more power can be transmitted using LVDC than traditional 400 VAC system. However, the converters generate current harmonics which can lead extra losses in DC network (Partanen et al. 2010).

One possible utilization of LVDC is to replace some overhead MV branch lines with LVDC technique. This will decrease the number of faults in MV distribution network, and therefore improve the overall reliability. The investment costs are also lower with LVDC, compared to the MV alternatives. On the other hand, replacing MV lines with LVDC will increase losses in the network. The expected lifetimes of the inverters are also short, only 10 to 15 years, which is less than a third of lifetimes of traditional network components (Partanen et al. 2010).

3 Faults in underground LV cable network

Underground cable faults can be divided to instant abrupt faults, for example, caused by excavator, and to slowly developing incipient faults. In this thesis, the focus is on the incipient faults. Incipient damages in the cable will slowly develop to electric faults, leading to a breakdown in the insulation system, and causing a power outage. Many factors govern the development speed of an electric fault due to an incipient damage in a cable. Fault development speed is dependent on, for example, the environmental conditions, such as ground moisture and impurities, and the load profile of the cable.

3.1 Ageing

Underground cables experience numerous ageing factors which, over the time, cause irreversible changes in the cable insulation system. Cable joints and terminations are also affected, which can lead to corrosion and high impedance contacts. In Table 3.1, ageing factors are categorized to thermal, electrical, environmental and mechanical factors.

Table 3.1. Ageing factors in underground cable insulation system (Densley, 2001).

Thermal	**Electrical**	**Environmental**	**Mechanical**
Maximum Temperature	Voltage	Oxygen	Bending
Ambient Temperature max / min	Frequency	Water / humidity	Tension
Temperature gradient	Current	Chemicals	Compression
Temperature cycling		(Radiation)	Vibration
			Torsion

These factors alone, or acting synergistically, can induce changes in the insulation material of the cables. This type of ageing is referred to as intrinsic ageing and it could have effect on large volume of insulation, such as overheating due overloading the cable. Ageing factors also interact with contaminants, defects and other localized changes in insulation structure, causing degradation of insulation. This type of ageing is referred to as extrinsic ageing. Degradation usually starts at localized regions, and gradually propagating through insulation. (Densley 2001).

Maximum temperature, to which cable is exposed, is determined by ambient temperature and by the maximum current transferred through the cable. Therefore, overloading can cause insulation temperature to exceed the highest operation temperature set by cable manufacturer. This will accelerate structural ageing in polymers, and therefore, shorten the life of the cable insulation significantly. Heat will also accelerate other ageing factors, like chemical reactions. Cables with XLPE insulation withstand higher temperatures than PVC insulated cables (Kärnä 2005).

Variation of current transferred through the cable causes temperature cycling. This recurring heating and cooling causes thermal expansion and –contraction, which can lead to movement in cable interfaces. Movement can eventually lead to high impedance contacts and excessive heating in cable joints and terminations (Densley 2001).

Underground cables are exposed to soil moisture and possible chemicals. Properties of polymers, used in outer sheath and insulation, determine cables ability to withstand moisture and chemicals. Chemical degradation is caused by formation of free radicals which leads to un-zipping and breaking the polymer chains. This reaction can be initiated internally by thermal or mechanical means, by oxidizing reaction, by hydrolysis or by UV ionizing reaction. Chemicals in soil can also damage the cable directly when cable is installed in polluted environment. PVC has good resistance against chemicals, but it permits more diffusion of water through than PE (Suntila 2009).

Electrical stress from normal operating voltage to LV cable insulation is very low. Thickness of insulation is determined rather from mechanical aspects than from dielectric strength requirements, and it is considerably oversized from dielectric strength point of view. However, in case of LV underground cable network is fed from overhead MV line, direct lightning strike to the transformer or to nearby MV lines can damage already aged cable or defected cable joint. Finnish DSOs have practical experience where especially cable joints have been destroyed after a thunderstorm.

UV radiation causes ageing in exposed polymers by breaking the polymer chains (Aro et al. 2003). Underground cables are safe from UV radiation, except for short lengths, for example, from pole-mounted transformer to under the ground. Carbon black is added to polymers during the manufacturing process, in order to decrease the effect from UV radiation (Suntila 2009).

3.2 Damage mechanisms

Actual damage mechanism for incipient faults in LV underground cables is relatively little studied phenomena, whereas lots of material can be found regarding fault propagation in MV or HV cables. Fault propagation in MV or HV cables is usually more straightforward due greater voltage stress over the insulation. Practical experiences from LV cable faults where fuse is ruptured and then, after it has been replaced, fault have disappeared for considerably long periods of time, shows their unstable nature.

3.2.1 Mechanical damage

Cable is exposed to significant mechanical stress during the cable installation process. Installation at sub-zero temperatures increases the stress, especially to thermoplastics used in cable insulation and sheath. Bending and torsion can cause defects in cable sheath as the thermoplastic cracks due breaking of the polymer bonds under tension. Cross-linking improves the thermoplastics mechanical durability. Conductors can also be damaged due excessive mechanical stress. Therefore, cable manufacturer defines the smallest bending radius and maximum pulling force allowed to different cables. (Kärnä 2005).

LV cables can be installed by traditional trench excavating or by ploughing. When installing to trench, cable has to be pulled along the ground. Cable sheath can therefore be damaged by sharp stone or by other sharp object left unnoticed. Nearby stones can damage the cable also afterward due pressure from the soil filled back to the trench, or due ground movement caused by ground frost.

Nowadays, LV cables are often installed by ploughing. Ploughing is done by pulling specially designed plough through the soil using tractor or excavator and by feeding the cable under the ground simultaneously. Cable plough and ploughing of an AMCMK-PE cable are presented in Figures 3.1a and 3.1b.

Figure 3.1. a) Cable plough b) Ploughing of AMCMK-PE -cable (Reka 2011)

Ploughing to suitable soil type is much faster than traditional trench excavating. Ploughing technique cannot be used in stony or rocky soil, or near existing underground cable network. Ploughing causes more mechanical stress to cable than traditional excavation technique, and any damage caused to cable sheath is left unnoticed. Stone, or another foreign item, in the cable feeding mouth of the plough can cause serious damage to cable sheath, as it may stuck between the cable and the feeding mouth. Preliminary ploughing without cable is usually done to ensure the suitably of the track and to remove any large obstacles, such as stones. (Lakervi et Partanen 2009, Pavo 2011)

Ground frost can reach almost to 2 meters in depth in Northern Finland, and almost to a meter in Southern Finland (Environment 2011). For non-concentric cables, for example AXMK, minimum installation depth allowed is 0,7 m when no external protection is used (SFS-6000-8-814 2007), which is close to an average installation depth in practice (Pavo 2011). Ground frost generates movement and pressure in the soil, causing mechanical stress to cables and cable joints buried under the ground.

The roots of trees and plants can also damage underground cables. The fault statistics from the DSOs showed that there were cases, where the same distribution cabinet had to be replaced twice, because of the roots of nearby tree had damaged also the new cabinet and cabling installed to the same location. Rodents are also known to damage the cables.

3.2.2 Leakage currents

Leakage current occur when conductive path is formed through cable insulation between phase conductor and concentric conductor or mass of earth. Many factors can cause the conductive path to form through cable sheath and insulation, but moisture is the key element in most cases. Mechanical damage to cable, or incorrectly done cable joint can allow water to penetrate through insulation. Impedance of the conductive path first limit the leakage current under the tripping point of protective device, in case of LV, typically a fuse. Therefore, the current leakage stay undetected until partial discharge activity occurs over the time.

Experiments with oil-impregnated paper (OIP) insulated LV cables show that shortly after the leakage current reached 100 mA, intensive discharges occurred leading to catastrophic failure of the cable. Study also revealed strong relation between conductor temperature and magnitude of leakage current. Especially rapid increase of temperature has been shown to increase the leakage current through insulation (Rowland et Wang 2007).

Although the results from OIP insulated LV cable experiments cannot be directly applied to thermoplastic insulated cables, it can be assumed that leakage current will cause discharges also in thermoplastic insulation. Magnitude of leakage current in real installation conditions will most probably raise over the time due ingress of moisture and deterioration of insulation.

3.2.3 Treeing

Although the treeing phenomena in polymer insulating materials have been studied for decades, the exact build-up mechanisms of trees remains somewhat unknown. Water tree is tree shaped microscopic formation of water, which develops through the insulation material. Water trees are formed due presence of water and electric field and they grow in parallel with electric field. Required electric field intensity for water trees to grow is commonly considered to be at least 1 kV/mm and RH should be over 70 % (Kärnä 2005). Water can get to insulation through damaged cable sheath, incorrectly done installation of cable or cable joint, or by penetrating the sheath by diffusion. PE and XLPE allow less water through by diffusion than PVC (Aro et. al 2003).

Water tree decreases cable’s dielectric strength, but it would not necessarily lead to breakdown in insulation. Breakdown strength of insulation penetrating water tree is often at least 2 kV/mm, therefore, water trees do not cause a serious threat to LV cables. On the other hand, water and chemical compounds initiate electrolysis, chemical reactions and oxidation around the tree area. This leads to deterioration of insulation material (Kärnä 2005).

3.2.4 Arcing

An arc is electrical discharge between two electrodes through gas, liquid or solid material. Arcs can initiate when the voltage stress over the insulation exceeds dielectric strength of insulation. It has shown that 95 % dielectric strength level for modern thermoplastic-insulated LV underground cables are at least 15 kV, when 50 Hz AC test voltage is used (Suntila 2009).

According to simulations done by *Hannu Mäkelä*, the highest overvoltage level, caused by direct lightning strike to pole-mounted distribution transformer, in studied LV underground cable network was 7,2 kV (Mäkelä 2009). Comparing this result to dielectric strength of LV cables, it can be seen that modern intact thermoplastic-insulated LV cables will probably withstand the voltage stress from direct lightning strike to the distribution transformer.

However, momentary discharges can initiate much lower voltage level when cable is damaged. Ingress of moisture and impurities can form conductive path through insulation, causing leakage current to flow through insulation. When the magnitude of leakage current exceeds certain level, transitory discharges begin to occur (Rowland et Wang 2007).

Insulation thickness in LV cables is oversized, compared to dielectric stress caused by low voltage. Thickness of insulation is determined by mechanical durability, rather than electrical factors. This causes the incipient LV cable faults to be often non-linear and unstable. In Table 3.2. incipient LV cable faults have been classified by their characteristics (Livie et al. 2008).

Table 3.2. Classification of incipient LV cable faults (Livie et al. 2008).

Condition	Classification	Characteristic
Unstable / Non-linear	Transitory	Irregular voltage dips
	Intermittent	Irregular fuse operations
	Persistent	Repetitive fuse operations
Stable / Linear	Permanent	Open circuit / Solid welds

Gradually developing incipient LV cable faults often initiate at transitory state. Flickering lights can be first sign of a emerging cable fault, since momentary arcing generates voltage transients. Severity and frequency of arcing depends on the state of conductive fault tracks formed inside the insulation, moisture and amount of impurities in faulty area. Those arcs self-extinguish, but permanent damage to cable insulation is done, since the arcs create conductive surface fault tracks inside the insulation. Therefore, unstable faults gradually develop toward stable permanent state, and the fault current eventually ruptures the fuse. Unstable fault can exist for days, or even for months, until it becomes permanent.

Practical experiences from DSOs support this theory (Gammon et. Matthews 1999, Clegg, 1994).

3.3 Examples of faulty LV cables

Following figures present three samples, taken from real faulty LV cables. Samples were provided by a Finnish DSO, along with assumptions of root cause for each fault.

Figure 3.2 shows permanently faulted part of underwater AXMK cable, and Figure 3.3 defect in cable sheath. Both pictures are from the same sample, which is probably damaged during the installation by a propeller of an outboard engine. Cable was permanently damaged few months after the installation.

Figure 3.2. Permanently faulted part of an underwater AXMK cable. Root cause of failure is probably a propeller of an outboard engine.

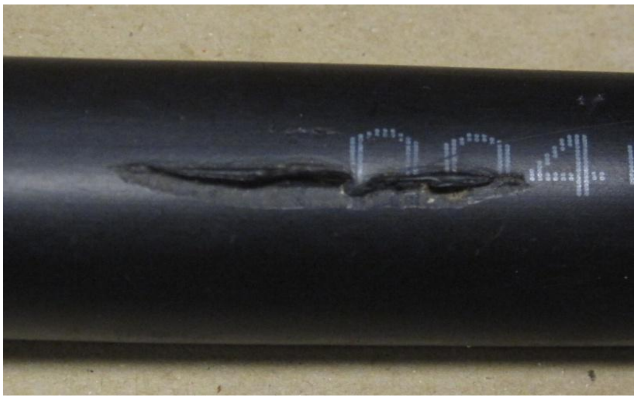

Figure 3.3. Cut in a sheath of an underwater AXMK cable. Probably caused by a propeller of an outboard engine.

Figures 3.4 and 3.5 are from the same underground AXMK cable sample, which has probably been damaged by a mole. Figure 3.4 shows permanently damaged part, with aluminum conductor oxidized to white aluminum oxide. Oxidation of aluminum requires large fault current. Figure 3.5 shows section of sheath material eaten away by a mole.

Figure 3.4. Permanently faulted part of an underground AXMK cable. Root cause of failure is probably a mole damaging the sheath.

Figure 3.5. Section of sheath material and insulation of an underground AXMK cable eaten away by a mole.

Figure 3.6 shows permanently damaged double sheathed underground Duolex cable. Cable is probably damaged during the installation by ploughing. There are couple of parallel cuts in different sides of cable.

Figure 3.6. Permanently faulted double sheathed underground cable. Cable is probably damaged during the installation by ploughing.

Although the root cause and the installation environment are different for each sample, the end result looks very similar in every case. Aluminum conductor has oxidized to white aluminum oxide and sheath surrounding the fault is swollen due pressure and heat produced by fault current. Sample from faulty double sheathed cable shows that even though they are mechanically more durable than single sheathed cables, they are not immune to the mechanical stress from installation.

3.4 Fault location

Before the faulty part of an underground cable can be replaced, exact location of the fault must be determined. Excavation is expensive and time-consuming, especially in urban areas. Therefore, unnecessary excavation should be avoided. In case of LV cable fault, there are often customers without service as long as the fault is being repaired. Therefore, fault location should be done as fast and as efficiently as possible. Fault location procedure can be divided to two parts; pre-location and pin-pointing. Fault is first tried to narrow to certain area, and then pin-pointed and confirmed to an exact spot before any excavating is done.

3.4.1 Pre-location

Fault location in LV network is usually more difficult than in MV network. MV cables can often be disconnected from both ends, without causing an outage to customers. There are usually no branches in MV cables, or them can easily be disconnected. LV cables are often branched, and disconnecting them could be time-consuming. Also the unstable nature of faults in LV cables can cause difficulties in fault locating, or even make it impossible until the fault becomes permanent (Clegg 1994).

Fault can often be narrowed to certain area with simple measurements and logical reasoning. Blown fuses, and information about which customers are out of service, narrows the possible fault location to certain area. Number of fuses blown and simple voltage measurements reveal type of the fault, such as one- or multi-phase open circuit, phase-to-phase short circuit, or phase-to-earth fault (Clegg 1994).

Sophisticated analyzers, such as a time domain reflectometer (TDR) -device, can also be used for pre-locating the faulty spot of cable. TDR device is connected to a faulty cable at secondary substation or at distribution cabinet, and it launches a pulse into the faulty cable. This pulse is completely or partly reflected from any impedance mismatch it encounters, such as joints, end of branches, or faults. Distance of mismatches can then be calculated by assuming the velocity of signal propagation to be constant for a given cable. Interpretation of TDR trace requires skill, and every branch in network causes attenuation in signal and more complex trace. Therefore, high impedance faults located far away from TDR device can remain undetected, since their weak trace gets lost in the noise produced by branches and other impedance mismatches (Clegg 1994).

On many occasions, it is possible to treat the fault by repeated re-energizing the faulty cable, in order to create a clear open circuit situation, or low-impedance short circuit. TDR trace should be recorded before the re-energizing is done, so any change in trace after re-energizing is done can give away the location of the fault. Re-energizing can be done by replacing the fuses, or by specially designed fault re-energizing device with build-in circuit-breaker (Clegg 1994).

Ongoing expansion of AMR (automatic meter reading) network will speed up the fault locating process in the future, as soon as the full potential of AMR meters can be utilized. Meters can send an alarm when individual customer is out of service. Therefore, by knowing which customers are affected by the fault, the network operator can quickly narrow the fault to certain area even before dispatching the workgroup. AMR meters can also detect potentially hazardous broken neutral situation, which can cause overvoltage to occur.

3.4.2 Pin-pointing

Extent of pin-pointing work to be done, depends on the accuracy and extension of pre-location. The most simplest case is when there is an obvious cause of fault, for example, sign of recent excavating work within the pre-located fault area. Excavator can cause also an incipient fault by damaging the cable sheath, but not completely destroying the cable and causing an abrupt fault. Fault can then develop, depending on severity of fault and soil conditions, within days or even months after cable sheath is originally damaged.

Heat, produced by fault current, can melt snow on the ground and thus give away the fault location. Burning of insulation or cable sheath materials generate certain odor, which can be detected by special analyzer or by a trained dog. In some cases, noise produced by arcing is loud enough to be heard on the ground, when the faulty cable is being re-energized (Clegg 1994).

When no visual or otherwise obvious clue about fault location is available, fault can be tried to pin-point by injecting audio frequency signals to faulty cable while following the cable route on the ground and using hand-held receivers to receive them. Fault can be detected from discontinuance of received signal. Audio frequency method is suitable only for detecting low-impedance-, or clear open circuit –faults. High impedance faults can be pin-pointed using a surge generator and sensitive ground microphone. A picture of surge generator and ground microphone is presented in Figure 3.7 (Clegg 1994).

Figure 3.7. SSG 500 Surge Voltage Generator and BM 30 Ground Microphone, equipped with digital Universal Locator UL 30. (Baur)

There are also commercially available on-line fault locators, designed especially to identify and locate high impedance intermittent faults, which cause fuses to blow occasionally. For example, Kehui T-P22 is locally or remotely operated TDR / TRS (Transient Recording System) -device, which is connected to all 3 phases of a faulty cable. It includes a 4 channel, 3 voltages and 1 current, transient recorder. TDR system is triggered based on voltage distortion and / or over-current. TDR trace is recorded before and during the arcing. Therefore, by comparing these two traces, fault location can be found in the spot where TDR trace have changed. A picture of Kehui T-P22 is presented in Figure 3.8 (Livie et al. 2008).

Figure 3.8. Kehui T-P22 Low Voltage Cable Fault Locator with test leads, current clamp and GSM –antenna (Kehui, 2007).

However, complexity of the network and attenuation can prevent the fault to be found with TDR. Therefore, T-P22 can also be used in Travelling Wave Fault Location, or TRS –mode. Two units are needed to operate in TRS –mode, one for each side of suspect fault location. One of the units is set to Master, which generates a continuous train of synchronizing pulses. These pulses are visible to both units, but too small to trigger the high speed transient recording. When arcing occurs, it produces two travelling waves which propagate away from the fault point in opposite directions. These waves triggers the high speed transient recording in both units. Fault transient, as well as synchronizing pulse, are then recorded by both units. By aligning edges of fault transient on the records from both units, fault location can be determined by measuring the time interval between the injected and received synchronizing pulses (Livie et al. 2008).

4 Condition measurements in underground cable network

Reliability demands on electricity distribution system are constantly increasing, together with efficiency demands on DSOs operation. Therefore, precautionary maintenance should be done as cost-efficiently as possible. Underground cable networks form a large part of electricity distribution system, and therefore, cost-efficient condition management of cable networks is crucial to meet constantly increasing demands of reliability and efficiency.

Condition measurements offer information about condition of underground cables, without a need of expensive excavation work to be done. Current condition measurement techniques are off-line methods, so the cable has to be disconnected before measurements.

4.1 Insulation resistance

Insulation resistance measurement is widely used, and relatively simple and inexpensive method to evaluate the condition of insulation. Cable must be disconnected for the measurement. Measurement is performed on one phase at the time, while the remaining phases are connected to earth potential. 5 kV DC voltage is commonly used when underground cables are being measured. Basic concept of insulation resistance measurement is presented in Figure 4.1 (Kärnä 2005).

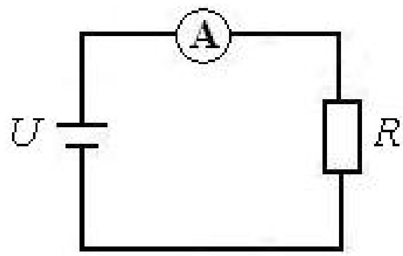

Figure 4.1. Basic concept of insulation resistance measurement.

Test voltage (U) *is* applied over insulation (R) and the current through insulation is measured. Insulation resistance can be the calculated

$$R = \frac{U}{I}, \tag{4.1}$$

where I is measured current through the insulation. Actual insulation resistance testers calculate the insulation resistance automatically.

Resolution of insulation resistance measurement is very low; it only shows whether the insulation is intact or not. On the other hand, low insulation resistance means the insulation to be certainly seriously damaged. Insulation resistance measurements are mainly used for verifying the electrical installations and to measure the condition of windings of rotating machines (Kärnä 2005).

4.2 Dielectric loss factor

Dielectric loss factor, or tan δ, is measured using AC voltage. Ideal insulation would consist only of capacitance, and it could be modeled simply using a capacitor. Practical insulation, however, includes also resistance, which allows small resistive leakage current through the insulation. Loss angle δ measures the ratio between capacitive and resistive currents as shown in Figure 4.2.

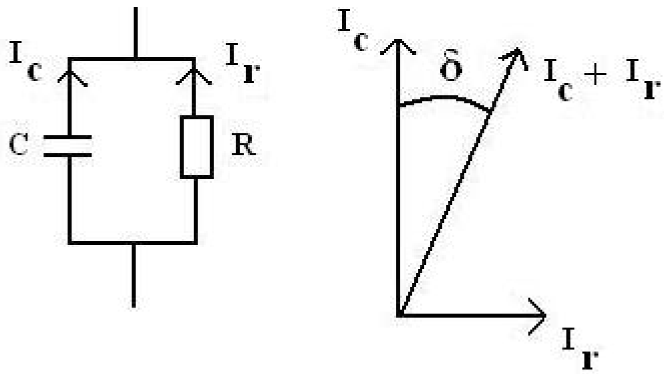

Figure 4.2. Equivalent circuit of insulation and definition of loss angle δ.

Tan δ and capacitance can be measured using the Schering bridge or current comparator bridge. Bridge measurement is based on comparing the specimen being measured to a known reference component. Compressed gas capacitor is usually used as a reference to capacitance, and resistor connected to series with capacitor is used as a reference to loss factor. Basic structure of the Schering bridge is presented in Figure 4.3 (Aro et al. 2003).

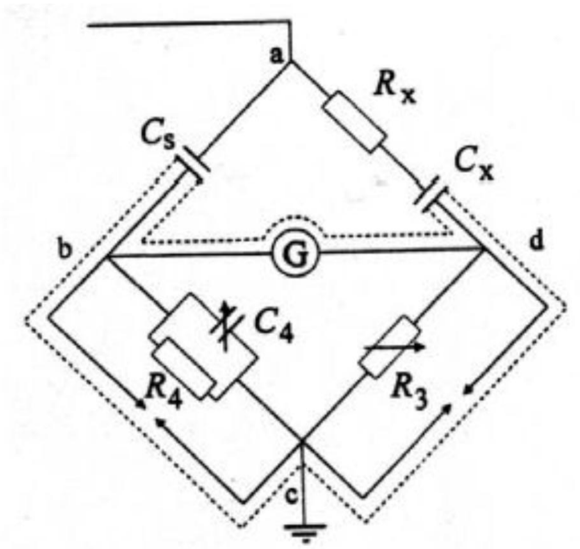

Figure 4.3. The Schering bridge (Aro et al. 2003).

R_x and C_x correspond to the resistance and capacitance of the specimen being measured, C_s is the reference capacitor, R_3 and C_4 are adjustable resistor and capacitor, R_4 is fixed resistor, and G is balance indicator. Test voltage is applied between a and c, and adjustable resistor and capacitor is adjusted until voltage between b and d is zero. Bridge is then said to be balanced, and values of R_x and C_x can be calculated based on known values of other components in the bridge. Actual measuring devices perform bridge balancing automatically, as well as calculating and recording the values for specimen being measured (Aro et al. 2003).

Value for tan δ can also be calculated from momentary values of voltage and current when test voltage is applied over the insulation. In case of ideal insulation, the current would be purely capacitive, and the sum of the product of voltage and current momentary values would be zero. When there is a resistive current involved, the sum differs from zero. This difference represents the real power consumed in insulation and it is called the dielectric losses. Tan δ can be then calculated from the magnitude of dielectric losses (Aro et al. 2003).

Tan δ is usually measured as a function of voltage. Voltage is raised to at least to the highest nominal voltage of the cable or other test specimen being measured. Both magnitude of tan δ at nominal operating voltage and its rise as a function of voltage are observed when the measurement results are being interpreted. Fundamental shapes of tan δ –curve in different example cases are presented in Figure 4.4 (Aro et al. 2003).

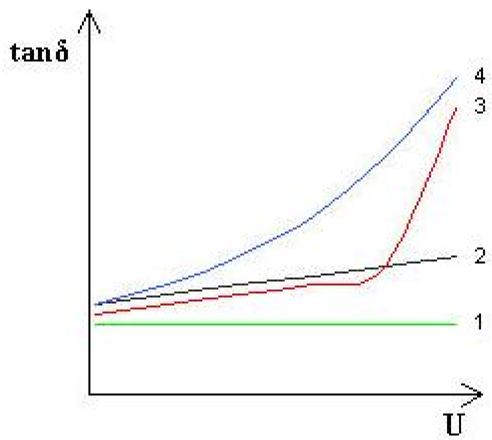

Figure 4.4. Fundamental shapes of tan δ –curve in different condition states of insulation material (Aro et al. 2003).

Curve 1 represents the ideal case. In practice, tan δ for healthy insulation is approximately constant as a function of voltage (curve 2). Sudden raise of tan δ at certain test voltage is a sign of ignition of partial discharges (curve 3). Curve 4 represents severely aged insulation.

With insulations which do not withstand partial discharges, such as thermoplastics, voltage dependence of tan δ is usually low, and the magnitude of tan δ is more significant when the condition of insulation is evaluated. Temperature of insulation has significant effect on the results of tan δ measurements, and temperature dependence of results vary according to the condition of insulation. Therefore, it is reasonable to carry out the measurements at different temperatures (Aro et al. 2003).

4.3 Partial discharge test

Partial discharge is a widely studied phenomenon. Ignition of partial discharge is usually a sign of a defect in insulation. Partial discharges are local small breakdowns in insulation, which do not cause total breakdown of insulation system. These discharges take place singly, in bursts or continuously and their energy is measured in picocoulombs. For thermoplastics, partial discharges cause irreversible damage in insulation and they could eventually lead to total breakdown, as the energy levels and general activity of partial discharges increase over the time (Clegg 1994).

Activity of partial discharges can be used as an indicator for condition of insulation. Partial discharges can be detected electrically, electromagnetically, acoustically or chemically. Direct electrical detection is based on measuring the current pulses partial discharges produce, when test voltage is applied over the insulation, as shown in Figure 4.5 (Aro et al. 2003).

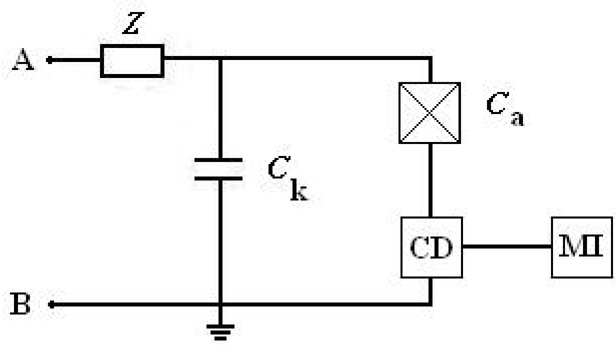

Figure 4.5. Basic concept of partial discharge measurement (Aro et al. 2003).

Test voltage is applied between A and B. Filter circuit Z is used for removing unwanted pulses from test voltage, which could interfere the measurement. Coupling capacitor (C_k) should have low inductance and be partial discharge free. C_a is the specimen being measured and CD is coupling device to transform the current pulses to voltage pulses. It could be impedance or pulse transformer. Measurement instrument (MI) could be sophisticated partial discharge analyzer, or simply an oscilloscope (Aro et al. 2003).

For MV and HV cables, novel condition monitoring techniques, based on detection of partial discharges, have been developed to be used on-line. Sensitive partial discharge (PD) sensor is either inductively or capacitively coupled to dielectric. The sensor could be, for example, high frequency current transformer around the lead from concentric conductor to earth. The signal from PD sensor is then passed through high-pass filter and several broadband amplifiers in cascade. Filtered and amplified signal is then digitalized and transferred to PC for analysis. In real installation environments, noise, attenuation and distortion of PD signals cause challenges for on-line PD measurement (Blackburn et al. 2005).

4.4 Differences between MV and LV networks

The main difference between LV and MV networks from condition measurements point of view is higher voltage stress in MV cables. Higher voltage stress causes fault propagation to be faster and more straightforward than in LV cables. Any defect or void in cable insulation will initiate PDs in MV cables as the strength of electric field over the void exceeds the breakdown strength of air. PDs occur also in damaged LV cables, but it requires serious damage in the cable, presence of moisture and leakage current. PD activity is also more random in damaged LV cables than in damaged MV cables. PD activity level can therefore be used for measuring the condition of a MV cable, but cannot be reliably used for evaluating the condition of a LV cable as the PD activity in LV cable usually means that the cable is already very severely damaged.

Topology of MV cable feeder differs from topology of LV cable feeder. A single MV cable usually runs between two secondary substations, connecting them together. Both substations are also usually equipped with disconnectors, allowing the cable to be disconnected for service or for off-line measurements. MV networks are usually built interconnected, so a single MV cable can often be disconnected without causing an outage. Exception for that is some rural underground MV networks where overhead lines are replaced with underground cables and very simple network structure and satellite secondary substations are used without any interconnections. However, also the cost from an interruption is much lower in those areas than in densely populated areas.

LV cable feeder consists of the main line and branches and customer connection cables connected to the main line. Branches can be connected through fuses in distribution cabinets, or directly without fuses in smaller cabinets or in vertical plastic tubes located under the ground. In densely populated urban areas, there are usually some interconnections between different LV networks. Overall, topology of LV network is more complex than MV network which makes fault location and condition measurements more challenging.

5 Novel on-line condition monitoring methods

This thesis included planning and executing laboratory measurements to study usability of high frequency signal injection techniques in condition monitoring of underground LV cables. Measurement setup and execution will be described briefly in this Chapter with the most important results. Theoretical approach and more detailed analysis of the measurements and results can be found from master's thesis "*Channel Estimation and On-line Diagnosis of LV Distribution Cabling*". Ideas and possible challenges regarding to the practical implementation of OCM to the LV networks are also presented in this Chapter.

5.1 Laboratory measurements

Objective of measurements was to determine whether it is possible to detect consistent change in high frequency signal response before an electrical fault develops when cable is damaged under wet conditions. Moisture alters characteristic impedance of the cable and therefore, it increases attenuation and it causes reflections.

General definition of high frequency band is a frequency range from 3 MHz to 30 MHz, however, in this thesis, the whole measurement range from 100 kHz to 100 MHz is referred as high frequency. Cable electrical condition was evaluated by insulation resistance measurements and by applying line voltage to the damaged cable.

5.1.1 Test setup

Two most commonly used modern LV cables in Finish distribution networks were selected; PVC insulated AMCMK and XLPE insulated AXMK. Properties of these cables are presented in Table 2.1.

High frequency measurements were carried out using Hewlett-Packard 4194A impedance / gain-phase analyzer (Figure 5.1). Frequency band from 100 kHz to 100 MHz was used.

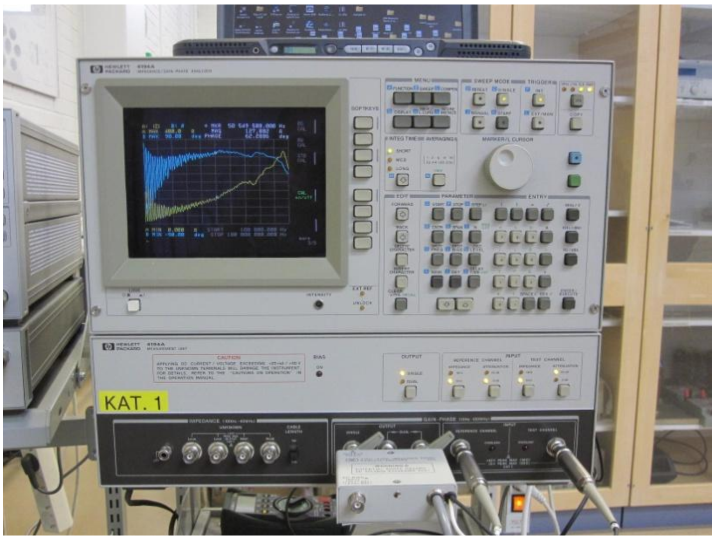

Figure 5.1. Hewlett-Packard 4194A impedance / gain-phase analyzer.

Insulation condition of damaged cables were tested by insulation resistance tester and by applying 380 V phase – to – phase voltage to cables. Voltage was limited to 380 V due limitation from isolation transformer used in test setup. Figure 5.2 shows voltage test setup.

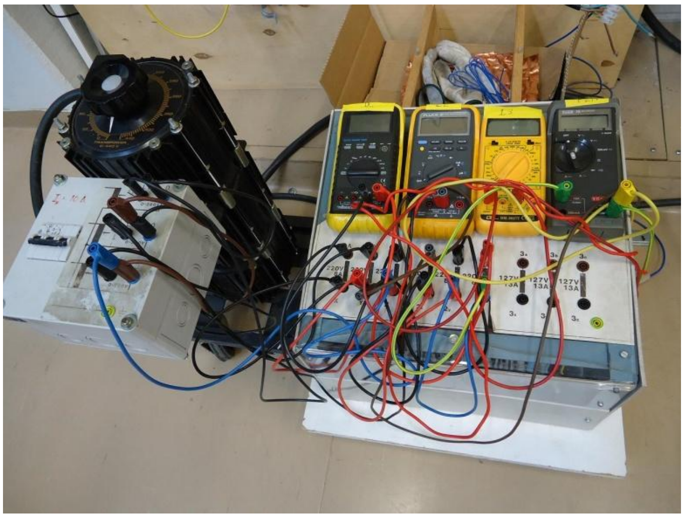

Figure 5.2. Voltage test setup. Variable autotransformer is connected to 1:1 isolation transformer in order to achieve galvanic isolation of damaged cables from common ground potential. Transformer neutral is connected to a copper plate located in water tank to provide a return path to possible phase – to – ground leakage current from damaged non-concentric AXMK cable. Phase currents and returning current from copper plate were measured using regular multimeters.

Two different test setups were built for single cable segments. In both cases, damaged part of the cables were submerged under regular tap water. Properties of tap water would not fully correspond with the properties of moisture in the soil, but it was used in order to maintain as controlled test environment as possible. However, lack of salt and other impurities cause the tap water to be less conductive than average soil moisture, which could affect especially to the leakage current measurements.

5.1.2 Long term water test

Tests were divided in two different categories, long-term water test and progressive damaging. Long-term water test were carried out with 25 m long samples of both cable types. A 10 cm long section of outer sheath and the polypropylene bands were cut away from both cables. Damage was done at 11 m from closest cable end. Insulation around the phase conductors were left intact. After the cables were measured dry, they were submerged under water. Figure 5.3 shows AMCMK –cable with section of sheath removed and Figure 5.4 shows submerged cables during the long-term water test.

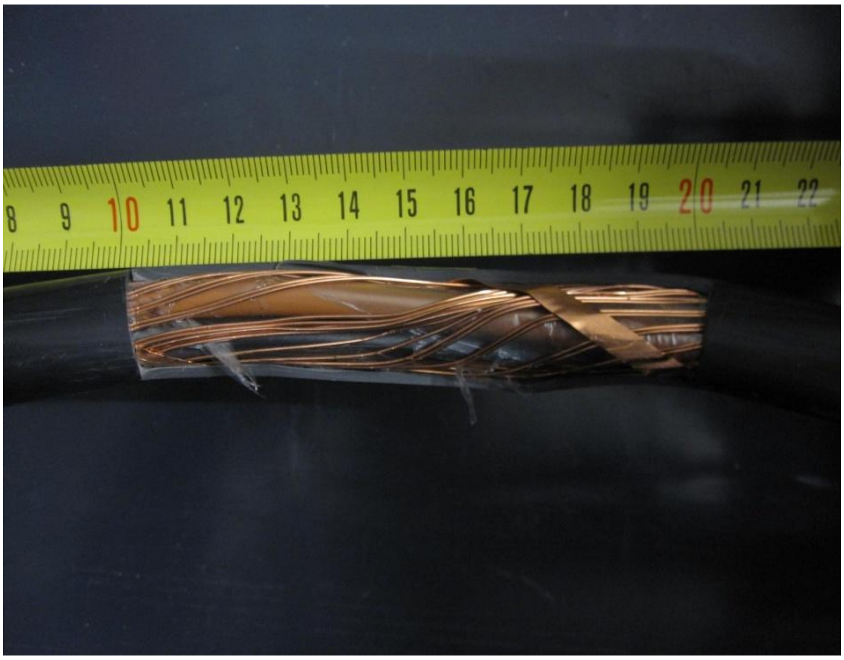

Figure 5.3. AMCMK cable with 10 cm long section of sheath and polypropylene tapes removed.

Figure 5.4. Test setup for long-term measurements. A 10 cm long section of sheath is removed from both cables and cables are submerged under tap water. Wooden clamps keep the cables securely in place and copper plate, which is connected to isolation transformers neutral, simulates the conductivity of the mass of earth.

Impedance, insulation resistance and possible leakage currents of submerged cables were measured regularly. In the beginning, test were carried out multiple times a day, but as the results started to show no change between two or more tests, testing interval was gradually extended to be carried out once a week.

Regular measurements were carried out for 51 days from the day the cables were originally submerged. During that time, there were no sign of increased leakage currents or decreased insulation resistance. Impedance measurements results for AXMK cable are presented in Figure 5.5, and for AMCMK cable in Figure 5.6. Both graphs are measured with cable ends open.

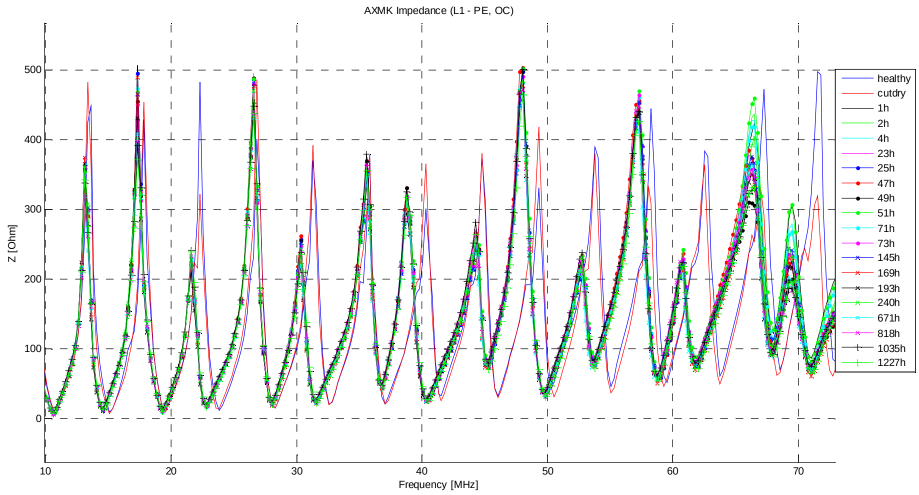

Figure 5.5. Long term impedance measurements of 25 m long AXMK cable sample. Number of hours on different curves point out the duration of which cable has been submerged under tap water with section of sheath removed. ‘Healthy’ and ‘cutdry’ are measured in dry conditions. Open circuit, measured between L1 and PEN.

When water gets under the sheath of cable, capacitance increases. That increases the signal transmission losses, which can be seen as decreased impedance and as shifting of resonance frequency peaks. As it can be seen from Figure 5.5, first noticeable difference between dry measurements (‘healthy’ and ‘cutdry’) and the wet ones can be seen in the frequencies below 20 MHz. However, the most clear difference can be seen in the frequency band from 50 MHz to 70 MHz. After the cable was submerged with section of sheath removed, there were no noticeable change between different measurements at the different time.

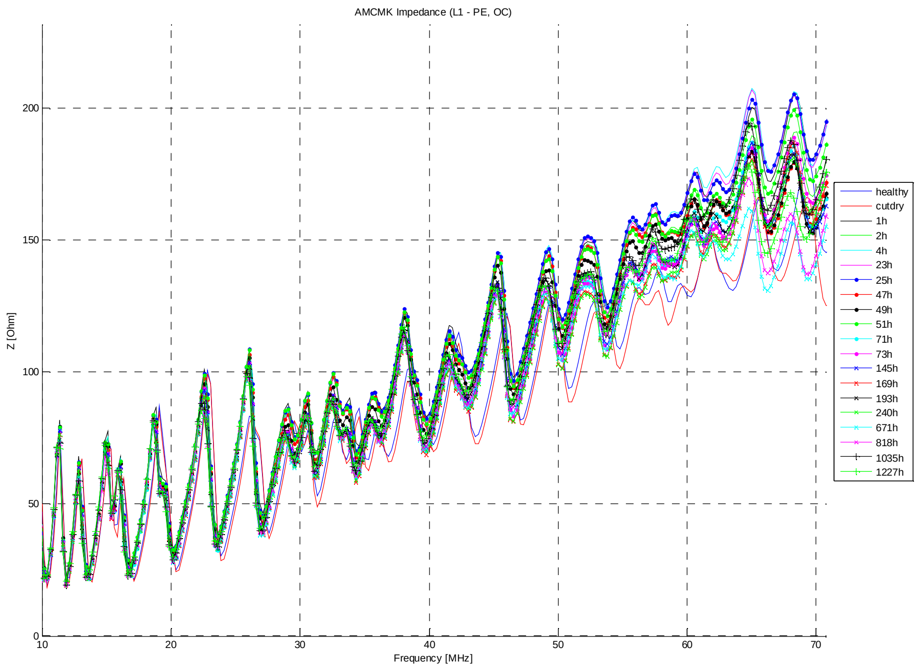

Figure 5.6. Long term impedance measurements of 25 m AMCMK cable sample. Number of hours on different curves point out the duration of which cable has been submerged under tap water with section of sheath removed. ‘Healthy’ and ‘cutdry’ are measured in dry conditions. Open circuit, measured between L1 and PEN.

Difference between dry and wet cables is not as clear with AMCMK as it is with AXMK (Figure 5.5). This is due higher attenuation of PVC, compared to the XLPE. Thus, AXMK or other XLPE insulated cables are more suitable for high frequency signal injection –based condition monitoring than the PVC insulated AMCMK. There are some differences between different wet measurements in the frequency band from 50 MHz to 70 MHz (Figure 5.7).

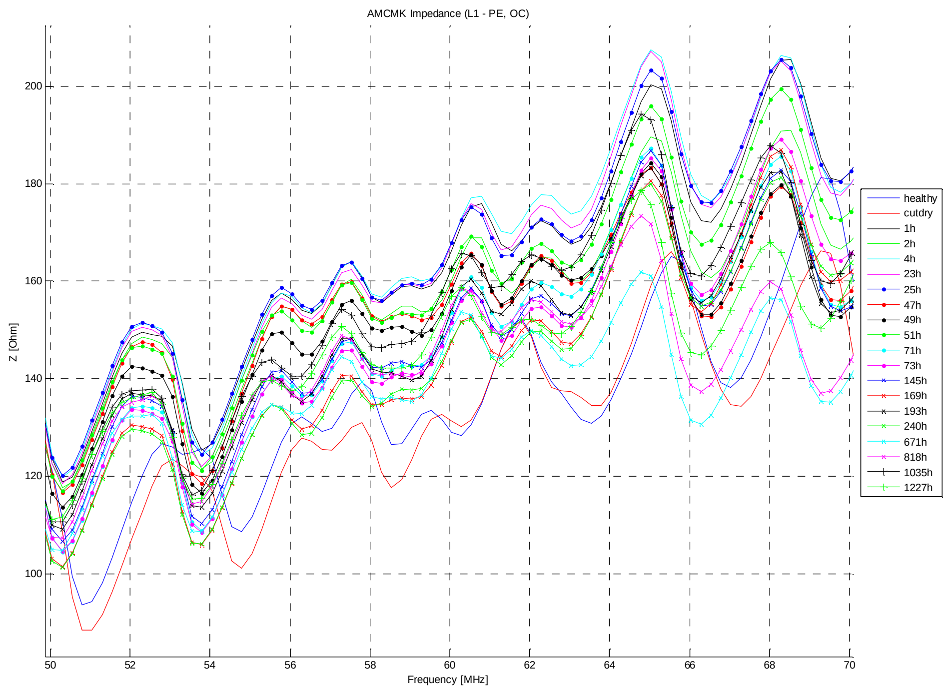

Figure 5.7. Long term impedance measurements of 25 m long AMCMK cable sample. Close up view of Figure 5.6 of frequency band from 50 MHz to 70 MHz. Open circuit, measured between L1 and PEN.

Although the different wet impedance curves are not in a perfectly logical order, there seems to be a trend that when the cable is submerged, impedance first increases. Then, after the cable has been submerged for several days, impedance curve starts to shift down again. One possible explanation could be that the length of the moist section of the cable is first limited to the part submerged under the water, and after the submerged part is thoroughly wet, the moisture starts to propagate longitudinally inside the cable between sheath and insulated conductors due capillary action. This will increase the capacitance, and if inductance remains constant, impedance will decrease. When the test setup was disassembled, it was noticed that several meters long part of the cables were wet, although the submerged part was only about half of a meter long.

It can also been seen from Figure 5.7 that although there are not so big difference in magnitudes of those impedance curves between dry and wet conditions, peaks of dry and wet curves are in the different frequencies. Furthermore, peaks of different wet measurements are in the same frequency, despite that there is some variation in magnitudes between different measurements.

5.1.3 Progressive damaging of insulation

Progressive damaging was done to two 50 m long samples of both cables. Part of sheath was removed similar way as in the long term measurements (Figure 5.3). Damage was done to 17 m from the closest cable end, which corresponds about one third of cable length. Similar water tank and copper plate setup was used as with the long term measurements (Figure 5.4). After mechanical damage to insulation was done, cables were submerged and left under the water for at least for 24 h. Cables were measured multiple times during that period.

With the first test samples, only a small 5 cm long cut was first done to the sheath (Figure 5.8), in order to have some intermittent results as the water slowly penetrates though the cut under the sheath.

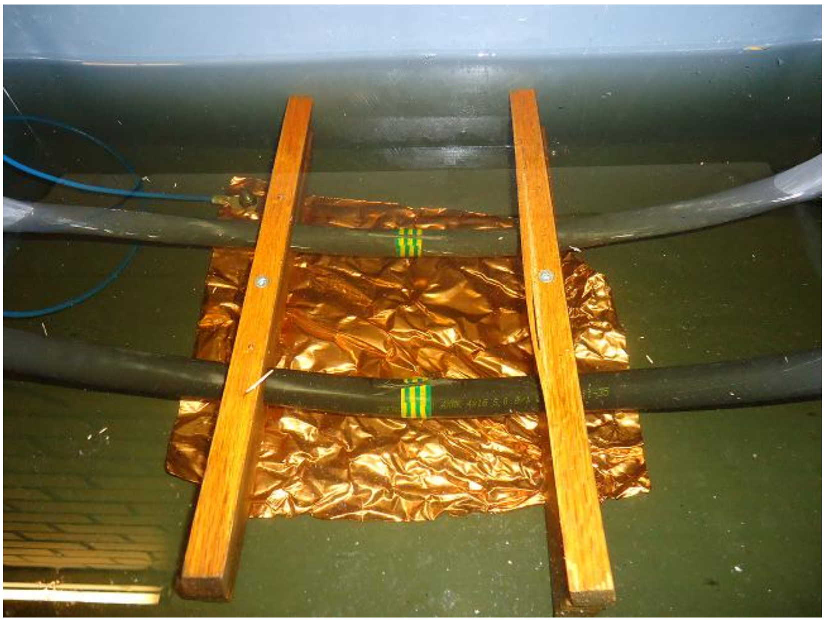

Figure 5.8. Submerged parts of first 50 m samples of both cable types with 5 cm long cut on the sheaths.

After the cables were submerged with the cut on the sheath, three separate measurements were done between 1,5 h interval. Then, larger section of sheath were cut away, and the damaging process of insulation was started. Only phase one (brown) insulation was damaged with the first 50 m samples. Insulation thickness was gradually decreased in three steps, until at the final step 30 x 3 mm area of bare aluminum conductor was exposed. First degree damage to AMCMK is presented in Figure 5.9 and the final degree to AXMK in Figure 5.10.

Figure 5.9. First degree damage on brown phase insulation in AMCMK cable.

Figure 5.10. Final degree damage on brown phase insulation in AXMK cable.

Results of impedance measurements with AXMK cable is presented in Figure 5.11.

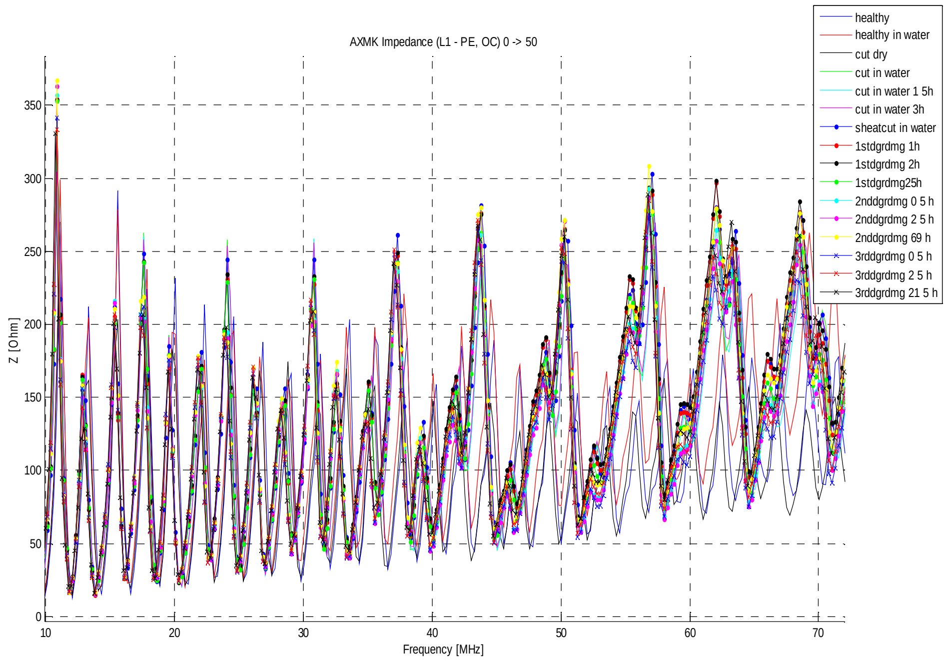

Figure 5.11. Impedance measurements of 50 m long AXMK cable sample with phase one insulation gradually damaged in three steps. Open circuit, measured between L1 and PEN.

Again, it can be seen that there is noticeable difference between dry and wet condition measurements but not so much difference between different grade of damage on the phase insulation after the cable has been submerged. There were no sign of leakage currents or decreased insulation resistance either until the insulation was damaged to that point when phase conductor was visible. Figure 5.12 shows close up view from frequency band from 50 MHz to 60 MHz.

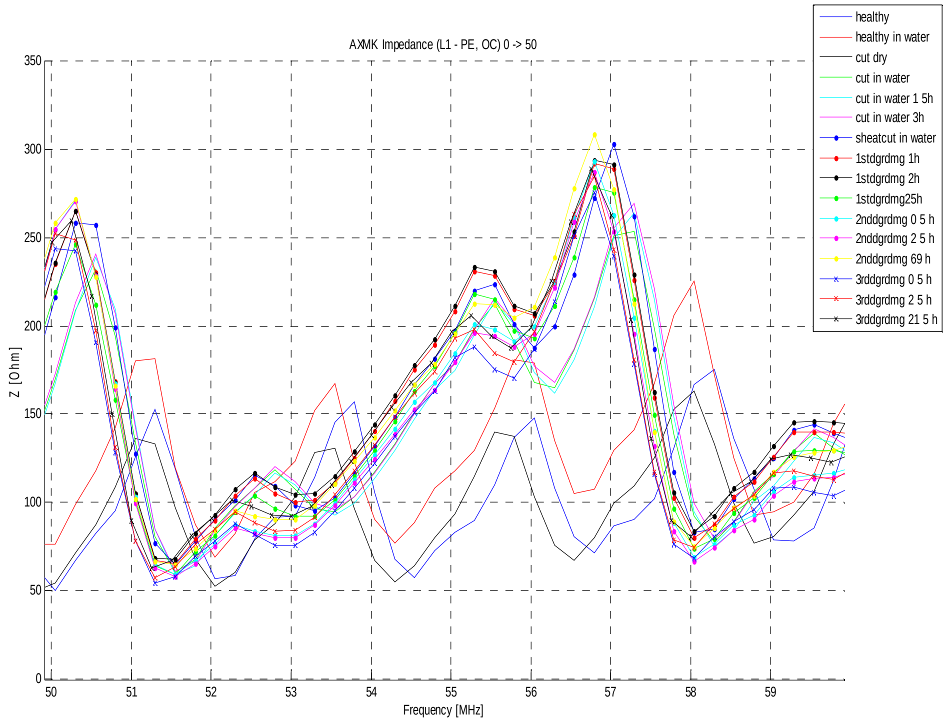

Figure 5.12. Impedance measurement results of progressive damaging of 50 m long AXMK cable sample. Close up view of Figure 5.11 of frequency band from 50 MHz to 60 MHz. Open circuit, measured between L1 and PEN.

Some difference at certain frequencies can be noticed between those measurements where only a small cut was made on the sheath and cable was submerged ('cut in water') and the rest of wet measurements. However, there is practically no change in three different measurements made between 1,5 h interval, so the submerged part of the cable was most probably already wet during the first set of measurements. Possible explanation for the difference between those and the rest of the wet measurements, with larger section of sheath removed, could be that the polypropylene taping was not damaged when the smaller cut was made. Therefore, the water could not get between the phase conductors, only between sheath and polypropylene taping. No noticeable change in impedance between different damage grades.

Second cable samples were damaged similar way, but two phases were damaged instead of one. This will cause the voltage stress over damaged insulations to be higher. With the non-concentric AXMK cable, also the resistance between two phases is lower than between a phase and copper plate due to the shorter distance over poorly conductive tap water. Damaged AMCMK cable with first degree damage on brown and black phases is presented in Figure 5.13.

Figure 5.13. AMCMK cable with first degree damage done on brown and black phases.

Again, the damaged cables were submerged under water and measured multiple times before degree of damage was increased. Because of no noticeable change between different damage grades was seen with the first test samples and because of limited time resources, insulation was damaged only in two steps this time. Second and the final degree of damage on AMCMK cable is presented in figure 5.14.

Figure 5.14. AMCMK cable with second degree damage done on brown and black phases.

AXMK sample was damaged similar way, but damage was done on phase one and phase three insulation. Impedance measurement results of AXMK sample is presented in Figure 5.15 and a close up view from frequency band from 35 MHz to 55 MHz in Figure 5.16.

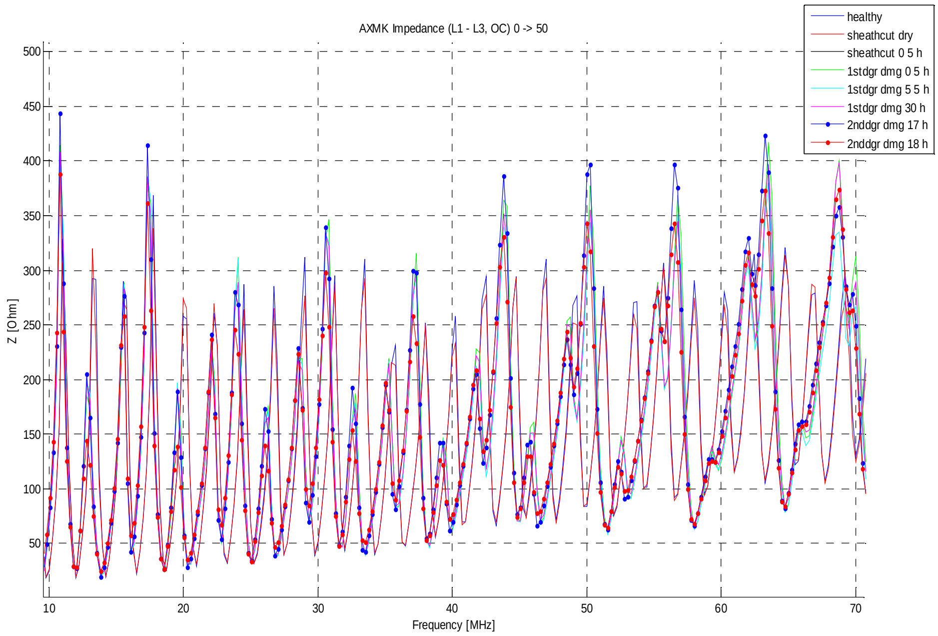

Figure 5.15. Impedance measurements of 50 m long AXMK cable sample with insulation around phases one and three gradually damaged in two steps. Open circuit, measured between L1 and L3.

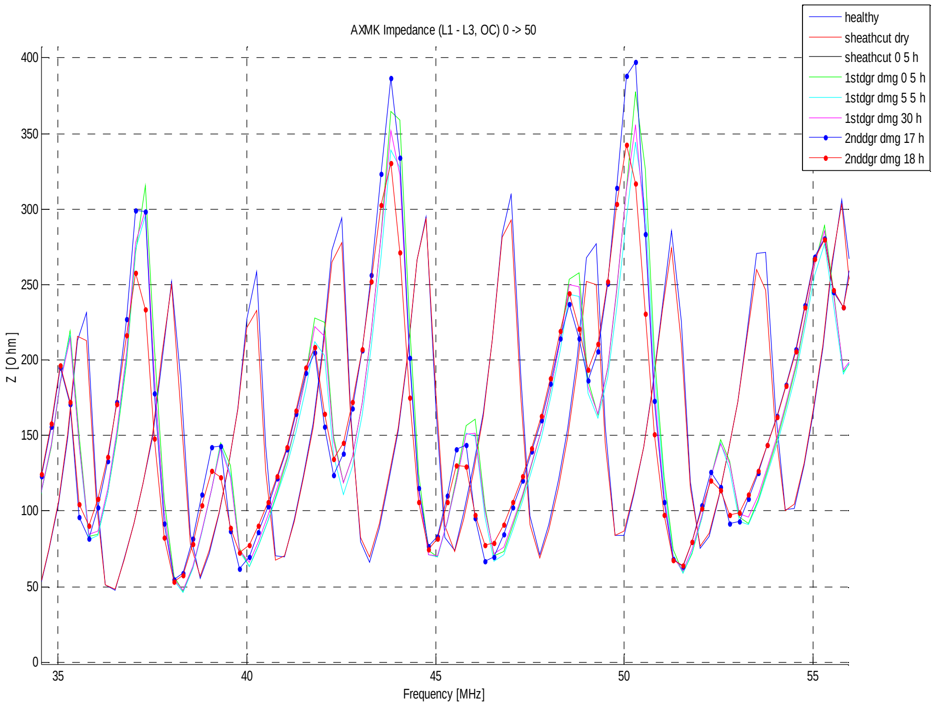

Figure 5.16. Impedance measurement results of progressive damaging of 50 m long AXMK cable sample. Close up view of Figure 5.15 of frequency band from 35 MHz to 55 MHz. Open circuit, measured between L1 and L3.

Again, very clear change in impedance response after the water gets under the sheath. At the certain frequencies, there are also a minor change between the different damage degrees, but considering that the cable with first degree damage would most probably still work and the cable with second degree damage would most probably not work anymore, the change is quite minor.

5.1.4 Grid setup

Measurements were also carried out with a simple grid model in order to identify the effect of joints and branches to the high frequency measurements. These impedance discontinuities will cause reflections to input signal and therefore, make identifying the actual damage from the signal response harder. Topology of the grid is presented in Figure 5.17

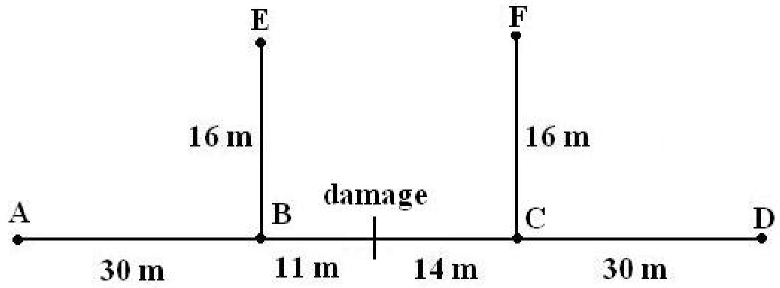

Figure 5.17. Topology of the grid setup. Grid consists of three segments of main line and two branches. Middle main line segment is damaged by cutting of a piece of sheath and submerging the cable under tap water.

Model grid was built using only AXMK –type cable. Open cable ends (A, E, F and D) were taken to the laboratory and every possible combination of cable end pairs were measured using the impedance / gain-phase analyzer and frequency band from 100 kHz to 100 MHz. Both impedance and gain & phase were measured. Branches were joined to the main line using cable lugs (Figure 5.18). Four separate measurements were carried out; to healthy grid, to damaged grid prior to submerging the damaged part, and two set of measurements with damaged segment submerged under tap water.

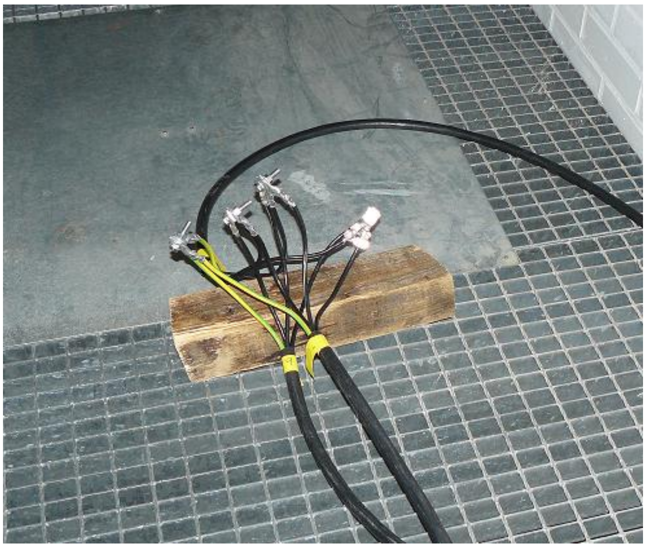

Figure 5.18. Connection point of a branch in the laboratory grid model.

Impedance measurement results from the point A (Figure 5.17) are presented in figures 5.19 and 5.20.

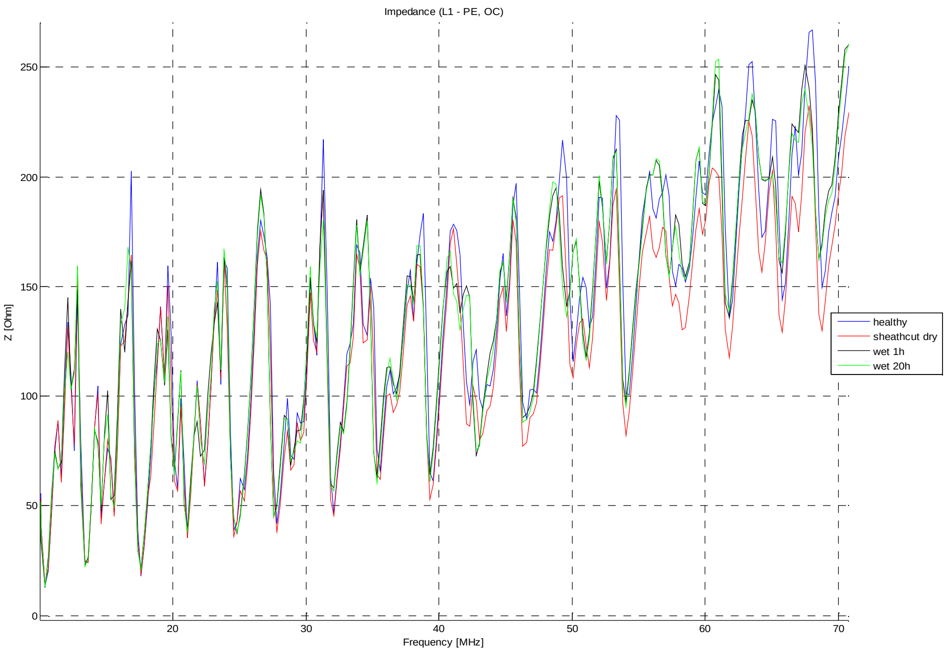

Figure 5.19. Impedance measurement results of grid setup between from the point A. Open circuit, measured between L1 to PEN.

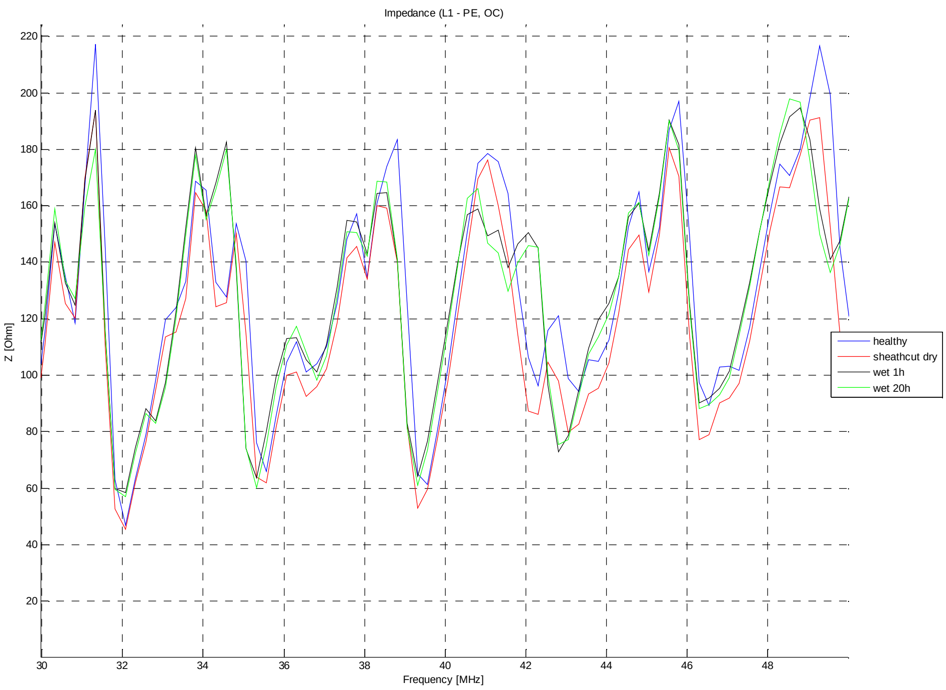

Figure 5.20. Impedance measurement results of grid setup from the point A. Open circuit, measured between L1 to PEN. Close up view of Figure 5.19 of frequency band from 30 MHz to 50 MHz.

It can be seen that there is again noticeable differences in impedance measurements between dry and wet measurements, although there are more noise due reflections from the branches and joints. In figure 5.21, results from gain & phase measurements from A to D (Figure 5.17) are presented in distance domain. Conversion from frequency domain through time domain to distance domain is done by inverse Fourier transform and by assuming a certain propagation speed to the measurement signal (Hernandez, 2012).

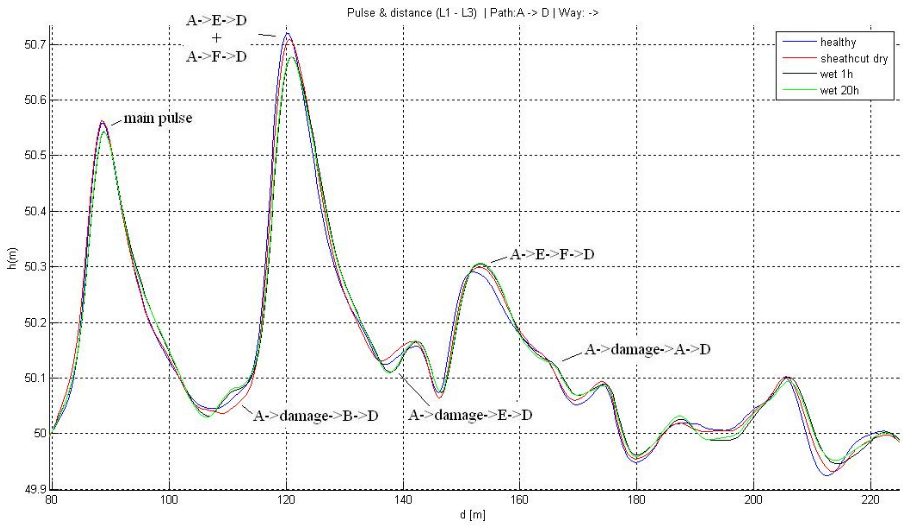

Figure 5.21. Results from gain & phase measurements from the grid point A to the point D presented in distance domain. Measured between L1 and L3 with the end of the branches being open. A value of 0,72 · c was used for signal propagation speed (Hernandez, 2012).

Markings in the Figure 5.21 are related to the Figure 5.17. As it can been seen, reflections from the open ends of branches, from the joints, and from the damaged part of the cable could be identified and located. Length of the connection cables, about 3 m in total, between analyzer and the grid setup should be taken in account when comparing figure 5.21 to the topology of the grid setup. Error in the distance will grow as the distance grows because of the error in the measurement signal propagation speed assumption will accumulate. Signal propagation speed also decreases when the signal passes through the damaged part due to higher capacitance.

5.1.5 Conclusions

There are noticeable difference both in impedance and gain & phase measurements between dry cable and cable with water under the sheath. Differences could be seen at single segment measurements and also with more complex grid model setup. Differences are more clear when using XLPE insulated AXMK than PCV insulated AMCMK. The most clear difference, compared to the healthy cable, comes when the water gets under the sheath and between insulated phase conductors. When phase insulators were gradually damaged, changes in frequency response were quite minor, compared to the change in frequency response between dry and wet cables.

There were no increased leakage current levels nor decreased insulation resistance levels until the aluminum conductor was exposed by removing both sheath and insulation around the conductor. There were no change in those either in long term water test, where both cable types were submerged for 51 days with section of sheath removed.

Test setup, however, did not fully correspond to the real environment. The biggest factor is the conductivity and purity of tap water used in setup. Tap water was chosen due its known properties and controllability of test environment, but lack of salt and other impurities makes it less conductive than actual moisture in soil. Also the line voltage was applied only for couple of minutes at the time due safety and practical limitations of the setup. Therefore, there were no constant voltage stress over the damaged insulation nor recurring heating and cooling cycles of the conductors because no load current was transmitted through the cables. All these factors mentioned could speed up the fault development process in the real installation conditions.

5.2 Implementation to LV networks

In this section, implementation of novel high frequency signal injection –based OCM techniques to LV distribution networks is examined mostly from DSO point of view. More detailed analysis of actual techniques from signal analysis point of view can be found from master's thesis *Channel Estimation and On-line Diagnosis of LV Distribution Cabling.* All ideas and descriptions presented in this section are more or less theoretical and further study is needed to determine whether this kind of system would actually be possible to be implemented to LV networks.

5.2.1 Communication between OCM system and network control software

Utilization of OCM requires data transmission between the OCM systems located on networks and network control room. Due the slowly progressing nature of incipient cable faults, data transmission would not have to be real time. If each monitored network includes its own embedded control system and fingerprint of the healthy networks frequency response, data transmission to the control room is only required when network is actually damaged and when occasional connection tests are made. Required bandwidth for the alarm is also very low, for example, including only the network and feeder IDs and the distance of possible damage from the secondary substation or from the customers connection point. Therefore, requirements for the data transmission channel between the OCM system in LV network and network control room are minimal, which allows many different options to be taken in consideration.

One interesting possibility is to take advantage of expanding automatic meter reading (AMR) -network. By the end of 2013, DSOs are required to have 80 % of their customers within the AMR system (A 1.3.2009/66). The main purpose of an AMR meters is to provide real time energy consumption data. However, installation of AMR meters is such a huge project that using them solely for energy metering is not economically profitable. Therefore, studies have been made in order to develop AMR meters towards being a smart terminal unit rather than just an energy consumption metering device (Keränen, 2009).

Finnish DSO *Vattenfall Verkko Oy* has successfully integrated the real time measurements from AMR meters to distribution management system (DMS) and implemented so called AMR-DMS system. AMR-DMS provides real time information about the state of LV networks at network control room. Certain situations, for example, voltage unbalance or zero conductor faults cause an alarm to appear on DMS (Keränen, 2009).

This integration of AMR meters and network control systems provides a possible way to connect the OCM system to network control room using the existing AMR reading system and AMR-DMS integration. The principle of AMR-DMS system and possible integration of OCM through AMR reading system is presented in Figure 5.22.

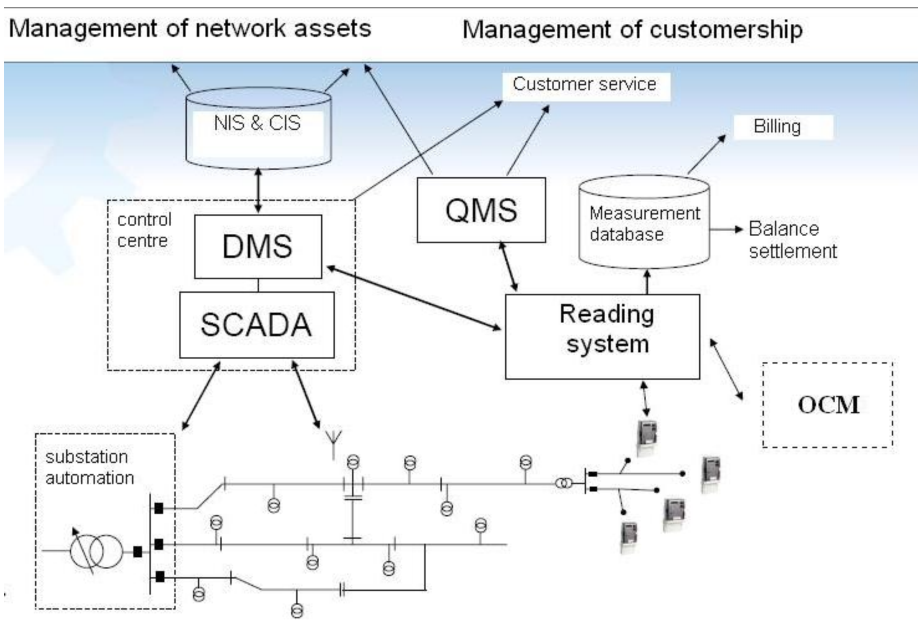

Figure 5.22. Possible integration of OCM to AMR-DMS system. (Modified from: Keränen, 2009)

In rural areas, communication between meters and reading system is usually handled directly via GSM/GPRS network. In more densely populated areas, communications between meters and reading system are centralized. Example of communications between AMR meters and reading system in both cases is presented in Figure 5.23.

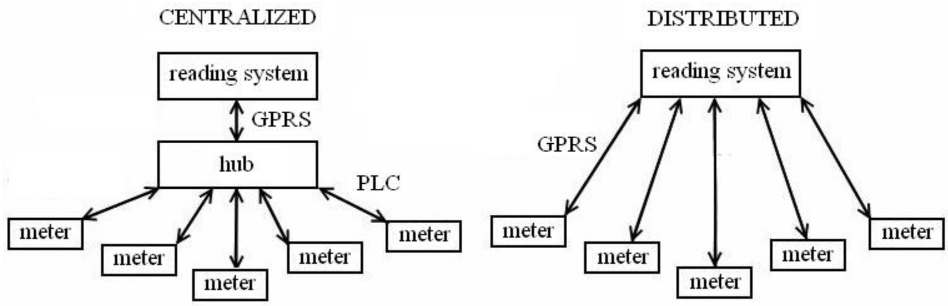

Figure 5.23. Examples of centralized and distributed communications between AMR reading system and meters. (Modified from: Valtonen, 2009)

In centralized communication architecture, a hub, located usually at secondary substation, communicates with meters via PLC or via radio and collects the data from each meter. Data gathered from meters is then sent from the hub to AMR reading system using, for example, GPRS connection. In distributed communications architecture, meters have direct point-to-point connection to the reading system (Valtonen, 2009).

5.2.2 Description of the OCM system

Main components of the OCM system would be the high frequency signal transmitter and receivers, embedded control system with the frequency response from the healthy network and communication between the transmitter and receivers. One transmitter unit could be installed at secondary substation, while the receivers could be integrated to the AMR meters at customer connection points. Rough presentation of system is presented in Figure 5.24.

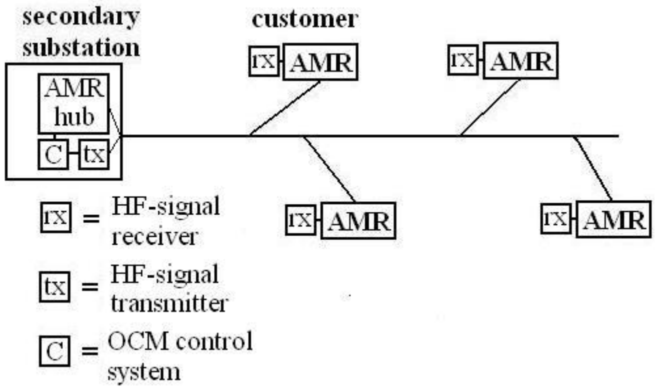

Figure 5.24. OCM system implemented to LV network with centralized read AMR meters.

Control system at substation uses the high frequency signal transmitter to transmit a high frequency sweep to the network at specified time interval. This interval could be, for example, once a day. Receiver units at customer connection points then receive that signal and store it temporarily to memory. Next, receiver units take advance of the AMR meters by sending received signal back to secondary substation using the communication between meters and the AMR hub. Control system reads the received signals and compares them to the previously stored fingerprint from healthy network. If comparison shows constant change in response, which exceeds the preset boundaries for multiple subsequent measurements, it changes the state from healthy to damaged. Next time the AMR meters are being read in that LV network, declaration of possible damaged cable reach the DMS though AMR reading system.

The first problem is to get the frequency response fingerprint from a certainly healthy network. If it is measured, then usability of this OCM system is limited only to new, certainly healthy LV networks. Even then, if a cable is damaged during installation and it is already wet when the fingerprint is being measured, system would not work properly. Also loads and nonlinear power supplies can cause problems to measurements. An ideal case would be that the fingerprint could be simulated by knowing the exact lengths and types of cables and joints used. Problem with the simulation is to get the models accurate enough to correspond with the real networks.

Second serious challenge to be solved is to determine the correct time to repair or replace a cable which is reported to have moisture under the sheath by OCM. Only conclusion from laboratory measurements, regarding to the lifetime of wet thermoplastic insulated LV cables, was that they survive at least two months with sheath partially removed under regular tap water. In order to determine the time it takes from that point when sheath is damaged and the moisture gets under the sheath, to the point when cable is no longer capable of carrying power, some real long-term tests are needed to be done in real installation environments with constantly energized cables carrying varying load currents. That kind of experiment, however, would take a lot of time and a lot of different cables in different installation conditions before anything conclusive results could be obtained.

According to the laboratory measurements, first noticeable changes in frequency response between healthy and wet cables could be seen at frequencies above 20 MHz, while the most clear results were usually between 40 - 60 MHz. Using such high frequencies, also signal attenuation causes problems and it sets a limit to the longest possible distance between transmitter and receiver units. Higher frequency causes more attenuation and shortens the maximum usable distance. For example, when using 30 MHz frequency, maximum distance for PVC insulated AMCMK would be 100 - 200 m. (Ahola, 2012)

Because customers are constantly changing the amount of load in the network, also the impedance seen from the network changes. This could cause problems to the measurements and therefore, measurements should be carried out during a night when variation of loads is at the lowest. There are still some base loads switching on and off though, such as heating appliances and refrigerators.

Measurement signal gets reflected from every impedance discontinuities, such as joints and open cable ends. Therefore, customer internal networks could cause problems to measurements due numerous reflections back to the distribution network direction. At densely populated urban areas, one secondary substation could have over ten different LV feeders. If the measurement signal is transmitted to the every feeder simultaneously, reflections from numerous branches at different feeders could also cause problems.

In order to prevent the reflections from customer internal networks and from different LV feeders, some signal filtering is needed. Filtering can be done either with hardware -based low pass –filters, or possibly, with software algorithms. The main problem with hardware filters is extra costs and increased power losses. One LV network can consist of over ten feeders and tens of customer connection points. Thus, cost from filters could easily increase the total implementation costs of OCM system per LV network, even though the cost of one filter is relatively low. According to source, pulse from TDR device can be filtered with simple series inductance, made from several turns of heavy duty flexible connection cable (Clegg, 1993 p.223). This would be very cheap solution, and if the cross section of the cable in the filter coil would be large enough, practically no extra losses are caused.

The main problem is physical size and placement of such coils. Filter coils must be connected in series between feeders and busbars at secondary substation and between AMR meter and customer internal network at customer side, i.e. so that communication between transmitter and receiver units and between AMR meters and AMR hub are not blocked. Thickness of the wire in customer side coils, however, could be much smaller than the thickness in secondary substation side, which makes them more compact in size.

Need of hardware –based filters could theoretically be avoided by using intelligent software algorithms. This would decrease both implementation costs and complexity of the OCM –system. However, those algorithms would need further research before usability of those could be evaluated and they are ruled out from consideration in this thesis.

The LVDC system, described in section 2.2, would solve the signal filtration problem, due to galvanic isolation between distribution DC-network and customers connected to it via inverters. Combined to the higher costs from a fault due higher transmission power capabilities, implementing the OCM system to LVDC system seems to be more promising than implementing it to the traditional LV AC system. Embedded control system in inverter units could also be taken advance of by integrating the OCM control system to the inverter units. This would decrease the implementation costs of OCM as the same hardware could be used to control both the inverter and the OCM system.

6 Economic evaluation of novel condition monitoring methods

When considering the utilization of novel techniques which requires investments to be done, both technical and economic analysis are needed. Technical aspects usually determine only the preconditions and whether the implementing of the new technique is possible or not. Actual decision about investment is usually done from economic aspects. Evaluation of a possible new investment in economical point of view is relatively straight forward task. First, all of the costs and benefits the new investment produces are needed to be determined. Then they are converted to comparable form with each other. Costs and benefits are then being compared and thus, revenue from possible investment can be calculated.

Non-recurring investment costs I can be divided to long term annual costs by using annuity method. Annuity AN is calculated

$$\mathrm{AN} = \frac{p/100}{1-\frac{1}{\left(1+\frac{p}{100}\right)^{n}}} \cdot I, \qquad (6.1)$$

where p is the interest rate per year and n is the number of years (Lakervi et Partanen 2009).

Annuity means equally sized annual costs, which are needed to cover the capital of investment and interest costs during the economic life of investment. Profitability of the investment can be evaluated by comparing the annuity to annual revenue or cost-savings produced by investment. (Lakervi et Partanen, 2009)

Although the evaluation method itself seems to be relatively simple, determining and evaluating all of the costs and benefits can be difficult. Especially when evaluating the implementation of totally new system, calculations are only indicative.

6.1 Fault costs

Nowadays, declaration about fault in LV network, in most cases, comes from end-customers. In the future, AMR meters could also be used as LV fault indicators. After the information about the fault has reached the DSO, repair crew is dispatched to fault site. Fault is then needed to be located by using methods described in section 3.4. As mentioned, fault locating can be time consuming, or in some unstable cases, even impossible until the fault becomes permanent. After the exact location of the fault is revealed some excavation is done, faulty part is cut away and replaced with a short segment of new cable. Throughout this whole period, some of the customers will most probably suffer an outage. Typical LV underground cable fault repair procedure and duration of each step are presented in Table 6.1. (JE-Siirto, 2012)

Table 6.1. Typical fault repair procedure and average duration of each step.

Step	Duration [h]
Analysis and pre-location	1
Pin-pointing	2-3
Excavation and repair	1-4
Total	**4-8**

DSOs have, depending the size of distribution network, one or more workers on call or a contract with an external service provider, in case a fault occurs outside office hours. In such cases, faulty cable can be temporarily bypassed with an on-ground cable or customers can be temporarily fed using mobile generators, while permanent repair is done later (Pavo, 2011). Thus, fault occurring during weekend or during night, could cause two separate interruptions and increase both labor and equipment costs.

When considering the possible benefits from OCM in LV cable networks, first logical step is to determine the costs a fault in LV network causes to DSO. Different fault-cost components are:

- Outage costs
- Equipment costs
- Labor costs
- Material costs

Outage costs consist of undelivered energy and harm caused to the customers, or HCC. Revenue loss from undelivered energy is very marginal, and therefore, it can be ignored. Monetary value for HCC has been determined by WTA/WTP – survey, asking customers how much damage an outage will cause to them and how much they are willing to pay for better reliability (Silvast et al. 2005). Outage cost parameters, based on results from the survey, are presented in Table 6.2.

Table 6.2. Outage cost parameter for different customer types. (Honkapuro et al., 2006).

Customer type	Unplanned interruption		Planned interruption	
	€ / kW	€ / kWh	€ / kW	€ / kWh
Residential	0,36	4,29	0,19	2,21
Agriculture	0,45	9,38	0,23	4,80
Industry	3,52	24,45	1,38	11,47
Public consumption	1,89	15,08	1,33	7,35
Commercial	2,65	29,89	0,22	22,82

Monetary value of HCC is dependant from the customer types and average interrupt power, outage type and outage duration. Annual HCC for network part under consideration can be calculated

$$\mathrm{HCC} = (\Delta P f l)(\mathrm{A} + t\mathrm{B}), \tag{6.2}$$

where ΔP is interrupt power, f is fault rate, l is network length, A is outage cost parameter €/kW, t is average duration of outage and B is outage cost parameter €/kWh.

DSOs are also required to pay compensation to the customers for outages lasting over 12 h, but average repair time for single incipient cable fault is usually below that. Furthermore, if repair would take considerably long time, faulty cable can be temporarily replaced with an on-ground cable, or customers can be fed using mobile generators. Therefore, compensation payments are ruled out from consideration.

Labor costs are dependent on the number of workers assigned to fault and the total duration of repair work, including the transitions and loading/unloading materials and equipment. Repair crew usually consists of one or two technicians when underground LV cables are being repaired (JE-Siirto, 2012 & Pavo, 2012).

Faults occurring outside office hours will increase the labor costs. Some DSOs have outsourced the repairs, in such case, hourly labor cost is a cost that external service provider charges from DSO. When DSO uses its own technicians, hourly cost of individual technician is wage plus insurances, pension contribution and other employment costs. These costs are taken in account by multiplying the employees hourly gross wage by a rough multiplier 1,7. Hourly wage, including all additions, of an average network technician could be assumed to be roughly 15 €/h (CLA, 2010), therefore, estimated cost of 25 €/h per technician is used to evaluate the labor costs.

Equipment costs consists mainly of excavating costs, operating costs of vehicles and possible operating costs of mobile generators. Excavation costs vary considerably depending on location of the fault site. Excavation in urban conditions is more expensive and time consuming because of paved streets and traffic. There are also numerous other underground cables and pipes running under the streets, which must be taken in account. Independent contractors charge DSOs between 60 - 100 €/h for excavating (JE-Siirto, 2012 & Pavo, 2011).

Operating costs of a mobile generator consists of maintenance and fuel costs. Fuel costs depend on the amount of energy produced, size and type of generator and the unit price of the fuel used. Fuel consumption of modern diesel generator is around 0,3 - 0,4 l/kWh (Diesel S&S 2011), depending on the size and load of generator.

6.2 Benefits from OCM

Providing 'real-time' information about condition of the LV underground cables, OCM can be utilized to increase the reliability of LV networks. Damaged cables could be repaired or replaced prior to permanent fault occurs. Therefore, considerable fault cost savings could be achieved with OCM -based preventive maintenance.

Average duration of interruption could be decreased significantly with OCM -based preventive maintenance. By knowing the exact spot of a defect in the cable, repair work can be prepared and planned in advance. Network technicians, required material, and equipment can be sent to the site and damaged part can be excavated up prior to disconnecting the cable. This will save not only interruption time, but also man-hours as time consuming fault location on site can be avoided.

Preventive maintenance will also decrease the number of unplanned interruptions. Customers can be informed in advance if interruption is needed and the interruption can be scheduled so it causes as minimal harm to the customers as possible. In some cases, interruption can be entirely avoided if network is interconnected and damaged cable can be temporarily bypassed. Also temporary on-ground cables or mobile generators could be used to maintain service during repairs.

Statistically, OCM, combined with efficient preventive maintenance system, will decrease the number of unplanned faults as well as average duration of a fault in LV network. This will improve the whole distribution systems reliability and possibly in some rare cases, it could be an alternative option to more expensive investment in MV network in order to increase the systems overall reliability.

The biggest fault cost savings will come from lower outage costs and from lower labor costs. Unplanned interruptions could be avoided by repairing or by replacing the damaged cable during planned interruption before it gets permanently faulty. Time saved from avoided fault analysis and fault location decrease both outage and labor costs. The effect of OCM on interruption type and duration and on labor costs in a typical LV cable fault, based on Table 6.1, is presented in Table 6.3.

Table 6.3. The effect of OCM on interruption type and duration and on labor costs in a typical LV cable fault.

Cost component	Without OCM [h]	With OCM [h]
Unplanned interruption	4-7	-
Planned interruption	-	0-2
Labor needed	5-8	2-4

There are also other minor possible savings that could be achieved by OCM. However, estimating a monetary value to those is very difficult and in addition, they are more speculative than those presented earlier. Therefore, they are only described shortly and they are not included in calculations.

Once the moisture gets under the damaged cable sheath, it could propagate longitudinally between the sheath and main insulation. If the insulation is intact, it could take considerably long time before the moisture causes an electrical fault. Over that time, the moisture propagates inside the cable and deteriorates the insulation over constantly growing length. Thus, by replacing the moist section of cable shortly after moisture under the sheath is detected, replacement of longer length, or at its worst, the whole cable could be avoided.

If the damaged cable is a part of a LV network which is reached close to its maximum transmission capacity and thus, it is due to be renovated in the near future, renovation could be planned and done at the same time as the damaged cable is being replaced. Without OCM, the fault will occur without a warning and most probably, only the faulty cable is replaced and the rest of the network is renovated later.
OCM allows also to schedule the excavation so that it causes minimal harm to traffic. When fault occurs under street in urban areas, excavation usually requires a permit from city officials.

Information gathered from OCM system could be also utilized in development of installation techniques and maintenance strategies. For example, different installation techniques could be compared by the proportion of damaged cables within a year from installation. Similar long-term test, than described in section 5.1.2, for cables with damaged sheaths could be done in real installation conditions by allowing a couple of damaged cables to develop an electrical fault. Results from those tests could then be used later to determine the optimal timing when the damaged cables should be replaced after being reported to be wet.

6.3 OCM costs

Costs from implementation of OCM system would be formed by hardware costs, installation costs, possible data transmission costs, software update costs and training costs of employees. System level costs, such as software updates and training of employees are not fully dependent on the number of actual OCM systems installed. Thus, system level costs per installed OCM system will decrease as the number of OCM systems, or on-line monitored LV networks, increase.

Evaluation of costs from implementation of totally new system is always only an indicative estimation. However, research and practical experiences from implementing of AMR meters could give some rough guidelines what would the installation and integration to the network management system costs be. Each year EMA (Energy Market Authority) publishes normative unit prices for different network components. According to the unit price listing for 2012, an AMR meter with nominal current 63 A or less, costs 200 € (EMA, 2012a). This price includes the price of the meter, in addition to installation, planning and other indirect costs caused to the DSO.

A study estimates more detailed costs from installation of AMR meters in Great Britain. Estimates are done in 2007 and with an assumption of 300 000 meters to be installed. Those estimates are presented in Table 6.4.

Table 6.4. Estimates of costs from installing AMR meters in Great Britain 2007 (Owen & Ward 2007).

	Cost [£]	Cost [€], 1 € = 1,226 £
AMR meter	25…35	31…43
Communications with GSM / GPRS (direct)	30…40	37…49
Communications with PLC or Radio	PLC: 15 Radio: 15…25	PLC: 18, Radio: 18…31
Installation	25…30	31…37
Meter + Communications + Installation	65…105	**80…130**

Cost estimates do not include any running costs. These estimates, together with the total cost for one AMR meter given by EMA, could be used in order to get some estimation of costs from implementation of OCM. Price given by EMA includes all direct cost components presented in Table 6.4, in addition of some indirect cost components, such as planning. By subtracting the direct costs per installed meter from the total price given by EMA, 70…120 € value for the indirect costs per installed meter could be achieved. This could be used as a rough estimation of indirect system level costs per installed OCM system. However, the study is made in 2007 and in Great-Britain where general price levels are different than in Finland, which could distort the comparison of these two different prices.

Existing communications from AMR meters to secondary substation and from secondary substation to AMR servers could be used, so communications would not necessarily cause any extra costs. Future generation of AMR meters could be equipped with receivers capable of receiving the high frequency measurement signal, so only physical installations would have to be done at secondary substation. Expected lifetime of currently installed AMR meters is around 15 a, so they need to be replaced in any case at the some point.

Hardware costs at secondary substation would be formed from high frequency signal transmitter, OCM control system, cabling, coupling interfaces, and miscellaneous accessories.

Cost for high frequency signal transmitter and receivers could be estimated from the cost of HomePlug AV –adapters. HomePlug AV –adapters utilize the PLC technique to transfer data via internal power network of a building. Adapters use frequency band from 2 MHz to 28 Mhz (Homeplug, 2012). Cheapest HomePlug AV –adapters cost less than 30 € (Verkkokauppa, 2012). Thus, cost of transmitter and receiver units would be minor when compared to total implementation costs of the OCM system.

If the OCM system would be productized and those systems would be installed to a wide range of LV networks, some company or companies would start to manufacture and sell the OCM systems as a package. Therefore, price of such system is not formed only from the costs of different components, but it has to cover also all manufacturing costs and a certain net margin for the manufacturer. Only reasonable way to get even some kind of estimation of the hardware cost of the whole system is to look for some finished product which is even somehow related to on-line condition monitoring of the LV networks.

One reference for whole hardware costs evaluation could be EDFmodGSM-230 –power quality module by MX Electrix Oy. Module is designed to be attached to the distribution network at customers connection point or at secondary substation and it monitors multiple power quality factors, such as phase voltages, total harmonic distortion (THD), flickering, etc. EDFmodGSM-230 is a finished product and it includes all necessary components to independently monitor and report the quality of power. It can also automatically send an alarm via GSM/GPRS network when preset boundaries for monitored variables are crossed. Price of an EDFmodGSM-230 module without installation costs and VAT is 580 € (MX Electrix, 2012).

Installation costs consists of labor costs and possible costs from a planned interruption. Installation costs are greatly dependent on that whether it is needed to pay a visit at every customer connection point and whether it is needed to cause a planned interruption. If customer side receiver units and possible low pass filters are integrated to the next generation of AMR meters, it the best case scenario, interruption could be avoided and only installation work is needed at the secondary substation. Installation costs could then easily be less than 100 €, if a worker costs to the DSO 25 €/h. Otherwise, if LV network feeds, for example, 50 separate customers and installation work is needed to be carried out at every customer and planned interruptions are needed, it is clear that total implementation costs would exceed the possible cost savings from the OCM system.

By adding up the installation costs, hardware costs and indirect costs, in the very best case scenario, total implementation costs of OCM per LV network could be around 1000 €. However, this would require a lot of integration to the next generation of AMR meters.

6.4 Application potential

Estimation of costs from implementation of totally new technique, as the OCM in LV cable distribution networks would be, is really difficult. Therefore, it is more reasonable to try to estimate how much the total implementation costs are allowed to be, compared to the annual cost save potential of the system. The maximum allowed implementation cost using different parameters can then be compared to rough implementation cost estimates to figure out the economic potential of the system.

Annual cost save potential from OCM is estimated based on the real fault statistics from two Finnish DSOs, as well as interviews concerning the fault repair procedures and typical durations in LV underground cable network faults. Obviously, these calculations are only indicative and they can vary considerably between different locations and companies. Therefore, sensitivity analysis is needed to figure out the effect of different parameters to the results.

The following curves show the break-even point for the total implementation costs of OCM for one LV network as a function of average interruption power from a cable fault. Savings in outage costs, labor costs and equipment costs are taken in account based on the information presented in sections 6.1 and 6.2. Equations are presented in Appendix I. Following parameters are used as a standard baseline and only the new values of parameters which are altered from these, are presented later:

Parameter	Description
l = 2000 m	length of the network covered with OCM
f = 0,6 [1/100 km, a]	fault rate for incipient faults
n = 15 a	lifetime of OCM hardware
p = 5 %	interest rate
t_f = 5 h	duration of fault interruption
t_{pi} = 1 h	duration of planned interruption
t_{rf} = 7 h	labor bound to fault repair
t_{rp} = 3 h	labor bound to planned repair
c_{lf} = 50 €/h	unit cost of labor for fault repair
c_{ef} = 50 €/h	unit cost of labor for planned repair
c_{lp} = 80 €/h	unit cost of equipment for fault repair
c_{ep} = 80 €/h	unit cost of equipment for planned repair
A, B	outage cost parameters from table 6.X

Network length is the total combined length of all LV feeders, i.e. the length which ‘collects’ the faults to that specific network according to the average fault frequency of incipient cable faults. Average interruption power means the average power of those customers who suffer an outage when a fault strikes to a random location of the network. Average interruption power is dependent on the network average power and topology, such as number of LV feeders and possible second level fuse protection inside distribution cabinets.

Three example LV networks from *Koillis-Satakunnan Sähkö Oy* are used as a reference for network lengths and average power of feeders. Networks are located in the centers of small cities, Ähtäri and Virrat. Key facts about those LV networks are presented in Table 6.5.

Table 6.5. Key facts about example LV networks.

Size of transformer [kVA]	Number of feeders	Total length of network [m]	Average power of different feeders [kW]
800	8	2270	2…58
500	7	3240	4…76
500	5	2115	16..30

Figure 6.1 shows the break-even point of implementation costs of OCM to a single LV network for three different customer types; residential, public consumption and service. OCM is assumed to turn a 5 h unplanned fault interruption into a 1 h planned interruption.

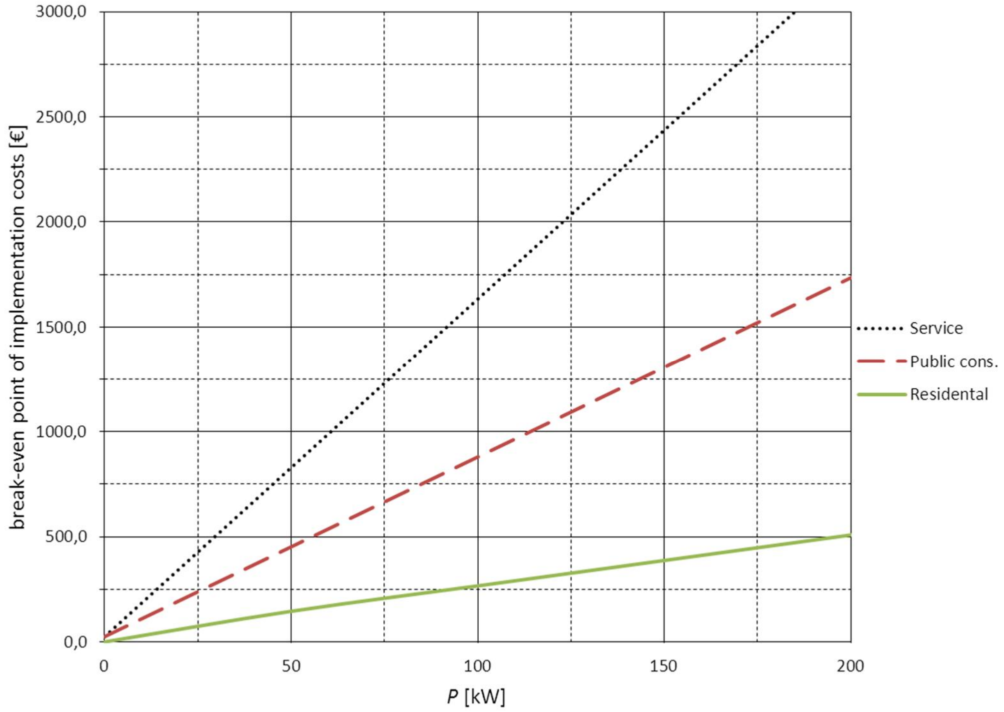

Figure 6.1. Break-even point of implementation costs of OCM to a single LV network as a function of average interruption power. No interconnections available to bypass the fault. OCM is assumed to drop the duration of interruption from 5 h to 1 h.

Outage costs form a majority of fault costs when interruption power is as high as over 100 kW, as it can be in urban areas. Therefore, different outage cost parameters have major impact on the cost save potential from OCM, and thus, on the break-even point of implementation costs.

More critical service type customers usually consume a lot more power than residential type customers and they often have own secondary substations, or at least the secondary substation is located near to them. Thus, average length of the LV network between substation and service customer is shorter than the average length of LV network between substation and residential customer. Therefore, the actual fault frequency which cause an interruption to service type customers is probably lower than the average fault frequency for whole LV network.

If the duration of fault repair seems to take more than few hours, or some critical customers, such as shops, are involved, temporary solutions like on-ground cables on mobile generators could be used to return the supply to the customers, even though the network is not built interconnected. Therefore, Figure 6.1 presents close to a best case scenario from the OCM potential point of view, because 5 h is sufficient time to restore the supply somehow in almost any LV cable fault case.

In densely populated areas, LV networks are usually built interconnected so the faulty cable can be bypassed by changing the switching state of the LV network. Therefore, interruptions caused by incipient cable faults could be avoided entirely by utilizing OCM in interconnected networks. At the same time, interconnections also decrease the interruption time without utilizing OCM as the supply for majority of customers could be returned as soon as the fault is narrowed to a single cable or to a pair of parallel connected cables. Figure 6.2 shows the break-even point of implementation costs for three different customer types when interruption lasts 2h without OCM and when it could be avoided entirely with OCM.

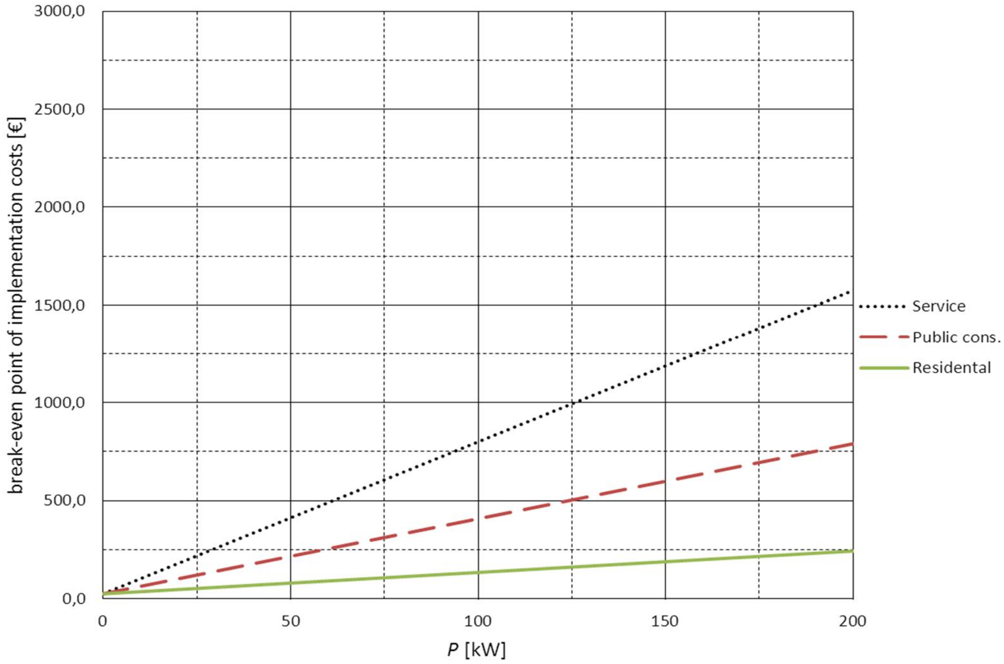

Figure 6.2. Break-even point of implementation costs of OCM to a single LV network as a function of average interruption power for different customer types. Interconnected network, no interruption when OCM is utilized and 2 h interruption without OCM.

Although the interruptions from incipient cable faults in interconnected network could be entirely avoided with OCM, the cost save potential from OCM is lower than in network without interconnections (Figure 6.1). This is due the fact that duration of unexpected faults also decrease as the supply to the majority of customers could be returned using the interconnections prior to the most time consuming part of repair procedure, pin-pointing of the fault and excavating, is started.

When comparing Figure 6.2 to the average power of feeders from example LV networks from KSS (Table 6.6), it seems that implementing the OCM to the LV network which feeds solely residential type customers is not economically profitable with given parameters. It should be noted, though, that example networks represent underground networks from cities with less than 10 000 residents. Thus, average transmission power of feeders located more densely populated cities would most probably be higher.

Fault frequency for incipient cable faults 0,6 / 100 km, a is obtained from six year fault statistics from two DSOs, *Parikkalan Valo Oy* and *Rovakaira OY*, totaling about 2300 km of LV underground cable network. Incipient faults were filtered from the record of all cable faults by removing all abrupt faults with obvious cause, for example, which were caused by an excavator. Obtained incipient cable fault frequencies for those companies were 0,55 and 0,65 / 100 km, a.

Although it seems that the deviation in incipient cable frequency between those companies is relatively low, the amount of data is too low for reliable statistical analysis. Fault statistics were asked from several DSOs, but only those two companies eventually provided them.

Incipient fault frequency is dependent on the average age of LV cable network, cable types used, installation methods, average soil type and other natural factors, such as ground frost. Therefore, it can vary considerably between different areas. Figure 6.3 shows the impact of different fault frequencies on the break-even point of implementation costs of OCM. Network is assumed to be interconnected and the average power is assumed to be divided in ratio of 70-30 between residential type and service type customers, corresponding a typical urban LV network.

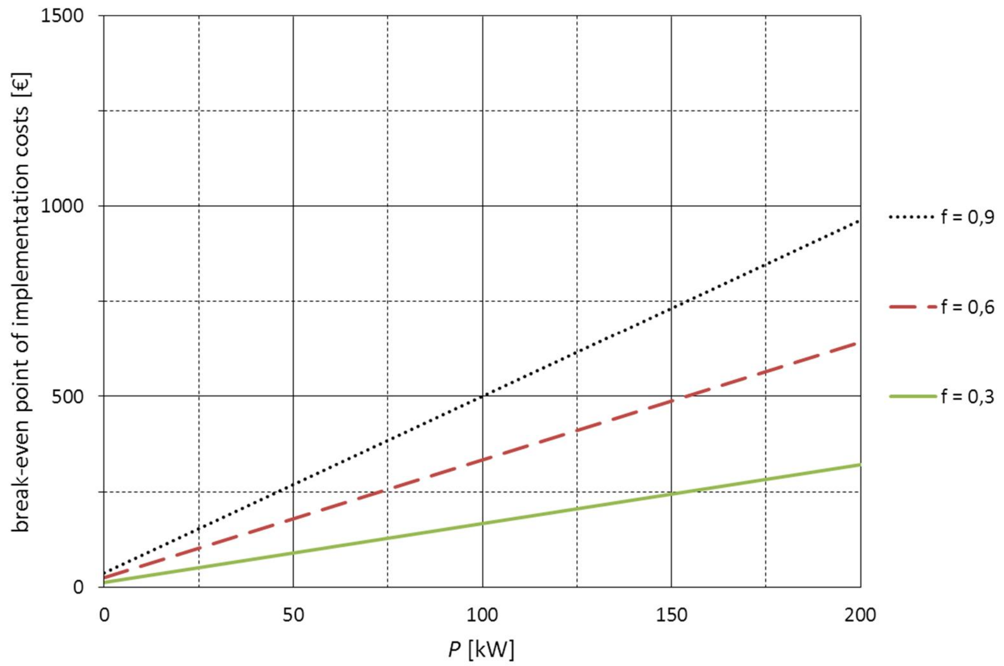

Figure 6.3. Break-even point of implementation costs of OCM to a single LV network as a function of average interruption power with different incipient fault frequencies [1 / 100 km, a]. Interconnected network, no interruption when OCM is utilized and 2 h interruption without OCM. Average power is divided between 70 % residential type and 30 % service type customers.

Outage costs form a majority of fault costs in urban LV networks where average transmission power of feeders can reach 100 kW or more. Fault frequency affects directly to annual outage costs and thus, it has big impact on the cost save potential from OCM. Differences in network lengths have exactly similar relative effect (Figure 6.4).

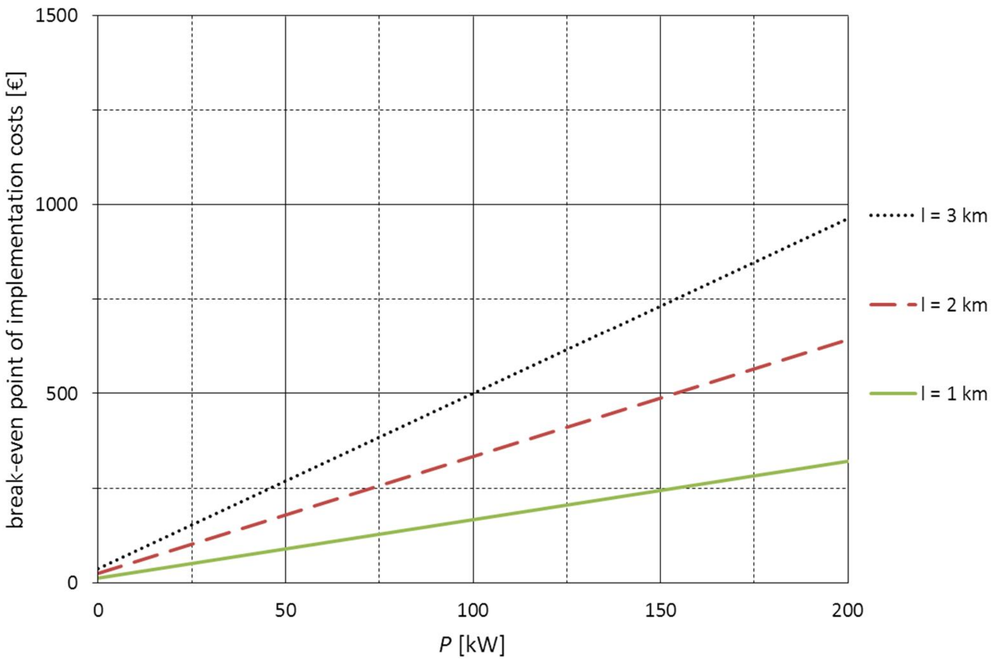

Figure 6.4. Break-even point of implementation costs of OCM to a single LV network as a function of average interruption power with different network lengths. Interconnected network, no interruption when OCM is utilized and 2 h interruption without OCM. Average power is divided between 70 % residential type and 30 % service type customers.

Present value of costs savings generated from whole lifetime of device is dependent not only on the annual cost saving, but also on expected lifetime of device and interest rate used. Therefore, those parameters have impact on the break-even point of implementation costs. Effect of different expected lifetimes is presented in Figure 6.5 and different interest rates in Figure 6.6.

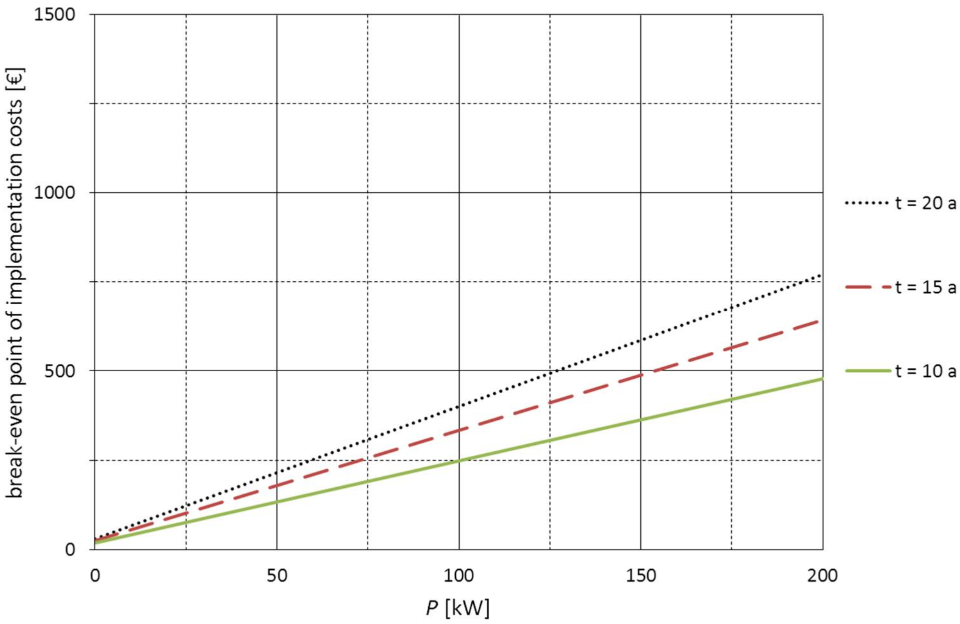

Figure 6.5. Break-even point of implementation costs of OCM to a single LV network as a function of average interruption power with different OCM system lifetimes. Interconnected network, no interruption when OCM is utilized and 2 h interruption without OCM. Average power is divided between 70 % residential type and 30 % service type customers.

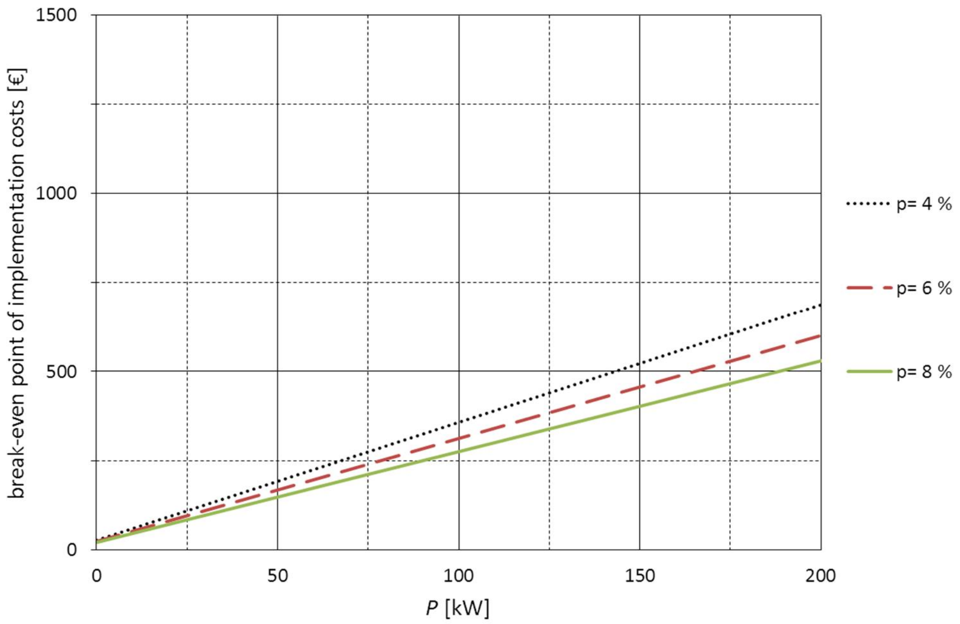

Figure 6.6. Break-even point of implementation costs of OCM to a single LV network as a function of average interruption power with different interest rates. Interconnected network, no interruption when OCM is utilized and 2 h interruption without OCM. Average power is divided between 70 % residential type and 30 % service type customers.

As it can be seen, different values for expected lifetime or interest rate have much less impact on the break-even implementation point than the parameters which affects directly on the annual outage costs. Higher interest rate decreases the present value of cost savings generated in the future and, therefore, higher interest rate means lower break-even point of implementation costs. EMA sets reasonable cost of capital both for community taxpayers, 4,58 % for 2012, and for municipal electricity utilities, 4,97 % for 2012 (EMA 2012b).

Cost save potential in labor and equipment costs are so minor compared to cost save potential in outage costs that altering those parameters would not have practically any effect on the break-even point of implementation costs.

When comparing these Figures to the implementation cost speculation in section 6.3, it could be noticed that the cases where this OCM system would be economically profitable in the current LV networks, are very limited. Especially, if the OCM system would have to be built totally separated, it would not be profitable investment. The more it could be integrated to other intelligent systems, for example to the AMR or, possibly in the future, to the LVDC, the higher would be the economic potential as the implementation costs decrease.

7 Conclusions

Incipient fault mechanism in modern, thermoplastic insulated LV underground cables is relatively unstudied phenomena. Numerous different thermal, electrical, environmental, and mechanical factors affect the durability of the cable and the speed of fault progression. Faults in LV cables can remain unstable state for considerably long periods of time. There are temporarily connected on-line TDR devices available to detect and locate also the unstable faults.

7.1 Technical aspects of OCM system

Laboratory measurements showed that in wet conditions, it is possible to detect and locate damage in modern thermoplastic insulated LV cables using high frequency signal injection techniques. Damage could be detected prior to permanent electrical fault develops. Theoretically, it is possible to implement an OCM system to LV network which automatically monitors condition of cables and alarms when cable damage is detected. Existing and expanding AMR network could be taken advance of when implementing the OCM system.

There are many technical challenges which are needed to be solved prior to such system could be implemented. The time it takes from the point damage first noticed to the point when permanent electrical fault appears must be determined in different installation conditions.

Frequency response fingerprint from healthy network should be able to be obtained through simulations and by knowing the exact topology of the network. Otherwise, if it is measured, OCM system could then be implemented only to new networks where fingerprint from certainly healthy network could be measured.

Reflections from customer internal networks and effect of varying impedances could be theoretically avoided by simple low pass series inductance filters, installed between AMR meters and customer internal networks. Customer end filters could be integrated to the next generation of AMR meters. Instead of using hardware filters, it might be possible to use some intelligent algorithms to filter out the reflections from signal. This, however, would need further research to be done.

LVDC system would be more promising platform to implement OCM than traditional LV AC system. Reflections from customer internal networks would be avoided because customer internal network is galvanically isolated from the distribution network. However, disturbance from the inverter units could affect the measurement. Inverter units in LVDC system include embedded control system, which could be utilized to control also the OCM system. Data transmission between network control room and LVDC system could be used to send declaration about damaged cable.

7.2 Economic aspects of OCM system

Majority of cost save potential from implementing the OCM system to LV networks comes from lowered outage costs. Annual outage costs are dependent on the number of faults per year, average duration of interruption, customer types and average interruption power from a fault. Most promising implementation sites would therefore be LV networks where high transmission power is divided between limited number of feeders, total length of network would be 2 km or more and at least one third of power is consumed by public consumption- or service –type customers. Even then, total implementation costs of OCM for single LV network should be less than 500 € for it to be profitable investment. It could be said that implementation to current LV networks as a separate system would not be profitable.

However, if the OCM system could be integrated to other intelligent systems, such as AMR or LVDC, implementation costs would decrease and the investment to OCM system could become profitable. Reliability demands for LV networks could also increase in the future, if distributed generation in LV networks becomes more common. This would increase the cost save potential from OCM making it potentially profitable investment in the future.

7.3 Further research topics

The major issue to be solved before the OCM system could be implemented is determining the correct timing of repairing the damaged cable. According to a source, even when there is some irregular arcing present, it could take several months until the fault becomes permanent (Clegg, 1993). Practically the only way to determine the durability of damaged LV cables is to leave samples of damaged cables in real LV network until permanent fault develops. However, there are lots of different factors, such as soil properties, load profile, cable type, etc. which most probably affect the durability of damaged cable. Therefore, organizing such real life testing would be challenging and time consuming task to do.

Feasibility with MV cables would also be interesting subject to study. There are many factors which makes MV network more interesting platform to implement OCM than LV network. Potential cost savings from decreased number of faults are much higher. MV network topology is more simple and ends of single cable segments are usually accessible at secondary substations. Fault progression speed is much faster once MV cable is damaged. However, structure of MV cables differ from the structure of LV cables and similar laboratory measurements have to be carried out with MV cables than what was done with LV cables.

This thesis presented only ideas and possible difficulties regarding to implementation of the OCM system to LV networks. More specific studies and practical tests are needed to determine how it is actually interfaced, for example, to the AMR system, and what are the real challenges which are needed to be solved.

8 Summary

This thesis consists of three different parts. Fault mechanisms in modern thermoplastic insulated low voltage cables were researched by literature study. Two most commonly used low voltage cables in Finnish distribution networks, AXMK and AMCMK, were selected to be tested in laboratory. Laboratory measurements were carried out in order to research feasibility of high frequency signal injection techniques in on-line condition monitoring of low voltage cables. Results show that it is possible to detect and locate damage in cable sheath when moisture penetrates through the damaged sheath.

Economic feasibility of possible novel on-line condition monitoring methods in LV distribution networks was studied based on the statistics and information from Finnish distribution system operators. Economic possibilities of novel on-line condition monitoring systems in low voltage distribution networks are very limited, unless the implementation costs can be reduced to a level low enough. This could be achieved, for example, by integrating the on-line condition monitoring system to existing systems such as the AMR, or possibly in the future, to the LVDC.

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APPENDIX I Equations for break-even point graphs

Total cost of an unexpected fault, including outage costs, labor costs and equipment costs:

$$X = \Delta P(\mathsf{A}_{\mathrm{f}} + t_{\mathrm{f}} \cdot \mathsf{B}_{\mathrm{f}}) + t_{\mathrm{rf}}(c_{\mathrm{lf}} + c_{\mathrm{ef}}), \quad \text{(I.1)}$$

where ΔP is interrupt power, $\mathrm{A_f}$ is outage cost parameter €/kW for fault interruption (table 6.X), t_{f} is duration of outage, $\mathrm{B_f}$ is outage cost parameter €/kWh for fault interruption, t_{rf} is duration of repair work, c_{lf} is unit cost of labor and c_{ef} is unit cost of equipment.

Total cost of an expected fault (with OCM implemented), including outage costs, labor costs and equipment costs:

$$Y = \Delta P\left(\mathsf{A}_{\mathrm{pi}} + t_{\mathrm{pi}} \cdot \mathsf{B}_{\mathrm{pi}}\right) + t_{\mathrm{rp}}(c_{\mathrm{lp}} + c_{\mathrm{ep}}), \quad \text{(I.2)}$$

where $\mathrm{A_{pi}}$ is outage cost parameter €/kW for planned interruption, t_{pi} is duration of planned interruption, $\mathrm{B_{pi}}$ is outage cost parameter €/kWh for planned interruption, t_{rp} is duration of repair work, c_{lp} is unit cost of labor and c_{ep} is unit cost of equipment.

Annual cost save potential by implementing the OCM would then be:

$$S = l \cdot f(X - Y), \quad \text{(I.3)}$$

APPENDIX I Equations for break-even point graphs

where l is the length of the network covered with OCM and f is the average fault frequency [1 / km, a].

Annuity of investment:

$$\mathrm{AN} = \mathrm{eps} \cdot C_{\mathrm{I}} \tag{I.4}$$

$$eps = \frac{p/100}{1 - \frac{1}{\left(1 + \frac{p}{100}\right)^{n}}}, \tag{I.5}$$

where C_{I} is total non-recurring investment, p is the interest rate per year and n is the number of years.

Break-even point between investment and annual cost savings as a function of transmission power could then be obtained from:

$$C_{\mathrm{I}} = l \cdot \frac{f(X - Y)}{\mathrm{eps}} \tag{I.6}$$