A PRACTICAL APPROACH TOWARDS ESTIMATING REMAINING MV CABLE LIFE

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ABSTRACT

A structured and practical approach to estimate the remaining life of MV cable systems is presented. It is shown that many factors affect the speed of degradation of a MV cable system and that the degradation mechanisms vary between different types of cables and accessories. It is also pointed out that various analytical methods exist to determine the extent of ageing. Finally, a practical approach to estimate remaining life of (a population of) cable systems is described.

INTRODUCTION

Operators of medium-voltage cable networks are being confronted increasingly frequently with the question: "How much longer will my cables (or better: *cable systems*, see below) remain reliably functional?" The relevance of this question is caused by the ageing of electricity networks on the one hand, whereas on the other hand regulatory approaches lead to a pressure on cost. Putting a cable out of service too early would mean a waste of money. However, keeping an old cable in service could mean that unacceptable risks are being taken. Reliability of supply may be compromised and depending on the regulatory approach, financial consequences could occur. The key to solving such issues is "knowledge of the specific issues involved".

Determining the remaining life of a cable and the related accessories (joints and terminations) can often be done with a surprising degree of accuracy, but in other cases such a determination can be strikingly difficult. The goal of this paper is to provide insight into these issues and to offer an overview over a method to be able to determine the remaining life - or more precisely the degree of degradation and the probability of failure - as effectively as possible, even with a minimum of expertise and resources. In addition, it will be discussed whether and when resources such as diagnostic tools or laboratory analyses are effective.

The outline of the paper is as follows. First, a short overview will be given over MV cables and accessories being applied presently and in the past. Then, ageing mechanisms for the various types of cables and accessories will be discussed. Thereafter, analytical methods to investigate the progress of various ageing mechanisms are described. Finally, a practical approach towards remaining life estimation is given, which is based on the relevant ageing mechanisms, the available analytical methods, the criticality of the circuit and the risk acceptance of the network operator.

MV CABLE SYSTEMS

In order to connect the cable to a circuit breaker, a fuse holder or a transformer, terminations are required. Besides, in many cases the required cable length is too long to be manufactured and transported in one piece, so that joints are necessary to connect the individual cable parts together. The reliability of the electricity transport by the cable connection is determined by all links of the chain. Therefore, it would be better to speak of a *cable system*, instead of a cable.

MV Cables

The two main types of MV cable are PILC (Paper Insulated Lead Covered) and XLPE (Cross Linked Polyethylene) cables. These names refer to the material being used to isolate the "live" parts of the cable from the surrounding earth, which is oil impregnated paper and polyethylene respectively. The first type, PILC cable, has been used for several decades, so that large parts of the present electricity networks consist of this type of cable. However, during the last 20 tot 30 years it has gradually given way to XLPE cable and hardly any PILC cables are installed anymore today.

Either copper or aluminium can be used for the conductors of both PILC and XLPE cable. For 10 kV, the most important voltage level for MV networks in the Netherlands, PILC cables tend to be three core belted cables. Older PILC cables sometimes have very small cross sections, such as 10 mm^2 and 16 mm^2. XLPE cables with a relatively small conductor cross-section (i.e. up to about 200 mm^2 to 250 mm^2) exist both as single core and as three core cables. Larger cross-sections are only manufactured as single core, because as three core they would become too heavy and difficult to handle and to bend.

In figures 1 and 2, the cross sections of a PILC and an XLPE cable are depicted respectively. Several layers can be distinguished, such as the conductor, the insulation, the earth sheath, and several sealing and protective layers.

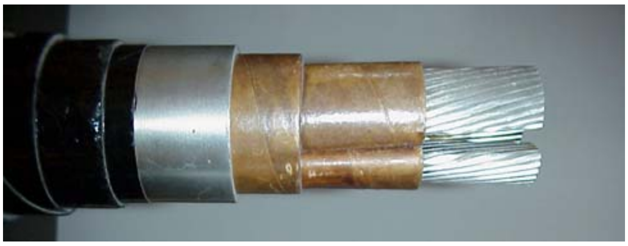

Figure 1. Three core PILC cable with aluminium conductor

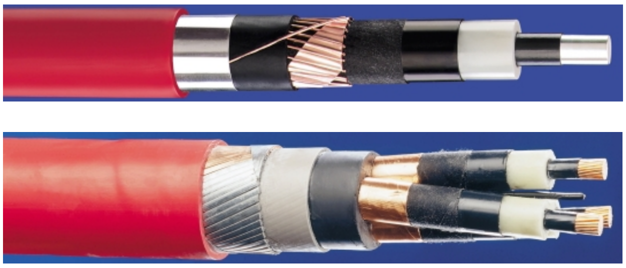

Figure 2. Single and three core XLPE cable, with aluminium and copper conductor (source: TKF)

Accessories

Accessories such as joints and terminations are an important part of the cable system. Although the cable is far more expensive than the accessories, the accessories often more affect the reliability of the cable system. There are various reasons for this:

- they are subjected to higher electrical, mechanical and thermal stresses;
- they are mounted in the field, and therefore sometimes under suboptimal circumstances (bad weather, darkness), particularly during outage situations;
- it is far more difficult or expensive to subject the accessories to a reliable testing procedure than the cable itself;
- the quality of the mounting of accessories is quite sensitive to workmanship and experience of the employees involved and naturally not all employees have the same skills in this respect.

Therefore problems negatively affecting reliability and durability of accessories, such as water ingress, mechanical stresses, voids that result from shrinking, etc. can easily occur.

Various types of accessories exist, particularly in case of joints. In this paper, only various types of straight joints (i.e. joints connecting the same type of cable) are treated. Other types of joints, such as transition joints, cross-bonding joints, T or Y joints (which are hardly used in the Netherlands in MV networks) will not be discussed. The variation in terminations to connect a cable to a transformer or circuit breaker is less; these will, however, also not be considered any further in this paper.

There are two main types of straight joints, namely filled joints and massive joints (see also figures 3 and 4). In filled joints, some type of insulating material (such as oil, silicon gel, resin or bitumen) is used to insulate the casing from the cable conductors and (in three conductor cables) the conductors mutually. In massive joints, the insulating material being used is solid from the outset. Processing of massive joints can be done through heat or cold shrinking or pre-moulded joints can be used. Some manufactures combine both principles, e.g. a shrink approach to connect the conductors of both cables, after which the joint is filled with some type of viscous material. Wrapping joints also form a combination of filled and massive joints: first, a massive material is used to connect the conductors and the two cable ends, which is afterwards impregnated.

The two main groups of MV joints and the various combination joint types have co-existed for long. Up to this moment, none has proven to be superior and many manufacturers provide joints of both types. To a large extent, the choice of a network operator seems to be based on his history. Causes for this could be the relatively long time required to evaluate the performance of joints so that it is difficult to obtain objective performance statistics, the relatively small amounts of money involved compared to other expenses of grid operators and the high cost of changing of one type of joint to another, due to the necessity to educate hundreds or even thousands of employees to work with a new type of joint. The latter argument particularly carries weight, because the competencies of the person installing the joint have a large impact on its reliability and durability, as pointed out above. For the same reason, Essent Netwerk considers the (perceived) user-friendliness to be an important factor in the selection of the applied type of joint.

Figure 3. Example of filled joint (source: Lovink Enertech)

Figure 4. Example of cold shrink joint (source: 3M)

AGEING MECHANISMS

In this chapter, a number of ageing mechanisms relevant for cable systems will be discussed. As mentioned above, the scope of the discussion will be limited to:

- PILC and XLPE MV cables
- Filled joints
- Massive joints

These components occur most frequently and are therefore on the one hand important determinants of reliability of supply and are on the other hand costly to replace preventively on a large scale. Further, as underground components, they can not be easily inspected visually. Therefore, in the next chapter, analytical methods that can be used to investigate these components will be presented.

MV Cables

In principle, all parts, or layers, of a cable have a finite life time and are subject to ageing. The ageing mechanisms, however, differ. The oil impregnated paper used as insulation material in PILC cables can age due to high temperatures, which can be caused by (a combination of) high current loads and/or a "bad" thermal environment, e.g. bad soil properties or other heat sources such as other cables nearby or district heating. This leads to the drying of the oil and de-polymerization of the paper, see also figure 5. This can result in electrical treeing and breakdown. The latter can also be caused by moisture ingress occurring after a breakdown of the cable or due to a corroded lead sheath. Finally, the armour can be corroded, which severely reduces mechanical strength of the cable. However, as long as the cable is not moved or touched with excavation works, this does not cause any problems.


Figure 5. Example of aged paper insulation

As for XLPE cables, the insulation can in theory also thermally age, causing de-polymerization. However, XLPE is a very stable material and as it is relatively new, XLPE cables have had only limited time to age. Therefore, practical cases of this phenomenon are not known to the authors.
Further, XLPE insulation can be affected by what is called "water-treeing" [1]. A water tree is a diffuse structure in a polymer with an appearance resembling a bush or a fan. They result from the degradation of polyethylene by means of a combined action of water and an electric stress. Water trees reduce the electric breakdown stress level of a polyethylene insulating material. Water trees can be made visible by several dyes, see figure 6 for an example.
In general, XLPE cables are divided into three generations, which roughly are the seventies, the eighties and thereafter. Most cables from the first generation have either been taken out of operation or cured. The second generation requires careful attention, but is much less prone to water treeing then the first, whereas in cables from the third generation, water treeing does hardly occur. The differences between the generations are formed by the purity of the XLPE, the extent of water tightness (both transversal and longitudinal) and the process being used for cross linking the polyethylene. Together, these factors determine the sensitivity of the insulation for water treeing.

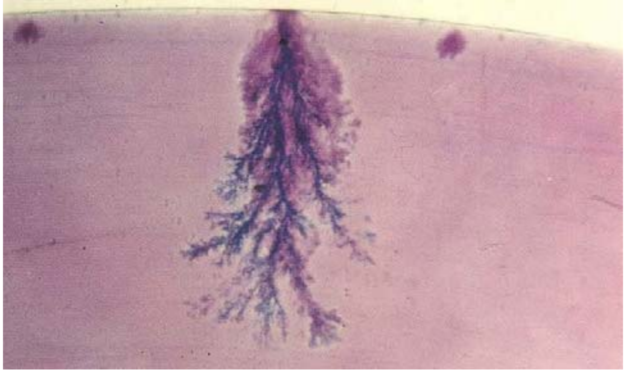
Figure 6. Example of "vented" water tree in XLPE

Before curing a cable that has water trees, the extent of electrical treeing of this particular cable should be investigated, especially after a cable failure where high voltage from network switching or fault location could have caused large water trees to create electrical trees. If the amount of electrical treeing has become too high (i.e. there is electrical treeing at many different locations in the cable), many failures can be expected, even after curing. So, replacement of such cables is the only valid option. Curing should not be carried out, because under circumstances water trees can block the growth of electrical trees [2].
The outer jacket of XLPE cables can crack due to third party damage or degeneration due to exposure to UV radiation. When no adequate precautions are taken to prevent moisture ingress (such as watertight foil or swelling fleeces) this could lead to water ingress causing water treeing. However, in third generation XLPE cables, this should not happen as these are generally transversally watertight.

Filled joints

Filled joints can be filled with a material that stays viscous (oil, silicon gel) or with a material that hardens (bitumen, resin). Most important ageing mechanisms of joints filled with a permanently viscous material are a low liquid level caused by the connected MV cables soaking up the liquid and contamination of the liquid, leading to reduced breakdown strength. Both phenomena result in partial discharges that may finally lead to a breakdown. Besides, conductor displacement due to heating of the conductors can occur. This leads to high electrical stress, that may cause a breakdown.
Most important ageing mechanism of joints filled with a material that hardens are cavities. Partial discharges will occur in these cavities and these may again finally lead to a breakdown.

Massive joints

The most important ageing mechanisms of massive joints, either heat shrink, cold shrink or pre-moulded, are caused by contamination of the joint before it is installed and voids between the conductors and the joint. Both are mainly caused by bad installation circumstances and inaccuracies, such as insufficient shrinking. They lead to partial discharges, that finally may cause a breakdown.

ANALYTICAL METHODS

In order to determine the status of cable systems and the actual progression of the ageing mechanisms described in the last section, various methods exist. These fall apart into three principal categories, namely:

- Desk studies
- Visual inspections and other investigation methods relying on relatively simple principles
- More advanced investigation methods and measurements

Desk studies comprise collecting information about the cable system under investigation, such as manufacturer's documentation, year of installation, outages that may have occurred, loading history, number and type of joints, results from historical investigations into the thermal resistance of the soil, maps of the cable route, presence of other sources of heat or special circumstances such as ducts along this route, etc. Desk studies can often quite easily exclude a whole number of ageing mechanisms. For instance, ageing mechanisms that are specific for certain types of components can of course be excluded if these components are not present in the cable system under investigation. Further, a cable system that has been very lightly loaded so far, will in principle not be thermally degraded.

However, desk studies do not tell much about the progress of the ageing mechanisms that can not be excluded. To this end, other methods are required. The first category are visual inspection methods, relying on direct visual inspection or other relatively simple methods for which no advanced equipment is needed. Examples of these are:

- visual inspection of the extent of corrosion of the lead sheath of a PILC cable or the crispness of the outer jacket of an XLPE cable
- visual inspection of the paper windings of a PILC cable
- foam test (crackle test) to determine moisture in paper insulation of a PILC cable by putting it into hot oil (140ºC) and see if the oil foams
- assessment of water tree sizes in an XLPE cable, using a staining procedure to make them visible, e.g. using a methylene blue dye solution

Although visual inspections do not require advanced equipment, samples from the cable must be taken in order to be inspected. This significantly increases the cost in comparison to desk studies, as switching actions and the installation of one or more joints will be required.

Disadvantage of visual inspections is that, for non-homogeneous ageing mechanisms, they only give local information. Further, they can not be sensibly used for joints, as the extent of ageing of joints varies quite much, even amongst joints in the same cable that have been installed at the same time, which is explained by the already mentioned sensitivity to workmanship.

More advanced investigations and measurements have been developed in order to acquire a more accurate picture of the cable system as a whole. The most important are:

- Outer sheath integrity test: a relatively high DC voltage is applied to the outer sheath and the leakage current is measured. A high leakage current means that the outer sheath (and maybe other layers as well) is damaged, making further investigations necessary.
- Partial discharge (PD) measurements (regularly with the cable system off-line, however on-line measurements are becoming possible). PD measurements can be applied to find voids in which partial discharges occur. The cable is energized to about its nominal voltage using an AC voltage source and voltage pulses corresponding to partial discharges are measured.
- Dielectric spectroscopy (DS) measurements to detect water treeing in older XLPE cables.

On-line PD measurements with localisation

PD-OL (Partial Discharge detection On-line with Localisation) is a new diagnostic system, which enables to detect and locate partial discharges from medium-voltage cables, while these cables remain on-line. The measurement system uses inductive sensors to measure the high-frequency pulses (from PDs) in the cable connection without galvanic contact. By using advanced synchronisation, adaptive calibration and signal processing techniques, high sensitivities can be reached with high localisation accuracy. The measured results are collected by the Control Centre at KEMA, where the data is analysed, interpreted and translated into risk values for the utility. With this system it becomes possible to not only measure the condition at one time instance, but monitor the cable's condition permanently. In this way it becomes possible to detect weak spots before they lead to a breakdown [3].

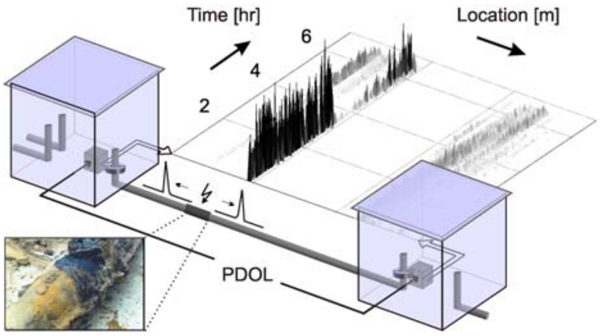

Figure 7. On line PD measurement

REMAINING LIFE ESTIMATION

As can be concluded from the above, estimating the remaining life of MV cable systems is by no means straightforward, due to the many phenomena that can occur and the many factors that play a role. For linear degradation processes, the remaining life R is defined as

$$R = A_p \cdot \left(\frac{D_{max} - D_p}{D_p} \right) \qquad (1)$$

in which A is age and D is the extent of degradation. The subscript p stands for “present” and “max” for maximum while still functioning adequately.

A practical method to estimate the remaining life of a MV cable system comprises the following steps [4]:

1. Determine the type of components of which the cable system to be investigated is composed (i.e. cable and accessories).
2. Determine the relevant defects for those components (see section on Ageing Mechanisms).
3. Identify all possible analytical techniques for each of these defects (this can involve desk work but can also include field measurements, see section on Analytical Methods).
4. Determine which analytical methods are worth carrying out by determining their cost and effectiveness.
5. Carry out the analyses and determine the extent of degradation D_p using the results.
6. Determine the remaining life R using equation (1), the results from step 5 and the acceptable maximum degradation D_{max}.
7. Evaluate the reliability of the estimate and decide whether or not to return to step 4 for additional analyses.

In step 4, the question whether analytical methods are of interest or not is determined by their cost and their effectiveness. The latter is a measure for the reliability of the results. The cost can be determined using classical calculation methods; the effectiveness must be estimated using literature and/or experience. The quotient of cost C and effectiveness E is the performance P, which is equal to

$$P = \frac{E\ [\%]}{C\ [Eur]} \qquad (2)$$

The methods with the highest values of P should be considered first as these are most cost effective.

Of course, the overall expenditure to determine the extent of aging is related to the criticality of the circuit. The same applies to the acceptable extent of degradation D_{max}. The value of D_{max} depends on the general policy, i.e. the risk acceptance, of the network operator and on the criticality of the individual circuit.

The procedure can also be applied to (a larger part of) a MV network, but the individual cable systems selected must in that case be representative of (the investigated part of) the network chosen. In practice, application to a larger population of cable systems will probably occur more frequently than to an individual cable system.

CONCLUSIONS

In this paper, a structured and practical approach to estimate the remaining life of MV cable systems was presented. It was concluded that many factors affect the speed of degradation of a MV cable system and that the degradation mechanisms vary between different types of cables and accessories. It was also pointed out that various analytical methods exist to determine the extent of ageing. Finally, the knowledge on failure mechanisms and analytical methods was integrated into a method to estimate remaining life, using the concept of maximum acceptable degradation and cost and effectiveness of a method.

FUTURE WORK

An important aspect of remaining cable life estimation is the relation between cable loading, cable temperature and degradation (see also [5]). In order to investigate this relation, Essent Netwerk and KEMA have started a long-lasting research effort in which cable loading and cable temperature are measured. By combining the measurement data and the loading history of the cable and correlating these with the extent of aging, to be determined by analysing cable samples (destructive testing), more insight can be acquired in the relation between temperature and aging rate.

ACKNOWLEDGEMENT

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