PRACTICAL ISSUES REGARDING THE USE OF DIELECTRIC MEASUREMENTS TO DIAGNOSE THE SERVICE HEALTH OF MV CABLES

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ABSTRACT

During the last decade, Very Low Frequency (VLF) testing for extruded distribution cables has gained interest among the North American utilities. The increasing interest is evidenced by recent research publications and discussions inside the expert community in which standards are being proposed and continuously discussed. While there is a general consensus as to the meaning of insulation dielectric properties, many open issues still remain for discussion in order to produce a more accurate evaluation. Consequently, this paper will discuss a number of the practical issues that arise when making these measurements at VLF on field aged and non-aged cables, particularly Tan δ measurements. The discussion is based on data from laboratory experiments and field testing.

KEYWORDS

Dissipation Factor, Tan δ, Diagnostics, and MV Cables.

INTRODUCTION

Medium voltage distribution cables and their accessories form a critical part of the power delivery system. Many of these systems employ insulations that have a relatively low permittivity and low dielectric losses. As the systems age the dielectric properties change such that they provide a very convenient way to monitor the degradation of the system insulation. In the majority of the cases, workers monitor the increase in dielectric loss which can be several orders of magnitude higher than when cables are new. This approach correlates well with the known mechanisms of degradation, namely the ingress of water (high permittivity and losses) and the subsequent growth of water trees [1].

During the last decade, Very Low Frequency (VLF) testing for extruded distribution cables has become very prominent among the North American utilities. The increasing interest is evidenced by recent research publications as [2] and [3], and discussions inside the expert community in which standards are being proposed and continuously discussed [4].

In practice it is convenient to measure the dielectric properties at VLF of 0.1 Hz as this both reduces the size and power requirements of the testing voltage source and increases the resolution of the measured value of the insulation losses [5]. While there is a general consensus as to the meaning of insulation dielectric properties, many open issues still remain regarding the definition of more accurate means of system evaluation. Therefore, this paper discusses a number of practical issues that arise when making these measurements at VLF on service aged cables, particularly dissipation factor (Tan δ) measurements. The discussion is based on data collected from laboratory experiments and field testing of MV cables.

The research presented here is part of the Cable Diagnostics Focus Initiative Project (CDFI) launched the in February 2005 by the Georgia Institute of Technology through the National Electric Energy Testing Research and Applications Center (NEETRAC). The intent of the initiative is to provide cable diagnostic technology assessment and development via a series of projects designed by the NEETRAC and Georgia Tech research team with technical advice from the initiative participants. The CDFI project participants are formed by utilities, cable diagnostic providers, cable manufacturers, and other interested parties as the U.S. Department of Energy (DOE).

BASICS OF TAN δ MEASUREMENTS

Tan δ is a measure of the degree of real power dissipation in a dielectric material and therefore its losses. In the case of underground cables, this test measures the bulk losses rather than the losses resulting from a specific defect. Therefore, Tan δ measurements constitute a cable diagnostic technique that assesses the general condition of the cable system insulation. Tan δ can be applied to all cable types; however, when interpreting test results care must be taken with respect to the specific cable insulation material, installation conditions, and accessories.

When modeling, the cable insulation system is simply represented by an equivalent circuit that consists of two elements; a resistor and a capacitor [6], see Figure 1. When voltage is applied to the cable, the total current (I) will be the contributions of the capacitor current (I_C) and the resistor current (I_R). Tan δ is the ratio between the resistor current and the capacitor current. The angle δ is the angle between I and I_C when they are represented as phasors [7].

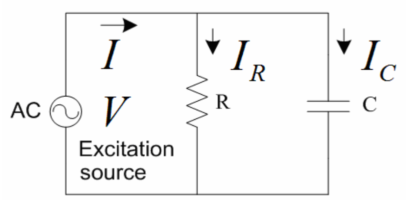

Figure 1: Equivalent circuit for Tan δ measurements

Factors which could influence the validity of the equivalent circuit are accessories, condition or design, neutral condition and extent of degradation. Therefore, they can cause the Tan δ measurement to indicate a condition that is not correct for the whole system but this can be overcome by performing periodic testing at the same voltage levels while observing the general trend in dissipation factor values [7]. Additional factors not so easily handled include temperature, moisture content, partial discharges, non-uniform degradation, and corrosion of the neutral wires. The last three of these factors are discussed in more detail later in the paper.

Additional information on the condition of the insulation may be obtained by repeating dissipation factor measurements at frequencies in the range of 0.01 to 100 Hz [5]; this is known as dielectric spectroscopy.

MEASUREMENT OF TAN δ

In field testing applications, the measurement is performed as an offline test in which the cable segment under test is disconnected from the grid at both ends and energized from a separate power supply with a fixed AC frequency typically of 60 or 0.1 Hz [6]. The frequency could also be in the range of 0.01 to 100 Hz [5]. The segment is typically energized using voltage levels of 1.0 and 2.0 times the phase to ground operating voltage [6].

In addition to field testing applications, laboratory experiments can also be conducted. In this case, samples under test are in controlled environmental conditions that include temperature and humidity. In this case, different voltage levels and frequencies can be used; thus providing more data for evaluation and diagnosis.

TAN δ MEASUREMENT ISSUES

Tan δ as any other diagnostics technique for power cables is not free of issues. These issues are important because they can influence the outcome of the diagnostic assessment thus leading to an incorrect evaluation. Therefore, a clear understanding on how the issues could influence the measurements and therefore the diagnosis is of paramount importance. This section addresses some of the major issues of Tan δ measurements in field testing applications.

As mention previously, the Tan δ can be considered as a measure of the average condition of a cable [8]. Therefore, the usefulness of Tan δ could be limited by its inability to give more specific information than an average condition of the insulation cable system; for example, non-uniform water tree degradation may not be properly assessed. In this case, additional tests may be required to account for this particular situation.

Nevertheless, a progressive increase of Tan δ value over time does indicate the presence of gradually growing water trees and therefore degradation. Thus in order to recognize this trend, records should be maintained over a period of time, typically several years. In this case, when the Tan δ measurements exceed historically established thresholds of its value and changes with voltage (tip-up) for a particular insulation type, cable design, and voltage levels, the cable may be evaluated to be degraded and therefore it could be scheduled for replacement. On the other hand, if the Tan δ is below the thresholds, then additional tests could be performed to determine whether the cable insulation is defective or not. Specifically, IEEE Std. 400 [6] suggests the application of VLF withstand test.

In some topologies the cable accessories, such as splices and terminations, could have an effect on the measured Tan δ values. However, this effect is likely to be most significant if the accessories, regardless of design, are degraded. In these cases, the accessories themselves could dominate the measurement especially at high voltages since the losses in the local accessories will be much higher than the cable insulation losses. Therefore, when interpreting high values for Tan δ measurements, the number of accessories, their condition, and types must be considered in order to evaluate their effects on the measurement.

Tan δ measurement is a popular diagnostic and has been mainly used in the U.S. for Polyethylene based insulation (HMWPE and XLPE). This Polyethylene focus has been due in the most part to the availability of basic diagnostic interpretation contained in the IEEE Std. 400 [6]. However, an issue that remains unstudied and unaddressed in the IEEE Std. 400 [6] is how to interpret the rest of the population that is comprised of different TRXLPE, EPR, and PILC cables. This interpretation issue is due to the fundamentally different permittivity, loss characteristics and aging mechanisms of these dielectrics.

TAN δ MEASUREMENTS

In order to address some of the Tan δ issues previously discussed and contribute to the area of power cable diagnostics using Tan δ technology, laboratory and field Tan δ measurements have been carried out. A description of the approach taken and the most important results are presented in the next sections.

Laboratory Tan δ Measurements

A testing protocol has been designed for the laboratory Tan δ measurements. The protocol is at VLF of 0.1 Hz and include voltage dependence tests for voltages of 0.5, 1.0, and 1.5 times the rated phase to ground voltage of the cable (U_o). The samples are tested in a controlled environment in terms of humidity and temperature. The humidity is kept bellow 80 % non-condensing and the temperature is maintained at around 18 ºC with changes allowed only up to 3 ºC. The voltage magnitude applied to the samples can be represented as a sequence of voltage steps each of which lasts for 1 min. The sequence is designed in order to assess the effect of the repeat voltages in the reproducibility of Tan δ values. The used voltage sequence can be seen in Figure 2.

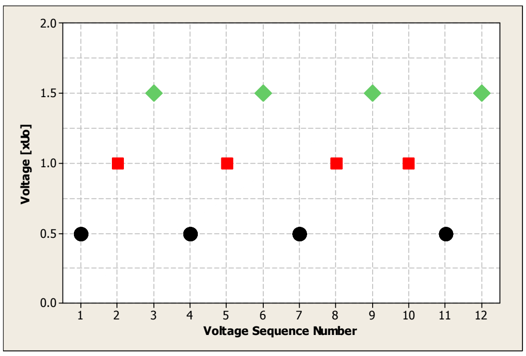

Figure 2: Test voltage sequence for laboratory Tan δ measurements

The sample set used in this experiment is composed of field aged cable samples and non-aged cable samples. The sample description is presented in Table 1. In order to add diversity to the sample set, a non-aged EPR sample is included as it is well known that a non-aged EPR sample has a constant Tan δ value with voltage and one order of magnitude greater than the equivalently aged XLPE or TRXLPE [9]. One important point to mention for the field aged samples is that all of them are the same type of cable, provided by the same utility and coming from the same service area. Therefore, it can be assumed that the aging conditions for them have been the same during their service life.

Table 1: Description of the sample set used for laboratory Tan δ measurements

Sample ID	Condition	Length	Year	Voltage Class [kV]	Insulation
S-2	Field Aged	25 m (80 ft)	1968	15	XLPE
S-3					
S-4					
S-5					
S-6					
S-7					
X-1	Non-aged		1999		
TR-1			1997		TRXLPE
E-1			2006		EPR
A-2	New		2005	25	TRXLPE
TR-2	Non-aged	61 m (200 ft)	1997	15	

The overall results for some of the samples are shown in Figure 3 in which Tan δ values are presented as a function of the voltage magnitude. Data for four samples are presented, three of the field aged samples and one of the non-aged samples. The dispersion in the values for the field aged samples is due to the repeat measurements at the particular voltage level of the voltage sequence.

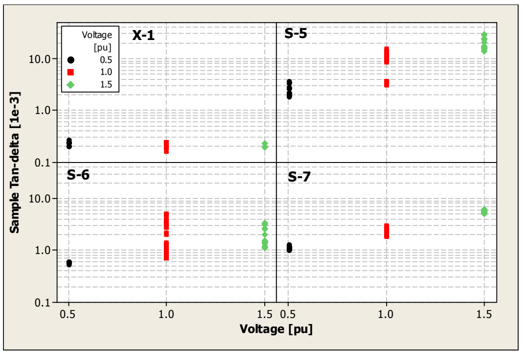

Figure 3: Some results for laboratory Tan δ measurements

As seen in Figure 3, there are several diagnostic features that can be used in order to characterize each sample by Tan δ measurements. The most attractive ones are:

- The Tan δ value as a function of voltage; particularly, the Tan δ value at each voltage level and its changes from one voltage level to another (commonly referred to as tip-up). In fact, this is the classical approach used by the IEEE Std. 400 [6].
- Another feature that could be potentially used is the scatter in the measurements. It is instructive to note that only the field aged samples exhibit considerable scatter at the voltage levels of U_o and 1.5 U_o as compared to the non-aged sample.
- The comparison between similar cables could also be useful for feature characterization. In particular, the field ages samples have a different Tan δ behavior even though they have been subjected to the same aging conditions during their service life.

Tan δ measurements at 60 Hz are performed in order to establish the correlation between values at the two frequencies; those results are not included in this paper.

In order to put the laboratory data in perspective, a comparison is performed in Figure 4 between the obtained Tan δ results and data reported in recent literature from Sweden [5], Canada [2], and Norway [10] for similar cable designs and laboratory tests. The comparison uses only XLPE cable and testing voltages up to 2.0 U_o and 0.1 Hz. Results show that the range of Tan δ values and tip-ups are in the same range as the values reported in the literature from the different countries. Figure 4 shows the comparison of Tan δ values.

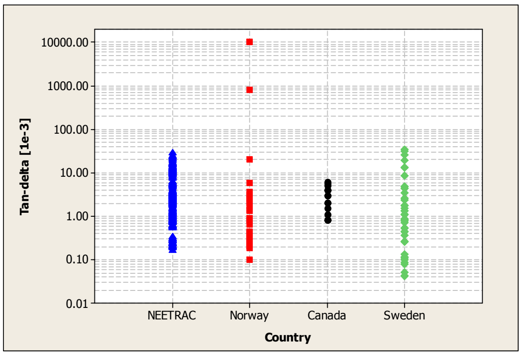

Figure 4: Comparison of Tan δ values from different countries, non-aged and field aged XLPE cables tested in the laboratory

Correlation with Service Performance - Determination of Breakdown

This part of the work has been conducted in two parts. Firstly, an assessment of the breakdown strength under VLF conditions and secondly a post mortem examination of the cables for treeing and defects. The VLF withstand test is selected because no evidence can be found in the literature about the application of this test in similar conditions as the ones proposed here. In addition, the test allows for the evaluation of failure risk during testing for the particular cable population under study. Only the field aged samples were subjected to this test in which all were taken to breakdown.

Results indicate that the breakdown voltage follows the Weibull model. This is an indication of the smoothness of the breakdown process without the presence of abnormal failure mechanisms [1], see Figure 5. In particular, a reduction of the percentage of failure or risk from around 30% at a test voltage of 2.0 U_o to around 2.6% at 1.0 U_o for this particular cable population is observed. This represents a considerable reduction of one order of magnitude in failure risk during testing. The two censored data correspond to two cable samples that failed under the 60 Hz Tan δ testing (S-5 and S-3) which followed the 0.1 Hz Tan δ testing.

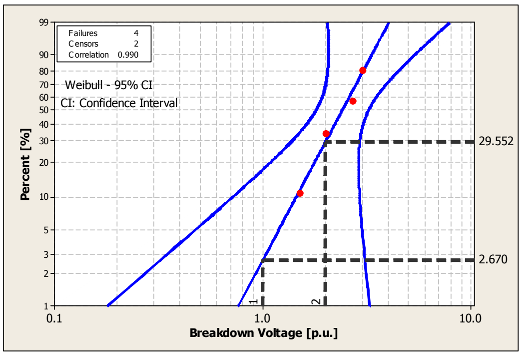

Figure 5: Breakdown performance under 01.Hz VLF of field aged samples – failures of higher loss samples at 60Hz are included as censored data

After breakdown, the failure locations were analyzed identifying the cause the failure. Typical tree contaminating defects were found and are shown in Figure 6.

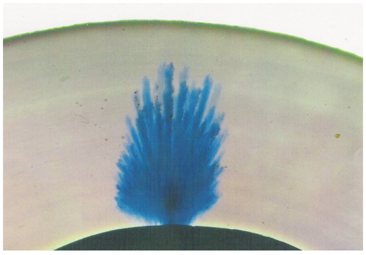

Figure 6: Typical defects observed in field aged samples

Figure 7 shows the correlation between the range of Tan δ values at U_o and the breakdown performance for the field aged samples. The left side of the plot corresponds to the samples that were tested using VLF and the right side corresponds to the two samples that failed under Tan δ measurements at 60 Hz. It is striking that the samples with the lowest Tan δ values show the highest breakdown performance.

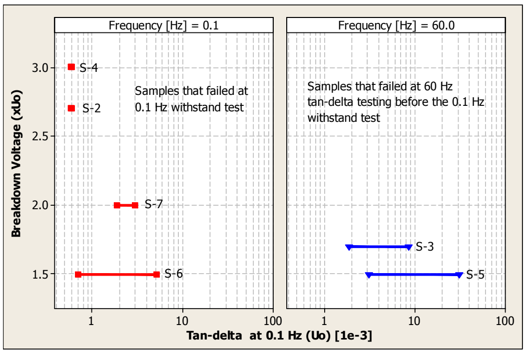

Figure 7: Correlation between the range of Tan δ values and breakdown voltage for 01.Hz VLF & 60Hz

Tan δ Measurements of Service Aged Cables Conducted in the Field

Laboratory measurements were supported with Tan δ measurements carried out in the field at one of the utilities participating in the CDFI project. The utility operated a 25 kV XLPE direct buried cable system and had seen a considerable number of failures.

Total replacement of approximately 10360 m (34000 ft) of cable was considered prior to testing. Tan δ measurements were conducted at 0.5, 1.0, 1.5 and 2.0 U_o. Figure 8 shows the cumulative distribution functions of the Tan δ field data for all test voltages, the vertical lines show the limits described for 2 U_o tests in the IEEE Std. 400 [6].

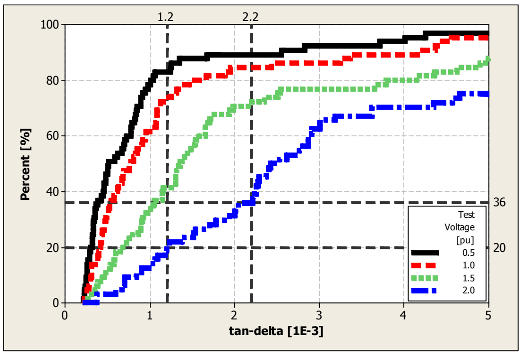

Figure 8: Cumulative distribution functions Tan δ field data for >10360 m (34000 ft) of cable measured in situ at four selected voltages

The results show that if the values given by the IEEE Std. 400 (Clause 8.4) [6] were considered in isolation for an assessment, then 64% of the cables are considered to be highly degraded, 16% to be aged, and only 20% to be in good condition. Follow-up records of failures after testing have been kept and to date no more failures have occurred. Similar results are obtained when evaluating the data using the tip-up criteria. This could be an indication that the values stated in the standard are perhaps too conservative and that more features are needed for a detailed evaluation.

INFLUENCE OF SOME FIELD CONDITION ISSUES ON THE INTERPRETATION USING THE STANDARD EQUIVALENT CIRCUIT

Tan δ measurements are most often interpreted in terms of a simple circuit within a parallel connected resistance and capacitance. This equivalent circuit lumps all of the contributions along the cable length into single circuit elements. Thus it should be clear that to achieve the correct interpretation the correct equivalent circuit needs to be used. In the course of the work reported here it has been determined that there are at least three important cases where the assumption of the simple equivalent circuit may not be completely appropriate:

- The presence of Partial Discharge (PD).
- Corroded Neutral wires.
- Non-uniform water tree degradation.

It has been seen in the laboratory measurements that there is an effect of PD on the measurements of Tan δ. This happened for at least two cases: corona at the terminations and PD from large voids within the cable insulation. The first case may perturb the measurement in that the corona discharge current adds to the measured leakage current.

Thus this may not really be considered as adding to the cable loss. Nevertheless, it does indicate the importance of ensuring discharge free terminations when conducting any sort of measurement in the field. The second case is a large void discharge within a cable. Figure 10 shows that the presence of internal PD can increase the measured Tan δ value for XLPE cables by almost an order of magnitude. If tested lengths of cable were to contain PD, which often comes from accessories, then this effect can complicate the diagnosis. The simple equivalent circuit does not account for this situation and thus a more elaborate model should be used.

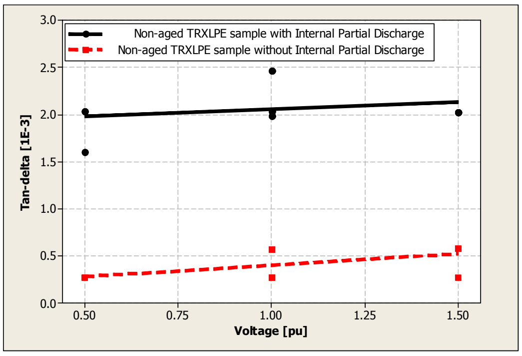

Figure 10: Effect of internal PD on the measured value of Tan δ for non-aged TRXLPE cables

When there is significant corrosion of the neutral wires, the Tan δ value will also contain a contribution from the equivalent model series resistance. The simple model approach assumes that the series resistance, comprised of the shield resistance, the neutral wire resistance and any contact resistance are negligibly small. However, this assumption is incorrect when there is significant corrosion of the neutral wires. In this case, the Tan δ will contain a contribution from the length dependent series resistance. Therefore, it is expected that there will be an increment in the Tan δ value that is a function of length when the neutral wires are corroded. In other words, the total power losses will be the result of the contribution of the bulk insulation losses and the length dependent series resistance losses. This leads to a situation similar to the one for partial discharge but with different diagnostic features. This situation has been observed in many field measurements.

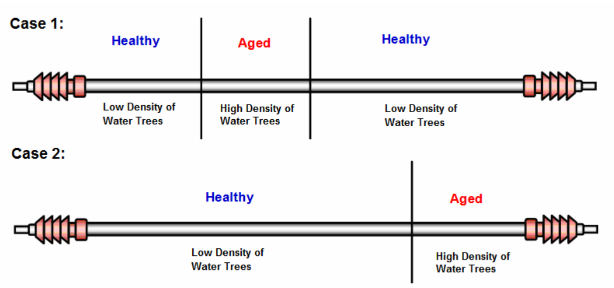

Figure 11: Some possible cases for a cable section with non-uniform water tree degradation

If higher density regions of water trees exist only in part of the cable segment length; then their effect on Tan δ would not be reflected in the measurement. In other words, the overall Tan δ value may be lower than the value that corresponds to the high density regions of water trees [8]. Figure 11 shows two cases for a cable section with non-uniform water tree degradation; the situation can be modeled by making the proper modifications to the equivalent circuit in order to identify useful diagnostic indicators for the Tan δ values and tip-up. In addition, a similar case would be degraded accessories with a healthy length of cable.

MEASUREMENTS AT LOWER TEST VOLTAGES

The field data has revealed a way in which Tan δ values may be collected and compared to data at lower stresses or testing voltages. The conditioning and comparison methods enable existing success criteria used at the higher stresses to be mapped to lower levels of stress. Thereby providing the same level of discrimination, but delivering this at lower stresses. This significantly reduces the risk of failure during the test. The level of risk reduction may conveniently be estimated from an appropriately parameterized version of the well known Weibull Equation [1] as mentioned before. An additional advantage is that the lowered stresses reduce the contribution from any accessories that might employ voltage sensitive constructions.

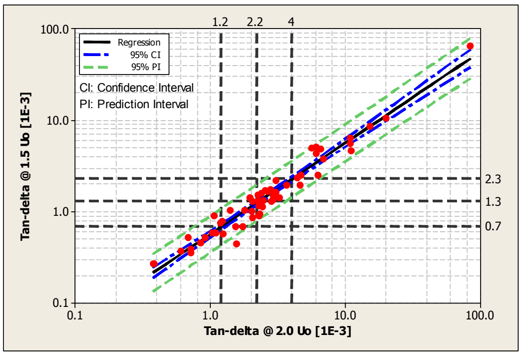

Figure 12: Correlation between Tan δ measurements from field testing at 2.0 U_o and 1.5 U_o for modified diagnostic criteria

Figure 12 shows the correlation between Tan δ measurements from field testing at 2.0 U_o and 1.5 U_o for modified diagnostic criteria. The voltage of 1.5 U_o represents a lower risk of failure to the cable system during testing. The plot shows a relationship between the data collected at the different voltages. The clarity of the plot is improved by adopting logarithmic scales which further facilitate the identification of the relationship. In this case, the relationship is linear in logarithmic terms, but this need not be so. It is sufficient that the relationship is clear. The vertical lines represent the already established success criteria from the IEEE Std. 400 [6]. In the absence of the relationship it is clear that an engineer wishing to utilize the experience set out in IEEE Std. 400 [6] is constrained to test at 2.0 U_o This forces the engineer to accept a higher level of risk than he may be comfortable with. With the relationship, it is a straightforward procedure for the engineer to translate the success criteria from the higher stress (1.2, 2.2 and 4 values on the upper X axis for 2.0 U_o) to a lower stress (0.7, 1.3 and 2.3 on left right hand Y axis for 1.5 U_o) thus reducing the risk. Therefore, such a relationship demonstrates that it is possible to develop criteria for different voltages in a very convenient way.

CONCLUSIONS

The paper has discussed a number of the practical issues that arise when making Tan δ measurements at VLF on service aged cables. The discussion has been based on data from laboratory experiments and field testing.

In the case of laboratory experiments, a diverse sample set of field aged and non-aged cables is used. The testing has been done at different voltage levels and considering the testing voltage sequence. Results indicate that there are a range of useful diagnostic features that can be used to characterize each sample.

The correlation between the Tan δ values at 0.1 Hz and the VLF (0.1 Hz) and 60 Hz breakdown performance have been presented. Results have allowed for evaluation of the risk of failure during testing. A considerable reduction of the risk of failure is observed when the testing voltage is reduced from 2 U_o to U_o. Therefore, it is clear that testing at lower voltages is desirable.

The paper has also shown evidence that service aged cables operate successfully with values well in excess of the Tan δ levels reported in IEEE Std. 400 [6]. Thus these levels may not be completely appropriate to be used in isolation for the particular cable design considered here or that a complete interpretation requires more diagnostic features than those captured within the standard.

The laboratory and field data have identified an approach whereby success criteria for tests at lower voltage levels may be developed whilst retaining the experience base. IEEE Std. 400 [6] describes appropriate levels of Tan δ and tip-up for 1.0 and 2.0 U_o. It has been shown that there is a clear relationship between the field Tan δ values at two test voltage levels. The relationship permits translation of Tan δ success criteria to tests at a lower voltage level.

Finally, a brief description has been presented on how the measured Tan δ values might be affected by the presence of PD, corroded neutral wires, and non-uniform water tree degradation. In this case, experience from laboratory and field Tan δ testing highlights the central role of the correct choice of equivalent circuit in the data interpretation.

FUTURE WORK

The findings presented in the paper suggest some interesting directions for work in the future:

- An approach for appropriate equivalent circuits that consider PD, neutral corrosion, and non-uniform water tree degradation.
- Determination of appropriate diagnostic criteria at lower test voltages than those conventionally used.

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