Second Seminar on Undergrounding of Electric Distribution Networks **1.2**

Segundo Seminário Sobre Utilização de Cabos em Redes Subterrâneas de Distribuição de Energia Elétrica

TESTING AND MEASUREMENT METHODS FOR CONDITION-BASED MAINTENANCE OF MEDIUM VOLTAGE NETWORKS

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ABSTRACT

Cable and sheath testing, loss factor measurement and partial discharge measurement deliver measurement values that provide different statements on the proper functioning and condition of a medium voltage cable. The article presents test and measurement processes and describes what results and information are useful during condition-based maintenance. In addition, it explains why diagnostic procedures can increase the profitability and availability even in new cables.

KEYWORDS

Maintenance, distributed network, medium voltage, XLPE cable, paper insulated mass-impregnated cable, joint, sheath testing, cable testing, loss factor measurement, partial discharge measurement, aging, quality check.

INTRODUCTION

Distributed network operators are in a dilemma: From the technical viewpoint and complying with the customers' wishes, they have succeeded in providing high network availability, while on the other hand they have to achieve network expansion and maintenance at low cost. Therefore, more operators are emphasising on condition-based maintenance of their medium voltage network. However, this strategy requires in-depth knowledge of the cable age. Equipment data such as manufacturer, type and age or experience values such as the failure rate and maintenance history can already deliver reference points. In fact the actual "technical age" of a cable is influenced by other factors. Diagnostic measurements such as the loss factor and partial discharge measurement allow you to analyse the age of a cable line with more certainty. Because of the progress in device technology today, both measurements can be carried out at low cost and in less time, which in turn has made cable diagnostics more important. Besides, experience from different countries in XLPE and paper insulated mass-impregnated cables and in various cable types enables reliable interpretation of the measurement results and produces additional fundamentals for maintenance decisions.

Diagnostic processes are not only used during evaluation of existing cable lines, but also new sections, as they allow us to assess the quality of the cable laying - in particular joint assembly - and to prevent subsequent failure or damage due to the early detection of poor assembly.

CABLE TESTS

Cable testing

Cable testing is done according to the VDE (Verband der Elektrotechnik Elektronik Informationstechnik e.V.) on XLPE cables with $3xU_0$ (VLF) for 1 h. This test after laying a new cable (Fig. 1) or restoration of a cable line conveys if the cable endures the test voltage at the time of testing. It is a pure function test and a positive result indicates no damage in the old cables.

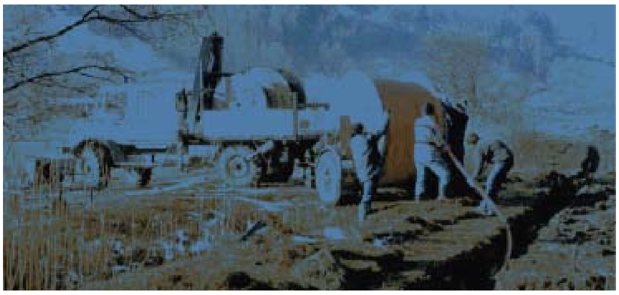

Fig. 1: After laying, a cable is tested for problem-free operation

Sheath testing

Sheath testing is used to test the function and operational safety of the outer, electrically isolating sheath of a cable. It is carried out in the form of the withstand voltage test - the sheath is tested for breakdown by applying a direct voltage - or as insulation measurement using direct voltage stimulation (Fig. 2). Here, the conductor is grounded and the voltage excitation and leakage current is recorded at the end of several minutes of measurement. The apparent insulation resistance determined in this way shows whether the insulation effect is reduced, e.g. due to moisture. On suspicion of damage, a sheath fault location is used to locate the fault.

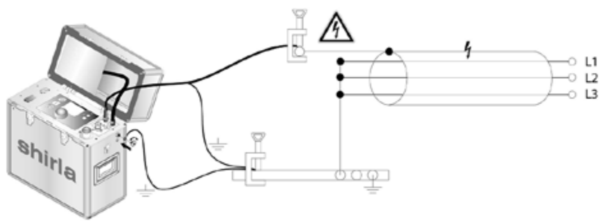

Fig. 2: Sheath testing is used for testing the function and safety of the outer cable sleeve

DIAGNOSTIC MEASUREMENTS

Loss factor measurement

During the loss factor measurement (also called tan δ measurement), the dielectric loss factor tan δ, i.e. the ratio of active power to reactive power of a capacity with applied voltage (here the cable) is measured. Unlike the sheath test, the measurement not only provides information on the quality of the sheath, but also on the insulation inside the cable. The tan δ measurement is done across a complete cable section, including joints. So it is an integral procedure. It allows analysis of the insulating medium in relation to its quality and the aging status that is influenced by thermal overload, poorly manufactured joints and terminations or moisture.

With the loss factor measurement, the aging of XLPE cables is recorded through water trees (Fig. 3). These water trees spread like small trees at damaged points in the insulation (Fig. 4) and from a certain size become "electrical trees", i.e. structures where local discharges occur. If this condition is reached only once, the desired insulation effect no longer exits. Therefore, early detection and estimation of the water trees is important for condition-based maintenance.

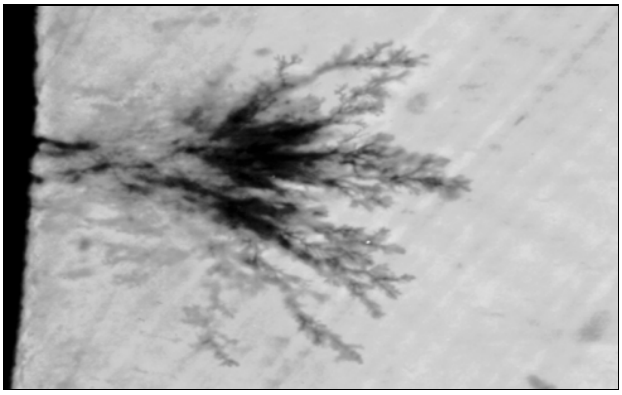

Fig. 3: Water tree

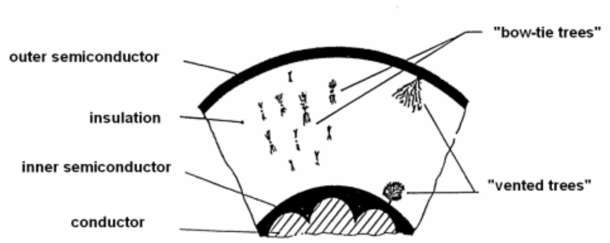

Fig. 4: Types of water trees

However, measurement at one voltage alone is not conclusive. Therefore, the tan δ measurement must be done at several voltages. Usually, measurements are done at $0/5xU_0$, U_0, $1.5xU_0$ and $2xU_0$ or even $1.7xU_0$. If measured values above the voltage are applied, a characteristic course is produced in aged cables (Fig. 5).

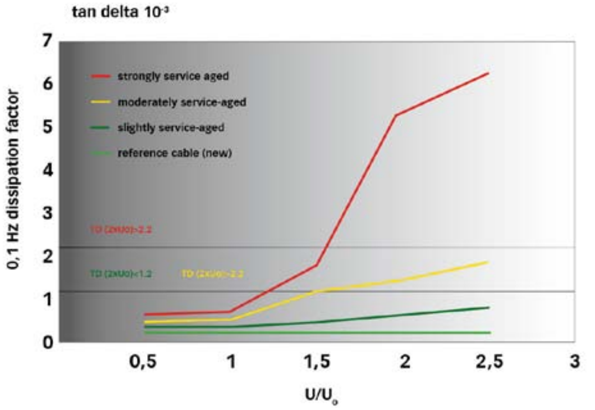

Fig. 5: Idealistic presentation of tan δ for XLPE cables of varying ages

Classification of the cable is possible with the help of the measured values (Fig. 6). For evaluation of XLPE cables using the tan δ, many companies use limit values as shown in Tab. 1.

Fig. 6: Results of the tan δ measurement in evaluation software

Tan δ (2 U_0) < 1.2 x 10^{-3} and [tan δ (2 U_0) - tan δ (U_0)] < 0.6 x 10^{-3}	Cable line OK
Tan δ (2 U_0) > 1.2 x 10^{-3} or [tan δ (2 U_0) - tan δ (U_0)] > 0.6 x 10^{-3}	Repeated testing advised in a few years
Tan δ (2 U_0) > 2.2 x 10^{-3} or [tan δ (2 U_0) - tan δ (U_0)] > 1.0 x 10^{-3}	Cable line (or defective sections) should be replaced

Tab. 1: Classification of XLPE cables using tan δ measurements

Limit values (Tab. 2) can be used even for evaluating the condition of paper insulated mass-impregnated cables. However in this type of cable, individual experiences should be included and the limits must be varied if required. For paper insulated mass-impregnated cables, a comparison of the different conductors is helpful in order to identify conductors that are highly aged or not working properly.

tan δ (2 U_0) < 50 x 10^{-3} and [tan δ (2 U_0) - tan δ (U_0)] < 10 x 10^{-3}	Cable line OK
tan δ (2 U_0) > 50 x 10^{-3} and < 70 x 10^{-3} or [tan δ (2 U_0) - tan δ (U_0)] > 10 x 10^{-3} and < 20 x 10^{-3}	Repeated testing advised in a few years
tan δ (2 U_0) > 70 x 10^{-3} or [tan δ (2 U_0) - tan δ (U_0)] > 20 x 10^{-3}	Cable line (or defective sections) should be replaced

Tab. 2: Classification of paper insulated mass-impregnated cables through tan δ measurements

The tan δ measurement reaches its limits when the cable diagnosis provides information on age damages or defects: As the loss factor measurement considers the entire cable, it is impossible to locate faults or to say whether one or more faults will lead to high measurement values. Therefore, a partial discharge measurement should also be conducted on affected lines.

Partial discharge measurement

Partial discharges (small short-circuits or breakdowns) can cause a cable insulation to "break" temporarily. Among other things, they occur at faults and hollow spaces in the cable, e.g. at electrical trees or joints and terminations. The partial discharge measurement (Fig. 7) with source location allows the diagnosis of paper insulated mass-impregnated cables and in XLPE cables contributes to a plus point with regard to dependability during evaluation and analysis of the transitions (joints, terminations). Interpretation of values (Fig. 8) demands experience, as the values clearly vary depending on the material. The insulation of an XLPE cable should show almost no partial discharges (measured values < 20 pC), while in paper insulated mass-impregnated cables even several hundred or thousand pC are not unusual. Knowledge of the location of joints and where the cable type changes (e.g. from paper insulated mass-impregnated to XLPE cable) is also helpful.

To acquire a good basis for decisions, in paper insulated mass-impregnated cables, it is especially useful to compare the values of all conductors of a cable and only then to make decisions on the classification. Highly varying values are mostly an indication of a fault.

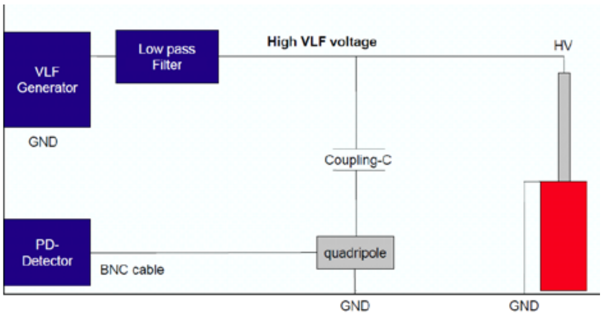

Fig. 7: Measurement setup for partial discharge measurement with a VLF generator

Fig. 8: Faults can be located exactly during the partial discharge measurement on cables

OPTIMUM VOLTAGE SOURCE

VLF measurement

VLF stands for Very Low Frequency and denotes a measurement frequency clearly below the operating frequency, e.g. 0.1 Hz. The low measurement frequency enables use of considerably smaller or lighter devices than during a 50 Hz measurement (or even 60 Hz), as the latter has to offer up to 500-times power as a VLF voltage source.

Conventional cable testing (according to VDE DIN 0276-620, IEEE P400.2, VDE DIN 0276-621, Cenelec HD 620 and Cenelec HD 621), tan δ measurement and partial discharge measurement can be performed at 0.1 Hz. A cable test van with a multi-functional 0.1 Hz voltage source is thus equipped for all relevant measurements on new and old cables and the measurements can be performed one after the other. Partial discharge measurement can even be done simultaneously with the cable test.

Voltage generators that generate the sine or rectangular shaped voltage largely free of distortions are optimum (Fig. 9). Ideally, positive and negative half-waves are identical in shape and size so that charging of the cable is prevented. Such charging would not be reduced immediately on completion of the measurement, hence there can still be a residual voltage during the recommissioning of the cable line, which can lead to damages.

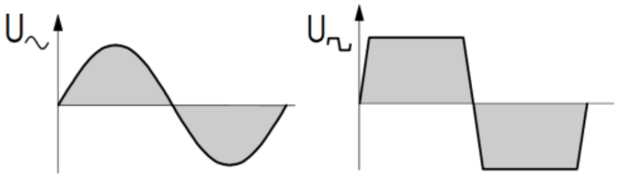

Fig. 9: Ideal sine-shaped and symmetrical rectangular signal

In addition, a VLF sine voltage is advantageous, as it is independent of the load. Hence, changes in the network structure, cable length or similar do not affect the tan δ measurement. Measurement values of a cable line taken at various times can thus be compared properly and trends can be detected.

The tan δ values for sine alternating voltages are mostly same at 0.1 Hz and 50 Hz, so that the VLF measurements allow clear conclusions on the behaviour during operation. Measurements with a sine at 0.1 Hz lead to a quicker and directional growth of water trees in XLPE cables. Bigger water trees that would have become electrical trees in the medium term can thus be brought to a breakdown within few minutes (Fig. 10) and easily located with the partial discharge measurement.

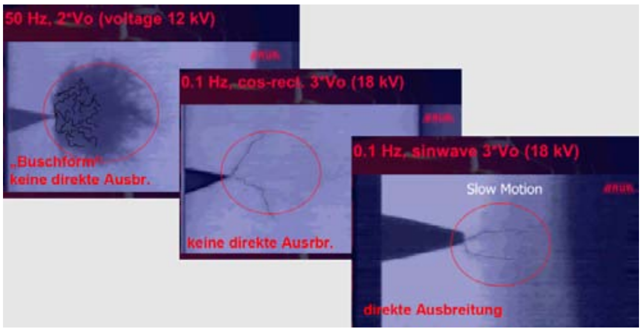

Fig. 10: Growth of water trees: left $2xU_0$ at 50 Hz, centre $3xU_0$ at 0,1 Hz with cos-rectangle, right 3xU0 at 0.1 Hz sine

VLF devices

For VLF diagnostic measurements and cable tests on medium voltage cables, the manufacturer offers various devices. The spectrum ranges from the complete cable test cars (Fig. 11) to compact devices for the cable testing and tan δ measurement (Fig. 12).

Fig. 11: Cable test vans

Fig. 12: Portable cable testing and diagnostic devices

The use of multi-functional devices with a VLF voltage source offers the opportunity to perform other measurements besides the cable testing using the same equipment (at times, even simultaneously) and thus decreases the time for additional diagnostic measurements.

PRACTICAL EXPERIENCES

Quality assurance in new cables

In new cables, diagnostic processes can contribute to quality assurance. Example: In Germany, a network operator tested a new network section comprising a dozen 10 kV cables. In addition to the cable and sheath test, the company performed a partial discharge measurement on the cables. Sheath defects were found at numerous cable sections. With a partial discharge measurement, a weak point was also detected at each 14th joint approximately, which would have remained hidden during the cable test. These jopints could thus be repaired before resuming regular operation, which in the long term is beneficial for the supply reliability.

Cost saving in existing cables

Cable diagnosis offers good opportunity to maintain older cable lines at low cost. Example: On an almost 2 km long line (Fig. 13) there were highly developed water trees. However, replacement of the complete line had to be avoided for cost reasons. The tan δ measurements showed that conductor 3 had aged a lot (Fig. 14) and after additional partial discharge measurements, partial discharges on specific sections of the line could be identified. Cable replacement was limited to two sections (together about 0.6 km) and the final loss factor measurement attested to the now good condition of the line. In this way, the laying costs could be reduced to about one-third. In such projects, the costs for diagnostic measurements hardly carry weight, as the time needed for a loss factor and partial discharge measurement is only about one hour. Therefore, a diagnostic measurement is already worth it when few meters of cable in the city centre can be saved during restoration.

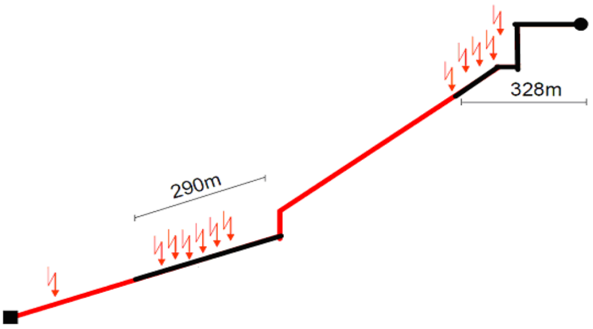

Fig. 13: About 2 km long cable line, laid in 1978 showed faults

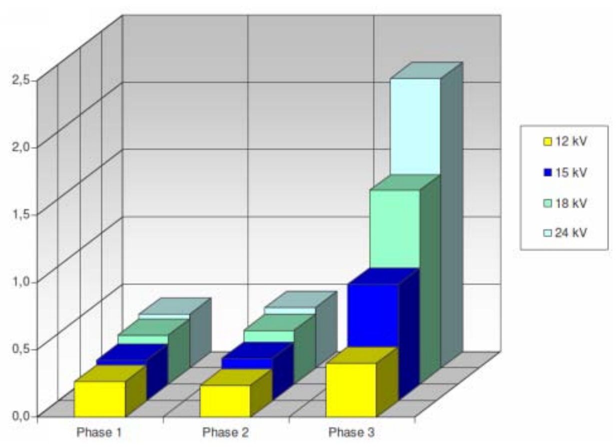

Fig. 14: The tan δ measurement of the cable line from Fig. 13 indicates a defective conductor 3

Increased power supply reliability

On a good 200 m long 6.6/11 kV cable line in an urban, Asian distribution network that consists of six different sections, a fault occurred in summer 2010. The fault was located in the centre of the track and was rectified by replacing a 11 m long cable section and the joints. A 15-minute cable test finished the cable successfully. Nevertheless, there was another defect 5 days after the repair and more sections were replaced. The tan δ measurement (Fig. 15) performed with a portable test and diagnostics device after the first repair showed that there was a big increase in the tan δ in conductor 2 on doubling the test voltage (from $0.5xU_0$ to U_0). As partial discharge values (Fig. 16) occurred on joints and were not critical, the joints had no influence on the tan δ values – they were traced to water trees in the cable.

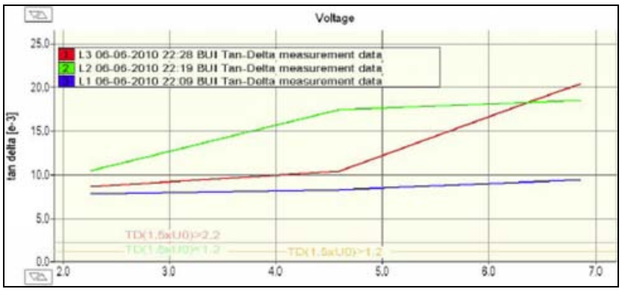

Fig. 15: The tan δ value indicated an operating risk on conductor 2 even after the first repair

Fig. 16: These partial discharge values must be assigned to sleeves and are in normal range

From this, the network operator concluded that the cable test can indeed reflect the current functioning, however is not in the position to detect operating risks. Only the combination of the loss factor measurement and the partial discharge measurement would have permitted conclusions on the condition of the cable line and indicated the - here very high - operating risk. The operator could have been spared a second cable fault and the repair few days after the first fault if he would have looked for and repaired other damages based on the diagnostic measurements. Based on this experience, this network operator will rely more on diagnostic measurements during the repair and maintenance of existing cables.

CONCLUSION

Neither cable data nor the cable testing are suitable for evaluating the condition of medium voltage cables, incl. joints and terminations, as the actual condition of the cable depends on the laying, environmental influences, load and other factors. Therefore, a lot of information delivered by the sheath test and the diagnostic process tan δ and partial discharge measurement is necessary. By including comparison data and experience values, information derived from the measurement values allows for a reliable statement on the aging status.

In practise, tried and tested measuring devices are those with a VLF generator, as in this way the cable test and the optional diagnostic measurements can be performed with the same voltage source - partly even simultaneously - at low cost.

To optimise the maintenance under economic and supply criteria, besides the technical measured values, even the importance of the cable line and fault statistics or even penalties on power failures must be included. Therefore, the use of a database with measured values and cable data and a cable information system (CIS) is important. In the CIS, the importance of the cable for the supply security and the “technical” cable age can be denoted through different colours, so that when planning maintenance measures or during faults, you can quickly detect the importance of the cable line and whether the aging condition values exist. More and more distribution network operators are resolving the “maximum availability” vs. "minimum cost" argument with such resources.