VLF-MWT – PRACITICAL EXPERIENCES OF A NEW WAY OF CABLE CONDITION ASSESSMENT

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ABSTRACT

Condition-based maintenance is an important and necessary strategy for coping with today's asset management requirements for an electric utility system operator. However, this requires an exact knowledge of cable conditions. Testing and diagnostic methods which provide meaningful results and are simple to apply in the field are an economical prerequisite. The Monitored Withstand Test (MWT) meets these requirements. The MWT consists of a combination of established methods for cable testing and diagnostics and provides the system operators additional information on the cables condition for optimal planning of repairs or replacements to minimize downtimes.

INTRODUCTION

Operators of distribution networks worldwide are facing similar challenges: Existing cable systems must be maintained most economically and investments in new cable lines must be secured while maintaining or improving the quality of the network. Many operators today use diagnostic procedures to resolve the conflicts in these objectives in the best manner from technical and economic perspectives. Simple cable testing is a common method described in various IEC, IEEE, CENELEC and other national standards. The wide acceptance of this method and the years of testing experience have also shown its limitations. The simple "passed" or "failed" statement allows no estimation about the remaining lifetime of the cable.

This circumstance has led to a broader acceptance of cable diagnostics, which provides information on the cable's condition. Evaluation of single measurement results and the combination of tan-delta (TD) and partial discharge (PD) measurement provides the operator with important information about the cable condition. Although cable diagnostics provides more relevant information for decision-making than a simple cable test, in the currently used application it cannot reveal how the cable would respond to the presence of an increased test voltage over a longer period (15 minutes to an hour).
To avoid the disadvantages of these individual methods, the National Electric Energy Test, Research and Applications Centre (NEETRAC) developed the VLF Monitored Withstand Test (MWT). A combination of VLF cable testing and diagnostics allows generating additional information with an optimum test time.

VLF CABLE TESTING – A FILED PROVEN METHOD

VLF (Very Low Frequency) was introduced to test the insulation of Medium Voltage (MV) underground cables after new installations, after repairs or as a routine measure at regular intervals.
The reasons for voltage testing are according to [2]:

- Detection of weak points which put reliable operation at risk using low test voltage levels
- Conversion or evolution of conductive inhomogeneous defects (water treeing) at low test levels into first partial discharge channels (electrical treeing)
- Bringing partial-discharge defects rapidly to breakdown by means of high channel growth speeds

By comparing different voltage sources (VLF Sinus, VLF Cos-Rect, 50/60Hz AC, Oscillating Voltage) it was found, that especially the VLF Sinus voltage is suitable for testing medium voltage- and especially PE/XLPE cables. The combination of a low PD incipient voltage, high channel growth speed and the capability to perform diagnostics must be considered [2]. These are the preconditions, to convert inhomogeneous defects and to bring partial-discharge defects rapidly to breakdown.

A typical VLF withstand test is performed with voltages between 2 and 3*Uo for the maximum time of one hour. Due to the representation in different standards (IEC/CENELEC/IEEE) and the easy application on site, VLF cable testing became a widely adopted method.
But the simple result (Pass/Fail) has its limitations, because it only offers the statement that the cable was ready for operation or damaged at the time of testing. Additionally, cable testing has lacked the ability to adapt the test duration to the condition of the cable and thus save time and money.

VLF TAN-DELTA DIAGNOSTICS – MORE VALUABLE INFORMATION

The tan-delta measurement is an important extension to the simple withstand test, because more information about the cable condition is available.
The tan-delta method is an integral measurement which can be adopted for all cable types and gives a statement about the condition of the whole cable line. Although there is no location information available, the interpretation of various tan-delta parameters allows distinguishing between different types of defects of the cable line. And this allows the system operator to define follow-up measurements like partial discharge- or cable sheath testing. With the combination of these methods it is possible, to interpret and locate different types of defects.

The VLF Sinus test voltage source allows to measure different tan-delta values at different voltage stages (e.g. 0.5, 1.0, 1.5 and 2.0*Uo)
MTD: Mean tan-delta: Average or mean value of tan-delta values at constant test voltage
ΔTD: Delta tan-delta: Change in tan-delta with changing test voltage
SDTD: Stability or standard deviation of tan-delta values at constant test voltage.
The measurement of these values allows an interpretation of different types of failures:
A high MTD value is an indicator of the presence of water trees.
If the ΔTD is high (increasing TD over test voltage), this could be an indicator for partial discharges or also for water trees. A negative ΔTD (decreasing TD over test voltage) could be an indicator for a vaporisation effect, e.g. in terminations.
A low SDTD indicates that the cable is in a good condition. An increasing SDTD indicates the presence of partial discharges. High SDTD values are an indicator for water ingress in joints.

THE MONITORED WITHSTAND TEST (MWT) – AN INGENIOUS COMBINATION

Before describing the MWT, let's examine the disadvantages of simple cable testing once again. As [1] explains, there are essentially three disadvantages:

- No estimate of the cable line's quality can be made before the test voltage is applied.
- The duration cannot be adapted to the condition of the cable.
- No estimate can be made of how well the cable test was passed nor whether the cable will fail in an hour or in ten years.

Combining VLF cable testing and VLF tan-delta diagnostics can avoid these limitations. It makes sense, to perform the MWT in two stages:

- "ramp-up"
- "MWT"-or "hold" stage

Ramp-up stage

Non-destructive tan-delta measurement as described before is performed prior to the actual MWT stage. Continuous monitoring of the measurement values (mean tan-delta, tan-delta stability, delta tan-delta) enables an initial estimation of the cable's condition to be made. As **Figure 1** shows, tan-delta measurements are performed typically at 0.5xUo, 1.0xUo and 1.5xUo.

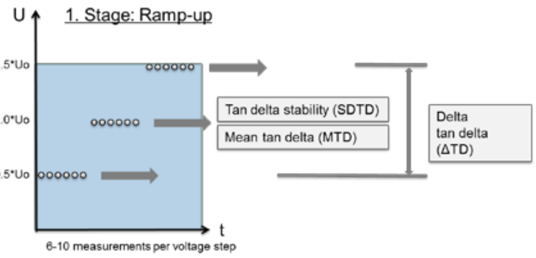


Figure 1 Sequence of the ramp-up stage

Various tan-delta indicators are determined and evaluated at each stage:

Ramp-up stage	
Indicator	*Calculation*
tan δ stability (SDTD)	Standard deviation of 6-10 measurements at Uo
delta tan δ (ΔTD)	Difference of the average values at 1.5 Uo and 0.5 Uo
mean tan δ (MTD)	Average value of 6-10 measurements at Uo

Table 1 Indicators during the ramp-up stage

The advantages of the ramp-up stage are apparent:

- An initial assessment of the cable line's condition is possible.
- Excessive stress from high test voltages on aged cable lines can be avoided by an initial condition evaluation.
- Tan-delta measurement is an established, commonly used method. Application experience and limit values for different regions are available.

MWT or hold stage

Cable testing and diagnostics are combined in the MWT stage.
According to [1], the MWT is only passed if

- no breakdown occurred during the MWT
- the tan-delta values determined prove to be stable (i.e. have a low standard deviation)
- the average tan-delta value is low

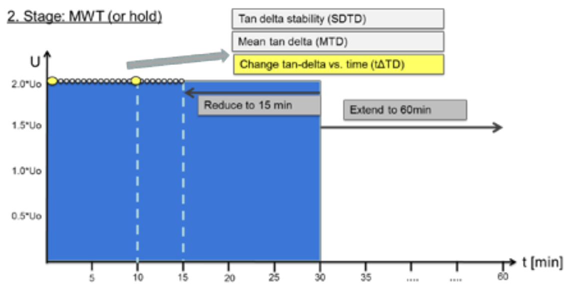


Figure 2 Sequence of the MWT stage

Figure 2 shows the sequence of the MWT stage. Various tan-delta measurement values are also determined and evaluated during application of the voltage. (See **Table 2**.)

MWT stage	
Indicator	*Calculation*
tan δ stability (SDTD)	Standard deviation of 6-10 measurements at Uo
mean tan δ (MTD)	Average value of 6-10 measurements at Uo
Change in tan δ vs. time (tΔTD)	The difference in the tan δ value from 0 to 10 minutes.

Table 2 Indicators during the MWT stage

Continuous evaluation of the measurement data from the ramp-up and MWT stages enables the optimum test duration for the cable line to be determined during testing. The user can adapt the time to the cable's condition based on the measurement results or the test system can suggest optimal test duration. In addition to the time saved, shorter tests have the advantage of exposing the cable to the higher test voltage only for the time actually necessary. But the user can also extend the test to cause existing weak points in the insulation to break down.

The benefits of the MWT stage can be summarized as follows:

- The condition of the cable line can be evaluated.
- The test duration can be adjusted to the cable's condition.
- The influence of the higher test voltage on the cable can be assessed.
- MWT is a useful combination of established, accepted methods.

VLF-PD – A PERFECT COMBINATION WITH VLF-TD

The VLF-Partial Discharge- (VLF-PD) is the perfect complement to the VLF-TD measurement, because it delivers additional helpful measurement parameters:

- PDIV (PD Inception Voltage)
- PD level according to IEC60270
- PD localization
- Localized PD phase resolved pattern

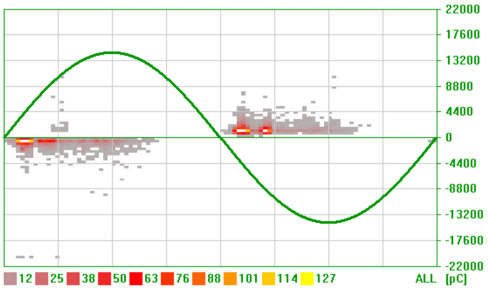


Figure 3 Example of a localized VLF-PD phase resolved pattern

Figure 3 shows a typical VLF-PD pattern. The pattern allows to distinguish between “internal” (cracks, cavities within the insulation material) - or “external” (corona) partial discharge.

CASE STUDY

Here is a practical example of why monitored withstand testing represents an important advance of previous testing and diagnostic measurements.

The cable tested (11 kV) has a total length of 234 metres (**Figure 4**) and is composed of various cable types (in other words, a mixed cable line).

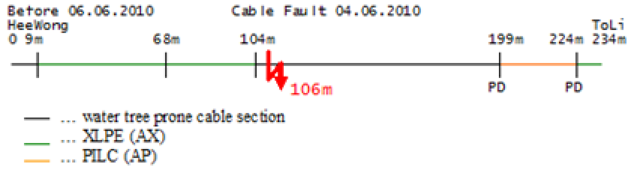


Figure 4 Structure of the cable line tested in June 2010

In June 2010, there was a cable fault in an XLPE-insulated cable line produced in 1989 (first generation). Cables produced during this period are known to develop water trees. An 11 metre section of this line was replaced by an XLPE cable of a newer type.

Diagnostic measurements (VLF tan-delta and partial discharge measurement) were performed after the repair.

The tan-delta results showed that the cable line was heavily aged by service. (See **Figure 5**)

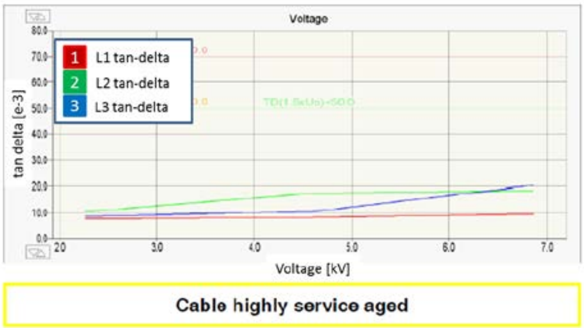
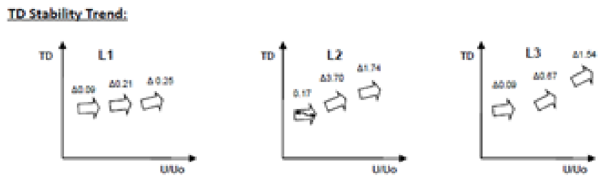


Figure 5 Tan-delta measurement after repair

Although the measurement values were below the TD limits for mixed cable lines, for the section of line at risk for water trees, the delta tan-delta (DTD) limit for XLPE cable was applied (DTD > 1.0E-3 as high operating risk). Here L2 and L3 showed a strong rise with increasing voltage, indicating water tree damage to the cable.

The TD standard deviations (SDTD) for L1, L2 and L3 were also used to assess the situation.

Figure 6 SDTD – tan-delta standard deviation for conductors L1-



L3 In **Figure 6** it can be seen that the SDTDs for L2 and L3 increase. This indicates the presence of water trees. Partial discharge measurement was carried out afterwards (**Figure 7**).

Figure 7 PD measurement result

The PD measurement data show partial discharges at the transition joints (on the PILC cable line) at 199 and 224 metres. Evaluation of the partial discharge and tan-delta measurement revealed that the high tan-delta values were caused by water trees. This is indicated by higher TD standard deviations for L2 and L3 at voltages below 1.0xUo and the increasing trend of tan-delta without partial discharge. Moreover, the partial discharge level is of an order of magnitude which does not affect the delta tan-delta. Afterwards, a 15 minute VLF cable test was performed at 2xUo. The result was that all three conductors passed the test despite the high tan-delta values. So the cable was put back into operation.
Four days later there was a cable fault at 125 metres, i.e. in the section endangered by water trees. Severe water tree damage was found in this part of the line.

This example shows quite clearly how a VLF Monitored Withstand Test would have been helpful at this location to avoid the cable fault shortly after restoration of service.

- The 15 minute VLF test made the water trees more severe, but at the end of the test the progress could not be determined. Here a VLF sinusoidal MWT would have indicated by the progression of the mean tan-delta (rising TD values) and tan-delta standard deviation that the faults had been exacerbated.
- The test duration could have been extended during the measurement (to 30 minutes, for example). The weak points (water trees in this case) would have grown worse and finally led to breakdown.
- Thus the MWT could have shown the influence of the test voltage on the cable.
- It would have been possible to estimate the "margin" of passing from the condition of the cable at the end of the MWT.

APPLICATION

It is important for the application of the VLF MWT, that the measurement is simple and automated. This requires a VLF sine voltage, because only this voltage shape allows a precise and combined tan-delta measurement. Additionally it is possible to perform the tan-delta measurement at a constant frequency, where limits and experience are available and where a comparison of different measurement results is possible. This fact allows the electric utility system operator to gain the experience with cable diagnostics.
For an easy application in the field it is necessary to automate the whole MWT measurement sequence.
An example of how these requirements can be implemented is the portable VLF truesinus® generator with an integrated tan-delta measurement like frida TD from BAUR (**Figure 8**).

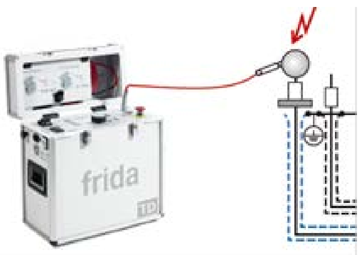


Figure 8 MWT test setup with BAUR frida TD

Here an integrated tan-delta measurement function enables the same connection to be used for cable testing and tan-delta diagnostics. This facilitates fully automated measurement runs without additional external devices.
It is also important for the various measurement results to be displayed clearly and continuously so the user can make decisions regarding the length of the MWT during measurement.

CONCLUSION AND OUTLOOK

It has been shown, that the Monitored Withstand Test (MWT) is a meaningful combination of already existing testing and diagnostic methods, which delivers additional information about the cable condition and which allows a time- and cost optimized and efficient testing.
The MWT is the ideal complement to the partial discharge measurement and the combination of both measurements gives more valuable information's.
The necessary test and measurement technology for an efficient application in the field is available.

The MWT is being promoted in North America and has already found a place in various standards.
The latest revision of IEEE400-2012 [3] (the IEEE Guide for Field Test and Evaluation of the Insulation of Shielded Power Cable System Rated 5kV and above) defines and describes the Monitored Withstand Test.
Also in the new revision of the IEEE400.2 standard (IEEE Guide for Field Testing of Shielded Power Cable Systems Using Very Low Frequency (VLF)) the MWT will play an important role in it as well.
The prerequisites for using the tan-delta MWT have been met. The first versions of the standards and the necessary measurement technology are available. Now it is a matter of using tan-delta MWT in the field and applying the experience from this in future discussions of limit values, also for various regions.

REFERENCES

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[2] Bach: Testing and Diagnostic Techniques for assessing medium-voltage service aged cables and new cable techniques for avoiding cable faults in the future
[3] IEEE400-2012 IEEE Guide for Field Testing and Evaluation of the Insulation of Shielded Power Cable Systems Rated 5kV and Above