Medium voltage cable diagnostics
condition based maintenance on power cables

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1. Summary

Condition Based Maintenance (CBM) on power cable circuits is an important part of asset management in a liberalised market place for electric energy. Repair before breakdown will be possible after determination of the local condition of the cable circuit. Repair before breakdown reduces the operational costs, increases availability, reliability, trust of customers and postpones investments to a later date. To identify cable weaknesses, cable diagnostics are needed to support CBM. In this paper, the integration of cable diagnostics with CBM will be discussed. Part of this discussion will be the impact of the professionalism of the people performing diagnostic testing on the one hand and the attitude of the network owners asking for diagnostic testing on the other hand.

2. Introduction

CBM for service aged medium voltage cable circuits is realised by means of cable diagnostics as part of the condition assessment of the underground cable network, see Figure 1.

Results of the condition assessment are input for the economical and technical assessment. This will give a maintenance concept for cable circuits as part of the total maintenance policy for the network.
If it is decided to replace a part of the cable because of an unacceptable risk on failure, such replacement will normally result in an increased reliability which has a number of additional advantages among which the most important are:

- increased customer satisfaction and trust (which in a liberalised market may result in a higher price for delivered energy)
- reduced costs for unplanned repair

In this paper, a method of CBM on power cables is given. Moreover, it will be shown that network owners may use the results of diagnostic testing in different ways, and if such testing result is not used in the right way, easily a network owner will be disappointed. This will be discussed under ‘Diagnostic dilemma’. A few words will be dedicated to CBM and testing of new cable circuits in the section ‘CBM and new cables’. A large part of this paper, the section ‘Economy of CBM’, will present the financial impact of diagnostic testing, in this case mainly focussed on the merits of partial discharge diagnostic testing. Finally, in the section ‘Diagnostic test methods for power cable’ a summary will be given of the various diagnostic methods used by network owners in the Netherlands and by KEMA.

In this paper, Uo is defined as the working system voltage between the conductor and earth screen.

3. CBM philosophy

In Figure 2, the philosophy of CBM on cable circuits is given in a flow chart. The history, the operational and the laying conditions, together with the importance of the cable circuit in the network (in particular for the customer), give clues for the decision to perform diagnostic testing (yes or no). It will be clear that if an important cable circuit has reached a specific critical number of failures per unit of time, diagnostic testing can help to decide whether

- the cable system is in good condition or
- there are remaining
week spots or
• the whole cable system is in bad condition.
Based on this knowledge, a recommendation can be made that should take into account external conditions such as installation, loading, required circuit performance in the future and so on.

This experience, together with the diagnostic experience obtained on other cable circuits can help to optimise the maintenance plan.

The maintenance plan for cable circuits has to be balanced with maintenance operations for other network elements such as lines and substations.

When discussing the cable circuit condition, it has to be taken into account that there is sometimes more than one ageing mechanism and moreover, that not all ageing mechanisms can be cached by means of partial discharge diagnostics. Two examples:

• If an extruded cable circuit has failing joints, a diagnostic test based on partial discharge detection may reveal a few more joints that do need replacement. But if the same circuit is suffering from water tree degradation, many future cable breakdowns will make the cable circuit unreliable and thus the projected joint replacement has to be seen in this new light, it can be waste of money.

• If a paper insulated lead covered cable is tested with a partial discharge test and it does not show any sign of cable insulation degradation or weakness of joints, then such a cable can be seen as reliable for future operation. But if at the same time lead sheath corrosion is taking place, the rate of this corrosion is probably determining the actual remaining life.

4. Diagnostic dilemma

It should be taken into account that a diagnostic test that will be performed only a few times during the cable life time in general is able to find only the defects with a slow degradation processes. Defects with a rapid process of degradation (i.e. a short period of time between the initiation, growth and breakdown) in most cases have already caused a failure long before or long after a diagnostic test will be or has been carried out respectively.

Consequently, such diagnostic tests cannot reveal most of the short term defects and thus not prevent all future cable failures and moreover, also not the failures caused by sudden external mechanical cable damages. Therefore, the application of diagnostic testing in general needs a thorough discussion in order to avoid unrealistic demands and expectations.
The diagnostic dilemma is based on this knowledge and will be introduced with the following example, considering a cable circuit with 42 joints. In this example by the way the impact of external damages is excluded:

- 5 joints are of poor quality giving them an expected mean remaining life of maximum 5 years; these joints generate measurable partial discharges and without further measures, they will initiate 1 joint failure per year in the next 5 years;
- in the same cable circuit there is one additional failure per year in other joints due to fast growing defects; related partial discharges can only be seen during a short period of time, say 1 week or 1 month, until joint failure.

In this example there the network owner was confronted with 2 unexplained joint failures per year (1 from a fast growing defect and 1 from a slow growing defect). Assume that a diagnostic test could identify the 5 joints that suffer from a long term degradation process. Two possible measures can be taken now by the network owner, each having their own consequences:

1. Measure 1: the network owner replaces the 5 identified joints. On the one hand, the joint replacement will prevent 5 future joint failures in the next 5 years. On the other hand, there are still some remaining joint problems, namely 1 per year (those failures caused by the short term degradation process). This is only fully understood by a network owner if he is experienced with the consequences, advantages and disadvantages of diagnostic testing. Such experience can be build up only if the network owner is understanding possible ageing processes and in addition is willing to perform visual inspections of the replaced joints, especially in the beginning of using diagnostic testing. Such feed back will help to understand the merits of diagnostic testing and to increase the effectiveness of the diagnostic tests too;

2. Alternative measure 2: the network owner is NOT replacing the 5 identified joints. Now there are still 2 joint failures per year. And, …. there is a possibility of as much as 50 % that the first new failure will not be in an identified joint.

This examples shows, that although the partial discharge diagnostic test was fully effective here, network owners can nevertheless become disappointed, depending on their CBM attitude. This can be overcome if a network owner is fully co-operating with testing people and when he is interested in the strengths and weaknesses of diagnostic testing. People performing such testing should be willing to support the network owner in this process, with realistic presentations. Network owners will benefit to a great extend from feed back from visual inspections which is one of the keys to get a successful CBM. And last but not least, a network owner must be able to identify his profits terms of money.
5. **CBM and new cables**

In the case that diagnostic tests are part of the commissioning procedure [1], certain mounting defects that would lead to an early failure can be found next to the already mentioned defects that suffer from long term ageing processes. Consequently, the effectiveness of a diagnostic test is the highest when it is combined with cable circuit (re)-commissioning. This is also convenient for reasons of planning efficiency, because diagnostic tests are integrated in the whole lot of commissioning tests.

6. **Economy of CBM**

Especially with an eye on partial discharge diagnostics, the economy of condition based maintenance will be discussed in this section. The reason to choose partial discharge diagnostics is, that this type of diagnostic testing is relatively expensive compared to many other types of diagnostic testing such as loss-factor measurements, dielectric spectroscopy, etc. This is mainly because of the time that is needed afterwards for data analysis. Consequently, the results given in this section are an example. Similar examples can be given for other diagnostic tests, under the condition that such tests are available and that their effectiveness has been proven.

One of the Dutch utilities (REMU) is performing the partial discharge diagnostic method since 1994. Until 1998, the total circuit length measured was 712 km [2]. The number of circuits diagnosed was 451. The number of repaired joints was 117 and the number of repaired cables was 10. During the diagnostic testing, 32 circuits did breakdown, their condition was too bad. The utility calculated the number of substations with prevented outage, which was 821. Taking into account

- the average outage time per failure,
- the type of customer that would suffer from an outage (household, industry, etc.),
- the costs of an outage per kWh and per minute (for each type of customer [3])

the client savings over this 5 years period were 2 million US$. The total costs for the diagnostics were about 700.000 US$. Consequently, the savings in 5 years time were about 1.3 million US$. Annual details are given in Table 1. The utility REMU reported, that the availability of the circuits increased, the financial claims decreased and investments can be focussed to those parts of the network that needed it mostly. Similar results were obtained in 1999 and 2000.

Customers in Europe, North America and the Caribbean had savings ranging from 80%-90% because of diagnosing so-called problem circuits. Instead of replacing complete cable circuits, only parts had to be replaced. The savings in those cases were quite substantial.
<table>
<thead>
<tr>
<th>Table 1</th>
<th>The economy of diagnostic pd testing for one of the Dutch utilities in the Netherlands, REMU</th>
</tr>
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<tbody>
<tr>
<td>2. Total length of cable diagnosed [km]</td>
<td>40</td>
</tr>
<tr>
<td>3. Number of measuring days</td>
<td>14</td>
</tr>
<tr>
<td>4. Number of circuits diagnosed</td>
<td>23</td>
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<tr>
<td>5. Number of failures during diagnosis</td>
<td>4</td>
</tr>
<tr>
<td>6. Number of repaired cables in circuit</td>
<td>3</td>
</tr>
<tr>
<td>7. Number of repaired joints in circuit</td>
<td>7</td>
</tr>
<tr>
<td>8. Number of repaired total</td>
<td>10</td>
</tr>
<tr>
<td>9. Number of circuits diagnosed more than once</td>
<td>14</td>
</tr>
<tr>
<td>10. Number of substation with prevented outage</td>
<td>166</td>
</tr>
<tr>
<td>11. Clients savings in 1000 USA$ (=k$)</td>
<td>482 k$</td>
</tr>
<tr>
<td>12. Total Costs REMU in 1000 USA$</td>
<td>14 k$</td>
</tr>
<tr>
<td>13. Total savings in 1000 USA$</td>
<td>468 k$</td>
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A utility in the USA calculated a saving of 30%, based on measurements on more than 50 circuits. An electric utility in Europe had a decrease of his failure rate with about 50%, because of diagnostic testing and condition based repair of joints and cable parts.

Since 1998, measurements are performed in Malaysia, at first with a KEMA set from the Netherlands, later on with a set owned by TNB Transmission. The training of the TNB engineers was partly a theoretical one and mostly done by training on the job. In 81 days 74 circuits were measured. 40 of them were transformer tails, existing in average of 3 cables per phase each. 34 cable circuits were distribution cable circuits. It appeared that a briefing before diagnostic testing is very advantageous. Testing engineers learn a lot about the history of the cables to be measured from the engineers and technicians of the network owner; recommendations can be focused to the actual situation now. In the case of TNB, the results were according to the expectations. On transformer tails a lot of bad terminations and bad cable pieces were detected. Transition joints between paper insulated cables and extruded cables gave problems and cables with high load were found to be notorious bad. The cables measured and repaired, based on the recommendations, have a significant lower breakdown rate than before. All transmission circuits measured did not show any breakdown after diagnose and repair. During measurement and shortly afterwards some breakdowns happened in distribution cable circuits. The condition of those circuits was too bad to withstand the diagnostic testing. The client accepted this as a statistical uncertainty.
7. Diagnostic test methods for power cable

In this section a selection of the most common tests that can be part of CBM is given. Not all utilities apply all test methods, their actual choice is depending on the level of integration of CBM in their maintenance policy, the experience they have with specific diagnostics, the specific characteristics of their network and the type of defects they have or can expect.

7.1 Diagnostic tests for power cables

The following diagnostic methods are available for medium-voltage power cables:

- partial discharge tests for locating weak spots in the joints, the terminations and in cable parts [2, 4, 5], (each having their own risk on failure) such as
  - moisture ingress in paper cable (moisture ingress is not always visible, f.i. a film of conducting water next to the lead sheath is not easily generating discharges)
  - electrical treeing in paper cable or in extruded cable or in resin joints or in premoulded joints or terminations
  - drying out of paper in a paper cable
  - low oil-level in joints or terminations in paper cable or in extruded cable
  - moisture ingress in joints or terminations in paper cable or in extruded cable
  - void formation in a bitumised joint in paper cable
  - loose screens because of oil ingress via terminations or external damage of the insulation screen for extruded cables [5, 6]

- dc withstand testing; for instance as pre-diagnostic method for electrical treeing in resin joints in paper cable

- ac withstand testing either with 0.1 Hz or near operating frequency with series resonant testing for extruded cables

- loss factor measurement with 50 Hz (or series resonant), 0.1 Hz or with an oscillating wave for paper cable or for extruded cable; especially extruded cable with a very high rate of degradation due to water treeing will show increased losses [7, 8]

- dielectric spectroscopy for paper cable and extruded cable; this is a sensitive way to measure losses at various frequencies (0.0001 Hz to 1 Hz) and various test voltages (up to 1 Uo); especially for extruded cables this will reveal water treeing in a much earlier stage than the above mentioned loss factor measurement [9]

- dc leakage current test (an unbalance or too high levels indicate the presence of one or more defects) for paper cable

- outer sheath test with dc, to check the integrity of the plastic outer sheath; mainly intended to detect external damage for extruded cable

- corrosion of the lead sheath; samples of the lead are needed; only for paper cable
• paper insulation; samples of the paper insulation can be inspected if a cable sample has become available from a paper cable
• visual checks on terminations, which can be done regularly for paper cable or for extruded cable
• determination of the g-factor of the soil in a cable trench, as part of the analysis of thermal aspects

7.2 Knowledge rules

Based on many testing results, KEMA has made a database with knowledge rules that can support diagnostic testing in general and partial discharge testing in particular. Test engineers may let a PC fire these rules if the statistical performance of partial discharges from a location are similar to the statistical performance of a defect found somewhere else in the past.

8. References