CHAPTER 10

Monitored Withstand Techniques

Jean Carlos Hernandez-Mejia

This chapter represents the state of the art at the time of release. Readers are encouraged to consult the link below for the version of this chapter with the most recent release date:

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

Users are strongly encouraged to consult the link below for the most recent release of Chapter 4:

Chapter 4: How to Start

DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

This document was prepared by Board of Regents of the University System of Georgia by and on behalf of the Georgia Institute of Technology NEETRAC (NEETRAC) as an account of work supported by the US Department of Energy and Industrial Sponsors through agreements with the Georgia Tech Research Institute (GTRC).

Neither NEETRAC, GTRC, any member of NEETRAC or any cosponsor nor any person acting on behalf of any of them:

a) Makes any warranty or representation whatsoever, express or implied,
    i. With respect to the use of any information, apparatus, method, process, or similar item disclosed in this document, including merchantability and fitness for a particular purpose, or
    ii. That such use does not infringe on or interfere with privately owned rights, including any party's intellectual property, or
    iii. That this document is suitable to any particular user's circumstance; or

b) Assumes responsibility for any damages or other liability whatsoever (including any consequential damages, even if NEETRAC or any NEETRAC representative has been advised of the possibility of such damages) resulting from your selection or use of this document or any information, apparatus, method, process or similar item disclosed in this document.

DOE Disclaimer: This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

NOTICE

Copyright of this report and title to the evaluation data contained herein shall reside with GTRC.

Reference herein to any specific commercial product, process or service by its trade name, trademark, manufacturer or otherwise does not constitute or imply its endorsement, recommendation or favoring by NEETRAC.

The information contained herein represents a reasonable research effort and is, to our knowledge, accurate and reliable at the date of publication.

It is the user's responsibility to conduct the necessary assessments in order to satisfy themselves as to the suitability of the products or recommendations for the user's particular purpose.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

10.0 MONITORED WITHSTAND TECHNIQUES

10.1 Test Scope

Simple Withstand tests are proof tests that apply voltage above the normal operating voltage to stress the insulation of a cable system in a prescribed manner for a set period of time (time-voltage recipe) [1-15]. This is similar to tests applied to new accessories or cables in the factory where a withstand voltage is applied to provide the purchaser with assurance that the component can withstand a defined voltage. An alternative and more sophisticated implementation of the simple withstand approach requires that, in addition to surviving an applied voltage stress, a system property is also measured during the test. The property measured should be selected to correlate with the condition of the system. This implementation of a withstand test, called Monitored Withstand test, is discussed in this chapter and is more sophisticated than a Simple Withstand.

In traditional Simple Withstand tests (VLF, dc, or resonant ac), a significant drawback is the absence of a straightforward way to estimate the "Pass" margin. Once a test (e.g. 30 min at 2 U_0, where U_0 is the nominal system operation voltage) is completed, it is impossible to differentiate among those cable systems that survived the test without failure. As a result, this test cannot distinguish cable system segments that pass the test, but would survive only minutes or days after the test from those that could last months or years after the test.

Thus, it is useful to employ the concept of a Monitored Withstand test whereby a dielectric property or discharge characteristic is monitored to provide additional data. There are four ways these data are useful in making decisions during the test:

1. Provides an estimate of the "Pass" margin for cable systems that have not failed during the hold phase of the Monitored Withstand test.
2. Enables a utility to stop a test after a short time if the monitored property indicates the cable system is near imminent failure on test thereby allowing the required remediation work to take place at a convenient (lowest cost) time.
3. Enables a utility to stop a test early (shorten the duration of the test) if the monitored property provides definitive evidence of good performance, thereby increasing the number of tests that could be completed and improving the overall efficiency of field testing.
4. Enables a utility to extend a test if the monitored property provides indications that the "Pass" margin was questionable, thereby focusing test resources on sections that present the most concern.

In fact, the design of the decision making process can be accomplished by advanced statistical analysis of the data accumulated during *CDFI Phases I* and *II*. This allows for the creation of defined and well-organized monitored withstand testing procedures that can be deployed in real time in the field.

10.2 How it Works

In a Simple Withstand test, the applied voltage is quickly raised to a prescribed level, usually 1.5 to 2.5 U_0 for a set amount of time. The purpose is to cause weak points in the cable system to fail during the elevated voltage application when the system is not supplying customers. This avoids a service failure and the associated reliability penalties as well as potential upstream fault current damage. Testing is usually scheduled by the utility so that it occurs at a time when the impact of a failure (if it occurs) is low and repairs can be made quickly and cost effectively.

In contrast, when performing a Monitored Withstand test, a dielectric or discharge property is monitored during the withstand period or "Hold" phase of the test (see Figure 1). The data and its interpretation should be accessible in real time during the test so that the decisions outlined above can be made.

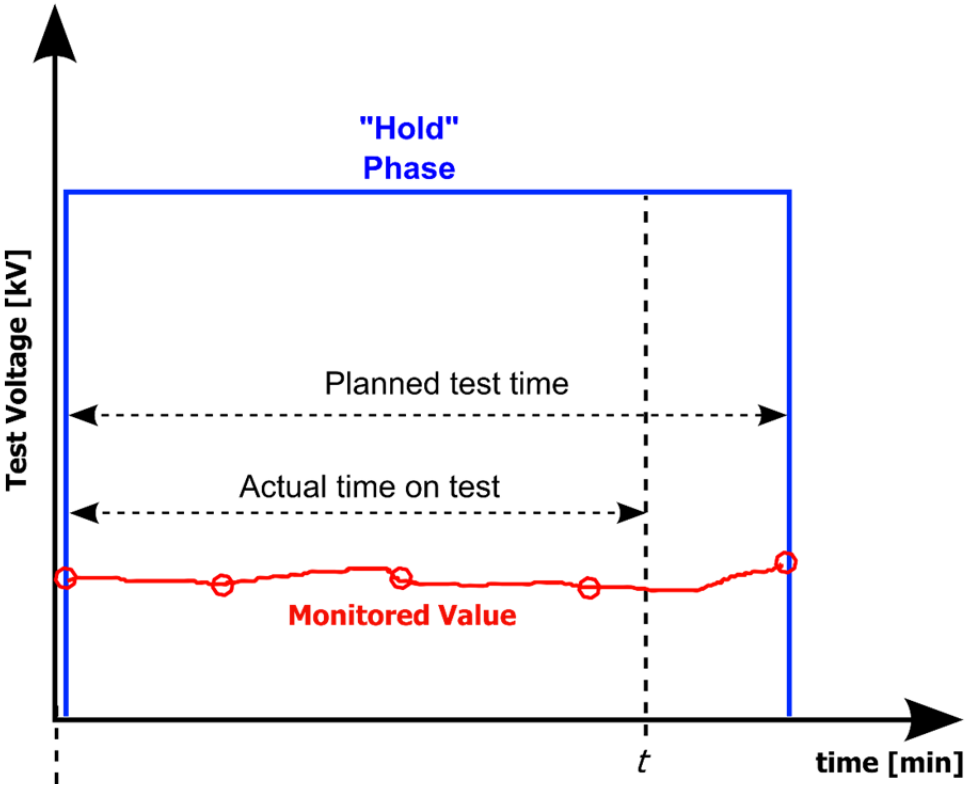

Figure 1: Schematic Representation of a Monitored Withstand Test

The dielectric or discharge monitored property are similar to those described in earlier chapters. However, their implementation and interpretation differs due to the requirement of a fixed voltage and a relatively long period of voltage application for the "Hold" phase of the test. Within these constraints, Leakage Current, Partial Discharge (magnitude and repetition rate) and Tan δ (stability, magnitude, and rate of change over time (speed)) [2] might readily be used as monitors.

10.3 How it is Applied

This technique is conducted offline with the system disconnected from the network. The applied voltage may be dc (not recommended for most applications), VLF (sinusoidal or cosine-rectangular), or 10 - 300 Hz ac using a resonant power supply. Typical testing voltages range from 1.5 - 4.0 U_0 [1-15] though the precise levels depend upon the voltage source, (VLF levels tend to be lower than dc). If a failure occurs during the test according to either of the two criteria (dielectric puncture or unacceptable monitored property) then the cable system is remediated or repaired and the circuit is retested for the full test time. The inadvisability of using damped ac voltages for withstand purposes is discussed later in Section 10.6.2.

In Figure 1, the schematic represents a monitored withstand test. The critical part of the test is the measurement and interpretation during the “Hold” phase. However, it is clear that the simple scheme in Figure 1 could be modified to allow an evaluation before the start of the withstand test as shown schematically in Figure 2. This approach is valuable in that it enables the field engineers to assess the condition of the cable system before embarking on the monitored withstand test.

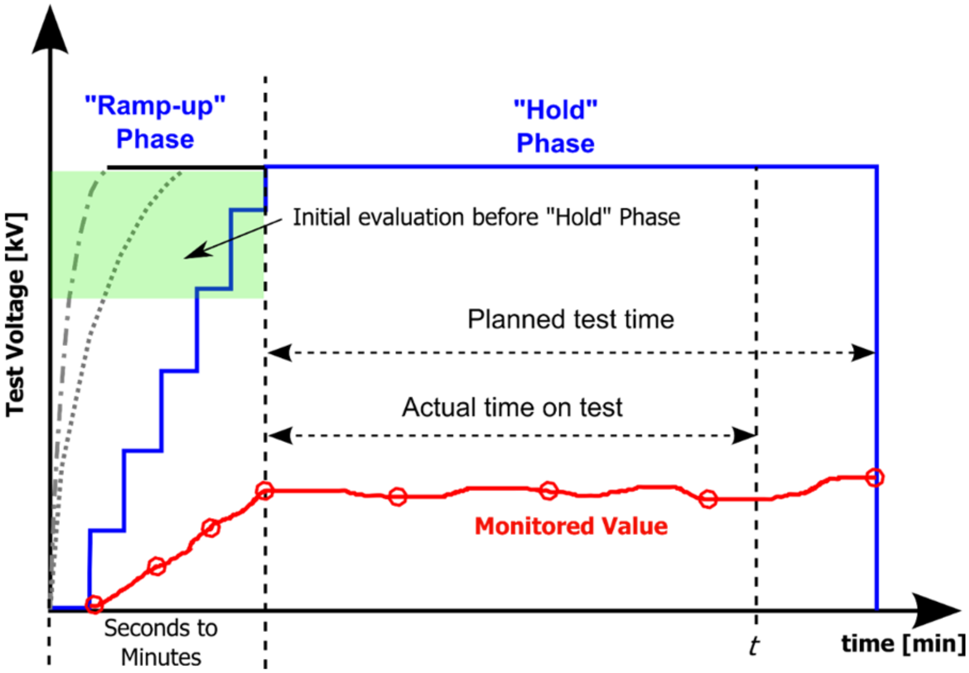

Figure 2: Schematic of a Monitored Withstand Test with Optional Diagnostic Measurement (Monitor)

Like other diagnostic techniques, Simple and Monitored Withstand tests require the application of voltages in excess of the service voltage for extended time periods (up to 60 min). However, unlike many other diagnostic test techniques, a failure on test (FOT) is an acceptable (almost desirable) outcome. The expectation is that the proof stress will cause the weak components to fail without significantly shortening the life of the vast majority of strong components.

The risk of excessive FOTs through unintended degradation of the stronger elements is reduced by using voltages closer to the service level and limiting the duration of the test. Either the number of cycles or time may be used to measure the length of application. However, the key is to avoid stopping the test *before* an electrical tree within the cable system has grown to the point of failure. Otherwise, the application of the elevated voltage could leave behind electrical trees that might cause a cable system to fail soon after service is restored. The choice of the appropriate property to monitor can help mitigate this risk. Appropriate voltage levels and times for the different energizing voltage sources appear in the Simple Withstand chapter (Chapter 9) of this document.

The advantages and disadvantages of Monitored Withstand testing are summarized in Table 1 and Table 2. These tables focus on the issues associated with the long-term (15 min or greater) monitoring of a given property or characteristic.

When consulting these tabulated summaries, it is assumed that the reader has a working knowledge of each of the diagnostic techniques discussed in earlier chapters. In some cases, the available data are sparse and the resulting summaries include more interpretation by the authors than in previously described diagnostic techniques.

Table 1: Advantages and Disadvantages of Monitored Withstand for All Possible Different Voltage Sources and Monitored Properties

Voltage Source	Monitored Value	Advantages	Disadvantages
Offline Resonant ac (10 – 300 Hz)	Partial Discharge	• The large number of cycles over the duration of the test increases the probability that a void-type defect will discharge, which increases the likelihood for detection • PD stability can be observed • There is guidance in industry standards on how to interpret results from short and long term PD tests on new HV systems	• There is little or no guidance in industry standards on how to interpret results from long term PD tests on aged systems
	Tan δ	• Not enough information to identify advantages	• There is little or no guidance in industry standards on how to interpret results from a long-term Tan δ test
AC Offline Very Low Frequency (0.1 Hz) Cosine Rectangular	Partial Discharge	Technology recently implemented – no field experience	
	Tan δ	Underlying technical assumptions not yet validated – limited field experience	
AC Offline Very Low Frequency (0.01 – 1 Hz) Sinusoidal	Partial Discharge	• Signals acquired at a slow enough rate that a qualitative interpretation may be made in real time	• There is little or no guidance in industry standards
	Tan δ	• Interpretation possible during the test, allowing for real time adjustments to the test procedure. • Guidance on interpretation available (IEEE and *CDFI* documentation)	• No unique disadvantages for withstand monitoring mode

Table 2: Overall Advantages and Disadvantages of Monitored Withstand Techniques	
Advantages	• Provides additional information over the simple “Pass” or “Not Pass” obtained from a Simple Withstand test. • Allows for the development of trending information during a single test. • Diagnostic stability can be established during the test. • Provides real time feedback so that the test may be adapted (test time increased or decreased) to fit utility objectives. • Cable system population under test can be selected to undergo different test phases (population amendment and risk management). • Many tests can be curtailed after 15 min and so Monitored Withstand requires considerably less total test time when compared to a Simple Withstand approach (40% to 60 % efficiency improvement). • Allows for the integration of outcomes from Simple Withstand test with those from other diagnostic techniques (two diagnostics and thus higher information content). • Less number of FOTs and thus less number of thumper tests for failure location, which results in reduced work and emergency cost.
Open Issues	• Can potentially provide means for estimating a “Pass” margin for cable systems that survive the “Hold” phase of the test. • Selection of the best monitored property (i.e. PD, Tan δ, or Leakage). • Implementation where only level-based assessments (Good/Bad) are available is unclear and may not be useful. • Voltage exposure (impact of voltage/time on cable system) caused by DAC voltages has not been established.
Disadvantages	• Adds complexity (interpretation, set up, and data recording) to Simple Withstand test. • Highly skilled and fast decision-making personnel required.

A critical issue for Monitored Withstand testing, like Simple Withstand, is the application time at the chosen voltage for the test. If the test time is too short then cable systems with localized defects that could cause service failures may be returned to service before the defect has the chance to fail during the test. Equally, a shortened test may not provide enough opportunity for the monitored feature to provide useful information. As an example, an upward trend in a monitored property with time usually indicates a problem. However, if the test time, and thus, the time to observe the trend is too short then it is more difficult to unambiguously identify the trend and make a diagnosis.

The work described in the Simple Withstand chapter (Chapter 9) suggests that 30 minutes should be the usual target test time. This is in accordance with the test time suggested by IEEE Std. 400.2 – 2013. This time may be increased to 60 minutes if the monitored data indicate instability or an upward trend that indicates unsatisfactory performance. The test time may also be reduced to 15 minutes if experience shows that the monitored data definitively confirm good cable system performance. Criteria for test time amendment appears later in this chapter.

10.4 Success Criteria

Monitored Withstand results fall into two classes:

- "Pass" – "No Action Required" and
- "Not Pass" – "Action Required" that may include "Further Study".

Thus, there are two ways a cable system might "Not Pass" a Monitored Withstand test:

1. Dielectric puncture and
2. No dielectric puncture AND non-compliant information from the monitored property as evidenced by:
   - rapid increase in monitored property at any time during the test
   - steady upward trend at a moderate level
   - instability (widely varying data)
   - high magnitude or
   - non-acceptable low "Pass" margin

On the other hand, there is only one way in which a cable system may "Pass" a Monitored Withstand test: no dielectric puncture and monitored data that falls within the pass criteria:

- stable and narrowly varying data and
- low magnitude, and acceptable high "Pass" margin

Figure 3 shows examples of the behavior in a monitored property over the course of a monitored withstand test. With the exception of the "Stable" example, all of the examples in Figure 3 may lead to a "Not Pass" result.

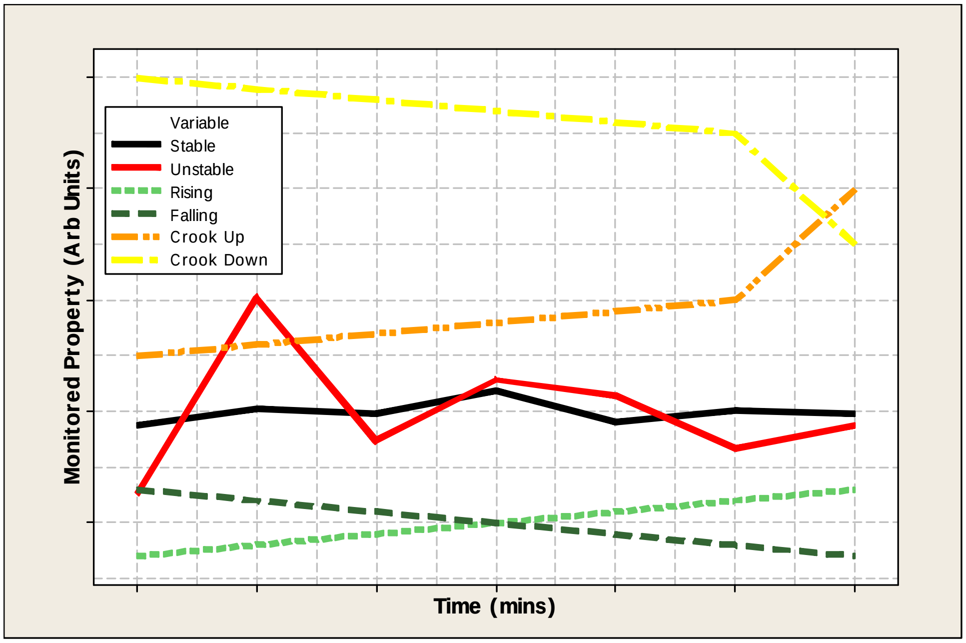

Figure 3: Possible Characteristic Shapes of Monitored Responses

10.5 Estimated Accuracy

If data is available, it is possible to estimate accuracies for Monitored Withstand based on the performance of the component diagnostic techniques (i.e. Simple Withstand plus PD, Tan δ, or Leakage). However, during the *CDFI* no data was available to assess the accuracy of Monitored Withstand testing.

10.6 *CDFI* Perspective

At the start of the *CDFI Phase I*, Monitored Withstand was not seen as a specific diagnostic technique. During the course of the project the advancements in technology (primarily that of VLF Tan δ) meant that this test was now technically possible; hence the concept was discussed and its diagnostic potential was exploited. *CDFI* has undertaken almost all of the fundamental application development work for this technique. Initially, it was also observed that there was virtually no information on the application and interpretation of Monitored Withstand tests. At that time, the limited information was based on "accidental" Monitored Withstand tests. As an example, PD tests at elevated voltages (greater than U_0) for a relatively long period of time *de facto* include a withstand element resulting from the application of the elevated voltage. In contrast, a monitored element can be used when conducting a dc or VLF Withstand test and some dielectric property, such as leakage current or dielectric loss.

During the course of *CDFI Phase I*, a number of Monitored Withstand test programs began and data were provided for analysis. The initial analysis of the data provided a preliminary understanding of the application of Monitored Withstand. This allowed *CDFI Phase I* to provide a preliminary review of this technique. *CDFI Phase II*, on the other hand, continued to study Monitored Withstand testing by gathering large datasets from more mature diagnostic programs. These data and the subsequent analysis have allowed for a more thorough review as compared to *Phase I*. The remaining sections in this chapter discuss the details of this expanded understanding.

10.6.1 Definition of a Withstand Test

To understand the applicability of Monitored Withstand tests, it is important to recall the fundamental elements that define a withstand test; these have been discussed previously in Chapter 9. A withstand test is carefully designed to overstress a cable system to an acceptable risk level and thus to be effective it must include the following three elements:

1. **A Defined Voltage Exposure:** The exposure is characterized by a voltage time waveform (waveshape) that includes a controlled magnitude (voltage metric such as peak or RMS voltage) and time of application (in terms of specified time, number of cycles, shots, or any other convenient time metric).
2. **A Repeatable Voltage Exposure:** The voltage exposure is repeatable. The waveshape is maintained during the voltage application (the same at the end as it was at the start) and that systems with similar characteristics (insulation type, lengths, etc.) experience essentially the same voltage waveshape**.**
3. **A Well-defined Failure Rate:** The failure rate during the withstand test ("Hold" phase for a monitored withstand test) must be higher than the failure rate at normal service voltage.

The "Hold" phase of a monitored withstand test should comply with all three elements for proper applicability.

10.6.2 General Monitored Withstand Framework

All Monitored Withstand tests, independent of the monitored value/parameter, have the same framework, which appears in Figure 4.

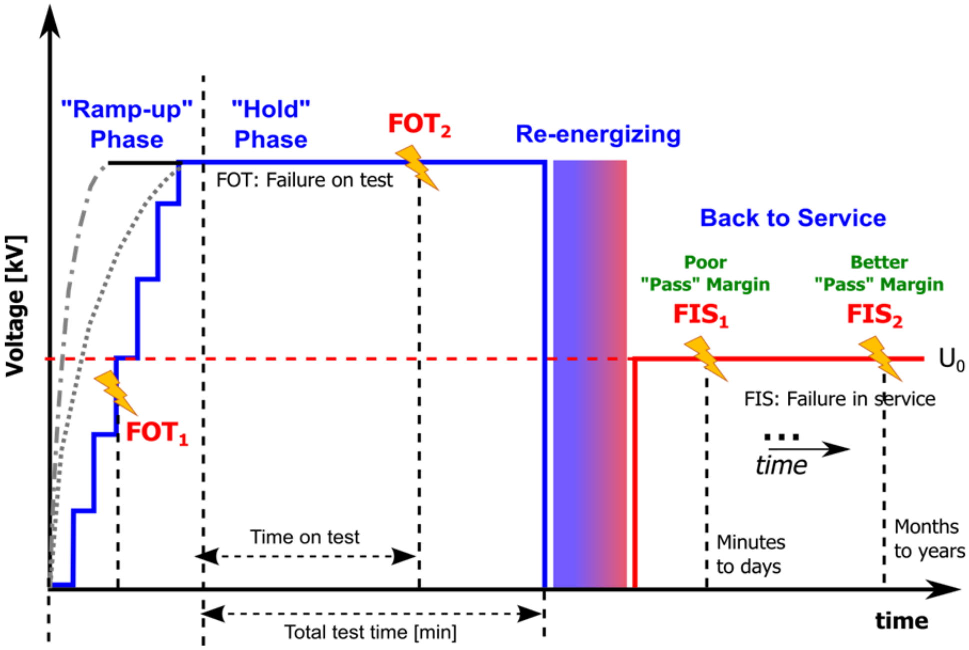

Figure 4: Monitored Withstand Test Framework

In Figure 4, four sequential phases are observed when performing a Monitored Withstand test as follows:

- **"Ramp-up" phase:** This is the initial stage of any Monitored Withstand test (i.e. after a cable system has been taken off-line and properly grounded for testing). This involves raising the test voltage from zero to the required withstand level. The monitored property can be recorded during this stage and may be used to further develop the condition assessment.
- **"Hold" phase:** This stage involves the actual withstand evaluation, the test voltage is held constant and the monitored property is recorded for the duration of the test.
- **Re-energization phase:** This stage involves all the actions and time required to put a cable system back in service once it has successfully completed the monitored withstand test without a FOT.
- **Back to Service phase:** This stage represents operation of the cable system after testing.

There are two possibilities for the timing of a failure during a Monitored Withstand test: (1) during the test itself ("Ramp-up" or "Hold" phases, FOT_1 or FOT_2, respectively, in Figure 4) or (2) after test (Back to Service Phase, FIS_1 or FIS_2 in Figure 4). If the failure occurs on test, then the Monitored Withstand test has successfully failed a weak location in the cable system and thus accomplished its goal. Under this scenario, a Monitored Withstand test does not differ much from a Simple Withstand test because both produce a failure irrespective of the monitored property behavior.

The most useful aspect of the monitoring portion is that it may be used to estimate the "Pass" margin (i.e. the system condition when no dielectric puncture occurred during the test). The concept of "Pass" margin is only possible under the Monitored Withstand framework. At this stage, the monitored property can be used to establish the degree of the "Pass" margin as either "Poor" or "Better". As shown in Figure 4, a "Poor" pass margin is defined as one in which the segment has a high likelihood of failing in service minutes to days after the test concludes, while a "Better" pass margin segment is likely to survive in service without failure months to years after the test. As with all other diagnostic techniques, the key is defining the "likely" part of the previous statement.

The additional information afforded by Monitored Withstand does not come for free because there is added complexity imposed by the diagnostics and decisions of the Monitored Withstand. However, it allows for decision making during test deployment and data analysis for condition assessment during and after the test has concluded. Therefore, in general, decisions and condition assessments can be undertaken at three points as follows:

- **At the end of the "Ramp-up" phase and before the beginning of the "Hold" phase:** The first decisions and condition assessments can be undertaken by evaluating the monitored value/parameters and deciding which systems go to the "Hold" Phase. The reasoning here is simple and is based on the potential that the monitored value/parameter has on detecting extremes on the good and bad conditions. Thus good or bad systems do not need further evaluation because their conditions have already been established and from a condition assessment perspective continuing to the "Hold" phase is not an optimal use of resources (this is Decision 1 on section 10.6.4).
- **During the "Hold" phase:** Decisions can only be undertaken here regarding the duration of the withstand phase. Decisions are then based on 'real time' observation and analysis of the monitored value. If the monitored value shows certain characteristics that can be correlated

to good or bad performance, then the planned test time can be amended to provide a least cost scenario; i.e. reducing total test time or avoiding failures under test on systems that can be remediated later with lower emergency costs (this is Decision 2 on section 10.6.4).

- **After the Monitored Withstand test has concluded:** The potential of a monitored withstand framework is also exploited after the test has concluded; because, additionally to the pass/fail information of the withstand phase, the behavior of the monitored value during the "Hold" phase can be used to determine a final condition assessment for those cable systems that made it to the end of the "Hold" phase without a failure on test (this is Decision 3 on section 10.6.4).

Decision making and condition assessment in the context of a monitored withstand framework are shown in Figure 5. Decision making and condition assessment in the context of a monitored withstand framework using VLF Tan δ measurements appear later in Section 10.6.4.

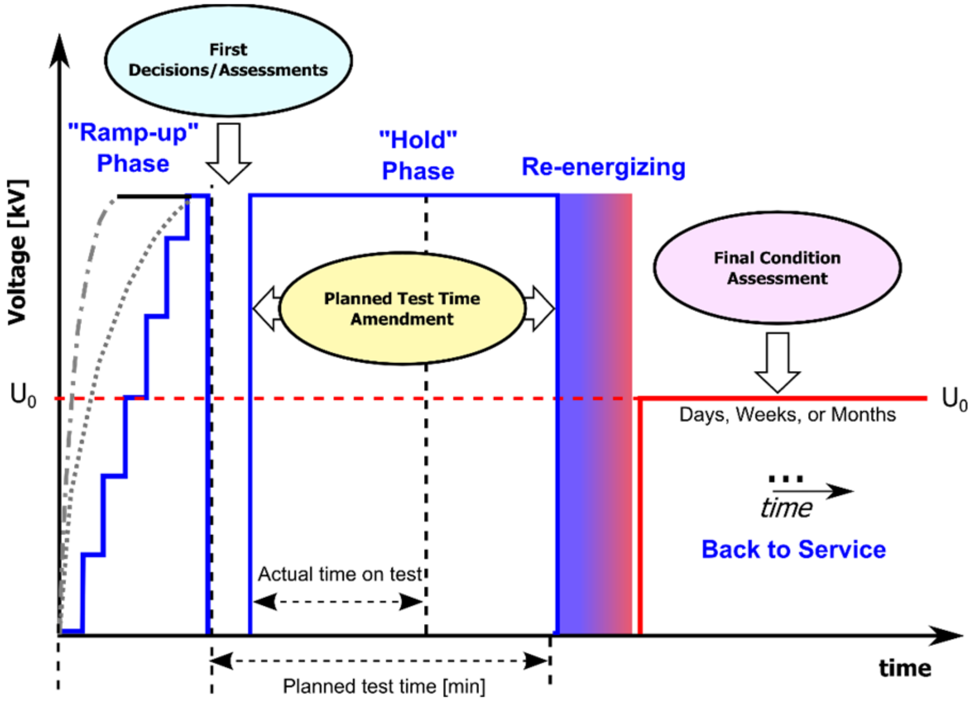

Figure 5: Decision Making and Condition Assessment in the Context of a Monitored Withstand Test Framework

10.6.3 Evolution of VLF Tan δ Monitored Withstand Criteria

CDFI Phase II was able to continue studying the use of VLF Simple Withstand combined with VLF Tan δ. The contributions made during *Phase I* were important; in fact, before the *CDFI*, the concept and application of monitored withstand tests were almost completely unknown to the industry. During *Phase II*, the industry has moved towards smaller and smaller voltage sources with diagnostic assessment tools (based on *CDFI* analyses and recommendations) integrated within them. *Phase I* showed the potential value of Monitored Withstand as a diagnostic tool and laid the groundwork for establishing data-driven assessment criteria. Meanwhile, *Phase II* was able to assemble a large dataset that could be used to define the critical levels for interpreting Monitored

Withstand data. To put this in perspective, the contributions of *CDFI Phases I* and *II*, Table 3 shows the evolution of VLF Tan δ monitored withstand criteria.

Table 3: Evolution of VLF Tan δ Monitored Withstand Criteria for MV Cable Systems

Year	**Assessment Hierarchy**	**Criteria & Issues**	**Comments (See 10.6.4)**
< 2001	None	None	No framework established
2004	***CDFI Phase I***		
2006	1. Trend 2. Stability 3. Level of loss	Initial Discussion	• Contribution of *CDFI Phase I* project based on statistical analysis of data from North American cables • Initial quantitative criteria on **Decision 3** – Final Assessment? Only for paper insulations • Initial quantitative criteria on **Decision 2** – Amend of test time? • First Tan δ Monitored Withstand brochure
2007		Qualitative Experiments	
2008 – 2010		• Criteria based on data • Included in discussions of IEEE Std. 400.2 – 2013	
2011	***CDFI Phase II***		
2011 – 2014	1. Trend 2. Stability 3. Level of loss	• Criteria based on data. • Included in update of IEEE Std. 400.2 – 2013	• Increase the size of the Tan δ monitored withstand database. • Criteria on **Decision 1** – Continue to "Hold" phase? • Criteria on **Decision 2** – Amend of test time? • IEEE Std. 400.2™ – 2013 release. • Continuing update of Tan δ brochure
2015	1. Speeds 2. Stability 3. Level of loss	• Criteria based on data • Verification of Tan δ diagnostic features and hierarchy • VLF Tan δ monitored withstand framework. • Evaluation of the "Ramp-up" Phase • Amendment of test time. • Evaluation of the "Hold" phase & Final Assessment • PCA-based analysis tool	• Contribution of *CDFI Phase II* Project based on statistical analysis of data from North American cables • Criteria on **Decision 1** – Continue to "Hold" phase? • Criteria on **Decision 2** – Amend of test time? • Criteria on **Decision 3** – Final Assessment? • Established complete framework. • Continuing update of Tan δ brochure

It is important to note the use of the term "Qualitative" in Table 3 is used to describe some of criteria in 2007. This term is used because the understanding in *CDFI Phase I* at the time was limited to which VLF Tan δ measurement values were "really good" and those that were "really bad" but there was not a defined threshold to separate these two categories. Thresholds and criteria were developed later once significant amounts of data were available.

10.6.4 Monitored Withstand Using VLF Tan δ

There are a number of monitored properties that could be utilized during a Monitored Withstand test. They each entail their own difficulties. This section describes the implementation of Monitored Withstand using VLF Tan δ as the monitored property. The basic framework appears in Figure 6.

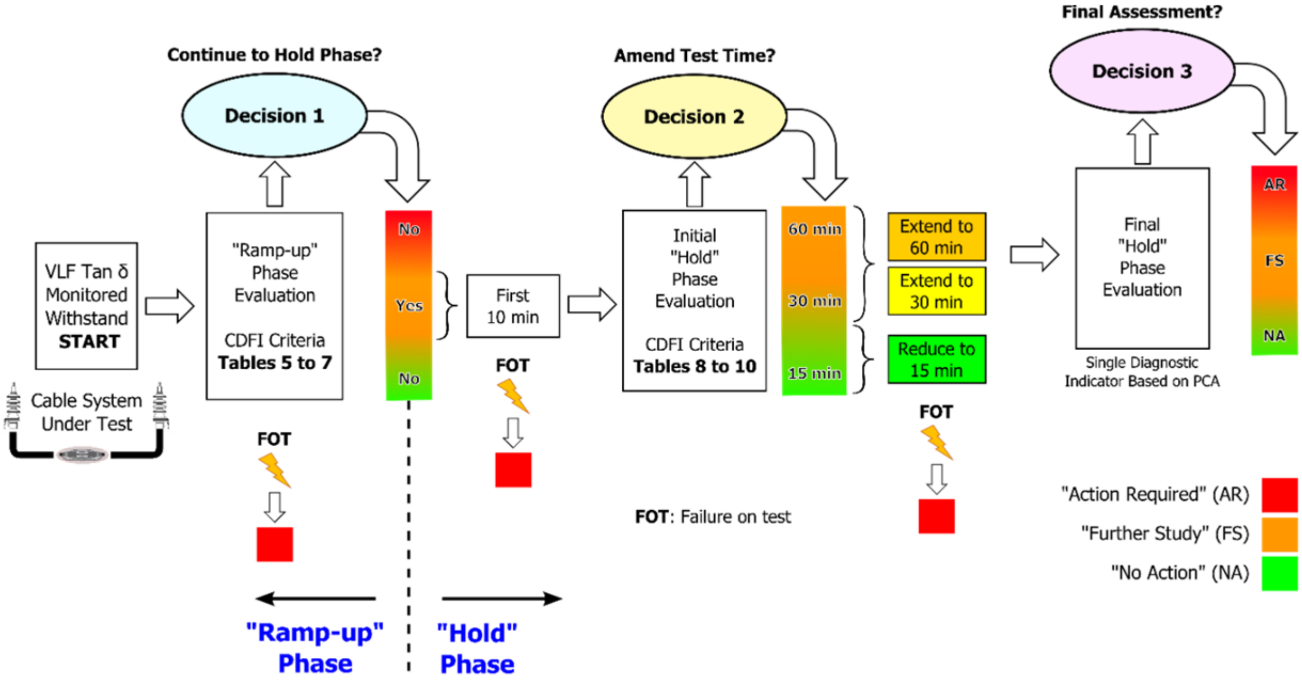

Figure 6: Monitored Withstand Test Framework using VLF Tan δ Measurements

As Figure 6 illustrates, there are three sequential decisions to be made as part of the Monitored Withstand test, namely:

- **Decision 1 – Continue to "Hold" phase?** It is based on the evaluation of the "Ramp-up" phase that can be related to a conventional VLF Tan δ test as described in Chapter 6 (Dissipation Factor – Tan δ). Therefore, Decision 1 can be made by both using reference tables or "Health Index" based on the PCA tool developed in the *CDFI*. Since Decision 1 has to be made on-site during the test, the use of reference tables is preferred over the PCA tool because it is faster and easier to use. Criteria for Decision 1 based on reference tables appear in Table 5 to Table 7 for all insulation types.

- **Decision 2 – Amend test time?** It is based on an initial evaluation of the "Hold" phase to amend test time. Since Decision 2 has also to be made on site during the test, reference table based criteria are also used. Criteria for Decision 2 based on reference tables appear in Table 8 to Table 10 for all insulation types.

- **Decision 3 – Final assessment?** If the monitored withstand test has concluded without a FOT, Decision 3 is based on a final evaluation of the "Hold" phase. Since this decision can be made after the test has concluded, it is made by estimating the "Pass" margin using a single diagnostic indicator based on PCA. This complication is not as time sensitive and so does not impact the decision making that must occur during the test.

Each of the above decisions is discussed in detail in Sections 10.6.4.1 through 10.6.4.3. It is important to note that Decision 1 and Decision 2 are made in real time as part of the testing procedure while Decision 3 can be made afterwards. Within each of these sections, criteria are provided for aiding users in making the real time and post-test decisions. These criteria were developed from an extensive VLF Tan δ Monitored Withstand database as summarized in Table 4.

Table 4: Description of the VLF Tan δ Monitored Withstand Database

Insulation Type	**Number of Tests**		**Tested Length**	
	Absolute [#]	**Proportion [%]**	**Absolute [mi]**	**Proportion [%]**
PE-based (i.e. PE, HMWPE, XLPE, & WTRXLPE)	618	44.6	366.7	39.4
Filled (i.e. EPR & Vulkene)	237	17.1	110.3	11.9
Paper (i.e. PILC)	513	37.0	409.2	44.0
Hybrid	17	1.2	43.9	4.7
Total	**1,385**	**100.0**	**930.0**	**100.0**

This database includes 1,385 tests on 930 miles of cable system made during 2007 - 2015. The tests encompass a wide variety of cable systems including PILC, PE-based, filled, and hybrid systems. Figure 7 shows the split in terms of both number of tests and length tested for each system type.

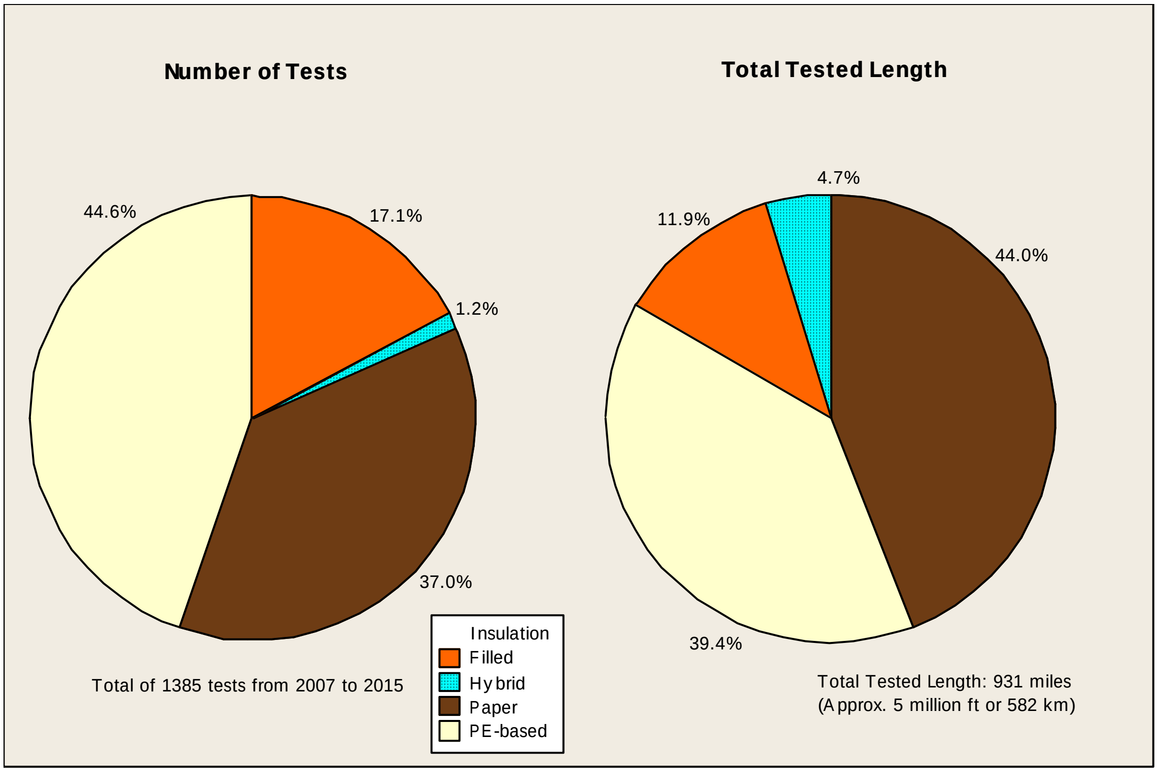

Figure 7: Description of the VLF Tan δ Monitored Withstand Database

Unfortunately, there are too few data to develop criteria for all system types. However, criteria were developed wherever possible as illustrated in the Decision 1 criteria discussed in the next section.

10.6.4.1 Decision 1 - "Ramp-up" Phase Evaluation – Continue to "Hold" Phase?

As seen in Figure 6, Decision 1 is based on the "Ramp-up" phase evaluation. During this phase, the test voltage is increased from zero to the required test voltage level in steps of 0.5 U_0 as the required withstand voltage level is usually greater than 1.5 U_0. The resulting "Ramp-up" phase consists of three steps of 0.5 U_0, U_0, and 1.5 U_0 with Tan δ measurements at each step. It is important to relate the evaluation of the "Ramp-up" phase to a conventional VLF Tan δ test as defined in Chapter 6 Dissipation Factor (Tan δ).

Consequently, the evaluation of the "Ramp-up" phase uses the following Tan δ diagnostic features listed in order of decreasing 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.
- **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, 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.

- **Level of Tan δ** – 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 8 shows examples of measured Tan δ data during the “Ramp-up” phase and the corresponding diagnostic features from a PE-based cable system. The diagnostic features for other insulation types (filled and paper) are the same as the ones described in Figure 8.

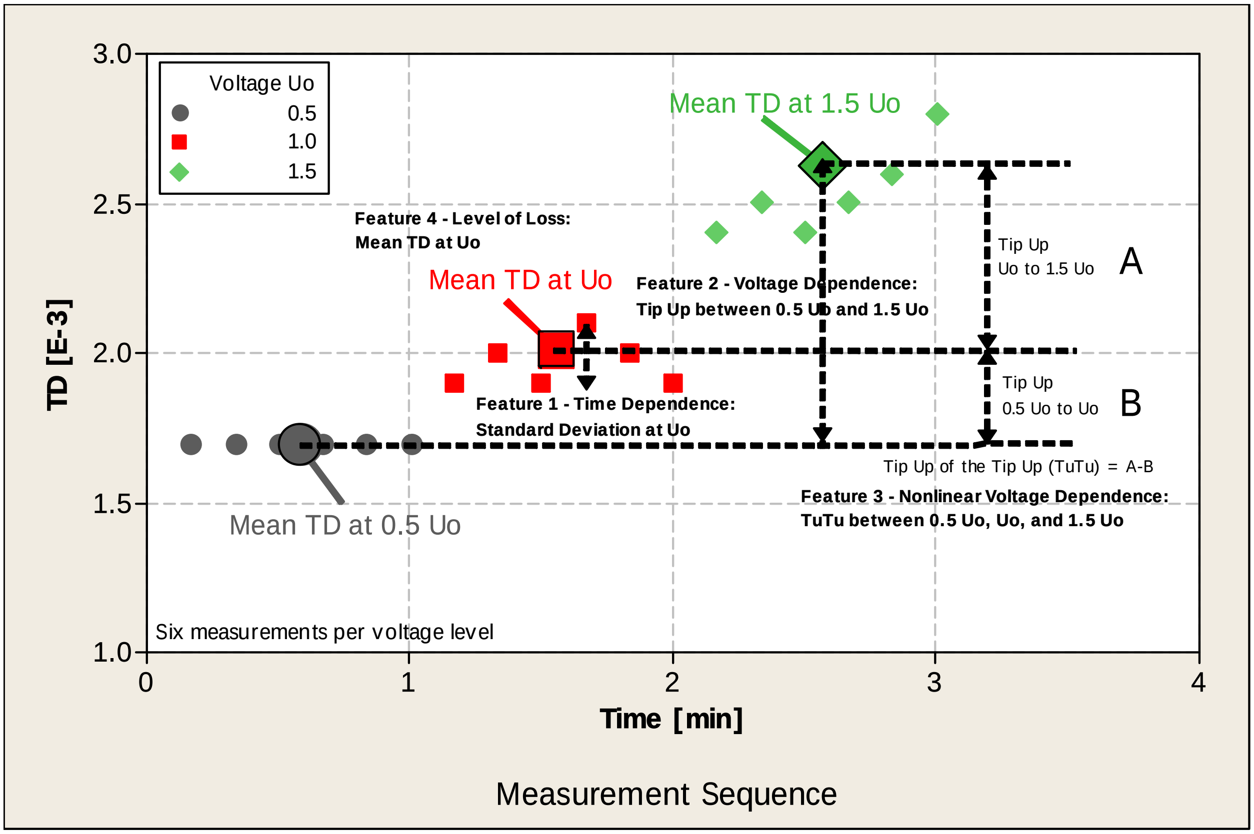

Figure 8: Examples of Measured Tan δ data and Diagnostic features from a PE Cable System during the “Ramp-up” Phase

The criteria for evaluation of the “Ramp-up” phase are the same as those developed in Chapter 6 but reappear in Table 5 to Table 7. In these tables, the typical Tan δ assessment classes of (“No Action Required”, “Further Study”, and “Action Required”) have been replaced with No/Yes to correspond to the Decision 1 question: Continue to “Hold” phase?

Table 5: *CDFI* Research Criteria for Evaluation of the "Ramp-up" Phase for PE-based Insulations (i.e. PE, HMWPE, XLPE, & WTRXLPE)

Decision 1 – Continue to "Hold" Phase?

"Ramp-up" Phase Evaluation [E-3]	**"No"***	**"Yes"****	**"No"*****
Stability for TD_{U_0} (standard deviation – STD)	<0.1	0.1 to 1.0	>1.0
	and	**or**	
Tip Up ($TD_{1.5U_0} – TD_{0.5U_0}$ – TU)	<6.7	6.7 to 94.0	>94.0
	and	**or**	
Tip Up Tip Up (TuTu) $\{(TD_{1.5U_0}–TD_{U_0}) - (TD_{U_0}–TD_{0.5U_0})\}$	<2.0	2.0 to 50.0	>50.0
Mean Tan δ at U_0 (TD)	**and**	**or**	
	<6.0	6.0 to 70.0	>70.0

* "Green No" – Cable systems condition is assessed as in the best performing 80% and thus it is unnecessary to continue to "Hold" phase because time and resources are saved.

** "Amber Yes" – Cable system condition cannot be determined during the "Ramp-up" phase and thus systems are further taken to the "Hold" phase for a final condition assessment.

*** "Red No" – Cable system condition is assessed as in the poorest performing 5% and thus it is unnecessary to continue to the "Hold" phase because the higher risk of FOT is likely to result in inefficient testing and high emergency repair costs. Systems in this category can be acted on in a planned manner by managing optimal time and costs.

Table 6: *CDFI* Research Criteria for Evaluation of the “Ramp-up” Phase of Filled Insulations (i.e. EPR & Vulkene®)

Decision 1 – Continue to “Hold” Phase?

“Ramp-up” Phase Evaluation [E-3]	**“No”***	**“Yes”****	**“No”*****
Unidentified Filled Insulations (i.e. EPR, Kerite, & Vulkene®)*			
Stability for TD_{U_0} (standard deviation – STD)	<0.1	0.1 to1.2	>1.2
	and	**or**	
Tip Up ($TD_{1.5U_0} – TD_{0.5U_0}$ – TU)	<3.0	3.0 to 30.0	>30.0
	and	**or**	
Tip Up Tip Up (TuTu) {($TD_{1.5U_0}$–TD_{U_0}) - (TD_{U_0}–$TD_{0.5U_0}$)}	<1.0	1.0 to 18.0	>18.0
Mean Tan δ at U_0 (TD)	**and**	**or**	
	<25.0	25.0 to 150.0	>150.0
Mineral Filled Insulations (i.e. EPR) Experience has shown that it is difficult to precisely identify the type of filled insulation in field-installed cable. The issues include: incorrect /missing records, obscured markings on the jacket, indistinct coloring, etc. In these cases, it is recommended to use the criteria for **Unidentified Filled**.			
Stability for TD_{U_0} (standard deviation – STD)	<0.1	0.1 to 0.8	>0.8
	and	**or**	
Tip Up ($TD_{1.5U_0} – TD_{0.5U_0}$ – TU)	<2.0	2.0 to 40.0	>40.0
	and	**or**	
Tip Up Tip Up (TuTu) {($TD_{1.5U_0}$–TD_{U_0}) - (TD_{U_0}–$TD_{0.5U_0}$)}	<1.0	1.0 to 25.0	>25.0
Mean Tan δ at U_0 (TD)	**and**	**or**	
	<16.0	16.0 to 75.0	>75.0

* “Green No” – Cable system condition is assessed as in the best performing 80% and thus it is unnecessary to continue to “Hold” phase because time and resources are saved.

** “Amber Yes” – Cable system condition cannot be determined during the “Ramp-up” phase and thus systems are further taken to the “Hold” phase for a final condition assessment.

*** “Red No” – Cable system condition is assessed as in the poorest performing 5% and thus it is unnecessary to continue to the “Hold” phase because the higher risk of FOT is likely to result in inefficient testing and high emergency repair cost. Systems in this category can be acted on a planned manner by managing optimal time and costs.

Table 7: *CDFI* Research Criteria for Evaluation of the "Ramp-up" Phase of Paper Insulations (i.e. PILC)

Decision 1 – Continue to "Hold" Phase?

"Ramp-up" Phase Evaluation [E-3]	**"No"***	**"Yes"****	**"No"*****
Stability for TD_{U_0} (standard deviation – STD)	<0.2	0.2 to 1.5	>1.5
	and	**or**	
Tip Up ($TD_{1.5U_0} – TD_{0.5U_0}$ – TU)	-30.0 to 22.0	-30.0 to -60.0 or 22.0 to 220.0	<-60.0 or >220.0
	and	**or**	
Tip Up Tip Up (TuTu) $\{(TD_{1.5U_0}–TD_{U_0}) - (TD_{U_0}–TD_{0.5U_0})\}$	<9.0	9.0 to 25.0	>25.0
Mean Tan δ at U_0 (TD)	**and**	**or**	
	<100.0	100.0 to 250.0	>250.0

* "Green No" – Cable systems condition is assessed as good and thus it is unnecessary to continue to "Hold" phase because time and resources are saved.

** "Amber Yes" – Cable system condition cannot be determined during the "Ramp-up" phase and thus systems are further taken to the "Hold" phase for a final condition assessment.

*** "Red No" – Cable system condition is assessed as extremely bad and thus it is unnecessary to continue to the "Hold" phase because the higher risk of FOT is likely to result in inefficient testing and high emergency repair costs. Systems in this category can be acted on in a planned manner by managing optimal time and costs.

The "Ramp-up" phase evaluation in Table 5 through Table 7 are intended to assist field personnel with deciding whether or not to continue to the "Hold" phase of the Monitored Withstand test. As defined above, cable systems with an evaluation of the "Ramp-up" phase resulting in a "Green No" do not require immediate additional actions and it can be assumed that they have successfully passed the Monitored Withstand test with an acceptable "Pass" margin. In other words, no failures are expected soon after the system is re-energized and returned to service.

Cable systems with an evaluation of the "Ramp-up" phase resulting in a "Red No" require remedial actions in the near future and thus it is assumed that they have not passed the Monitored Withstand test. In this event, the remedial actions following a "Red No" evaluation should be sequentially undertaken as follows:

- review data for a rogue measurement in the sequence – most common in the first voltage cycle
- confirm insulation type to ensure that criteria apply
- verify the integrity of the terminations and if compromised replace them and repeat the test
- retest in the near future and observe trends (6 months to a year) or

- place on "watch list" and consider system replacement in the near future

When the evaluation of the "Ramp-up" phase is an "Amber Yes," the "Hold" phase of the test is deployed; details on how the "Hold" phase is deployed are discussed in the next section.

The expected outcomes for Decision 1 appear in Figure 9. They are based on the evaluation of all VLF Tan δ data contained in the *CDFI* database. These expected outcomes used later in the chapter through examples of analyses on real data from the field.

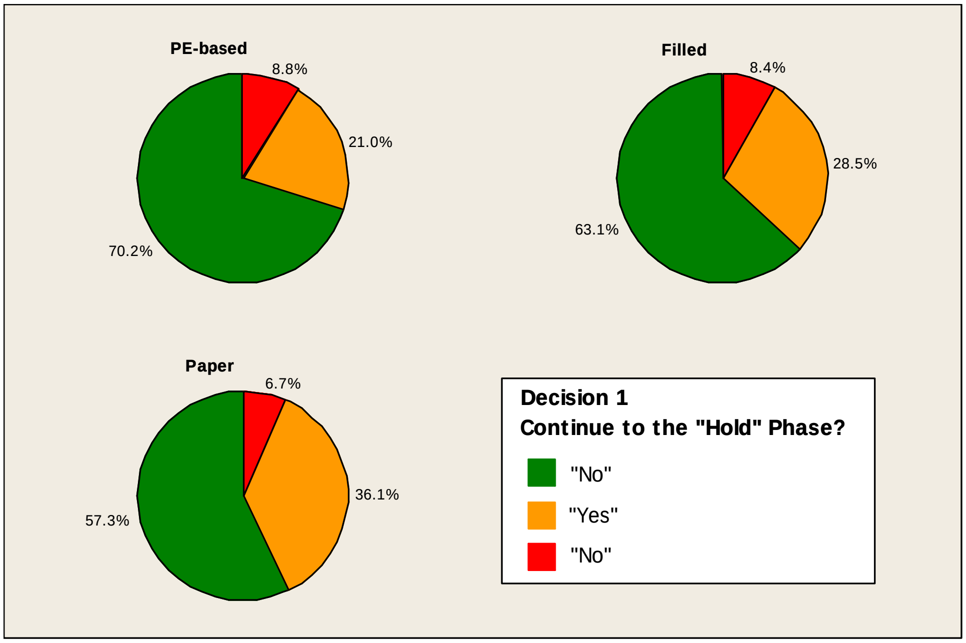

Figure 9: Outcomes for Decision 1 – Continue to the "Hold" Phase?

Once a decision is made to proceed with the "Hold" phase, the next decision (Decision 2) to be made is "how long to test".

10.6.4.2 Decision 2 – "Hold" Phase Evaluation – Amend Test Time?

The recommended test time in IEEE Std. 400.2 – 2013 for the "Hold" phase on field-aged cable systems is 30 min at 0.1 Hz. This time may be extended or reduced if a Monitored Withstand is performed and the monitored property shows specific behavior. Unfortunately, the IEEE guide does not provide a clear indication on how to evaluate the behavior. Thus, the amending of test times is a decision that must be made in the field while the test is underway. This constitutes Decision 2 shown in Figure 6.

As with Decision 1, the available data were analyzed using the same principles to determine those conditions under which the test time can be shortened or extended. This results in a set of criteria that by necessity must be evaluated during the Monitored Withstand test.

Before reviewing the criteria themselves, it is instructive to examine the differences between the interpretations of Tan δ measurements during the “Ramp-up” phase and those made during the “Hold” phase. As seen earlier, work within the *CDFI* has suggested the following hierarchy for Tan δ measurement interpretation during the “Ramp-up” phase (ranked from most important to least important):

- Tan δ Stability (STD)
- differential Tan δ or Tip-Up (TU)
- Tip Up of the Tip Up (TuTu)
- Tan δ level (magnitude) (TD)

Ideally, these or similar features would be used for Decision 2, However, the constant voltage level during the “Hold” phase does not permit all of the same features (i.e. the TU and TuTu are not available). However, the hierarchy aids in understanding the dependencies that should be considered when characterizing Tan δ measurements even under a constant test voltage. The “Ramp Up” phase approach examines Tan δ variability with time, linear and non-linear variability with voltage, and absolute level of loss. The constant voltage obviously eliminates the possibility of looking at the variability with voltage but the time variability and absolute loss level are still feasible but special attention must be given to the variability in the length of the test (15, 30, or 60 min). Therefore, the need to improve the approach is driven by the long times used for the “Hold” phase and because the user is more likely to be interested in the trend (increasing or decreasing) of the instability and the absolute loss level.

To address these issues, taking into account the above discussion and what is readily available to the user onsite when conducting the test, a set of diagnostic features were defined for the purpose of amending the test time. They are meant to be evaluated test times between 0 and 10 minutes and are as follows:

- **Absolute change in Tan δ:** This feature is quantified by the absolute difference between the Tan δ instantaneous values at 10 and 0 min. It provides information on both time variability and level of loss for the considered time period.
- **Tan δ Stability:** This feature is quantified by the standard deviation (STD) of Tan δ measurements between 0 and 10 minutes and consequently provides the time variability information within the time period.
- **Tan δ level:** This feature is quantified by the mean of Tan δ measurements between 0 and 10 minutes and consequently provides the level of loss information within the time period.

Each of the above features is available for any Monitored Withstand test. The critical levels for each of these features (80th and 95th percentiles) were determined for all insulation types and appear in Table 8 through Table 10. The cumulative distribution functions that were used to generate the critical levels for PE-based insulations (i.e. PE, XLPE, WTRXLPE) appear in Figure 10. For example, in Figure 10, the absolute change in Tan δ between 0 min and 10 min ($|TD_{10}-TD_0|$) can be interpreted as having 80% of the data lie below 0.6 E-3 and thus reducing the planned test time to 15 min is limited by this threshold. Similarly, considering the 95% percentile, the planned test time is extended to 60 min by values of $|TD_{10}-TD_0|$ bigger than 8 E-3.

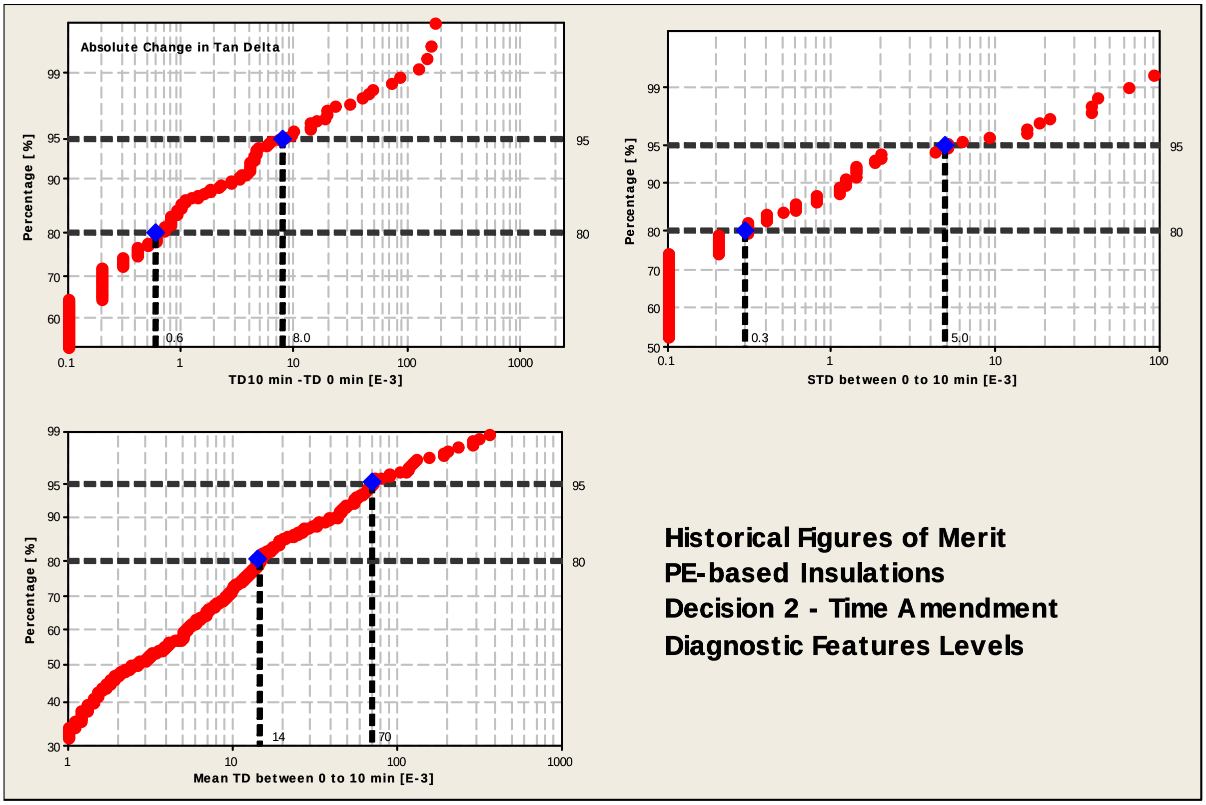

Figure 10: Determining Critical Levels for Diagnostic Features for Test Time Amendment from Research Data (PE-based Insulations)

Subsequently, the criteria for test time amendment for all insulation types are shown in Table 8 through Table 10.

Table 8: *CDFI* Research Criteria for Time Amendment of the “Hold” Phase of PE-based Insulations (i.e. PE, HMWPE, XLPE, & WTRXLPE)*		
Decision 2 – Amend Test Time?		
“Hold” Phase Evaluation [E-3]	**“Reduce to 15 min”**	**“Extend to 60 min”**
Absolute Change in Tan δ $\lvert TD_{10}-TD_0 \rvert$	<0.6	>8
	and	**or**
Tan δ Stability (Standard Deviation – STD_{10})	<0.3	>5
	and	**or**
Tan δ Level (Mean Tan δ – TD_{10})	<14	>70

* Based on data as described in Table 4

Table 9: *CDFI* Research Criteria for Time Amendment of the "Hold" Phase of Filled Insulations (i.e. EPR & Vulkene)*

Decision 2 – Amend Test Time?

"Hold" Phase Evaluation [E-3]	**"Reduce to 15 min"**	**"Extend to 60 min"**
Absolute Change in Tan δ $\lvert TD_{10}-TD_0 \rvert$	<0.6	>6
	and	**or**
Tan δ Stability (Standard Deviation – STD_{10})	<0.3	>5
	and	**or**
Tan δ Level (Mean Tan δ – TD_{10})	<13	>105

* Based on data as described in Table 4

Table 10: *CDFI* Research Criteria for Time Amendment of the "Hold" Phase for Paper Insulations (i.e. PILC)*

Decision 2 – Amend Test Time?

"Hold" Phase Evaluation [E-3]	**"Reduce to 15 min"**	**"Extend to 60 min"**
Absolute Change in Tan δ $\lvert TD_{10}-TD_0 \rvert$	<1.4	>5
	and	**or**
Tan δ Stability (Standard Deviation – STD_{10})	<0.6	>5.4
	and	**or**
Tan δ Level (Mean Tan δ – TD_{10})	<80	>180

* Based on data as described in Table 4

Using the above criteria, the expected outcomes for Decision 2 appear in Figure 11. These results are used in the case studies that appear in Section 10.6.4.4.

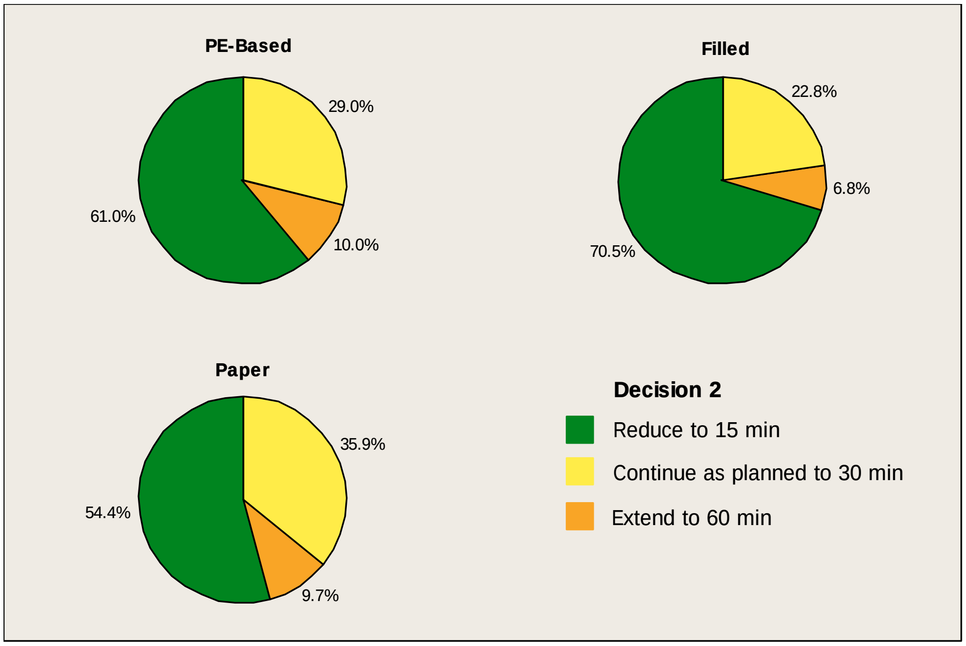

Figure 11: Outcomes for Decision 2 Using *CDFI* Research Data – Amend Test Time?

If the segment under test successfully completes the "Hold" phase without a FOT, then the final step is to provide a condition assessment. The details of how this assessment is conducted are described in the next section.

10.6.4.3 Decision 3 – "Hold" Phase Evaluation – Final Assessment?

Once a VLF Tan δ monitored withstand test has concluded without a FOT, a final evaluation of the "Hold" phase data is required. The utility engineer must then confront a condition assessment that involves a multitude of potential features. This is represented in Figure 6 as Decision 3 – Final Assessment. This assessment can be accomplished by estimating a qualitative "Pass" margin that is derived from diagnostic features obtained from the "Hold" phase. The "Pass" margin is useful to classify cable systems into three categories or classes:

- **"No Action Required"** – Systems in this category are assumed to have aa adequate"Pass" margin and are not expected to fail in the near future. Failures, if any, are expected to appear months or years after testing. Therefore, systems can be returned to service without any major concerns.
- **"Action Required"** – Systems in this category are assumed to have a poor/low "Pass" margin and if no action is taken and these systems are returned to service, failures are expected to appear in the near future minutes to days after testing. Actions following an "Action Required" assessment should include placing the cable system on a "watch list" and considering replacement in the near future.
- **"Further Study"** – This category covers systems in which a clear evaluation of the "Pass" margin cannot be accomplished. Therefore, a final condition assessment is not straightforward. However, actions following a "Further Study" class may aid in finding a final assessment and are described below.

Cable systems with an evaluation of the "Hold" phase resulting in "Further Study" may require remedial actions in the near future that should be sequentially undertaken as follows:

- review data for a rogue measurement in the sequence – most common during the first few voltage cycles
- confirm insulation type to ensure that criteria apply
- verify the integrity of the terminations and if compromised, clean or replace them and repeat the test
- retest in the near future and observe trends (6 months to a year) or
- place on "watch list" and consider system replacement in the near future

The estimation of the "Pass" margin is not a simple process. The diagnostic features needed to evaluate the "Hold" phase must first be determined and then considered together for the final assessment. Fortunately, irrespective of insulation type, the features can be determined by Cluster Variable Analysis (CVA) [16] and then the grouping of features for the final assessment can be accomplished by Principal Component Analysis (PCA) [16-17]. Both the cluster variable analysis and the PCA are described in detailed in the Appendix A and Appendix B, respectively.

To develop the final assessment, a set of features that built upon those identified during the Tan δ Ramp assessment (Decision 1) were examined. This set was more limited in terms of the types of features (voltage dependence could not be used). As a result, the set used as a starting point for the Cluster Variable and Principal Component Analysis the following feature set:

1. **Tan δ Stability (STD)** – This feature represents the time dependence and is reported as the standard deviation of sequential measurements at the particular test voltage level irrespective of it is a 15, 30, or 60 min test.
2. **Initial Tan δ (Init TD)** – This feature represents the initial measured loss level at the beginning of the "Hold" phase irrespective of it is a 15, 30, or 60 min test.
3. **Final Tan δ (Final TD)** – This feature represents the final measured loss level at the end of the "Hold" phase irrespective of it is a 15, 30, or 60 min test.
4. **Level of Tan δ (Mean TD)** – This feature represents the average level of loss over the full "Hold" phase irrespective of it is a 15, 30, or 60 min.
5. **Speed (rate of change over time) of Tan δ between 0 and 5 min (SPD 0-5)** – This feature represents an estimate of the rate of change in time of the loss level (Tan δ) during the first 5 minutes of the "Hold" phase. More importantly, this feature also provides information about the trend of the measurements during the period under consideration; i.e. positive values indicate an increasing trend and *vice versa*.
6. **Speed of Tan δ between 5 and 10 min (SPD 5-10)** – This feature represents an estimate of the rate of change in time of the loss level (Tan δ) during the second 5 minutes of the "Hold" phase.
7. **Speed of Tan δ between 10 and 15 min (SPD 10-15)** – This feature represents an estimate of the rate of change in time of the loss level (Tan δ) during the third 5 minutes of the "Hold" phase.
8. **Speed of Tan δ Between 0 and final test time (SPD 0-t_{final})** – This feature represents an estimate of the overall rate of change of the loss level (Tan δ) with time for a completed "Hold" phase irrespective of it is a 15, 30, or 60 min test.

An example of measured data during the “Hold” phase with the previously described diagnostic features appears in Figure 12.

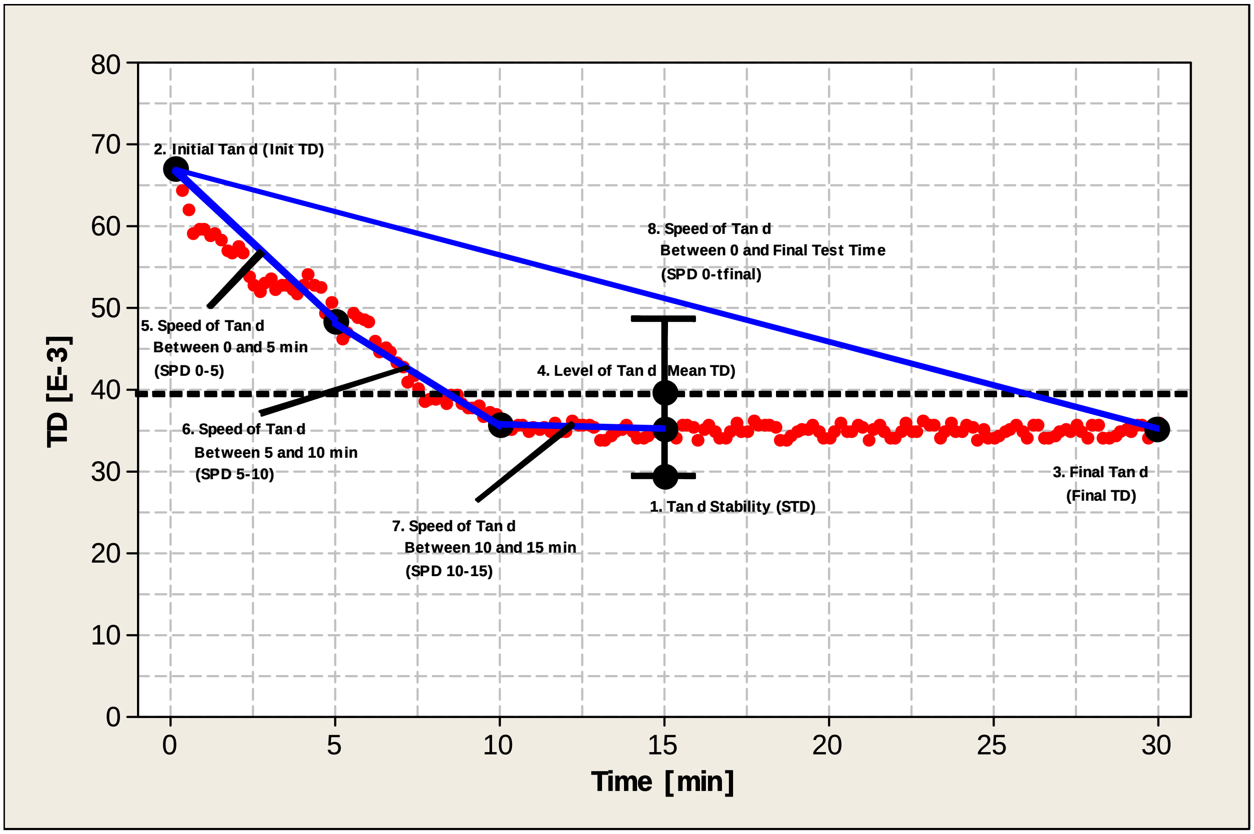

Figure 12: Example of Real Measured Tan δ data and Diagnostic features from a PE Cable System during the “Hold” Phase

As described above, eight features are available for determining the appropriate assessment class. Cluster Variable Analysis (reduces the feature set) and Principal Component Analysis (finds the best combination of features) were used to identify which features to include in the condition assessment. This was done for all three insulation classes (PE-based, filled, and PILC). The details of this feature reduction/identification are discussed in Appendix C, Appendix D, and Appendix E for PE-based, filled, and PILC, respectively. The remaining discussion in this section focuses on the results of these analyses.

Table 11 shows the “recipes” that result from completing the CVA and PCA for each of the insulation types. As this table shows, the features and their positions within the principal components change depending on the insulation type.

Table 11: Comparison of PCA Results by Insulation Type

Insulation Type		
PE-based	**Filled**	**Paper**
Number of Principal Components		
4	3	3
Variability Described by Principal Components		
98.0	96.0	94.7
“Hold” Phase Tan δ Diagnostic Features by Principal Component		
PC1 – STD and SPD 0-t_{final} PC2 – SPD 0-5 PC3 – Mean TD PC4 – STD	PC1 – SPD 0-t_{final} and STD PC2 – Mean TD PC3 – SPD 10-15	PC1 – SPD 10-15 and STD PC2 – SPD 0-t_{final} PC3 – Mean TD
“Hold” Phase Tan δ Diagnostic Features Hierarchy of Importance		
Overall and Initial Speeds (SPD 0-t_{final} and SPD 0-5) Variability (STD) Level of Loss (Mean TD)	Overall Speed (SPD 0-t_{final}) Variability (STD) Level of Loss (Mean TD)	Middle and Overall Speeds (SPD 10-15 and SPD 0-t_{final}) Variability (STD) Level of Loss (Mean TD)

With the PCA recipe and the known behavior of a new cable system, it is then possible to compute a PCA distance that essentially quantifies how different a tested cable system is from a new system with similar characteristics. The resulting distributions of these “distances” for the data contained in the *CDFI* database for Monitored Withstand appear in Figure 13. It is important to note that the distributions are different at small distances (i.e. near new) but quite similar at larger distances (poor condition).

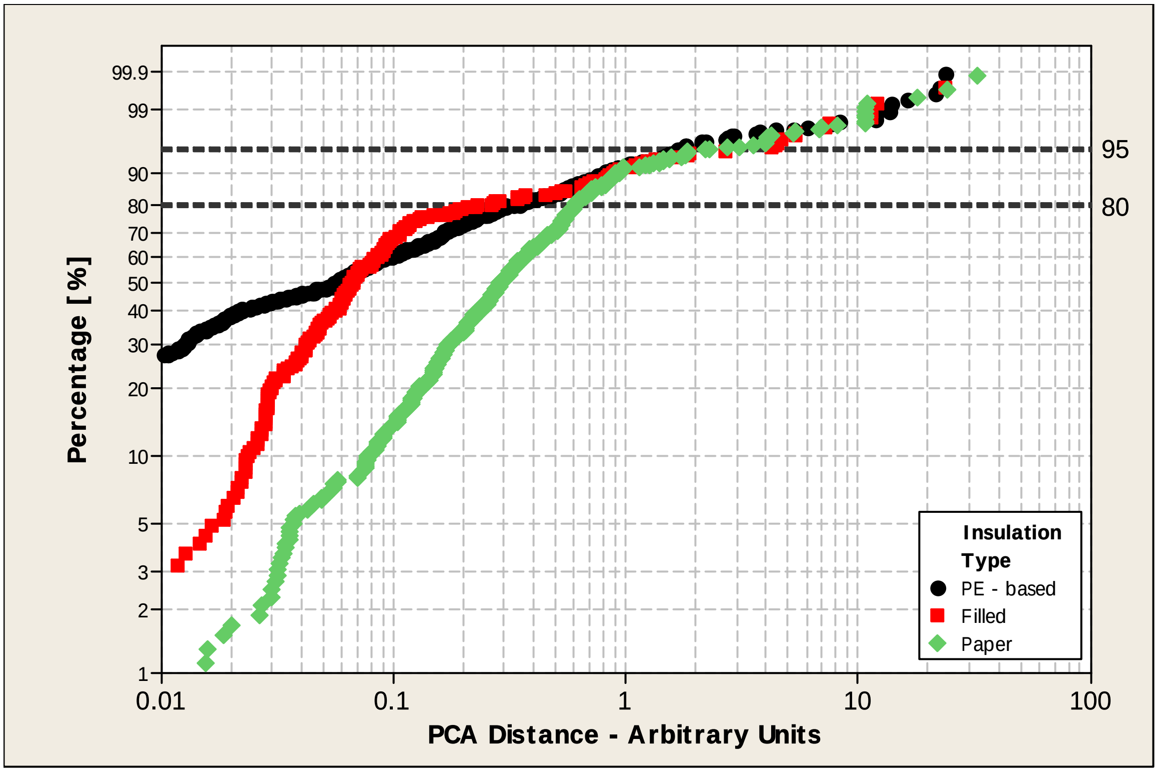

Figure 13: Comparison of Empirical Cumulative Distributions of the PCA Distance used for Evaluation of the "Hold" Phase by Insulation Type

Figure 13 also shows the typical thresholds that were used throughout *CDFI* research and so these define the separations from the different assessment classes for each insulation type. "Action Required" (> 95%) is virtually the same for each of the insulations. There is a more pronounced difference at the "Further Study" threshold (80%). Results from Figure 13 and Table 11 provide indications that when the PCA results are considered together, there are issues to be imparted for all insulation types. These issues appear below:

- The number of diagnostic features used to describe the "Hold" phase can be reduced to four or five features. These features cover more than 95% of the data variability.
- The type and importance of the diagnostic features is generally the same regardless of the insulation type; speeds are the more important features, followed by the variability, and the level of loss.
- The differences observed in the PCA distances (Figure 13) strongly suggest that valuable knowledge of VLF Tan δ Monitored Withstand is gained from collating experience. Furthermore, it shows that the data must be collected separately for different insulation types.

The following section illustrates the use of these results in case studies.

10.6.4.4 Case Studies

To improve the understanding of the application of the VLF monitored withstand framework, this section presents examples of how the framework is deployed using real data from the field.

- **Case Study 1:** Data for a service-aged XLPE cable system that has been assessed by the framework as "Further Study" at the end of the ramp, but test ultimately curtailed to 15 min.
- **Case Study 2:** Data for a service-aged XLPE cable system that has been assessed by the framework as "Further Study" at the end of the ramp, but test ultimately extended to 30 min.

In both cases, the VLF monitored withstand data are presented graphically in Figure 14 and Figure 15 and the results of employing the Monitored Withstand framework appear in Table 12 and Table 13, respectively.

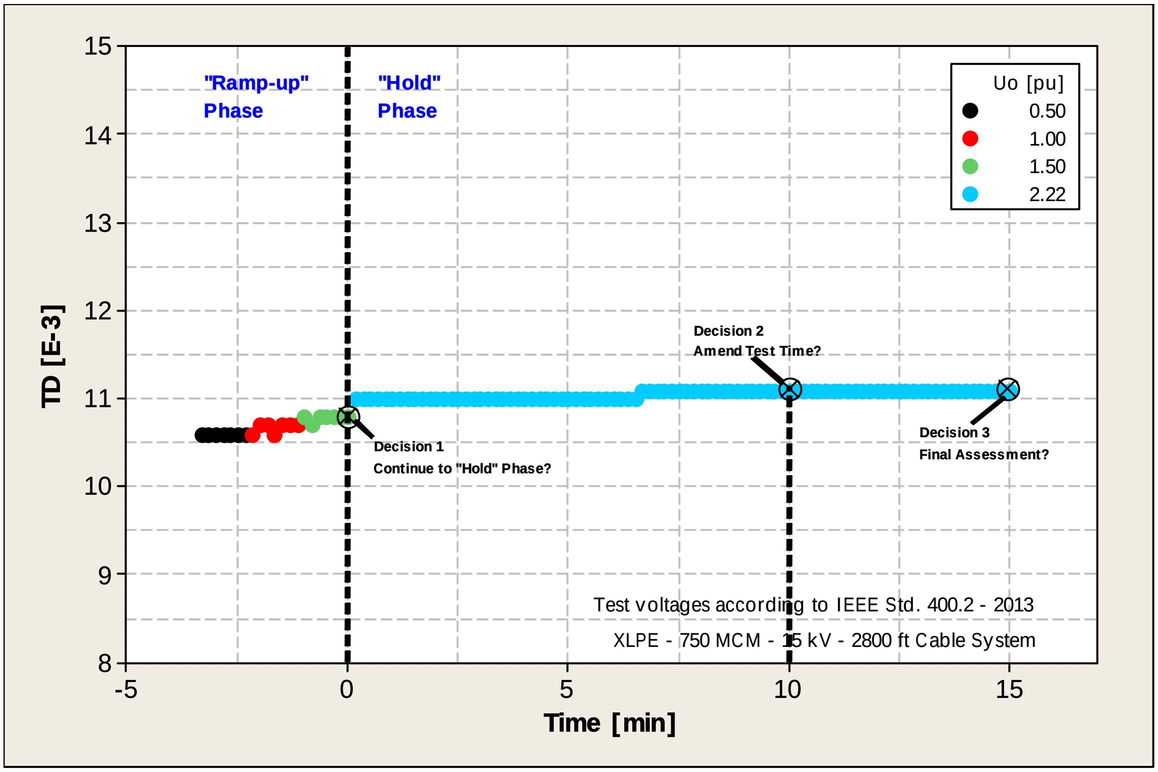

Figure 14: Case Study 1: Field VLF Tan δ Monitored Withstand Data for a Service Aged XLPE Cable System Ultimately Assessed as "No Action"

Table 12: Case Study 1 - Field VLF Tan δ Monitored Withstand Data and Decision Making Framework for a Service Aged XLPE Cable System Assessed as “No Action”
(Tan δ from Figure 14)

Decisions Made On Site

Decision 1 – “Ramp-up” Phase Evaluation – Continue to “Hold” Phase?

Diagnostic Feature	**STD [E-3]**	**TU [E-3]**	**TuTu [E-3]**	**TD [E-3]**
Feature Value	0.01	0.3	0.1	10.70
Assessment based on the criteria presented in Table 5				
Individual Feature Assessment	“No”	“No”	“No”	“Yes”
Overall Feature Assessment	“Yes”			

Decision 2 – “Hold” Phase Evaluation – Amend Test Time?

Diagnostic Feature	**$\lvert TD_{10}-TD_0 \rvert$ [E-3]**	**STD_{10} [E-3]**	**Mean TD_{10} [E-3]**
Feature Value	0.1	0.05	11.4
Assessment based on the criteria presented in Table 8			
Individual Feature Assessment	“Reduce to 15 min”	“Reduce to 15 min”	“Reduce to 15 min”
Overall Feature Assessment	“Reduce to 15 min”		

Decision Taken After Test

Decision 3 – “Hold” Phase Evaluation – Final Assessment?

Feature	**SPD 0-5 [E-3/min]**	**SPD 5-10 [E-3/min]**	**SPD 0-t_{final} [E-3/min]**	**STD [E-3]**	**Mean Tan δ [E-3]**	**PCA Distance**	**Percentage Rank [%]**
Feature Value	0.002	0.002	0.002	0.010	11.00	0.12	64.00
Assessment Based on Health Index from PCA (Table 18 and Figure 23)							
Overall Feature Assessment	“No Action”						

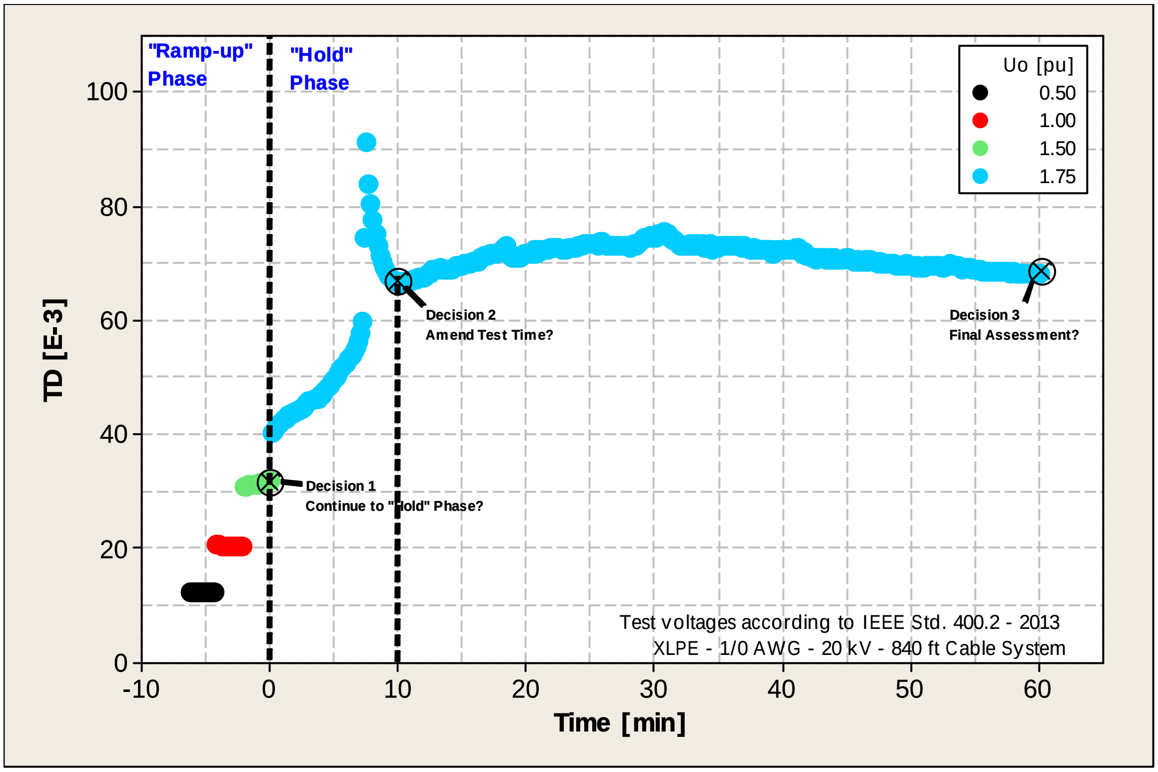

Figure 15: Case Study 2: Field VLF Tan δ Monitored Withstand Data for a Service Aged XLPE Cable System Ultimately Assessed as "Further Study"

Table 13: Case Study 2 - Field VLF Tan δ Monitored Withstand Data and Decision Making Framework for a Service Aged XLPE Cable System Assessed as "Further Study" (Tan δ from Figure 15)

Decisions Taken On Site

Decision 1 – "Ramp-up" Phase Evaluation – Continue to "Hold" Phase?

Diagnostic Feature	**STD [E-3]**	**TU [E-3]**	**TuTu [E-3]**	**TD [E-3]**
Feature Value	0.10	19.00	2.80	20.70
Assessment based on the criteria presented in Table 5				
Individual Feature Assessment	"Yes"	"Yes"	"No"	"Yes"
Overall Feature Assessment	"Yes"			

Decision 2 – "Hold" Phase Evaluation – Amend Test Time?

Diagnostic Feature	**|TD$_{10}$-TD$_0$| [E-3]**	**STD$_{10}$ [E-3]**	**Mean TD$_{10}$ [E-3]**
Feature Value	26.40	12.70	55.0
Assessment based on the criteria presented in Table 8			
Individual Feature Assessment	"Extend to 60 min"	"Extend to 60 min"	"Extend to 30 min"
Overall Feature Assessment	"Extend to 60 min"		

Decision Taken After Test

Decision 3 – "Hold" Phase Evaluation – Final Assessment?

Feature	**SPD 0-5 [E-3/min]**	**SPD 5-10 [E-3/min]**	**SPD 0-t$_{final}$ [E-3/min]**	**STD [E-3]**	**Mean Tan δ [E-3]**	**PCA Distance**	**Percentage Rank [%]**
Feature Value	1.98	3.30	0.47	8.20	68.70	1.44	93.50
Assessment Based on Health Index from PCA (Table 18 and Figure 23)							
Overall Feature Assessment	"Further Study"						

10.6.4.5 Comparison with Simple VLF Withstand

The previous sections have focused on the implementation and interpretation of the Monitored Withstand test. However, the question remains what additional benefit a user gets for the added complication implicit in the Monitored Withstand approach. It is, therefore, useful to compare the monitored withstand framework with its Simple VLF Withstand counterpart in terms of inputs (time) and outputs (subsequent actions). The comparison produces some unintuitive results that are worth exploring. This section provides such a comparison assuming that the same group of cable systems was assessed by both Simple and Monitored Withstand frameworks.

Assume that the test population has the following characteristics:

- 1,000 Aged XLPE cable systems
- the average length of a cable system/segment is 1,000 ft
- anticipated FOT rates during the "Hold" phase correspond to the ones estimated during *CDFI Phase I* (2.7% of 1,000 ft segments)

Figure 16 shows the estimated "Hold" phase performance of the Simple Withstand program. In total, 1,000 withstand tests are performed for 30 min each. This produces 27 FOTs corresponding with a failure rate of 2.7 %.

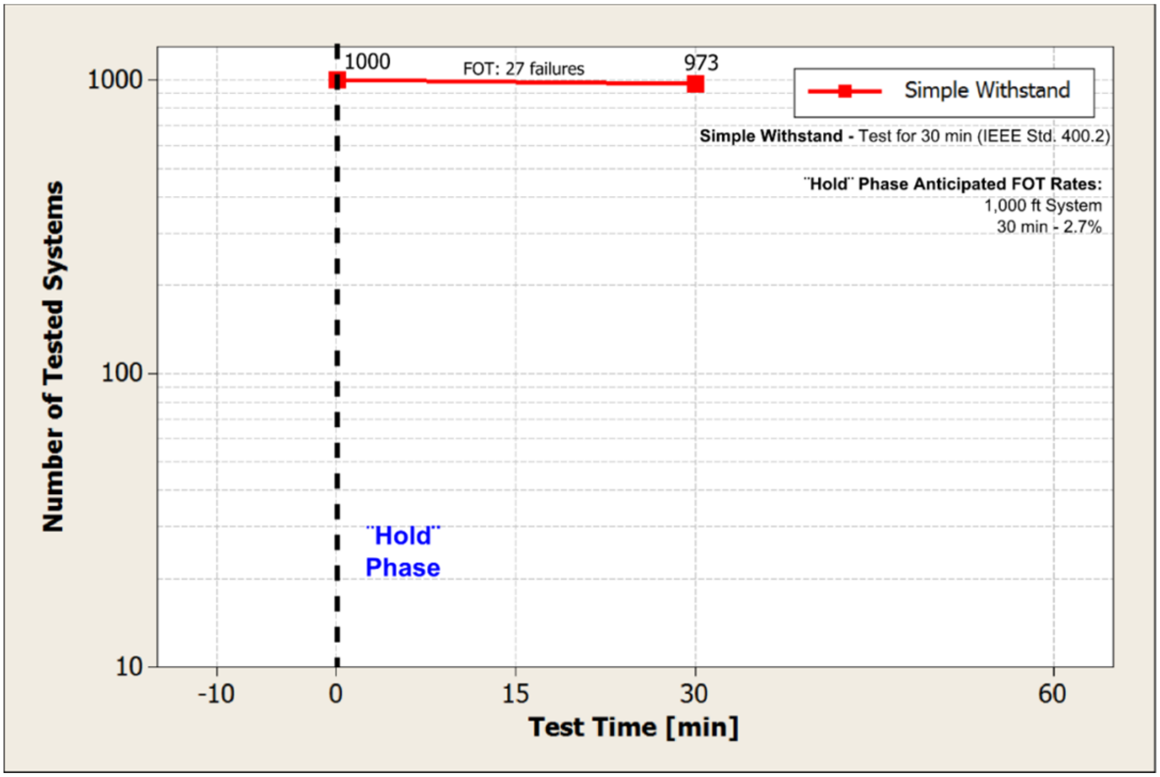

Figure 16: Simple VLF Withstand Framework on the Basis of Number of Tested Cable Systems and Test Time for PE-based Insulations

Performance estimates for the Monitored Withstand framework for this set of cable systems appear in Figure 17. In this case, the number of tested systems (blue solid line) declines significantly as a result of Decision 1 (702 "No Action Required" and 88 "Action Required"). This implies that only 210 cable systems proceed to start the "Hold" phase. Stepping back to Decision 1 for this example, it is important to remember that there are two potential implementations of Decision 1:

a) Only "Further Study" ("Amber Yes") systems are considered to move forward to the "Hold" phase or,

b) Both "Further Study" ("Amber Yes") and "Action Required" ("Red No") systems are considered to move forward to the "Hold" phase.

In the example presented here, the implementation described in (a) above is the one that is considered using the *CDFI* criteria presented in Table 5 to Table 7.

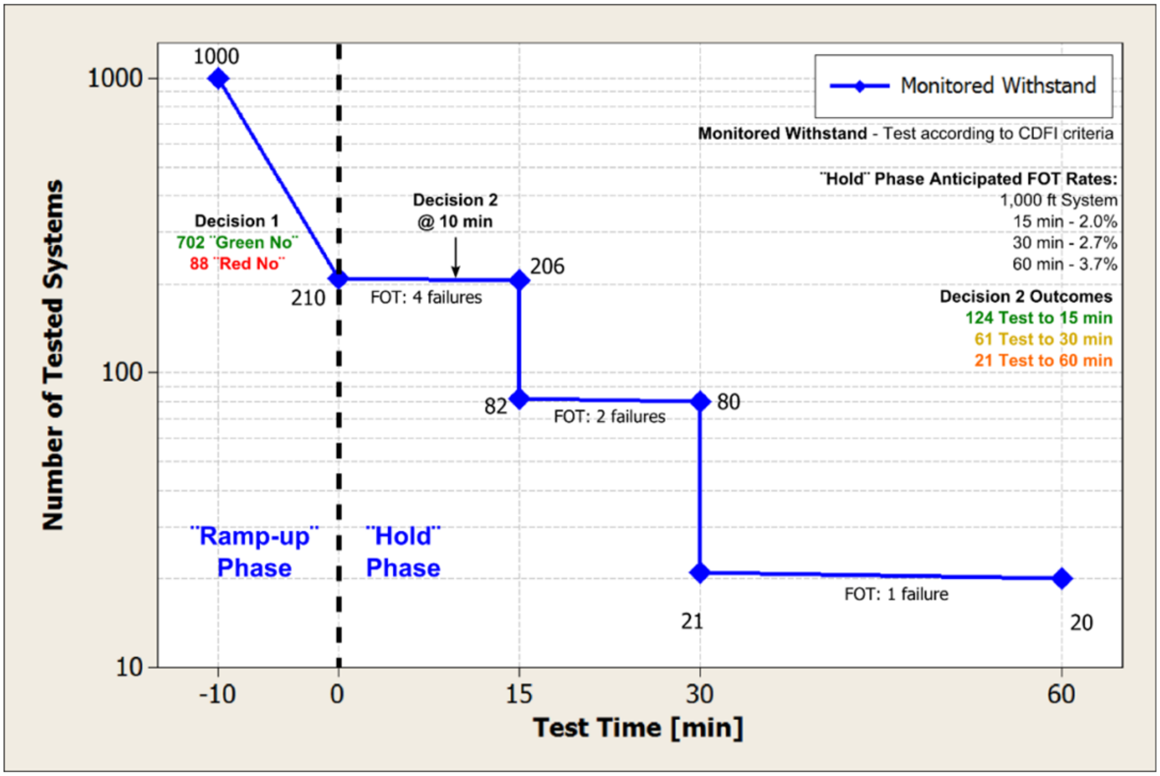

Figure 17: Monitored VLF Withstand Framework on the Basis of Number of Tested Cable Systems and Test Time for PE-based Insulations

Figure 17 follows the 210 cable systems that enter the "Hold" phase after passing Decision 1. After the first 15 min, there will have been on average four failures. At this point (Decision 2), 124 of these systems can stop their respective withstand tests while the remaining 82 cable systems must continue. As the systems reach the 30 min point, two cable systems will experience dielectric failures and an additional 59 cable systems will be in position to end their withstand tests. The remaining 21 cable systems will continue to 60 min with one system failing before 60 min. It is worth examining some of these steps in more detail and compare them with the Simple Withstand framework, Figure 18 shows the comparison between Simple VLF (Red) and VLF Tan δ Monitored (Blue) withstand frameworks on the basis of number of tested cable systems and test time for PE-based insulations.

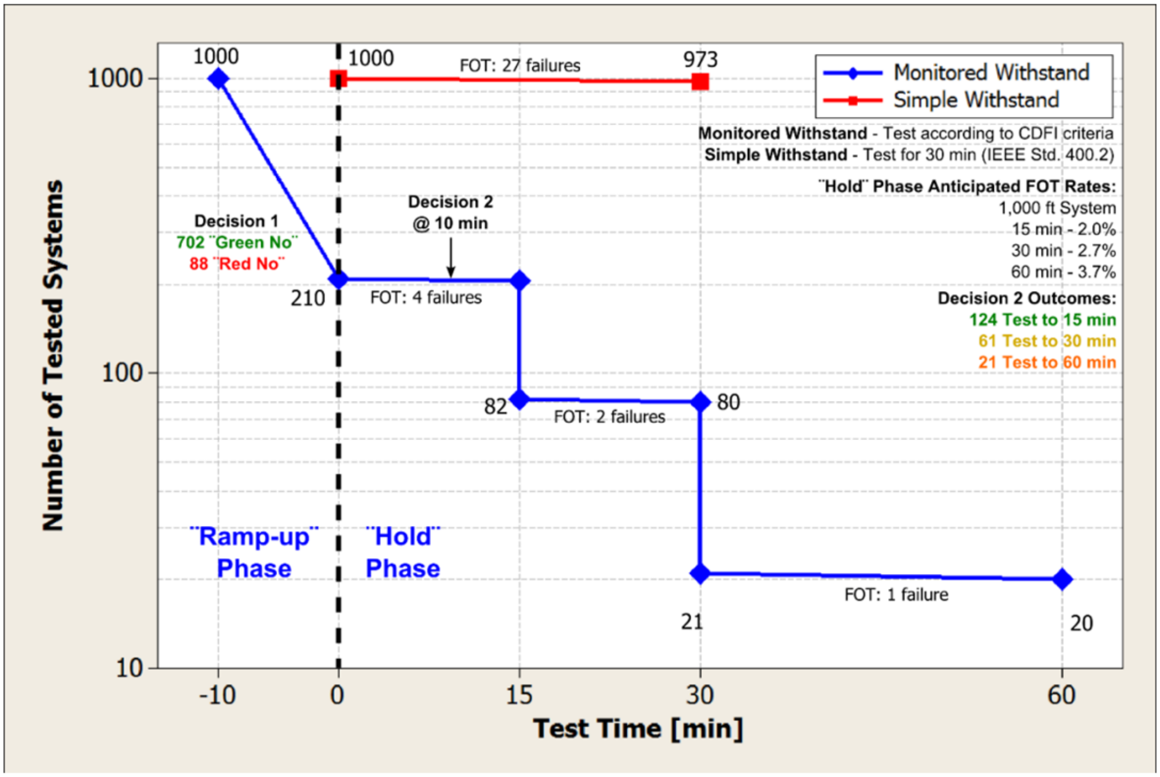

Figure 18: Comparison between Simple VLF (Red) and VLF Tan δ Monitored (Blue) Withstand Frameworks on the Basis of Number of Tested Cable Systems and Test Time for PE-based Insulations

Interpretation of Figure 18 reveals that there are considerable differences in how the number of tested systems changes as each framework evolves over test time. In particular, note for the Monitored Withstand framework that the number of tested systems that actually go on to the “Hold” phase is considerably reduced by the diagnostic selection made by Decision 1. A similar effect on the number of tested segments can also be observed at 15 min during the “Hold” phase where again the number of tested systems is considerably reduced by Decision 2. The reduced number of tested segments can have a considerable impact on the total test time of the complete Monitored Withstand test program when compared to a Simple Withstand approach. It is also important to mention that since the number of tested systems is reduced during the test there is also an impact on the number of FOTs and consequently the required emergency actions. In this context, immediate remedial actions refer to actions needed to be undertaken to repair a system that has had a FOT.

The comparison shown in Figure 18 has also been performed for filled and paper insulations and includes additional details such as:

- condition assessment criteria
- number of test set-ups
- expected number of FOTs during the “Hold” phase
- expected number of systems requiring immediate action
- expected number of systems requiring action on a planned basis
- estimation of the “Pass” margin

- availability of diagnostic information on surviving systems and
- total maximum test times are selected for comparison

Table 14, Table 15, and Table 16 show the comparisons for PE-based, filled, and PILC cable systems, respectively.

As seen in Table 14, the VLF Tan δ Monitored Withstand framework improves upon all aspects of the Simple VLF Withstand framework. In particular, the Monitored Withstand approach leads to a reduction in the total required test time (30,000 min (500 h) versus 15,009 min (250 h)). This represents a 50% reduction in the required time. In addition, the number of systems that require immediate or planned action is 95 (7 immediate and 88 planned) for Monitored Withstand as compared to 27 immediate actions for Simple Withstand. This can be viewed a number of ways but is not unexpected since the Monitored Withstand framework classifies systems with unusual estimated "Pass" margins as systems that require action on a planned basis. It is somewhat utility dependent as to the relative importance of immediate and planned actions.

Table 15 shows a similar difference when Monitored Withstand and Simple Withstand are employed on a set of filled cable systems.

Table 14: Comparison between VLF Tan δ Monitored and Simple Withstand Frameworks for PE-based Insulations

Comparison Issue	**Framework**	
	Simple VLF Withstand	**VLF Tan δ Monitored Withstand**
Condition Assessment Criteria	Tested for 30 min as recommended in IEEE Std. 400.2 – 2013	*CDFI Phase II* evaluation of “Ramp-up” and “Hold” phases: • **Decision 1** – Continue to “Hold” phase? • **Decision 2** – Amend test time? • **Decision 3** – Final Assessment?
Number of Test Set-ups	1,000	1,000
Expected Number of FOTs during the “Hold” phase	27	7*
Availability of Survival Information from Withstand (“Hold” Phase)		
Surviving Systems	Yes for 973 Systems	Yes for 203 Systems
Total	1,000 Systems	210 Systems
Availability of Diagnostic Information from Monitored Value		
Estimation of the “Pass” Margin	Not Possible	Well Established **Decision 1** – 1,000 Systems **Decision 2** – 206 Systems **Decision 3** – 203 Systems
Surviving Systems	None on 973 systems that passed “Hold” Phase	Yes on 993 systems and allows condition assessment and planning
Total	0 Systems	1,000 Systems
Expected Number of Systems Requiring Action after Test		
Immediate	27	7
Planned	0	88**
Total	27	95
Total Maximum Test Time		
Total Test Time	30,000 min (500 h)	15,009 min (250 h)***

* Estimation based on the anticipated FOT rates from *CDFI Phase I* and shown in Figure 18.

** 88 cable systems are assessed as “Red No” from the evaluation of the “Ramp-up” phase and thus are considered to require planned action after test.

*** The total maximum test time is approximately 50% of the total maximum test time for the Simple VLF Withstand framework.

Table 15: Comparison between VLF Tan δ Monitored and Simple Withstand Frameworks for Filled Insulations

Comparison Issue	Framework	
	Simple VLF Withstand	**VLF Tan δ Monitored Withstand**
Condition Assessment Criteria	Tested for 30 min as recommended in the IEEE Std. 400.2 – 2013	*CDFI Phase II* Project evaluation of "Ramp-up" and "Hold" phases: • **Decision 1** – Continue to "Hold" phase? • **Decision 2** – Amend test time? • **Decision 3** – Final Assessment?
Number of Test Set-ups	1,000	1,000
Expected Number of FOTs during the "Hold" phase	27	7*
Availability of Survival Information from Withstand ("Hold" Phase)		
Surviving Systems	Yes for 973 Systems	Yes for 276 Systems
Total	1,000 Systems	283 Systems
Availability of Diagnostic Information from Monitored Value		
Estimation of the "Pass" Margin	Not Possible	Well Established **Decision 1** – 1,000 Systems **Decision 2** – 279 Systems **Decision 3** – 276 Systems
Surviving Systems	None on 973 systems that passed "Hold" Phase	Yes on 993 systems and allows condition assessment and planning
Total	0 Systems	1,000 Systems
Expected Number of Systems Requiring Action after Test		
Immediate	27	7
Planned	0	84**
Total	27	91
Total Maximum Test Time		
Total Test Time	30,000 min (500 h)	16,105 min (268 h)***

* Estimation based on the anticipated FOT rates from the *CDFI Phase I* and shown in Figure 18.

** 84 cable systems are assessed as "Red No" from the evaluation of the "Ramp-up" phase and thus are considered to require planned action after test.

*** The total maximum test time is approximately 54% of the total maximum test time for the Simple VLF Withstand framework.

Table 16 illustrates that paper systems have somewhat unique differences as compared to either extruded insulation type.

Table 16: Comparison between VLF Tan δ Monitored and Simple Withstand Frameworks for Paper Insulations

Comparison Issue	Framework	
	Simple VLF Withstand	**VLF Tan δ Monitored Withstand**
Condition Assessment Criteria	Tested for 30 min as recommended in the IEEE Std. 400.2 – 2013	*CDFI Phase II* Project evaluation of "Ramp-up" and "Hold" phases: • **Decision 1** – Continue to "Hold" phase? • **Decision 2** – Amend test time? • **Decision 3** – Final Assessment?
Number of Test Set-ups	1,000	1,000
Expected Number of FOTs during the "Hold" phase	27	12*
Availability of Survival Information from Withstand ("Hold" Phase)		
Surviving Systems	Yes for 973 Systems	Yes for 349 Systems
Total	1,000 Systems	356 Systems
Availability of Diagnostic Information from Monitored Value		
Estimation of the "Pass" Margin	Not Possible	Well Established **Decision 1** – 1,000 Systems **Decision 2** – 354 Systems **Decision 3** – 349 Systems
Surviving Systems	No for 973 Systems	Yes on 988 systems and allows condition assessment and planning
Total	0 Systems	1,000 Systems
Expected Number of Systems Requiring Action after Test		
Immediate	27	12
Planned	0	67**
Total	27	79
Total Maximum Test Time		
Total Test Time	30,000 min (500 h)	18,940 min (316 h)***

* Estimation based on the anticipated FOT rates from the *CDFI Phase I* and shown in Figure 18.

** 67 cable systems are assessed as "Red No" from the evaluation of the "Ramp-up" phase and thus are considered to require planned action after test.

*** The total maximum test time is approximately 63% of the total maximum test time for the Simple VLF Withstand framework.

Finally, a comparison between VLF Tan δ Monitored Withstand frameworks between insulation types is shown in Table 17 based on the expected number of condition assessment decisions on site and after test, expected number of systems requiring action after test, and total maximum test time for the test program example considered in this section.

Table 17: Comparison between VLF Tan δ Monitored Frameworks Including all Insulation Types

Comparison Issue	PE-based	Filled	Paper
Expected Number of Condition Assessment Decisions			
On Site			
Decision 1 Continue to "Hold" phase?	1,000	1,000	1,000
Decision 2 Amend test time?	206	279	354
After Test			
Decision 3 Final Assessment?	203	276	349
Expected Number of Systems Requiring Action after Test			
Immediate	7	7	12
Planned	88	84	67
Total	95	91	79
Total Maximum Test Time			
Total Test Time	15,009 min (250 h)	16,105 min (268 h)	18,940 min (316 h)
Relative to a Simple Withstand Framework	50%	54%	63%

10.6.5 Monitored Withstand Using Partial Discharge

The quantities of field data provided or gathered where PD is the monitored property for the Monitored Withstand test were not sufficient for developing condition assessment decisions. While technically feasible, the actual implementation of such a program, confirmed by *CDFI* tests/experience, is complicated by the intrinsic difficulties of the PD test setup and analysis (see Chapter 7 and Chapter 8 for details on PD testing). As a result, although conceptually possible, the *CDFI* has not developed a perspective on this technique. Additional suggestions are discussed in Section 10.7.1.

10.6.6 Monitored Withstand with Damped ac (DAC) Voltage Sources

Damped ac voltage sources have often been mentioned in the industry for use in withstand testing. However, as DAC has proven ineffective for withstand tests (see Section 10.6.1); then the inadvisability of DAC voltage sources for monitored withstand tests becomes evident.

Therefore, at the present time, DAC voltage sources do not meet the definition of a withstand test (Simple or Monitored) and thus are not recommended. Field data are needed to show the pass and fail capability and to provide evidence for the third element that defines a withstand test.

10.6.7 Monitored Withstand Using DC Leakage Current

Leakage Current data are primarily gathered during withstand tests utilizing dc voltage sources. The use of dc withstand tests for aged-cable extruded cable systems has been highly discouraged for the last two decades because of the accumulated space charge and its impact on system performance once the cable system is re-energized with 60 Hz. At least one utility continued to utilize dc for its withstand program during the *CDFI* and recorded some leakage current data. These data were limited in scope and thus could not be analyzed in the same manner as the available VLF Tan δ data. As a result, the *CDFI* has not developed a perspective on this technique. Additional suggestions are discussed in Section 10.7.1.

10.7 Outstanding Issues

Monitored Withstand came into existence during the term of the *CDFI* research and so is one of the "younger" techniques available. As such, there remain a number of outstanding issues of which the more important are discussed below.

10.7.1 Monitored Withstand Framework – PD and Leakage Current

During the *CDFI Phase II*, it was not possible to collect enough data for PD and dc leakage current during a Monitored Withstand test to properly establish a framework for these two monitored properties. However, the *CDFI* perspective considers that it is likely that, the hierarchy observed and confirmed by data from Monitored Withstand programs employing dielectric loss measurements, could be generalized for any other monitored property. This is due to the fact that all the levels of the monitored property hierarchy are logically correlated with system performance (i.e. steeper trends, bigger variability, and increased absolute magnitude of the monitored property all should indicate poorer cable system condition). Therefore, the hierarchy for PD and Leakage Current could be conceptualized as follows:

1. Trends within the monitored period. These are likely to be categorical attributes: flat, upward trend, downward trend, etc. They can also be characterized by speeds (e.g. average change per unit time of the monitored property for a pre-established period within the test time.).

2. Stability or scatter of the monitored property for a pre-established period within the test time.
3. Absolute level of the monitored property for a pre-established period within the test time.

Therefore, the Monitored Withstand frameworks for PD and Leakage Current remain as open issues that may be addressed by future research programs.

10.7.2 Criteria Based on Local and Global Data

The criteria for VLF Tan δ Monitored Withstand 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, criteria are segregated only by insulation type.

Unfortunately, there could be cases where the criteria cannot be ideally applied to a particular case of an individual utility. Indeed, this is specifically recognized in IEEE Std. 400.2 – 2013 where a local utility 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 would be necessary to generate local data and thus criteria that are based solely on an individual utility's cable system.

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. Therefore, local criteria cannot be developed unless a significant effort is expended during the test. A utility just starting a diagnostic program must rely on the global criteria until they can generate enough data for local criteria to be useful.

10.8 References

1. P. Mohaupt, M. Baur, and T. Schlick, “VLF Testing and Diagnosis on Medium Voltage Power Cables,” IEEE 10th Inter. Conf. on Transmission and Distribution Construction, Operation, and Live Line Maintenance, pp. 202-209, Apr. 2003 IEEE ESMO.
2. C. Goodwin, “Practical Smart Withstand Programs for MV Cable Systems,” IEEE Insulated Conductors Committee, Subcommittee F Spring 2010.
3. P. Werelius, P. Tharning, R. Eriksson, B. Holmgren, and U. Gafvert, “Dielectric Spectroscopy for Diagnosis of Water Tree Deterioration in XLPE Cables,” IEEE Trans. on Dielectrics and Electrical Insulation, vol. 8, no. 1, pp 27-42, Mar 2001.
4. R.N. Hampton, R. Harley, R. Hartlein, and J. C. Hernández, “Practical Issues Regarding The Use Of Dielectric Measurements To Diagnose The Service Health Of MV Cables,” *International Conference on Insulated Power Cables; JICABLE07*, Versailles France, June 2007.
5. J. C. Hernández-Mejía, R. G. Harley, R. N. Hampton, and R. A. Hartlein, “Characterization of Ageing for MV Power Cables Using Low Frequency Tan-delta Diagnostic Measurements,” IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 16, Issue 3, pp. 862-870, June 2009.
6. J. Perkel, Y. Del Valle, R. N. Hampton, J. C. Hernández-Mejía, and J. Densley, “Interpretation of Dielectric Loss Data on Service Aged Polyethylene Based Power Cable Systems using VLF Test Methods,” Accepted for publication on the IEEE Transactions on Dielectrics and Electrical Insulation.
7. J. C. Hernández-Mejía, J. Perkel, R. Harley, N. Hampton, and R. Hartlein, “Correlation between Tan δ Diagnostic Measurements and Breakdown Performance at VLF for MV XLPE Cables,” IEEE Trans. on Dielectrics and Electrical Insulation, February 2009, pp. 162-170.
8. R. N. Hampton, R. Harley, R. Hartlein, and J. C. Hernández, Practical Issues Regarding The Use Of Dielectric Measurements To Diagnose The Service Health Of MV Cables, *International Conference on Insulated Power Cables; JICABLE07*, Versailles France, June 2007.
9. H. R. Gnerlich, “Field Testing of HV Power Cables: Understanding VLF Testing,” IEEE Electrical Insulation Magazine, vol. 11, no. 5, pp. 13–16, Sep./Oct. 1995.
10. S. C. Moh, “Very low frequency testing - Its effectiveness in detecting hidden defects in cables,” 2003 CIRED (17th International Conference on Electricity Distribution), Barcelona, Paper 84, May 12–15, 2003.
11. R. N. Hampton, J. Altamirano, J. Perkel, and J. C. Hernandez, “VLF Tests Conducted by NEETRAC as Part of the *CDFI*,” IEEE Insulated Conductors Committee, Fall 2007 Meeting, Scottsdale AZ, 2007.
12. R. N. Hampton, J. Perkel, J. C. Hernandez,, M. Begovic, J. Hans, R. Riley, P. Tyschenko, F. Doherty, G. Murray, L. Hong, M. G. Pearman, C. L. Fletcher, and G. C. Linte, “Experience of Withstand Testing of Cable Systems in the USA,” CIGRE 2010, Paper No. B1-303.
13. C. Goodwin, H. Oetjen, and M. Peschel, “Use of VLF Methods in Utility Reliability Programs - Basic Concepts,” IEEE Insulated Conductors Committee, Subcommittee F, Fall 2009 Meeting, Scottsdale AZ, 2009.
14. J. Perkel, J. Altamirano, and N. Hampton, “Investigation of VLF Test Parameters,” IEEE Insulated Conductors Committee, Subcommittee F, Spring 2010 Meeting, Nashville, TN,

2010.
15. IEEE, “IEEE Guide for Field Testing of Shielded Power Cable Systems Using Very Low Frequency (VLF) (less than 1 Hz),” IEEE Std. 400.2 – 2013, Jun. 2013.
16. R. Duda, P. Hart, and D. Stork, “Pattern Classification,” Second Edition, John Wiley & Sons, Inc., New York, 2000, ISBN 0-471-05669-3.
17. Box G. E. P., Hunter W. G., and Hunter J. S., Statistics for Experimenters, John Wiley & Sons, Inc., New York, NY, USA, 2nd Edition, 2005, ISBN-100-471-71813-0.

10.9 Relevant Standards

- 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)*
- IEEE Std. 400.3™ – 2006: *IEEE Guide for Partial Discharge Testing of Shielded Power Cable Systems in a Field Environment*
- IEEE Std. 400.4™ – 2014: *Omnibus - IEEE Draft Guide for Field-Testing of Shielded Power Cable Systems Rated 5kV and Above with Damped Alternating Current Voltage (DAC)*
- IEEE Std. 404™ – 2006: *IEEE Standard for Extruded and Laminated Dielectric Shielded Cable Joints Rated 2500 V to 500 000 V*

10.10 Appendix

10.10.1 Details of Feature Elimination Using Cluster Variable Analysis

One of the problems that occur when considering a large number of Tan δ diagnostic features is how to organize these features (stability, changes with time/voltage at various levels, and magnitudes) into meaningful groups or clusters. Cluster variable analysis is useful because it identifies key variables that explain the principal dimensionality (not variability) of the data. It is used to classify the data into groups when the groups are initially unknown. One important reason to cluster the variables is to reduce their number but, more importantly, it 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 another feature is joined with a different cluster. This process continues until all clusters are joined into one. The complete process, from the initial cluster variable analysis to the final feature selection, is explained later in the chapter for all insulation types.

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 [17] 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 the following equation,

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

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 of 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. However, a good similarity level to cut the dendrogram is that level at which a sudden change in the number of initial clusters is observed.

Examples of dendrograms appear in Appendix C, D, and E.

10.10.2 Single Diagnostic Indicator Based on Principal Component Analysis (PCA)

Principal Component Analysis (PCA) is a method that combines diagnostic features to create a single diagnostic indicator that puts any set of measurements in context with the "Hold" phase Tan δ measurements database. Therefore, through the single diagnostic indicator, the "Pass" margin can be estimated.

The PCA technique is useful because 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 [16-17].

The technique provides a predictive model with guidance on how to interpret or "weigh" the primary measurement features. It also allows 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; however, some of the redundancy has been previously filtered by the cluster variable analysis discussed earlier.

To illustrate and easily understand the essentials of the PCA technique, Figure 19 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. Comparing the areas clearly shows that area 2 is smaller and, therefore, has less variance than the original configuration in Area 1. As mentioned above, this process reduces the dimension of a dataset to as few or as many principal components as are needed.

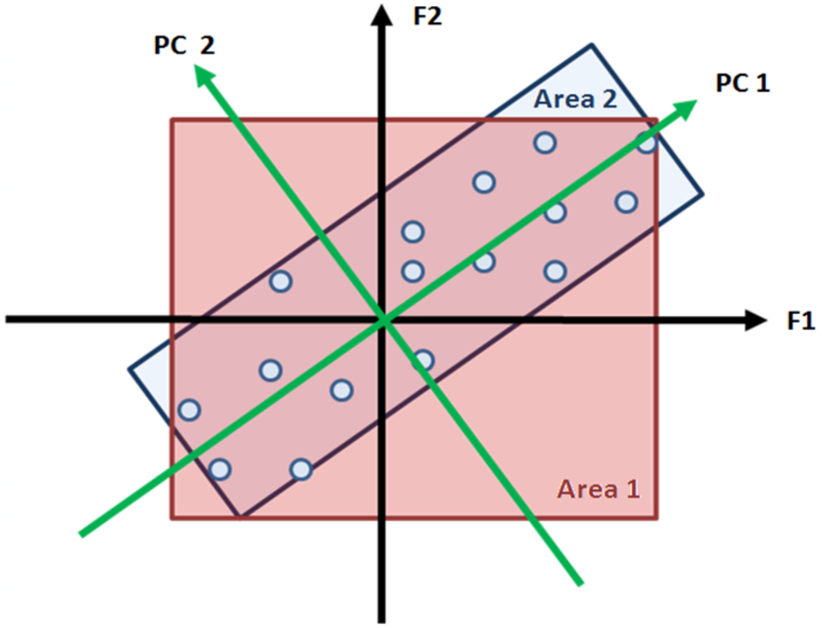

Figure 19: Graphical Interpretation of Principal Component Analysis (PCA)

Once the dimensionality has been reduced, the selected principal components can be used to compute a PCA distance from a known set of PCA transformed diagnostic features providing in this way the single diagnostic indicator. The process to compute the single diagnostic indicator appears in Figure 20.

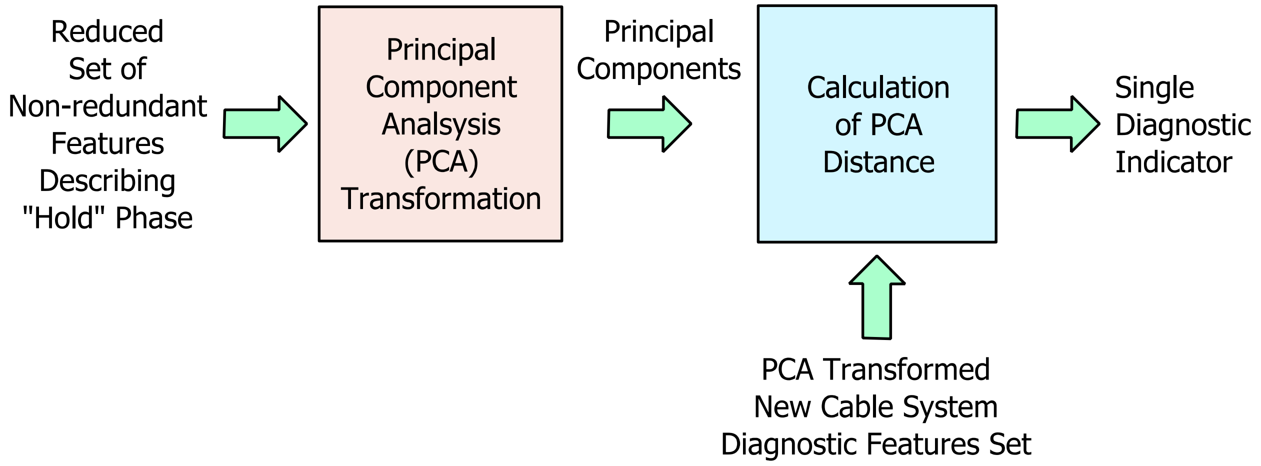

Figure 20: Calculation of the Single Diagnostic Indicator from PCA

As seen in Figure 20, the known set of PCA transformed diagnostic features corresponds to features of a new cable system and this allows for establishing a critical diagnostic for the single diagnostic indicator and its corresponding “Pass” margin. In this case, the critical levels are also determined using the Pareto Principle [17], for two critical levels at the 80th and 95th percentiles of the data. The interpretation of the single diagnostic indictor based on PCA distance and its corresponding “Pass” margin (Decision 3 on Figure 6) is as follows

:

- Cable systems showing a PCA distance bellow the 80th percentile have a good “Pass” margin and thus are classified as “No Action Required.”
- Cable systems showing a PCA distance between the 80th and 95th percentiles have an uncertain “Pass” margin and thus are to be classified as “Further Study.”
- Cable systems showing a PCA distance beyond the 95th percentile have a poor “Pass” margin and thus are classified as “Action Required.”

The interpretation of the single diagnostic indicator based on PCA distance completes the picture of the Monitored Withstand test framework using VLF Tan δ measurements and it is one of the more important contributions of the *CDFI*. The next sections show results of the “Hold” phase evaluation for all insulation types.

10.10.3 PE-Based Insulation Final Assessment

This appendix describes the analysis process employed on the available VLF Tan δ Monitored Withstand data to develop criteria for making the condition assessment for PE-based cable systems. Also discussed are the test cases used to validate the approach.

Results of the cluster variable analysis of the diagnostic features used to characterize the “Hold” phase for PE-based insulations appear in Figure 21. As a reminder, the feature descriptions are also below:

1. **Tan δ Stability (STD)** – This feature represents the time dependence and is reported as the standard deviation of sequential measurements at the particular test voltage level irrespective of it is a 15, 30, or 60 min test.
2. **Initial Tan δ (Init TD)** – This feature represents the initial measured loss level at the beginning of the “Hold” phase irrespective of it is a 15, 30, or 60 min test.
3. **Final Tan δ (Final TD)** – This feature represents the final measured loss level at the end of the “Hold” phase irrespective of it is a 15, 30, or 60 min test.
4. **Level of Tan δ (Mean TD)** – This feature represents the average level of loss over the full “Hold” phase irrespective of it is a 15, 30, or 60 min.
5. **Speed (rate of change over time) of Tan δ between 0 and 5 min (SPD 0-5)** – This feature represents an estimate of the rate of change in time of the loss level (Tan δ) during the first 5 minutes of the “Hold” phase. More importantly, this feature also provides information about the trend of the measurements during the period under consideration; i.e. positive values indicate an increasing trend and *vice versa*.
6. **Speed of Tan δ between 5 and 10 min (SPD 5-10)** – This feature represents an estimate of the rate of change in time of the loss level (Tan δ) during the second 5 minutes of the “Hold” phase.
7. **Speed of Tan δ between 10 and 15 min (SPD 10-15)** – This feature represents an estimate of the rate of change in time of the loss level (Tan δ) during the third 5 minutes of the “Hold” phase.
8. **Speed of Tan δ Between 0 and final test time (SPD 0-t_{final})** – This feature represents an

estimate of the overall rate of change of the loss level (Tan δ) with time for a completed "Hold" phase irrespective of it is a 15, 30, or 60 min test.

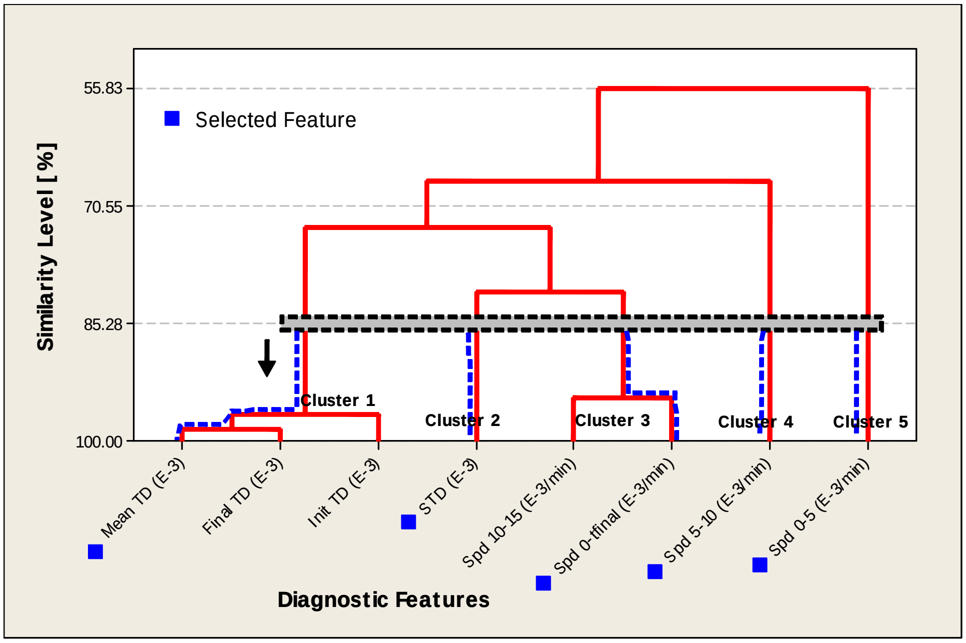

Figure 21: Cluster Variable Analysis Results for PE-based Insulations (Based on data as described in Table 4)

As Figure 21 shows, when a similarity level of approximately 85% is chosen to cut the dendrogram, five clusters result:

- Cluster 1 – Mean TD, Final TD, and Init TD
- Cluster 2 – STD
- Cluster 3 – SPD 10-15 and SPD 0-tfinal
- Cluster 4 – SPD 5-10
- Cluster 5 – SPD 0-5.

In the approach presented here, each cluster may be represented by one single diagnostic feature from within that cluster. The selection of the diagnostic feature to represent each cluster appears in Figure 21 by the blue dashed lines and thus the final selected set of features is indicated by the blue squares.

The cluster variable analysis results also provide insight into the types of features applicable for the PCA as well as their relative importance. The assumption here is that features that are more dissimilar may be more important. Following this logic, the more important features are the speeds (clusters 3, 4, and 5); particularly at the beginning of the "Hold" phase when higher speed magnitudes are generally observed, followed by the STD (cluster 2) and loss level (cluster 1). The results of the cluster variable analysis shown in Figure 21 indicate that five of the initial set of eight diagnostic features should be considered for the PCA.

PCA was applied to the "Hold" phase monitored withstand database of PE-based insulations. Figure 22 shows the transformation from two Tan δ diagnostic features (STD and SPD 0-t_{final}) 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 diagnostic indicator by itself. It does enable the construction of simplified and appropriate feature maps that may enhance the classification potential of the diagnostic features when they are appropriately combined. The principal component feature maps provide a single condition assessment descriptor. The transformation can be observed in Figure 22 in which the application of the PCA transformation reveals a clearer connection between PC1 and PC2 (right side of Figure 22) as compared to the original data (STD and SPD 0-t_{final} shown on the left side of Figure 22).

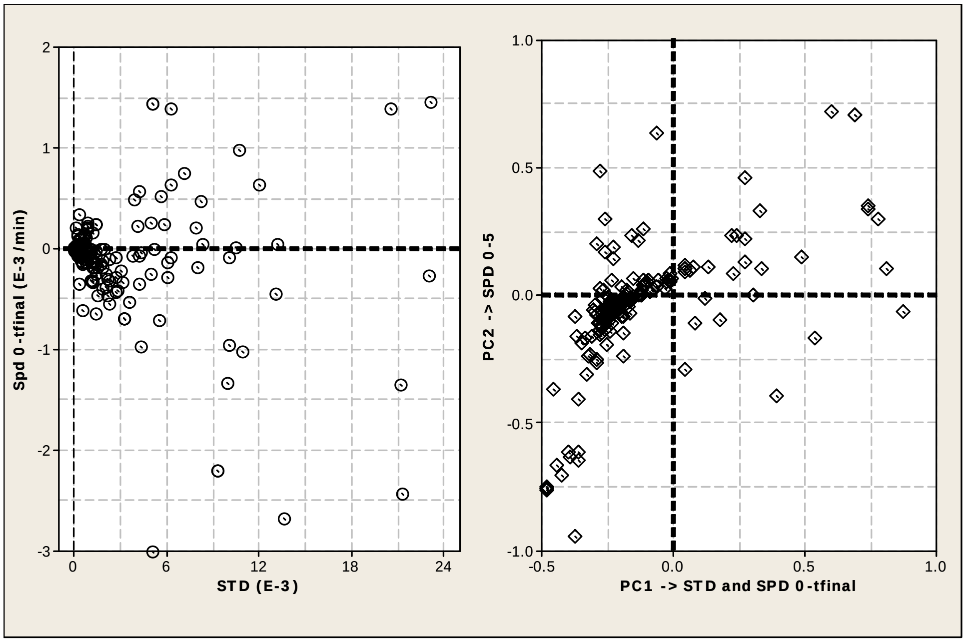

Figure 22: STD vs. SPD 0-t_{final} (left) and PC1 vs. PC2 (right) – PE-based Insulations

Applying PCA to the full database yields the principal components shown in Table 18. This table shows the percentage of variance accounted for by each principal component (i.e. the variability) as well as the diagnostic features that contribute the most to each component. Results from Table 18 indicate that only four principal components are required to describe 98% of the data variance. It is, therefore, reasonable to utilize four principal components.

Table 18: PCA Variances and Component Composition for PE-based Insulations

Principal Component	Variance Described by Component [%]	Cumulative Variance [%]	"Hold" Phase Tan δ Diagnostic Features
PC1	49	49	STD and SPD 0-t_{final} (Variability and trend)
PC2	28	77	SPD 0-5 (Trend)
PC3	12	89	Mean TD (Level of Loss)
PC4	9	98	STD (Variability)
PC5	2	100	Not relevant

The main observation from the PCA results in Table 18 is that they also give an indication of the importance and relevance of the "Hold" phase Monitored Withstand Tan δ diagnostic features. The features can be ranked in importance as:

1. trend of the measurements (SPD 0-t_{final} and SPD 0-5)
2. time dependence (STD) and
3. loss level (Mean TD)

The overarching question is - How to combine all diagnostic features into a single indicator?

The identification of suitable Principal Components also allows these components to be combined together to form a set of coordinates. The approach adopted elsewhere within *CDFI* has been to calculate the Euclidean distance between the data point and a reference point. The greater the distance, the less like the reference point is to the newly acquired data point. Applying this principle to these data, the best choice for a reference point is a new cable system. As a result, the distance calculated essentially quantifies the gulf between a new cable system and an aged system.

Figure 23 shows the combined PCA distance of the four principal components for all the available Monitored Withstand data from PE-based cable systems. If all the data are ranked from smallest (most like new) to largest (least like new) this gives the rank position, which can easily be converted to a percentage. In practice, the resulting graph might conveniently be regarded as the "Pass" margins for the population of cable systems tested. The interpretation is straightforward as the higher rank positions represent those cable systems that are least "like new" while the low rank positions correspond to those systems that most "like new".

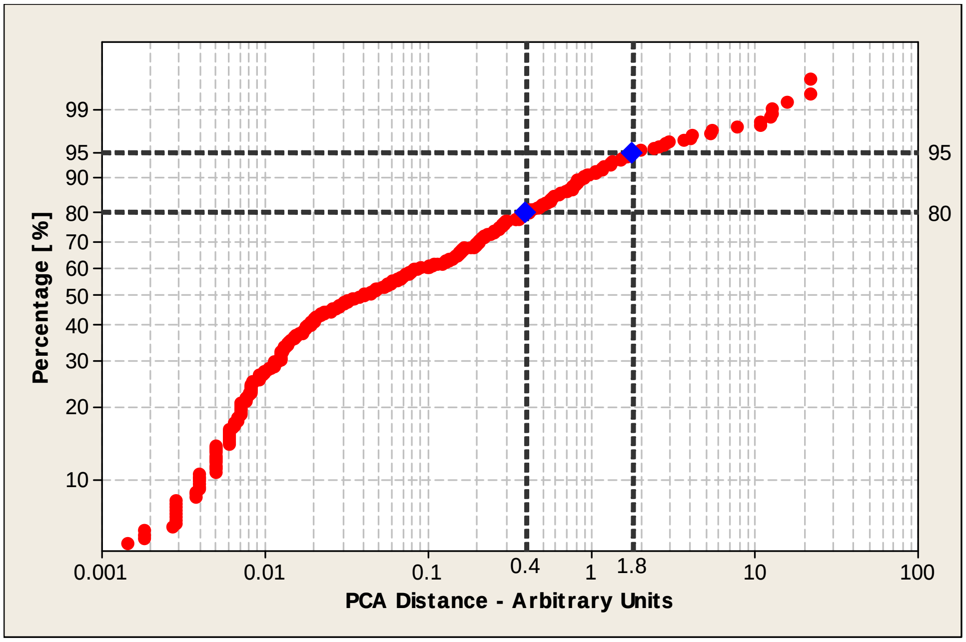

Figure 23: Empirical Cumulative Distribution of the PCA Distance used for Evaluation of the "Hold" Phase for PE-based Cable Systems

Critical level for the single diagnostic indicator can be established using the same Pareto Principle as before. The 80th and 95th percentage ranks appear in Figure 23 and they correspond to PCA distances of 0.4 and 1.8, respectively. The critical levels for the single diagnostic indicator are then used to establish the final condition assessment and thus address Decision 3, "Hold" Phase evaluation, of the Monitored Withstand framework. The critical levels for the single diagnostic indicator and corresponding condition assessment categories appear in Figure 24.

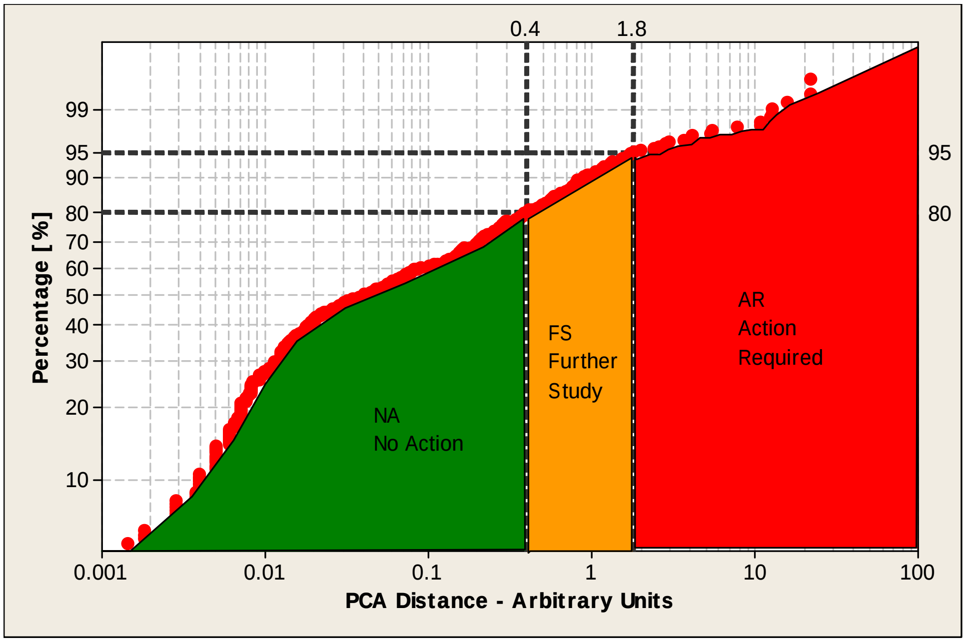

Figure 24: Empirical Cumulative Distribution of the PCA Distance used for Evaluation of the "Hold" Phase for PE-based Cable Systems with Condition Assessment Categories

Several case studies using experimental data/features illustrate the application of the research PCA to the evaluation of the "Hold" phase of a Monitored Withstand test. The summary of these case studies appears in Table 19.

Table 19: Cases Studies for "Hold" Phase Evaluation for PE-based Insulations

Case No.	Description	SPD 0-5 [E-3/min]	SPD 5-10 [E-3/min]	SPD 0-t_{final} [E-3/min]	STD [E-3]	Mean Tan δ [E-3]	Percentage Rank [%]
1	New System	0.002	0.002	0.002	0.01	0.1	2.9
2	Features at 80% level and Pos. Speeds *	0.350	0.350	0.350	15.00	0.3	76.0
3	Features at 80% level and Neg. Speeds *	-0.350	-0.350	-0.350	15.00	0.3	74.0
4	Features at 95% level and Pos. Speeds *	3.000	3.000	3.000	5.00	70.0	95.0
5	Features at 95% level and Neg. Speeds *	-3.000	-3.000	-3.000	5.00	70.0	94.0
6	Utility Test 1	0.420	0.140	0.227	0.80	10.1	69.0
7	Utility Test 2	2.500	-0.480	0.067	5.20	6.3	89.0
8	Utility Test 3	3.960	2.480	1.460	23.10	200.0	96.0

* The 80% and 95% diagnostic feature levels correspond to level of the diagnostic features for "Hold" phase" Evaluation – Decision 2 – Amend Test Time? as shown in Table 8 considering constant speed values during the period under evaluation.

In Table 19, the following examples are included:

- **Case 1:** New PE cable system that lies within the 0.03st percentile. This translates to an extremely good "Pass" margin. Case 1 is represented in Figure 25 by the solid black circle symbol.
- **Case 2:** All diagnostic features set to their respective 80% levels (black square symbol in Figure 25) with positive speeds. It is important to note here that all the features at the 80% level yield a percentage of 76.0%. Therefore, there is an acceptable correlation between the feature levels and the overall assessment considering all features together.
- **Case 3:** All diagnostic features are at their respective 80% levels with negative speeds. In this case all of the features set at the 80% level yield a percentage of 74.0%. Therefore, there is again good correlation between the feature levels and the overall condition assessment.
- **Case 4:** All diagnostic features are set at their 95% levels (black triangle symbol in Figure 25) with positive speeds. In this case, the percentage is exactly 95.0%. Therefore, there is a good correlation between the feature levels and the overall assessment considering all

features together.

- **Case 5:** All diagnostic features set at their 95% levels with negative speeds. In this case, the percentage is 94.0%. Note again the good correlation between the features levels and the overall condition assessment.
- **Case 6:** Real case and represents one of the low to mid performers. The PCA indicates that in 2014 the cable system is within the upper "No Action" category with a rank of 69.0%.
- **Case 7:** Real case and represents one of the mid to high performer. The PCA indicates the cable system is within the "Further Study" category with a rank of 89.0%.
- **Case 8:** Real case and represents one of the poorest performer in a cable system (black diamond symbol in Figure 25). The PCA indicates that in 2013 the cable system is within the poorest 4% of all PE-based cable systems.

The symbols in Figure 25 represent selected test cases used as examples and their computed PCA distance (rank) results appear in Table 19.

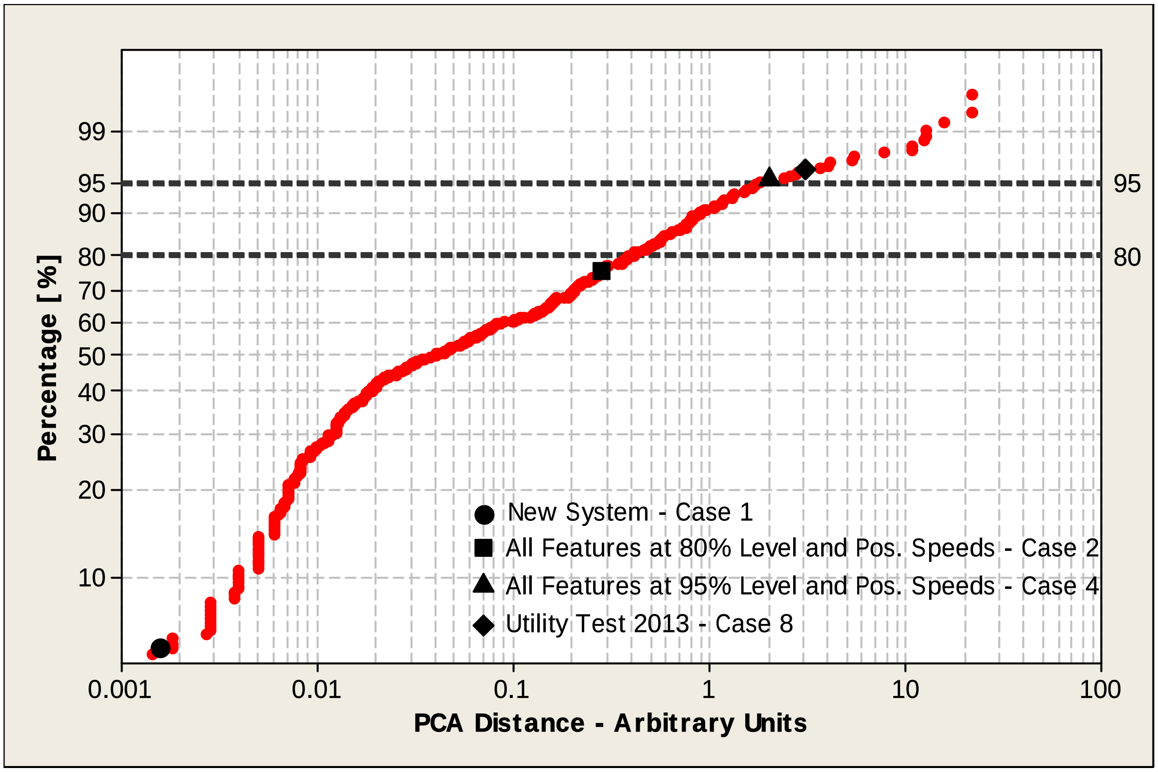

Figure 25: Empirical Cumulative Distribution of the PCA Distance from CDFI Research Used for Evaluating the "Hold" Phase for PE-based Cable Systems with Relevant Case Studies from Table 19

Observe that in Table 19 there are only small differences between the ranks of Cases 2 and 3 and Cases 4 and 5. This is because the distance approach only considers the magnitude of the trend and not its direction (i.e. positive speeds (not vectors) compared to negative speeds). At first glance, this may be perceived as a disadvantage of the PCA distance approach. However, even though negative trends (negative speeds) generally indicate better system conditions than systems with positive trends (positive speeds) to date there is no theoretical nor experimental basis to support this belief, however reasonable, for PE-based insulations.

10.10.4 Filled Insulation Final Assessment

This appendix describes the analysis process employed on the available VLF Tan δ Monitored Withstand data to develop criteria for making the condition assessment for filled cable systems. Also discussed are the test cases used to validate the approach.

Results of the cluster variable analysis of the diagnostic features used to characterize the "Hold" phase for filled insulations appear in Figure 26. Note that the same feature set as was used in Appendix A is used in Figure 26.

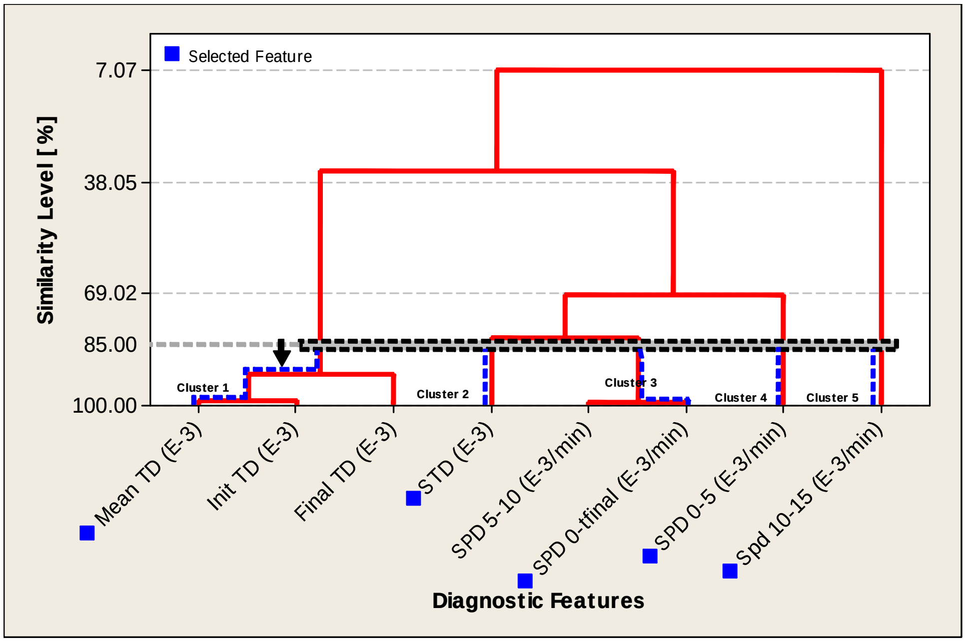

Figure 26: Cluster Variable Analysis Results for "Hold" Phase Features for Filled Insulations (Based on data as described in Table 4)

Using the same approach as was used for PE-based insulations, the dendrogram can be reduced to four clusters. In fact, the same features are identified for Filled insulations as PE-based insulations.

Applying PCA to the filled insulations database yields the principal components shown in Table 20. This table shows the percentage of variance accounted for by each principal component as well as the diagnostic features that contribute the most to each component. Results from Table 20 indicate that only three principal components are required to describe approximately 96% of the data variance.

Table 20: PCA Variances and Component Composition for Filled Insulations

Principal Component	Variance Described by Component [%]	Variance Described by Component Cumulative [%]	"Hold" Phase Tan δ Diagnostic Features
PC1	51.8	51.8	SPD 0-t_{final} and STD (Trend and Variability)
PC2	25.9	77.7	Mean TD (Level of Loss)
PC3	18.3	96.0	SPD 10-15 (Trend)
PC4	3.7	99.7	Not relevant since these components only describe 4% of the variability
PC5	0.3	100.0	

Figure 27 shows the combined PCA distance of the three principal components for all the available filled insulation Monitored Withstand data. The approach is again the same as the PE-based insulation example in Appendix C. However, the features and feature order used is quite different. Furthermore, the distances that correspond to the 80th and 95th percentiles are quite different at 0.4 and 2.7, respectively.

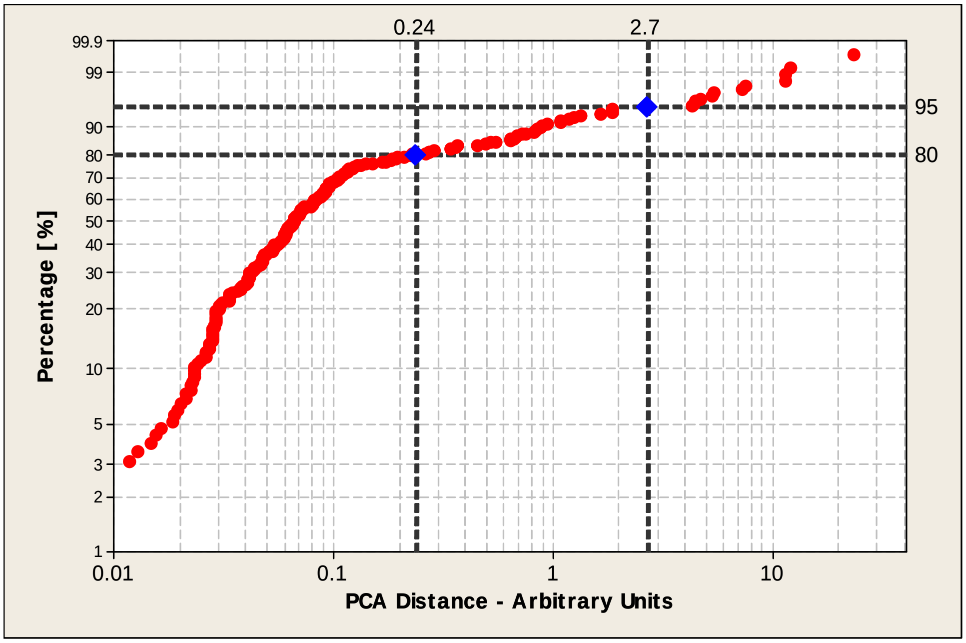

Figure 27: Empirical Cumulative Distribution of the PCA Distance used for Evaluation of the "Hold" Phase for Filled Cable Systems

Several case studies using experimental data/features illustrate the application of the PCA to the evaluation of the "Hold" phase of a monitored withstand test and they appear in Table 21.

Table 21: Cases Studies for "Hold" Phase Evaluation for Filled Insulations

Case No.	Description	SPD 10-15 [E-3/min]	SPD 0-5 [E-3/min]	SPD 0-t_{final} [E-3/min]	STD [E-3]	Mean Tan δ [E-3]	Percentage Rank [%]
1	New System	0.002	0.002	0.002	0.01	3.5	2.5
2	Features at 80% level and Pos. Speeds *	0.060	0.060	0.060	0.30	13.0	77.0
3	Features at 80% level and Neg. Speeds *	-0.060	-0.060	-0.060	0.30	13.0	79.0
4	Features at 95% level and Pos. Speeds *	0.600	0.600	0.600	5.00	105.0	94.0
5	Features at 95% level and Neg. Speeds *	-0.600	-0.600	-0.600	5.00	105.0	94.0
6	Utility Test 1	-0.040	-0.040	-0.033	0.30	5.3	72.0
7	Utility Test 2	-0.520	-0.100	-0.287	1.70	22.8	93.0
8	Utility Test 3	1.680	1.120	0.470	5.20	130.7	96.0

* The 80% and 95% diagnostic feature levels correspond to the level of the diagnostic features for "Hold" phase Evaluation – Decision 2 – Amend Test Time? as shown in Table 9 considering constant speed values during the period under evaluation.

In Table 21, the following examples are included:

- **Case 1:** New Filled cable system lies at the 0.03st percentile. This translates to an extremely good "Pass" margin. Case 1 is represented in Figure 28 by the solid black circle symbol.
- **Case 2:** All diagnostic features set at their respective 80% levels (black square symbol in Figure 28) with positive speeds. Note here that all the features at the 80% level yield a percentage of 77.0%. Therefore, there is a good correlation between the feature levels and the overall assessment considering all features together.
- **Case 3:** All diagnostic features set at their respective 80% levels with negative speeds. Note here that all the features at the 80% level yield a percentage of 79.0%. Therefore, there is again good correlation between the features levels and the overall condition assessment.
- **Case 4:** All diagnostic features set at their 95% levels (black triangle symbol in Figure 28) with positive speeds. In this case, the percentage is 94%. This implies good correlation between the feature levels and the overall assessment considering all features together.
- **Case 5:** All diagnostic features set at their 95% levels with negative speeds. In this case, the percentage is again 94.0%. There is once again good correlation between the feature levels and the overall condition assessment.

- **Case 6:** Real case that represents one of the mid to high performers. The PCA indicates that the cable system is within the mid to higher "No Action" category with a rank of 72.0%.
- **Case 7:** Real case that represents one of the mid to high performer. The PCA indicates the cable system is within the "Further Study" category with a rank of 93.0%.
- **Case 8:** Real case that represents one of the poorest performers (black diamond symbol in Figure 28). The PCA indicates that the cable system is within the poorest 4% of all filled insulated cable systems.

The symbols in Figure 28 represent selected test cases used as examples and their computed PCA distance (Percentage) results appear in Table 21.

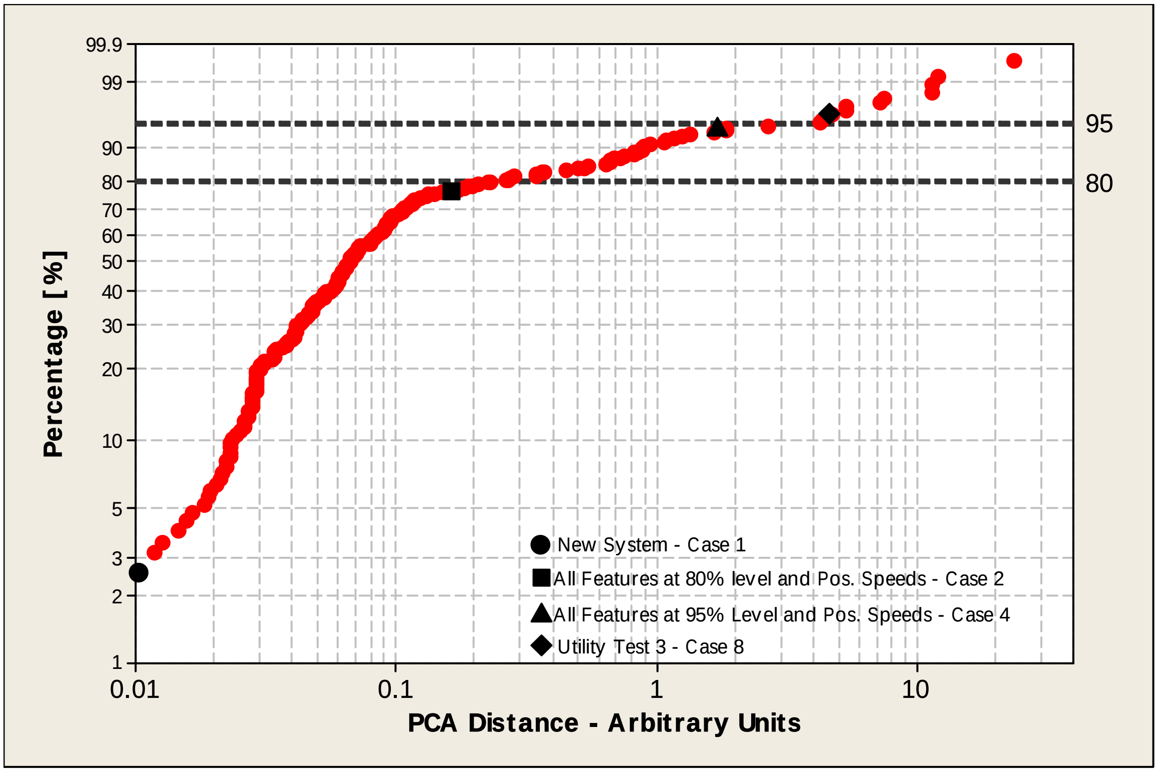

Figure 28: Empirical Cumulative Distribution of the PCA Distance used for Evaluation of the "Hold" Phase for Filled Cable Systems with Relevant Case Studies Presented in Table 21

10.10.5 PILC Insulation Final Assessment

The set of diagnostic features used to characterize the “Hold” phase for paper insulations is the same set used for PE-based insulations as described earlier in Figure 12. Consequently, results of the cluster variable analysis of the selected set of diagnostic features appear in Figure 29. Note that the feature set is identical to the filled and PE-based studies.

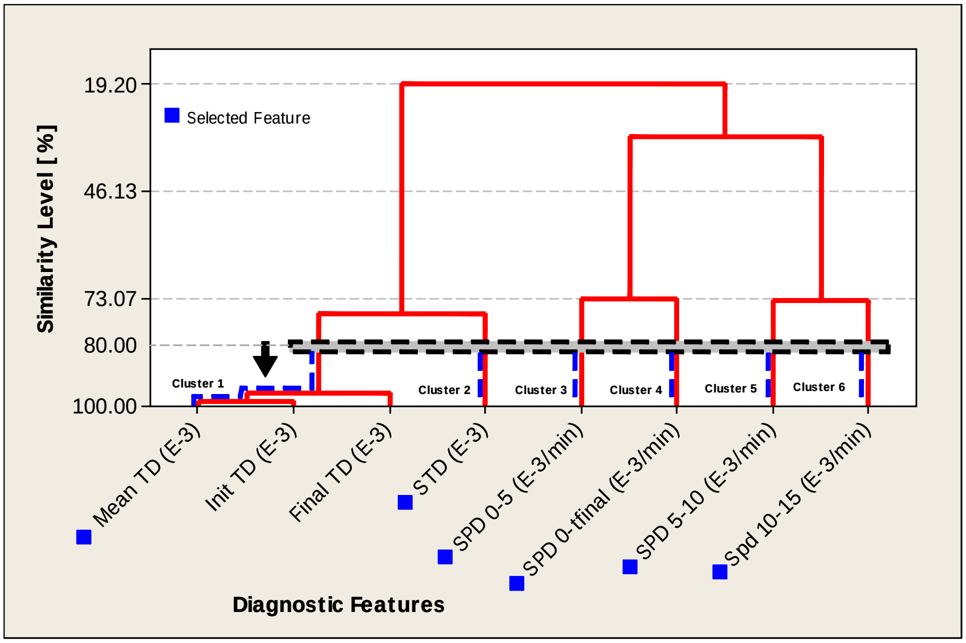

Figure 29: Cluster Variable Analysis Results for the Diagnostic Features Selected to Characterize the “Hold” Phase for Paper Insulations (Based on data as described in Table 4)

The results of the cluster variable analysis shown in Figure 29 indicate that six of the initial eight diagnostic features should be included in the PCA.

Applying PCA to the paper insulation database yields the principal components shown in Table 22. This table shows the percentage of variance accounted for by each principal component as well as the diagnostic features that contribute the most to each component. Results from Table 22 indicate that only three principal components are required to describe approximately 95% of the data variance.

Table 22: PCA Variances and Component Composition for Paper Insulations

Principal Component	Variance Described by Component [%]	Variance Described by Component Cumulative [%]	"Hold" Phase Tan δ Diagnostic Features
PC1	44.4	44.4	SPD 10-15 and STD (Trend and Variability)
PC2	29.0	73.4	SPD 0-t_{final} (Trend)
PC3	21.3	94.7	Mean TD (Level of Loss)
PC4	3.0	97.7	Not relevant since these components only describes approximately 5% of the variability
PC5	2.0	99.7	
PC6	0.3	100.0	

In the same manner as PE-based and filled insulations, the use of the PCA technique has allowed developing a combined diagnostic indicator scheme in which all independent diagnostic features are considered together for a final condition assessment.

Figure 30 shows the combined PCA distance of the three principal components for all the available Monitored Withstand data of paper insulated cable systems.

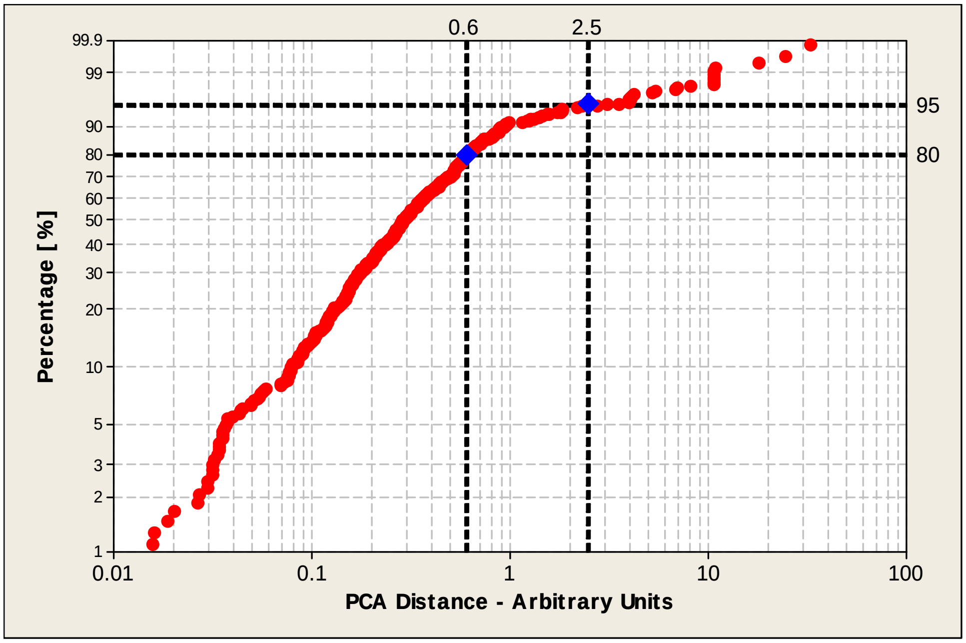

Figure 30: Empirical Cumulative Distribution of the PCA Distance used for Evaluation of the "Hold" Phase for Paper Cable Systems

Critical levels for the single diagnostic indicator can be established in the same manner as shown before by considering the critical level located at the 80th and 95th percentage ranks. The 80th and

95th percentage ranks appear in Figure 30 and they correspond to PCA distances of 0.6 and 2.5, respectively. Several case studies illustrate the application of the PCA to the evaluation of the "Hold" phase of a monitored withstand test and they appear in Table 23.

Table 23: Cases Studies for "Hold" Phase Evaluation for Paper Insulations

Case No.	Description	SPD 10-15 [E-3/min]	SPD 5-10 [E-3/min]	SPD 0-t_{final} [E-3/min]	SPD 0-5 [E-3/min]	STD [E-3]	Mean Tan δ [E-3]	Percentage Rank [%]
1	New System	0.002	0.002	0.002	0.002	0.01	12.0	1.9
2	Features at 80% level and Pos. Speeds *	0.140	0.140	0.140	0.140	0.60	80.0	74.6
3	Features at 80% level and Neg. Speeds *	-0.140	-0.140	-0.140	-0.140	0.60	80.0	74.6
4	Features at 95% level and Pos. Speeds *	0.500	0.500	0.500	0.500	5.40	180.0	93.1
5	Features at 95% level and Neg. Speeds *	-0.500	-0.500	-0.500	-0.500	5.40	180.0	93.1
6	Utility Test 1	0.040	0.080	0.100	0.180	0.40	32.7	30.1
7	Utility Test 2	-0.040	-0.060	-0.100	-0.200	0.40	131.5	89.6
8	Utility Test 3	-4.640	-17.70	-0.750	20.100	32.10	169.0	98.7

* The 80% and 95% diagnostic features levels correspond to level of the diagnostic features for "Hold" phase Evaluation – Decision 2 – Amend Test Time? as shown in Table 10 considering constant speed values during the period under evaluation.

In Table 23, the following examples are included:

- **Case 1:** New paper cable system that lies within the 0.02st percentile. This translates to an extremely good "Pass" margin. Case 1 is represented in Figure 31 by the solid black circle symbol.
- **Case 2:** All diagnostic features set at their respective 80% levels (black square symbol in Figure 31) with positive speeds. Note here that all the features at the 80% level yield a percentage of 74.6%. Therefore, there is a good correlation between the feature levels and the overall assessment considering all features together.
- **Case 3:** All diagnostic features set at their respective 80% levels (black square symbol in Figure 31) with negative speeds. Note here that all the features at the 80% level yield a percentage of 74.6%. Again, there is good correlation between the feature levels and the overall condition assessment.
- **Case 4:** All diagnostic features set at their 95% levels (black triangle symbol in Figure 31) with positive speeds. In this case, the percentage is 93.1%.

- **Case 5:** All diagnostic features set at their 95% levels (black triangle symbol in Figure 31) with negative speeds. As before, the percentage is 93.1%.
- **Case 6:** Real case and represents one of the low to mid performers. The PCA indicates that the cable system is within the lower to mid "No Action" category with a rank of 30.1%.
- **Case 7:** Real case and represents one of the mid to high performer. The PCA indicates the cable system is within the "Further Study" category with a rank of 89.6%.
- **Case 8:** Real case and represents one of the poorest performers (black diamond symbol in Figure 31). The PCA indicates that the cable system is within the poorest 2% of all paper insulated cable systems.

The symbols in Figure 31 represent selected test cases used as examples and their computed PCA distance (rank) results appear in Table 23.

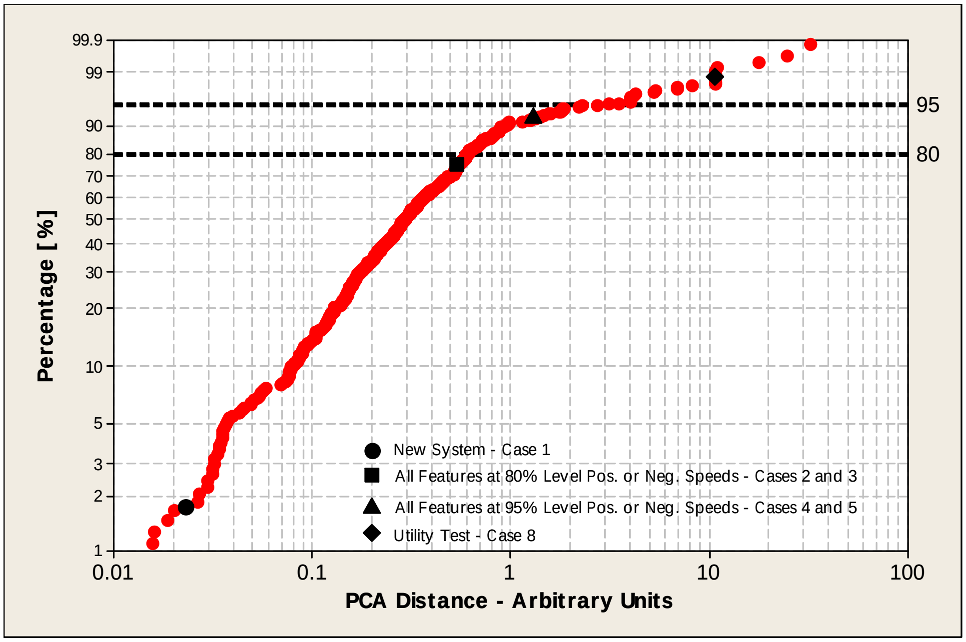

Figure 31: Empirical Cumulative Distribution of the PCA Distance used for Evaluation of the "Hold" Phase for Paper Cable Systems with Relevant Case Studies Presented in Table 23