ESTIMATION OF RISK OF OPERATION (REMAINING LIFE) OF UNDERGROUND MV POWER CABLE SYSTEMS

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INTRODUCTION

Asset managers of electric infrastructures often deal with the following question: “how long will my cable circuits last”. This question has its origin in the increasing need to postpone replacement of cable systems as much as possible. Many cable networks are at age, so what to do? Take the risk and continue or replace it. The key factor to support management decisions like this is knowledge about cable systems and all matters related to it.

The estimation of remaining life may be very difficult, however the estimation of the risk of operation over time may be less difficult to do. In this paper a method is described to estimate the degree of degradation and the risk of failure with limited resources. It will be indicated when desktop studies or diagnostics or laboratory analysis may be needed.

ESTIMATION OF RISK OF OPERATION (REMAINING LIFE), DEFINITIONS

Remaining Life

In this paper we focus on individual cable systems, however, this method is also applicable to underground cable networks. When analysing (parts of) underground cable networks the chosen individual cable systems (more than one) has to represent the total network.

The approach is straightforward. The cable circuit consists of components. The potential relevant defects of those components and the way these defects may influence the remaining life is assessed. The remaining life is defined as the period of time, taken from now on, after which the “risk of failure” is increased until beyond the limits set by the network owner.

The wording “risk of failure” is deliberately used. There are no existing methods to determine precisely the moment of failure. A stochastic process determines the actual moment of failure. It does not only depend on the degree of degradation but also e.g. on the occurrence of voltage transients.

For the determination of the potential defects and the corresponding degree of degradation, some analysis is needed. Sometimes a rather simple desktop analysis will do, sometimes measurements on site or in the laboratory may be more effective. However the most effective method will not be always the best solution to choose. Each analysis will cost money and will give some outcome. Costs and outcome have to be weighed before taking the decision for application.

The outcome of an analysis is not always perfect, not even in very promising situations. The expected effectiveness of the analysis is of crucial importance and may depend on local circumstances. This effectiveness of the analysis will have to be taken into account when the remaining life is determined.

Definitions

Before discussing the procedure we have at first to state some definitions.

Time (t): The unit of time is year. The cable circuit is taken into service at \( t = 0 \). The current time is given as \( t_{\text{now}} \).

Remaining life (Rlt): The unit is also year. Remaining life is the remaining difference of time between the moment of analysis (\( t_{\text{now}} \)) and the time where the risk of failure reaches an unacceptable level.

Remark: The level at which the failure rate becomes unacceptable is determined by the network owner. The network owner thus decides about the allowed risks.

Degradation (D): The degree of degradation. The remaining life depends on the degree of degradation. This dependence may be linear or non-linear. In most cases the actual dependency will be non-linear, but may be estimated as linear in the working area [5]. The calculation of Rlt for a linearized or a linear case is presented by equation (1).

\[
Rlt = t_{\text{now}} \cdot \left( \frac{D_m}{D_{\text{now}}} - 1 \right)
\]  

Degradation (D) is a rather understandable notion. In the case that water trees are growing or the partial discharge level is increasing or the lead sheath is corroding, this means that the degradation is increasing. For easy handling a number is given to the amount of degradation.

The cable circuit is taken into operation, the degree of degradation will be usually \( D = 0\% \). At the moment of analysis, so at \( t_{\text{now}} \), it is \( D_{\text{now}} \).

The maximum allowed degradation \( D_m \) is defined as the degree of degradation when the risk of failure has increased beyond the limits set, \( D_m = 100\% \). Either the degree of degradation may grow up to 100% or it may be stated being 100% because of a diagnostic measurement result, confirmed by an expert. Management decisions may set technical limits to 100%, e.g. in case of lead corrosion a remaining thickness of 30% of its original thickness is set to \( D_m = 100\% \). A water tree length of 35% of the insulation thickness delivers \( D_m = 100\% \).
Effectiveness of an analysis method (E): The effectiveness of an analysis method is measure of the ability to determine the degree of degradation by means of this analysis method. Physical aspects do not only determine this. Also other matters as the experience of a test team, the experience of technicians with a certain analysis method within their own network, the complexity of the interpretation of a diagnostic measurement and so on determine the overall effectiveness of an analysis method. An expert has to determine the effectiveness of the applied analysis methods.

Efficiency of an analysis method (R)
The efficiency of an analysis method is determined by the ratio of the effectiveness and the related costs:

\[ R = \frac{E(\%)}{Costs(k\,€)} \]  

**PROCEDURE AND ANALYSIS METHODS**

**Procedure**
The procedure for the determination of the remaining life of a cable circuit is as follows:

- Determine the relevant components in the circuit (cable type, accessory types)
- Determine per type the relevant potential defects
- Call up all possible analysis methods per defect (one or more, see the examples further on); the methods may be desktop studies or on-site measurements. Each method has its own effectiveness and related costs.
- Select the analysis methods with the highest efficiency, being the ratio of effectiveness and costs.
- Perform the selected analysis methods and determine the degree of degradation per analysis, see the examples.
- Determine the remaining life
- Evaluate the results

Of course this approach may be applied as a part of a wider investigation to assess the condition of the network. This investigation may cover aspects as:

- Set goals the remaining life of a (part of) network under consideration.
- Determine the rules for the selection of the cable circuits or network parts to be subject of the investigation.
- Apply per cable circuit the above mentioned procedure.
- Evaluate the total result of the analysis and of the determination of the remaining life.
- Take decisions about potential next steps.

**Analysis Methods**
The applicable analysis methods for MV underground cable circuits are:

- On-site diagnostic measurements called LS1, LS2, PD and DS
- (Visual) inspections, called VV1 – VV6
- Desktop studies called B1 – B4

**Presentation of Information:** In figure 1 of example 1 an example is given of the spreadsheet that contains all the relevant information for a cable circuit. The construction of the circuit is given in the header. The columns give the components, types of defect, analysis methods, effectiveness, costs, efficiency, D\text{now} and Rlt. The rows give the information per the component in the circuit.

**EXAMPLE 1**

Example 1 concerns a belted 8/10 kV PILC. The length is 4,000 m. The age is 40 years and it installed directly in the soil consisting of regular sand. At engineering stage, the load was rated to max. 200A. There are 12 bitumen joints installed, 1 oil-filled joint and 2 oil-filled 3-phase terminations. The first 30 years the load was less than 50%. The next 4 years the load went up to 50% and the last 6 years up to 60%. With view on the increasing, high load, the question is what the remaining life may be. It is noted that 2 years ago 1 bitumen filled joint broke down and was replaced by the oil-filled joint. The short circuit current will be switched off within the standard protection time. Figure 1 gives the overview.

By listing up the components, the expected types of defect, the possible analysis methods per defect type, the effectiveness and the costs one may calculate the efficiency per analysis method. The ones with the highest ranking, in this case the desktop study, will be selected for execution. Next to that, the utility has some doubts about the quality of the remaining bitumen joints. So the desktop study B2 and the PD localization method were selected. The outcome of B2 was a degree of degradation less than 45%. B2 makes uses of the Arrhenius equations to determine the degree of degradation (e.g. for every 6 K temperature increase of the paper insulation, the speed of aging doubles). The PD localization showed one bad joint that needs to be replaced within 1 year.

For situation a) with a continuous load of 60%, the remaining life Rlt will be better than 10 years, after replacement of the indicated bad joint.

For situation b) with the next five years a load of 60% and after that a load over 70%, the desk study indicates a remaining life Rlt > 9 years. Next to that, for this type of bitumen joints it is well known that the maximum load they are able to endure is 70%. Because of that, the Rlt = 5 years because of the joints. Increase of the load over 70% needs replacement of the 11 bitumen filled joints with another type of joint.
Remaining life analysis circuit A – situation b

- PILC
  - 12 bitumen joints (2 years ago one failed)
  - 1 oil-filled joint (since 2 years)
  - 2 oil-filled terminations
- Load: 30 years: < 50 %, 4 years: 50 %, 6 years: 60 %

<table>
<thead>
<tr>
<th>Component</th>
<th>Expected types of defect</th>
<th>Possible analysis methods</th>
<th>Effectiveness E (%)</th>
<th>Costs (k€)</th>
<th>Efficiency R = E / k€ (%/k€)</th>
<th>Result analysis method</th>
<th>Rlt (year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PILC</td>
<td>thermal</td>
<td>PD</td>
<td>90%</td>
<td>4,1</td>
<td>22</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>VV2</td>
<td>90%</td>
<td>2,8</td>
<td>32</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B2</td>
<td>70%</td>
<td>1</td>
<td>70</td>
<td>Dnow &lt;45%</td>
<td>&gt; 10 years</td>
</tr>
<tr>
<td>12 bitumen joints</td>
<td>voids</td>
<td>PD</td>
<td>80%</td>
<td>4,1</td>
<td>20</td>
<td>1 joint has risk 2</td>
<td>1 year</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>risk 2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>11 joints: -</td>
<td></td>
</tr>
<tr>
<td>1 oil-filled joint</td>
<td>low oil level</td>
<td>PD</td>
<td>80%</td>
<td>4,1</td>
<td>20</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>moisture</td>
<td>80%</td>
<td>4,1</td>
<td>20</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2 oil-filled</td>
<td>low oil level</td>
<td>PD</td>
<td>80%</td>
<td>4,1</td>
<td>20</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>terminations</td>
<td></td>
<td>moisture</td>
<td>80%</td>
<td>4,1</td>
<td>20</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

* Situation a): Continuous load of 60%
** Situation b): First next 5 years load will be 60% and after that 70%

Figure 1 Example 1, belted 8/10 kV PILC

The evaluation shows that for situation a) the cable circuit insulation may last for at least 10 years with a certainty of 70%, being the effectiveness of the analysis method B2. After replacement of the indicated bad joint, it is very likely (E = 80%) that no joints will fail in the next 10 years. For situation b) it shows that the cable insulation may last for at least 9 years with a certainty of 70%. After replacement of the indicated bad joint, it is very likely that the other joints will be no problem for the next 5 years. After increasing the load up to 70% the bitumen joints are the limiting factor.

This way of analyzing the remaining life of a cable circuit gives a clear framework for the assessment of the condition and the remaining life of a cable circuit.

EXAMPLE 2

Example 2 concerns a 12/20 kV XLPE cable circuit with a length of 3,000 m and is suspected to suffer from water trees. The data of the circuit is as follows: Year of taking into service 1981, 3 single core cables, conductor is 400 mm² Al stranded without longitudinal water blocking, insulation XLPE steam cured, outer sheath is PVC, no longitudinal water blocking underneath, load is < 60%, 18 heat shrink joints and 6 heat shrink terminations, no breakdown until now. Figure 2 shows that the analysis methods with the highest efficiency are the desktop studies B3 and B2. Result of B2 is Dnow = < 10%, meaning a remaining life Rlt > 114 years.

Remaining life analysis circuit XLPE cable 1980 3 km 400 mm²

- XLPE steam cross-linking
- 18 oil-filled joints
- 6 heat shrink terminations
- Load: 23 years: < 60 %, future load 100 % of In

<table>
<thead>
<tr>
<th>Component</th>
<th>Expected types of defect</th>
<th>Possible analysis methods</th>
<th>Effectiveness E (%)</th>
<th>Costs (k€)</th>
<th>Efficiency R = E / k€ (%/k€)</th>
<th>Result analysis method</th>
<th>Rlt (year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer sheath damages</td>
<td>LS2</td>
<td></td>
<td>0%</td>
<td>n.v.t.</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Thermal insulation</td>
<td>PD</td>
<td>B2</td>
<td>1%</td>
<td>90%</td>
<td>4,1</td>
<td>1</td>
<td>90</td>
</tr>
<tr>
<td>Water trees [1]</td>
<td>DS</td>
<td>VV4</td>
<td>90%</td>
<td>15%</td>
<td>3,6</td>
<td>25</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>VV5</td>
<td></td>
<td>100%</td>
<td>4,8</td>
<td>4,8</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>B3</td>
<td></td>
<td>60%</td>
<td>0,3</td>
<td>23,8</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>Heat shrink joints 18</td>
<td>Voids and sharp edges</td>
<td>PD</td>
<td>80%</td>
<td>4,1</td>
<td>20</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Heat shrink terminations 6</td>
<td>Voids and sharp edges</td>
<td>PD</td>
<td>80%</td>
<td>4,1</td>
<td>20</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Figure 2 Example 2, 12/20 kV XLPE cable steam cured, PVC sheath, no water blocking
Result of B3 is that this cable type is suspect to water tree growth, meaning that remaining life $R_{lt} = 0$. To verify that, it was decided to perform DS, the dielectric spectroscopy measurement. Outcome of DS was a remaining life $R_{lt} = 3.8$ year. The remaining life was extended with 4 years because of application of the diagnostic measurement DS.

The remaining life is determined by water tree growth. The cable circuit is near to its end. After 4 years there will be an unacceptable risk of operation. That means either replace the cable within 4 years from now on or impregnate the cable insulation via the conductor to improve the condition.

The remaining life is limited because of water trees and not because of thermal degradation. The asset manager operation may decide to operate this cable up to 100% of its nominal rating. With B2 it is calculated that in that case the remaining life of the insulation because of the thermal degradation will be at least 15 years. There is no problem to be expected by operation with a continuous 100% load. Figure 2 gives the overview of the analysis.

Example 3

Example 3 concerns a belted 6/10 kV PILC with an age of 60 years in 2003. De load reaches up to nearly 100%. The accessories are not suspect of limiting the remaining life. The annual increase of the load is 3%. The loading shows a typical summer-winter pattern, see figure 3. The winter pattern is lasting for 3 months and the summer pattern for 9 months. For the calculation of the thermal degree of degradation of the paper insulation, the patterns are simplified, as indicated.

Figure 3 Example 3 daily load pattern in January (top), May (middle) and August (low)

Analysis method B2 was applied. The result is presented in figure 4. With continuing increase of load with 3%/year, $R_{lt} = 9$ years. However in that case it has to be noted that the load may grow in the winter period up to 135%. Suppose that the asset manager will not allow a load over 100% than the remaining life $R_{lt} = 16$ years (red line in figure 4). This load of 100% will be reached after 6 years.

**DIAGNOSTICS AS PART OF CONDITION ASSESSMENT**

Asset managers that want to know the remaining life or the condition or the failure rate of their underground cable network may follow the procedure described before. They select cable circuits for further analysis in such a way that they will analyse the circuits that will contribute the most to the criteria set, e.g. the important ones with the most bad track record. They apply the described method and may determine the remaining life with the given method. In the next part results are given of two utilities applying partial diagnostics as the one and only analysis method. When doing that, this is often called as CBM. [2, 3, 4]. These utilities use the outcome for improving the remaining life and the performance of their underground cable network.

**ENECO-Midden 2002, 2003 and 2004**

The utility ENECO-Midden applies regularly partial discharge localization measurements on its MV cable network. They apply an effective set of selection rules, as described in detail in [2] and 33]. Table 1 presents the results of 2002, 2003 and 2004. The results are expressed in Risk Classes 1 up to 4, meaning that a component with risk class 1 needs to be replaced on a short term and with class 2 within 1 year [2, 3, 4]. A component with class 3 needs to be measured again after 1-2 years (trend determination); class 4 does not need any action. Next to that the results are given in percentage of components that need attention.

In 2002 60% of the cable circuits diagnosed did not need any action. By means of a new set of rules for the selection of circuits to be diagnosed [2, 3], the percentage of circuits that did not need any attention was decreased to 25% in 2003 and to 30% in 2004. The percentage of circuits that needed replacement was improved from 29% to 53% in 2003 and to 43% in 2004. The “hard” financial benefits were increased too, resulting in a net positive outcome as described in [2, 3].

**Table 2**

Table 2 presents the results for each component type. It has to be noted that the so-called Nekaldiet joints (a certain type of cast resin joint) were applied about 30-40 years ago and that these joints seems to have reached their end of life. Result is that their knowledge rules, do allow only low values and low number of partial discharges. Next to that it is often not known whether it is a Nekaldiet joint or a bitumen joint. This is reflected by the question mark in table 2.
Table 1 Diagnostic results of ENECO-Midden

<table>
<thead>
<tr>
<th>Risk class</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
</tr>
</thead>
<tbody>
<tr>
<td># of cable circuits</td>
<td>62 = 100%</td>
<td>94 = 100%</td>
<td>105 – 100%</td>
</tr>
<tr>
<td>Class 1-4</td>
<td>21%</td>
<td>31%</td>
<td>25%</td>
</tr>
<tr>
<td>Class 2-4</td>
<td>8%</td>
<td>22%</td>
<td>18%</td>
</tr>
<tr>
<td>Class 3-4</td>
<td>11%</td>
<td>22%</td>
<td>27%</td>
</tr>
<tr>
<td>Class 4</td>
<td>60%</td>
<td>25%</td>
<td>30%</td>
</tr>
</tbody>
</table>

Table 2 Results per component of ENECO-Midden

<table>
<thead>
<tr>
<th>Component</th>
<th>Class 1 and 2</th>
<th>Class 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>200 2</td>
<td>200 3</td>
</tr>
<tr>
<td>Bitumen</td>
<td>14</td>
<td>20</td>
</tr>
<tr>
<td>Fluid-filled</td>
<td>7</td>
<td>6</td>
</tr>
<tr>
<td>Cast resin (Nekaldiet)</td>
<td>17?</td>
<td>12?</td>
</tr>
<tr>
<td>Terminations</td>
<td>-</td>
<td>9</td>
</tr>
<tr>
<td>Cable parts</td>
<td>1</td>
<td>9</td>
</tr>
</tbody>
</table>

Utility in a European Country

An electric utility in a European country started an intensive CBM program on its underground cable network because there were regions with a high number of unexpected outages per 100 km length and because the National Regulator had put rather severe penalties on outages lasting longer than 30 min. In 2000 and 2001 they have executed several pilot projects [2]. These pilot projects showed that their goals, improving of the performance of the underground cable network, could be reached. At CIRED 2003 it was reported that the failure rate had improved in comparison with similar network parts that were not diagnosed.

In 2002 and 2003 KEMA was involved in this project by diagnosing 2,500 cable circuits. The activities consisted of checking the length of each circuit, localizing joint positions, localizing weak spots by means of partial discharge diagnostics [2, 3] and assign risk classes to them and finally locate the weak spots with class 1 and 2 on the cable route.

Results were that 55% of the cable circuits had discharges, divided as follows: 12% of the circuits had components with class 1 or 2 (need to be replaced), 22% had class 3and 21% had class 4. And the other 45% of the diagnosed cable circuits had hardly any discharge activity. So the total percentage of circuits that not needed attention was 66%.

These results were confirmed by visual inspections on replaced components. They were in conformity with the expectations of the utility. Verbally it was stated that the failure rate has improved. The utility will continue its CBM program on underground power cables.

Discussion

From the ENECO example it can be concluded that the proper circuits were selected by application of effective selection rules. Using the results of the partial discharge analysis method may make an effective recommendation for action. The components that were limiting the remaining life could be removed. The remaining life was extended.

The method applied has enough quality, in the meaning of predicting remaining life \( R_{lt} \), to be used.

SUMMARY AND CONCLUSION

The method for the estimation of remaining life or better for an increased risk of operation gives the user a structured way for assessing the condition of an underground cable circuit or a cable network (part), taking into account the past loading and the expected future loading of this circuit. Each component of the subjected circuit is analyzed, taking into account potential causes for deterioration (weak spots or defects) and methods for analyzing the effect of these defects on the degree of degradation. The analysis methods consist of desktop studies, on-site (diagnostic) measurements and laboratory measurements. Each analysis method has its own effectiveness, a measure for the certainty of the outcome and efficiency, being the ration between effectiveness and costs. The analysis methods with the highest efficiency should be applied first, resulting in a certain degree of degradation and in remaining life, in dependency of the future load and of the past load.

The conclusions are:

1. This method to determine remaining life \( R_{lt} \) can be used in practice and gives insight indeed in the remaining life. It provides objective clarity about the difficult object of remaining life and can be used in supporting management decisions.
2. The method can easily be incorporated in existing CBM techniques. Analysis techniques as PD-measurements, Dielectric Spectroscopy, desk studies and so on can all be optimally used in an effective and efficient way.
3. Using CBM circuit selection criteria and knowledge rules, diagnostics may be applied there where they are most needed and may add the highest value to the utilities goals regarding reliability and failure rate. Diagnostic measurement programs themselves became cost effective using the described methods.

REFERENCES