CHAPTER 6

Dissipation Factor (Tan δ)

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http://www.neetrac.gatech.edu/cdfi-publications.html

Users are strongly encouraged to consult the links below for the most recent releases of Chapter 4, CDFI brochures, and Tan δ Assessment Tool:

Chapter 4: How to Start
CDFI Brochures
Tan Delta Assessment Tool

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6.0 DISSIPATION FACTOR (TAN δ)

6.1 Test Scope

Tan δ measurements determine the amount of real power dissipation in a dielectric material. A comparison of this measured value to a known reference value for the type of dielectric measured is used to establish the condition of the tested system based on how much the dielectric loss differs from the reference value. For cable systems, reference values can be based on:

- values measured on adjacent phases (A, B, C)
- values measured on cables of the same design and vintage within the same location
- values measured when the cable was new
- how the values vary over time (trending)
- how the value varies during the measurement (stability)
- how the value changes as a function of applied test voltage
- how the value changes as a function of frequency
- industry standards
- an experience library.

Tan δ is most powerful if the specific cable and accessory components under test are known. This allows for a direct comparison between the measured value and:

- The expected values for known materials/components or
- Previous measurements on the same system.

6.2 How It Works

Applying an ac voltage and measuring the phase difference between the voltage waveform and the resulting current waveform provides the Tan δ value. This phase angle is used to resolve the total current (I) into its charging (I_C) and loss (I_R) components. Tan δ, also called Dissipation Factor (DF), is the ratio of the loss current to the charging current, as shown in Equation 1.

$$DF = \frac{I_R}{I_C} = \frac{\sqrt{I^2 - I_C^2}}{I_C}$$ **Equation 1**

The angle δ appears in a phasor diagram in Figure 1.

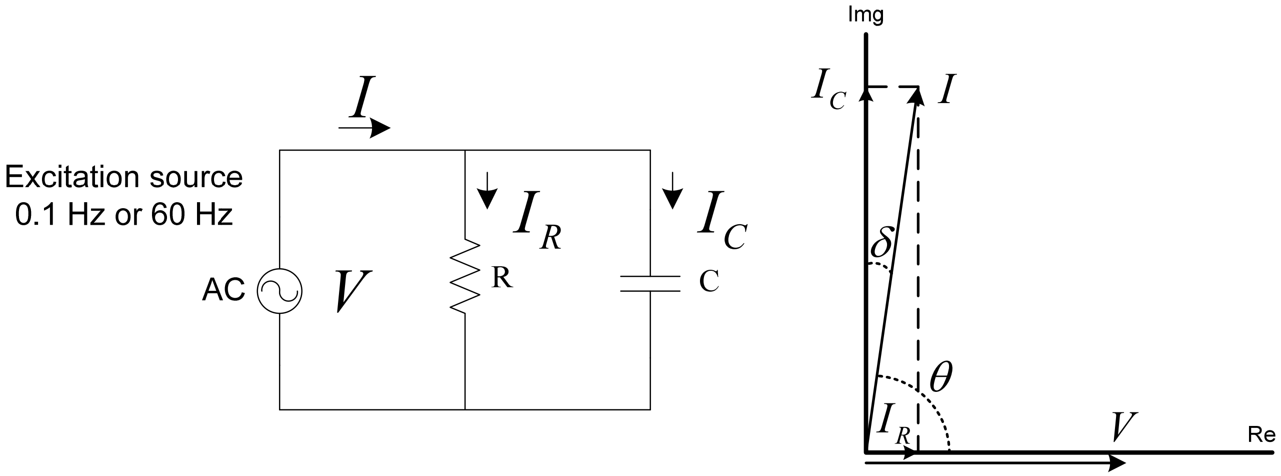


Figure 1: Equivalent Circuit for Tan δ Measurement and Phasor Diagram

Figure 1 shows an equivalent circuit for a cable, consisting of a parallel connected capacitance (*C*) and a voltage dependent resistance (*R*). The Tan δ measured at a frequency ω and voltage V, is the ratio of the resistive (I_R) and the capacitive (I_C) currents according to Equation 2.

$$DF = \tan(\delta) = \frac{I_R}{I_C} = \frac{V/R}{V/(1/\omega C)} = \frac{1}{\omega RC} \qquad \textbf{Equation 2}$$

The terms "Tan δ" and dissipation factor are used interchangeably.

6.3 How It Is Applied

The cable system under test is disconnected from the grid and energized from a separate power supply with a fixed ac frequency (e.g. 60 Hz or Very Low Frequency (VLF) ac). The system is typically energized using a voltage level of 0.5 to 2 times the system operating phase to ground voltage, U_0. Each Tan δ system utilizes different connection methodologies. Users should consult their equipment literature and/or vendor for specific details. In general, once the measurement system is connected to the circuit, a pre-programed series of voltage steps are used to energized the cable system while at the same time the system measures the Tan δ. Field measurements are generally performed at 0.1 Hz and so currently available measurement systems generate a single Tan δ measurement with each 10 s cycle of the voltage.

Summaries of the advantages and disadvantages of using Tan δ as a cable system diagnostic appear in Table 1 and Table 2.

Table 1: Advantages and Disadvantages of Tan δ Measurements as a Function of Voltage Source

Source Type	Advantages	Disadvantages
60 Hz ac Offline	• Testing voltage waveform has the same frequency as the operating voltage. • Voltages higher or lower than the operating voltage can be applied.	• Energizing test equipment is large, heavy, and expensive and is typically not used for Tan δ measurements. • No field data available for establishing criteria. • Tan δ is less sensitive at 60 Hz than at lower frequencies due to the increased magnitude of the capacitive current [2].
0.01 – 1 Hz ac Offline VLF	• Energizing test equipment is small and easy to handle. • Tan δ is more sensitive at lower frequencies than at 60 Hz due to the reduced magnitude of the capacitive current [3]. • Can test long systems. • Clear and accepted criteria available (IEEE Std. 400.2 - 2013). • Significant experience available. • Widespread use and multiple vendors.	• Testing voltage waveform is not the same frequency as the operating voltage. • When using a Cosine-rectangular waveform, Tan δ has to be approximated.

Table 2: Overall Advantages and Disadvantages of Tan δ Measurement Techniques

Advantages	• Test results provided as simple numerical values can easily and quickly be compared to other measurements or reference values. • Four basic Tan δ features at VLF can be ranked in order of importance in making an assessment. (Features are discussed later.) • Provides an overall condition assessment (cable, terminations, and joints). • Measurements on a given phase can be compared to adjacent phases, so long as the phases have the same configuration. (Also applies to T-branched or other complex system configurations if all phases are essentially the same.) • The value can be an indication of the overall degree of water treeing in XLPE cable. • There is minimal influence from external electric fields/noise. • Periodic testing provides numerical data for comparison with future measurements to establish trends. • Data obtained at lower voltages (U_0 versus 2 U_0) are often as useful as data obtained at higher voltages. • Measured values that change as a function of test system length can be indicative of problems such as corroded neutrals. • When measured values change (are unstable) during a test, it may indicate that a component is progressing to failure. • Simple numeric results enable a quick risk assessment prior to testing at higher voltage levels. • Data may be reanalyzed and reinterpreted if needed as better criteria emerge. • Results are obtainable regardless of system length or number of accessories. • Results can detect poor performing accessories or cable lengths. • There is a low risk of failure on test. • Can be used to differentiate the loss characteristics of different EPR insulation materials. • Measurements made over time can be used to predict the rate of aging/degradation of a cable system.
Open Issues	• Methods to interpret results for hybrid systems need to be established. • Initial analysis indicates tan δ measurements may detect corroded neutral problems, but further exploration is needed to establish the relationship between Tan δ and degree of corrosion. • How different applied VLF voltage frequencies affect the measured loss criteria is not yet determined. • How temperature affects loss measurements, especially for high loss cables, needs further exploration. • Voltage exposure (impact of voltage on cable system) caused by 60 Hz ac and VLF has not been established. • Effect of single or isolated long water trees on Tan δ measurements. • Usefulness of commissioning tests for comparison with future tests.
Disadvantages	• Cannot locate discrete defects. • Cable system must be taken out of service for testing. • By itself is not an effective test for commissioning newly installed cable systems.

The application of high voltages (voltages above the normal system operating voltage) for a long period (defined by either cycles or time) may cause some level of further degradation of an aged cable system (see more detailed discussion in Section 2.0). The impact of this effect should be considered for all offline elevated voltage applications, including those that involve dielectric loss measurements. The precise degree of degradation depends upon the cable type, voltage magnitude, frequency, and time of application. Thus, when undertaking dielectric loss measurements, a utility should consider that a system can fail during the test and they may want to consider having a repair crew on standby. The subsequent section on expected outcomes provides some guidance on the likelihood of failure on test.

To enhance the effectiveness of a Tan δ test in assessing cable degradation, the dielectric loss should be periodically observed, preferably over a period of several years. In general, an increase in the Tan δ in comparison to previously measured values indicates additional degradation has occurred [1-8].

Dielectric loss is also measureable as a function of frequency. This approach, Frequency Dielectric Spectroscopy (FDS), is more commonly employed in the laboratory then the field and so is beyond the scope of this chapter.

Some accessories specifically employ stress relief materials with non-linear loss characteristics (dielectric loss changes nonlinearly as a function of voltage). Some researchers have suggested that these materials might have an influence on the measured loss values. However, the evidence available indicates that the type of stress relief may have a smaller effect on the overall loss measurement for the system than losses associated with severely degraded or improperly installed accessories.

Generally speaking, the best practice is to perform periodic testing at the same voltage level(s) using the same voltage frequency and waveshape over a period of several years so that a general trend in Tan δ over time can be established.

6.4 Success Criteria

The success criteria presented here corresponds to the approach outlined in the recent update of the IEEE Std. 400.2 – 2013 [9], which was the result of important research contributions from *CDFI Phase I*. In this new standard, Tan δ results appear in terms of three specific diagnostic features. The features in order of importance are:

- **Tan δ Stability** – This feature represents time dependency and is normally reported as the standard deviation (STD) of sequential measurements at U_0. However, the inter-quartile range (span of the middle 50% of the data) may also be used.

- **Differential Tan δ (Tip Up)** – This feature represents voltage dependency and is normally reported as the simple algebraic difference between the means of a number of sequential measurements taken at two different voltages (the difference between medians may also be used). In this case the voltage levels are 0.5 U_0 and 1.5 U_0.

- **Tan δ** Magnitude – This feature represents the level of loss and is normally reported as the mean of a number of sequential measurements (the median of these measurements may also be used) at U_0.

Figure 2 shows examples of measured Tan δ data and diagnostic features from a polyethylene (PE) insulated cable system in service that illustrate graphically the features defined above. The diagnostic features for other insulation systems are the same, though their magnitudes may be different.

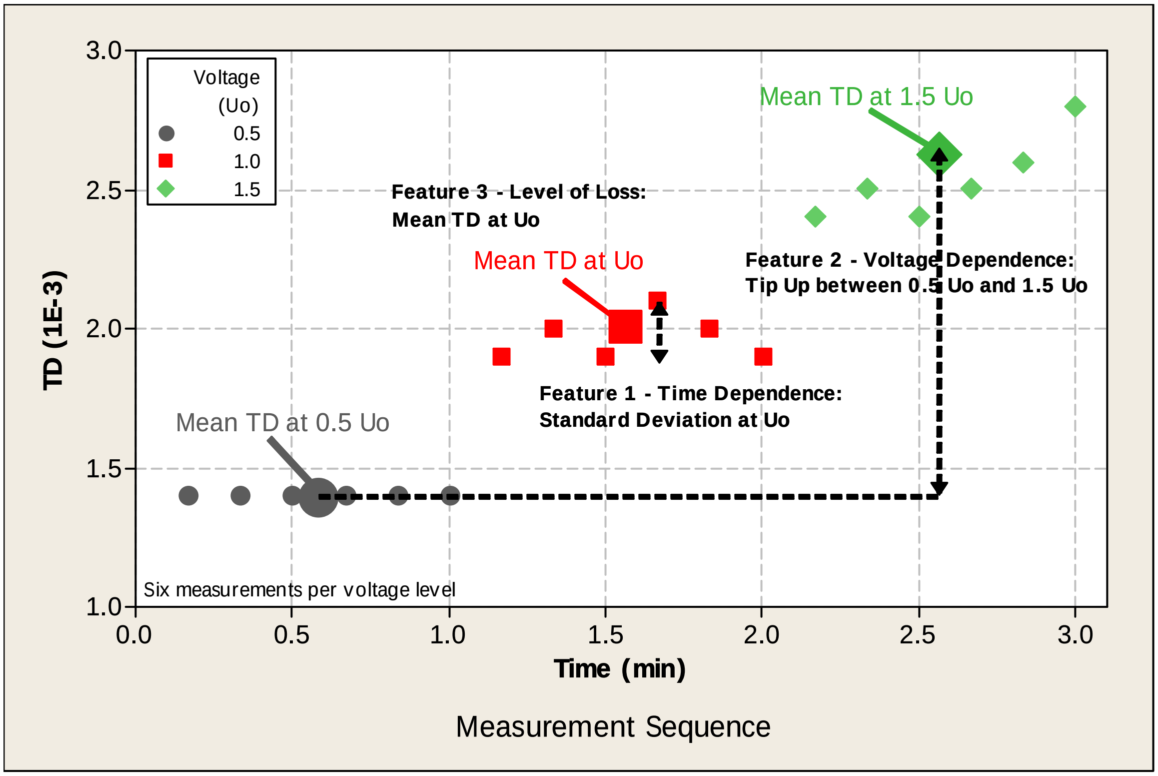


Figure 2: Example of Measured Tan δ data from a PE Cable System in Service and Tan δ Diagnostic Features

The Tan δ measurement results are often interpreted using rules such as those in Table 3 to Table 6 where test values fall into three classes: "No Action," "Further Study Advised," and "Action Required." However, the basic measured data are usually reported, which is valuable as it makes it possible to:

- Reinterpret the data when/if new assessment knowledge becomes available,
- Track trends, and
- Compare with adjacent cable lengths.

Establishing the success criteria for dielectric loss measurements is complicated in that the values depend not only on the cable system quality and degradation/aging, but also on the cable and accessory technologies employed on the tested cable system. More importantly, it must be understood that, for different insulations, installations, and cable types, the STD, Tip Up, and Tan δ figures of merit can vary significantly from each other. Therefore, the Tan δ diagnostic features work best when comparing present measurements against established historical figures of merit for a particular cable system type as a whole (i.e. the cable +terminations+ joints). Table 4 through Table 8 show historical figures of merit derived from the research effort (note that some of these data were provided by the project participants) that may be used for condition assessment for aged PE-based (i.e. PE, XLPE, TRXLPE cables), aged filled insulations (i.e. EPR and Vulkene$^{®}$ cables), and aged oil impregnated paper (i.e. PILC cables) respectively. In Table 4 to Table 6, U_0 is the cable phase to ground operating voltage. The values given in Table 4 to Table 8 can also be given in percentages, in which case the values are multiplied by 100, for example, 0.1E-3 becomes 0.01 %. Finally, the columns in Table 4 to Table 8 are listed in the order of importance of the diagnostic features to insulation deterioration, i.e., the time dependence is the most important followed by the voltage dependence followed by absolute value of the level of loss.

Table 3: Pass and Not Pass Indications for Tan δ Measurements

Test Type	Cable System	Pass Indication	Not Pass Indication
0.1 Hz	XLPE	See Table 4 to Table 8 for IEEE Std. 400.2 – 2013 Criteria See *CDFI* Perspective Section for 2013 *CDFI* Criteria Utility specific criteria may be developed using the same principles used for IEEE Std. 400.2 – 2013 and the *CDFI* Perspective	
	HMWPE WTRXLPE		
	EPR		
	PILC		
>0.1Hz, <60 Hz	XLPE	Data is limited, so there is no unified criteria	
	HMWPE WTRXLPE		
	EPR		
	PILC		
60 Hz	XLPE		
	HMWPE WTRXLPE		
	EPR		
	PILC		

Table 4: Figures of Merit Based on CDFI Research (2010) for 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 @ Uo (E-3)		Tip Up (E-3)		Tan δ @ Uo (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

Table 5: Figures of Merit Based on CDFI Research (2010) for Condition Assessment of Service-aged Filled Insulations using Tan δ at 0.1 Hz

Condition Assessment	Filled Insulation System	STD @ Uo (E-3)		Tip Up (E-3)		Tan δ @ Uo (E-3)
No Action Required	*** If it is not possible to definitively identify a Filled Insulation**	**<0.1**	**and**	**<5**	**and**	**<35**
	Carbon-filled (Black) EPR	<0.1		<2		<20
	Mineral-filled (Pink) EPR	<0.1		<4		<20
	** Discharge resistant EPR	<0.1		<6		<100
	** Mineral-filled XLPE	-		-		<100
Further Study Advised	*** If it is not possible to definitively identify a Filled Insulation**	**0.1 to 1.3**	**or**	**5 to 100**	**or**	**35 to 120**
	Carbon-filled (Black) EPR	0.1 to 2.7		2 to 120		20 to 100
	Mineral-filled (Pink) EPR	0.1 to 1		4 to 120		20 to 100
	** Discharge resistant EPR	0.1 to 1		6 to 10		100 to 350
	** Mineral-filled XLPE	-		-		100 to 350
Action Required	*** If it is not possible to definitively identify a Filled Insulation**	**>1.3**	**or**	**>100**	**or**	**>120**
	Carbon-filled (Black) EPR	>2.7		>120		>100
	Mineral-filled (Pink) EPR	>1		>120		>100
	** Discharge resistant EPR	>1		>10		>350
	** Mineral-filled XLPE	-		-		>350

* Experience has shown that it is quite difficult to precisely identify the type of filled insulation used for field-installed cable. The issues encountered include: incorrect or missing records, missing or obscured markings on the cable jacket, indistinct coloring, etc. In these cases it is recommended to use the criteria for the collated datasets.

** Insufficient data have been collected to make precise estimates of criteria; consequently, the criteria are likely to contain considerable errors. However, they are included here to provide some guidance to engineers encountering these insulation systems in the field.

Table 6: Figures of Merit Based on CDFI Research for Condition Assessment of Service-aged Paper Insulated (PILC) using Tan δ at 0.1 Hz

Condition Assessment	STD @ Uo (E-3)		Tip Up (E-3)		Tan δ @ Uo (E-3)
No Action Required	<0.1	and	-35 to 10	and	<85
Further Study Advised	0.1 to 0.4	or	-35 to -50 or 10 to 100	or	85 to 200
Action Required	>0.4		<-50 or >100		>200

Annex G of IEEE Std. 400.2 – 2013 also provides guidance for interpreting Tan δ results of new power cable systems. The criteria appear in Table 7 and Table 8. However, the standard also points out that the data available (2010) from VLF diagnostic tests on the different types of newly installed power cable systems are limited; thus, the values given in Table 7 and Table 8 may change as additional data are accumulated. Therefore, at this time the values must be considered as provisional criteria and they may be used as guidelines for engineering information only. A well thought out condition assessment of newly installed power cable systems involves the deployment of additional diagnostic tests.

Table 7: Criteria Based on CDFI Research for Assessment of Newly Installed Power Cable Systems with PE-based Insulations (XLPE and TRXLPE)*

Condition Assessment	STD @ Uo (E-3)		Tip Up (E-3)		Tan δ @ Uo (E-3)
Acceptable	<0.1	and	<0.8	and	<1.0
Further Study Advised	>0.1	or	>0.8	or	>1.0

* Provisional criteria due to sparse data; thus they may be used for engineering information only

Table 8: Criteria Based on CDFI Research for Assessment of Newly Installed Conventional Mineral-filled EPR Cable Systems*

Condition Assessment	STD@ Uo (E-3)		Tip Up (E-3)		Tan δ@ Uo (E-3)
Acceptable	<0.1	and	<0.8	and	<1.0
Further Study Advised	>0.1	or	>0.8	or	>1.0

* Provisional criteria due to sparse data; thus they may be used for engineering information only

As seen from Table 4 to Table 8, the Tan δ diagnostic includes values that are time dependent (STD at U_0), voltage dependent (Tip Up between 0.5 U_0 and 1.5 U_0), and values that are absolute (Tan δ at U_0). They are used as figures of merit or compared to historical data to grade the condition assessment of the power cable insulation:

- The "**No Action Required**" condition assessment means that 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.
- The "**Further Study Advised**" condition assessment means that additional information is needed to make an assessment. The additional information could come from previous system failure history or additional assessment from an additional diagnostic test; for example, a monitored withstand test can be performed after the Tan δ test and the information from the monitored withstand test could be used to enhance the diagnostics leading eventually to a condition assessment of "No Action Required" or "Action Required." In other cases, a partial discharge diagnostic test may be warranted.
- The "**Action Required**" condition assessment means that the cable system has an unusually high set of Tan δ characteristics that may be indicative of poor insulation condition and should be considered for replacement or repair immediately after the test or in the near future. These results may also be used to trigger further testing using additional diagnostic techniques.

The above condition assessment classes are intended to guide the remedial actions, if any, the cable system user should take to return the system to a reliable operating condition. As defined above, systems that are assessed as "**No Action Required**" do not require immediate additional actions. However, if a cable system is assessed as "Further Study Advised" or "Action Required," then additional actions should be undertaken. The timing of the additional action will be a function of the circuit sensitivity and available resources. Naturally, a circuit that falls into the "Action Required" category would likely need more urgent attention than a circuit that falls into the "Further Study Advised" category.

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 measurements,
- Compare with previous tests or results from other phases of the circuit,
- Conduct a VLF withstand test (30 min) according to the voltage levels established by IEEE Std. 400.2 – 2013, or,
- Place on "watch list" and plan a retest in the future (three to five years).

In addition to the first four actions following a "Further Study Advised" condition assessment, actions following an "**Action Required**" condition assessment might also include:

- Conduct a VLF withstand test (60 min) according to the voltage levels established by the

current IEEE Std. 400.2 – 2013 or
- Retest in the near future and observe trends (one to two years).

In addition, if the tested circuit exhibits Tip Up or Tan δ stability values that are outside the limits provided in Table 4 to Table 8, there may be a section of severely damaged/degraded cable or accessory insulation. Similarly, if there is a significant increase in the Tan δ level during the test with increasing voltage from 0.5 U_0 to U_0, there may not be a need to raise the voltage to test at 1.5 U_0, as the significant increase is an indication that the cable system is highly degraded and there is a risk of initiating electrical trees in the severely damaged insulation that could degrade it further or cause it to fail during the test. In this case, the cable system condition should be assessed as “Action Required”.

The figures of merit presented in Table 4 to Table 8 have been 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 from North America. To determine the threshold level between classes, the tables use the probability criteria of the 80 %. This was selected based on the 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. The figures of merit are constructed so that they may be used with the basic insulation system information available to test engineers at the time of the field investigation. More details of how the figures of merit are derived are given later in the section that provides *CDFI Phase I* and *Phase II* perspectives.

There are some circumstances where the precise cable design (e.g., shielded or belted paper insulated cables and conducting or non-conducting insulation shields on some types of filled insulation cables) or system composition or insulation material or vintage is known. In these cases, the figures of merit are useful guides. However, a utility can develop its own “cable system specific” criteria to provide better discrimination using the approach described above. These nuances are not included in these tables because only a small number of installations were precisely identified to enable the discrimination. As an example, several formulations of EPR (the mineral-filled class) have been used; however the formulations that may be definitively identified represent only 2% of all filled insulation data.

6.5 Estimated Accuracy

CDFI Phase I explored, developed, and completed success criteria that the IEEE Std. 400.2 – 2013 Working Group considered and have included in the update of the standard. As a reminder, according to the IEEE Std. 400 – 2001, the success criteria for the Tan δ diagnostic measurements at VLF of 0.1 Hz are:

- **Pass** – Tan δ value at 2 U_0 of less than 1.2E-3 and a Tip Up (difference in Tan δ between $2U_0$ and U_0) of less than 0.6E-3 and,
- **Not Pass** – Tan δ value at 2 U_0 of more than 1.2E-3 and a tip up (difference in Tan δ between $2U_0$ and U_0) of more than 0.6 E-3.

Subsequently, Table 9 was generated, which shows the resulting estimated accuracies based on IEEE Std. 400 – 2001 using Pass/Not Pass criteria. In this case, accuracy is defined as the percentage of the time that the diagnostic correctly predicted the performance of the tested cable system segment over the evaluation horizon (1-3 years after the test was performed). Pass accuracy is the percentage of the time that the test results indicated the segment was good and the segment did not fail over the evaluation horizon. Table 9 shows that pass accuracy is quite high. Not pass accuracy is the percentage of the time that the test results indicated the segment was not good and the segment did fail over the evaluation horizon. Table 9 shows that not pass accuracy is much lower than the pass accuracy. Fortunately, far more circuits fall into the pass category than the not pass category.

Table 9: Summary of Tan δ Accuracies
(Pass and Not Pass Criteria are based on IEEE Std. 400 – 2001 Criteria)

Accuracy Type		**Tan δ**	
		Raw	**Length Adjusted**
Overall Accuracy (%)	Upper Quartile	74.8	59
	Median	60.0	59
	Lower Quartile	45.8	59
	Number of Datasets	8	8
	Length (miles)	136	136
Pass Accuracy (%)	Upper Quartile	100	98.7
	Median	100	98.7
	Lower Quartile	92.0	98.7
	Number of Datasets	7	7
	Length (miles)	134	134
Not Pass Accuracy (%)	Upper Quartile	53.5	9.8
	Median	7.9	9.8
	Lower Quartile	0.1	9.8
	Number of Datasets	8	8
	Length (miles)	136	136
Time Span (years)		2000 – 2008	
Cable Systems		XLPE, WTRXLPE, PAPER, HMWPE	

6.6 *CDFI* Perspective

Participating utilities provided several extensive Tan δ datasets for both phases of the *CDFI*. Because the data provided was numerical and represented a physical property measurement, it lent itself to extensive analysis and processing. Although a significant amount of discussion and analysis was performed on Tan δ data in this project, the *CDFI* does not endorse this (or any other) diagnostic. The significant focus on this technique is a natural consequence of having large volumes of analyzable numeric data from utilities willing to make it available for use in this project.

Dielectric Loss data are numerical values that make field analysis and real-time decision making possible. This has contributed to the volume of work performed in the *CDFI*. Dielectric Loss measurements are a transparent diagnostic in that the raw data are available to the user. These data are numeric and can easily be compared to critical values for decision-making. They may also then be re-analyzed should the critical values change. This allows for the accumulation of large amounts of data since the testing method and the values it produces do not change. Only the critical values change, so there is little need to conduct additional pilot programs to verify the impact of these changes since the relevant data are already available.

6.6.1 Changes in Perspective From *Phase I* To *Phase II*

The *CDFI Phase II* has allowed further study of the application of Tan δ as a diagnostic tool for cable systems. While the contributions made during *Phase I* were extremely important, the contributions of *Phase II* have proved to be equally important. Both phases of the project have influenced the way this technology is deployed in the field and induced utilities to deploy condition-based maintenance programs. The project also showed the dielectric loss measurement technique can be applied to HV power cable systems and has led Tan δ equipment manufacturers to develop smaller, easier to use diagnostic test units.

Phase I of the *CDFI* showed how a significant amount of data may be collated to garner data driven assessment criteria for power cable systems. Specifically in the case of VLF Tan δ, data classified using a single set of percentiles has enabled a consistent and relatable set of performance criteria to be established. To put this in perspective, Table 10 shows the evolution of Tan δ criteria for condition assessment of cable systems.

Table 10. Evolution of VLF Tan δ Criteria for Condition Assessment

Year	Assessment Hierarchy	Criteria & Issues	Comments
< 2001	Tan δ	None	-
2001 – 2004	Tan δ Tip Up ($2U_0$ & U_0)	PE criteria only included in IEEE Std. 400^{TM} – 2001	IEEE Std. 400 – 2001 release No technical basis Not based on data
2004	***CDFI Phase I***		
2007	Tan δ Stability (U_0) Tip Up ($1.5U_0$ & $0.5U_0$) Mean Tan δ (U_0)	Qualitative	Contribution of *CDFI Phase I* research – based on statistical analysis of data from North American cables and first *CDFI* Tan δ Brochure
2008 – 2010		• Criteria based on data. • Included in update of IEEE Std. 400.2 – 2013.	
2011	***CDFI Phase II***		
2011	Tan δ Stability (U_0) Tip Up ($1.5U_0$ & $0.5U_0$) Mean Tan δ (U_0) Tip Up of the Tip Up (TuTu)	• Criteria based on data. • PCA* analysis. • Combined diagnostic features added. • HV Subprotocol established.	Contribution of *CDFI Phase II* research – based on statistical analysis of data from North American cables and update of *CDFI* Tan δ Brochure
2013	Tan δ Stability (U_0) Tip Up ($1.5U_0$ & $0.5U_0$) Mean Tan δ (U_0) Tip Up of the Tip Up (TuTu)	• Verification of Tan δ diagnostic features. • Value of adding data. • Tan δ and Injection. • Tan δ mode analysis. • Principle for making feeder assessment.	Contribution of *CDFI Phase II* research – based on statistical analysis of data from North American cables and continuing update of *CDFI* Tan δ Brochure IEEE Std. 400.2 – 2013 release

*Principal Component Analysis

As Table 10 shows, Tan δ criteria for power cable systems have evolved considerably over the last 12 years. The contribution of the *CDFI* research has been significant not only in the evolution of the diagnosis criteria, but also how to approach real scenarios in the field. The number of diagnostic features has increased and the condition assessment is now made considering a combined "Health Index", which will be discussed in later sections. The analyses have been formatted such that they may be readily used in the field to provide real-time guidance on the appropriate decisions that a user might take to proactively manage their cable system assets.

Other contributions of the *CDFI Phase II* research include:

- Update on reporting and interpretation of VLF Tan δ measurements as a diagnostic tool for condition assessment of power cable systems including a new diagnostic feature that takes into account the non-linear voltage dependence.
- The nature and importance of the Tan δ diagnostic features have been verified.
- The Tan δ database has increased in size including measurements from many different types of power cable systems.
- The VLF Tan δ features have been combined using advanced data analysis tools to provide a single condition assessment metric that defines a "Health Index" for the power cable system.
- The value of correctly acquiring new data and thus increasing the size of the Tan δ database has been demonstrated.
- The uncertainty of the diagnostic threshold levels has been presented and understood.
- A protocol for condition assessment using VLF Tan δ for HV has been proposed and verified through field test measurements.
- The changes in the condition assessment classes over time have been analyzed and presented.
- A method for analyzing power cable systems at the feeder level has been proposed.
- Indication of the effect of cable rejuvenation (injection) on Tan δ measurements and power cable systems has been analyzed and demonstrated.
- The application of VLF Tan δ as a tool for assessing the condition of hybrid power cable systems is introduced.
- Comparisons between the development of local and global criteria have been discussed.

The following sections provide the detail behind these contributions.

6.6.2 Measurement Approaches

There is one primary means of measuring dielectric loss: Constant ac (VLF or 60 Hz). This approach includes 60 Hz ac, VLF ac – sinusoidal, and VLF ac – cosine-rectangular voltage sources. They both measure capacitive and resistive currents to determine the system dielectric loss. The 60 Hz ac and VLF ac– sinusoidal approaches use relatively conventional measurement algorithms.

In all cases, the result is a numeric value. The excitation voltage may be varied in either approach so a differential Tan δ or Tip Up may be determined. In addition, the change in Tan δ with time may be monitored, quantified, and analyzed to obtain further information about the cable system. The reporting of numeric data and consistent measurement processes makes comparison between approaches and re-assessments straightforward.

Most of the data reported within the *CDFI* has come from the VLF ac – sinusoidal approach.

6.6.3 Reporting and Interpretation

The success criteria presented in this section represent the latest data analysis performed during *Phase 2* of the *CDFI*. It is an expansion of the criteria presented previously in that it considers an additional diagnostic feature identified by the research (the Tip Up of the Tip Up or TuTu). The Tan δ diagnostic features considered here are listed in order of importance as follows:

- **Tan δ Stability** – This feature represents the time dependence and is normally reported as the standard deviation (STD) of sequential measurements at U_0. However, the interquartile range (span of the middle 50% of the data) may also be used.
- **Differential Tan δ or Tip Up** – This feature represents the voltage dependence and is normally reported as the simple algebraic difference between the means of a number of sequential measurements taken at two different voltages (the difference between medians may also be used), in this case the voltage levels are 0.5 U_0 and 1.5 U_0.
- **Tip Up of the Tip Up (TuTu)** – This feature represents the nonlinear voltage dependence and it is reported as the algebraic difference between two Tip Ups: the Tip Up between 1.5 U_0 and U_0 and the Tip Up between U_0 and 0.5 U_0.
- **Tan δ Magnitude** – This feature represents the level of dielectric loss and is normally reported as the mean of a number of sequential measurements (the median of these measurements may also be used) at U_0.

Figure 3 shows examples of measured Tan δ data and diagnostic features from a PE cable system in service for illustration of the new feature. The diagnostic features for other insulation systems are the same as those described in Figure 3.

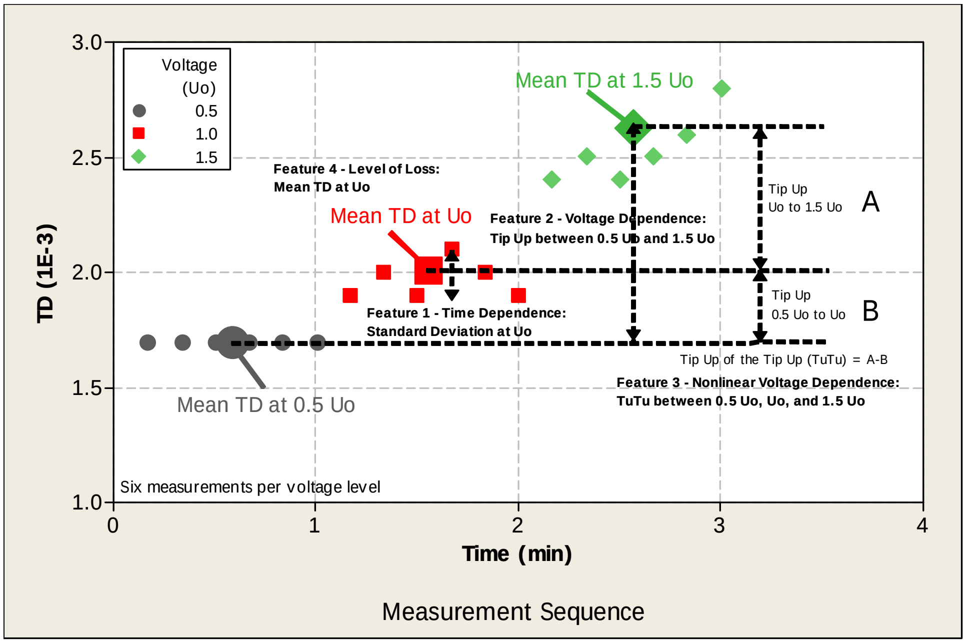


Figure 3: Example of Measured Tan δ data from a PE Cable System in Service and Tan δ Diagnostic Features for the *CDFI Phase II* Perspective

To aid in understanding the meaning of the TuTu, Table 11 shows the guidelines for characterizing this voltage dependent diagnostic feature. Table 11 presents three cases. The first case considers linear voltage dependence. In this case, the value for the TuTu is zero since the change in Tan δ values between testing voltages are the same (see systems A and B in Figure 3). In the second (nonlinear, convex) case, the TuTu is always positive and indicates that changes on the insulation losses increase more dramatically as the test voltage increases. Lastly, the third nonlinear (concave) case exhibits a TuTu that is always negative indicating that changes in insulation losses decrease as the test voltage increases. The changes in the TuTu for the different insulation types are discussed later in this Chapter.

Table 11: Guidelines for Interpretation of Voltage Dependence Feature (TuTu)

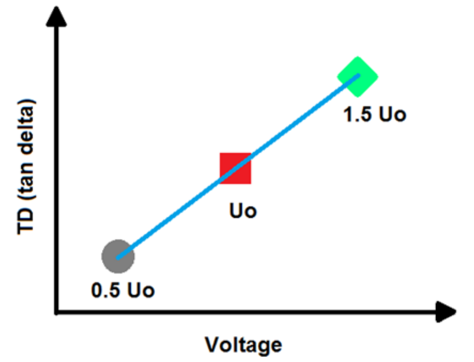
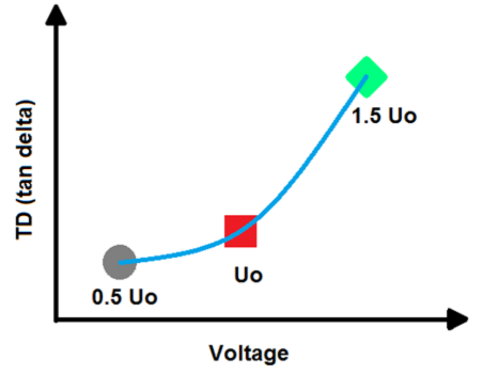
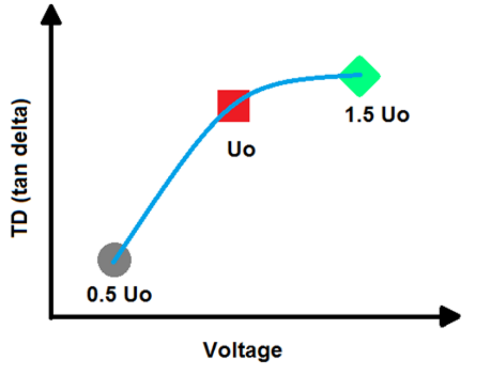
Voltage Dependence	Illustration of Tan δ vs. Voltage	TuTu Sign	Implications
Linear		0	Tip Up (U_0 and $0.5\ U_0$) = Tip Up ($1.5\ U_0$ and U_0)
Nonlinear Convex Unusual PD or non-linear		+	Tip Up (U_0 and $0.5\ U_0$) $<$ Tip Up ($1.5\ U_0$ and U_0)
Nonlinear Concave Time Issue – drying out		-	Tip Up (U_0 and $0.5\ U_0$) $>$ Tip Up ($1.5\ U_0$ and U_0)

Figure 4 shows a majority of the Dielectric Loss data collected in the *CDFI* in a box and whisker format. This excludes the data from the Monitored Withstand technique that is covered in Chapter 10. Figure 4 also includes the four Tan δ diagnostic features for all cable insulation types tested; filled, paper, and PE.

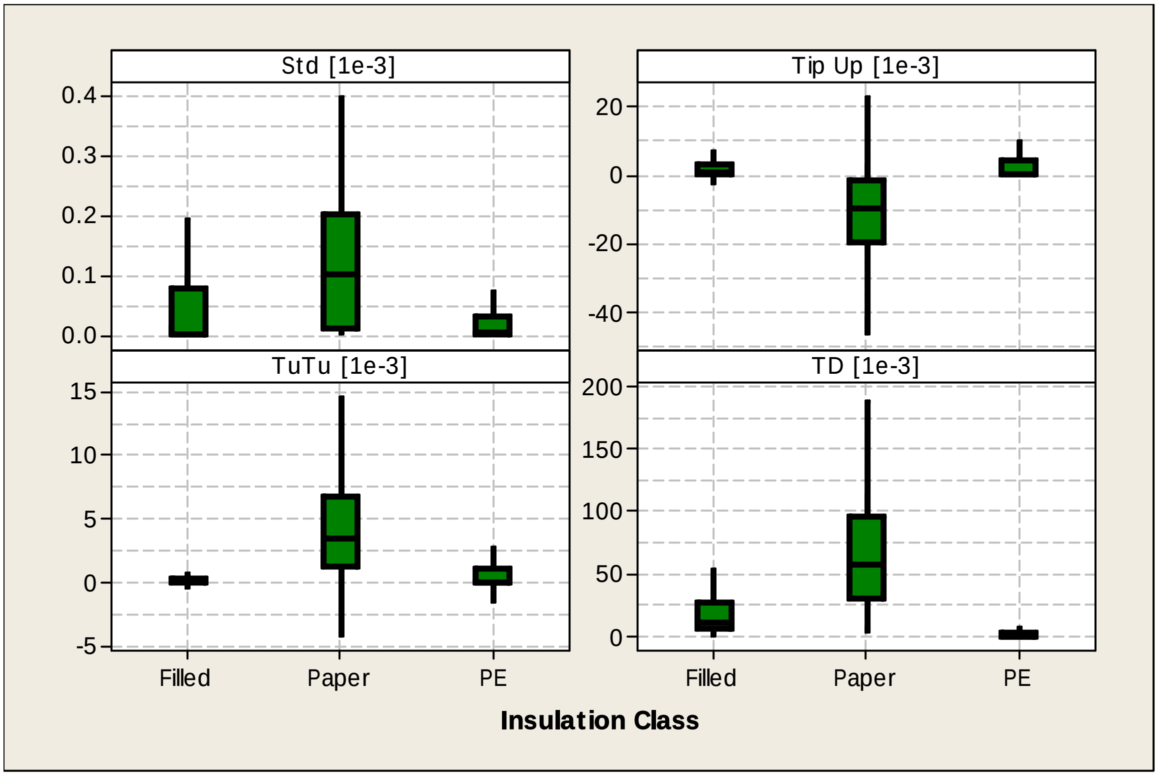


Figure 4: Dielectric Loss Feature Data segmented for Insulation Class

The data in Figure 4 represent more than 3,500 cable segments with a mean length of approximately 1,000 ft. The total length for this population exceeds 770 conductor miles. The horizontal lines within the boxes represent the median and the box itself the inter-quartile range between the first and third quartiles.

6.6.4 Establishing Critical Levels With Multiple Features

In the past, engineers have tried to find "perfect" criteria that absolutely separate the Tan δ values of components that go on to fail from those that do not. Naturally, it is not possible for a diagnostic to be that accurate. Even to approach this goal requires a significant amount of service data on Tan δ and failures, which are difficult to acquire. This is especially true for dielectric loss data that are typically collected by utilities. An alternative approach developed from the research in the *CDFI* identifies critical dielectric feature levels that separate "usual" from "unusual" data. This is the classic Shewart or control chart approach, which uses the mean and standard deviation as a metric to define a "normal" value. In the simplest form, data are unusual if either:

a) One value lies more than three standard deviations from the mean or
b) Two sequential values are more than two standard deviations from the mean.

This approach is useful, but it does not take full advantage of the information available in Tan δ data. As an alternative to this approach, NEETRAC developed a database for Dielectric Loss data based on NEETRAC field tests and augmented it with data provided by participating *CDFI* utilities (AEP, Duke Energy, Intermountain REA, National Grid, and PG&E). As a result, knowledge rules for Tan δ could be further refined. The following sections describe the current database and its use in determining Tan δ critical diagnostic levels. This work relies on a hierarchy for Dielectric Loss features:

- First Tier – Stability
- Second Tier – Tip Up or Differential Tan δ
- Third Tier –Tip Up of the Tip Up or TuTu
- Fourth Tier –Tan δ

The database covers at least 22 discrete test areas and more than 3,500 data entries. The number of data with the associated system lengths and the percentage of data as a function of system lengths appear in Figure 5 and Figure 6, respectively. The term "Filled" refers to all cables with EPR or Vulkene® insulation, "Paper" refers to PILC cables, and "PE" refers to all cable with polyethylene based insulations, including HMWPE, XLPE, and WTRXLPE insulations.

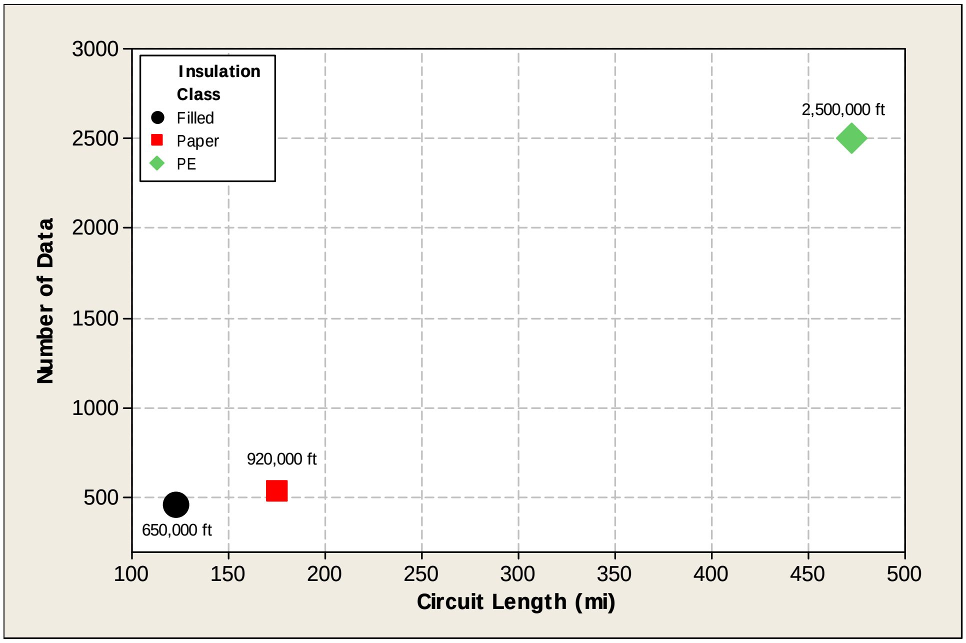


Figure 5: Tan δ Data and Corresponding Circuit Length (4.1 Million Feet)

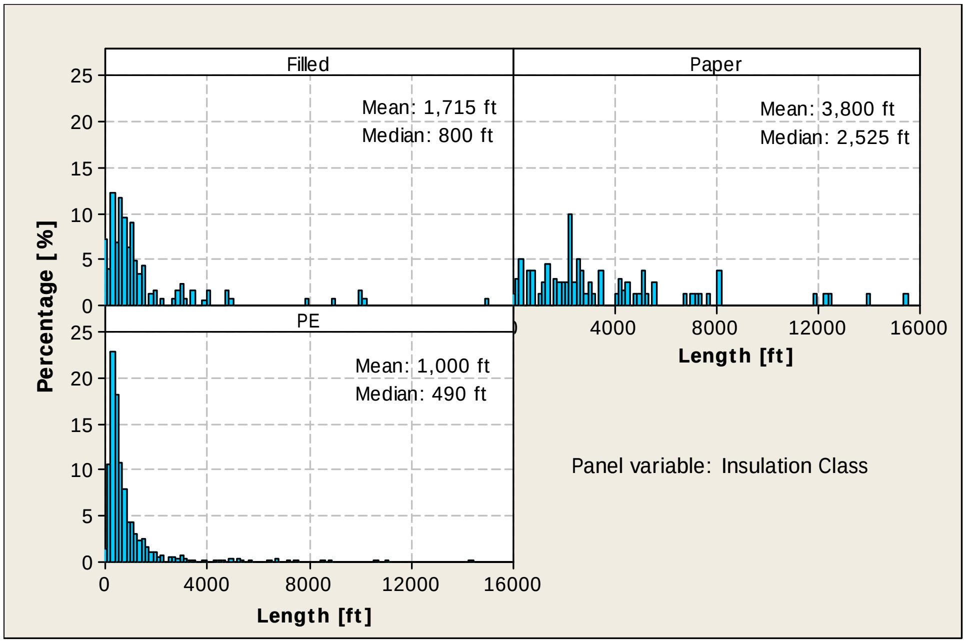


Figure 6: Histograms of Tested Lengths by Insulation Type

To determine Tan δ critical diagnostic levels, the Pareto Principle discussed earlier is applied to set two critical levels at the 80th and 95th percentiles of the data. The choice of the 80th percentile comes from the principle that says that 80% of the problems come from the worst 20% of the population. In contrast, the choice of the 95th percentile relies on the fact that any data point above this level is considered to be highly "unusual." The power of this approach is that it utilizes the whole dataset (cable systems that perform well and those that do not). Thus, it is self-updating as more data becomes available. However, as the decision points are made at the upper percentiles, updating can cause what appear as large changes in values. This is due to the shallow nature of the curves in the upper reaches that produce large changes in value for small changes in percentile.

Figure 7 shows the distribution of Tan δ stability measurements at U_0 for each insulation class (PE, Filled, and Paper). Stability, in this case, is assessed by the standard deviation of the data.

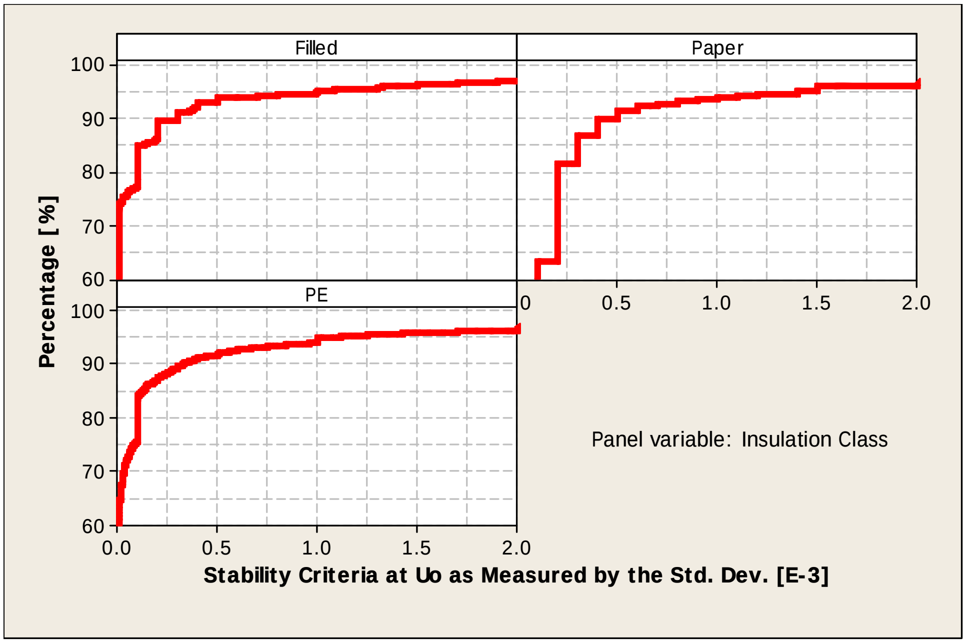


Figure 7: Cumulative Distribution of all Cable System Stability Values at U_0 Collated as Part of *CDFI* Research

Figure 8 and Figure 9 show the distributions of Tip Up data for different ranges of Tip Up where Tip Up is the difference in Tan δ measured at $1.5U_0$ and $0.5U_0$.

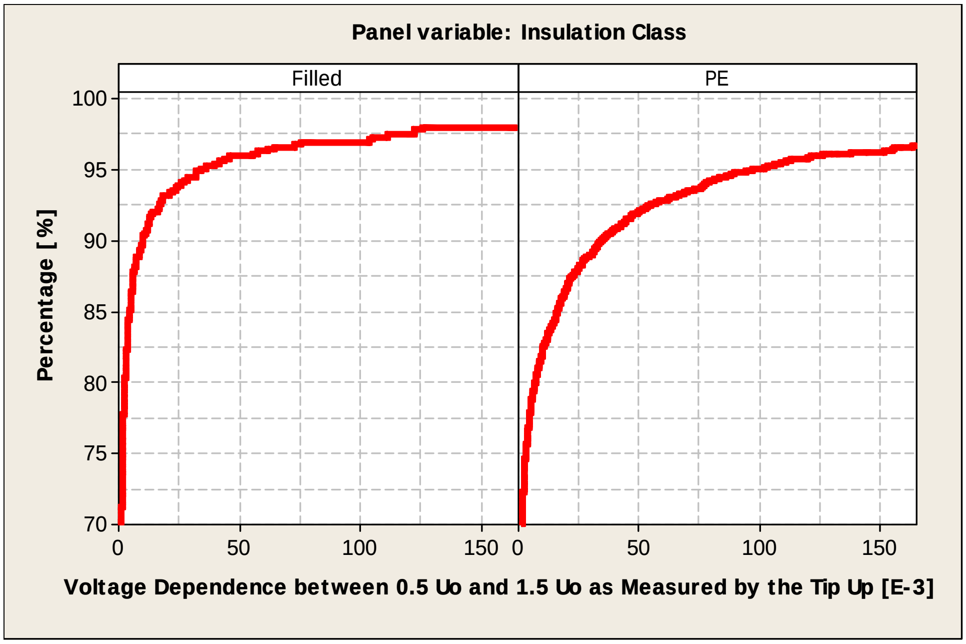


Figure 8: Cumulative Distribution of all Cable System Tip Up Criteria – Filled and PE Collated as Part of *CDFI* Research

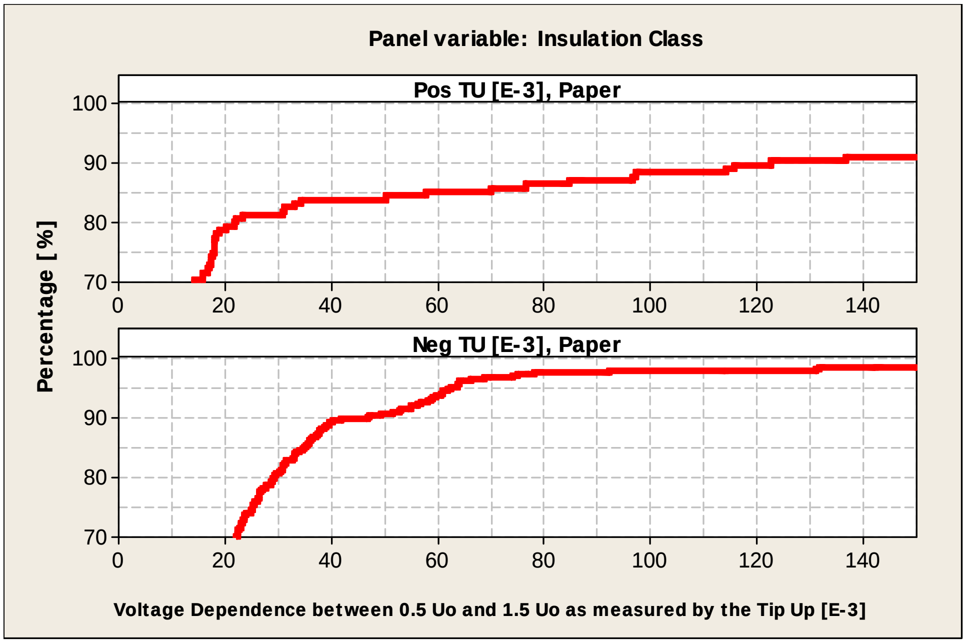


Figure 9: Cumulative Distribution of all Cable System Tip Up Criteria – Paper Collated as Part of *CDFI* Research

Figure 10 shows the cumulative distributions of all the cable system TuTu values.

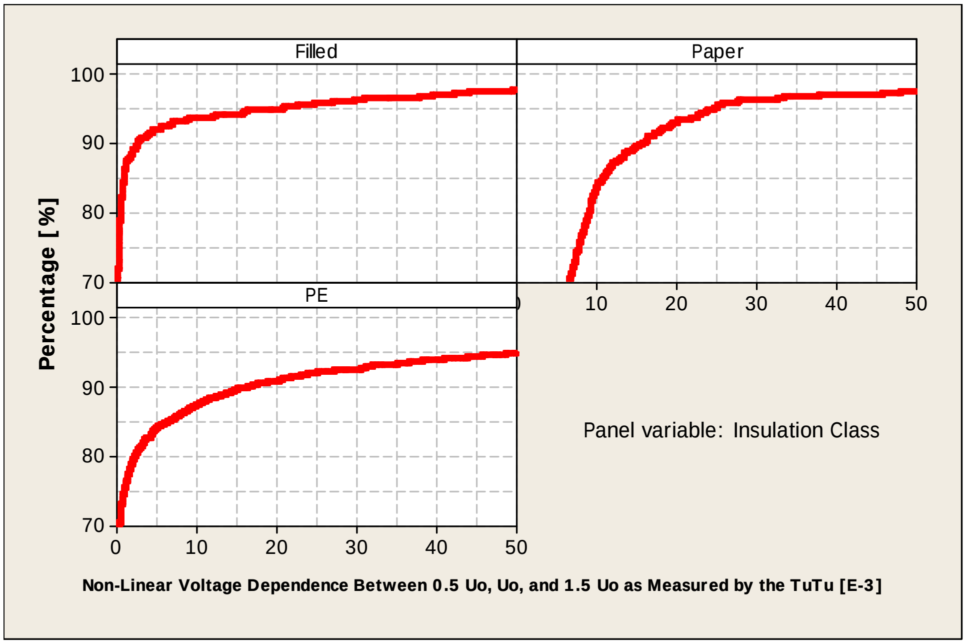


Figure 10: Cumulative distribution of all the Cable System TuTu Collated as Part of *CDFI* Research

Finally, Figure 11 shows the distributions of Tan δ measured at U_0.

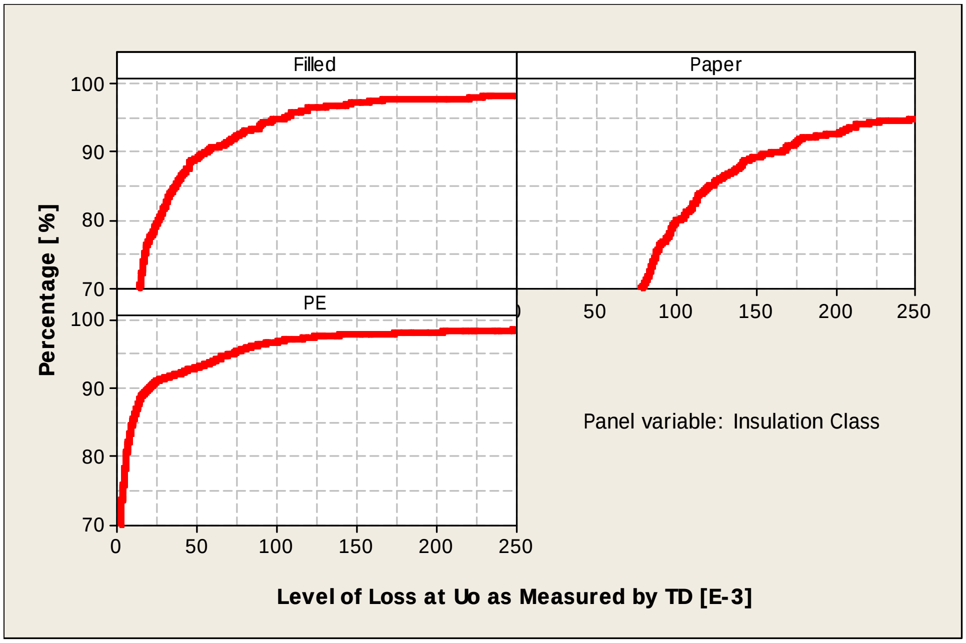


Figure 11: Cumulative distribution of all the Cable System Tan δ at U_0

Taking into account the 80th and 95th percentiles for the Tan δ features presented in Figure 7 through Figure 11, criteria for condition assessment of the different types of insulations were developed. Underlying these criteria is the basic understanding of what values represent good and poor performance, i.e. unstable time data (high standard deviations), large voltage dependences (high tip ups and tip ups of the tip ups), and large losses (high Tan δ values) are all characteristics of a poorly performing cable system. In other words, "good" segments lie to the left and "poor" segments lie to the right of the graphs in Figure 7 to Figure 11. The criteria developed from the research work appear in Table 12 to Table 14. As before, the condition of a cable system is assessed as: "No Action Required", "Further Study Advised", and "Action Required". Each of these assessments is defined by specific percentiles as follows:

- "No Action Required" encompasses the lowest 80% of the data,
- "Further Study Advised" encompasses the next lowest 15% (80% - 95%) of the data, and,
- "Action Required" encompasses the highest 5% (95% -100%) of the data.

These definitions appear graphically in Figure 12.

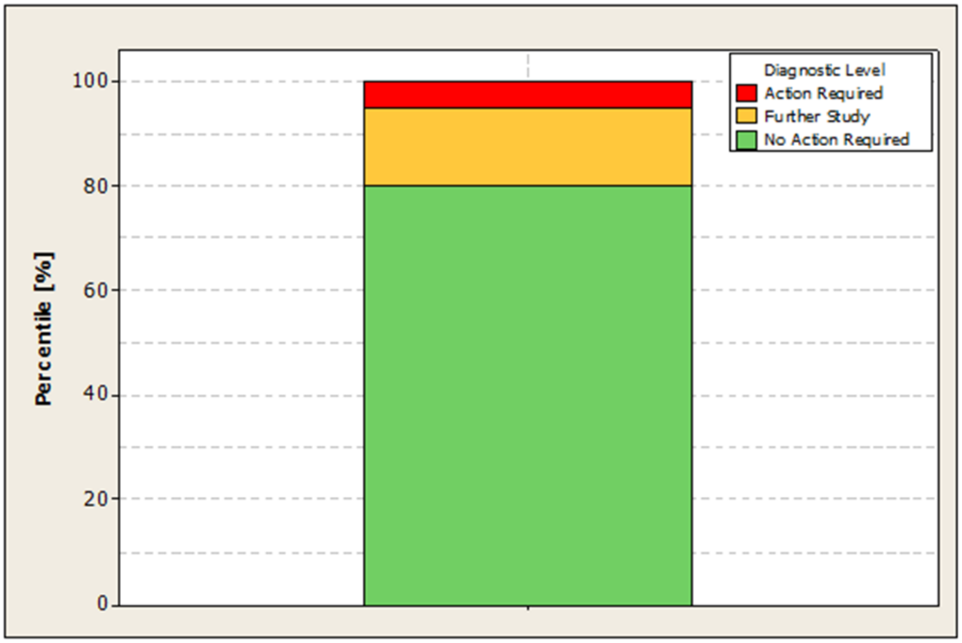


Figure 12: Percentiles Included in Each Diagnostic Level

Table 12 through Table 14 are based on these guidelines. As part of the ongoing dissemination of information from the *CDFI*, NEETRAC has made these tables available to the *CDFI* members. The hierarchy for diagnosis using Tan δ is as follows:

1. Tan δ Stability – stability is assessed by the standard deviation of dielectric loss at U_0 (other approaches are possible)
2. Tip Up – difference in the mean values of Tan δ at selected voltages
3. Tip Up of the Tip Up – difference between Tip Ups
4. Tan δ (mean value at U_0).

The criteria shown in Table 12 through Table 14 (2013) are different from those shown in Table 4 to Table 6 (2010), criteria that correspond with the IEEE Std. 400.2 – 2013, as they were developed with later and more complete datasets. The IEEE Std. 400.2 Working Group plans to include the additional diagnostic feature (TuTu) for the next standard revision.

Table 12: 2013 Criteria Developed from *CDFI* Research Work for Condition Assessment of PE-based Insulations (PE, HMWPE, XLPE, & WTRXLPE)

Condition Assessment [E-3]	**No Action Required**	**Further Study Advised**	**Action Required**
Assessment of PE-based Insulations (i.e. PE, XLPE, WTRXLPE)			
Stability for TD_{U_0} (standard deviation)	<0.1	0.1 to 1.0	>1.0
	&	**or**	
Tip Up ($TD_{1.5U_0} - TD_{0.5U_0}$)	<6.7	6.7 to 94.0	>94.0
	&	**or**	
Tip Up Tip Up $\{(TD_{1.5U_0} - TD_{U_0}) - (TD_{U_0} - TD_{0.5U_0})\}$	<2.0	2.0 to 50.0	>50.0
	&	**or**	
Mean TD at U_0	<6.0	6.0 to 70.0	>70.0

Table 13: 2013 Criteria Developed from *CDFI* Research Work for Condition Assessment of Filled Insulations (EPR & Vulkene®)

Condition Assessment [E-3]	No Action Required	Further Study Advised	Action Required
Assessment of Unidentified Filled Insulations (i.e. EPR, Kerite, & Vulkene®) *			
Stability for TD_{U_0} (standard deviation)	<0.1	0.1 to 1.2	>1.2
	&	or	
Tip Up ($TD_{1.5U_0} - TD_{0.5U_0}$)	<3.0	3.0 to 30.0	>30.0
	&	or	
Tip Up Tip Up $\{(TD_{1.5U_0} - TD_{U_0}) - (TD_{U_0} - TD_{0.5U_0})\}$	<1.0	1.0 to 18.0	>18.0
	&	or	
Mean TD at U_0	<25.0	25.0 to 150.0	>150.0
Condition Assessment of Mineral Filled Insulations (i.e. EPR) *			
Stability for TD_{U_0} (standard deviation)	<0.1	0.1 to 0.8	>0.8
	&	or	
Tip Up ($TD_{1.5U_0} - TD_{0.5U_0}$)	<2.0	2.0 to 40.0	>40.0
	&	or	
Tip Up Tip Up $\{(TD_{1.5U_0} - TD_{U_0}) - (TD_{U_0} - TD_{0.5U_0})\}$	<1.0	1.0 to 25.0	>25.0
	&	or	
Mean TD at U_0	<16.0	16.0 to 75.0	>75.0

* Experience has shown that it is difficult to precisely identify the type of filled insulation of field-installed cable. The issues encountered include: incorrect /missing records, missing or obscured markings on the cable jacket, indistinct coloring, etc. In these cases it is recommended to use the criteria for **Unidentified Filled** data.

Table 14: 2013 Criteria Developed from *CDFI* Research Work for Condition Assessment of Paper Insulations (PILC)

Condition Assessment [E-3]	**No Action Required**	**Further Study Advised**	**Action Required**
Assessment of Paper Insulations (i.e. PILC)			
Stability for TD_{U_0} (standard deviation)	<0.2	0.2 to 1.5	>1.5
	&	or	
Tip Up ($TD_{1.5U_0} – TD_{0.5U_0}$)	-30.0 to 22.0	-30 to -60 or 22 to 220	<-60.0 or >220.0
	&	or	
Tip Up Tip Up $\{(TD_{1.5U_0}–TD_{U_0}) - (TD_{U_0}–TD_{0.5U_0})\}$	<9.0	9.0 to 25.0	>25.0
	&	or	
Mean TD at U_0	<100.0	100.0 to 250.0	>250.0

The above condition assessment classes are intended to guide the remedial actions, if any, that the cable system user should take to return the system to a reliable operating condition. Criteria for a newly installed cable system have not changed and are the same as those presented earlier in Section 5.4.

As defined above, systems that are assessed as “No Action Required” do not require immediate additional actions. However, if a system is assessed as “Further Study Advised” or “Action Required,” then additional immediate actions should be undertaken as follows.

As discussed earlier, actions following a “Further Study Advised” assessment might include a number of factors to consider. They were discussed earlier under Table 8, but are worth repeating here:

- review data for a rogue measurement value – most common in the first voltage cycle
- confirm insulation type to ensure that criteria apply
- clean or re-clean terminations and repeat measurements
- compare with previous tests or other results from other phases of this system if possible
- conduct a VLF withstand test (30 min) according to the voltage levels established by the IEEE Std. 400.2 – 2013
- place on “watch list” and plan a retest in the future (three to five years).

In addition actions following an “Action Required” condition assessment might also include:

- conduct a VLF withstand test (60 min) according to the voltage levels established by the current IEEE Std. 400.2 – 2013
- retest in the near future and observe trends (one to two years)

If there is a significant difference in Tan δ with increasing voltage (Tip Up) or a significant variation of Tan δ with time (STD), there may be a section of severely damaged or degraded insulation in the cable or accessory. Similarly, if there is a significant increase in the Tan δ level during the test with increasing voltage from 0.5 U_0 to U_0, there may not be a need to raise the voltage to test at 1.5 U_0, as the significant increase is an indication that the cable system is highly degraded and thus there is a considerable risk of initiating electrical trees in the severely damaged insulation. In this case, the cable system condition is assessed as "Action Required."

There are some circumstances where the precise cable design (e.g., shielded or belted paper insulated cables and conducting or non-conducting insulation shields on some types of filled insulation cables) or system composition or insulation material or vintage is known. In these cases the figures of merit are useful guides. However, a utility can develop its own "cable system specific" criteria to provide better discrimination, using the approach described above. These nuances are not included in these tables because only a small number of installations are identified with enough precision to make it worthwhile. Furthermore, the differences that have been identified are not statistically significant for the data available. As an example several formulations of EPR (the mineral-filled class) have been used, however the formulations that may be definitively identified represent 2% of the filled data.

The overall condition assessment of the system is defined by the most "serious" condition of any of the dielectric loss features. In other words, if any one criterion indicates the system is "Action Required," then the final assessment is "Action Required" regardless of what the other two criteria indicate. See Table 15 for examples. Prioritizing or differentiating between systems with the same overall assessment requires looking at the remaining two criteria. This scheme is very similar to the level-based systems used for other diagnostic techniques. However, in this case, the knowledge rules (i.e. the critical levels, the level criteria (80 % and 95 %), and the database) are available to the user.

Table 15 shows all possible combinations for establishing the overall condition assessments resulting from several combinations of Stability, Tip Up, and Tan δ assessments made using the above criteria. As Table 15 shows, there is one way to produce a "No Action Required" overall assessment while there are seven and 21 combinations that would produce "Further Study Advised" and "Action Required," respectively. Fortunately, in practice the most common condition assessments are "No Action Required."

Table 15: Overall Assessments for all Stability, Tip Up, TuTu, and Tan δ Combinations
No Action Required = Green, Further Study = Orange, Action Required = Red

Case	Stability	Tip Up	TuTu	Tan δ	Overall Assessment
1	🟩	🟩	🟩	🟩	🟩
2	🟩	🟩	🟧	🟧	🟧
3	🟩	🟩	🟥	🟥	🟥
4	🟩	🟧	🟩	🟧	🟧
5	🟩	🟧	🟧	🟧	🟧
6	🟩	🟧	🟥	🟥	🟥
7	🟩	🟥	🟩	🟥	🟥
8	🟩	🟥	🟧	🟥	🟥
9	🟩	🟥	🟥	🟥	🟥
10	🟧	🟩	🟩	🟧	🟧
11	🟧	🟩	🟧	🟧	🟧
12	🟧	🟩	🟥	🟥	🟥
13	🟧	🟧	🟩	🟧	🟧
14	🟧	🟧	🟧	🟧	🟧
15	🟧	🟧	🟥	🟥	🟥
16	🟧	🟥	🟩	🟥	🟥
17	🟧	🟥	🟧	🟥	🟥
18	🟧	🟥	🟥	🟥	🟥
19	🟥	🟩	🟩	🟥	🟥
20	🟥	🟩	🟧	🟥	🟥
21	🟥	🟩	🟥	🟥	🟥
22	🟥	🟧	🟩	🟥	🟥
23	🟥	🟧	🟧	🟥	🟥
24	🟥	🟧	🟥	🟥	🟥
25	🟥	🟥	🟩	🟥	🟥
26	🟥	🟥	🟧	🟥	🟥
27	🟥	🟥	🟥	🟥	🟥

This approach uses the most severe feature assessment to generate the overall condition assessment. A more sophisticated approach would recognize the extra information held within the 2nd, 3rd, and 4th (tip up tutu and tan δ) features. This is explored later in the Chapter where a Principal Component Analysis (PCA) is used to determine a more precise assessment that considers all four features.

6.6.5 Feature Selection

The methodology described in Section 6.6.4 is applicable to any multi-modal data (i.e. data that cannot be modeled with a single probability distribution). In the case of Tan δ, the available features include Tan δ at different voltages, Differential Tan δ, and Tan δ Stability. Ideally, one would prefer to use as few features as possible to make a condition assessment but then the question becomes: What features to use?

There are a number of ways to approach the problem of feature selection when there are only a few features available. One of the methods adopted by the *CDFI* is Performance Ranking. This method looks at the diagnostic feature's ability to correctly rank a group of tested systems as to their relative performance in service. This work took place in the laboratory and the metric used to evaluate service performance is the breakdown strength. Figure 13 shows the results of the first laboratory assessment of the breakdown strength of 1970's vintage XLPE insulated cables under VLF excitation. As this figure shows, there can be significant differences in the breakdown strength of aged cable systems. Figure 26 shows a field verification of this approach.

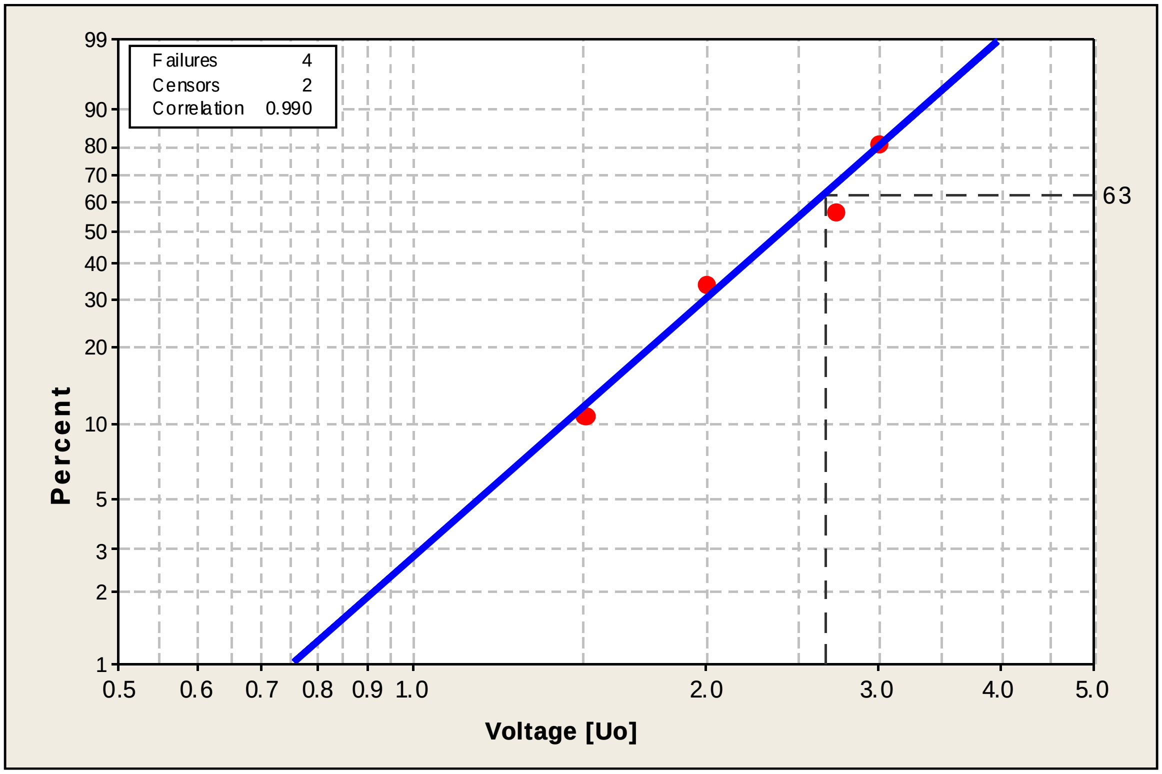


Figure 13: VLF Breakdown Voltage of Highly Aged XLPE Cables in Weibull Format

Prior to determining these breakdown strengths, all three of the dielectric loss features were measured. Thus after failure it was possible to examine which of these pre-mortem features best predicted the final breakdown strength outcome. The Performance Ranking approach involves identifying the best predictor of the breakdown strength using a Performance/Diagnostic Rank correlation plot as shown in Figure 14.

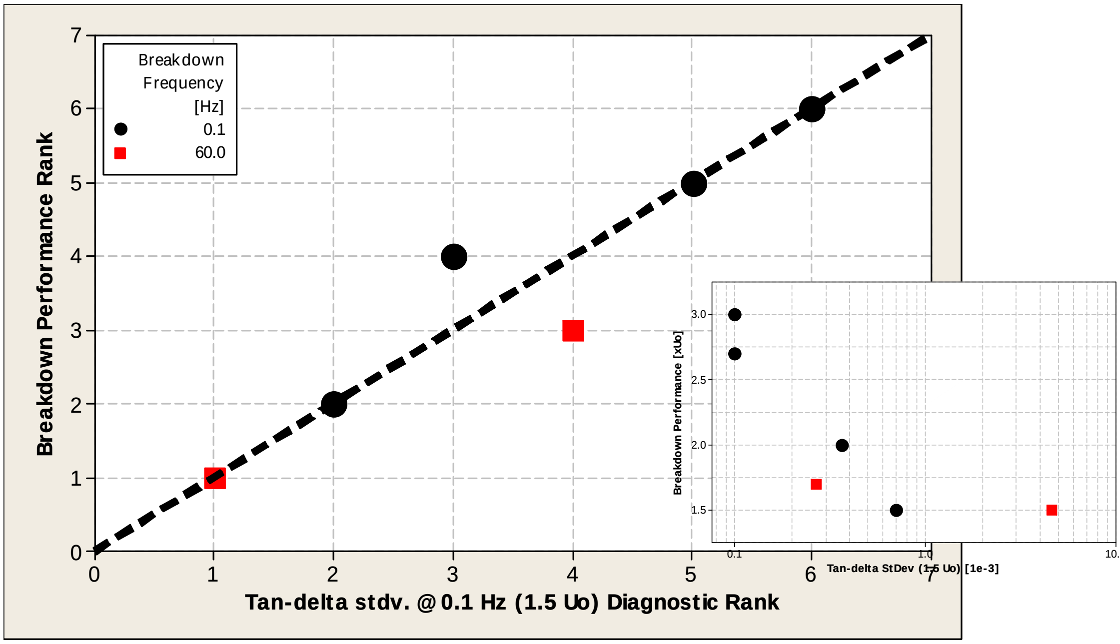


Figure 14: Correlation Between VLF Breakdown with Tan δ Stability (Standard Deviation) at 1.5 U_0 Rankings. Inset is the Data Correlation of VLF Breakdown with Stability (Standard Deviation)

The graphical results in Figure 14 may then be analyzed numerically using the Pearson Correlation Coefficient (Table 16).

Table 16: Performance and Diagnostic Rank Correlations

Tan δ Diagnostic Feature	Correlation Coefficient	*P*-Value
Mean Tan δ (1.5 U_0)	0.771	0.072
Tip Up (1.5 U_0 – 0.5 U_0)	0.771	0.072
Tan δ Stability (1.5 U_0)	0.943	0.005

Table 16 shows that the feature with the highest significance (i.e. 1 – *P*-Value) is Tan δ Stability. This feature quantifies how the measured Tan δ values change throughout the measurement period. The smaller this value, the greater the stability. Since a stable dielectric loss is indicative of a "good" dielectric, it makes sense that this would be a primary indicator of a cable system's condition. Analysis of all the available features indicates that an alternative hierarchy to the traditional Dielectric Loss/Tan δ approach in IEEE Std. 400™ – 2001 may be more appropriate. This hierarchy is as follows:

First Order Feature: Tan δ Stability – paper cables are in general more stable.

Second Order Feature:	Differential Tan δ or Tip Up – paper cables typically have negative tip ups whereas PE cables have positive values.
Third Order Feature:	Dielectric Loss Tan δ – although overlapping the typical levels of loss are different for the insulation systems.

6.6.6 Mitigating the Risk of Failure on Test

In many cases, testing uses voltages that are higher than the operating voltage of the cable system. In these cases, there is a finite risk of failure for the elements under test. When such failures occur, the result is commonly termed a "Failure on Test" (FOT). The risk of FOT decreases by using test voltages close to or below the normal service voltage and by limiting the duration of the test voltage.

Figure 13 above shows the breakdown performance of aged XLPE cables. This analysis shows that the data fits a Weibull probability distribution and confirms that there are no "extra" failure modes for test voltages up to 3 U_0. This enables risk estimates to be made for various test voltages. IEEE Std. 400 – 2001 suggests the use of 2 U_0 for measuring Dielectric Loss and the Tip Up. As can be seen from Figure 13, this voltage has a risk of failure of approximately 30%.

On the other hand, the probability of failure could be reduced by 70% (30% probability down to 10 % probability) if the test voltage was reduced from 2 U_0 to 1.5 U_0. Of course, this is only useful if measurements at lower voltages provide the same level of information as measurements at higher voltages. This effect is studied in Figure 15 and Figure 16 using data correlation plots. The key finding is that both for Tan δ and Tip Up, the values are different at the different voltages. However, the *same rankings* occur. In other words, the lowest value at 2 U_0 is still the lowest value at 1.5 U_0. This shows that the lower (reduced risk) test voltages may be used without any loss in resolution. It is important to note that the criteria established using higher voltages should not be directly used for measurements made at lower voltages, but the correlation curves (the fitted line in Figure 15) provide a means to translate the criteria from one voltage to another.

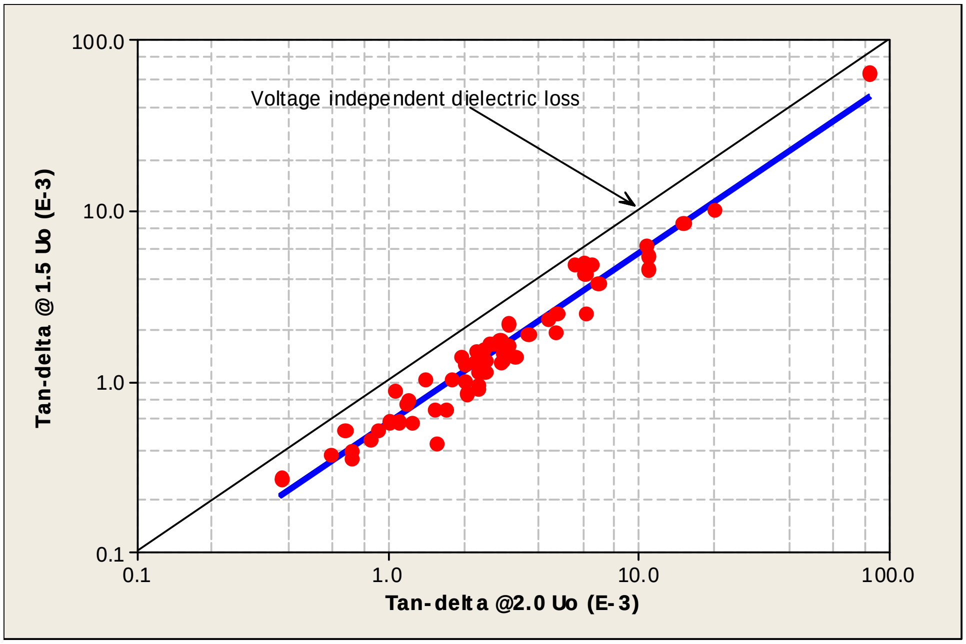


Figure 15: Correlation of Dielectric Loss Data Collected at Different VLF Test Voltages

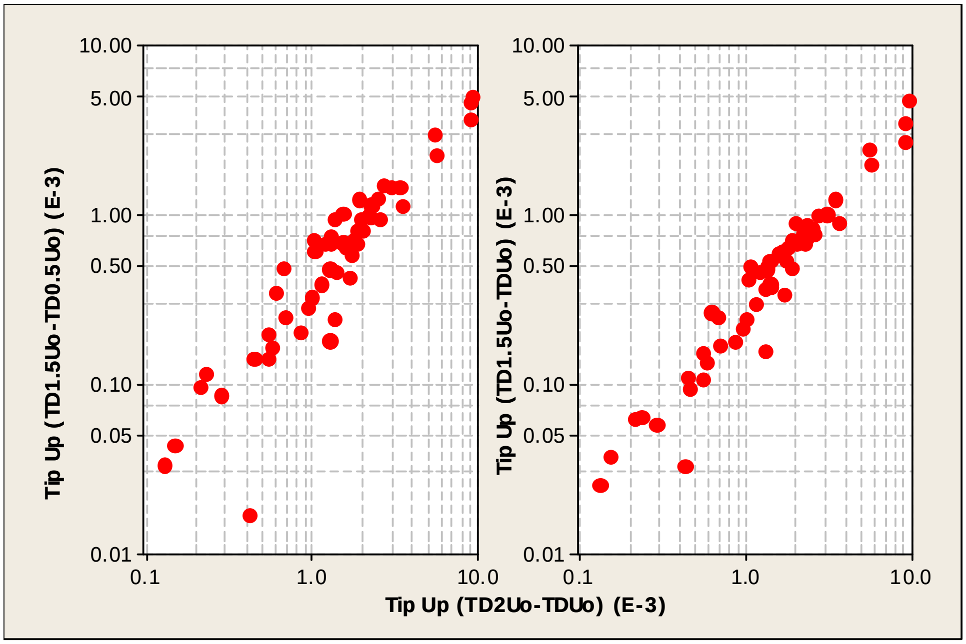


Figure 16: Correlation of Differential Loss (Tip Up) Data Collected at Different VLF Test Voltages

Since the same information can be obtained at lower risk, all *CDFI* measurements and analyses have been conducted by:

- Considering the Tip Up over a U_0 difference (the same as IEEE Std. 400 – 2001) but the interval being from 1.5 U_0 to 0.5 U_0 instead of 2 U_0 to U_0.
- Using the standard deviation of successive measurements at U_0 as the stability criteria

- Using the mean of successive measurements at U_0 as the Tan δ value

The additional benefit of doing this is that the measurements are made at or below the voltages specified in IEEE Std. 400.2 – 2013 for simple VLF Withstand Tests. Naturally, it is sensible to make dielectric loss measurements at voltages that are equal to or below the voltage levels used for VLF Withstand tests. It also makes it more convenient, because it allows the tester to make Tan δ measurements while the VLF withstand test is underway.

6.6.7 Importance of Context

Sometimes testing is performed on an individual cable system in isolation from other, similar systems. When this is done, the utility has to judge the condition of the system by comparing the measured values to values outlined in documents such as IEEE Std. 400.2 – 2013. However, as discussed earlier, there is significant value in comparing the results to results on other, similar cable systems. In this case, the measured features (Stability, Tip Up, TuTu, and Tan δ) are considered in a hierarchical manner but the condition assessment levels are derived from comparisons with other local measurements rather than (or in addition to) external data sources such as IEEE Std. 400.2 – 2013. This approach appears in Figure 17 where data for adjacent subdivisions are segregated. Through inspection of these data, it is possible to select a subdivision (say Cambridge Highlands) and then identify the systems that have results that are noticeably different from the majority of the systems in that subdivision. These are likely the systems requiring the most urgent attention within that subdivision. However, this approach does not identify which systems need immediate attention.

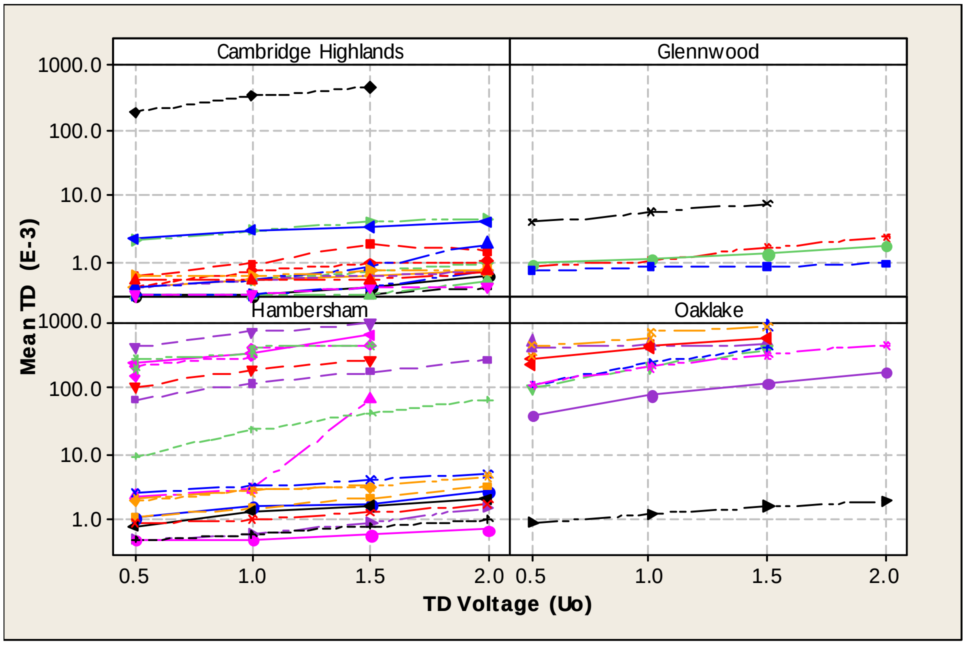


Figure 17: Dielectric Loss Data for Aged XLPE Cable Systems

6.6.8 Usefulness of Length Analyses/Correlations

As noted earlier, Tan δ measurements provide the dielectric loss for the whole cable system, including the cable terminals and splices but cannot identify the source of the loss. This leaves the question: Does the loss measurement reflect the condition of the entire system, or does a small section have a high loss while the remainder has a low loss? To date, there does not appear to be a direct method of answering this question. However, comparing the measurement results with the physical characteristics of each cable system (such as the number of cable joints and the system lengths) it is possible to establish what may be causing a given system to have a high loss.

Simulations where cable systems are modeled as a series of parallel resistors and capacitors show that the dielectric loss of a system sometimes varies as a function of the system length when the loss measurement is affected by factors such as corroded neutral wires. The most convenient way to visualize this is in a log-log plot. Figure 18 shows typical field data that demonstrate how the condition of the neutrals can affect dielectric loss measurements. In general, Tan δ should be independent of the tested length except in the case of corroded neutrals where the Tan δ tends to increase with length. As Figure 18 illustrates, the Hambersham and Oaklake subdivisions display increasing Tan δ values with increasing circuit length. Such a trend is not readily visible in the Cambridge Highlands or Glennwood subdivisions.

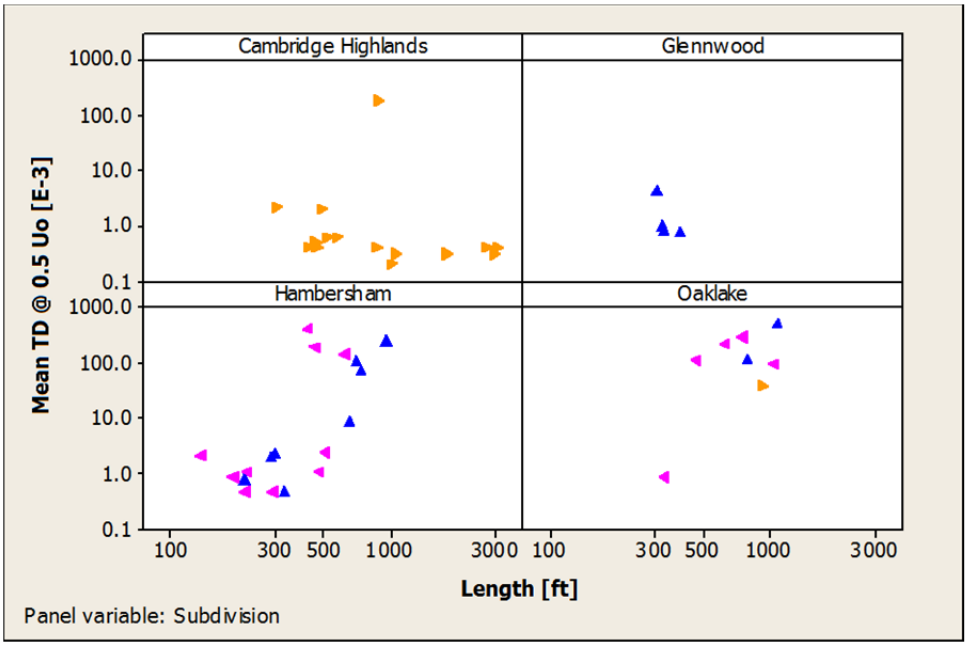


Figure 18: Dielectric Loss versus Length Representation for the Data shown in Figure 17

Similar observations apply to Figure 19. In this case, each system was first tested using Tan δ and then tested using a VLF Simple Withstand (see Chapter 9 for more information). Those systems that failed during the VLF Withstand show a length dependence as compared to those systems that went on to pass the VLF Withstand. Data are available for both filled and PE-based insulations.

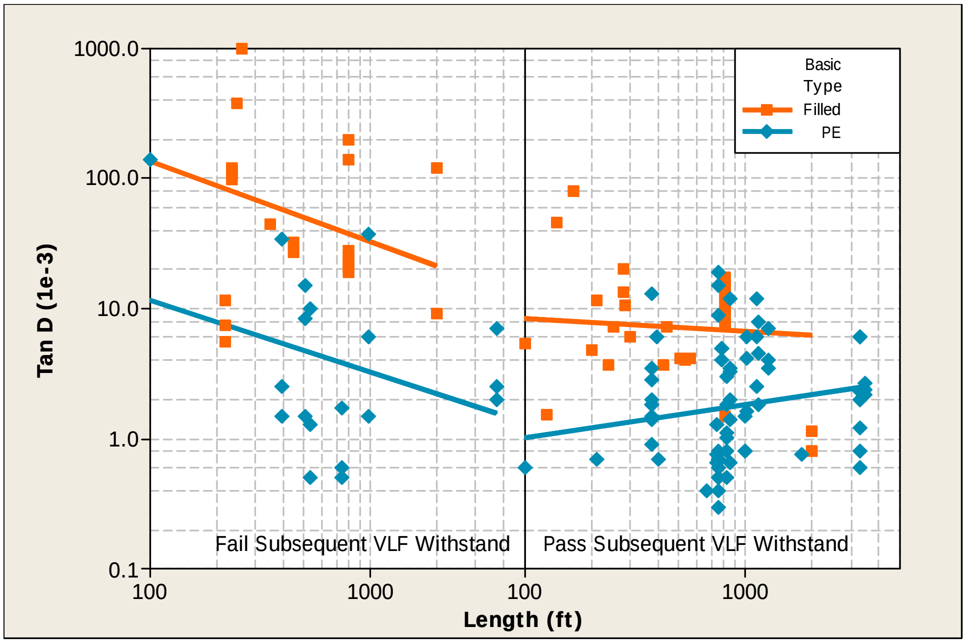


Figure 19: Dielectric Loss versus Length Segregated by Insulation Type (Filled and PE) with Performance in Subsequent VLF Withstand Tests

The forms of the curves shown in Figure 18 and Figure 19 may be interpreted using the descriptions in Table 17.

Table 17: Interpretation of the Slopes of the Dielectric Loss versus Length Graphs

Graph Form	Diagnosis	Example
Flat (Loss independent of length)	Uniform level of loss for all parts of the cable system.	Figure 18 (Cambridge Highlands)
Random (No clear length dependence)	No clear pattern of loss for the cable system population (see Figure 18 – Cambridge Highlands). Each system is different from all others.	Figure 19 (Cables pass subsequent VLF Withstand tests)
Upward Slope (Loss increases with length)	Neutral issues (the equivalent system is not a simple parallel representation of a resistor and a capacitor, but has a series resistance too). Either corroded neutrals or poor contact between the neutral and the insulation screen can cause this to occur.	Figure 18 (Hambersham)
Downward Slope (Loss decreases with length)	Isolated high loss portions (bad accessories or heavily water treed regions) within a large proportion of low loss cable can cause this to occur.	Figure 19 (Cables fail subsequent VLF Withstand tests)

From this information, it is apparent that analyzing dielectric loss with respect to system length can yield useful information.

6.6.9 Expected Outcomes

The distribution of the dielectric loss data as a function of voltage source appears in Table 18. Figure 20 shows the individual lengths of cable systems tested using dielectric loss techniques.

Table 18: Distribution of Dielectric Loss Measurements by Source Type and Deployment

Source Type	Deployment	
	Laboratory [Conductor Miles]	Field [Conductor Miles]
60 Hz AC	0.3	--
Damped AC	--	--
VLF AC	1.5	770.8

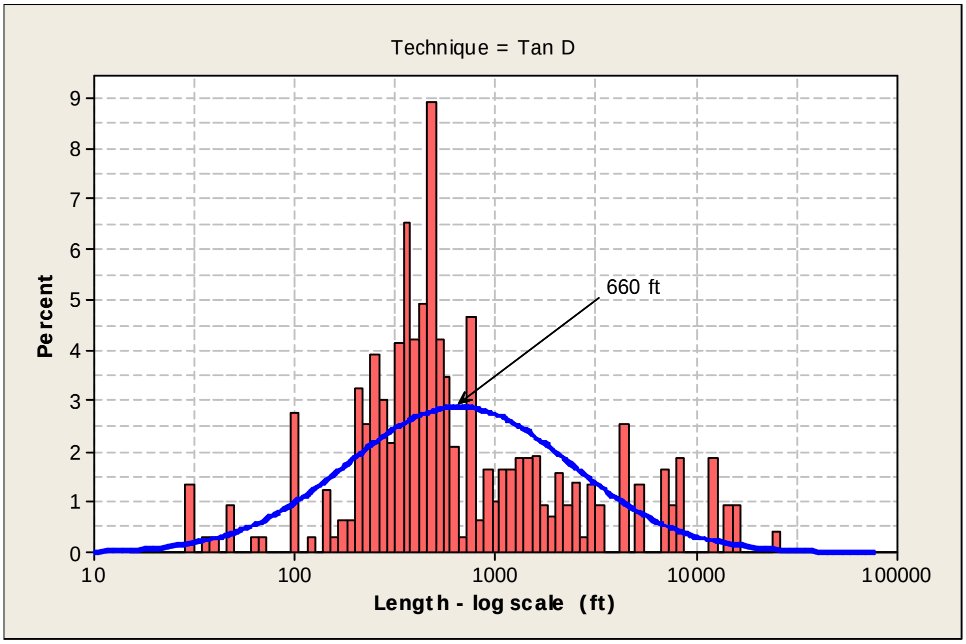


Figure 20: Cable System Lengths Tested with Dielectric Loss Techniques

The analysis of reported data is useful in a number of ways:

- It may be used to estimate potential testing scenario results.
- It places the results in context so that uncharacteristically high or low values are easily identifiable.

An analysis of all Tan δ field measurements gathered during the *CDFI* using a sinusoidal VLF (0.1 Hz) voltage source has established how the data correlate to the IEEE Std. 400 – 2001, IEEE Std. 400.2 – 2013, and *CDFI* Perspective performance requirements. The analysis results appear in Figure 21 to Figure 23.

Figure 21 classifies the data according to IEEE Std. 400 – 2001, using Tan δ and Tip Up criteria as “either/or” requirements. Thus, a system with Tan δ of 1.5E-3 and a Tip Up of 2E-3 is classified as “Highly Degraded” based on the Tip Up whereas the Tan δ would suggest a classification of “Aged.” Note that the standard does not have criteria for paper or filled systems.

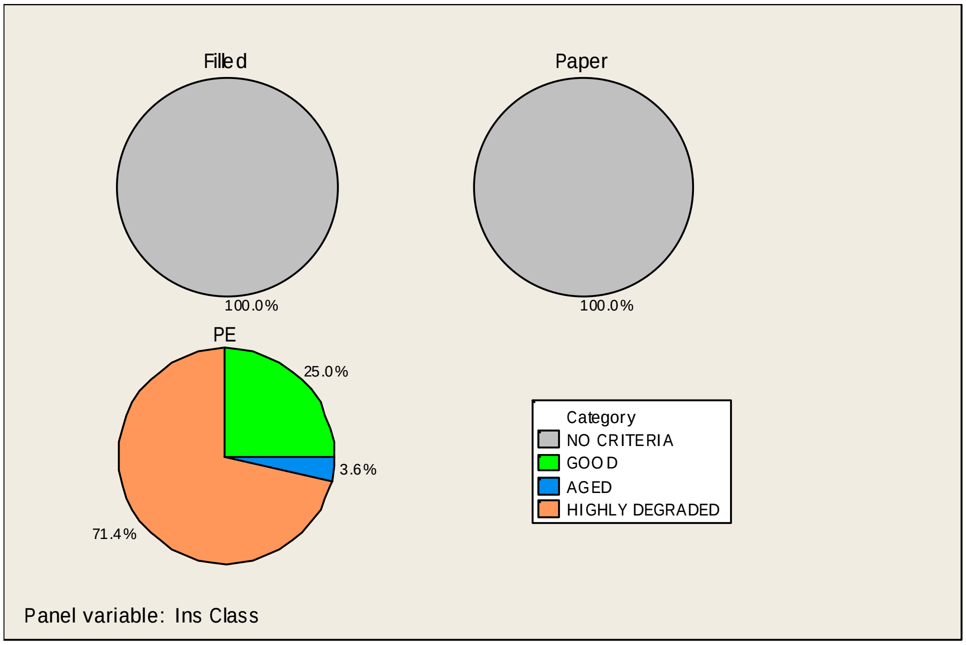


Figure 21: Distribution of Dielectric Loss Classifications Using Criteria Presented in IEEE Std. 400 – 2001

Figure 21 clearly shows the concerns with IEEE Std. 400™ – 2001 in that these levels classify more than 70 % of the systems as “Highly Degraded.”

Figure 22 shows the same dielectric loss data used in Figure 21 but classified using the “atypical” approach developed in the *CDFI* for the Differential Tan δ and Tan δ, with the values derived from the analyses shown in Table 4 to Table 6. In this approach, filled and paper insulations may be addressed.

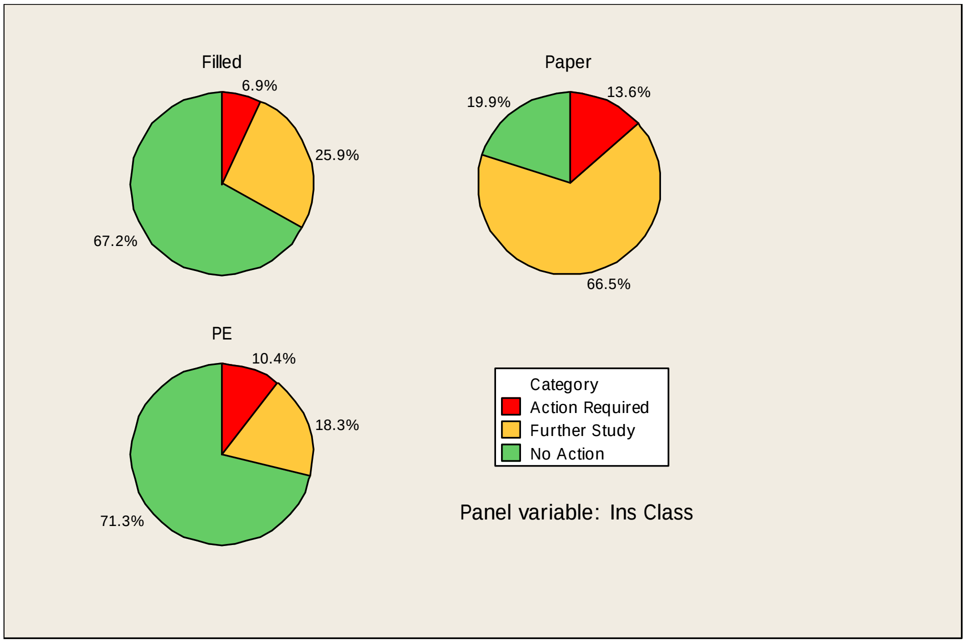


Figure 22: Distribution of Dielectric Loss Classifications Using Criteria Presented in the IEEE Std. 400.2 – 2013

Similarly, Figure 23 shows the same dielectric loss data used in Figure 21 and Figure 22 but classified using the latest criteria considered by the *CDFI* perspective with the diagnostic features and values shown in Table 12 to Table 14. In this approach, filled and paper insulations are addressed.

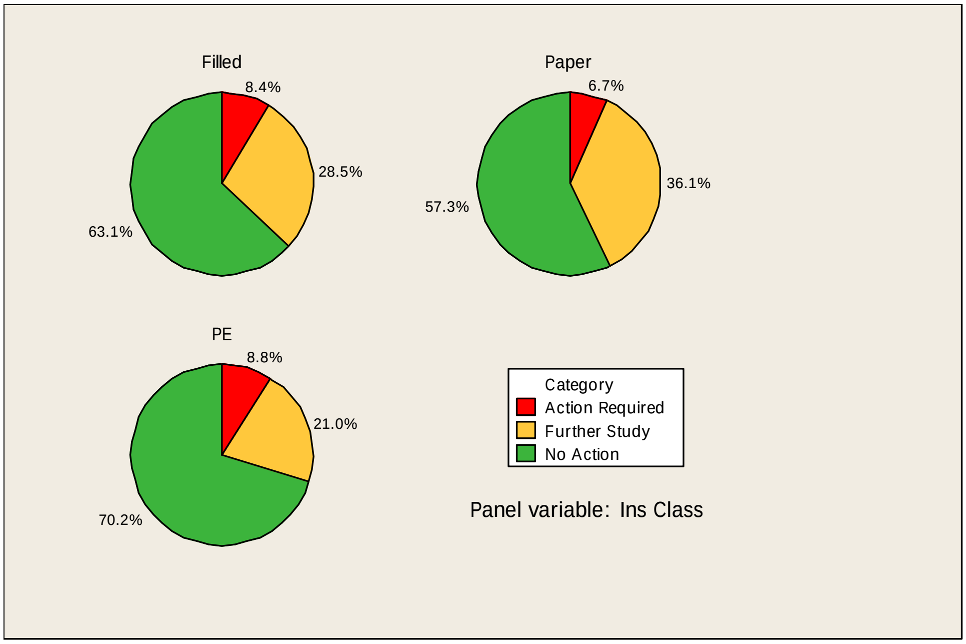


Figure 23: Distribution of Dielectric Loss Classifications Using Criteria Presented in the *CDFI* Perspective

As seen in Figure 22 and Figure 23, the distribution of dielectric loss classifications using the criteria presented in the IEEE Std. 400.2 – 2013 and the *CDFI* criteria is relatively similar for PE-based and filled insulation classes. However, for the Paper insulation class a considerable change is observed for those power cable systems that are classified as "No Action" and "Further Study Advised". These discrepancies may be due to the bigger dataset that has been considered for developing the latest *CDFI* criteria, 2013 compared to 2010. Therefore, this issue can be interpreted as an indication that the criteria for condition assessment in IEEE Std. 400.2-2013 for power cable systems with paper insulations may already be out of date.

Stepping back to Figure 22, it considers all the Tan δ data combined as one dataset. However, it is also useful to examine how different utility datasets distribute among the condition classes. Figure 24 shows the distribution for each insulation type and class for the "atypical" approach using the box and whisker format. Figure 24 allows a utility to determine how similar its measurements are to other utilities. Figure 25 gives the length-adjusted occurrence of the classes for the different datasets in Figure 24, also in box and whisker format. Not surprisingly, the distribution for each utility (shown by the individual data points) is different.

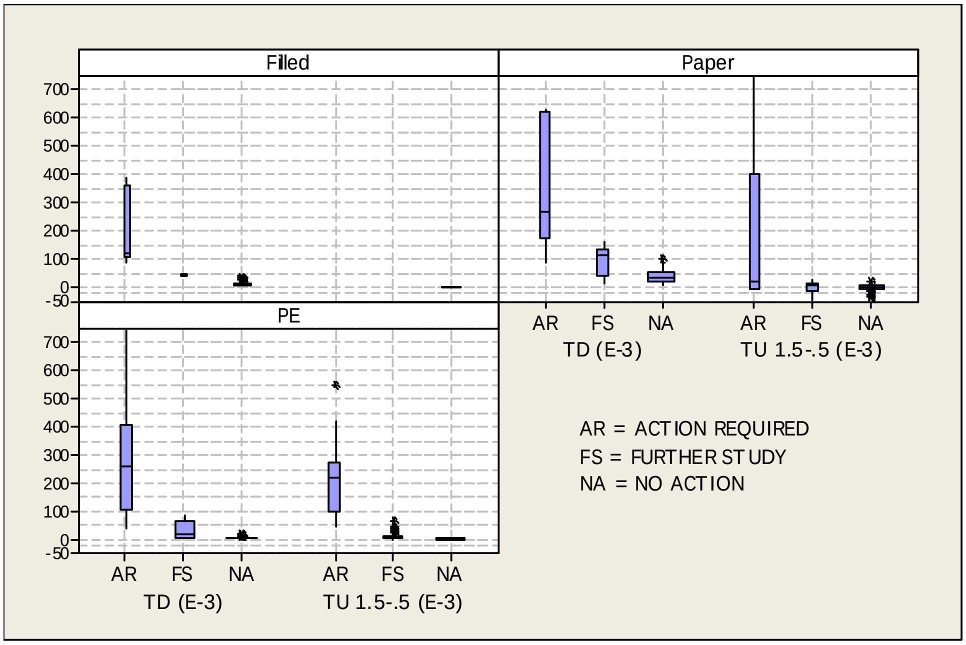


Figure 24: Tan δ and Differential Tan δ Data for the Dielectric Loss Classifications Based on Identifying "Atypical" Data (Figure 22)

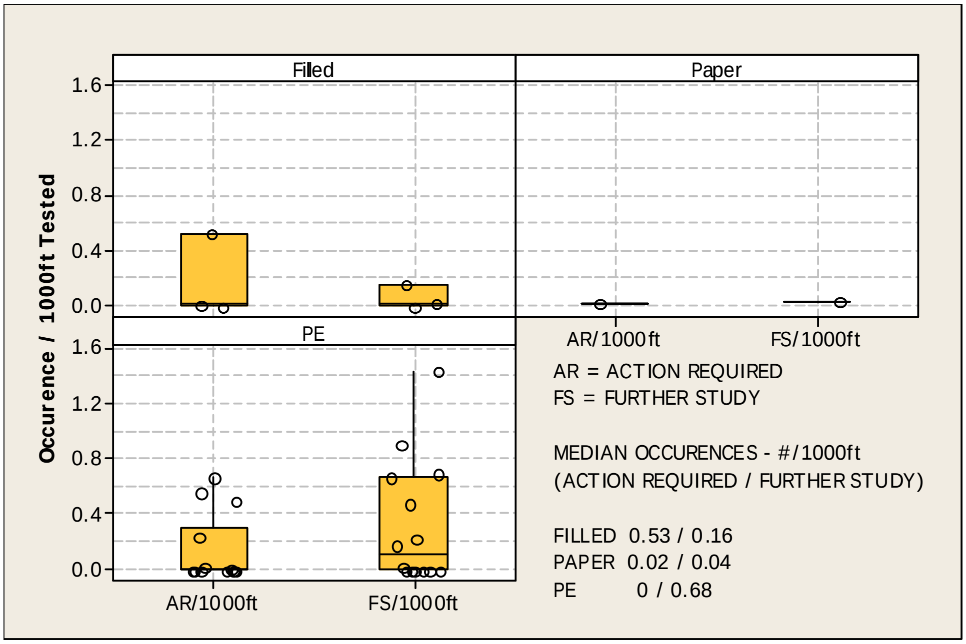


Figure 25: Occurrence of Dielectric Loss Classifications Based on "Atypical" Data

Figure 22 shows that using the "atypical" levels and multiple features results in a distribution much closer to what a utility might expect. Failure data are also available for these classifications and the usual Weibull time analysis of these data appears in Figure 26. These data result from measurements made by or supplied to the *CDFI*. These systems were left in service and their performance (measured by service failures) was tracked. The lower times correspond to the failures during the dielectric test (FOT). The quality of the fit is also worth noting since the distribution fits the available data well, which leads to several significant observations.

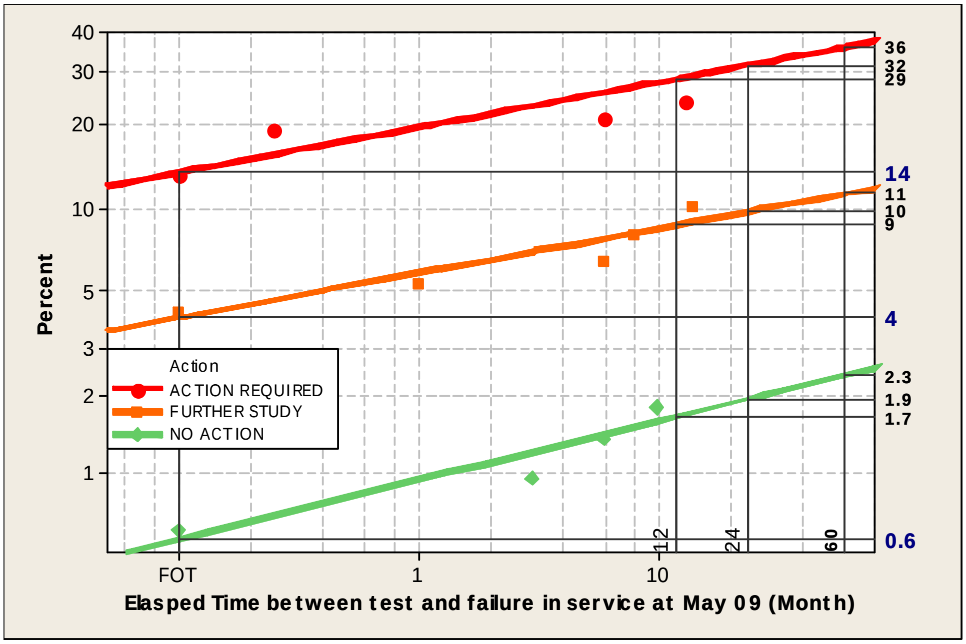


Figure 26: Diagnostic Performance Curves for Tan δ

These curves show that the likelihood of failure, if no actions are performed after testing, follow the classifications from the "atypical" approach reasonably closely (i.e. a system classed as "Action Required" has the highest probability of failure). Thus, these data show that there is a strong relationship between the cable system dielectric loss and subsequent service reliability. That is, an elevated Dielectric Loss feature (Tan δ, Tip Up, or Unstable Tan δ) indicates a higher risk of failure in service than cables with lower value Dielectric Loss features. As is the case with almost all diagnostics, even the most severe classification is not necessarily an immediate "death sentence." It clearly takes time for even the worst systems to fail. The vertical percentile lines in Figure 58 show the probabilities of failure for each condition assessment at selected times after test. Even after five years of service, only 36% of the worst systems failed. Note that the Stability, Tip Up, and Tan δ criteria were generated using only the measurement data, not the failure data. These criteria were then used to assess each of the systems for which both measurement data and failure data were available. The results of this analysis appear in Figure 26. An alternative approach to the data-directed methods employed above is to construct criteria that best relates the measurement data to the corresponding failure data.

One of the major issues with different diagnostic techniques and implementations is how to compare the different recommendation hierarchies. The Performance Curves in Figure 58 allow the conversion of any class designation into a probability of failure for any chosen time. For example, in the "atypical" approach for Tan δ, Table 19 shows how these data may be renamed.

Table 19: Diagnostic Class Renaming Example

Classification	Prob. of Failure within 2 Years [%]	Alternate Classification
No Action	2	Level 1
Further Study Advised	10	Level 5
Action Required	32	Level 16

In addition to the correlation between dielectric loss and service performance shown in Figure 26, similar and complementary evidence appears in Figure 27. In this figure, the performance of power cables installed in an industrial environment were first tested for dielectric loss and then subjected to a VLF (generally 0.1Hz sinusoidal) withstand test. These data are the same as those used for Figure 19 but appear here in a box and whisker format. These data show that for both the filled and unfilled (PE) cable cases, cable systems possessing elevated Tan δ (the Tip Up and Stability were not measured for these systems) had a much higher chance of failing the subsequent VLF test. Although it is difficult to correlate failures on withstand with service performance, it is clear that the cable systems with higher losses are electrically weaker and this normally correlates with shorter life.

Another conclusion from the research is (see Figure 27) is that filled and unfilled systems that have Tan δ > 20E-3 or 10E-3, respectively, have a much lower likelihood of passing a VLF withstand test.

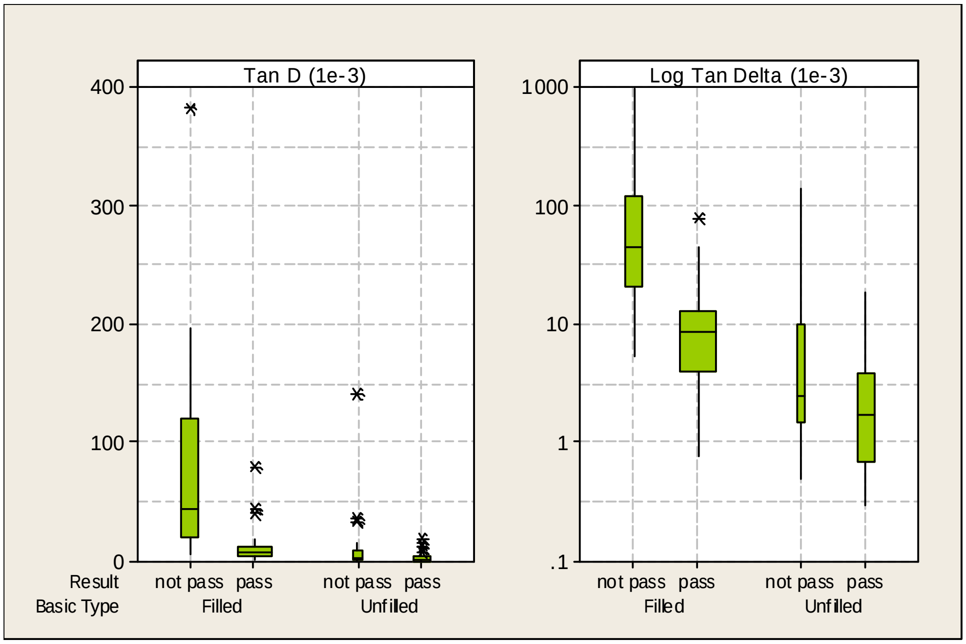


Figure 27: Relationship between VLF Withstand Performance and Dielectric Loss

The Diagnostic Performance Curves in Figure 26 and box and whisker plot in Figure 25 are very useful as they enable utilities to make an informed interpretation of the dielectric loss diagnostic data and assess what is likely to occur for different action scenarios. Table 20 demonstrates how a utility might use these collated research data to develop a scenario prior to the start of the testing and thereby be better prepared for any consequences. This scenario uses 14 miles of MV cable system with 80 systems. It is important to recognize that these data originate from the available field data and have generally followed the IEEE Std. 400 – 2001 $2U_0$ testing philosophy rather than the reduced risk approach described earlier. Thus, the estimated failures for systems after 5 years (26 %, 4 %, and 11 % for Filled, Paper, and PE, respectively) are likely to be high (conservative estimates) if the reduced-risk scheme is used.

Table 20: Example Scenario Evaluation

Insulation System	**No Action / Further Study / Action Required [Cable Systems]**	**Predicted Failures**		
		FOT	**After 2 Years**	**After 5 Years**
Filled	43 / 13 / 25	7	19	21
Paper	2 / 4 / 75	1	3	3
PE	1 / 55 / 25	3	7	9

6.6.10 Combined Assessment - Tan δ Principal Component Analysis (PCA)

Decision making based on Tan δ criteria is a topic of ongoing research and analysis. As discussed previously, the approach proposed in IEEE Std. 400.2 – 2013 to Tan δ criteria is to construct a three tier/diagnostic feature approach using three primary useful diagnostic features: Tan δ Stability (STD-time dependence), Tip Up (TU-voltage dependence), and Mean Tan δ (TD-level of loss). Circuits were classified as "No Action Required", "Further Study Advised", or "Action Required" depending on the most severe assessment from these three Tan δ diagnostic features.

This is useful information, but at times it can be difficult to interpret. As an example, one possible result is that Stability and Tip Up could indicate "No Action Required" but the Mean Tan δ could indicate "Further Study Advised". In this case, it is not clear how to interpret the overall results. The interpretation becomes even more difficult when the fourth proposed diagnostic feature (TuTu – non-linear voltage dependence) is considered. Ideally, a method is needed to combine all four features to create a single "Health Index" that puts any set of measurements in context with the Tan δ database. The principal component analysis (PCA) method is one means of accomplishing this research goal.

In order to obtain a single "Health Index" from all four diagnostic features, the *CDFI* recently updated a variety of techniques and explored new approaches. From all techniques that have been explored, the PCA is the most attractive since it takes a given set of points in a high dimensional space and then reduces the dimensionality to a more manageable number. In other words, the PCA technique summarizes the data with several assumed independent variables to a smaller set of derived variables without sacrificing the potential for classification. In fact, the classification capability is enhanced by the PCA.

The technique provides a predictive model with guidance on how to interpret or "weigh" the primary measurement features. It also allows for a physical meaning to be ascribed to the resulting composite factors, i.e. the Principal Components. The PCA approach identifies linear combinations of factors and generates the principal components that better represent the data. The first component has or describes the largest portion of the variance, followed by the second, and then the third, and so on. The PCA redistributes the variance in such a way that the first k components explain as much as possible of the total variance of the data. It must be noted that the higher the variance the higher the potential for better classification.

Another important reason for choosing the PCA technique is that in many data analysis/mining scenarios, seemingly independent variables are highly correlated, which affects model accuracy and reliability. PCA is able to detect such correlations and then essentially exclude the redundant information.

To illustrate and easily understand the essentials of the PCA technique, Figure 14 shows a qualitative explanation of the technique. The circles represent a dataset in which there are two features (axes) and the variance within this dataset with respect to these features is represented by the area of the rectangle denoted as Area 1. The PCA method attempts to reduce the variance by generating new axes that are linear combinations of the available two features. This causes a rotation/translation of the original axes from F1-F2 to PC1-PC2. The new variance can then be thought of as the area of the rectangle represented by Area 2. By comparing the areas, it is clear that area 2 is smaller and, therefore, has less variance than the original configuration in Area 1. As mentioned above, this process can be used to reduce the dimension of a dataset to as few or as many principal components as are needed.

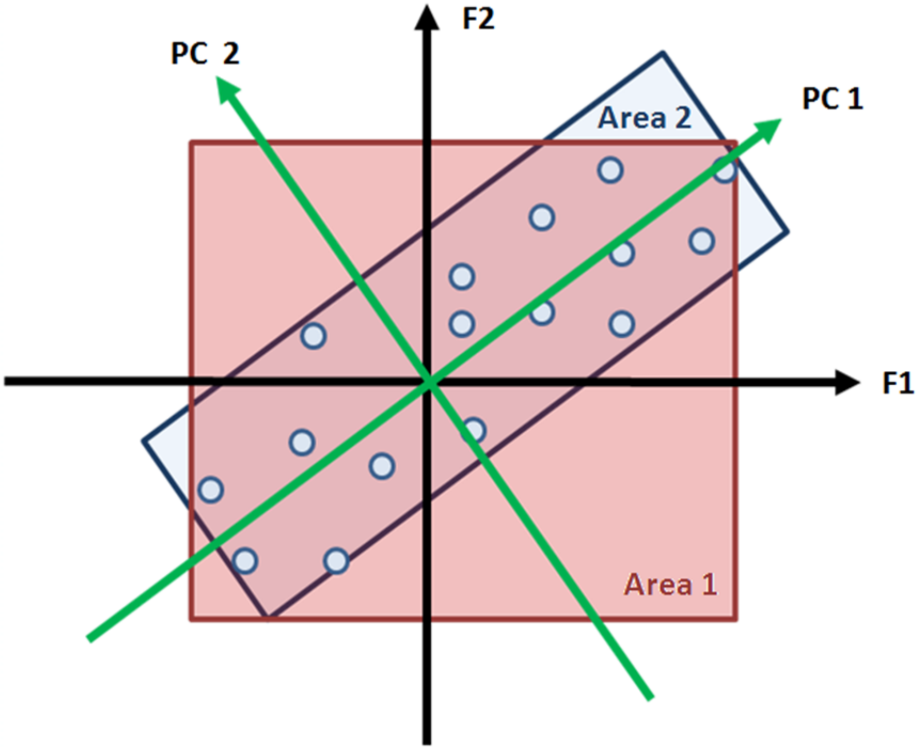


Figure 28: Graphical Interpretation of Principal Component Analysis (PCA)

The PCA technique has been applied to the PE Tan δ database and Figure 28 shows the transformation from the first two Tan δ diagnostic features (STD and TU) to the first two principal components (PC1 and PC2). As mentioned previously, the PCA reduces the dimensionality; however, this technique does not directly provide a single descriptor by itself, essentially it enables the constructions of simplified and appropriate feature maps that may enhance the classification potential of the diagnostic features when they are combined in the right manner; the principal components feature maps can then be used to provide a single condition assessment descriptor as it is shown later. The transformation can be observed in Figure 29 in which the application of the PCA technique clarifies the connection between PC1 and PC2 (right side of Figure 29) as compared to the original data, in this case STD and TU (left side of Figure 29).

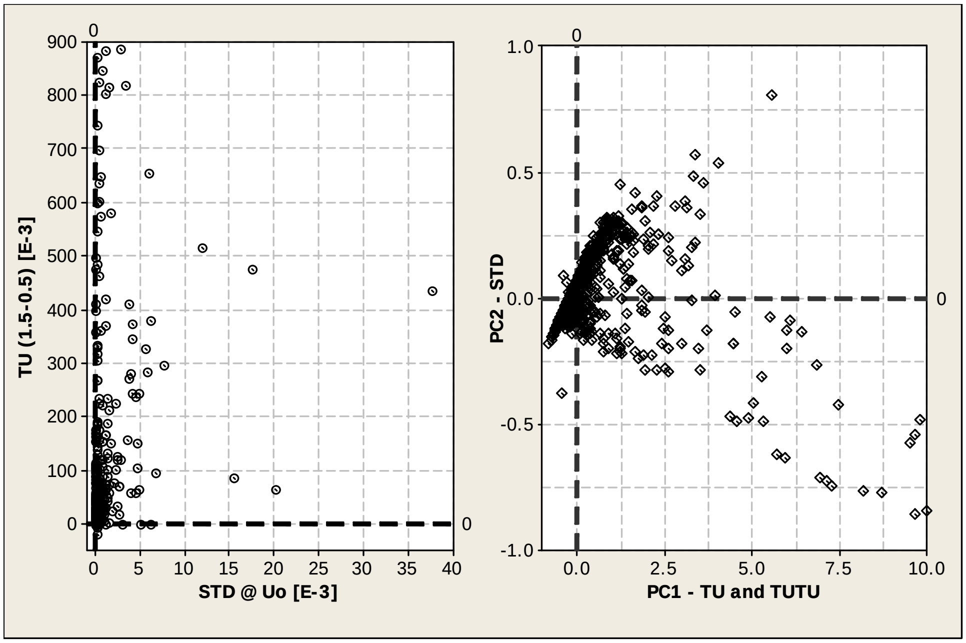


Figure 29: Scatter Plots of STD vs. TU (left) and PC1 vs. PC2 (right) – PE-based Insulations

Applying PCA to the PE Tan δ data yields the principal components shown in Table 21. This table shows the percentage of variance accounted for by each principal component as well as the diagnostic features included in each component. Results from Table 21 indicate that only three principal components are required to describe 97 % of the variance; therefore, this is the number of principal components considered here.

Table 21: PCA Variances and Component Composition for PE-based Insulations

Principal Component	Variance Described by Component [%]	Variance Described by Component Cumulative [%]	Tan δ Diagnostic Features
PC1	50	50	TU & TuTu (Voltage Dependence)
PC2	25	75	STD (Time Dependence)
PC3	22	97	TD (Level of Loss)
PC4	3	100	Not relevant since this component only describes 3% of the variability

Another important result from Table 21 is that PC1 describes 50 % of the variability and it is composed of TU and TuTu, features that consider the Tan δ voltage dependence. PC2 describes 25 % of the variability and it includes STD, and lastly, PC3 describes 22 % of the variability and it is mainly composed of TD. Also note that PC4 is not relevant since it only describes 3 % of the variability of the data; therefore, this principal component is not taken into account in the analysis.

The main conclusion of the PCA research shown in Table 21 is that they also give an indication of the importance and relevance of the Tan δ diagnostic features; from the analysis the voltage dependence of measurements (TU and TuTu) is the most important factor followed by the time dependence (STD) and level of loss (TD) when the variability of the data is considered. These results should not be confused when compared with the results shown in *Phase I* of the *CDFI*. In *Phase I*, the importance and relevance of the features was determined using VLF breakdown correlations as compared to the PCA approach used in *Phase II*. In both cases the voltage dependence, time dependence, and level of loss were found to be independent diagnostic features; therefore, it can be assumed that they carry independent information. The overarching question is how to combine all diagnostic features in to a single indicator, which is discussed below.

The use of the PCA technique has allowed the development of a combined diagnostic feature scheme in which all independent features are considered together for an ultimate condition assessment. The combined diagnostic feature scheme is based on the computation of the PCA distance, i.e. given a set of principal components related to a set of measurements, how these components deviate from a known reference point. The PCA distance is computed using the principal components' values and a reference point that in this case corresponds to Tan δ measurements of a new cable system. Figure 30 shows the combined PCA distance of the three principal components for all the available data of PE insulated cable systems. In Figure 30, the percentage or rank position is given by the Y-axis values and, in practice, might conveniently be regarded as a "Health Index". The higher the rank position, the worse the cable system condition relative to all similar systems. The symbols in Figure 30 represent selected test cases used as examples and their computed PCA distance (rank) results appear in Table 22. This table may be considered as an independent test of the research for the PCA Health Index.

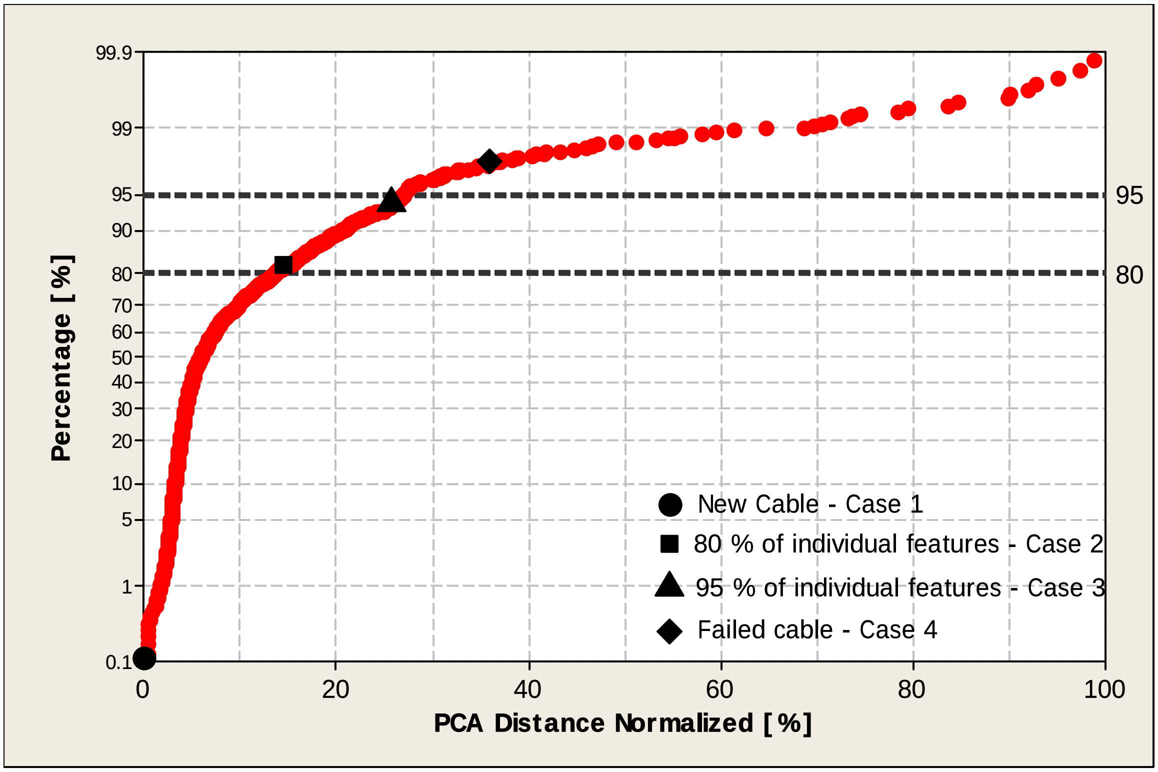


Figure 30: Empirical Cumulative Distribution for the Normalized PCA Distance for PE-based Cable Systems

Table 22: Test Cases for Tan δ Principal Component Analysis for PE-based Insulations

Case No.	Description	STD [E-3]	TU [E-3]	Tan δ [E-3]	TuTu [E-3]	Rank [%]
1	New Cable	0.00	0.00	0.10	0.00	0.10
2	Features at 80 % level	0.05	5.00	4.00	3.00	82.0
3	Features at 95 % level	0.50	80.00	50.00	58.00	93.9
4	Failed Cable*	3.60	247.00	316.00	17.00	97.6
5	Utility test 2007	0.00	0.80	2.80	0.00	79.0
6	Utility test 2010	0.00	1.80	6.00	0.60	84.5

* failure after 27 months from test date

In Table 22, the following examples are included:

- Case 1 represents that a new PE cable system lies at the 0.1st percentile. This translates to an extremely good “Health Index”. Case 1 is represented in Figure 30 by the solid black circle symbol.
- Case 2 represents the situation in which all diagnostic features are at their respective 80 % levels (black square symbol in Figure 30). Note here that all the features at the 80 % level yield a “Health Index” of 82.0 %. Therefore, there is a good correlation between the feature

levels and the overall assessment considering all features together.

- Case 3 shows the situation in which all the diagnostic features are at the 95 % level (black triangle symbol in Figure 30), in this case the "Health Index" is 93.9%, Note again the good correlation between the features levels and the overall condition assessment.
- Case 4 is a real case and represents the poorest performer in a cable system that was tested in 2007 and failed in service 27 months later (black diamond symbol in Figure 30). The PCA indicates that back in 2007 the cable system was within the poorest 3% of all PE-based cable systems. This case is also represented.
- Case 5 and Case 6 are also real cases and represent a retest of a cable system after three (3) years of operation – Georgia Power: Wimbledon Woods (See field test data from previous quarterly reports).

In Table 22, note the change on the diagnostic features between Cases 5 and 6 after three years of operation shows this cable system went from "No Action Required" to "Further Study Advised". The "Health Index" changed from 79.0 % to 84.5 %, this represents a degradation in the rank position of about 2 % per year. Additionally, inspection of mid-range and lower ranks shows that, as might be expected, there is a degradation of rank position here as well, but the rate is much lower: approximately 0.3 % to 0.5 % per year. Information of this type is invaluable to an asset manager when deciding which cable systems need repair or replacement. In this case, an asset manager could prioritize within the "Action Required" and "Further Study Advised" classes. It is important to recognize that there is no capacity to ascribe a definite lifetime to the cable system but it can assist in prioritization.

The previous paragraphs have emphasized the usefulness of the PCA technique in creating an accurate condition assessment tool for PE-based cable insulations; however deriving the optimum PCA features to achieve improved classification is a topic that needs to be addressed for each cable insulation separately (PE-based insulations, Filled insulations, and PILC) since some rules cannot be used for all insulations. Appendix A presents the studies carried out for each type of cable insulation.

6.6.11 Analysis of Tan δ Diagnostic Features By Cluster Variable Analysis

The cluster variable analysis of all Tan δ diagnostic features has been performed for PE-based insulation. The cluster variable analysis is chosen because it provides another means of selecting a number of reduced features by taking into account the correlation between features rather than their variability used in the principal component analysis (PCA) approach. The next paragraphs describe the analysis.

As seen, one of the problems present when considering a large number of Tan δ diagnostic features is how to organize them into meaningful groups or clusters. In the case of the Tan δ diagnostic features the organization can be accomplished by performing a cluster variable analysis of the features. Its results are compared with the results from the PCA.

Cluster variable analysis is useful in this research 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.

The analysis is an agglomerative hierarchical method that begins with a separate treatment of all features, each forming its own cluster. In the initial step, the two features closest together are joined. In the next step, either a third feature joins the first two (now considered as a stand-alone cluster), or to another feature is joined with a different cluster. This process continues until all clusters are joined into one. The complete procedure, from the initial cluster variable analysis to the final feature selection, is explained later in the section.

The agglomerative hierarchical method uses the distances between variables when forming the clusters. These distances are based on a single dimension that uses the absolute Pearson correlation coefficient between features. The correlation coefficient can be translated to a level of similarity between clusters. The level of similarity can be used as a tool to compare the relationship between features or clusters.

The similarity level between two features or clusters, e.g. features or clusters i and j, is given by:

$$S_{ij} = \frac{100(1 - d_{ij})}{d_{max}} \qquad \textbf{Equation 3}$$

where,

S_{ij}: Similarity level between features or clusters i and j,
d_{ij}: distance measure between features or clusters i and j, based on the absolute Pearson correlation coefficient,
d_{max}: Maximum distance between the initial set of features before starting the clustering procedure.

The interpretation of the level of similarity is quite straightforward. The level of similarity is a number that ranges from 0% to 100%. A similarity level approaching 100% indicates that the features or clusters under investigation are redundant, i.e. they carry essentially the same information. In other words, the features or clusters are highly correlated; thus, they contribute little to solving an eventual classification problem. In contrast, a level of similarity approaching 0% indicates that the features or clusters under investigation are complementary or uncorrelated. Thus, the likelihood of using these features or clusters in an eventual classification problem with good results is higher than using redundant features or clusters.

There are several algorithms available for the clustering of the Tan δ diagnostic features and each them may yield different results. However, here, the group average and the furthest neighbor methods are used in the cluster variable analysis of the Tan δ diagnostic features. Specifically, the group average method is used in the agglomerative procedure during clustering. The clustering process is as follows:

1. Initially each feature is declared a cluster and all distances between clusters are calculated.

2. Two clusters with the smallest distance between them are fused together and declared to be a new cluster. This is the beginning of the agglomerative process.
3. All distances between clusters are again calculated and the agglomerative process continues until the number of clusters is one.
4. Once one cluster is left, the number of clusters to be considered for the final feature selection is determined by choosing a similarity level.

The results of the clustering procedure can be represented graphically in a tree-like plot, also known as a dendrogram plot. The dendrogram plot for the cluster variable analysis represents the features under analysis on the x-axis and the level of similarity between features and clusters on the y-axis. The clusters are represented by vertical and horizontal lines between the features.

Determining the number of clusters for the final feature selection can be termed as "cutting the dendrogram". Cutting the dendrogram is akin to drawing a line across the dendrogram to specify the final grouping at a particular similarity level. There is no pre-established procedure on choosing the similarity level for cutting the dendrogram. Results of the cluster variable analysis for the Tan δ features are shown in Figure 31.

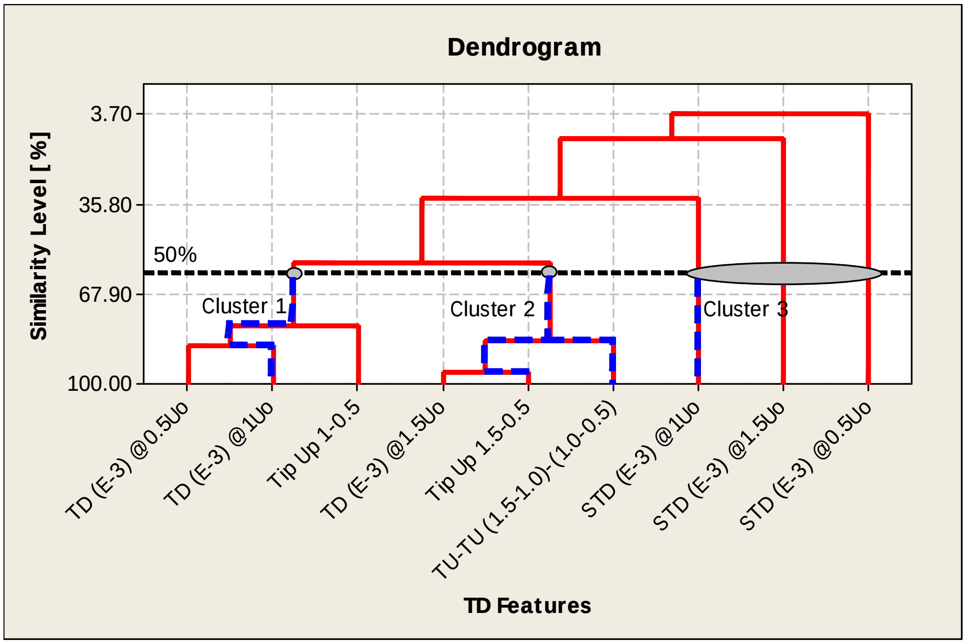


Figure 31: Research Dendrogram of the Cluster Variable Analysis of Tan δ Diagnostic Features

As seen in Figure 31, when a similarity level of 50% (typical value) is chosen to cut the dendrogram, five clusters are obtained. However, three clusters are considered in this case. Cluster 1 is composed of the features Tan δ at 0.5 U_0, Tan δ at U_0, and the Tip Up between U_0 and 0.5 U_0; cluster 2 is composed of the features Tan δ at 1.5 U_0, Tip Up between 1.5 U_0 and 0.5 U_0, and the TuTu; and cluster 3 is composed of all the standard deviations at all voltage levels.

Results of the cluster variable analysis in Figure 31 show that three of the four previously determined important diagnostics features using the PCA analysis group in different clusters.

These results are in accordance with the PCA analysis since they indicate that variability of the measurements, changes in Tan δ with voltage and absolute Tan δ values have to be considered separately in a scheme of reduced features.

The four important features obtained from the PCA analysis appear in Figure 31 by the blue-dashed lines. Note that the Tip Up between 1.5 U_0 and 0.5 U_0 and the TuTu are similar greater than approximately the 70% level; therefore, these two features can be thought of as carrying the same information. However, this is a topic of ongoing study and a more detailed analysis would be required to properly determine the differences between these two features. The primary conclusion of the cluster variable analysis is that their results are similar to those from the PCA analysis with respect to the type of features that should be considered for an improved condition assessment using a reduced number of Tan δ diagnostic features.

6.6.12 Value of Increasing Database Size

The Tan δ research work focuses on the application of statistical methods to the analysis of Tan δ data. When the statistical methods are used, then the question of how much date data are needed has to be addressed. These methods extract useful information from data; discovering relationships that have not previously been known. Additionally, by understanding and obeying statistical methods knowledge can be distinguished from speculation. Statistical methods are mathematical techniques that involve the following steps: (1) describing data, (2) gathering data, (3) organizing data, (4) analyzing data, and (5) interpreting data.

Therefore, the fundamental parts of any statistical analysis are the data, which can come in many forms. In this case, the data are sets of numeric values of the diagnostic features, a set of diagnostic features can be seen as a fingerprint for the related specific cable system. In general, as more data are available for analysis and interpretation, results tend to be more statistically significant and valid. The statistical confidence is an indication of the probability of a result not having occurred by chance. The adding of new data is a careful process since these data must be described, gathered, and organized using the same initial criteria. In other words, any additional data must be consistent with the original or previous datasets. This process is critical to the successful development of any criteria.

In this section the value of adding more data for statistical research was explored. To accomplish this, Tan δ stability data for PE-based cable systems were collected for a number of years. The data appear in Figure 32 by means of the probability distribution plots for two selected periods; all data collected to 2007 and all data collected to the end of 2011.

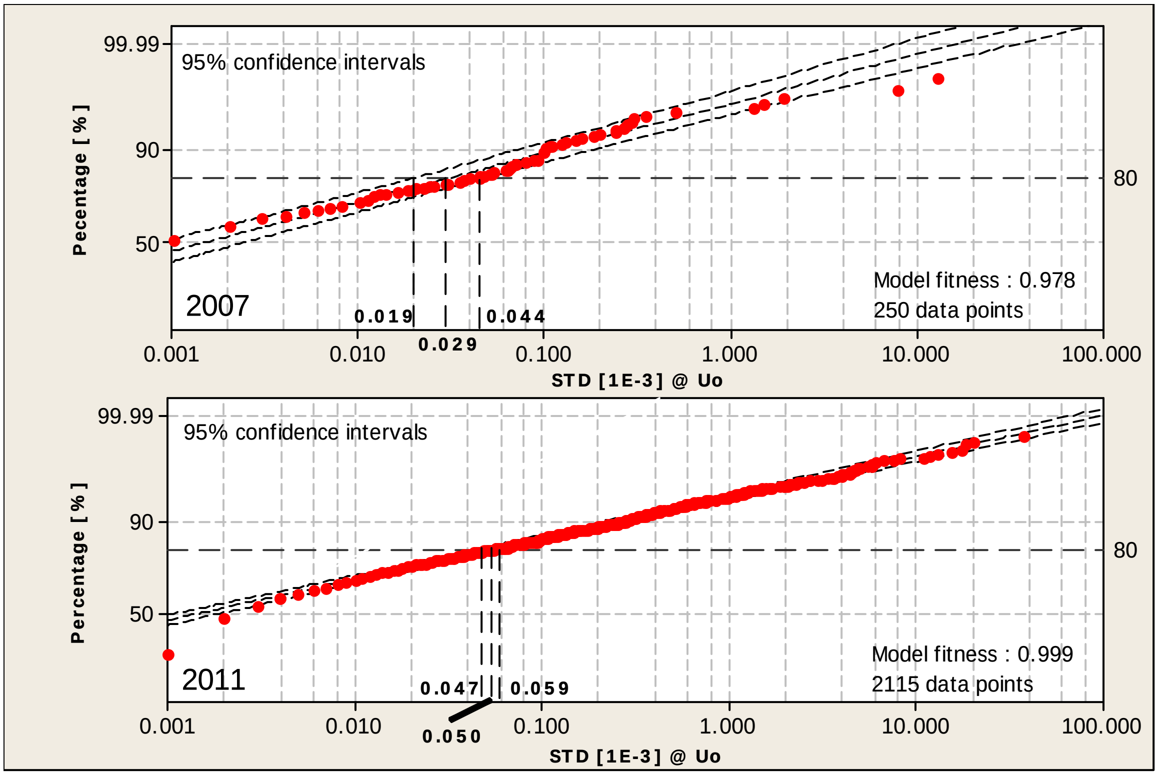


Figure 32: Comparison of 2007 (250 Data Points) and 2011 (2115 Data Points) Probability Distribution Plots for Tan δ Stability at U_0 Using Weibull Distributions and 95% Confidence Intervals

Figure 32 shows the comparison of the 2007 and 2011 probability distribution plots for the diagnostic feature Tan δ stability and U_0 using Weibull distribution parametric fits with 95% confidence intervals. The raw data are represented by the black dots, the Weibull fits and 95% confidence intervals by the dotted lines. The first case (top of Figure 32) considers the data collected up to 2007 and the second case (bottom of Figure 32) considers all the data collected up to the end of 2011, for comparison the two cases have the same scales and ranges on the two axes.

The 2007 dataset includes 250 data points while the 2011 dataset includes 2,115 data points. In relative terms, the 2007 dataset represents approximately 12% of the data in the 2011 dataset. The 2011 dataset is approximately 750% larger than the dataset from 2007. Table 23 shows a comparison of the 80th percentile estimates from the 2007 and 2011 Weibull curves in Figure 32.

Table 23. Summary for Comparison of 2007 and 2011 Probability Distribution Plots for Tan δ Stability at U_0 Using Weibull Distributions and 95% Confidence Intervals

	Case	
	Initial – 2007	***2011***
No. of data points	250	2,115
Model fitness index	0.978	0.999
Feature at 80% level [1E-3]	0.029	0.050
Lower 95% CI* [1E-3]	0.019	0.043
Upper 95% CI* [1E-3]	0.044	0.063
Range 95% CI* [1E-3]	0.025	0.020
Relative 95% CI* Range [%]	86	24

* CI: Confidence Interval

As seen in Table 23, adding more data to the analysis produces several clear benefits:

- The level for the feature is more statistically significant since the level for the 2011 case represents a greater population of cable systems; therefore, it can be inferred that the true estimated feature threshold for the whole universe of cable systems is closer to this value than the level obtained in the 2007 case.
- The population of systems tested through 2007 represents an incomplete sample set as multiple large gaps are present in the data (dataset jumps from 0.55 to 1.4). No gaps are visible in the 2011 dataset up to a stability of 9E-3.
- The width of confidence interval is significantly reduced in the 2011 dataset (by over 28%). This implies that that this estimate has a higher degree of certainty as compared to the 2007 dataset.
- The difference in the 80th percentiles estimates shows that the 2007 dataset was obtained from "healthier" cable systems than those that were tested through 2011. Applying the 2007 dataset estimate would have added 4% of the population to the "Further Study Advised" and "Action Required" classes.

Another important fact that must be noted is that in both cases the model fitness index is acceptable by being higher than 0.90; however, the model fitness index for the second case is better than the first case, which again shows the value of adding more data to the statistical analysis.

Similar statistical analyses can be realized for the other Tan δ diagnostic features; and in fact, they are presented in the next section in which the multimodal nature of the data is considered.

6.6.13 Tan δ Data Mode Analysis PE-based Insulations

The previous section has shown the value to the research of adding accurate data over time to the statistical analysis of the Tan δ diagnostic features. Specifically, it has been shown that as more data are available more precise threshold estimation and confidence intervals are realized.

However, the preceding section has only shown the analysis for one of the Tan δ diagnostic features, i.e. the first tier that corresponds to the standard deviation of the Tan δ measurements at U_0. In this case, it has been shown that the Tan δ stability data are modeled with a high degree of confidence by a single Weibull distribution. However, for the other Tan δ diagnostic features a more detailed modeling analysis is required since they cannot be modeled by a single Weibull distribution.

When data can be modeled by a single Weibull distribution the probability distribution plot and the data itself form a straight line, as seen in Figure 33. A qualitative assessment of the accuracy of model fitting can be accomplished by observing how the model lines for the estimation and confidence intervals correlate with the data points. This qualitative assessment can be expressed quantitatively by the model fitness value; if the model fitness value is high (usually more than 0.90) then the model can be used to completely represent the statistical nature of the data.

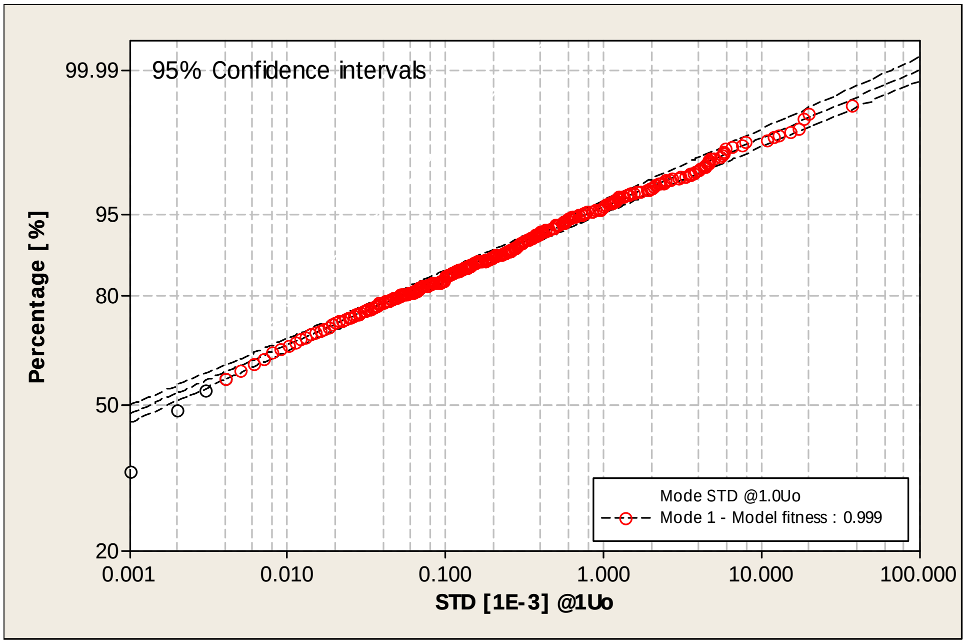


Figure 33: Probability Distribution Plot for Tan δ Stability at U_0 by Mode – PE Insulated Cable Systems

In some cases, the data cannot be represented by a single Weibull model. When this is the case, the data on a probability distribution plot do not lie on a single straight line; however, it can be modeled by several straight lines over specific ranges defined by limits on both axes of feature values and percentages. In this way, each line would represent the model for the data between the limits. Each separate model in the data is referred to as a mode; therefore, in a case in which the data can be represented by two straight lines, the data is said to have two modes.

Determining the number of modes and their limits is generally not a simple task. Usually heuristic techniques are applied to accomplish this goal. However, determining only the number of modes is a relatively easy task that is generally accomplished by performing a qualitative assessment of the probability distribution plot as the graphical representation enables the critical points to be readily identified. As an example, consider Figure 34 that represents the probability distribution plot of the second tier or diagnostic feature (i.e. Tip Up between $1.5U_0$ and $0.5U_0$). As seen in Figure 34, the data in this case can be represented by two straight lines or models that intersect around 50%; therefore, it is clear that the data have two modes. Moreover, Figure 35 shows the probability distribution plot of the third tier or diagnostic feature (i.e. Tan δ at U_0); as seen in the figure, this feature is also composed of at least two modes. The limit in this case is also approximately 50%.

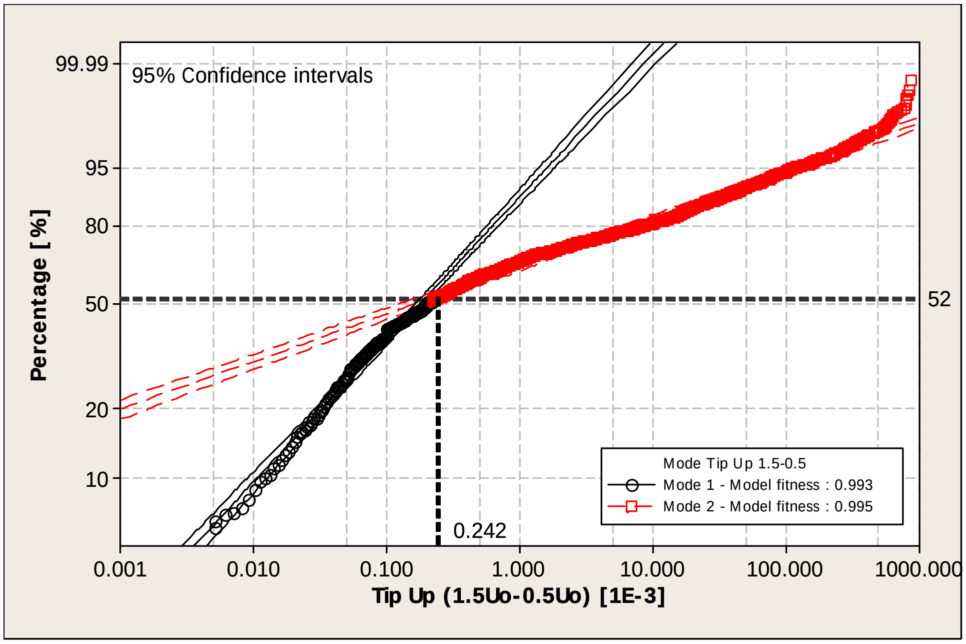


Figure 34: Probability Distribution Plot for Tip Up ($1.5U_0$-$0.5U_0$) by Mode – PE Insulated Cable Systems

Determining the limits between modes is not simple. In fact, there is no known established method to accomplish this. However, the limits are determined here by solving an optimization problem. Specifically, the limits between modes are determined by maximizing the model fitness for the two modes. In other words, the mode limits are determined in a way that the best model representation is accomplished for both modes. To find the limits in this way, an exhaustive search is performed around the possible values from the qualitative assessment; then, the limits that yield the best results are selected as the solution.

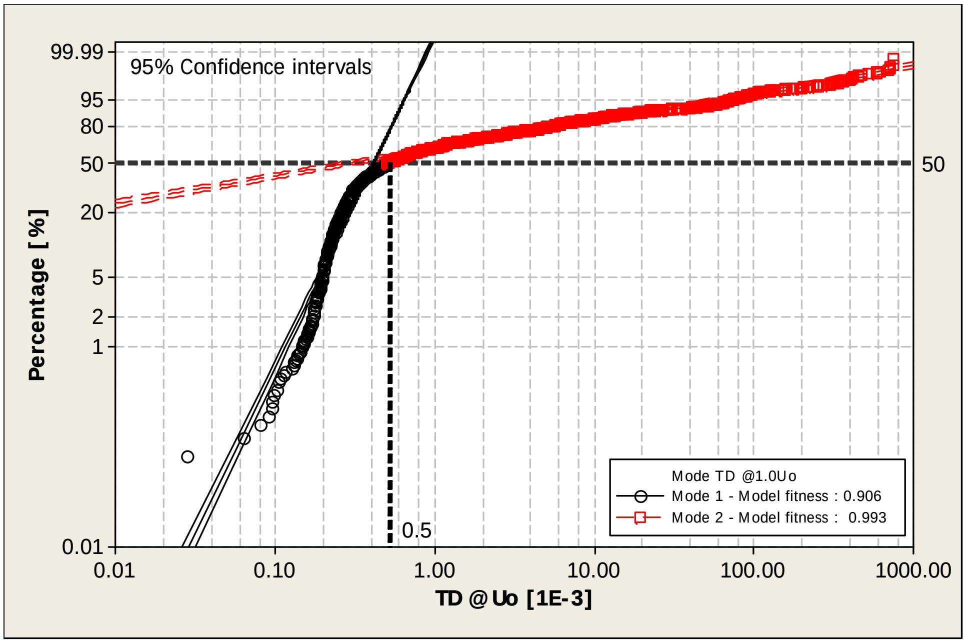


Figure 35: Probability Distribution Plot for Tan δ at U_0 by Mode

This procedure determined the mode limits for the second and third tiers or Tip Up between $1.5U_0$ and $0.5U_0$ and Tan δ at U_0. Results of the procedure appear in Figure 34 and Figure 35 respectively.

As observed in Figure 34 and Figure 35 both diagnostic features show two modes, the results of the analysis for determining the mode limits appear in Table 24 including the Tan δ Stability diagnostic features.

Table 24. Summary of Data Mode Analysis for Tan δ Features

Feature	No. Modes	Mode Limits [%] / [1E-3] (Y-axis/ X-axis)	Model Fitness Index
Tan δ Stability - STD (U_0)	1	-	0.999
Tip Up - TU ($1.5U_0$ & $0.5U_0$)	2	52/0.242	Mode 1: 0.993
			Mode 2: 0.995
Tan δ - TD (U_0)	2	50/0.5	Mode 1: 0.906
			Mode 2: 0.993

As seen in Table 24, the Tan δ stability at U_0 diagnostic feature is composed of only one mode whilst the Tip Up between $1.5U_0$ and $0.5U_0$ and Tan δ at U_0 are each composed of two modes. Note also that for all diagnostic features and modes the model fitness index is high which indicates that data are properly modeled when modes are considered. The most important use of mode analysis is that results can determine the 95% confidence intervals of the diagnostic features' thresholds presented in Table 25.

Table 25: Criteria for Condition Assessment of PE-based Cable Systems – Collation of Research Data to December 2011

Condition Assessment	Tan δ Stability at U_0 [E-3]		Tip Up ($1.5U_0 – 0.5U_0$) [E-3]		Tan δ at U_0 [E-3]
PE, HMWPE, XLPE, & WTRXLPE					
No Action Required	<0.05	and	<5	and	<4
Further Study Advised	0.05 to 0.5	or	5 to 80	Or	4 to 50
Action Required	>0.5		>80		>50

This is an important research contribution because generally assessment values are thought of as crisp thresholds when in fact they are results of statistical analyses of data and therefore they always contain a level of confidence related to them. The level of confidence is determined and clarified here by using the mode analysis to properly model the data. The 95% confidence interval limits for Tan δ features thresholds from Table 25 appear in Table 26 considering the two levels of 80% and 95% of condition assessment.

Table 26. Modal Analysis Results for the 80% and 95% Confidence Interval Limits for Tan δ Diagnostic Feature Thresholds Shown in Table 25.

Diagnostic Feature	95% Confidence Interval Limits [E-3]					
	80% Level			95% Level		
	Value (Table 25)	Lower Limit	Upper Limit	Value (Table 25)	Lower Limit	Upper Limit
Tan δ Stability - STD (U_0)	0.050	0.047	0.059	0.50	0.41	0.61
Tip Up - TU ($1.5U_0$ & $0.5U_0$)	5.00	4.14	6.04	80.00	64.53	99.17
Tan δ - TD (U_0)	4.00	3.45	4.64	50.00	42.34	59.00

Table 26 shows the modal analysis results for the 80% and 95% confidence interval limits for Tan δ diagnostic feature thresholds shown in Table 25. As an example, if the diagnostic feature of Tan δ stability at U_0 is chosen at the 80% level, the threshold value is 0.05 (see Table 25) and there is a 95% probability that this threshold is between the range of 0.047 and 0.059. Therefore, care must be taken when the threshold values are used as they are a range rather than individual values. In practice, when diagnostic features are close to or at these threshold values, additional cable system information must be considered to determine a condition assessment. If, for example, the condition assessment falls between “No Action Required” and “Further Study Advised”, those actions specified by a “Further Study Advised” condition could be performed to more clearly determine a valid condition assessment.

6.6.14 High Voltage Systems Sub Protocol

The majority of VLF portable diagnostic equipment is designed for testing MV cable systems up to 35 kV. However, newer VLF technology has allowed for testing voltages up to 90 kV. Therefore, voltage restrictions for VLF testing of HV power cable systems have disappeared; however, the main issue is to reduce the testing time and risk of failure during the test by maintaining significant diagnostic features for condition assessment.

The *CDFI* has also explored diagnostic tests on 46 kV (XLPE) and 69 kV (XLPE) HV cable systems as well as subsea cables (XLPE and Paper). In both cases, it is desirable from the utility perspective to keep test voltage levels at or below operating voltage. In the case of subsea cables, the critical and costly nature of these systems makes it unlikely that a utility would want to stress these systems above normal operating voltage. As a result, *CDFI* proposes to utilize a reduced voltage protocol for making Tan δ measurements on these types of cable systems.

The standard approach used in the *CDFI* for medium voltage cable systems is shown in Figure 36. Several measurements are made at each voltage using a 0.1 Hz VLF source with a maximum voltage of 1.5 U_0 for a Tan δ Ramp test and 2.2 U_0 for a Monitored Withstand.

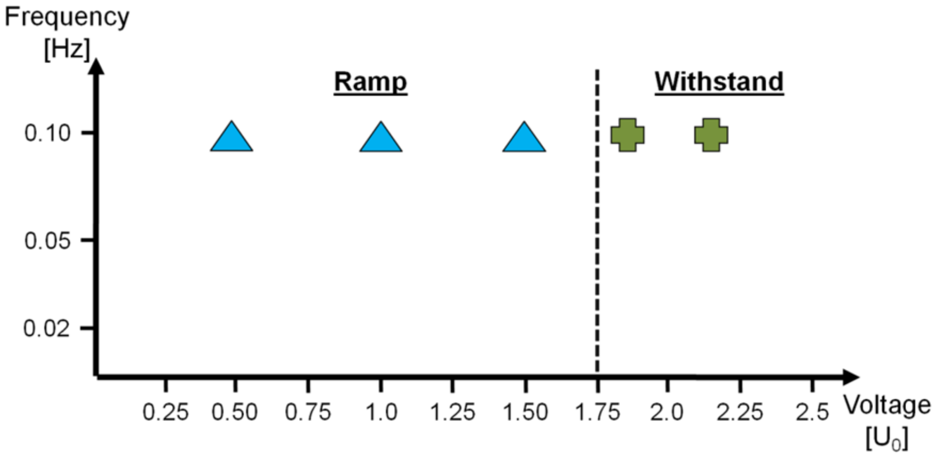


Figure 36: Medium Voltage Tan δ Protocol and Withstand Voltage Levels

In the case of HV and subsea cable systems, tests conducted as part of the *CDFI* perspective consider lower voltages (all test voltages less than or equal to U_0) as well as multiple frequencies. The protocol appears in Figure 37.

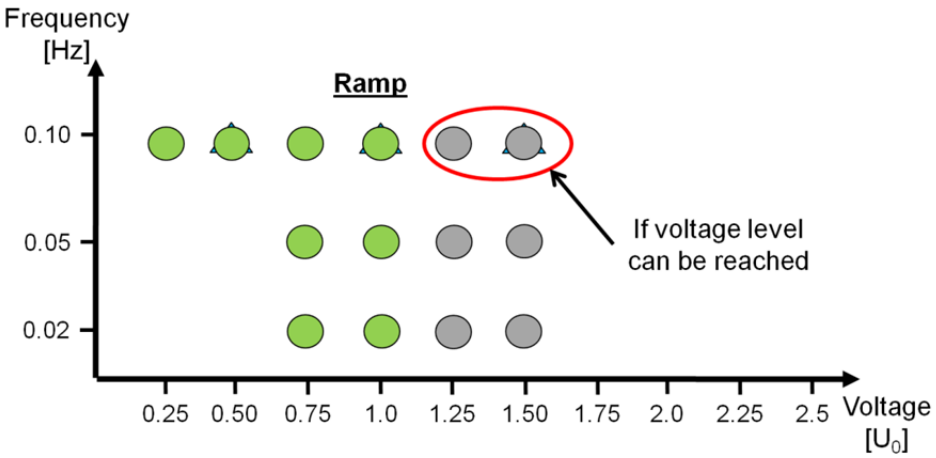


Figure 37: High Voltage/Subsea Tan δ Protocol

The additional voltage steps in the HV/subsea protocol allow gaining a better understanding of the linearity of the voltage dependency. The protocol in Figure 37 also makes use of the variable frequency capability of VLF units to test at frequencies as low as 0.02 Hz. This is otherwise known as Frequency-Domain Spectroscopy (FDS). Past work with IREQ and their Time-Domain Spectroscopy (TDS) unit has shown that additional information can be obtained using a variable frequency approach.

The following diagnostic features can be used in the assessment:

- Tan δ Stability at U_0 and 0.1 Hz,
- Tip Up/Differential Tan δ between U_0 and 0.5 U_0 at 0.1 Hz,
- Tip Up of the Tip Up on Tan δ between 0.25 U_0 and 0.5 $U_{0,}$ 0.5 U_0 and 0.75 $U_{0,}$ 0.75 U_0 and U_0 at 0.1 Hz,
- Tan δ Stability at U_0 and 0.02 Hz,
- Frequency Stability – Mean Tan δ at 0.02 Hz, Mean Tan δ at 0.05 Hz, and Mean δ at 0.1 Hz.

An example of Tan δ measurements from research on a 69 kV cable system shows the value of the added voltage steps. Figure 38 shows the Tan δ for this three phase system considering the MV protocol and limiting the voltage to U_0 (as requested by the utility). Also, three phases have some voltage dependence but since measurements were only made at two voltage levels there is no way to examine the non-linear nature of the voltage dependence.

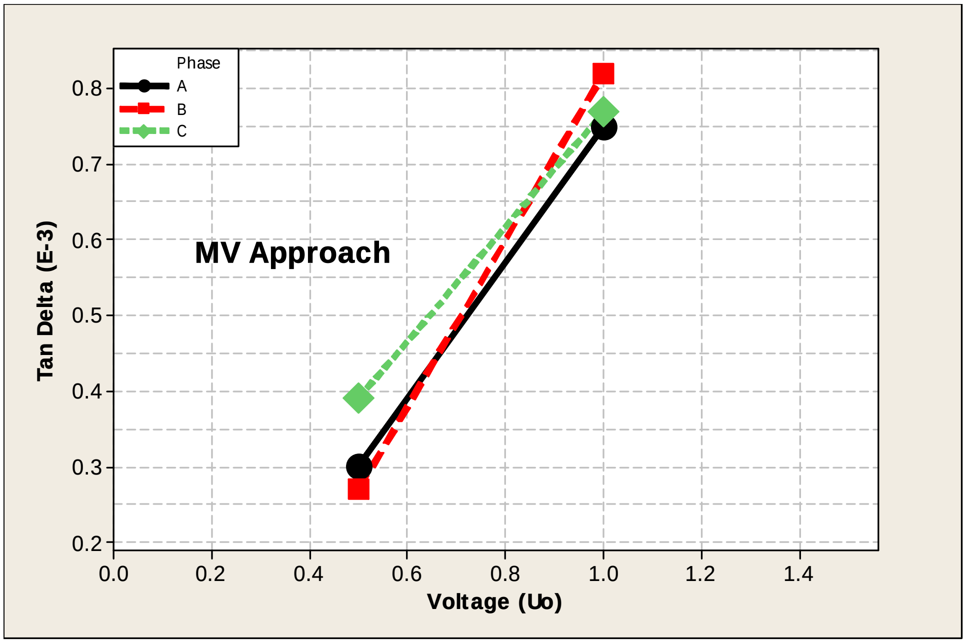


Figure 38: Medium Voltage Tan δ Approach on a 69 kV Cable System

Figure 39 shows the same three phase system tested according to the HV/subsea protocol. Clearly, the voltage dependence is non-linear and different for each phase.

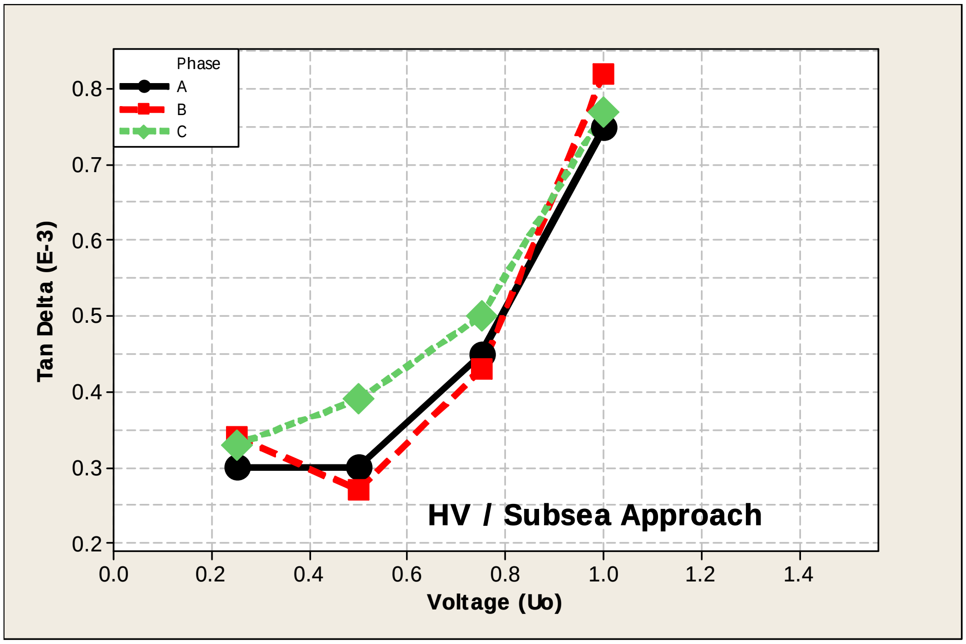


Figure 39: HV/Subsea Tan δ Approach on a 69 kV Cable System

The frequency dependence of the Tan δ, Tip Up, and Stability are also valuable as shown in the sample test of Figure 40. This figure shows the Tip Up – Tan δ map for four systems with measurements made at 0.1 Hz and 0.02 Hz. The Tan δ increases at a lower frequency as expected, but the Tip Up for Cable 3 and Cable 4 increased at 0.02 Hz. These Tip Ups were identical at 0.1 Hz.

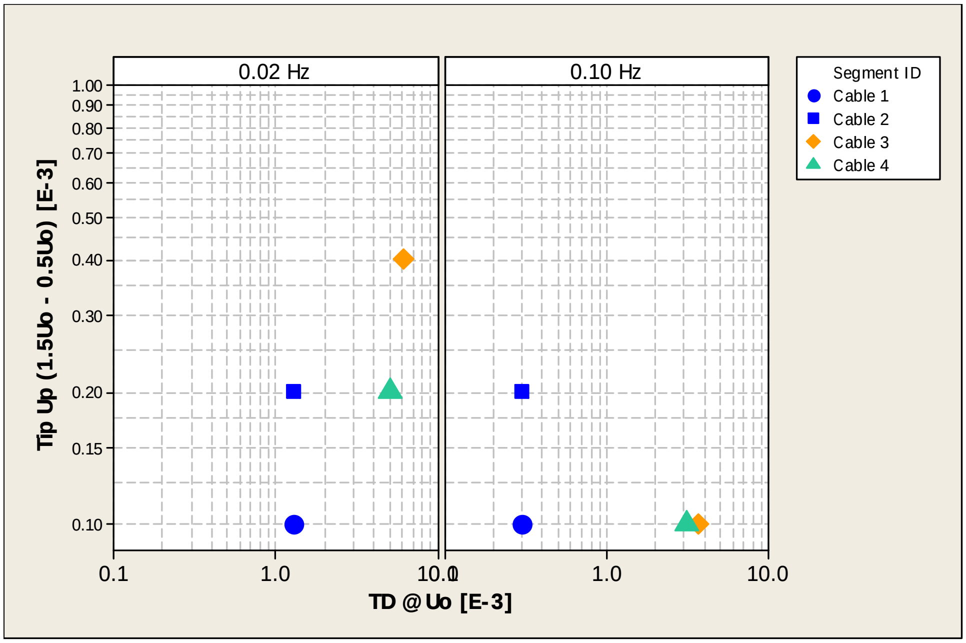


Figure 40: Sample Frequency Domain Spectroscopy Data for Four Circuits – 0.02 Hz (Left) and 0.1 Hz (Right)

This additional information will be useful as greater numbers of HV and subsea cable systems are tested. As more data are collected, the development of assessment criteria is possible by establishing threshold values to segregate between the different condition assessment classes.

6.6.15 Retests of PE-based Insulations

Most texts on Tan δ testing note the benefits of comparing previous measurements. One of the goals of field tests performed in *CDFI Phase II* is to revisit systems that were originally tested as part of *CDFI Phase I* to establish what changes in condition these systems experienced over the intervening years. These tests were conducted with the goal of understanding the outcomes of diagnostic tests. Thus, the sections were not remediated but were left in service to establish their service performance. Thus, if the criteria had been followed in 2007, service failures would have been prevented.

Several such retests have been completed and the data have been collated together to give a sense of the level of change that systems experienced. Table 27 contains a summary of the test results for the 70 systems that were retested as part of *CDFI Phase II*.

Table 27: Summary of VLF Tan δ Retest Results

		TO					
		1-3 Years Between Tests			3-5 Years Between Tests		
		No Action Required	Further Study	Action Required	No Action Required	Further Study	Action Required
FROM	No Action Required	18	1	0	13	0	0
	Further Study	11	2	1	3	7	1
	Action Required	2	1	1	0	0	9
	TOTAL	37			33		

Several observations result from the data in Table 27:

- Cable systems with good performance remained good (97%),
- Several cable systems assessed as “Further Study” improved in performance (56%) as a result of utility actions.
- 44% of “Further Study” systems remained the same or degraded further.

6.6.16 Age Lines

The condition assessment using VLF Tan δ in conjunction with the power cable system age allow for estimating the evolution of the condition assessment over time; in other words, a quantitative estimation of how the power cable systems are changing assessment classes with time can be accomplished. This information is of extreme importance because if the power system age is known, then a prognosis can then be made on how it will transition between condition assessment classes in the future. This increases the importance of knowledge-based supported decision making for asset management of power cable systems.

Particularly, field tests at Snopud, Duke Energy, and WE Energies have provided, in addition to VLF Tan δ test data, the installation year for each of the tested systems. It is, therefore, possible to consider these data to expand the research to develop the concept of Tan δ age lines. The Tan δ provide an estimation of what percent of cable systems are in each condition assessment class as time evolves. This analysis has only been performed for PE-based insulations. Figure 41 shows two age lines for Tan δ measurements, specifically:

- “Further Study Advised or Worse” – It is necessary to combine the “Further Study

Advised" and "Action Required" classes in order for the data censoring to work out properly. As a result, the percentage of "Further Study Advised" systems is the difference between the "Further Study Advised and Worse" curve and the "Action Required" curve.

- "Action Required" – The age line for systems classified as "Action Required".

Furthermore, the assigned assessment class was determined using the *CDFI*-PCA assessment tool discussed earlier.

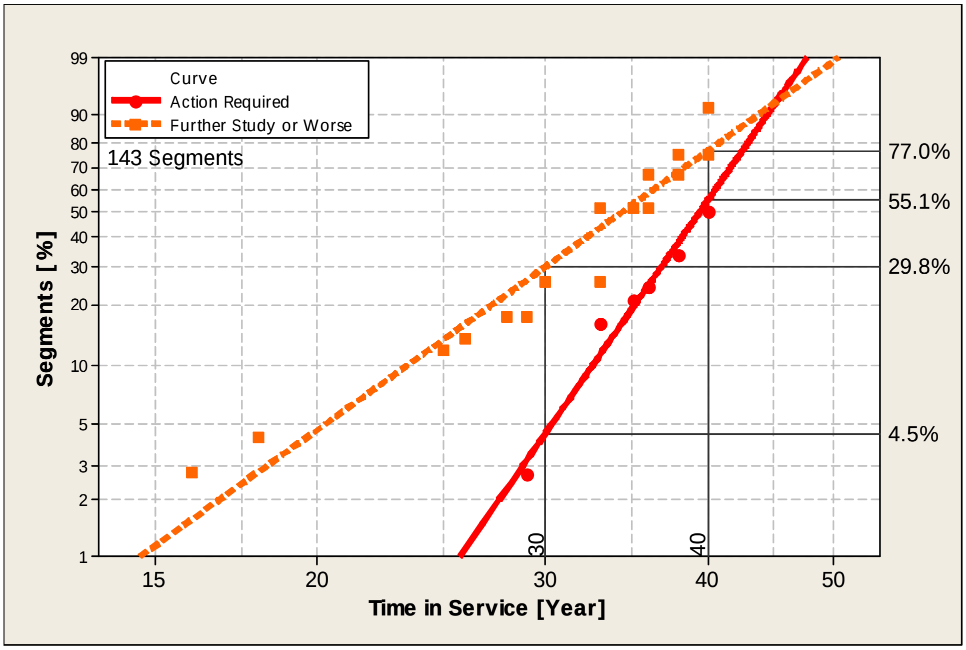


Figure 41: Tan δ Age Lines – "Further Study Advised & Worse" and "Action Required"

As Figure 41 shows, the percentage of systems assessed as "Action Required" increases with age. Table 28 shows how the 30-year prediction compares to the 40-year prediction.

Table 28: Comparison of 30 and 40 Year Tan δ Assessments

Assessment Class	Age	
	30 Years [%]	40 Years [%]
No Action Required	70.2	23.0
Further Study	24.3	21.9
Action Required	4.5	55.1

Figure 41 provides the utility with useful planning information that can establish which areas should be tested. It also provides guidance as to how systems in the "No Action Required" class transition to "Further Study Advised" and, eventually, to "Action Required". This is important as the utility must continue to manage its cable system long after the initial round of testing is completed.

6.6.17 Feeder Assessments

It is becoming increasingly common for utilities to test three phase systems as part of their VLF Tan δ diagnostic programs. The criteria provided to date by the *CDFI* only presents guidance at the individual power cable system or “Phase” level and do not expressly discuss how the three phases can be considered as a single feeder section or in other words a “Feeder” level assessment. The most obvious approach used for adapting the current criteria is to simply take the worst recommendation/assessment and apply this to the entire feeder section; i.e. the overall condition assessment at the “Feeder” level would be the worst case from the condition assessment at the “Phase” level.

As an example, a feeder with two phases assessed at the “Phase” level as “No Action Required” while the third phase is “Action Required” would yield a “Feeder” level assessment of “Action Required.” However, this ultimately leads to a higher than expected percentage of “Action Required” and “Further Study Advised” when one considers feeder sections. Therefore criteria for assessment at the ‘”Feeder” level based on the same approach developed within the *CDFI* for Tan δ that identifies critical dielectric feature levels that separate “usual” from “unusual” feeders is required.

To properly assess these feeder sections, it is necessary to develop a different set of criteria that not only addresses the percentile issue above but also considers the potential phase-to-phase differences. The following features are suggested for the *CDFI* for condition assessment at the “Feeder” level:

- Maximum Phase Tan δ Stability – The highest Tan δ stability of all three measured at U_0.
- Tan δ Range for Three Phases – The difference between the highest Tan δ at U_0 and the lowest Tan δ at U_0.
- Poorest Phase Tip Up – The highest Tip Up measured in any one of the three phases.
- Poorest Phase TuTu – The highest Tip Up of the Tip Up (TuTu) measured in any one of the phases.
- Maximum Phase Mean Tan δ – The highest mean Tan δ measured on any one of the three phases at U_0.

The same approach used to develop the current *CDFI* Tan δ criteria at the “Phase” level could be employed to identify the critical levels for “Further Study Advised” and “Action Required.” It will be necessary to increase the percentiles from the 80th and 95th percentiles in order to obtain a class distribution that is in line with the intended 80/15/5 (“No Action Required”/“Further Study Advised”/“Action Required”) that has been used in the past to separate “usual” from “unusual” feeders. The new percentiles can be obtained using probability theory and, for ease of analysis, the assumption is made that the features are statistically independent. This assumption is likely rather weak for the Tip Up and TuTu and the Maximum Phase Tan δ and Tan δ Range but it does allow for a straightforward and relatively simple solution. This appears in Equation 4 for the class “Action Required”.

$$\binom{5}{1}P(AR)\big(1-P(AR)\big)^4+\binom{5}{2}P(AR)^2\big(1-P(AR)\big)^3 \\ +\binom{5}{3}P(AR)^3\big(1-P(AR)\big)^2 \\ +\binom{5}{4}P(AR)^4\big(1-P(AR)\big)+P(AR)^5=0.05$$ **Equation 4**

where,

P(AR): Probability of "Action Required,"
$\binom{x}{y}$: "x choose y" = $\frac{x!}{(x-y)!y!}$.

Equation 4can then be solved numerically to yield a probability of "Action Required" of 0.01. This in turn implies that the new "Action Required" percentile should be set to the 99th percentile. The "No Action Required" percentile can be similarly calculated to yield the 96th percentile. The remaining 3% between 96% and 99% would then correspond to the "Further Study Advised" class.

Similar equations can be derived and solved to yield the appropriate percentiles for different numbers of features. The general form for the probability calculation for "No Action Required" and "Action Required" using a set of independent features correspond to Equation 5 and Equation 6, respectively.

$$P(NA)^n=0.80$$ **Equation 5**

where,

P(NA): Probability of "No Action Required" (can be thought of as the dividing point between "No Action Required" and "Further Study Advised."

$$\sum_{i=1}^{n}\binom{n}{i}P(AR)^i(1-P(AR))^{n-i}=0.05$$ **Equation 6**

The challenge with the above equations is selecting features that are truly independent. Additional work is needed in this area. However, the equations have been applied to the *CDFI* paper insulation (PILC) database and criteria for condition assessment at the "Feeder" level have been developed from this research, these criteria appear in Table 29.

Table 29: VLF Tan δ Criteria for PILC Cable Systems at “Feeder” Level from *CDFI* Research

FEEDER ASSESSMENT

These criteria CANNOT be used unless data are available for all five features *

Condition Assessment [E-3]	No Action Required	Further Study Advised	Action Required
Max Phase Stability for TD_{U_0} (standard deviation)	< 1.2	1.2 to 2.3	> 2.3
	and	or	
Tan δ Range for Three Phases (Max Mean TD_{U_0} –Min Mean TD_{U_0})	< 30	30 to 50	> 50
Poorest Phase Tip Up ($TD_{1.5U_0} - TD_{0.5U_0}$)	-45 to 24	-57 to -45 or 24 to 30	< -57 or > 30
	and	or	
Poorest Phase TuTu $\{(TD_{1.5U_0} - TD_{U_0}) - (TD_{U_0} - TD_{0.5U_0})\}$	< 16	16 to 23	> 23
	and	or	
Max Phase Mean TD_{U0}	< 170	170 to 210	> 210

* If all five features are not available, use the worst condition assessment at the “Phase” level as the assessment for the “Feeder” level.

In the assessment scheme shown in Table 29, the condition of a cable system is assessed as: “No Action Required”, “Further Study Advised”, and “Action Required”. Once a circuit is assessed as “Further Study Advised” or “Action Required”, additional work is needed to restore the feeder to reliable operation.

In the case of a “Further Study Advised” assessment, the following actions are recommended:

- Review data for a rogue measurement in the sequence – most common in the first acquisition,
- Re-clean terminations and repeat measurements,
- Compare measurements with previous tests or other results from other phases of the circuit,
- Place on “watch list”,
- Confirm type of PILC circuit – belted or H-type. Belted cables use higher loss oils and are, generally speaking, older than H-type designs. Belted designs would likely produce increases in Tip Up, TuTu, and Mean Tan δ.

- Investigate condition of oil-filled switches used for sectionalizing or disconnecting transformers – a comparison of the phases could identify unusual switch behavior. Also, an analysis of Tan δ as a function of the number of switches in each circuit would be useful for determining whether or not the switches have a significant effect on Tan δ,
- Disconnect all cable terminations from switchgear and retest (if practical for the specific switch gear involved), or
- Consider feeder to feeder comparisons.

The recommended actions for circuits assessed as "Action Required" are the same as the actions for "Further Study Advised" with the following additions:

- Conduct IEEE Std. 400.2 – 2013 Monitored Withstand test for 60 min,
- Retest in near future, or
- Place on "watch list" and consider remedial actions (replacement or repair) for the feeder.

There are some circumstances where the precise cable design (e.g., shielded or belted, conducting or non-conducting shield), system composition, insulation material, or vintage is known. Therefore, in these cases the database would allow for the development of "cable system specific" criteria to provide better discrimination. A case study illustrating these circumstances follows.

The *CDFI* has had the opportunity to compare "Phase" and "Feeder" condition assessments using the different available criteria for a utility feeder PILC database. Specifically, since 2010, the utility has maintained an underground cable system diagnostic program for its PILC feeder circuits. One of the primary diagnostics used in this program is VLF Tan δ. In total, 72 feeder circuits of 6.9 kV (U_0) were tested with a total of 213 phase tests completed. This includes tests from 2010 through March 2012.

Using the utility VLF Tan δ results in and the criteria presented in Table 6, Table 14, and Table 29, it is useful to construct a summary table that shows how the feeder *CDFI* customized criteria compare to the phase IEEE and *CDFI* criteria. Table 30 contains this summary.

Table 30: Summary of the Utility Specific Condition Assessments for Each of the Available Criteria Sets

Criteria	**Assessment Class Distribution**		
	No Action Required	**Further Study Advised**	**Action Required**
Assessment at "Phase" Level [%]			
IEEE Std. 400.2 – 2013 (Table 6)	47	43	10
CDFI Perspective – (Table 14)	51	37	12
Assessment at "Feeder" Level [%]			
Feeder IEEE Std. 400.2 – 2013	39	39	22
Feeder *CDFI* Perspective	37	45	18
Feeder *CDFI* Perspective (Table 29)	82	4	14

The comparison between assessments at the feeder level using the different criteria appear graphically in Figure 42.

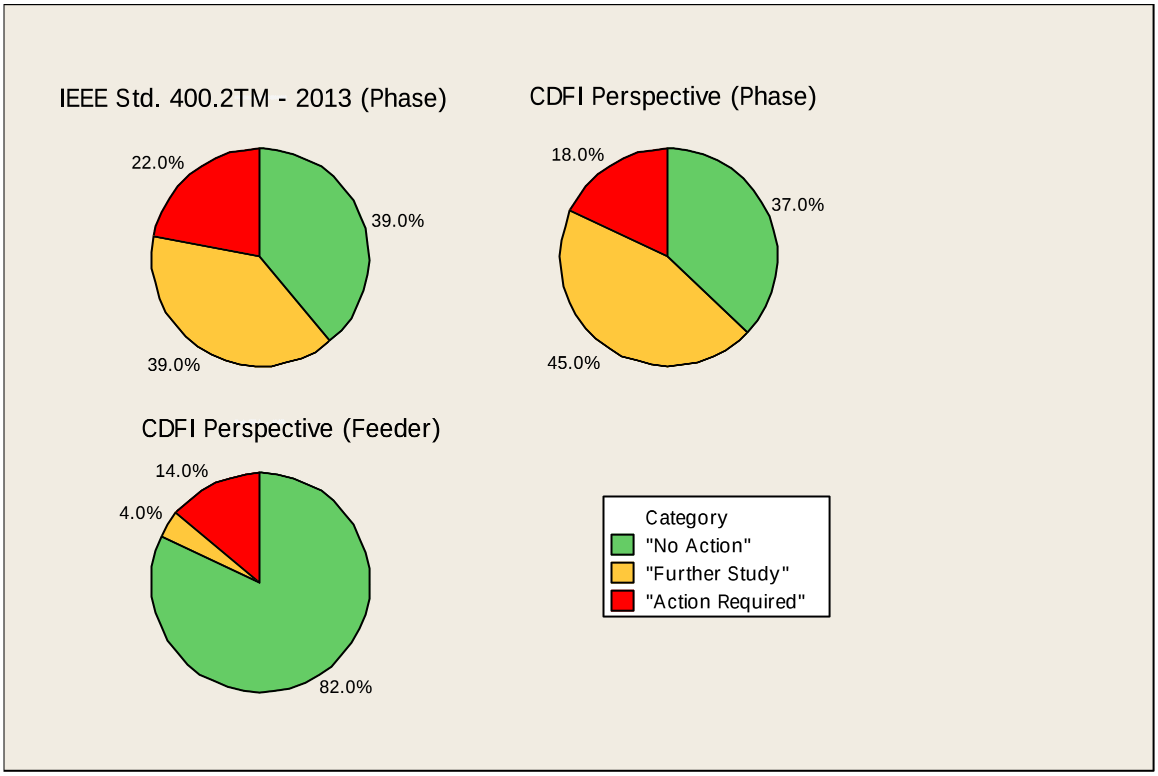


Figure 42: Comparison of Utility Condition Assessments at the "Feeder" level for each of the Available Criteria Sets

As seen in Table 30 and Figure 42, using VLF Tan δ Criteria for PILC Cable Systems at the "Feeder" Level, the overall assessments for the "Feeder" level are distributed between classes much closer to expectations (85%/15%/5%). Thus, these criteria could be used in place of either the IEEE or *CDFI* criteria for assessment at the "Feeder Level" of PILC power cable systems.

6.6.18 Cable Injection

The *CDFI Phase II* has deployed VLF Tan δ measurements on power cable systems recently injected for cable rejuvenation; more importantly, compared those measurements with the ones of cable systems planned or rejected for cable rejuvenation in the same subdivisions. The diagnostic field tests were performed on Duke Energy URD type underground cable systems located in Ohio and Indiana, 7.2 kV XLPE unjacketed (15 kV cable design). Five subdivisions were tested. The cable systems in the Ohio subdivisions have been injected using the un-sustained (low pressure) technology while the cable systems in the Indiana subdivisions have been injected using the sustained (high pressure) technology. The field tests performed in Ohio and Indiana are the first experience within the *CDFI* to test injected cable systems and compare results with non-injected systems. All of these systems have seen similar operating field conditions.

At the time of testing, there were two injection technologies used by Duke Energy to rejuvenate their XLPE cable systems. The technologies were the un-sustained and sustained methods; specifically, the un-sustained method was used in Ohio and the sustained method was used in Indiana. One *CDFI* objective is to determine how rejuvenation might affect Tan δ values. This knowledge will enhance the assessment of rejuvenated cable systems over their extended service life. In addition, all of the generated information will be relevant to other utilities that now perform, or plan to perform, cable injection on a regular basis.

The two injection technologies are different but share the same underlying physical mechanisms and chemical principles:

- All terminations are replaced.
- All (sustained) or many (un-sustained) splices are replaced.
- Water is expelled from the conductor by the injection fluid.
- Remnant water between the conductor strands, insulation, and water trees reacts with the silicone based fluid and is chemically bonded to the injection fluid.
- Oligomerization (a chemical process that converts monomers to a finite degree of polymerization) reactions occur with the water and the extended (not crosslinked) molecules diffuse more slowly (maximizing retention).
- The exclusion and binding of the water with the injection fluid is postulated to retard the growth of further water tree areas inside the bulk cable insulation, this is a topic of ongoing study.
- Special (hydraulic) splices and terminations are used.
- After injection, cable system reliabilities are reported to be improved, this improvement can be due to:
  1. Replacement of all poorly performing (aged) terminations.
  2. Replacement of many poorly performing (aged) splices.
  3. Improved moisture barriers for the new splices and cable conductor.
  4. Reduced rates of tree growth within the bulk cable insulation.

Independent of the injection technology used, the integrity of the neutral is checked before injection. If the neutral is degraded by more than 50%, the cable system is rejected. Neutral integrity is assessed by the technology provider using the TDR and Ohm-Check techniques.

Injection may also not be possible if there are more than two splices and/or the fluid cannot be pushed through the system. The fluid reaction times are typically between 21 days and 6 months for the unsustained and sustained technologies respectively; but times also depend upon temperature, moisture content, and reaction fluid technology. All tested power cable systems have completely reacted before testing.

Therefore, this section presents an analysis on how cable injection affects the Tan δ measurements represented here by four Tan δ diagnostic features. Given the limited number of Tan δ measurements made on injected cable systems it is not yet clear how the injection process influences Tan δ. In fact, the complex nature of the injection process makes it difficult to predict how injection affects the dielectric characteristics of the insulation. As shown before, the PE-based *CDFI*-PCA tool was used to determine the overall assessment of cable systems (i.e. “No Action Required”, “Further Study Advised”, or “Action Required”). While this is the best criteria available to date, this approach may not be the most suitable assessment method for injected cable systems as the insulation now includes other compounds not found in new PE-based insulations. Therefore, it is useful instead to directly compare the raw measurement data.

Figure 43 shows the box plots of each Tan δ diagnostic feature by injection and injection technology. Remember that only one injection technology was used in any particular subdivision. It is, therefore, best to compare each injection technology with its corresponding group under “No Injection” as this represents the subdivisions in the same state.

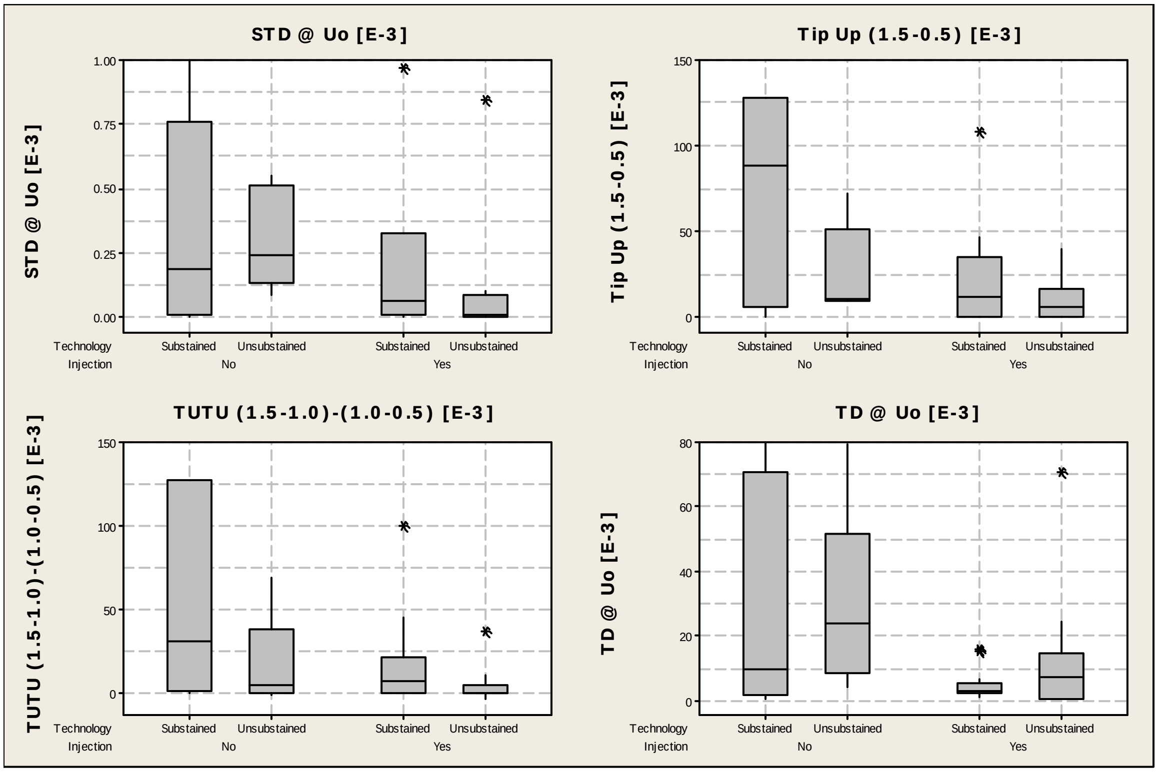


Figure 43: Tan δ Diagnostic Features by Injection Technology

Figure 43 illustrates that in general (and independent of the injection technology), all diagnostic features have narrower ranges and lower magnitudes on the injected systems. In other words, the test results indicate that these systems are in overall better condition than those that were not injected.

When comparing injection technologies, Figure 43 gives an indication that the un-sustained injection method has lower ranges and magnitudes for Stability, Tip Up, and TuTu than the sustained (high pressure) method. The cables injected using the sustained method, on the other hand, display lower Tan δ at U_0. However, it is important to emphasize that this observation is only valid for the cases studied herein; thus, these results cannot be generalized. The results are in general systemic; however, a similar conclusion might be expected.

Thus, the field experience reported has identified the following advantages of the cable injection:

- Accessories are replaced, which minimizes the likelihood of their causing near-term future failures.
- Cable system neutral condition is evaluated; only systems with 50% of remaining neutral or better are injected.
- Water is pushed out of the conductor and replaced by the injection fluid which over time polymerizes and acts as a conductor blocking agent.
- Injection fluid diffuses through the insulation and reacts with the water in the aged water-tree regions; however, this has not yet been confirmed by the *CDFI*.
- According to the system operators, injection overall has helped on improving system reliability; however, the mechanisms of how this is accomplished have not yet been assessed.

6.6.19 Effect of Splices

There has been ongoing debate within IEEE-PES-ICC and other organizations as to the effect of accessories on the Tan δ measurement. It is, therefore, useful to examine the Tan δ as functions of the number of splices. It has been suggested that terminations and splices could have a significant effect on the measured Tan δ values. The accessories themselves could overly influence the measurement, and this has generally been observed for the two following cases:

- The insulation losses for a certain type of accessory (e.g. resistive field grading accessories) are higher than the cable insulation losses.
- Traditional accessory types that have reached highly degraded condition and thus their insulation losses are higher than the cable insulation losses.

Therefore, when performing Tan δ measurements, if possible, the number of accessories, types, and conditions should be considered in order to evaluate their effects on the Tan δ value of the cable system. It is important to recall that for field testing applications, the focus on deploying diagnostics is to assess the condition of the power cable system as a whole; i.e. cable plus accessories. Thus in this scenario, if Tan δ measurements indicate an “Action Required” and it is due to a highly degraded accessory, then the application of Tan δ is considered successful.

During *CDFI Phase II*, Tan δ field test data have been collected to help understand the effect of the number of splices on Tan δ measurements. The data have been obtained from two testing sites:

- The first site is an aged URD with power cable system of 7.2 kV U_0, XLPE, unjacketed, and 15 kV cable design.
- The second site is a new feeder type power cable system of 20 kV U_0, jacketed, and 35 kV cable design.

Results for the Tan δ magnitude at U_0 as a function of number of splices for the first and second sites appear in Figure 44 and Figure 45, respectively.

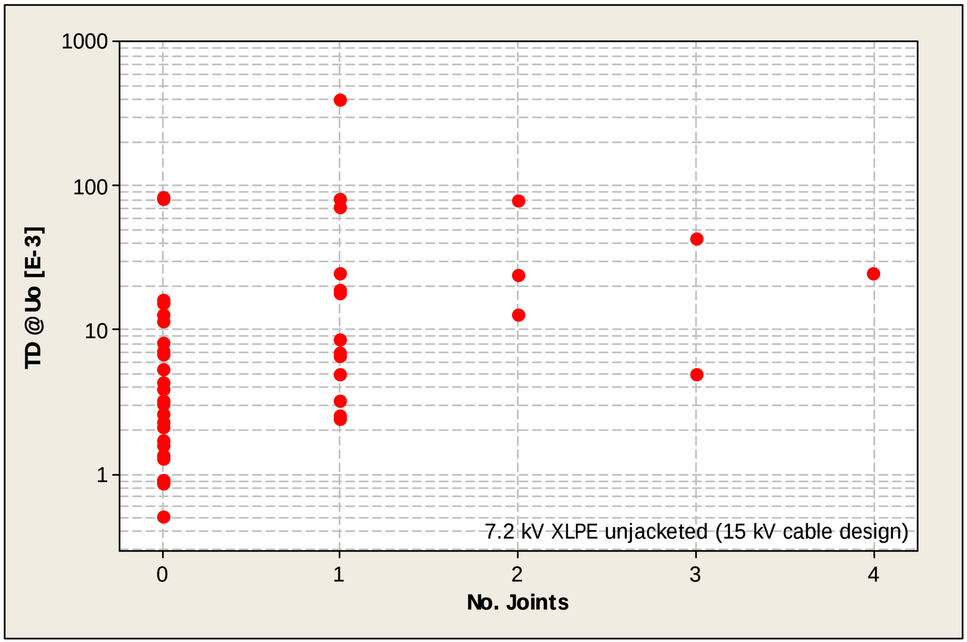


Figure 44: Tan δ versus Number of Joints (1st Site) for an Aged XLPE System

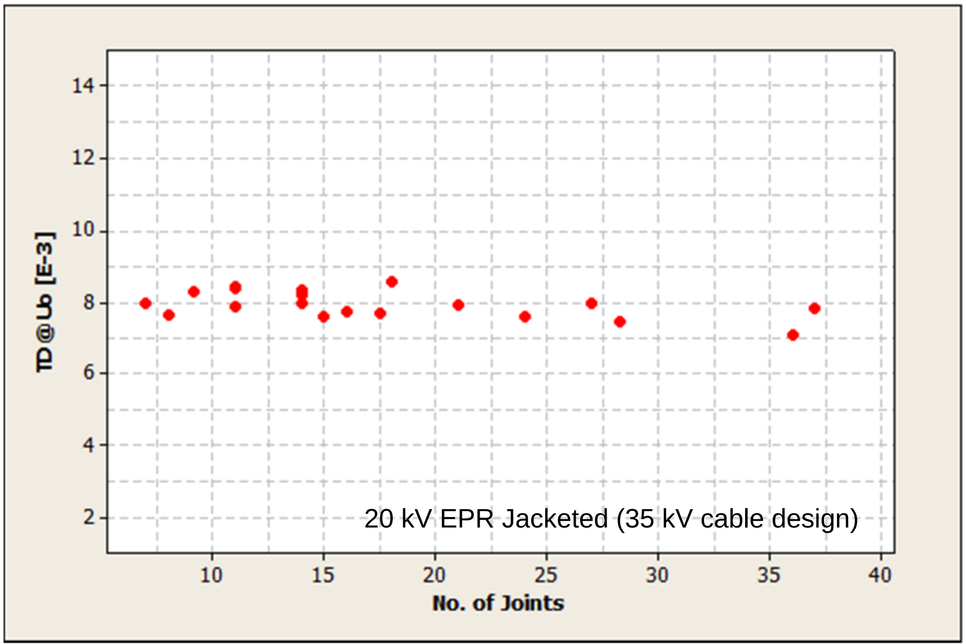


Figure 45: Tan δ versus Number of Joints (2nd Site) for a New EPR System

As the figures illustrate, there is no discernible change in the Tan δ with increases in the number of joints. Moreover, as mentioned before, it is sometimes conjectured that higher Tan δ magnitudes are due to the presence of splices; however, this is not supported by the data.

6.6.20 Hybrid Circuits

As power cable systems age, degrade, and eventually fail, it is common that newer power cable system technologies are introduced; these situations are commonly described as a hybrid power cable system. The most common hybrid system configurations are Paper/Filled or Paper/PE-based or Paper/Filled/PE-based. In addition, they typically have more splices, some of which have different kinds of weaknesses located at different junctures along the power cable system.

These situations present a dilemma for selection of diagnostics as it is unclear which of the power cable diagnostic technologies is most appropriate. For example, DC hipots have been used effectively for the commissioning of paper power cable systems; however, they have been proven to be detrimental to PE cables. Thus condition-based maintenance strategies in such networks require a combination of diagnostic technologies and differentiated interpretation of tests over time.

In other words, the numerous parameters of the hybrid arrangement limit the application of single indicator evaluation and decision models. Still, it is possible to pinpoint weak cable sections with a multi indicator approach and a differentiated analysis; for example, the application of VLF Tan δ together with PD (Partial Discharge). A more thorough description of the application of combined diagnostics is explained later in the handbook.

Based on many years of practical field experience, experts support the definition of individual evaluation criteria. Pinpointing of degraded cable sections or joint locations is easily attainable if PD activity can be measured. Moisture ingress prone cable sections can be identified by knowing the power cable system cable details over its entire length. Moisture ingress in splices is also a major cause of degradation and system faults. Moisture ingress prone cables can be identified with VLF testing. Water tree aging can be understood from the behavior of the VLF Tan δ stability trend as well as the response of TD over several voltage steps.

In Hybrid cables, a PILC section in good condition shows natural losses that are much higher compared to the Tan δ of a highly serviced, aged XLPE section. Accordingly, the Tan δ result of a hybrid cable system needs to be carefully considered as highly serviced, aged cables may not be recognized. The maintenance VLF withstand test according to IEEE 400.2 is an important tool to confirm that no hidden weaknesses are present.

Often the Tan δ is highly influenced by moisture ingress into splices. In general, the Tan δ stability and the Tan δ trend are clear indicators of moisture ingress in splices. In general, if there is moisture ingress in the splices, the Tan δ might indicate:

- Moderate to highly fluctuating values throughout each voltage level.
- Decreasing Tan δ values throughout each step voltage level, this is due to small amounts of moisture in either a splice or termination that vaporizes during voltage application.
- Strongly increasing Tan δ values throughout each voltage level, which can be due to tracking inside the splice or termination.

Thus, the analysis of the Tan δ time variability using the standard deviation appears to be the only parameter allowing identification of degradation in hybrid power cable systems.

Nevertheless, a progressive increase of Tan δ values over time for sequential tests indicates the presence of gradually increasing degradation. Thus, in order to recognize this trend, records must be maintained over time, typically several years. In this case, through experience and heuristic knowledge, when the Tan δ measurements exceed historically established thresholds of magnitude and stability for a particular hybrid system configuration, consequence, and voltage levels, the cable system might have degraded to a point requiring replacement. On the other hand, if the Tan δ is below the established thresholds, then additional tests could determine whether the system insulation is perhaps defective.

In conclusion, higher insulation losses over time and increases in instability as functions of testing voltage are indicators that the insulation of a hybrid power cable system may be approaching failure. Therefore, even for complex situations, experience shows that knowing how to use diagnostic testing results makes it possible to develop a testing strategy focused on diagnostic parameters that have not yet been defined in the standards.

6.7 Outstanding Issues

6.7.1 Criteria Based on Local and Global Data

The criteria for VLF Tan δ as well as those developed for other diagnostic techniques are intended, by the nature of this project, to be industry-wide criteria that include test results from as many utilities as possible. This provides a global perspective on each diagnostic technique. This perspective does not distinguish between the variety of system designs, environmental conditions, and installation practices used by the utilities supplying the data. The result is a large dataset that represents the experience of many utilities. At present, data are segregated by insulation class only. Unfortunately, there are cases where this approach may not generate criteria that are ideal for an individual utility. Indeed, this is specifically recognized in IEEE Std. 400.2 – 2013 where a local perspective is advocated. This is due to the many factors that can contribute to system aging such as the manufacturer, vintage, cable/accessory design, operating environment, and operating conditions. In such cases, it is necessary to generate local criteria that are based solely on an individual utility's test data.

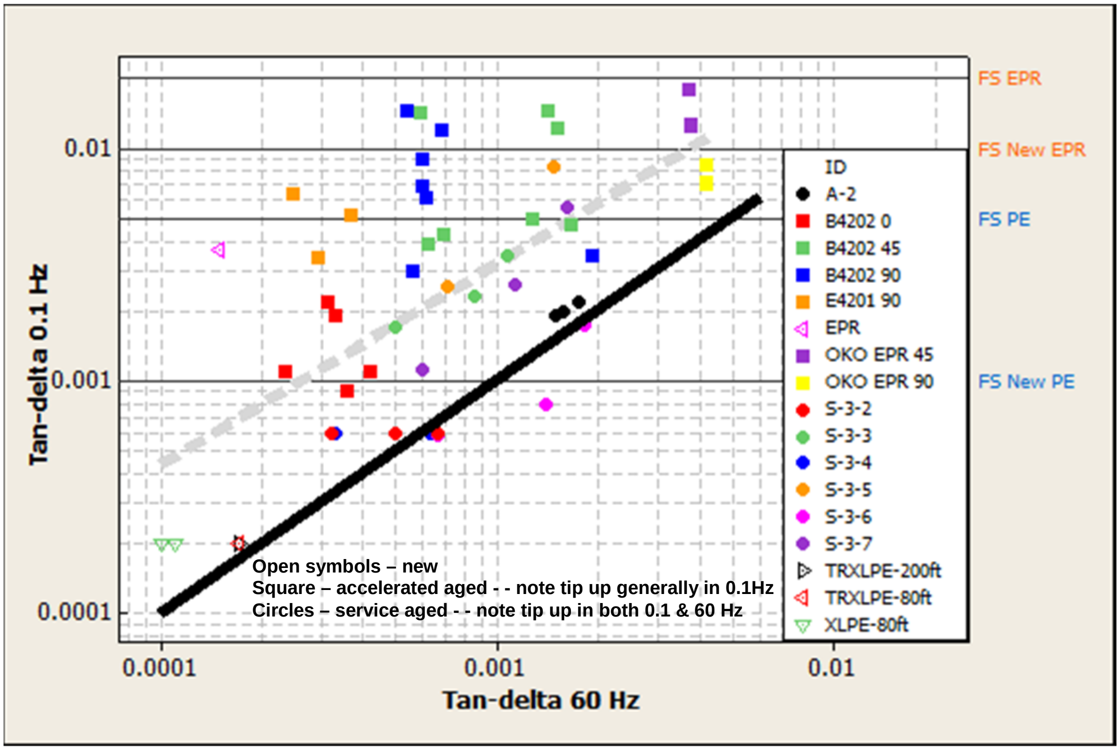
The process of developing local criteria is the same as that used to determine global criteria within *CDFI* (see previous quarterly reports and the *CDFI Phase I* final report for more information). The challenge is having enough data from the specific utility to facilitate this process. As a consequence, local criteria cannot be developed unless significant effort has already been expended in testing. A utility just starting a diagnostic program must rely on the global criteria until they can generate enough data for local criteria to be determined.

6.7.2 Very Low Frequency (VLF) and Power Frequency

The *CDFI* has shown that VLF Tan δ measurements provide much information about the insulation condition of power cable systems. However, the condition assessment can also be accomplished by performing Tan δ measurements at a power frequency of 60 Hz; in fact, measurements at a specific power frequency are commonly used in laboratory approval tests (here the frequency can range from between 49 Hz to 61 Hz according to the standards). However, for field testing applications, the deployment of Tan δ at 60 Hz has several challenges to overcome. To test a power cable system with 60 Hz power requires a power supply of high reactive power capacity. This requires bigger, more expensive, and difficult to handle test equipment. Thus, it is nearly impossible to test a power cable system of several thousand feet with a 60 Hz power supply. , It takes 600 times less reactive power to test a typical VLF cable system at a frequency of 0.1 Hz than it does at 60 Hz.

Furthermore, the magnitude of Tan δ numbers increases as the frequency decreases, making measurement easier. However, the changes on Tan δ with frequency are not proportional to the frequency change; they are the result of complex physical processes that occur inside the bulk insulation and depend on various factors that include insulation parameters (not strictly constant with frequency), temperature, moisture content, operating conditions, aging process, system design, and voltage. Thus, Tan δ measurements at 60 Hz cannot be directly compared with those at 0.1 Hz; however, a correlation between the measurements at the different frequencies can be established. The relation between Tan δ measurements at the different frequencies has been and still is a topic of ongoing study, analysis, and discussion inside the power cable system community.

Figure 46 shows the correlation between Tan δ measurements (U_0) at 60 Hz and 0.1 Hz. The data encompass tested cable of extruded insulations including PE-based and EPR in the laboratory. Service aged, accelerated aged, and new cable conditions are considered here for the Tan δ correlation.



Open symbols – new
Square – accelerated aged - - note tip up generally in 0.1Hz
Circles – service aged - - note tip up in both 0.1 & 60 Hz

Figure 46: Correlation between Tan δ (@ U_0) at 60 Hz and 0.1 Hz (Horizontal Lines Represent the Limits for "Further Study Advised" for Aged and New PE-based and Filled Cable Systems (See Table 7, Table 8, Table 12, and Table 13)

Figure 46 clearly shows that there is not a perfect 1:1 correlation (represented by the black line) between Tan δ measurements at 60 Hz and 0.1 Hz. Nevertheless, there is some correlation represented by the gray line that could be useful in translating diagnostic criteria from one frequency to the other. The actual correlation between measurements is represented by the gray dashed line. Moreover, Tan δ values at 0.1 Hz are generally larger than those at 60 Hz because of the greater sensitivity of 0.1 Hz Tan δ measurements as compared to 60 Hz.

6.8 References

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10. A. Jonscher, *Dielectric Relaxation in Solids*, Chelsea Dielectrics Press, 1983.

6.9 Relevant Standards

- IEEE Std. 400 – 2001 Omnibus: *IEEE Guide for Field Testing and Evaluation of the Insulation of Shielded Power Cable Systems*
- IEEE Std. 400 – 2012: *IEEE Guide for Field Testing and Evaluation of the Insulation of Shielded Power Cable Systems Rated 5 kV and Above*
- IEEE Std. 400.1 – 2007: *IEEE Guide for Field Testing of Laminated Dielectric, Shielded Power Cable Systems Rated 5 kV and Above With High Direct Current Voltage*
- IEEE Std. 400.2 – 2004: *IEEE Guide for Field Testing of Shielded Power Cable Systems Using Very Low Frequency (VLF)*
- IEEE Std. 400.2 – 2013: *IEEE Guide for Field Testing of Shielded Power Cable Systems Using Very Low Frequency (VLF) (less than 1 Hz)*

6.10 Appendix

Section 6.6.10 described the overall approach used by the research to produce a "Health Index" assessment from the Principal Components of PE cable systems. The following section provides the fine details of the PCA procedures for the three main insulation classes. The general approaches are the same for each; however, the ultimate outcome will be colored by the level of physical understanding and data fidelity.

At this point, it is important to recognize that the PCA approach adopted here is not an anonymous statistical procedure as might be applied in a neural network (artificial intelligence) solution. In this case, the selection of features and interpretation of the PC distances ultimately depends upon an understanding of the physics of the measurements and the degradation. Consequently the outcomes will evolve as that understanding improves. This is particularly true for the PILC analyses described later.

6.10.1 Principal Component Analysis for PE-based Insulations

The Tan δ features considered in this study were:

- **Stability of Tan δ (STD)**: stability measured by the standard deviation for sequential measurements made at U_0, where U_0 is the phase-to-ground system operating voltage
- **Tip Up (TU):** differential Tan δ between $1.5U_0$ and $0.5U_0$
- **Tan δ (TD):** mean Tan δ measured at U_0
- **Differential Tip Up (TuTu):** the difference of Tip Ups over a $0.5\ U_0$ span

The values for the features above correspond to Tan δ measurements for PE-based insulation cables (PE, XLPE, WTR-XLPE) contained in the database. This database includes 2,507 Tan δ tests. In this dataset, 2,008 of the tests have all the required measurements present. These field measurements were collected from May 2006 until June 2013 in 39 areas, from 10 different utilities.

Several combinations of the Tan δ features defined above were tested using PCA. The objective was to find the combination that would better classify the condition of a cable system as compared with the total population of the database. The combinations included various functions of the Tan δ features as: linear terms, quadratic terms, compounded terms (multiplication of two features), and logarithmic function (for better scaling a particular feature). In each combination, a PCA was carried out and the resulting principal components were combined to create a single "Health Index", mathematically called the PC-distance.

This PC-distance corresponds to the Euclidean distance from a pre-defined origin in the three dimensional space spanned by the orthonormal base of the first three principal components (components that explain the largest portion of the variance). In this case, the pre-defined origin corresponded to Tan δ values of a new PE-based insulation cable, thus the smaller the magnitude of the PC-distance, the more similar the condition is to a new cable while larger values imply increasingly deteriorated condition.

Once the PC-distances were calculated for all 2,008 tests, a ranking scheme was defined to assess the condition of the cables: all samples with PC-distance above the 80th percentile were classified as "Further Study Advised" and all results above the 95th percentile were declared as "Action Required".

In order to test the accuracy of the classification scheme for each combination of Tan δ features a test set with known cable conditions was used:

- New cable: expected to fall in the low percentile area (origin),
- Cable with individual features at 80% level: expected to classify around the 80th percentile,
- Cable with individual features at 95% level: expected to classify around the 95th percentile,
- Cable failure: expected to classify at the 95th percentile or above,
- Four cables with increasingly degraded condition: expected to classify around 80th percentile with increased percentile for each sample,

The values of the Tan δ features for each sample in the test set appear in Table 31. Table 32 shows the 12 combinations of Tan δ features that were evaluated. Among those combinations, only three of them were able to perform an acceptable classification of the test samples in Table 31.

Table 31: Tan δ features for PE-based insulation cables

Sample	STD	TU	TD	TuTu
New cable	0	0	0.1	0
Cable with individual features at 80%	0.05	5	4	0
Cable with individual features at 95%	0.5	80	50	60
Failed cable	3.6	247	315	17
Consecutive degradation of cable, Stage 1	0	0.8	2.8	0
Consecutive degradation of cable, Stage 2	0	1.2	5.4	-0.2
Consecutive degradation of cable, Stage 3	0	1.8	6	0.6
Consecutive degradation of cable, Stage 4	0.9	58	48.7	21.6

The difference in the classification results for the three combinations was negligible. In all of them:

- A new cable is classified as the 0th percentile,
- A cable with individual features at the 80% level is classified as the 82nd percentile,
- A cable with individual features at the 95 % is level classified as the 94th percentile,
- The cable failure classified at the 98th percentile,
- The four cables with increasingly degraded condition are classified as being in the 79 th, 83 rd, 84 th, and 93 rd percentiles.

The results are categorized as Correct (the test cases were ranked in the correct order AND gave the correct percentile) or Incorrect (the test cases were NOT ranked in the correct order NOR gave the correct percentile) Therefore, additional criteria were required for choosing the final combination of features. The cumulative variance was taken into consideration as well as the coefficients associated with each principal component. Analysis of the coefficients showed that one of the combinations was able to decouple the effects of the stability of Tan δ (STD) and the Tan δ (TD) itself in an optimal fashion.

This combination considered: (i) a quadratic term for the stability of Tan δ (STD^2), (ii) a linear term for the Tip Up (TU), (iii) a logarithmic function for the Tan δ (log (TD)), and (iv) a linear term for the differential Tip Up (TuTu).

Table 33 shows the coefficients for the principal components of the selected combination of features described above. When looking at the values in Table 33, it was possible to determine that

- the first principal component (PC1) mainly contained the information of the Tip Up and the differential Tip Up (the largest coefficients in that column (0.68 and 0.64 respectively) are associated to these features),
- the second principal component, PC2 enclosed the information of the stability of Tan δ (coefficient equal to 0.99),
- the third principal component (PC3) primarily held the contribution of the Tan δ (coefficient equal to 0.91).

Table 32: Combination of Features for PE-based Insulation Cable Systems

Features										Classification of Test Set	Cumulative Variance	Rank of Test Set (percentiles)
STD	TU	TD	TuTu	log(TD)	STD^2	TD^2	log(TD)^2	STD·TD	STD·log(TD)			
☑	☑	☑	☑							Incorrect	-	-
☑	☑	☑	☑					☑		Incorrect	-	-
	☑		☑					☑		Incorrect	-	-
☑	☑		☑	☑						**Correct**	97.8%	[0.05, 82, 94, 98, 79, 83, 84, 94]
☑	☑		☑	☑					☑	**Correct**	88.6%	[0.05, 82, 94, 98, 78, 83, 84, 93]
	☑		☑						☑	Incorrect	-	-
	☑	☑	☑		☑					Incorrect	-	-
☑	☑		☑			☑				Incorrect	-	-
	☑		☑		☑	☑				Incorrect	-	-
	☑		☑	☑	☑					**Correct** ***Optimal***	97.5%	[0.05, 82, 94, 98, 79, 83, 84, 93]
☑	☑		☑				☑			Incorrect	-	-
	☑		☑		☑		☑			Incorrect	-	-

☐ Basic Tan δ features ☐ Additional Tan δ feature (this report) ☐ Experimental Tan δ features

Table 33: Coefficients for Best Combination of Features for PE-based Insulations from *CDFI* Research

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Feature	PC1	PC2	PC3
STD^2	0.03	**0.99**	-0.14
TU	**0.68**	-0.02	-0.12
Log(TD)	0.36	0.1	**0.91**
TuTu	**0.64**	0.09	0.37

The combination of Tan δ features detailed above have both an acceptable cumulative variance of 97.5% and principal component's coefficients that allow for each principal component to have a physical meaning (PC1 being Tip Ups, PC2 being Stability of Tan δ, and PC3 being Tan δ). It was for these reasons it was selected for the final implementation of a PCA condition assessment tool for PE-based insulation cables.

6.10.2 Principal Component Analysis for Filled Insulations

A study similar to the one presented for PE-based insulations was conducted for the case of filled-based insulation cables. Experience has shown that sometimes it is difficult to precisely identify the type of filled insulation of field-installed cable. The issues encountered include: incorrect /missing records, obliterated or obscured markings on the cable jacket, indistinct coloring, etc. For this reason, several types of filled insulations are included: EPR (black EPR, mineral filled EPR), Kerite, and Vulkene®.

The Tan δ features considered in this study were the same as in the previous case: Stability of Tan δ (STD), Tip Up (TU), Tan δ (TD), and Differential Tip Up (TuTu).

The values for these features correspond to Tan δ measurements for filled insulation cables contained in the most recent database. This database includes 463 samples, 273 of them having field measurements for all four features noted above. These field measurements were collected from May 2006 until June 2012 in nine utilities.

Analogous to the PE-based insulations case, several combinations of the Tan δ features defined above were tested using PCA. The objective was to find the combination that would better classify the condition of a cable as compared with the total population contained in the database.

In order to test the accuracy of the classification scheme for each combination of Tan δ features, the test set defined below was used:

- Cable with individual features at 80% level considering the full database of 463 tests: expected to classify around the 80th percentile,
- Cable with individual features at 95% level considering the full database of 463 tests: expected to classify around the 95th percentile,
- Cable with individual features at 80% level considering a subset of the database of 273

tests: expected to classify around the 80th percentile,

- Cable with individual features at 95% level considering a subset of the database of 273 tests: expected to classify around the 95th percentile.

The values of the Tan δ features for each sample in the test set appear in Table 34.

Table 34: Tan δ features of Test Set for Filled insulation cables

Sample	STD	TU	TD	TuTu
Cable with individual features at 80%, full database – 471 data	0.35	10	35	1
Cable with individual features at 95%, full database – 471 data	1.5	180	120	100
Cable with individual features at 80%, subset of database – 273 (all features reported)	0.2	10	28	1
Cable with individual features at 95%, subset of database database – 273 (all features reported)	2.8	215	103	100

Table 35 shows the twelve combinations of Tan δ features that were evaluated. For these combinations, the PC-distance was calculated with respect to the point defined by the first quartile of the data (the definition of a new cable was not used in this case because there are several distinct types of insulation in this group).

Among those combinations, only three were able to perform an acceptable classification of the test samples in Table 34. The difference in the classification results for the three combinations was negligible: cables with individual features at 80%, for both the full database and a subset of it, classified as 82nd percentile and cables with individual features at 95% classified between the 95th and the 98th percentile (full database and subset of the database respectively).

Additional criteria were considered for choosing the final combination of features: the cumulative variance and the coefficients associated with each principal component. There were no distinctive differences between the combinations for neither of them, for the filled insulation case, was not possible to separate the interdependences of the stability of Tan δ and the Tan δ.

Since none of the combinations are shown to be better than the others, the final combination of Tan δ features was chosen to be the same as for the PE insulated cables: (i) a quadratic term for the stability of Tan δ (STD^2), (ii) a linear term for the Tip Up (TU), (iii) a logarithmic function for the Tan δ (log (TD)), and (iv) a linear term for the differential Tip Up (TuTu).

However, the analysis for the different combinations should be repeated once more data have been gathered and/or a better test set can be defined with filled insulation cables of known condition.

Table 35: Combination of Features for Filled Insulation Cable Systems

Features										Classification of Test Set	Cumulative Variance	Rank of Test Set (percentiles)
STD	TU	TD	TuTu	log(TD)	STD^2	TD^2	$log(TD)^2$	STD·TD	STD·log(TD)			
☑	☑	☑	☑							Incorrect	-	-
☑	☑	☑	☑					☑		Incorrect	-	-
	☑		☑					☑		Incorrect	-	-
☑	☑		☑	☑						**Correct**	96.6%	[82, 95, 82, 98]
☑	☑		☑	☑					☑	**Correct**	97.15%	[82, 95, 82, 98]
	☑		☑						☑	Incorrect	-	-
	☑	☑	☑		☑					Incorrect	-	-
☑	☑		☑			☑				Incorrect	-	-
	☑		☑		☑	☑				Incorrect	-	-
	☑		☑	☑	☑					**Correct *Selected***	96.3%	[82, 95, 82, 98]
☑	☑		☑				☑			Incorrect	-	-
	☑		☑		☑		☑			Incorrect	-	-

☐ Basic Tan δ features ☐ Additional Tan δ feature ☐ Experimental Tan δ features

6.10.3 Principal Component Analysis for Paper Insulations

A PCA study was also carried out in the case of PILC cables. This case the research was much more complex than the previously presented for PE-based insulations and filled insulations, because:

- PILC data exhibit both positive and negative Tip Ups,
- There is not a good physical understanding (in terms of origin and direction of degradation) of the physical meaning behind PILC Tan δ data,
- There has been considerable material and design evolution over the life cycle of PILC cables and,
- Most PILC cables in underground systems are 3-core cables.

No comprehensive or relevant studies have been found in literature to understand the physical phenomena involved in having a positive or negative Tip Up, or in characterizing the degradation of a cable by the change in the Tan δ value over different voltage levels. Empirical evidence seemed to indicate that having higher values of Tan δ (either positive or negative) imply a worse cable condition, but there was no indication on how to compare the assessment of a cable with a positive Tip Up versus one with a negative Tip Up of equal magnitude.

Considering this lack of information, it was decided to carry out independent PCA studies for the positive and negative Tip Ups. In addition, having 3-core cables added the differences between phases as an additional variable for cable assessment.

PCA study with basic features for PILC insulations

The basic Tan δ features considered in the study were: Stability of Tan δ (STD), Tip Up (TU), Tan δ (TD), and Differential Tip Up (TuTu). The values for these features correspond to Tan δ measurements for PILC cables contained in most recent database as of July 2012. This database includes 562 samples, 190 of them having field measurements for all four features above.

Further analysis of the available data indicated that only 16 samples out of 190 had a positive Tip Up, therefore the PCA analysis was carried out using the 174 samples with negative Tip Ups. These negative values were multiplied by a factor of -1 in the PCA, in order to preserve the criteria of larger numbers meaning worse cable condition.

Analogous to the PE-based and filled insulations cases, several combinations of the Tan δ basic features were tested using PCA. The objective was to find the combination that would better classify the condition of a cable as compared with the total population of the database.

In order to test the accuracy of the classification scheme for each combination of Tan δ features the test set defined below was used:

- New cable: expected to fall in the low percentile area (origin),
- Cable with individual features at 80% level considering the full database of 562 samples: expected to classify around the 80th percentile,

- Cable with individual features at 95% level considering the full database of 562 samples: expected to classify around the 95th percentile,
- Cable with individual features at 80% level considering a subset of the database of 174 samples: expected to classify around the 80th percentile,
- Cable with individual features at 95% level considering a subset of the database of 174 samples: expected to classify around the 95th percentile.

The values of the Tan δ features for each sample in the test set appear in Table 36.

Table 36: Tan δ features of Test Set for PILC cables

Sample	STD	TU	TD	TuTu
New Cable	0	2	16	0
Cable with individual features at 80%, full database – 562 data	0.1	35	90	8
Cable with individual features at 95%, full database – 562 data	0.4	50	200	20
Cable with individual features at 80%, subset of database – 190 having all features	0.2	28	94	8
Cable with individual features at 95%, subset of database database – 190 having all features	0.3	40	152	20

Table 37 shows the twelve combinations of Tan δ features that were evaluated. All combinations classified the test set similarly, with three of them performing slightly better. A common problem for the classification was to have the percentiles too polarized at the upper end:

- Cables with individual features at 80%, both full database and subset, classified below the 80th percentile,
- Cables with individual features at 95%, both full database and subset, classified well above 95th percentile.

The first part, misclassification at 80th percentile, implies the application of a non-conservative criterion to the single "Health Index" defined by the PC-distance, i.e. a cable with all individual features at 80 % of their corresponding values will classify as a healthy cable. On the other hand, having an extreme classification at the 95th percentile region implies that the granularity for degraded cables is nonexistent; therefore, there is no possibility of prioritizing cables classified in the "Action Required" category.

Among the combinations, three provided an acceptable classification of the test set in Table 36. The misclassification error for these three combinations was small: cables with individual features at 80%, for both the full database and a subset of it, classified as 78-80th percentile and cables with individual features at 95% classified between the 95th and the 100th percentile (subset of the database and full database respectively). In these cases, the misclassification can be explained by the relatively small size of the PILC database (174 samples as compared to 273 of filled insulation and 2008 of PE-based insulation).

By looking at the results in Table 37, the combination of (i) a quadratic term for the stability of

Tan δ (STD^2), (ii) a linear term for the Tip Up (TU), (iii) a quadratic term for the logarithm of Tan δ ($\log(TD)^2$), and (iv) a linear term for the differential Tip Up (TuTu), seemed to have a better classification performance. However, the analysis for the different combinations should be repeated when more data have been gathered on PILC cables.

Table 37: Combination of Features for PILC cables

Features										Classification of Test Set	Cumulative Variance	Rank of Test Set (percentiles)
STD	TU	TD	TuTu	log(TD)	STD^2	TD^2	$log(TD)^2$	STD·TD	STD·log(TD)			
☑	☑	☑	☑							Polarized	-	-
☑	☑	☑	☑					☑		Polarized	-	-
	☑		☑					☑		Polarized	-	-
☑	☑		☑	☑						Polarized	-	-
☑	☑		☑	☑					☑	Polarized	-	-
	☑		☑						☑	Polarized	-	-
	☑	☑	☑		☑					**Correct**	94.5%	[3, 78, 100, 77, 96]
☑	☑		☑			☑				Polarized	-	-
	☑		☑		☑	☑				**Correct**	94.1%	[1, 78, 100, 77, 95]
	☑		☑	☑	☑					Polarized	-	-
☑	☑		☑				☑			Polarized	-	-
	☑		☑		☑		☑			**Correct** ***Selected***	94.1%	[2, 80, 100, 78, 96]

☐ Basic Tan δ features ☐ Additional Tan δ feature ☐ Experimental Tan δ features

PCA Study with Additional Features for PILC Insulations

The analysis in the previous section included the same features as in the case of the PE-based insulation and Filled insulation cables. Three additional PCA studies were carried out to enhance the previous analysis so the additional complexities of PILC cables could be taken into account.
The topics explored were:

- Use of the differences between the Tan δ (TD) values of the three phases as condition assessment features,
- Use of the geographical location of the cable as a condition assessment feature – this is believed to be a practical alias for the age/design information of the cable system,
- Use of both, differences in phases and location as condition assessment features.

To be able to have a larger dataset, the set of the basic features was reduced to only three features: Stability of Tan δ (STD), Tip Up (TU), and Tan δ (TD). In this way, it was possible to identify 55 samples having information on all three basic features plus location.

In order to represent the information provided by the differences between the 3 phases of a cable, a single feature was selected to be added to the existing basic features: the variable "Range", which is defined as the difference between the maximum and the minimum Tan δ value among the three phases in a cable:

$$Range = Max_{a,b,c}\,(Tan\ \delta @ 1U_0) - Min_{a,b,c}\,(Tan\ \delta @ 1U_0)$$

Example: if $\text{Tan}\ \delta_{\text{phase a}} = 3$, $\text{Tan}\ \delta_{\text{phase b}} = 2$, and $\text{Tan}\ \delta_{\text{phase c}} = 10$, then the Range = 10-2 = 8

The calculations of the Ranges between the three phases of all cables samples provided the results in Table 38.

Table 38: Statistical Values for Differences Between PILC	
Minimum Range among 55 samples	0.4
Maximum Range among 55 samples	50.3
Average Range among 55 samples	8.4
Standard Deviation of Range among 55 samples	9.2

In addition to the values presented in Table 38, it was possible to define the following rules based on the empirical distribution presented in Figure 47:

- "Further Study Advised" for Range feature: all Range values above 10 (80th percentile),
- "Action Required" for Range feature: all Range values above 20 (95th percentile).

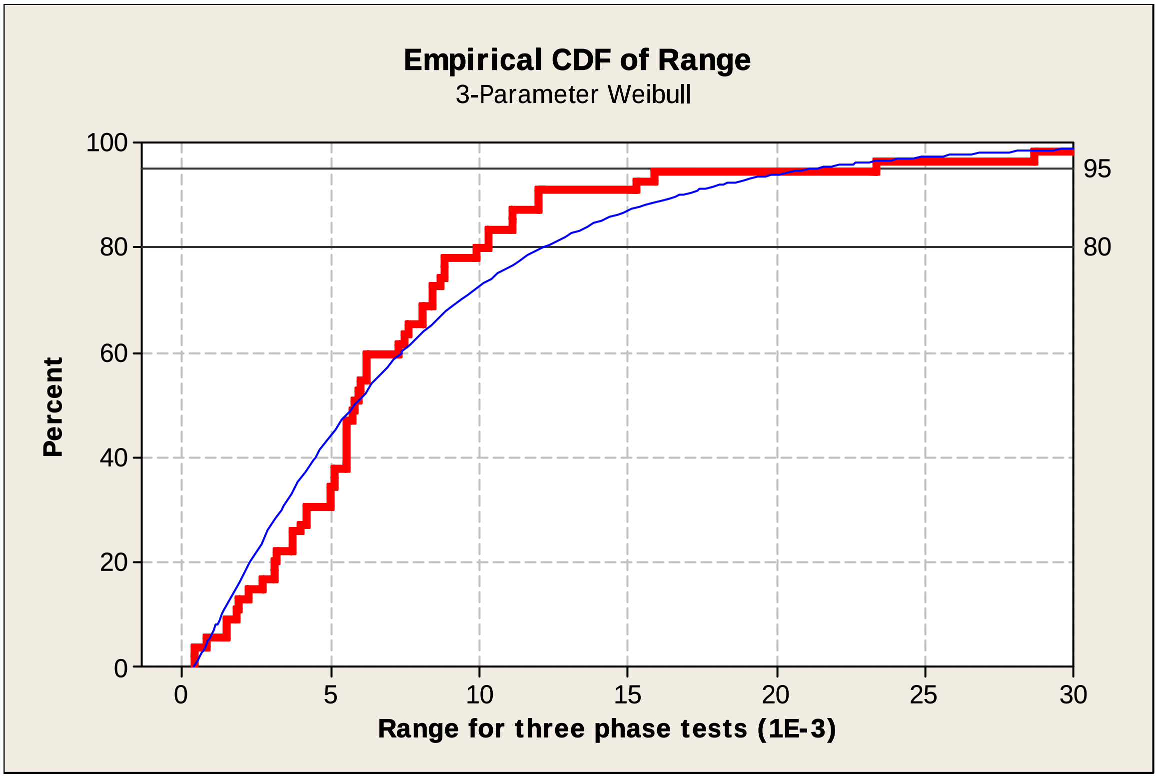

Figure 47: Empirical CDF of Differences in Tan δ for 3 Core Cables (PILC Insulations)

In the case of the location, by analyzing the data in the database, it was possible to determine three distinct geographical areas, and the average of Stability of Tan δ (STD) and Tan δ (TD), was computed for each one (Table 39). The average of Tan δ was chosen to be used as the location mark.

Table 39: Average Values for Tan δ (TD) and Tan δ Stability (STD)

Area	Average TD [1E-3]	Average STD [1E-3]
Location 1	159.1	0.8
Location 2	64.7	0.1
Location 3	83.2	0.3

Study 1: Research Using Basic Tan δ features and Range feature

The PCA results for the first study considered the following features: Stability of Tan δ (STD), Tip Up (TU), logarithm of Tan δ (log(TD), and Range. The idea was to test how the classification of a given cable changed as a result of having larger differences with respect to the other two phases of the same cable. The test set used in this study appears in Table 40.

Table 40 shows that five cable conditions were tested and then re-tested with a different value for the Range feature: the values for the Range features were selected to represent a sample below the 80th percentile (Range = 5), between the 80th and the 95th percentile (Range = 15), and above the

95th percentile (Range = 35).

Table 40: Tan δ and Range Features of PILC Test Set

Sample	**STD**	**TU**	**TD**	**Range**
New Cable	0	2	16	[5,15,35]
Cable with individual features at 80%, full database	0.1	35	90	[5,15,35]
Cable with individual features at 95%, full database	0.4	50	200	[5,15,35]
Cable with individual features at 80%, subset of database	0.2	28	94	[5,15,35]
Cable with individual features at 95%, subset of database	0.3	40	152	[5,15,35]

Table 41 shows the obtained results.

Table 41: PCA Research Results for Study with Basic Tan δ and Range Features

Sample	**No Action Required Range = 5**	**Further Study (80th percentile) Range = 15**	**Action Required (95th percentile) Range = 35**
New Cable	**4**	23	87 Concerning too high
Cable with individual features at 80%, full database	73 Improve with TuTu	**82**	94
Cable with individual features at 95%, full database	96	97	**99**
Cable with individual features at 80%, subset of database	76 Improve with TuTu	**84**	95
Cable with individual features at 95%, subset of database	91	93	**98**

Results shown in Table 41 indicate that for each of the five samples, the condition of the given cable progressively deteriorates, as the difference between phases is greater. As an illustration, consider a cable with individual features at 95% of the full database, progressively classified as the 96th, 97th, and 99th percentiles. However, this effect is overdone when the sample is a new cable (percentile changes from the 4th to the 87th percentile).

This indicates that the Range feature has promise for classification use, yet a better understanding of the effect of the differences between phases has to be acquired before it is acceptable as an assessment feature (i.e. it is necessary to determine whether a new cable having a large difference with respect to the other phases is really subjected to a higher probability of failure).

Study 2: Basic Tan δ Features and Location feature

The PCA research results for the second study considered the following features: Stability of Tan δ (STD), Tip Up (TU), logarithm of Tan δ (log(TD)), and Location (via a Location alias). The purpose of the test was to determine whether the association of a given sample with a geographical cluster could improve the classification. The following test set was used:

Table 42: Tan δ and Location Features of Test Set for PILC cables

Sample	STD	TU	TD	Location Alias
New Cable	0	2	16	65
Cable with individual features at 80%, full database	0.1	35	90	85
Cable with individual features at 95%, full database	0.4	50	200	160
Cable with individual features at 80%, subset of database	0.2	28	94	85
Cable with individual features at 95%, subset of database	0.3	40	152	160

The cable samples in Table 42 were tested with and without the location feature. Table 43 shows the obtained results.

Table 43: PCA Results of Study with Basic Tan δ and Location Features

Sample	Without Location Alias	With Location Alias
New Cable	39	21
Cable with individual features at 80%, full database	78	67
Cable with individual features at 95%, full database	100	100
Cable with individual features at 80%, subset of database	84	79
Cable with individual features at 95%, subset of database	95	98

The comparison of the research results in Table 43 indicated that the use of the Location alias feature did not improve the classification of the test samples.

Study 3: Basic Tan δ features, Location and Range features

The PCA results for the last study considered the following features: Stability of Tan δ (STD), Tip Up (TU), logarithm of Tan δ (log(TD)), Location, and Range. The following test set was used:

Table 44: Tan δ features, Location and Range Features of Test Set for PILC cables

Sample	**STD**	**TU**	**TD**	**Loc. Alias**	**Range**
New Cable	0	2	16	65	[5,15,35]
Cable with individual features at 80%, full database	0.1	35	90	85	[5,15,35]
Cable with individual features at 95%, full database	0.4	50	200	160	[5,15,35]
Cable with individual features at 80%, subset of database	0.2	28	94	85	[5,15,35]
Cable with individual features at 95%, subset of database	0.3	40	152	160	[5,15,35]

Table 45 shows the obtained results.

Table 45: PCA Study Results for Basic Tan δ, Location, and Range Features

Sample	**No Action Required** Range = 5	**Further Study** (80th percentile) Range = 15	**Action Required** (95th percentile) Range = 35
New Cable	**21**	30	82
Cable with individual features at 80%, full database	59	**72**	91
Cable with individual features at 95%, full database	96	97	**100**
Cable with individual features at 80%, subset of database	61	**79**	94
Cable with individual features at 95%, subset of database	93	94	**98**

The comparison of the results in Table 41, Table 43, and Table 45 indicate that the combined use of the Location and Range features improve the classification of the test samples as compared with the case of only using the Location feature; however, this improvement is insufficient to surpass the results obtained by using only the Range feature.

In summary, for the additional features explored in this section, the most promising is the Range feature which takes into account the differences between the 3 phases of a 3-core cable. The use of this feature requires further investigation once more data can be compiled. Possible choices for including this variable as an assessment feature include: (i) replicate the analysis presented above, (ii) expand the PCA analysis to consider all three phases at the same time (10 dimension PCA), or (iii) utilize the Range feature as a separate condition assessment tool.