IMPROVING RELIABILITY BY FOCUSING ON THE QUALITY AND CONDITION OF MEDIUM VOLTAGE CABLES AND CABLE ACCESSORIES

Osmo SIIRTO
Helen Electricity Network Ltd. – Finland
osmo.siirto@helen.fi

Jukka VEPSÄLÄINEN
Helen Electricity Network Ltd. – Finland
jukka.vepsalainen@helen.fi

Aki HÄMÄLÄINEN
Helen Electricity Network Ltd. - Finland
aki.hamalainen@helen.fi

Mika LOUKKALAHTI
Helen Electricity Network Ltd. – Finland
mika.loukkalahti@helen.fi

ABSTRACT

The paper presents the processes and technologies that are used in the asset management of MV (medium voltage) underground cable network to maintain the cable assets in a good condition. In order to offer good premises for distribution networks with a high reliability and a long lifetime, the commissioning and installation quality is essential. The procedures how Helen Electricity Network Ltd (Helen) has achieved and maintained the low failure rate in a medium voltage network is described. This development in the processes of Helen has decreased the failure rate in the newly installed network and thus has decreased the customer interruption costs and the costs in the corrective maintenance.

INTRODUCTION

Lifecycle analyses in electric power systems often reveal a phenomenon called "Bathtub Curve". The curve represents the idea that the lifetime of devices can be viewed as comprised into three distinct periods: an "early failure" period where the failure rate decreases, a "random failure" or "useful life" period, where the failure rate is constant over time and "wear-out" period, where the failure rate increases over time [1]. Interruption statistics show that as an average about 70 to 80% of the interruptions in European countries are caused by failures in medium voltage network [2]. Failures without an external factor are in many cases consequences of partial discharges (PD) in the insulation evolving into earth faults. These internal faults can be prevented or mitigated either by quality requirements and quality monitoring in the procurement and installation phase, or by condition monitoring of the existing MV cables and cable accessories.

The failure rate of network components increase when the age of the component is proceeding towards the expected lifetime of the component, thus forming the right end of the failure rate curve. Distribution utilities have long-term replacement investment plans to mitigate this effect. However, focusing on the other end of the bathtub curve is also important, that is mitigating the effects that are causing early in lifetime experienced network faults. These "Infant mortality" faults form the left end of the bathtub curve. For example MV cables and cable accessories may have a significant infant mortality rate.

The different processes in which a utility may influence the quality in the new MV cable network are:

- type and quality requirements of MV cables and cable accessories
- commissioning and product acceptance of cables and cable accessories
- quality of installation
- handling the cables during the work and quality of excavation
- testing and condition monitoring
- asset management during the lifetime of the cables: especially guiding the outside excavation workers.

MV CABLE CONDITION MONITORING

The most dangerous defects in polymeric insulation are caused by electrical degradation. Partial discharges, electrical trees and water trees are the most important mechanisms [3]. IEC60270 defines, that there are partial discharges when electrical discharges are only partially connecting the insulation between the electrodes [4]. Partial discharges do not result in an immediate destruction of the insulation, the insulation destruction occurs gradually over time. The PD measurement is a condition monitoring technique used to facilitate the detection of incipient faults in high voltage electrical insulation systems such as cables, gas-insulated switchgears and power transformers. The measurements of dielectric response and partial discharges are the main diagnostics methods applied in Finland [5]. Methods used for off-line PD are VLF (Very Low Frequency), DAC (Damped AC Voltage) and resonant reactor. The DAC method is mainly used in Finland. The test system is a resonant circuit composed of the capacitance of the cable and a parallel switchable coil, which together form an oscillation circuit [6]. The results of different methods are not directly comparable with each other, so it is advisable to use the chosen method in all measurements. Off-line PD measurements are suitable for example to the quality assurance of MV cable installations. Also a utility is able to measure with voltage higher than the nominal voltage to better detect weak points in the network.

One disadvantage of offline PD measurements is, that the method requires to take the particular MV network part out of service. There are also methods to measure partial discharges online. During recent years, this technology has advanced rapidly and there are commercial solutions and services available. Online PD measurements enables condition monitoring of the MV network assets and

provides information to the life cycle planning. An example of online PD measurements can be seen in Figure 1. Partial discharges are presented as a function of monitoring time and date and the length of the measured connection [7].

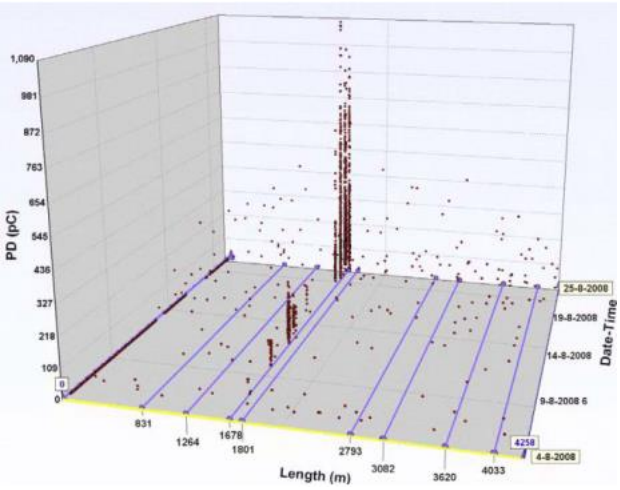


Figure 1. An example of online PD measurements [7]

COMISSIONING OF MV CABLES AND CABLE ACCESSORIES IN HELEN

Helen Electricity Network Ltd. Helen is the responsible DSO in Helsinki with about 375,000 customers. Helsinki is the capital of Finland with governance offices and business headquarters and there is a high demand for good power quality. The total length of the distribution network is about 6300 km of which 1600 km in the MV network. The peak load in Helsinki has been about 830 MW. The MV network is almost all cabled, underground coverage is 99.7%.

The procedures for selecting the type and quality requirements of MV cables and cable accessories are as follows. The selected MV cable type is a XLPE-insulated AHXAMK-W 20 kV. This cable type was selected in year 1988 and since that, Helen has been using almost exclusively this cable type. The cable type fulfills the standards CENELEC HD 620 S2:2010 Part 10 Section F and IEC 60502-2 [8-9]. The cable type has both the vertical and horizontal water tightness. There is a tape layer, which expands with water and therefore forms a barrier to the propagation of the longitudinal water. The primary function for the aluminum laminate layer is the touch protection, besides that it forms also the water tightness in the vertical direction. For above reasons the selected cable type has no water tree problems, which typically are causing MV faults in some other types of cables.

There are several manufacturers for the AHXAMK-W 20 kV cable and for the cable accessories. All new tendered products go through the same procedure:

- Test certificates for the acceptance of relevant standards
- the current specifications for the Al-laminate ground joint of cable accessories shall be at least equal to that of the Al-laminate
- joints shall have accepted standard impact test results for mechanical resistance
- Test installations are organized for example in contractor's premises (installation, contractor's and installer's comments), installation procedures are trained to the contractors before using the products in the network.
- Installation in the real network with a possibility to a partial discharge (PD) measurements.
- Informing both the manufacturer and the contractors of the acceptance and for the possibility of using the product in the distribution network of Helsinki.

There is also a material technology group in Helen with perspective to design, construction, maintenance and life cycle issues.

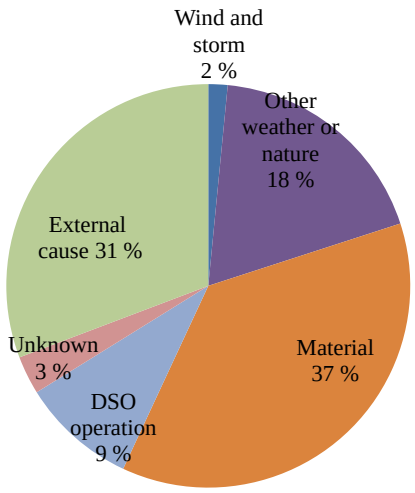
After the selection and installations the new manufacturer information is being inserted to the asset data in Helen's Network Information System (NIS). This will assist in a case if any problems arise regarding a new product. In case of faults in cables and cable accessories, the cause of a failure is determined in cooperation with the product representative.

Helen does not purchase directly MV cables or cable accessories, the distribution network contractors propose components in their tenders, and component types are accepted according the above procedures.

The majority of the distribution network installations is done by contractors with a long-term contracts from three up to five years. The quality is one evaluation criteria in the request for tenders and contractors are valued for the quality they promise in tenders. Also in contracts there are quality incentives, contractors get rewarded for a good quality and penalties for an inadequate quality. The method is a light modification of an alliance method. Alliancing is a successful procurement method in fostering an integration practice between diverse teams involved in delivering construction projects [10]. Helen is using plastic installation pipes for MV cables in order to enable common construction of streets and electricity distribution and to mitigate the harm of excavation. The pipes act as an added mechanical protection and they separate the cables from any sharp objects in the soil.

STUDY ON FAULTS IN MV CABLE NETWORK

In addition to a long tradition of a quality focused asset management and the previously described procedures in the material selection and purchasing, Helen has continuously performed comprehensive internal studies of fault statistics. In year 2010 there were multiple faults in the MV network of Helsinki. That was over twice as many faults as in the previous year. Besides aging there were also other challenges in the network asset management. Over time the MV cable network had become fragmented with several joints, thus forming a potential risk for additional failures. Therefore a study on the health and condition of the MV network was initiated. The fault statistics of the MV network showed, that the two major causes for faults were either material related or external causes, Figure 2.



Year 2010 MV network, total 65 faults

Figure 2. MV network faults in Helsinki year 2010

The section Material included both the material and old installation faults. Also the faults statistics from years 2004-2010 show how the faults are distributed between MV cables and cable accessories, Table 1.

Table 1. The distribution of MV cable faults in Helsinki years 2004-2010

Cables	41 %
Joints	38 %
Terminals	21 %

The percentages indicates that further study and actions should be taken both on MV cables and on cable accessories. Besides studying the fault distribution between MV cables and cable accessories, also the fault rates of different cables, joints and terminal types were examined. The fault rates of different cable types are presented in Table 2.

Table 2. The fault rates of different MV cables in Helsinki years 2004-2010

MV cable type	Failure rate [faults per 100 km]
XLPE-cable AHXAMK-W	0.4
Oil-paper cable APYAKMM	2.4
Oil-paper cable PYLKLJ/ PLKVJ	9.2
All types + joints and terminals	0.9

The performed study revealed, that there were striking differences in the fault rates of different MV cable types, Table 2. The last cable types PYLKLJ or PLKVJ in Table 2. are also the oldest MV cables in Helen's network.

The scenarios on the development of the network asset age was also performed. The scenarios showed that if continuing with the replace rate of that time, the oldest cables cable type would exceed their estimated maximum economical lifetime and also that the asset age of network cables would grow year by year.

In Denmark, there has been concern about the mixed MV networks consisting both on XLPE and oil-paper insulated cables. Statistics in Denmark have already noticed the growth of fault rates in heterogeneous networks. At the same time, when the number of oil-paper to XLPE transition joints has grown, also the number of faults in the network have been increasing [11]. Defects appear to be linked with the increased number of transition joints. Danish failure rate for XLPE cables, approximately 0.5 failures per year per 100 km is very low. In comparison, the overall failure rate for MV oil-paper cables in Denmark is close to 3 failures per year per 100 km [12]. In Portugal, there are four different MV voltage levels. The Portuguese 10 kV underground network with the higher percentage of old cables has the highest failure rate. This indicates the relation between the age and failure rate. The Portuguese oil cables has a failure rate of 4.7 and dry type cables 3.2 failures per year per 100 km [13]. In a cable accessory failure study in USA, it was noticed that cable accessories have a significant infant mortality rate. Newly installed cable accessories account for 20 % of accessory related failures. Workmanship was found as the primary cause of failures representing nearly 50 % of the total failures. The study highlights that an improved training is the most cost-effective mean of improving reliability [14]. A survey among twenty U.S. utilities was conducted between years 2006-2007. The average failure rate in MV cable system was 7.5 failures per year per 100 km [15].

In Nordic oil-paper cables, failures are detected 4-5 times more than with XLPE cables [16]. Helen has similar experiences. The failure rate of oil-paper cables is rising. The paper insulation has been associated with a significant portion of defects in joints. However, because of accelerated replacement investments the total share of oil-paper cables has decreased the total failure rate which has been on very low level.

The different reviewed fault statistics are presented in Table 3.

Table 3. The fault rates of different MV cables systems [12-16]

MV cable type	Failure rate [faults per 100 km]
Helsinki 2004-2015 all type	0.9
Sweden 2003-2007 all type	2.0
Denmark Oil type 1998-2007	2.4
Denmark XLPE 1998-2007	0.6
Portugal Oil type 2001-2013	4.7
Portugal dry type 2001-2013	3.2
USA before 1998 all type	4.3
USA, 20 util. all type 2006-2007	7.5

The failure rates in Table 3 show the results of the long-term quality focused asset management. Concentration to the quality and the condition of materials and installations and in maintenance have benefitted in keeping Helen's MV cable network failure rate in a very low level.

Conclusions and observations of the MV cable study

Conclusions and suggestions of the performed MV network study were as follows.

- The replacement investments of old MV cables should be accelerated, starting with the oldest oil-paper cables with the highest fault rates.
- Start examining the installation quality of the relatively new (0-5 years) MV joints and terminals, arisen from temporary network installations. Start off-line partial discharge (PD) measurements as part of the normal MV network construction and commissioning test process.
- Contractors are required to photograph different cable installation phases.
- Continue and develop the work sites auditing procedure in order to prevent external failures.
- Considering to participate on the research project of online cable monitoring.

ACTIONS AND RESULTS

In addition to Helen's own studies, the utility participated also national research projects in order to get and combine wider aspects and experiences of failures procedures and statistics of underground cables. The project KaLifi concentrated on the analysis and estimation of the remaining lifetime of different cable insulation types used in Finland [5]. A new MV cable replacement ratio was calculated based on the findings of KaLifi-study. Thus, to reduce the amount of the oldest MV cables with the highest fault rate, Helen accelerated the replacements of MV cables using this new increased replacement ratio. The amount of oil-paper cable PYLKLJ/ PLKVJ has reduced 40 % between the years 2011 and 2016

The examining the installation quality was done in co-operation with the manufacturer's representative. One of the survey findings was, that there were installation faults in some of the joints and terminals. This lead to a new conclusion: test new types of cable joints and terminals which can be shrunk without heat. Test installations were carried out with cold shrink joints and terminals. Now for joints and terminals both heat shrink and cold shrink technologies are accepted if they fulfill the requirements described before.

Together with testing and training with new material types, the network contractors were trained for correct and faultless installations using material types already in use. Training was carried out with a supervision of manufacturer's experts concentrating on the proper work quality on making joint and terminals.

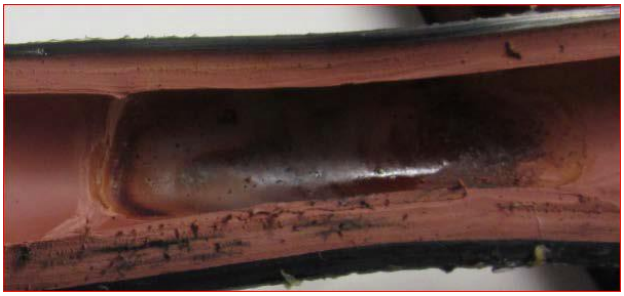


Figure 3. An example of an incomplete heating and PD damages in an MV cable. This was found with PD measurements prior to its acceleration to an interruption.

Off-line PD measurements had been performed in Helsinki and about 30 % of the MV-network have been measured. The measurements have also been done successfully on connections consisting both MV cables and MV switchgears. There have been several findings from the measurements. The condition of cable lines with multiple cable types is on an average in a weaker condition than cable lines with only one cable type. This observation applies to the condition of cables, joints and terminals. However with lines consisting only of XLPE-types cables, joints and terminals are more often deteriorated than cables. Based on the measurements it can be noted, however, that the condition of the cable is not directly proportional to the age of the cable.

High PD-levels are not necessarily causing major visible changes in the insulation material. In newly installed cable accessories, the cause of the failure is often connected to an incomplete installation.

Also an online PD measurement research project in the MV network of Helsinki has been started together with DNV, a company providing online MV cable monitoring as a service.

As a part of a large reliability improvement project in Helsinki [17-19], Helen has taken into operation the compensation of the earth fault current in the 20 kV network of Helsinki. The compensation reduces the earth fault current so, that the operation can be sustained, thus avoiding customer interruptions. On singe phase earth faults the voltage of the sound phases can reach the phase-to-phase voltage. This creates stress to the network and there is a risk for multipole failures [20]. PD measurements were made in the testing phase of the earth fault current compensation when starting the project in the first two substations. Total of about one hundred points were measured and only on few sights increased levels of PD was observed. The extended PD measurements were stopped after this, since these measurements had revealed the good condition of the MV cable network. The commissioning of the earth fault current compensation was then continued without separately large PD measurements.

The obligation to photograph different cable installation phases was added in the new contracts. This is seen as a mean for an enhanced self-supervision of the installation

quality. Also new solutions on which the contractors are able to take pictures with mobiles and insert them directly into work reports are in testing.
The procedures of auditing external failures have been developed. On large network projects, Helen is contacting in advance the building contractors to advise and to emphasize the importance and hazards of the existing cable network. The precaution of electrical cables was also included in the metropolitan area excavation course, which is mandatory for excavation contractors in Helsinki.

CONCLUSIONS

Many of the procedures and actions presented in this paper are developments in the processes of both the DSO and service providers. This highlights the cost-effectiveness of the methods. New technologies like condition monitoring of MV cable network will help the utilities to detect failures before they evolve into customer interruptions. Used together with other technologies the benefit can be even increased. The MV cable network has withstood the added voltage stress of earth fault current compensation have benefitted the success of MV earth fault compensation in Helsinki. Concentration to the quality and the condition of materials and installations and in maintenance have benefitted in keeping the MV cable network failure in a very low level.
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