INTEGRAL CABLE CONDITION ASSESSMENT

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ABSTRACT

Motivation for condition based assessment

Practical experiences with different diagnosis measurements

A combination of measurement methods lead to an economic cable assessment

INTRODUCTION AND PURPOSE

Distribution network operators throughout the world face the same problem: maximizing the availability of the grid while keeping the costs of maintenance low, two goals that often work against each other. Yet meeting both is desirable as a matter of policy and technology to ensure the reliability of power supply. For operating resources in particular, which are generally inaccessible (medium-voltage cable in the present case), it is difficult to find the best path in this conflict of objectives. Cable stock in medium and low-voltage networks account for 60 to 80 percent of the actual replacement value in the distribution network [1] and thus is deserving of the best possible strategy not only for network construction and expansion but for maintenance as well.

In evaluating different strategies, three groups of factors must be kept in mind:

- Technical/organisational aspects like operational safety and reliability, work safety, stress on cables in operation, repairs incurred, importance of the cable line to the reliability of the power supply, frequency and probability of failure, availability of maintenance crews, equipment and spare parts.
- Economic aspects like repair costs, personnel capacity costs, maintenance costs, consequential costs of power failures due to loss of earnings or recourse claims by third parties, capital expenses for spare parts and equipment and consequential damages due to network faults.
- Social aspects like reliability of supply risk for non-commercial facilities and reputation damage as a result of power failures

These factors, which are cited in Guideline 420 from CIGRE [2], are increasingly accompanied by policy demands by regulatory authorities, for example, who implement a sort of "benchmarking" for mains operation with the aim of optimising costs through market competition and thus contribute to setting budgets.

Given that the medium-voltage network experiences the most failures per year [2,3], maintenance of the distribution network is very important. According to the source cited, in the Netherlands – a country with relatively high mains availability – there are about 0.25 power failures per customer caused at the medium voltage level each year, responsible for about 70 minutes without power. For comparison, high voltage is responsible for about 0.075 failures and 35 minutes. [1] assumes that with a ratio of about 60 percent paper-insulated cables and 40 percent XLPE cables, a statistical average of one cable failure per 100 km medium voltage cable network will occur each year. Nonetheless, high voltage networks are given higher priority in matters of maintenance and condition monitoring than the distribution network. However, today many mains operators are already applying high voltage knowledge and experience to medium voltage systems and operate their distribution network with greater commitment – and often with great success, financially as well.

EVALUATING CABLE CONDITION

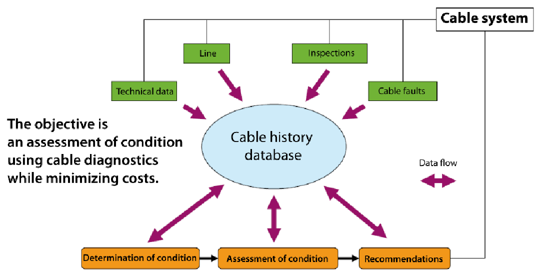

Figure 1: Systematic condition evaluation of medium-voltage cables [4]

The condition of the cable is defined by quantitative and qualitative factors. Qualitative factors include product-specific ones, such as manufacturer, design, type and age,

as well as historical data such as utilisation (operating condition), cable faults, the number of sections and joints, and repairs incurred.

Additional information, for example regarding geographical conditions, is also advantageous. The qualitative factors can also be drawn from an ERP system such as SAP and a GIS.

Quantitative technical factors are the frequency of partial discharges (PD), PD inception and extinction voltage, the dissipation factor (see below), and recovery voltage or relaxation current.

This information must be determined individually for each cable or each cable section. It should be mentioned at this point that conventional cable testing by VDE methods on (V)PE cables with $3xU_0$ for 1 hour does not result in reliable statements regarding the condition of the cable. This testing, carried out after commissioning or restoring a line, merely reveals whether the cable was able to cope with the test voltage at the time of testing. Possible damage to older cables, for example from transient grounds, cannot be detected reliably.

Moreover, the importance of the cable to the grid is relevant for evaluating measures such as repair or replacement. One measure which can be used in this regard is the amount of energy not delivered due to failures (excluding those due to outside influence). This is determined by the number of failures and their duration, the consumers connected and the structural function of the cable and/or redundancy in the relevant network segment.

Practical examples of economic benefits

The question is whether it is worth the effort to measure the dissipation factor (tan δ) and the partial discharge. The answer is 'yes'. Particularly for the sections of line critical for power supply or those which have become prominent by failures, but for others as well. The time required for measuring the dissipation factor and partial discharge is altogether about 70 minutes. The cost for diagnostic measurements is about that of ten metres of cable (including excavation), but valuable information is obtained which indicates whether an exchange or repair makes sense or whether the cable can continue to be used despite its advanced age. Moreover, unexpected damages can be avoided, which require fast (and often expensive) responses, and repairs can be limited to what is truly necessary. Here is a practical example from the RWE Rhein-Nahe-Hunsrück regional centre:

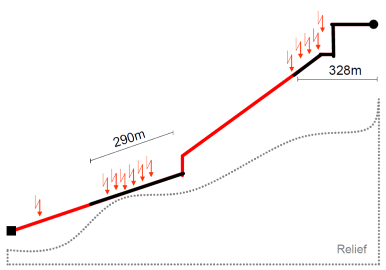

Figure 2: A stretch of cable approximately 1945 metres, type NASXSY / 150 mm², laid in 1978 [4].

The cable line shown in Figure 2 appears to have numerous faults – with topography as a contributing factor in some cases – and various damage due to water trees. However, replacing a line of nearly 2 kilometres should be avoided if possible. Measurement of the tan δ (Figure 3) showed that conductor 3 had aged considerably. Further measurements (partial discharge measurements and VLF testing) enabled the limits of the damaged areas to be determined. Only 618 metres of cable altogether in two sections needed to be replaced. Total costs for this, including all ancillary costs for fault location, testing, etc. ran to 67,455 Euros. Replacing the entire cable line would have cost 199,415 Euros. Thus diagnostic measurements and subsequent determination of the faulty sections reduced costs by two-thirds.

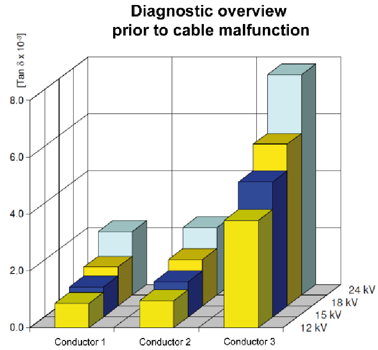

Figure 3: Measurement of tan δ on the cable line from Figure 2. Indications of severe ageing were found on conductor 3 [4].

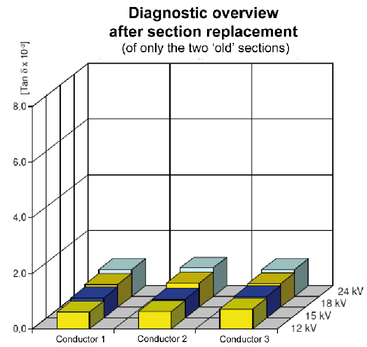

Figure 4: Values of tan δ on the two replaced sections of cable line from Figure 2 [4].

Another example: Vattenfall Europe Netservice GmbH tested a new network section in Berlin, which consisted of 12 cables for 10 kV with a total length of about 150 kilometres and altogether some 180 joints and 72 terminations [5]. In addition to testing with 18 kV and sheath testing with 5 kV DC, the company carried out a partial discharge measurement on the cables. Sheath defects were found in 13 cable segments and (only) by partial discharge measurement was it also possible to identify the same number of weak points in the cable joints. Thus it was possible to demand service for the joints while they were still under warranty. Moreover, the partial discharge measurement and repair of the weal spots ensured that the new mains connection will operate without disturbances for a long time. This procedure enabled future recourse claims from possible power failures to be avoided.

Which diagnostic procedures make sense?

Before discussing diagnostics procedures, a short explanation regarding cable testing: In Germany, for example, testing for the commissioning of medium-voltage cables must be carried out in accordance with VDE 0276-HD620, which is intended to ensure safe operation and reliable function. For a plastic-insulated cable, this involves applying a test AC voltage of $3xU_0$ at 0.1 Hz for 60 minutes. The result of the test is "pass" or "fail". Sheath testing is added to the regimen, for PE-insulated cables with up to 5 kV DC, for PVC cables up to 3 kV DC. This is also a pass or fail test.

However, for cable assets it is of interest to determine how long and how well a cable line can continue to function. For new lines, this is primarily a concern as to whether the lines and associated equipment have been prepared as well as possible for use. Sheath testing, dissipation factor measurement, provide the answer to these questions.

SHEATH TESTING

In sheath testing, the outermost electrically insulating sleeve of a cable system is investigated. Common methods are withstand voltage testing – in this case application of DC voltage until breakdown – and insulation measurement. In insulation measurement, DC voltage excitation is used to determine the amount of voltage excitation and the leakage current at the end of a nominal measurement period (of some 5 minutes) with the conductor earthed [6]. Here the capacitive current, polarisation current, leakage current of the dielectric and currents from conductivities based on changes of state combine. The apparent insulation resistance is then derived from the voltage and current at the end of the measurement period (when an essentially steady state is achieved). Among other things, sheath testing is used to check the reliability of the network and detect functional impairment of the insulation, due for example to water penetration. Any damages are located by additional sheath fault testing.

DISSIPATION FACTOR MEASUREMENT

The dissipation factor is measured with the following arrangement:

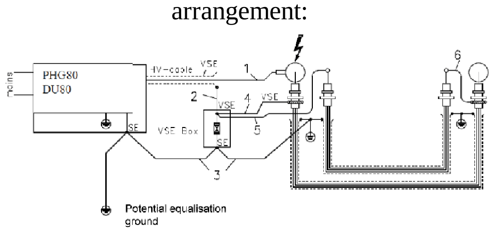

Figure 5: Connection of the BAUR PHG80/DU80 testing device to measure tan δ [9]

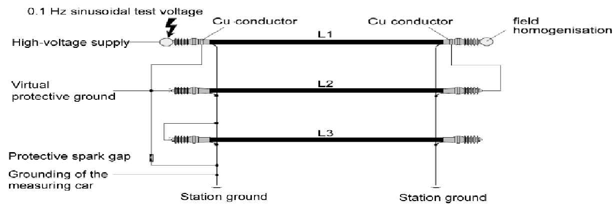

Figure 6: Connection diagram for tan δ measurement. Here, the measurement is on conductor 1, signal return via conductor 2 and conductor 3 is earthed [10].

The device depicted in Figure 5 for measuring the dissipation factor evaluates the measurement signals by Fourier analysis to determine tan δ. The dissipation factor determined is independent of the cable length. The measurement is non-destructive over the entire cable section. Thus dissipation factor measurement is a global diagnostic procedure which does not harm materials. The test result requires interpretation. For this purpose it is necessary to take measurements at multiple voltages, typically $0.5xU_0$, U_0, $1.5xU_0$ and $2xU_0$ (or possibly $1.7xU_0$).

The following chart shows why measurements are necessary at various voltages: A severely aged cable often exhibits about the same tan δ as a new cable at U_0. As the voltage is increased, the steep rise of the value indicates the presence of water trees (quite apparent at $2xU_0$ and $2.5xU_0$).

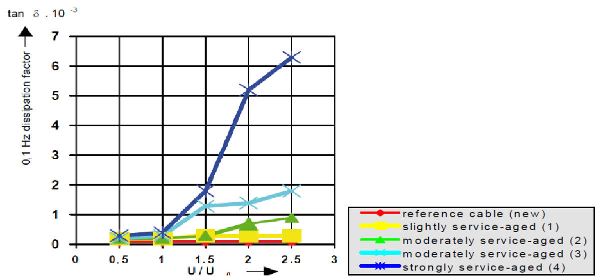

Figure 7: Examples of dissipation factors for various old or aged cables [11]

The highest measuring voltage is also below that used for cable testing ($3xU_0$), which places less stress on the cable. Moreover, measuring the dissipation factor requires only a few minutes at $2xU_0$ (about 5), so the cable is not subject to continuous stress. (Laboratory testing of aged cable sections has shown that with ten cables, none were damaged by a voltage of $2xU_0$ applied for 5 minutes during tan δ measurement, whereas under cable testing conditions nine of ten suffered breakdown [see 10].)

During the measurement, the connection conditions (as per the manufacturer's recommendations) and temperature should be kept as uniform as possible, because tan δ is temperature-dependent [10].

In the meantime, experience from thousands of measurements in Europe has shown that measurement can be classified as follows (when the equipment is used according to the manufacturer's specifications):

For PE/XLPE cables

$\tan\delta\,(2U_0) < 1.2 \times 10^{-3}$ $[\tan\delta\,(2U_0) - \tan\delta\,(U_0)] < 0.6 \times 10^{-3}$	Cable line OK
$\tan\delta\,(2U_0) > 1.2 \times 10^{-3}$ $[\tan\delta\,(2U_0) - \tan\delta\,(U_0)] > 0.6 \times 10^{-3}$	Should be re-tested in a few years
$\tan\delta\,(2U_0) > 2.2 \times 10^{-3}$ $[\tan\delta\,(2U_0) - \tan\delta\,(U_0)] > 1.0 \times 10^{-3}$	The cable line should be replaced

For paper-insulated cables

$\tan\delta\,(2U_0) < 50 \times 10^{-3}$ $[\tan\delta\,(2U_0) - \tan\delta\,(U_0)] < 10 \times 10^{-3}$	Cable line OK*)
$\tan\delta\,(2U_0) < 70 \times 10^{-3}$ $[\tan\delta\,(2U_0) - \tan\delta\,(U_0)] < 20 \times 10^{-3}$	Cable line OK*)
$\tan\delta\,(2U_0) > 70 \times 10^{-3}$ $[\tan\delta\,(2U_0) - \tan\delta\,(U_0)] > 20 \times 10^{-3}$	The cable line should be replaced*)

*) Paper-insulated cables should exhibit similar values for all three conductors; many mains operators use a limit value of 50×10^{-3}

It is basically worthwhile to check the ageing of important cable lines every few years. If a value (for XLPE cables) is found in the yellow range, a repeated measurement in two years is a good idea.

A sinusoidal alternating current at 0.1 Hz has proven good as a test voltage for dissipation factor measurement. There are two reasons for this. The first is that the same voltage source can be used for tan δ measurement as for standard cable testing, so the effort and expense with equipment remains low and no additional manual work is necessary for device connections. For measurement and testing after (partial) renovation of a line, this has time and cost benefits.

The second reason is the significance of the tan δ at 0.1 Hz. The tan δ values for 0.1 Hz and 50 Hz sinusoidal AC voltage are in the same range [11], so measurements at 0.1 Hz (aka very low frequency or VLF measurement) enable conclusions to be drawn regarding operational scenarios. VLF technology also provides the opportunity to use smaller devices , because voltage sources for 50 Hz are big, cumbersome and heavy.

Moreover, compared to sheath testing, tan δ measurement not only provides information about the quality of the sheath but also about the insulation further inside the cable, which for safe, long-term operation is more valuable.

Measurements of tan δ have their limits if the cable diagnosis reveals clear signs of ageing damage or defects: Since dissipation factor measurement considers the entire cable, it is not possible to locate faults precisely or to say whether one or more faults has led to the unacceptable measurement values. Therefore further study of the damaged cable line by partial discharge measurement is called for.

Another hint for those who want to subject new cable to dissipation factor measurement as well: As Figure 13 shows, for many types of new cable, the tan δ is still relatively high as long as the cross linking reactions in the cable still take place and the inevitable outgassing is not complete. Only after a few years (see the axial minimum) is this chemical process at an end and the subsequent rise to be seen as a clear indication of the formation of water trees.

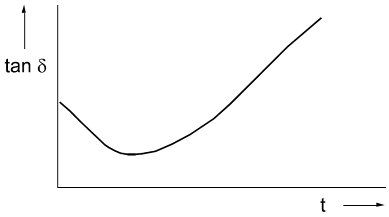

Figure 8: Qualitative representation of tan δ as a function of cable age [10].

PARTIAL DISCHARGE MEASUREMENT

Partial discharges are neither short circuits nor breakdowns but can lead to breakdown in short order.

They occur, for example, at fault locations and in hollow spaces in the cable due to ageing or the formation of water trees, or at joints or terminations, lasting less than a microsecond. Cables can also exhibit partial discharges when new due to mechanical damage or improper jointing. Thus partial discharge measurement is justified for new cables as a quality control measure as well as older systems for purposes of diagnosis and fault location. Partial discharge measurement with location of the source of the partial discharge closes the gap in insulation diagnostics for paper-insulated cables and increases the reliability of assessments for plastic cables.

A key criterion for assessing the condition is the frequency of partial discharges at a location. In other words, if clusters of partial discharges occur at very specific spots. Moreover, such a place with critical partial discharges must be able to be pinpointed in order to carry out repairs where needed and with low cost and effort. Therefore partial discharge measuring equipment for cables is typically differs from that for other operating resources, including integrated runtime measurement which enables faults to be located with nearly meter accuracy.

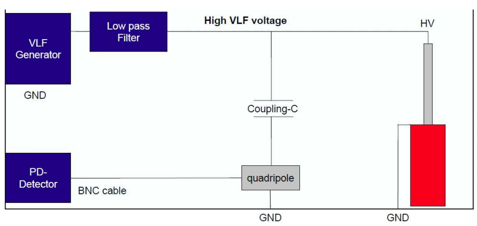

Figure 9: Shows the basic arrangement for partial discharge measurement.

Figure 10: Result of a partial discharge measurement of a mixed cable [4].

The partial discharge measurement values provide information on the cable condition for plastic-insulated and paper-insulated cables. However, the interpretation of the values must ensue with intuition, or better yet experience, as there are considerable differences in measurements depending on the material. Thus, for example, plastic cable insulation should essentially be free of partial discharges (measured values below 20 pC), but paper-insulated cables can show values of several hundred or thousand pC. Strong variations are typically also found at joints and terminations.

In order to make the right decisions based on the values in condition-based maintenance, the data for all conductors of a cable should be noted and compared. Large differences are indicative of a fault. Moreover, a proprietary “knowledgebase” is useful for compiling comparative values for other cables of the same type, for example. Users can also expect help from the IEEE: The organisation intends to publish reference values for assessing condition, which will simplify classification as “potentially critical” or “not a concern”.

SUMMARY

Evaluating the condition of medium-voltage cables requires more to be considered than just a single factor such as the age of the cable. To perform condition-based maintenance of the distribution network and use capital equipment in the best manner, a multitude of information is required. As far as technical information is concerned, sheath testing and diagnostic procedures for dissipation factor measurement and partial discharge measurement are among the most valuable sources. In combination, these enable reliable assessments of the ageing condition for plastic-insulated cables and also provide information on weak points such as joints. The values of both diagnostic procedures are also helpful in evaluating the condition of paper-insulated cables. However, here the wealth of experience is less and the possible factors of influence (such as drying, water content, etc.) are more numerous and of greater magnitude. Therefore paper-insulated cables must be evaluated with care. Here as well the diagnostic procedures provide evidence that allows cables to be classified. Strategic planning of investments is facilitated and these need not be driven by events.

Modern devices with a 0.1 Hz sinusoidal generator enable cable testing and diagnostic procedures to be performed with one voltage source and thus little effort and expense. Moreover, some devices also have the DC voltage source needed for sheath testing.

To optimise condition-based maintenance with regard to economic and social criteria as well, it is important not to rely on technical measurements alone. The importance of the cable line must be taken into account as well as experience (i.e. failure statistics) for cables of the same type. The technical evaluation of quality cannot and should not be the only basis for strategic decisions.

Which factors mains operators consider in making decisions and how these are weighted are a matter of individual judgement, because there are various initial conditions to be considered depending on age, growth, maintenance and topology. Fortunately, there are more possibilities than ever before to weight and summarize the information collected in ways to solve the dilemma of conflict between the objectives of maximum availability and lowest cost, thanks to comprehensive software tools and available knowledge from many areas regarding the existing cable stock and maintenance status as well as detailed documentation of grids (topology, network diagrams and statistics) and simple options for diagnostics.

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