Methods and Experience of Very Low Frequency (VLF) Diagnostic Testing to Support Asset Management of Critical MV Circuits

Jean Carlos HERNANDEZ-MEJIA; Josh PERKEL; Nigel HAMPTON; Georgia Tech-NEETRAC, USA,
jean.hernandez@neetrac.gatech.edu, joshua.perkel@neetrac.gatech.edu, nigel.hampton@neetrac.gatech.edu
JF DRAPEAU; Hydro Quebec-IREQ, CAN, Drapeau.Jean-Francois2@ireq.ca

ABSTRACT

Utilities find that the small footprint, ready availability of VLF (very low frequency) voltage sources, and well-established condition assessment criteria are beneficial when undertaking condition based maintenance. In this paper, the authors address the application of VLF diagnostic testing coupled with other complimentary techniques to support the asset management of critical Medium Voltage (MV) cable circuits. Circuits are considered critical when the risk of failure profile and related consequences are significantly different to traditional distribution applications. This situation is increasingly common and is not straightforwardly addressed in the current literature.

KEYWORDS

VLF, Diagnostic Testing, Asset Management, Condition Based Maintenance, Critical Infrastructure

INTRODUCTION

Utilities all over the world, and especially in North America, are facing a significant future challenge to maintain and renew their ageing assets [1]. Utility assets (like most equipment) degrade over time and eventually reach the point at which their performance is lowered sufficiently that they can no longer perform their intended functions. Equipment populations with assets that are far enough into this process produce service failures [2-6].

Effective asset management strategies require the availability of appropriate information on the performance of the assets themselves. In essence, the extra information comes from an effective diagnostic program whose results enable the utility to undertake “smart maintenance” in that only those assets that will likely impact the reliability in the near future receive some form of remediation.

To address this need for underground cable systems, voltage sources were developed during the last two decades that utilize AC frequencies in the range of 0.02-0.1 Hz [7, 8]. These sources provide an AC waveform from a unit that maintains the compact size of DC test equipment while avoiding the detrimental of DC on polymeric insulations.. These sources became known as Very Low Frequency (VLF) sources [3-11]. The possibility of augmenting the withstand capability with diagnostics such as dielectric loss and partial discharge further increases the usefulness [5, 8, 9].

Guidance on use and interpretation of the VLF technology is provided in the IEEE 400 – 2012 [7] and the IEEE 400.2 – 2013 [8] for both withstand and dielectric loss operations. This guidance is focused primarily on single diagnostics for conventional land distribution cable systems. The need for the use of coupled diagnostics on critical cable systems, where the risk profile is quite different to conventional distribution circuits, is not currently addressed in normal references. In this context, critical cable systems may be considered as those associated with

- long length subsea / river crossings,
- power plants, and
- life safety systems.

These applications are considered critical because their risk of failure profile and related consequences are significantly different to traditional distribution applications and require a number of extensions to the standard diagnostic testing paradigm.

This work considers these issues and uses a number of case studies to illustrate important differences and to describe the solutions employed. These include:

- Decision protocols – provision of interim outcomes to support implementation or cessation of tests.
- Diagnostic features – the circuit value supports a more in depth analysis.
- Maximizing the diagnostic power from coupled and /or complementary techniques. .

DEFINITION OF A CRITICAL CIRCUIT

The definition of a critical MV circuit will likely change from utility to utility; specific cases may require unique parameters to define whether the circuit is critical or not.

In this paper, the categories that are used to establish the criticality of a circuit are as follows:

- **Impact to the end customer**: this category includes circuits that support critical infrastructure (*e.g.* hospitals, airports, agencies, high profile customers, dense commercial/industrial/tourist areas, etc.).
- **Reliability**: This category includes circuits that may impact reliability indices (*i.e.* SAIFI and SAIDI).
- **Circuit Access/Location:** Circuits whose location and/or access are difficult (*e.g.* power plants, subsea applications, etc.).
- **Maintenance Strategy:** It some cases criticality is determined by the ability to address any issues on the circuit. There are cases where repair or replacement requires additional work or costs leading to prolonged downtime. It is also possible that for old or special circuits, replacements are simply not available.
- **Other:** Any other parameters that may arise for a particular case that cannot be covered by the categories described above.

In general, the definition of the criticality of a circuit may require more than one of the categories previously described. In terms of diagnostic testing, critical circuits can be further classified into three broad groups as follows:

- **New Critical Circuits:** These include new circuits that are *de facto* critical or new circuits replacing an existing critical circuit. In this group, the risk of failure under testing for voltages above the rated circuit voltage is generally considered minimal and actually desirable when compared to future failures in service.

- **Existing Critical Circuits with diagnostic record:** This is the group where trending in diagnostic measurements was carried out. Thus, the trend as well as the diagnostic levels may be used for assessment.
- **Existing Critical Circuits with no diagnostic record:** As no diagnostic record exists, the risk profile is unknown. In these cases, special attention must be given since there is no condition knowledge available prior to commencing the testing.

Possible actions taken for each group as well as case studies appear in later sections, this constitutes the main contribution of the work reported here. Additionally, follow-up tests after diagnostics may be used to further enhance the condition assessment with the goal of better understanding the aging rate or speed of degradation.

TEST PROTOCOL & CIRCUIT CRITICALITY

This section presents decision protocols that are deployed on the different types of critical circuits defined above.

New Critical Circuits

These circuits involve new systems that are either new installations and/or replace existing critical infrastructure. Such circuits enable the diagnostic process to begin with circuit construction and includes the following stages:

1. **Factory Tests:** The suite of complimentary electrical and material tests performed by the manufacturer.
2. **Cable Quality Assurance:** Perform dimensional checks and quality checks to ensure that the cable complies with all specifications and quality required by the utility and industry standards.
3. **Commissioning Test:** Electrical tests performed on site that include installation and acceptance tests.
4. **Operation Performance:** Maintenance tests and observation of trends as the circuit ages.

In these cases a utility is more willing to invest time energy and effort in the diagnostic process. This is usually manifests as multiple complimentary diagnostics applied before a circuit is energized. This is in comparison to most existing circuits where a single diagnostic approach is usually employed.

Critical Circuits with Diagnostic Record

These circuits have assessment data from periodic maintenance tests available which may then be used for trending. The trend can be used as an additional diagnostic indicator. If a considerable change is observed with sequential tests, then the risk of failure during a future test and normal operating conditions should be re-evaluated.

Effective trending is more than simple changes in diagnostic measurements between sequential tests, *i.e.* comparing with the last test. In the authors' experience, the trend evolution is more robustly determined through analysis using trending analysis techniques such as Shewhart Control Charts, Cumulative Sum (CUSUM) Control Charts, and/or Crow-AMSAA (Army Materiel System Analysis). These trending analysis techniques [12] use statistical tools for extracting the underlying pattern behavior in the time series of diagnostic data and may even be used to predict future outcomes.

The trending can be carried out either at the individual circuit level (*i.e.* multiple measurements on the same circuit) or on a population of circuits. The circuit population approach considers the conditions of many circuits and has the advantage that it requires less time to implement.

Table 1: Example trending using Health Indices [3,5, 6]

Test	T-8 years	T-4 years	T-1 years
Diagnostic Outcome	No action Required	No action Required	Further Study
Health Index	70th percentile	78th percentile	85th percentile

Consider a possible case shown in Table 1. If each test is considered in isolation then no single test at T -1, 4, 8 years would be certain to trigger remedial action [3, 5]. However, a test at year 0 using traditional VLF diagnostic techniques (*i.e.* Tan δ with three test voltage levels of 0.5 U_0, U_0, and 1.5 U_0 to IEEE 400.2 – 2013 [8] yielded a Further Study with a 90th percentile Health Index would elicit action. Furthermore, the action would be informed by the current data and the trend in Table 1.

If the circuit owners are very risk adverse to failure during testing, test parameters can be adjusted to minimize the risk. The most straightforward approach is to limit the test voltage to the rated operational voltage (U_0). However, in doing so the decision-making is more difficult as the well accepted criteria in Table 2 cannot be used as the data at 1.5U_0 are missing, and hence, the Tip Up (TU) feature is not available. Fortunately, this is likely not a big practical issue for these circuits as is the assessment may be augmented with the trend data. This is not the case when there is no diagnostic record. Such situations are discussed in the following section.

Table 2: Figures of Merit for Condition Assessment of Service-aged PE-based Insulations (*e.g.* PE, XLPE, and TRXLPE) using Tan δ Measured at 0.1 Hz [7] (Table 4)

Condition Assessment	STD U_0 [E-3]		TU $1.5U_0$-$0.5 U_0$ [E-3]		TD U_0 [E-3]
No Action Required	<0.1	and	<5	and	<4
Further Study Advised	0.1 to 0.5	or	5 to 80	or	4 to 50
Action Required	>0.5		>80		>50

Critical Circuits with no Diagnostic Record

This is the most difficult scenario for critical circuits since previous diagnostic information is not available. The only plausible protocol that can be deployed here is to obtain diagnostic information by minimizing as much as possible the risk of failure during test.

During VLF Tan δ diagnostic testing, the risk is intrinsically low. For instance, it has been estimated that the risk during a VLF withstand test for an aged circuit during the 30 min hold phase is approximately 4.5% for a 300 m (~1,000 ft) circuit [5]. Hence, if the number of critical circuits is 10 % of the total circuit population, the risk of failure then reduces to 0.45% or one critical circuit failure for every 200 critical circuits that are tested.

Even though the risk of failure for VLF testing is considerably small, in the context of insulation testing, this risk can be further minimized if the testing voltage is kept to a maximum *rms* value equaling the system voltage – U_0.

Traditional standards such as IEEE 400.2 – 2013 [8] provide only a brief discussion of critical circuits; however, no guidance nor diagnostic criteria are provided. To aid in this issue, the authors have developed new diagnostic criteria that is presented in detail in the next section. With periodic testing and the diagnostic criteria, trends can be established and evaluated to enhance the condition assessment of the critical circuits.

TAN δ FEATURES FOR ASSESSMENT WHILE MINIMIZING RISK OF FAILURE ON TEST

What Features to Use

In order to minimize the risk of failure during test, the test voltage should be limited to the operational phase-to-ground voltage (U_0). The Tan δ diagnostic criteria presented here corresponds to the approach outlined in the Cable Diagnostic Focused Initiative (CDFI) Phase II [5]. Tan δ results appear in terms of three specific diagnostic features. The features in order of importance are:

- **Tan δ Stability (STD):** Tan δ time dependency and is normally reported as the standard deviation (STD) of sequential measurements at a particular voltage level.
- **Differential Tan δ (TU)**: Tan δ voltage dependency and is normally reported as the algebraic difference between the means of a number of sequential measurements taken at two different voltages levels.
- **Tan δ Magnitude (TD):** The level of dielectric loss and is normally reported as the mean of a number of sequential measurements at a particular voltage level.

Since the testing voltage is limited to U_0, a total of five diagnostic features can be used for diagnosis: Tan δ stabilities and magnitudes at 0.5 U_0 and U_0, and the differential Tan δ between U_0 and $0.5U_0$.

In order to evaluate the five diagnostic features as well as their correlation, intrinsic taxonomy, and consider a reduced number of them according to the approaches presented by IEEE 400.2 – 2013 [8] and the CDFI [5], cluster variable analysis [11] is used for analysis of the diagnostic data from PE-based insulation.

Cluster variable analysis is useful because it identifies key variables that explain the principal dimensionality (not variability) of the data. It is used to classify the data into groups when the groups are initially unknown. One important reason to cluster variables is to reduce their number; but more importantly, clustering variables is used in this research to understand the taxonomy and meaning of the Tan δ diagnostic features when the test voltage is limited to U_0. Diagnostics features with high similarity levels carry similar diagnostic information and thus they can be merged in a cluster; the cluster is represented by one of its features. Figure 1 shows the results for the cluster variable analysis of the five Tan δ diagnostic features.

As seen in Figure 1, when a similarity level of 70% is chosen to cut the dendrogram [11], three clusters are obtained. The similarity level was selected to generate three clusters similarly to the IEEE 400.2 – 2013 [8] and CDFI Phase II [5] approaches. In Figure 1, Cluster 1 is composed of the TD at 0.5 U_0, TD at U_0, and STD at 0.5 U_0, Cluster 2 is composed only of STD at U_0, and Cluster 3 is composed only of the TU between U_0 and $0.5U_0$. Once the number of clusters is determined, one diagnostic feature is selected from each cluster to represent it. In this case, the selected features to represent each cluster are: Cluster 1: TD at U_0, Cluster 2: STD at U_0, and Cluster 3: TU between U_0 and $0.5U_0$

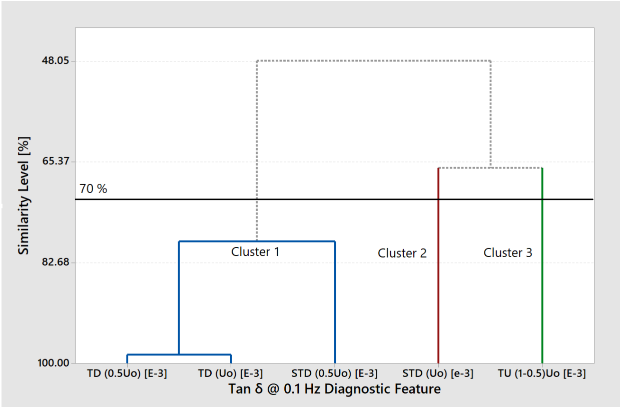

Figure 1: Cluster Variable Analysis of Tan δ Diagnotic Features – Dendrogram

Diagnostic Testing Criteria

Figures of Merit (2019) for condition assessment of service-aged PE-based Insulations critical MV circuits (*i.e.* PE, XLPE, and TRXLPE) using Tan δ Measured at 0.1 Hz are shown in Table 3.

Table 3: Figures of Merit (2019) for Critical MV Circuit Condition Assessment of Service-aged PE-based Insulations (*i.e.* PE, XLPE, and TRXLPE) using Tan δ Measured at 0.1 Hz

Condition Assessment	STD U_0 [E-3]		TU U_0-0.5 U_0 [E-3]		TD U_0 [E-3]
No Action Required	<0.1	and	<2.4	and	<6
Further Study Advised	0.1 to 1.0	or	2.4 to 60	or	6 to 70
Action Required	>1.0		>60		>70

The figures of merit presented in Table 3 were derived from empirical cumulative distribution functions (CDF) for the data consisting of data points obtained during maintenance tests on aged cable systems, mainly in utilities in North America. To determine the threshold level between classes, the tables use the 80th percentile. This was selected based on the well-known Pareto principle that the best ranked 80 % of a population only accounts for 20 % of the issues/problems and 95 % of the poorest values are considered to be extremely unusual. As an example instance, Figure 2 shows the CDF for the TU between U_0 and $0.5U_0$, with the figures of merit at the 80% and 95 % levels.

As seen in Table 3, the Tan δ diagnostic includes values that are time dependent (STD at U_0), voltage dependent (TU between U_0 and $0.5U_0$), and values that are absolute (TD at U_0). They are used as figures of merit or compared to historical data to grade the condition assessment of the cable system as:

- "No Action Required" -The cable system does not exhibit unusual dielectric loss characteristics, but it should be retested at some later date to observe the trend of the Tan δ diagnostic characteristics over time.
- "Further Study Advised" - Additional information is needed to make an assessment. This could come from previous system failure history or an additional assessment using another diagnostic test.
- "Action Required" - The cable system has an unusually high Tan δ characteristics that may indicate poor condition and should be considered for replacement or repair immediately or in the near future.

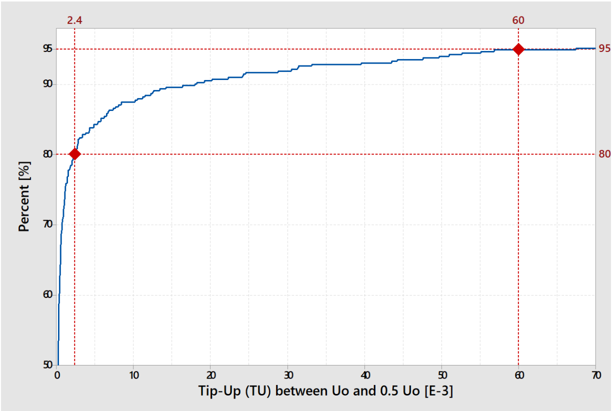

Figure 2: Cummulative Distribution Function for TU between U_0 and $0.5U_0$

The condition assessment classes above are intended to guide the remedial actions, if any, the cable system user should take to return the system to a reliable operating condition. Actions following a "Further Study Advised" assessment might include:

- Review data for a rogue measurement values – most common in the first voltage cycle,
- Confirm insulation type to ensure that criteria apply,
- Clean or re-clean terminations and repeat,
- Compare with previous tests or other phases of circuit,
- Conduct a VLF extended time test at U_0 for at least 15 min to observe trend and time stability of the Tan δ,
- Retest in the near future (one to two years).

This approach is applicable to critical circuits using EPR or PILC cables. These cases are not covered in this paper.

CASE STUDIES

This section presents studies where VLF diagnostic testing was used to support the management of critical MV circuits.

New Circuit that is Critical

This case study corresponds to a new circuit that is considered *de facto* critical. Specifically, the circuit is a bay crossing in the USA with limited accessibility once it is put into service. In addition, the circuit provides power to a tourist area with high economic impact.

The circuit is a feeder-type cable system and is composed of four parallel runs (three phases for normal operation and a spare phase). The cable is a 25 kV design, large conductor, EPR insulation, and jacketed. The total length of each completed phase is approximately 3,230 m (~10,600 ft) and includes one joint per phase located at the approximate midpoint of the circuit. Joints and test terminations are heat-shrink designs. The circuit is operated at 7.2 kV nominal. The geographical layout appears in Figure 3.

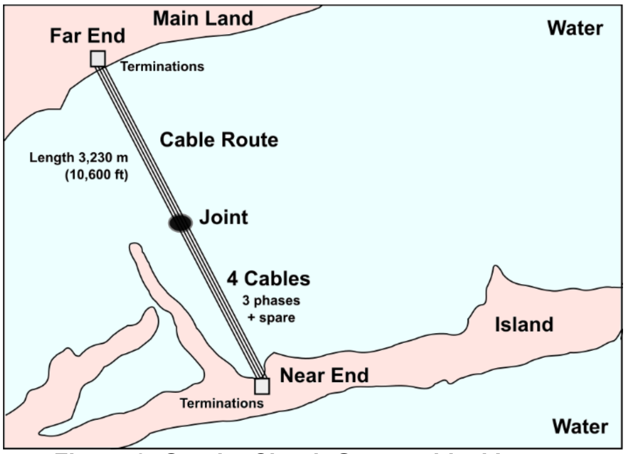

Figure 3: On-site Circuit Geographical Layout

The test protocol included tests in the laboratory, factory, and field and included:

- Cable quality assurance tests.
- dc conductor resistance measurements.
- 60 Hz ac PD: Performed at 52.3 kV [10].
- ac withstand test at 52.3 kV (3.6 U_0) for 5 min [10].
- Tests performed in the field for commissioning:
- Time Domain Reflectometry - for circuit length, joint location verification and metallic shield integrity
- VLF (0.1 Hz) Tan δ measurements to IEEE 400.2 [8].
- Damped ac PD measurements to IEEE 400.4 – 20 [9].
- VLF (0.1 Hz) PD measurements for verification of Damped ac PD results.

As a result of the critical nature multiple complimentary, and in some cases duplicate, diagnostics were deployed.

During the commissioning tests, PD activity was detected in one of the joints with an inception voltage of approximately 17 kV. The criticality meant that it was valuable to spend the time and effort getting a confirmation with an independent diagnostic technique. The PD occurrence and location was confirmed. These data enabled the utility to undertake appropriate remediation procedures; thereby, ensuring reliable operation. Without the diagnostic testing, the sections would have been placed directly into service without the ability to intervene.

One major lesson learned here was that it is advantageous to conduct interim testing at the jointing stage prior to final / complete installation. This permits a defective accessory to be addressed, thereby minimizing costs.

Critical Circuit Due to its Location

This case study represents a critical circuit, located in a power plant, where there is previous diagnostic information available. The circuit is large copper conductor, 5 kV design, and XLPE insulated shielded. The cable was manufactured in 1974, and was in service for approximately 40 years in extreme operating conditions.

The critical circuit asset management protocol here is part of a proactive predictive/preventative maintenance program managed by the utility at the power plant. The cable circuits at power plants are considered critical infrastructure because loss in their reliability would manifest as compromised operation.

The circuit was removed from service due to steadily declining test results that took its condition assessment class from "Further Study Advised" to "Action Required" (see Table 2). The utility was interested in understanding the degradation of this cable, in order to proactively maintain and address 17 other critical circuits with same age and identical operational conditions.

Table 4: VLF Tan δ Measurements Results

Test Voltage [kV/ U_0]	TD U_0 [E-3]	STD U_0 [E-3]	TU U_0-0.5 U_0 [E-3]
1.5 / 0.5U_0	424.35	1.2	>575.65
2.9 / U_0	834.25	10.6	
4.4 / 1.5U_0	> 1000	No Data	

A series of electrical and physical tests were performed on this cable, including VLF Tan δ, VLF Tan δ Monitored Withstand and physical examination/dissection. A summary of the results appears below.

- The cable shows an unusually high Tan δ. The condition of the cable insulation was graded as "Action Required" following IEEE 400.2 – 2013 [8] condition assessment recommendations, the unusual Tan δ measurements are shown in Table 4.
- Although it was not possible to complete the required measurements at 1.5U_0 (Table 2) sufficient features were available to determine that the cable represents the poorest 1.6% of all the XLPE cable systems measured in North America using Tan δ Interpretation Tool developed during the CDFI [5].
- The cable failed the VLF Tan δ monitored withstand approximately 5 min after 7 kV was applied (IEEE 400.2 – 2013 [8]).
- Large size contaminants were found in the cable insulation at various locations along the cable length. The sizes varied from 19 mil to 52 mil (largest dimension). This exceeded the maximum permitted by for utility applications at that time [12].
- Multiple vented and bowtie water trees were found. Figure 4 is an example of a bridging water tree. Since the circuit was removed before failures occurred, those bridging water trees did not cause a failure in service, but there was a high probability that they could convert to an electrical tree likely from the low strength region within the water tree.

As samples of the cable were available a water tree diagnostic approach, analogous to a medical biopsy, was used [6] to compliment the VLF tests. This approach considered the water treeing (type / size / density) together with the meta data (age / cable design) to estimate a Cable Health Index. The computations showed that this cables was within the 90th percentile *i.e.* one of the poorest 10% of cables analyzed and had very similar attributes to cables that had failed in service.

Consequently, the test and decision protocols used after the circuit was removed from the field showed that this cable is significantly degraded - within poorest 5% using the criteria developed here (Table 2), within poorest 10% based on Cable Health Index [6] and poorest 2% using the conventional IEEE approach. These three diagnoses suggest that if this cable is representative of the condition of the remaining 17 cables as expected, then immediate action is required to maintain security of the power plant

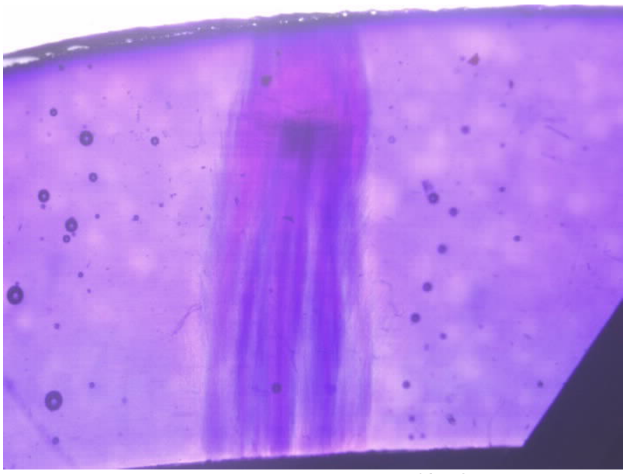

Figure 4: Water Tree through 100% of Insulation

Critical Circuits with No Diagnostic Record

This case study corresponds with the case of a 42 years aged (XLPE cable) circuit supplying a critical load on the premise of a research center. This circuit was considered critical because it was the only remaining spare circuit neighboring the main that was already out of service because of a previous cable failure. The tests took place at a moment in the year where temperatures were very cold (December). Any failure occurring during or after the tests would imply shutting down the access for people to the building and use of emergency supply to avoid any damage due to freezing inside the building.

The circuit was a 3ϕ feeder-type cable system consisting in a cable with no joint. The cable was a 28 kV design, unjacketed, operated at 25 kV. The total length of each phase was approximately 345 m (~1150 ft).

The test program included TDR, VLF Tan δ and Time Domain Dielectric Spectroscopy (TDDS) [14,15]. In order to avoid any possibility of occurrence of failure on test, the choice was made to limit the test voltage for VLF Tan δ and TDDS to operational voltage. Accordingly, test voltages were set to 0.5 U_0 and U_0. Results of testing are shown in Figure 5 and Figure 6.

It is interesting to note that both VLF Tan δ and TDDS results show a clear voltage dependence between 0.5 U_0 and U_0 and time stability issues, which are signs of degraded XLPE insulation. Calculated VLF Tan δ features are as follows (assessed with criteria proposed in Table 3):

- STD @ U_0 [E-3] = 0.51 (Further Study Advised)
- TU (U_0-0.5 U_0) [E-3]= 10.8 (Further Study Advised)
- TD (U_0) [E-3]= 12.6 (Further Study Advised)

However, considering previous experience and preliminary proposed criteria [16], TDDS features might be considered as having a suspicious condition and thus warranting closer study. This situation is not uncommon when dealing with critical circuits as the choice to user lower voltages than commonly used deprives the diagnostics of some of their certainty.

The cautious way used for handling the tests proved to be the correct way to proceed since a cable failure actually occurred less than 48 hours after the circuit was reenergized after testing. Because of the way the test were carried out, execution of the testing was ruled out as having possibly caused the failure, which was rather attributed to the extreme poor condition of the cable in itself.

As a conclusion, this testing program has allowed to collect valuable interpretative diagnostic information since non-destructive measurements could have been carried out on a cable in a condition “just about to fail”.

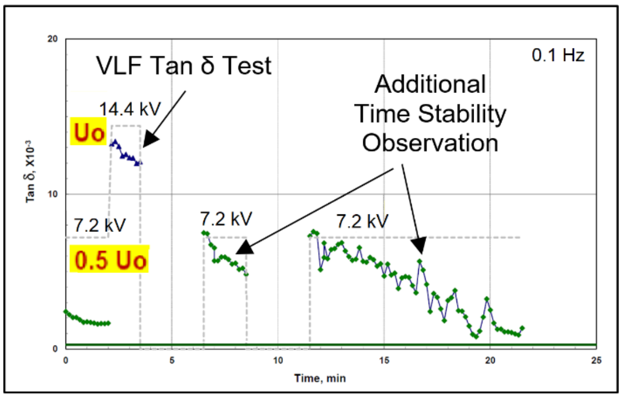

Figure 5: Time Evolution of VLF (0.1 Hz) Tan δ Testing

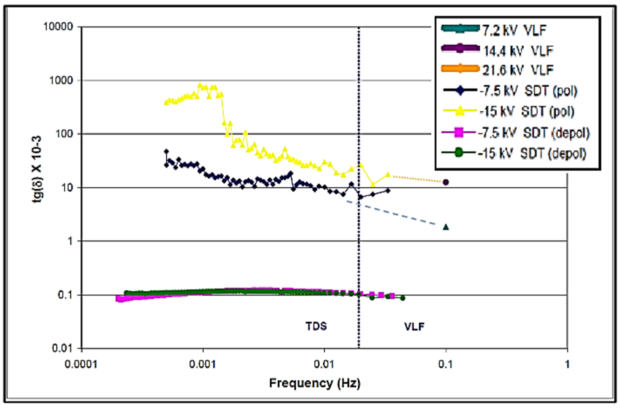

Figure 6: Combined Results of TDDS and VLF Tan δ Testing on a Dielectric Loss Spectrum

CONCLUSIONS

This paper presented methods and experiences with VLF diagnostic testing together with other complementary techniques and analyses to support the asset management of critical MV circuits. The work can be used as guidance by utility engineers to maintain reliable operation of their important assets. Based on the work reported here, the conclusions are as follows.

The manner in which a MV critical circuit is defined will likely change between utilities. However, it is important to develop a methodology to recognize such critical circuits and that modifications to diagnostic protocols can be made to both reduce risk and maintain effectiveness.

In the cases in which the risk of failure is reduced below the low levels of standard protocols, the authors have developed new condition assessment criteria based on VLF (0.1 Hz) Tan δ diagnostic features for PE-based insulations.. Figures of merit and recommended actions after tests are also presented. Moreover, it is recognized that it is not uncommon, when the user chooses lower voltages, that the diagnostic outcomes are not as crisp as when more elevated voltages are used (consider the case of commissioning soak tests). This is a drawback that comes with the reduced risk and can be mitigated, to give more certainty to the ultimate classification, through the use of a second complimentary diagnostic.

Finally, this paper presented three case studies illustrating the application of a modified VLF approach and other complimentary diagnostic techniques to support the asset management of critical MV circuits

REFERENCES

1. BLACK R.M., The History of Electric Wires and Cables; Peter Peregrinus, 1983; ISBN 0-86341-001-4.
2. DISSADO L., and FOTHERGILL J., Electrical Degradation and Breakdown in Polymers, IEE Materials and Devices Series 9, Peter Peregrinus Ltd., London, 1992, ISBN 0-86341-196-7.
3. PERKEL J., DEL VALLE Y., HERNANDEZ-MEJIA J.C., and HAMPTON R.N., Repeated Field Tests – Utility Case Studies of the Value of Trending, JICABLE 2015, Paris, France.
4. PERKEL J., HAMPTON R.N., HERNANDEZ-MEJIA J.C., DRAPEAU J.F., and DENSLEY J., Challenges associated with the interpretation of dielectric loss data from power cable system measurements, JICABLE 2011, Paris, France.
5. Cable Diagnostic Focused Initiative Phase II, , Dept of Energy Award No. DE-OE0000188, Feb. 2016.
6. RN Hampton, J Perkel, D Wiliams “Asset Management using Data Driven Health Indices for Water Treeing”, Jicable19, Versailles France, June 2019; Paper D 10.1
7. IEEE Std. 400, IEEE Guide for Field Testing and Evaluation of the Insulation of Shielded Power Cable Systems Rated 5 kV and Above.
8. IEEE Std. 400.2 – 2013, IEEE Guide for Field Testing of Shielded Power Cable Systems Using Very Low Frequency (VLF) (less than 1 Hz).
9. IEEE Std. 400.4 – 2015, IEEE Guide for Field Testing of Shielded Cable Systems Rated 5 kV and Above with Damped Alternating Current (Damped ac) Voltage.
10. ICEA S-94-649 – 2013, Standard for Concentric Neutral Cables Rated 5 Through 46 kV.
11. DUDA R., HART P., and STORK, D., Pattern Classification, Second Edition, John Wiley & Sons, Inc., New York, 2000, ISBN 0-471-05669-3.
12. Louis B. Mendelsohn, Trend Forecasting With Technical Analysis – Trade Secrets Series, Marketplace Bokks, ISBN 1-883272-91-2.
13. AEIC CS5-82, Specification for Thermoplastic and Crosslinked Polyethylene Insulated Shielded Power Cables Rated from 5 to 46 kV.
14. DRAPEAU J.F. & Al., Time Domain Spectroscopy (TDS) as a Diagnostic Tool for MV XLPE Underground Lines, JICABLE 2007, Paris, France.
15. POTVIN C. & Al., Diagnostic Testing of MV Accessories by Time Domain Spectroscopy (TDS), JICABLE 2007, Paris, France.
16. DRAPEAU J.F., Proposal for a New Interpretative Grid and Diagram for Diagnostics Tests Based on Dielectric Loss Measurements (VLF Tan δ and TDDS), Sub F IEEE Insulated Conductor Committees, Spring 2019.