INTRODUCTION

Since 1994 the 0.1 Hz cable diagnostic method has been applied. At first the objective of the users (electric utilities) was mainly to diagnose cables with a bad reputation. Later on their objective was often focused on CBM on power cable systems. Originally the use was mainly focused on single cable sections. Criteria for distinction between real bad spots, bad spots and up-coming bad spots were developed and checked by means of visual inspection of replaced parts. Knowledge rules per type of component were developed, leading to recommendations for maintenance actions. A lot of (positive) experience was built up. Examples of utility applications show the usefulness, such as from REMU, a utility in the Netherlands and of ENEL Distribuzione, a utility in Italy. They focus on the cost/benefit analysis and on the method for selection of cable sections to be diagnosed.

Most publications on this subject show success stories only. However, there are also doubts about the usefulness of pd diagnostic testing. Expectations for positive results may be very high and then disappointment may be near. There are various items that make a pd diagnostic test effective or not. Those items are both on the side of the diagnostic test as on the side of the network owner. The various pd diagnostic methods, although all having their own special features and area’s of applicability, hardly influence the usefulness of PD diagnostic testing as part of CBM on power cable systems. It is mainly the experience of test engineers, the availability of good and well-proven knowledge rules, the accuracy of circuit data available and the co-operation between the testing people on one hand and the network-owner on the other hand that are decisive. Within acceptable limits, lack of cable circuit data may lead to a decrease of the accuracy of the recommendations for action.

Results of diagnostic measurements of several utilities show the different aspects of diagnostic testing and its effectiveness as part of CBM: Yes or No?

CBM ON MV POWER CABLE SYSTEMS AND DIAGNOSTICS AND UTILITY APPLICATIONS

PD Cable Diagnostics as Part of A Maintenance Strategy

The decision to perform pd cables diagnostics or not is difficult. It depends on many things as is illustrated in Figure 1. Starting point is the maintenance strategy of the asset manager regarding the cable network. The maintenance strategy determines the criteria for selection of cables to be diagnosed. In the first place the selection depends on the historical operation performance and expected future operation (e.g. loading) (in relation to a specific cable or accessory type). It is also depending on the importance of the cable circuit in the network. It will be clear that if an important cable circuit has reached a specific critical number of failures per unit of time pd diagnostic testing can help to decide whether the cable has a good condition or some remaining weak spots has a bad condition (the whole cable system). The condition, load and importance of other cable circuits in the network and other network parts as lines, transformers and switches give additional information that helps to decide how often a specific cable circuit has to be diagnosed. And if diagnosed, it assists to decide whether an immediate repair or even replacement is needed (if needed at all). It all ends up in a maintenance plan. More extensive information on this subject is given in [1]. Examples of applications are given in the following sections.

Application at REMU, The Netherlands

REMU is one of Dutch utilities. Its underground 10 kV network counts 4 732 km circuit length with 26 633 joints and 30 128 terminations. Table 1 presents the failure distribution in 2001. It was decided to focus on maintenance of cable circuits.
TABLE 1 Failures in the REMU MV grid in 2001.

The cost-benefit analysis is based on the cable criteria used for selection for diagnosis, as discussed later. The cost part of this cost-benefit analysis was defined as follows:

- Diagnostic measurements costs
- Personnel costs
- Early replacement costs before failure
- Engineering costs

The benefits are to divide in so-called “hard”-benefits and in “soft”-benefits. The benefits are the costs that were prevented because of diagnostics:

**Hard benefits for the utility:**
- Repair costs after failure
- Reduction of number of follow-up failures (each breakdown will originate at least one follow-up failure)
- Loss of kWh sold
- Reduction of penalties because of outages (e.g. In the Netherlands longer than 4 hrs € 35.- per household)

**Soft benefits for utility and/or society:**
- Loss of goodwill at customers,
- Losses in the society because of breakdowns

The cost-benefit analysis showed that the hard benefits and the related costs are more or less in balance. But if the soft benefits are taken into account too, then repair before breakdown, because of diagnostics, is favourable. Taking into account that the penalty regime may change (influence of the Regulator), resulting in increase of the penalties, it is clear that the hard benefits will become higher than the costs, delivering a real positive result.

**The selection criteria** for cable circuits to be diagnosed are based on the consequences of a breakdown for the power delivery and for the related costs for the utility. A circuit with a lot of joints is more vulnerable to failure than a route with no joints, which is because joints in general are less reliable than cable is. Dynamic loading will age the circuit much more than stable loading. An outage in a region fed by a single circuit will last much longer than a region fed by a meshed network. And of course the type of customer may determine the penalties. Also the kind of soil and direct related failures in a supply area are weight factors. Each selection criterium is given a value of 1 till 4 (4 is the most important). Next to that each selection criterium has its own factor determining the weight (ranking) in comparison with the other criterias.

**Knowledge rules** for the translation of diagnostic measurement results for each type of component to actions were developed, making use of the measurement results over the last years. The actions are defined as replace on a short term (class 1), replace within 1 year (class 2), measure again after 4 years (class 3) and no action needed (class 4). REMU states “diagnostic measurements without knowledge rules does not make sense”.

The knowledge rules are developed making use of the results of the visual inspections after diagnostic repair. The visual inspections deliver the justification for the proposed action.

<table>
<thead>
<tr>
<th>Value</th>
<th>Expected outage time (# of switching operations)</th>
<th>Type of region</th>
<th>Loading current (Power)</th>
<th>Load pattern</th>
<th>Number of joints</th>
<th>Kind of soil</th>
<th>Total failures in a supply area</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No or automatic restore</td>
<td>Residential areas</td>
<td>0 – 20 A</td>
<td>≤ 70% and constant</td>
<td>≤ 1</td>
<td>Sandy soil</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>One Shopping centres</td>
<td></td>
<td>20 – 70 A</td>
<td>≥ 70% and constant</td>
<td>2 - 7</td>
<td>Clay soil</td>
<td>1-2</td>
</tr>
<tr>
<td>3</td>
<td>2 or 3 Offices and hospitals</td>
<td></td>
<td>70 – 120 A</td>
<td>≤ 70% and very dynamic</td>
<td>8 - 13</td>
<td>Peat soil</td>
<td>3 – 4</td>
</tr>
<tr>
<td>4</td>
<td>4 or more Industrial areas</td>
<td></td>
<td>≥ 120 A</td>
<td>≥ 70% and very dynamic</td>
<td>≥ 14</td>
<td>Peat soil</td>
<td>≥ 5</td>
</tr>
<tr>
<td></td>
<td>Multiplication factor</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Value | 1,5 | 1 | 1,5 | 2 | 1 | 1 |

TABLE 2 Criteria for selection for diagnostic measurements
Application at ENEL Distribuzione, Italy

The Italian Regulator has put a penalty on each outage lasting longer than 30 minutes. That has put a lot of pressure on ENEL Distribuzione, responsible for the MV network in Italy. A lot of measures are taken to reduce the outage time. One of the measures was that ENEL decided to perform diagnostic measurements on parts of its underground cable network, consisting of about 125,000 circuit km length. The criteria for the selection of the cable lines and its cable sections are based on economic criteria and technical criteria. The economic criteria are related to the penalty that is assigned to the line in case of outage and to the costs of repair and of performing diagnostic measurements. The technical criteria are based on the failures statistics for the different regions and provinces and on the local situation.

ENEL performed in 2000 and 2001 pilot projects. Those pilot projects gave input for the decision to start a vast diagnostic test program, lasting in 2002 and 2003. Part of the pilot project was to get insight in the effectiveness of the diagnostic method and of the relation between measurement results and proposed actions. Visual inspections after repair of diagnosed parts delivered justification and improvement of the knowled rules. ENEL requested the proposal of diagnostic actions, based on the measurement results: replace on a short term (LC1), replace within 1 year (LC2), measure again after 1 year (LC3) and no action needed for the first (5) years). ENEL knows of course that certain types of defects do not generate partial discharges and can not be diagnosed with PD diagnostics. Also ENEL knows that certain type of defects have such a high growth rate that it may lead to an early breakdown. So ENEL decided to allow a certain percentage of proposed actions that may not be confirmed by a visual inspection. In the next section attention will be payed to this matter.

ENEL is constantly monitoring the defect percentages not confirmed by visual inspections, failures after test without partial discharges and percentage number of defects related to number of tests done, thus to maintain this activity economically viable.

PAPER CABLE DIAGNOSTICS, WEAK SPOTS AND PARTIAL DISCHARGES

Background of Weak Spots and Relation with PD Diagnostics

Figure 2 gives some possibilities for ageing of paper insulation and the effect on partial discharges.

Weakening of the paper because of ageing (Figure 2a). This ageing is influenced by the electric field stress, by the temperature, by moisture ingress and by other factors. Some waxing of the compound used for impregnation may be the consequence. Result may be a lot a rather small partial discharges, with no short-term danger for the life of the cable. A local attack on the quality of insulation, such as lack of compound in a butt gap or between layers or a pinhole may generate large pd’s (Figure 2a).

Electrical treeing between the layers or in the paper itself may generate large pd’s (Figure 2b). However in case of an electrical tree being in balance with the electric field, no pd’s will be generated and even the tree may not grow anymore [2]. The capacitive current running through the tree and the electrical resistance of the tree determines the voltage between the tip of the tree and the conductor. The tree will be in balance as the voltage on the tip-off the tree has nearly the same value as the voltage because of the electric field.

Extensive electrical treeing of the paper insulation will hardly generate pd’s (Figure 2c). This is for most people pretty unexpected. It is caused by the fact that the resistance of the tree can be small. A leakage current is the result, partial discharge does not occur.

Figure 2 Ageing effects in paper insulation: a) weakening of paper itself or local attack. b) electrical treeing with high resistance value. c) electrical treeing with low resistance value.

Figure 3 shows the relation between the level of pd’s measured, the average growth rate and an indication of critical levels for pd’s, used for proposals for action. As can be seen, a discharge level generating a class 4 (no action) may be caused by a defect in the phase just before a “natural death”. Even no pd’s may be measured just before breakdown. This is a reason why pd diagnostics is effective in most but not all of the cases. Apart from that, defects having discharges with a low value will be difficult to detect too from a noise point of view.
It should also be taken into account that a pd diagnostic test that will be performed only a few times during the cable lifetime in general is able to find only the defects with 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 so-called ‘diagnostic dilemma’ is based on this knowledge. In figure 4 this is illustrated. Because of internal and of external reasons, a new weak spot may start to grow. Internal reasons are e.g. because of loading or of short circuits (thermal-mechanical effects on the insulation, pressure effect on the compound and so on). External reasons may be because of damage or corrosion of the outer sheath (moisture ingress) or other.

All methods use a pd sensor at one cable end only and the partial discharges are located by processing the difference in arrival time of the first incoming pulse and the one that arrives after reflection on the other cable end. The pd magnitude is calculated from the pulse size and usually a calibration procedure is needed to get realistic pd values. Long lengths above 3,5 km may be measured by means of a sensor at each end [3]; at the moment realized only with the 0,1 Hz test method.

Relevant Features of PD Diagnostics

Relevant characteristics that play a role in the decision whether there is a weak spot or not and what maintenance action has to be taken, are listed and discussed below.

1. Wave form of the test voltage: some people claim that the waveform of the test voltage should be as realistic as possible (among others its frequency). However, there is no evidence that this is really a parameter that matters. Certainly, there will be differences in for instance pd densities and pd levels per test method, but these differences can be overcome by defining knowledge rules per test method. Another point of interest is that in the case of many discharging spots it is probably possible that pd’s are generated at more or less the same time if the test voltage frequency is high. This may cause unwanted interference of pd pulses. Here the pd methods with a low frequency power source have an advantage.

2. Measuring time and number of pd’s registered: if the number of pd’s expected is high, which is for instance the case in some PILC cables or if many weak spots are present, then it is important that the measuring time can be extended in such a way that enough pd’s can be traced from all potential weak spots. Methods where pd’s and their locations in the
3. Accuracy of localization and suppression of disturbances: under normal conditions: disturbances (interfering with pd’s) can be suppressed by simple means in such a way that the localization of pd’s is possible with an accuracy of about 1 % of the cable length. Additional computerized tools for further suppression of disturbances are not depending on the pd diagnostic method. The use of such tools and also the way the noise can be suppressed by making the right cable connections and measuring set-up is far more depending on the level and experience of the measuring engineers.

4. Cable length: the maximum cable length that can be diagnosed is in the range of 3 km to 4 km. In longer cables the pd pulses get too much attenuation for a proper detection or recognition. Going beyond a cable length of 3 - 4 km means that the cable has to be split in shorter lengths or that the pd sensors have to be placed on both cable ends, which last solution is used in [3].

5. Additional information: if a method offers the possibility to generate additional information (such as inception voltage, phase information, discharge density, etc.) then this information can be of additional value. It is certain that all pd diagnostic methods offer various elements of this additional information. Concerning for instance the inception voltage, which is used to check whether pd’s from a specific location are generated also under service conditions, it would be interesting to see how the various pd diagnostic methods transfer their data to such service voltage levels.

6. Number of cables diagnosed per day: if short cables are diagnosed with only a limited number of potential weak spots (for instance a 500 m long XLPE cable circuit with 2 joints) then it is possible for all methods to measure 4 or even more cable circuits per day. The level of automation here is important. One can say that it is the author’s impression that the maximum number is mainly limited by the speed with which a network owner can switch power cables on and off. However, in the case of long cables with several pd locations (sometimes PILC itself is generating many pd’s!) and higher disturbance levels, automated operation is very risky and continuous monitoring of the incoming pd’s and analysis results is needed. In such cases 2 cables per day is far more realistic. Therefore, the diagnostic method is less decisive than the complexity of the cable circuit.

7. Transportability of measuring equipment: small equipment has the advantage that it can easily be combined in a van with other cable maintenance or fault location equipment, which is the case for methods based on the impulse voltage or oscillating wave. Equipment size and weight become less relevant if the diagnostics are applied by third parties or by own but specialized personnel.

8. Co-operation with the network owner: the network owner and its attitude are important for successful diagnostics. You can compare this with the relationship between a medical doctor and a patient. It can be difficult for a medical doctor to give the right diagnoses if a patient is only willing to ‘offer’ his/her body and not his/her complaints or when patients are not willing to take part of a learning cycle.

9. Circuit knowledge: without detailed knowledge about the circuit length, cable types, accessory types and joint locations it is hardly possible to conclude whether a discharging location is a weak spot or not. Assume you have a joint with many discharges of 2000 to 10.000 pC. In case of a resin joint this is reason to have a rapid replacement. But, in case of an oil filled joint connected to a PILC cable it is very well possible that the oil level in the joint has become too low because some oil from the joint has penetrated the cable causing some sparking of conductor connectors in the joint. No reason for immediate actions (although this defect is not wanted). In other words: correct circuit data is very important. Cable length and joint positions sometimes can be found with time domain-reflection equipment. Anyhow, those network owners that have a good administration of their network are in advantage over network owners that don’t have this. Lack of cable circuit data may lead to a decrease of the accuracy of the recommendations for actions, within acceptable limits.

10. Experience of measuring engineers: short cables with a limited number of discharging spots are not too difficult to analyze. Especially if knowledge rules are available that can support these engineers, a good result is possible. In situations where there are a lot of disturbances experienced measuring engineers are needed to generate at least some useful data. Examples of difficult situations are:
   a) many discharging locations, partly hidden by other discharging locations
   b) interfering pulses from other sources
   c) different cable types (mixed network)
   d) uncertainty about joint positions and cable length.

11. Knowledge rules: if a diagnostic method is being used already for several years by many different network owners, then there is probably also a database available where experiences are collected. Such databases are very important. They offer the possibility to generate reliable answers for specific categories of cable types and accessory types.

12. Automation facilities: any diagnostic method is able to have some automation build in. It is the author’s experience that it is very dangerous to rely on this automation too much.
But for simple situations, it can help a lot to speed up the diagnostic process. Automation has the following elements:

a) disturbance suppression  
b) discharge location finder (i.e.: placing time markers at each of two pulses from one discharge)  
c) statistical data processing (i.e.: calculate per discharge location the discharge density, mean level, pattern, etc.)  
d) comparison with knowledge rules in a database  
e) reporting  

From what it said above, one main conclusion is that all methods mainly differ with respect to the test voltage waveform. Such differences are not very important if knowledge rules are used that are based on this specific test regime and verified by visual inspections on parts that are replaced because of the diagnostic measurements. Far more important are practical circumstances as experienced measuring engineers, co-operating network owners, reliable circuit information and the availability of knowledge rules.

CONCLUSION AND FUTURE DEVELOPMENTS

The decision to implement CBM on power cable systems and the use of cable diagnostics to enable it depends strongly on the strategy of the asset manager and external factors as given by the Regulator. Decisive is the economical advantage, gained with prevention of unexpected outages (claims), with repair before breakdown and with investment focused on cable systems that really need it. However expectations for positive results may be very high and then disappointment may be near. There are various items that make a pd diagnostic test effective or not. Those items are both on the side of the diagnostic test as on the side of the network owner. It is mainly the experience of test engineers, the availability of good and well-proven knowledge rules (based on results of visual inspections), the accuracy of circuit data available and the co-operation between the testing people on one hand and the network-owner on the other hand that are decisive. Results of diagnostics measurements as part of CBM at several utilities show the different aspects and its effectiveness as part of CBM. Yes or No of cable diagnostics depends highly on the strategy and the goals to be achieved. Cable diagnostics do not deliver “heaven on earth” but may act as a powerful tool for the asset manager.

The following items need further development:

For the selection criteria for cables to be diagnosed, the synergy and value of the multiplication factors used by REMU for the different items need further tuning or determining.

Knowledge rules are still under development; especially if network owners start to use pd diagnostics for the first time; the application of ‘standard’ knowledge rules must be seen as a first step; expectations should not be over-stressed.

Co-operation between network owners and their maintenance offices: slowly there is a change to condition based maintenance. People that are promoting or introducing diagnostic testing on one hand need support, but on the other hand must be careful: equipment only is not enough. Testing of long cables (more than 4 km) is not a problem anymore since it is possible with a patented time synchronization technique to diagnose a cable on both cable ends at the same time. This doubles the cable length that can be diagnosed to 8 or even 10 km. In this way also branched cables can be diagnosed [3].

Pd on-line measurement for diagnosing and locating weak spots with live voltage with the same intention as off-line diagnostic measurement.

REFERENCES

[1] Schaik, N. van., Steennis E.F et all, Condition Based Maintenance on mV cable circuits as a part of asset management; philosophy, diagnostic methods, experiences and the future; CIRED 2001, Amsterdam


