Simultaneous Partial Discharge and Tan Delta Measurements: New Technology in Cable Diagnostics

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Abstract—In this paper, a focus was placed on the ability to decrease the amount of testing time while monitoring tan delta and PD simultaneously. Healthy and unaged cables do not need to be subjected to unnecessary stresses if no clear abnormalities are detected in diagnostic values. A case study was presented and able to show that testing time and costs can also be reduced for severely aged cable systems. New technology on the market allowing for the simultaneous monitoring of tan delta and partial discharge during monitored withstand testing gives utilities and test personnel time-efficient and cost-optimized testing solutions for new and service-aged cables. The result is a significant reduction in testing time and the ability to realize condition-based and cost-optimized maintenance plans.

Index Terms—Cable diagnostics, monitored withstand test, partial discharge, simultaneous diagnostics, tan delta.

I. INTRODUCTION

Inspection, commissioning, and maintenance testing of high voltage equipment for the power transmission and distribution network is an important procedure to ensure the reliable performance of the electric power supply. For many years practices have been in place for high voltage AC testing at power frequency or high voltage DC testing in laboratory or field settings for insulation quality assessment. New technologies have been introduced and existing standards have been updated to allow for very low frequency (VLF) testing, typically conducted at 0.1 Hz [1-5]. This technology has the added benefit of keeping the equipment more portable and practical for on-site testing of underground cables, as the charging current is 600 times less than that at 60 Hz.

The simplest VLF testing technique to assess the quality of electrical insulation is the withstand test, in which the cable is subjected to a test voltage significantly higher than the operating voltage. The higher test voltage allows for potential weak points or pre-damaged areas of the cable to breakdown during the test and the defective insulating material is subsequently replaced. Unfortunately, the withstand test is only a “go or no-go” test. If the cable does not breakdown during the time period of elevated test voltage, defined in IEEE and IEC standards [1-3], there is no further information for the operator to determine whether the insulation is truly healthy or how long a cable may stay in service without leading to failure.

Cable diagnostics, on the other hand, allows for a gentler procedure to gather more information on the state of the cable insulation without damaging the cable. Tan delta and partial discharge (PD) diagnostics are the most common testing techniques used for cable diagnostic purposes. Tan delta measurements are a precise and non-destructive method to provide important information on the losses present that contribute to ageing in cable insulation. These losses could include the presence of water trees in XLPE cables, moisture in joints and terminations, and the presence of partial discharges. PD diagnostics can be used to pinpoint defects in joints and terminations, electrical trees in polymeric cables, insufficient oil insulation in PILC cables, and mechanical damage of the cable sheath.

By combining the ability to safely and efficiently measure tan delta and PD simultaneously, the number of diagnostic tests that can be conducted in the shortest amount of time is maximized. Increased knowledge and understanding of the cable condition will help to reduce unnecessary outages and make it possible to realize a condition-based and cost-optimized maintenance program. Important information is provided that can be used to improve system reliability. Repair costs can be reduced by conducting condition-based maintenance on only the most vulnerable cables and prevent unnecessary and costly outages.

This paper discusses the benefits of conducting simultaneous or parallel tan delta and PD diagnostic tests on medium voltage cables for the electric utility industry. A case study is presented that shows how simultaneous testing can expose “hidden” faults that would be extremely difficult to detect when only using single diagnostic techniques.

II. BENEFITS OF SIMULTANEOUS CABLE DIAGNOSTIC TESTING

With the introduction of the IEEE 400.2 standard [2], operators and utility personnel were given access to an easy to interpret guide with information for conducting VLF withstand and diagnostic techniques on service-aged medium and high voltage cables. The guide provides recommended test voltage levels for installation, acceptance, and maintenance tests. As VLF utilizes a sinusoidal waveform, tan delta and partial discharge can also be monitored, which is known as a monitored withstand test (MWT).
which leads to lower test and downtime costs for the utility. Much faster than if solely conducting a simple withstand test, the first 15 minutes of the test do not have to be subjected to increased voltage stresses for unnecessary lengths of time. Hence, testing time is reduced and the cable can be returned to service much faster than if solely conducting a simple withstand test, which leads to lower test and downtime costs for the utility.

A. VLF Tan Delta Diagnostics

NEETRAC conducted a highly intensive study on the effects and benefits of monitoring tan delta values with VLF voltages on medium-voltage power cables [6, 7]. Their results and findings also helped to shape the MWT technique that allows for a combination of a withstand test while monitoring tan delta (TD-MWT).

A typical test sequence for a TD-MWT is shown in Figure 1. During the initial ramp-up phase, 6-10 measurements are conducted at 0.5Uo increments and mean tan delta, tan delta stability (standard deviation), and the differential tan delta (tip-up) are measured. These values can be compared to condition assessment criteria included in the IEEE 400.2 standard. These are threshold values pertaining to different cable types, such as XLPE, EPR, and PILC, that are based upon statistical analysis of the many measurements conducted during the NEETRAC study using Pareto principle and cumulative distribution [7]. The final stage of the measurement is conducted at 2Uo, known as the hold phase, in which the tan delta value is continuously monitored over time.

A typical test procedure lasts between 30 and 60 minutes, depending on the severity of insulation damage from the tan delta results. In general, the worse the tan delta results, the longer the test should be conducted in order to cause breakdown during the test, rather than have an unexpected failure in service. Therefore, cables in excellent condition with stable tan delta values well below known threshold values for the first 15 minutes of the test do not have to be subjected to enhanced stresses for unnecessary lengths of time. Hence, testing time is reduced and the cable can be returned to service much faster than if solely conducting a simple withstand test, which leads to lower test and downtime costs for the utility.

B. VLF PD Diagnostics

The disadvantage of conducting a pure tan delta diagnostic is that singular defects cannot be located along the length of cable because tan delta is the average value of dielectric losses for the whole cable system. VLF PD measurements, on the other hand, can be used to show PD sources within a cable body, joint, or terminations to help in determining the extent of ageing or degradation in cables. A TDR-based PD distance location makes it possible to determine the exact location of the cable weak point for any potential repairs.

The same principle as described above for tan delta applies to the monitoring of PD during a withstand test (PD-MWT). Detailed procedures are described in IEEE 400.3 [8]. In general, the voltage is slowly raised towards the withstand voltage level while monitoring PD activity. If PD is present, then the inception voltage (PDIV) is measured. The voltage is then raised and held at the withstand voltage level for 30 to 60 seconds while recording the magnitude, number of pulses, and location of PD activity. Afterwards the voltage is slowly reduced and the extinction voltage (PDEV) is recorded. If no PD activity is recorded during the voltage rise to the withstand test level, then the voltage can be maintained at this level for a maximum of 30 minutes, unless PD does occur in the meantime.

There are no specifically defined test procedures for monitoring PD during a withstand test. The major IEEE and IEC standards that call for withstand testing and give recommended voltage levels depending on class of cable, do also take into account that the age of the cable system, its installation environment, and the history of failures or past PD tests must always be evaluated [1, 3]. Therefore, the voltage levels and test times are only given as recommendations and can always be changed by the utility or test personnel.

The PD-MWT is a simple and effective tool to locate sources of PD activity that could lead to breakdown of service-aged cables. The technique is also very beneficial to determine whether poor workmanship leads to areas of PD activity during installation or acceptance testing. If no PD is recorded in the initial part of the test, then the cable does not have to be subjected to increased voltage stresses for a significant amount of time, which again, leads to less downtime and testing costs for the utility. One of the largest disadvantages, however, is PD testing is unable to locate and evaluate water treeing in polymeric insulation. This can only be located if a water tree creates a sufficiently large electric stress and initiates an electrical tree.

C. VLF Simultaneous Tan Delta & PD Diagnostics

The combination of applied diagnostic methods using VLF tan delta and VLF PD simultaneously can be coined the term Full Monitored Withstand Test (Full MWT). The test sequence is the same as described in Figure 1, where tan delta and PD are measured at the different voltage intervals. This intelligent monitored withstand test technique provides significantly more information than a simple withstand test alone or even a TD-MWT or PD-MWT. An example of a typical test set-up during on-site testing is shown in Figure 2.

The highlight of this test is the condition-based test duration, which allows a shortened duration for good cables, effectively reducing costs. Good cables are only exposed to elevated test voltages for a short amount of time and are not subjected to unnecessary stress. Conversely, length of testing of badly serviced-aged cables can also be reduced because the weak points and potential fault areas are pinpointed at a faster rate.

![Figure 1. Typical test sequence for a tan delta monitored withstand test (TD-MWT) according to IEEE 400.2. The graph is divided into a “voltage ramp-up” phase and a “voltage hold” phase.](image)
Testing time and costs can be reduced by 50% if tan delta and PD are measured simultaneously, rather than sequentially. The test duration can even be reduced up to 75% when monitoring of tan delta and PD is conducted during the Full MWT, as testing of healthy cables can be stopped after 15 minutes.

Furthermore, simultaneous monitoring allows for a better identification of “hidden faults”, such as moisture ingress in joints and water trees that have been converted into electrical trees during the withstand testing period. Due to the high amount of energy of a breakdown event, determining the locations of these potential fault areas and conducting the proper repair actions before breakdown occurs will help to protect the insulation integrity of the remaining cable and its components, and reduce costs associated with sudden service outages.

III. CASE STUDY

A 131 m long, single-phased 15 kV class XLPE cable was tested using the Full MWT test method according to the test set-up shown in Figure 2. Tan delta was measured using the BAUR Frida TD and PD was measured with the BAUR PD-TaD 60 coupling capacitor according to IEC 60270. From the initial calibration for the PD measurement a joint was detected at 61 m, as seen in Figure 3. A known joint was also located at 6 m; however, this could not be seen during the calibration due to its close proximity to the coupling capacitor.

A. Tan Delta Results

Figure 4 shows the tan delta results from the Full MWT conducted on the cable. The top of the graph shows the mean tan delta values of the voltage ramp phase with 8 tan delta measurements conducted at 0.5\(U_o\), 1\(U_o\), and 1.5\(U_o\) voltage levels, respectively. Each individual measurement result is shown as a small dot and the trend stability (standard deviation) is displayed. The BAUR Frida TD was programmed to depict the assessment criteria thresholds for XLPE according to IEEE 400.2 [2]. These results show that the cable was clearly in bad shape. Only at 0.5\(U_o\) was the cable in a “risk” state, and at nominal voltage and above, it was always in a “high risk” state. According to IEEE 400.2 action is required for this cable, as at \(U_o\) the mean tan delta is above 50, time stability is over 0.5, and the delta tan delta (tip-up) is above 80, the results of which are shown in Table 1. The linear increase in tan delta with voltage, as well as the upward trend in tan delta stability is clearly indicative of an increase in leakage current. These findings might also correlate to moisture ingress or the presence of water trees. The improvement in tan delta over time during the voltage hold phase (Figure 4, bottom) seems to correlate well with the notion that the cable is experiencing moisture ingress. The downward slope is indicative of a drying effect from the application of voltage for an extended period of time.

<table>
<thead>
<tr>
<th>Voltage Level</th>
<th>Mean Tan Delta</th>
<th>Standard Deviation</th>
<th>Delta Tan Delta</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5(U_o)</td>
<td>44.281</td>
<td>2.581</td>
<td></td>
</tr>
<tr>
<td>1(U_o)</td>
<td>92.360</td>
<td>4.534</td>
<td>139.90</td>
</tr>
<tr>
<td>1.5(U_o)</td>
<td>139.90</td>
<td>7.851</td>
<td>95.618</td>
</tr>
</tbody>
</table>

Table 1. Result from the tan delta measurement during the voltage ramp-up phase. MTD, SDTD, and ΔTD stand for mean tan delta, standard deviation tan delta, and delta tan delta, respectively.
that the joint at 6 m and the joint located at 61 m were the weak points of the cable. Moisture ingress had been evident from the very poor tan delta values and a drying effect could be witnessed during the withstand hold phase. Since tan delta gives an average value of dielectric loss for the whole cable and its accessories, it does not give information on where in the cable the problem areas are located. Without the simultaneous monitoring of PD, the logical conclusion of this test would have been to continue the MWT until breakdown had been achieved. However, this process could take up to one hour of testing time. Moreover, if the cable had not broken down in one hour, one would have to either take the risk of placing a severely aged cable back into service and expect an eventual unplanned outage in the near future or replace the entire cable itself. Both options correlate with more costs for the utility.

The suggestion after conducting the Full MWT was to replace or re-splice the joints located at 6 and 61 m. This would be a significant reduction in repair costs and time, as only a small fraction of the cable needed to be repaired. Following any repair work, it should be noted that an additional test should be conducted in order to test proper workmanship that the repair was conducted adequately before returning the cable to service.

One must also note that the cable used in this case study was relatively short and only had two joints. Therefore, the conclusion to repair these joints was made fairly easy from the test results. Most underground systems are longer and contain significantly more joints. Especially older hybrid systems, i.e., mixture of PILC and polymeric cables, will be much more difficult to evaluate. This is when combining the most amount of diagnostic information into one test routine becomes particularly important.

### IV. Conclusion

In this paper, a focus was placed on the ability to decrease the amount of testing time while monitoring tan delta and PD simultaneously. Healthy and unaged cables do not need to be subjected to unnecessary stresses if no clear abnormalities are detected in diagnostic values. A case study was presented and able to show that testing time and costs can also be reduced for severely aged cable systems. New technology on the market allowing for the simultaneous monitoring of tan delta and PD during monitored withstand testing gives utilities and test personnel time-efficient and cost-optimized testing solutions for new and service-aged cables. The result is a significant reduction in testing time and the ability to realize condition-based and cost-optimized maintenance plans.

### REFERENCES


Dominique Bolliger (M’09) was born in Oakland, MD, USA in 1984. He received the B.Sc. degree in chemistry from the University of Basel, Switzerland in 2008 and the Ph.D. degree in materials science from the University of Connecticut in 2013, working under the guidance of Prof. Steven Boggs. He is currently working as Technology Manager at HV TECHNOLOGIES, Inc. in Manassas, VA. He was previously employed by Von Roll in Breitenbach, Switzerland, working in research and development of mica-based insulation systems, and by BAUR GmbH in Sulz, Austria, working as Global Product Manager for cable diagnostics and insulating oil test equipment.