# LOW FREQUENCY DIELECTRIC SPECTROSCOPY APPLICATIONS TO AGED MEDIUM VOLTAGE POWER CABLE DIAGNOSTICS

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## ABSTRACT

*Low frequency dielectric spectroscopy (LFDS) based dielectric loss diagnostics on aged MV cable systems can provide unique advantages over 'conventional' fixed frequency 0.1Hz (VLF) tan δ measurements. Such advantages include enhanced interpretative potential and ability to discriminate between various aging mechanisms. Despite the above advantages, there is very limited published information on field experiences with LFDS based techniques for MV cables. This paper will present currently utilized field application protocols for MV cable LFDS, frequency domain dielectric spectroscopy (FDDS) based experience case studies, and FDDS interpretation guidance to extend the value of dielectric loss based condition assessment beyond that gained from fixed 0.1Hz VLF tan δ measurements alone.*

## KEYWORDS

Dielectric spectroscopy, condition assessment, FDDS, LFDS, TDDS, VLF, medium voltage cable

## INTRODUCTION

The need for new diagnostic methods to assess the condition of cables led to extensive research in the 1990s and early 2000s to characterize changes in dielectric properties of insulation systems [1][2]. The successful application of Frequency Domain Dielectric Spectroscopy (FDDS) and Time Domain Dielectric Spectroscopy (TDDS) to monitor the insulation of power transformers paved the way for the development of commercial equipment to perform these tests in the field and provided insights into the potential for these technologies to test cables.

Oil-paper and mass-impregnated cables were found to be well suited for the use of dielectric spectroscopy techniques, due to their similarities with power transformer insulation systems [2]. Neimanis et al. showed that the average moisture content in mass-impregnated cable insulation could be estimated by measuring the minimum value of tan δ in the $10^{-3}$ to $10^{3}$ Hz range and using a master calibration curve developed in the laboratory [3]. Lennon further demonstrated the sensitivity of FDDS to changes in moisture content in paper insulation of mass-impregnated cables caused by thermal aging [4].

For extruded cables, and specifically XLPE insulated cables, the initial focus of dielectric spectroscopy was characterization of water related degradation through FDDS [2]. Werelius et al. demonstrated the sensitivity of the technique to water treeing damage in the $10^{-1}$ Hz to 1 Hz range [5]. The frequency and voltage-dependent dielectric loss (tan δ) and capacitance were noted to be useful parameters to monitor. Subsequent work found similar results for tests conducted in the field and the laboratory [6][7][8][21]. The voltage dependency of tan δ at low frequency for water related damage was also highlighted in these publications. These studies, and others not included in this short review, led to the development of the Very Low Frequency (VLF) – 0.1 Hz - tan δ methodology and associated acceptance criteria that is widely used today to characterize water related degradation of cables in the field [9]. Features from FDDS results have been used to characterize the severity of water treeing in XLPE insulated MV cables, and in particular discriminate the effect of bridging versus non-bridging water treeing effects [5][6][10][21]. FDDS has also been shown as sensitive to thermal related degradation of the cable insulation in the $10^{-4}$ to $10^{2}$ Hz range, especially in terms of tan δ and capacitance frequency response [11][12][13].

FDDS measurements conducted in the lower frequency range (i.e. below 0.1 Hz) require longer times which are not always practical in the field. The application of TDDS can provide a faster means to obtain very low frequency characterization of the dielectric material while providing additional defect discrimination benefits. An up to date review of TDDS application and interpretation for MV cable systems is provided in [14] by Institut de recherche d'Hydro-Québec (IREQ), who have conducted extensive investigations in the application of this technique.

This limited literature review shows that FDDS can provide enhanced diagnostic capability for insulation degradation when compared to fixed low frequency testing at 0.1 Hz, with the potential to discriminate between different types of aging. However, little practical information is available in the literature about field deployment of this technique. This paper thus introduces field validated methodologies for FDDS testing, recommendations for interpreting FDDS test results, and a few FDDS based case studies highlighting their unique diagnostic features. The content of this paper is based on more than a decade of practical field experience from FDDS testing of primarily 5 – 15kV extruded and oil-paper cable systems in utility and plant environments.

## THEORY

As noted in the introduction, Zaengl [1] provided a detailed description of the theory behind FDDS testing. Only a brief overview of this theory is thus included here.

FDDS testing is used to illustrate the frequency dependence of the dielectric loss (tan δ) and capacitance of a test object, although voltage, time and temperature dependence characteristics of tan δ and capacitance can also be illustrated through multi-variable measurements. FDDS results are obtained from direct, highly accurate measurements of the complex impedance over variable voltage and frequency, calculated using Ohm's Law $Z^* = U/I$ (where Z and U/I are complex entities). Although various impedance models can be used, the complex capacitance model is very often used in insulation diagnostics to represent results. This model represents the insulation impedance as a complex capacitance C(ω), where C''/C' represents the tangent delta and C' the material capacitance. The impedance can additionally be normalized against the geometric capacitance ($C_g$, the capacitance of an equivalent air-insulated medium) to express the data in the form of complex permittivity ε(ω). A real cable insulation system exhibits a dielectric response which varies with frequency, type and severity of degradation, temperature, humidity and accessory characteristics. Key formulae are summarized below.

$$Z(\omega) = \frac{1}{j\omega C(\omega)} \; where \qquad [1]$$

$$C(\omega) = C'(\omega) - jC''(\omega) \qquad [2]$$

$$C'(\omega) = Re\left\{\frac{1}{j\omega Z(\omega)}\right\} and \; \varepsilon'(\omega) = \frac{C'(\omega)}{C_g} \qquad [3]$$

$$C''(\omega) = -Im\left\{\frac{1}{j\omega Z(\omega)}\right\} and \; \varepsilon''(\omega) = \frac{C''(\omega)}{C_g} \qquad [4]$$

$$tan\,\delta(\omega) = \frac{C''(\omega)}{C'(\omega)} = \frac{\varepsilon''(\omega)}{\varepsilon'(\omega)} \qquad [5]$$

## METHODOLOGY

Practically, FDDS involves the application of a variable frequency AC voltage applied to the cable under test, in order to measure capacitance (C') and tangent delta (C''/C') versus frequency (and normally voltage). The time it takes for an AC waveform to complete one cycle increases as the frequency decreases. Due to such time constraints, 'pure' FDDS tests on cable systems typically do not usually go lower than $10^{-1}$ or $10^{-2}$ Hz. Beyond this general methodology overview, the practical application of FDDS measurements differs between oil-paper insulated cables and extruded cables as discussed below.

### Oil-Paper Insulated Cables

Oil-paper insulated cables should be subjected to FDDS using a variable frequency low voltage (typically $200V_{pk}$ but may be as high as $2kV_{pk}$) signal generator. The test procedure consists of energizing the cable and recording data in the frequency range of typically 0.001 to 1000 Hz (dependent on test cable capacitance and practical considerations). It is suggested to avoid voltages higher than a few kilo-volts (practically $2kV_{pk}$) due to the 'Garton Effect' [15]. As a result of the Garton Effect, measurements of dielectric losses on oil-paper insulated cable systems show a decrease in loss with increasing test voltage. Dielectric losses obtained at low voltages are thus more accurate for use in interpreting diagnostic measurements on oil-paper cable systems [3][16].

### Extruded Cables

Extruded cables should be subjected to FDDS using a variable frequency, variable high voltage (typically maximum 20 – $30kV_{pk}$) signal generator / amplifier combination. The test procedure consists of energizing the cable and recording data in a variable frequency range with a maximum typically between 1 – 100Hz, (dependent on test cable capacitance and applied test voltage), and a minimum determined by practical time constraints (typically 0.1 or 0.01Hz). The test procedure for extruded cables includes recommended protocols from IEEE 400.2-2013 [9], but with additional frequency and voltage steps. Specifically, the recommended protocol consists of energizing the cable up to $1.5U_o$ or $2.0U_o$ with intermediate steps at $1.0U_o$, and $0.5U_o$, where $U_o$ is the nominal operating line-ground voltage of the cable. At each voltage step, the complex impedance (and hence capacitance and tan δ) is measured. The typical sequence of voltage application is as follows:

1. $0.5U_o$
2. $1.0U_o$
3. $1.5U_o$
4. $0.5U_o$ *(Repeat for Hysteresis Check)*

The measurement at 0.5 $U_o$ is repeated in order to check for hysteresis effects in the dielectric loss current and capacitance, which refers to the difference between the initial and final mean tan δ values measured at $0.5U_o$.

## FDDS RESULTS INTERPRETATION

### Oil-Paper Cables

Moisture is one of the most common causes of deterioration of oil-impregnated paper insulated cables. Moisture can penetrate the insulation from outside due to leaks in the lead sheath but also be a result of water produced as a by-product of thermal aging of the cellulose, which also acts as a catalyst for further aging. Intrusion of moisture into the insulation system could also directly increase leakage current, causing localized thermal runaway and eventual failure. The moisture content of PILC cable insulation can be estimated using an empirical formula based on minimum $\tan\delta$ [3]:

$$mc\% = 15.3 + 2.53\ln(\tan\delta_{min}) \qquad [6]$$

Where $\tan\delta_{min}$ is the global minimum value across the measured spectrum (0.001 to 1000 Hz). The results can be interpreted based on Table 1, which is a simplified version of the above equation and includes a qualitative judgement of condition based on the measured tan δ results and frequency response. Since the use of FDDS results from field-aged cables is an evolving diagnostic technique, the data interpretation methodology in Table 1 are considered guidelines that may evolve as further field data is gained. Although the methodology has been successfully applied in practical application, further research is required to understand the limitations of these empirical formulae for field aged oil-paper cables.

**Table 1: Example FDDS data interpretation for oil-paper insulated cables** [3][16]

| Minimum Tan δ | Estimated average moisture [%] | Condition |
|---|---|---|
| 0.002 – 0.0035 | Below 1.0 | Good |
| 0.0035 – 0.005 | 1.0-2.5 | Moderately aged |
| 0.005 – 0.01 | 2.5-3.5 | Considerably aged |
| Above 0.01 | Above 3.5 | Bad condition |

FDDS can also potentially be employed for detecting other defects such as carbonization, oil and paper contamination, and oil starvation (dryness). IEEE has developed an FDDS guide for oil-filled transformers with examples of non-moisture related defects, aspects of which can in principle be used for oil-paper cables [17].

## Extruded Cables

The '*conventional*' component of FDDS data interpretation for extruded cables follows similar principles to the traditional VLF 0.1 Hz test. Specifically, the measured mean 0.1Hz tan δ at $U_o$, the 0.1Hz Δ tan δ or 'tip-up' between $1.5U_o$ and $0.5U_o$, and the standard deviation of 0.1Hz tan δ at $U_o$ (or all voltages) can be analysed against published interpretation guidance. The most prevalent guidance including statistically derived thresholds for PE, XLPE and EPR insulated cables are from IEEE 400.2 [9], EPRI [18], and NEETRAC [19].

The '*advanced*' interpretation of FDDS data, namely the assessment of frequency and voltage dependent features of tan δ and capacitance / permittivity can provide unique and potentially valuable additional data. Recommended interpretation guidance is summarized in Table 2, in order of prevalence (and usefulness) in application.

**Table 2: Extruded cable FDDS interpretation guidance**

| ASSESSMENT FACTOR | INTERPRETATION NOTES |
|---|---|
| Mean Tan δ Hysteresis | ***Description:*** Comparing the frequency-dependent tan δ variations between an *initial* and *repeat* measurement at the lowest voltage step (i.e. typically $0.5U_o$).<br>***Diagnostic Value:*** Tan δ hysteresis is indicative of degradation mechanisms which exhibit longer dielectric relaxation time constants (e.g. severe bridging water treeing) [5][6][10][21]. |
| Mean Tan δ Low Frequency Dependence | ***Description:*** Degree of frequency dependence (i.e. slope) of tan δ in 'low' frequency' (LF) region, i.e. between 0.01 and 0.1Hz, or 0.1 and 1Hz, versus applied voltage (i.e. $0.5 – 1.5U_o$).<br>***Diagnostic Value:*** This characteristic is indicative of high dc conductivity ($\sigma_{dc}$) contribution, LF polarization loss (ε'') or a combination thereof [5][10][11]. Such LF behavior may also exhibit voltage dependence. These characteristics can help assess varying degrees of water treeing and discriminate water treeing from other forms of degradation such as wet joints, thermally aged cables, or thermally aged accessories. The LF tan δ(ω) behavior of non-linear graded (i.e. heat-shrink) accessories needs to be considered, particularly for shorter cables. |
| Mean Tan δ High Frequency Dependence | ***Description:*** Degree of frequency dependence (i.e. slope) of tan δ in 'high' frequency region i.e. between 1 and 10Hz, or 10 and 100Hz, versus applied voltage (i.e. $0.5 – 1.5U_o$).<br>***Diagnostic Value:*** This characteristic is indicative of high series resistance effects (i.e. aged semi-conductive screen, high shield resistance, shield corrosion/breakage). |
| Tan δ Non-Standard Fixed Frequency Metrics | ***Description:*** Mean tan δ, Δ tan δ, and standard deviation at fixed frequencies ≠ 0.1Hz.<br>***Diagnostic Value:*** Separation of and improved sensitivity to the LF and HF tan δ frequency dependency effects noted above. |
| Capacitance (C') Frequency Dependence | ***Description:*** Magnitude and degree of frequency dependence (i.e. slope) of C' (or ε') across measured frequency region.<br>***Diagnostic Value:*** C' (or ε') frequency dependency can indicate severe degradation effects causing insulation permittivity changes (i.e. thermal / radiation aging) [11][12][13] and geometric influences [20]. |
| Tan δ or C' Dielectric Response Trending | ***Description:*** Relative comparison of tan δ vs. frequency curves measured over time, or at varying environmental conditions.<br>***Diagnostic Value:*** Assessing tan δ or C' FDDS time trends can identify and characterize aging effects over time, and discriminate tan δ variations due to changes in ambient temperature versus actual aging [11][20]. |

## FDDS CASE STUDIES

The following section presents select case studies where FDDS tests were performed by the authors of this paper with test protocols and both '*conventional*' and '*advanced*' interpretation guidance as noted above.

### 25kV Rated (23kV$_{L-L}$) XLPE Cable (Shield Mechanical Damage / Corrosion)

Testing of an aged 175m length 25kV rated, 23kV$_{L-L}$ operating 3-phase XLPE insulated cable circuit was performed in 2018 at a thermal generation plant. The cable under test had a history of previous failures, necessitating a thorough field condition assessment of the cable to assess its suitability for continued service.

The overall condition assessment approach for this circuit included FDDS including 0.1Hz VLF tan δ, diagnostic (60Hz) partial discharge (PD) and time domain reflectometry (TDR). The results of the 0.1Hz VLF tan δ based assessment is provided in Table 3. A modified test protocol was deployed for FDDS / VLF tan δ testing to limit the maximum voltage to $U_o$ given the age, failure history and criticality of the circuit, resulting in voltage steps between $0.25 – 1.0U_o$. The 0.1Hz tan δ assessment indicated all metrics in the '***Good'*** region, suggesting no signs of moisture-related degradation on the phases.

**Table 3: 0.1Hz VLF Tan δ results summary – XLPE Circuit (assessment as per IEEE 400.2-2013 [9])**

| Voltage | $U_0$ | *X* | *Y* | *Z* |
|---|---|---|---|---|
| *Mean VLF-TD* | 1.0 | 1.22e-3 | 1.20e-3 | 2.15e-3 |
| *VLF-DTD (Modified)* | 1.0-0.5 | 0.02e-3 | 0.15e-3 | 0.20e-3 |
| *VLF-TDTS* | 1.0 | 0.01e-3 | 0.02e-3 | 0.02e-3 |

Advanced interpretation of FDDS results (referring to Table 2) showed:

- Low mean tan δ frequency dependence in the low frequency region (i.e. between 0.1 - 1Hz), for X, Y and Z phases, as seen in Figure 1.
- Mean tan δ frequency dependence in the high frequency region (i.e. between 1 – 10Hz) for X and Z phases, as seen in Figure 1. Figure 2 shows this effect (in order of severity) more clearly, in terms of relative calculated slope (between 1 – 10Hz) and applied voltage.
- Mean tan δ at non-standard fixed frequency (between 0.1 – 2Hz) for the Z phase cable which was approximately 2x higher relative to the Y phase (which exhibited the lowest mean tan δ).

Referring to Table 2, the FDDS assessment indicated the lack of any water treeing, thermal aging or wet joint type defects. FDDS also provided strong evidence indicating the presence of high series resistance effects within the X and Z phases, suspected to be the result of shield breakage / corrosion. Following the FDDS tests, diagnostic (60Hz) PD testing showed Phase Resolved PD characteristics indicating shield defect related PD activity at voltages below $U_o$, at minimum on Z phase. Furthermore, a review of maintenance data (previous cable failure repair) from the circuit revealed historical visual evidence of shield degradation on this circuit. The condition assessment data (crucially including the FDDS results) led to confident cable condition severity ranking, defect discrimination, and a recommendation for short-term replacement of the cable lengths and associated accessories to lower risk of in-service failures.

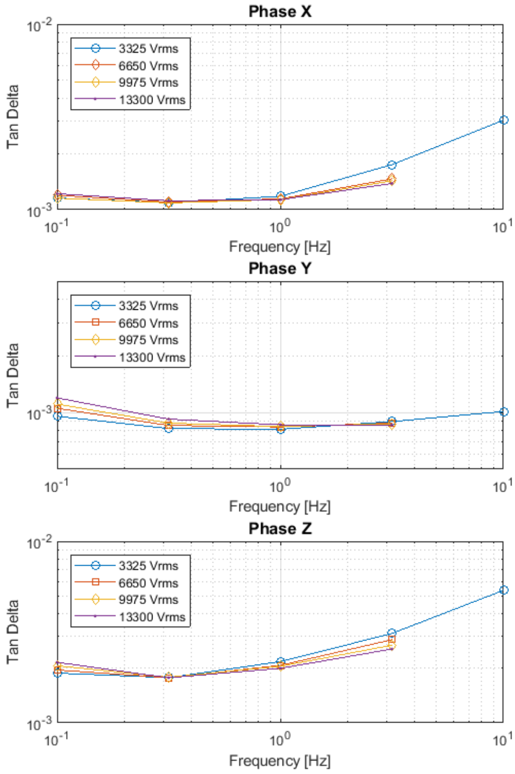

**Figure 1: FDDS tan δ versus frequency and applied voltage plots, XLPE**

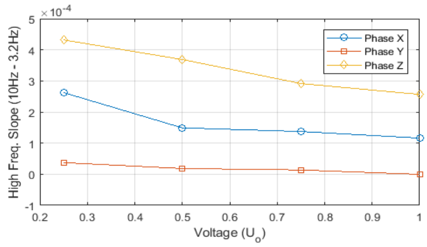

**Figure 2: FDDS Tan δ high frequency Slope (1 – 10Hz) versus applied voltage (0.25 – 1.0Uo), XLPE**

## 15kV Rated (4.16kV$_{L-L}$) XLPE Cable (Bridging Water Treeing)

Testing of an aged 1200m length 15kV rated, 4.16kV$_{L-L}$ operating 3-phase XLPE insulated cable circuit was undertaken in 2016 at a nuclear power plant. The testing was intended to comprehensively assess the condition of the cable, motivated by previous anomalous data obtained from testing 4 years prior. The previous data, limited to 0.1Hz VLF tan δ and DC insulation resistance, indicated signs of insulation degradation requiring further investigation.

The overall condition assessment approach for this circuit included FDDS including 0.1Hz VLF tan δ, diagnostic 60Hz PD testing, and TDR. The results of the fixed frequency 0.1Hz VLF tan δ based assessment are provided in Table 4. The 0.1Hz tan δ assessment placed selected metrics for the Red and White phases in the '***Further Investigation Required***' regions, indicating potential signs of moisture-related degradation in these phases, coupled with a need for additional diagnostic information.

**Table 4: 0.1Hz VLF Tan δ results summary - XLPE (assessment as per IEEE 400.2-2013 [9])**

| Voltage | $U_0$ | ***Blue** (A)* | ***Red** (B)* | ***White** (C)* |
|---|---|---|---|---|
| *Mean VLF-TD* | 1.0 | 0.83e-03 | 5.52e-03 | 0.70e-03 |
| *VLF-DTD* | 1.5-<br>0.5 | 0.23e-03 | 48.9e-03 | 7.57e-03 |
| *VLF-TDTS* | 1.0 | 0.02e-03 | 0.15e-03 | 0.03e-03 |

Advanced interpretation of FDDS results (referring to Table 2) showed:

- Significant mean tan δ frequency and voltage dependence in the low frequency region (i.e. between 0.01 – 0.1Hz) for B and C phases, as seen in Figure 3.This behavior is referred to as a '*Transition to Leakage*' type dielectric response in literature [5]. Figure 4 shows this effect (in order of severity) clearly, in terms of calculated slope (between 0.01 – 0.1Hz) and voltage. B phase exhibits voltage dependent slopes, eventually exceeding 3/ω.

- Significant mean tan δ hysteresis in B and C phases. Figure 5 shows this effect clearly.

- Mean tan δ at non-standard 0.01Hz fixed frequency was between 5 – 16x higher relative to 0.1Hz for the B and C phases, as per Table 5.

Referring to Table 2, the FDDS assessment indicated the presence of significant dc conductivity ($\sigma_{dc}$) contribution and voltage-dependent polarization loss (ε'') in the C and B phases (in order of severity). In conjunction with the observed tan δ hysteresis effects, this indicated the presence of moderate to severe (bridging) water treeing in these phases, as opposed to thermal aging or wet joint type defects. Following the FDDS tests, diagnostic (60Hz) PD testing showed no indication of latent 'dry-electrical' defects in the cable or accessories, and TDR testing showed impedance anomalies that were likely attributable to known splice locations on phases, rather than areas of degradation.

The FDDS driven condition assessment results noted above led to confident cable condition severity ranking and defect discrimination, and a recommendation for full-scale replacement of at least the B and C cable phases to minimize risk of in-service failures. As the utility was intending initially to execute extensive splice repairs based on historical 0.1Hz VLF tan δ and DC insulation resistance results, the assessment re-targeted their action plans.

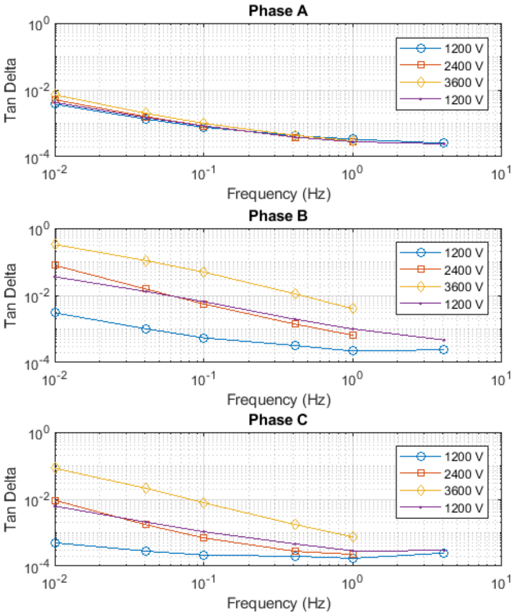

**Figure 3: FDDS Tan δ vs. frequency, XLPE**

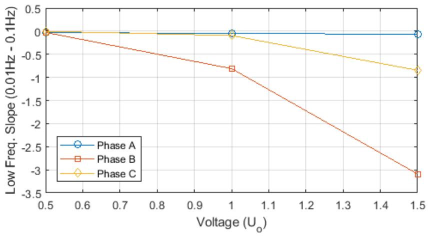

**Figure 4: Tan δ low frequency Slope (0.01 – 0.1Hz) versus applied voltage (0.5 – 1.5Uo), XLPE**

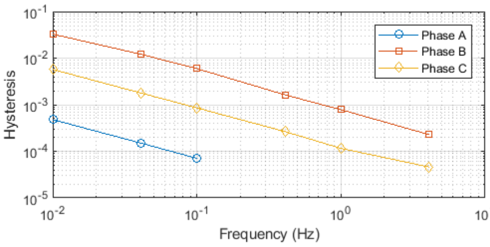

**Figure 5: Tan δ hysteresis vs. frequency, XLPE cable**

**Table 5: Comparison of fixed frequency 0.01Hz tan δ metrics relative to 0.1Hz – XLPE**

| Evaluation | 0.1Hz | 0.01Hz | % Difference 0.01 – 0.1Hz. |
|---|---|---|---|
| **Phase A** | | | |
| *Mean Tan δ @ 1$U_0$* | 0.83e-3 | 5.11e-3 | *610 %* |
| *Mean Δ Tan δ (1.5$U_0$ – 0.5$U_0$)* | 0.23e-3 | 3.43e-3 | *1500%* |
| *Tan δ STDEV @ 1$U_0$* | 0.017e-3 | 0.091e-3 | *540%* |
| *Tan δ Hysteresis* | -0.071e-3 | -0.478e-3 | *680%* |
| **Phase B** | | | |
| *Mean TD @ 1$U_0$* | 5.53e-3 | 78.5e-3 | *1420%* |
| *Mean Δ Tan δ (1.5$U_0$ – 0.5$U_0$)* | 48.9e-3 | 325.0e-3 | *670%* |
| *Tan δ STDEV @ 1$U_0$* | 0.146e-3 | 6.661e-3 | *4560%* |
| *Tan δ Hysteresis* | -5.95e-03 | -32.7e-3 | *550%* |

## Oil-Paper Cable (Contamination and Moisture Ingress)

Testing of an aged 7000m length, 115kV, oil-paper insulated, 3-phase cable circuit was performed in 2016 at a transmission utility. It is noted that although this case reflects an HV rather than MV cable system, the methodology applied for FDDS testing is identical for either scenario (due to use of low voltages to account for the 'Garton Effect' as previously noted). The motivation here was to assess the condition and target repair requirements for the Phase A cable following a splice failure, which resulted in moisture and contamination intrusion into the splice manhole.

FDDS testing at 140$V_{rms}$ over a frequency range of 0.01 – 100Hz range was performed on one (920m) sub-section of Phase A (following removal of the failed splice), and the two remaining (7000m) phases of the cable circuit. After initial testing, Phase A was treated through oil circulation/conditioning and then re-tested. Mean tan δ and capacitance (C') results of these tests (including the 'post-treatment' tests can be seen in Figure 6.

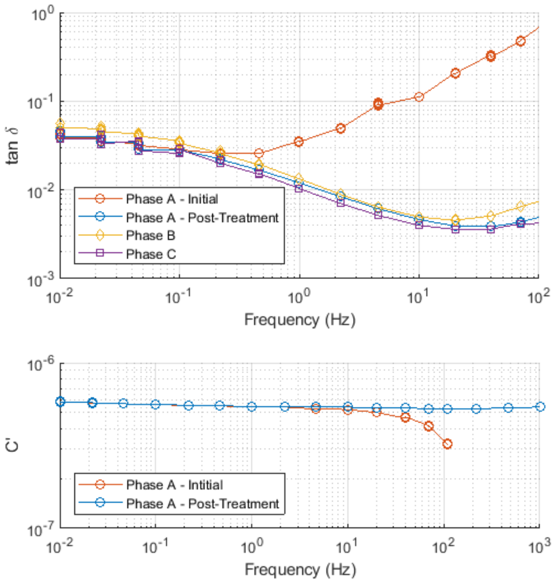

**Figure 6: FDDS Testing of PILC Cable**

The above results show a high initial minimum tan δ value for the Phase A cable over the tested range, as well as significantly higher dielectric losses and non-linear behaviour of C' in the 1 – 100Hz range. Following treatment through oil circulation/conditioning, the tan δ response matched the remaining (B and C) phases and the C' high frequency non-linear behaviour was eliminated. The FDDS targeted maintenance actions thus allowed the utility to reduce the risk of in-service failure on Phase A, and limit further maintenance actions to a single splice repair rather than oil-paper cable replacement.

## CONCLUSIONS

LFDS based diagnostics on aged MV cable systems can provide unique advantages and complementary information compared to ‘conventional’ fixed frequency 0.1Hz (VLF) tan δ measurements alone. In the case of FDDS, these advantages are based on utilizing ‘advanced’ features related to the frequency and voltage dependence of tan δ and capacitance (C’). Such advantages are primarily driven by enhanced capabilities of FDDS (relative to fixed frequency 0.1 tan δ) in terms of:

- Diagnostic interpretation;
- Degradation severity assessment;
- Mode of degradation discrimination;
- Diagnostic trending;
- Ambient temperature versus aging discrimination.

This paper has provided recommendations to practically apply ‘advanced’ FDDS interpretation guidance (i.e. beyond that limited to the 0.1Hz component), based on published literature and the authors’ field experiences. The paper has also presented brief case studies to illustrate examples of using FDDS data in practical field situations for advanced condition assessment of installed extruded and oil-paper cable systems, particularly where minimizing the risk of in-service failures is crucial, and targeted repair decisions are required.

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### GLOSSARY

**FDDS:** Frequency Domain Dielectric Spectroscopy
**LFDS:** Low Frequency Dielectric Spectroscopy
**VLF:** Very Low Frequency
**PDC:** Polarization Depolarization Current
**TDDS:** Time Domain Dielectric Spectroscopy