Diagnostic Testing of Underground Cable Systems
(Cable Diagnostic Focused Initiative)

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The information in this handbook came from a number of sources, including various specifications, technical publications, diagnostic test providers and consulting engineers as well as the general experience within NEETRAC.

All of the information in this report has been included at the discretion of NEETRAC.

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SUMMARY

This report summarizes an extensive effort made to understand how to effectively use the various diagnostic technologies to establish the condition of medium voltage underground cable circuits. These circuits make up an extensive portion of the electric delivery infrastructure in the United States. Much of this infrastructure is old and experiencing unacceptable failure rates. By deploying efficient diagnostic testing programs, electric utilities can replace or repair circuits that are about to fail, providing an optimal approach to improving electric system reliability.

This is an intrinsically complex topic. Underground cable systems are not homogeneous. Cable circuits often contain multiple branches with different cable designs and a range of insulation materials. In addition, each insulation material ages differently as a function of time, temperature and operating environment. To complicate matters further, there are a wide variety of diagnostic technologies available for assessing the condition of cable circuits with a diversity of claims about the effectiveness of each approach. As a result, the benefits of deploying cable diagnostic testing programs have been difficult to establish, leading many utilities to avoid the their use altogether.

This project was designed to help address these issues. The information provided is the result of a collaborative effort between Georgia Tech NEETRAC staff, Georgia Tech academic faculty, electric utility industry participants, as well as cable system diagnostic testing service providers and test equipment providers.

Report topics include:

- How cable systems age and fail,
- The various technologies available for detecting potential failure sites,
- The advantages and disadvantages of different diagnostic technologies,
- Different approaches for utilities to employ cable system diagnostics.

The primary deliverables of this project are this report, a Cable Diagnostic Handbook (a subset of this report) and an online knowledge based system (KBS) that helps utilities select the most effective diagnostic technologies for a given cable circuit and circuit conditions.

Through the efforts of this project, many of the confusing issues associated with the deployment of cable system diagnostics were clarified. This includes the development of:

- A methodology for mapping test results to cable circuit failures.
- A methodology for accessing the accuracy of a given diagnostic technology.
- A Knowledge-Based Systems program for selecting cable diagnostic technologies.
- An approach to assessing the economic issues associated with diagnostic testing.

There is no doubt that cable system diagnostic testing can be used to improve system reliability. However, to be effective, the technology should be appropriate to the circuit to be tested. Setting accurate and reasonable expectations is also a critical part of the process.

In general, the work performed in the CDFI led to the following observations:

- Diagnostic tests can work. They often show many useful things about the condition of a cable circuit, but not everything desired.

- Diagnostics do not work in all situations. There are times when the circuit is to complex for the diagnostic technology to accurately detect the true condition of the circuit.

- Diagnostics are generally unable to determine definitively the longevity of the circuit under test. Cable diagnostics are much like medical diagnostics. They can often tell when something is wrong (degraded), but it is virtually impossible to predict the degree to which a detected defect will impact the life of the system tested.

- Field data analysis indicates that most diagnostic technologies examined do a good job of accurately establishing that a cable circuit is “good”. They are not as good at establishing which circuits are “bad”. In most cases, there are far more good cable segments than bad segments. However, it is virtually impossible to know which “bad” circuits will actually fail. Therefore, utilities must act on all replacement & repair recommendations to achieve improved reliability.

- The performance of a diagnostic program depends on:
  - Where diagnostic is used
  - When the diagnostic is used
  - Which diagnostic to use
  - What is done afterwards

- A quantitative analysis of diagnostic field test data is very complex. The data comes in many different formats and the level of detail is extremely variable. However, an in-depth analysis of the data clearly highlights the benefits of diagnostic testing.

- Diagnostic data require skilled interpretation to establish how to act. In almost all cases, the tests generate data requiring detailed study before a decision can be made on whether to repair or replace the tested cable circuit.

- No one diagnostic is likely to provide sufficient information to accurately establish the condition of a cable circuit.

- Large quantities of field data are needed to establish the accuracy/limitations of different diagnostic technologies. Table 1 summarizes the quantities of data analyzed during the CDFI.

Table 1: Data Analysis Summary by Diagnostic Technique

Diagnostic Technique	Field Performance [Approx Conductor miles]
DC Withstand	78,105
Monitored Withstand	149
PD Offline	490
PD Online	262
Tan δ	550
VLF Withstand	9,810

- It is important to have appropriate expectations – diagnostics are useful but imperfect.

The above statements do not imply that diagnostic testing should be avoided. In fact, the contrary is true. Users should recognize and consider these issues before a testing program begins. When applied properly, diagnostic testing will provide information that can be used to effectively lower cable system failure rates. There is still much to learn, but cable diagnostic testing is a rapidly developing field. Increasingly useful technologies and new approaches are currently being developed that will increase the effectiveness, understanding, and economic success of performing cable system diagnostic testing programs.

CDFI Dissemination

A number of different mechanisms were used to disseminate results from this project to the CDFI participants as well as the general public. This includes update meetings with the participants (as a group and individually), papers published in technical journals, presentations to technical committees and regional meetings for all interested parties. A summary of these activities appears below.

Papers

1. **Experience of Withstand Testing of Cable Systems in the USA**, Hampton, R.N., Perkel. J., Hernandez, J.C., Begovic, M., Hans, J., Riley, R., Tyschenko, P., Doherty, F., Murray, G., Hong, L., Pearman, M.G., Fletcher, C.L., and Linte, G.C., CIGRE 2010, Paper No. B1-303

2. **Characterization of Ageing for MV Power Cables Using Low Frequency Tan-delta Diagnostic Measurements**, JC. Hernandez-Mejia, RG. Harley, RN Hampton, RA Hartlein,

IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 16, Issue 3, pp. 862-870, June 2009.

3. **Determining Routes for the Analysis of Partial Discharge Signals Derived from the Field,** Hernández-Mejía, J.C.; Perkel, J.; Harley, R.; Begovic, M.; Hampton, N., and Hartlein, R., IEEE Trans. on Dielectrics and Electrical Insulation, December 2008, pp. 1517-1525.

4. **Correlation between Tan δ Diagnostic Measurements and Breakdown Performance at VLF for MV XLPE Cables,** Hernández-Mejía, J.C.; Perkel, J.; Harley, R.; Hampton, N., and Hartlein, R., IEEE Trans. on Dielectrics and Electrical Insulation, February 2009, pp. 162-170

5. **Some Considerations on the Selection of Optimum Location, Timing, and Technique, for Diagnostic Tests,** RA Hartlein, RN Hampton, and J Perkel, IEEE Power Engineering Society (PES) General Meeting Panel Session, Pittsburg, PA, 2008.

6. **Validation of the accuracy of practical diagnostic tests for power equipment;** M. Begovic, RN. Hampton, R. Hartlein, J.C. Hernandez-Mejia, and J. Perkel, CIGRE 2008, Paris, Study Committee D1, Paper 205

7. **On Distribution Asset Management: Development of Replacement Strategies**, Miroslav Begovic, Joshua Perkel, Nigel Hampton, and Rick Hartlein; IEEE PES PowerAfrica 2007 Conference and Exposition, Johannesburg, South Africa, 16-20 July 2007.

8. **Practical Issues Regarding The Use Of Dielectric Measurements To Diagnose The Service Health Of MV Cables**, R.N. Hampton, R. Harley, R. Hartlein, and J.C. Hernandez; International Conference on Insulated Power Cables, *JICABLE07*, Versailles France, June 2007.

9. **Validating Cable "Diagnostic Tests"**, M Begovic, RN Hampton, R Hartlein, J Perkel, International Conference on Insulated Power Cables, *JICABLE07*, Versailles France, June 2007.

Presentations at Conferences, Regional Dissemination Meetings, Symposia and Update Meetings

Group	Date
Investigation of VLF Test Parameters; Josh Perkel, Jorge Altamirano and Nigel Hampton; IEEE ICC; Nashville TN.	Mar 2010
MEDE	Feb 2010
Regional Meeting 4 – New York	Oct 2009
Regional Meeting 3 – Columbus	Sept 2009
Regional Meeting 2 – Atlanta	Sept 2009
Regional Meeting 1 – San Ramon	Aug 2009
South Eastern Electricity Exchange	June 2009
IEEE ICC Educational Session - Orlando	May 2009
NRECA – Underground Distribution Group	May 2009
Eaton Network Underground Conference - Clearwater	Mar 2009
California Energy Commission – Berkeley CA	Feb 2009
Update Meeting - Atlanta 5	Nov 2008
EPRI ECTN – Cable Diagnostics Symposium - Chicago	June 2008
IEEE Power Engineering Society – Atlanta Chapter	Feb 2008
California Energy Commission – Berkeley CA	Feb 2008
Update Meeting - Atlanta 4	Feb 2008
VLF Tests conducted by NEETRAC as part of the CDFI; R.N. Hampton, J. Perkel; JC Hernandez and J Altamirano; IEEE ICC Scottsdale Arizona	Oct 2007
Selection – the most critical part of the maintenance process; R.N. Hampton, J. Perkel; IEEE ICC, Scottsdale Arizona	Oct 2007
How accuracy impacts the economic benefits of cable diagnostic programs; M. Begovic, R.N. Hampton, R. Hartlein, and J. Perkel; IEEE ICC Subcommittee C; Scottsdale Arizona	Oct 2007
VLF Diagnostics; RN Hampton, and J Perkel; IEEE Insulated Conductors Committee Spring 2007 Orlando Florida	Mar 2007
Update Meeting - Atlanta 3	Feb 2007
Training Course on Cable System Failures - Atlanta	Feb 2007
Update Meeting - Atlanta 2	May 2006
Update Meeting - Atlanta 1	Feb 2005

International Standards Activities

CDFI has supported significant work within IEEE Insulated Conductors Committee on the revision of IEEE Std. 400™ Omnibus and IEEE Std. 400.2™ on VLF testing. The project has assisted the working group chairs as these revisions are completed. A brief summary of each of these contributions is included in the following sections.

IEEE Std. 400™ Omnibus

The latest draft of this guide went to the working members for comment before the Spring 2010 ICC meeting held in March. CDFI supported comments to the working group vice-chairman, Jacques Cote. The most significant support was the inclusion by the utility writing group of a diagnostic testing recommendation table. This table provides guidance as to which diagnostic tests are useful for different situations. CDFI developed the Knowledge-Based System (KBS) for the selection of diagnostic tests to fulfill this same objective. NEETRAC suggested completing the table using a portion of the output from the KBS. This essentially amounts to a similar approach as that of the utility writing group but provides the same information using a broader expert base (35 experts).

IEEE Std. 400.2™ VLF Field Testing

The working group currently preparing a revision to IEEE Std. 400.2™ on VLF field testing also presented its latest draft during the Spring 2010 ICC meeting in March. The approach used by NEETRAC for extracting the thresholds for Dielectric Loss measurements based on the available data will be applied to produce criteria in the revised format. To date, NEETRAC holds the largest collation of Tan δ available in the industry.

Discussions

During the course of the project detailed discussions / dissemination / technology transfer on practical cable system diagnostics took place with the following CDFI participants:

Participant	Number of Interactions (Approximately)
Alabama Power	3
Cablewise / Utilx	2
CenterPoint Energy	1
Consolidated Edison	5
Duke Power Company	8
Commonwealth Edison & PECO	2
First Energy	1
Florida Power & Light	3
Georgia Power	8
HDW Electronics	3
High Voltage, Inc.	3
HV Diagnostics	8
Hydro Quebec	5
IMCORP	8
NRECA	3
Oncor (TXU)	2
Pacific Gas & Electric	3
PEPCO	3
Southern California Edison	3
Southwire	2
TycoElectronics	1

CDFI Participants

Twenty-two industrial sponsors, including electric power utilities and manufacturers that provide products and services to electric utilities supported the CDFI through direct cost sharing. Many of these companies also supported the project by providing test data, technical advice and by making their utility systems available for testing. These companies appear below:

Ameren
American Electric Power
Centerpoint
Consolidated Edison Company of New York
Cooper Power Systems
Duke Energy
Exelon - Commonwealth Edison & PECO
First Energy
Florida Power & Light
GRESCO
Hydro Quebec
NRECA
Oncor
Pacific Gas & Electric
Pacificorp
PEPCO
Prysmian Cables and Systems
Public Service Electric & Gas
Southern California Edison
Southern Company
Southwire
Tyco Electronics

Note: Companies in italic font are manufacturers/distributors; others are electric utilities.

In addition, six cable system diagnostic providers participated in the project by providing in-kind cost sharing in the form of technical advice, test data, test equipment or test services. The list of participating diagnostic providers appears below:

Cablewise/Utilx
HDW Electronics[1]
High Voltage, Inc.
HV Diagnostics[2]
HV Technologies[3]
IMCORP

[1] US representative for SEBA KMT
[2] US representative for Baur GmbH, Austria, in 2005-2006
[3] US representative for Baur GmbH, Austria, in 2007-2010

GLOSSARY

The definitions below pertain to their use within this document. These definitions may differ slightly from those used by other sources.

Acceptance Test: A field test made after cable system installation, including terminations and joints, but before the cable system is placed in normal service. The test is intended to detect installation damage and to show any gross defects or errors in installation of other system components.

Breakdown: Permanent failure through insulation.

Cable System: Cable with installed accessories.

Combined Diagnostic Test: A test where two or more diagnostic tests are carried out simultaneously. Each diagnostic provides distinct information on a cable system.

Crosslinked Polyethylene (XLPE): A thermoset unfilled polymer used as electrical insulation in cables.

Damped AC (DAC) Test: A combined diagnostic test that uses dielectric loss estimation and Partial Discharge detection and where the voltage source is formed by a decaying oscillation of a resonant circuit formed between the cable capacitance and an external inductance. The alternating frequency is in the range 30 Hz to 300 Hz.

Diagnostic Test*:* A field test made during the operating life of a cable system. It is intended to determine the presence, likelihood of future failure and, for some tests, locate degraded regions that may cause future cable and accessory failure.

Diagnostic Time Horizon: The period of time that the result of a diagnostic may be projected forward in time and still be considered accurate. This will vary for each diagnostic and interpretation method and is not well defined. It may be thought of as the point at which a diagnostic result would change from one classification to a more severe one.

Dielectric Loss: An assessment of the electric energy lost per cycle. A poorly performing cable system tends to lose more energy per AC cycle. Measurements can be made for selected voltages or over a period of time at a fixed voltage. The stability of the loss, the variation with voltage and absolute loss are used to estimate the condition. Data can be derived from time based (if sufficient time is taken) or frequency-based test methods.

Dielectric Spectroscopy: Measures of the dielectric property at different frequencies. The absolute loss and the variation with frequency are used to estimate the condition. Data can be derived from time-based (if sufficient time is taken) or frequency-based test methods.

Electrical Trees: Permanent dendritic growths, consisting of non-solid or carbonized micro-channels, that can occur at stress enhancements such as protrusions, contaminants, voids or water trees subjected to electrical stress. The insulation is damaged irreversibly at the site of an electrical tree.

Ethylene Propylene Rubber (EPR): A type of thermoset-filled polymer used as electrical insulation in cables and accessories. There are several different formulations of EPR and they have different characteristics. For purposes here, the term also encompasses ethylene propylene diene monomer rubber (EPDM).

Extra High Voltage (EHV): Cable systems within the voltage range 161 kV to 500 kV, though more often between 220 kV and 345 kV. Also referred to as Transmission Class, though usually has higher design stress levels than HV.

Extruded Dielectrics: Insulation such as EPR, HMWPE, PE, WTRXLPE, XLPE, etc. applied using an extrusion process.

Filled Insulation: Extruded insulations where a filler (Carbon Black or Clay) has been incorporated to modify the inherent properties of the base polymer. This class includes all types of EPR, Vulkene etc.

High Voltage (HV): Cable systems within the voltage range 46 kV to 161 kV, though more often between 66 kV and 138 kV. Also referred to as Transmission Class though usually has lower design stress levels than EHV.

Installation Test: A field test conducted after cable installation but before jointing (splicing) or terminating or energizing. The test is intended to detect shipping, storage, or installation damage. It should be noted that temporary terminations may need to be added to the cable to successfully complete this test.

Jacket: An extruded outer polymeric covering for cables designed to protect the cable core and the metallic shielding (wires, tapes or foils).

Joint: A device to join two or more sections of power cable together. A joint includes a connector to secure the cable conductor and a stress controlling / insulating body to manage the electrical stress.

Laminated Dielectrics: Insulation formed in layers typically from tapes of either cellulose paper or polypropylene or a combination of the two. Examples are the PILC (paper insulated lead covered) and MIND (mass-impregnated non-draining) cable designs.

Leakage Current: The current component that flows in the resistive element of the insulation of a cable system. This current component corresponds to current that is in phase with the applied AC voltage and continues flowing once the cable capacitance has been charged under DC voltage conditions. Leakage currents are believed to increase as the system degrades.

Maintenance Test: A field test made during the operating life of a cable system. It is intended to detect deterioration and to check the serviceability of the system.

Mass Impregnated Non Draining Cable (MIND): A cable design using paper insulation impregnated with a thick compound such that the compound does not leak out when the lead is breached.

Medium Voltage (MV): Cable systems within the voltage range 6 kV to 46 kV, though more frequently between 15 kV and 35 kV. Also referred to as Distribution Class.

Metallic Shield: A concentric neutral surrounding the cable core. The shield provides (to some degree) mechanical protection, a current return path, and, in some cases, a hermetic seal (essential for impregnated cables).

Monitored Withstand Test: A test in which a voltage of a predetermined magnitude is applied for a predetermined time. During the test, other properties of the test object are monitored and these are used, together with the breakdown (pass or fail) results, to determine the condition of the cable system.

Offline Test: A diagnostic where energizing and measurement equipment are temporarily coupled to the cable system, while the system is removed from voltage and not carrying load. The measurement equipment is removed after test and the system returned to normal voltage and load. Measurements are made at any voltage selected by the test equipment operator with all the load components removed from the cable system under test.

Online Monitoring Test: A diagnostic where measurement equipment may be permanently coupled to the cable system, while the system is under voltage and carrying normal load, and monitored remotely at any desired occasion to determine the cable system health.

Online Test: A diagnostic test where measurement equipment is temporarily coupled to the cable system, while the system is under voltage and carrying load, and monitored remotely for a selected period of time to determine the cable system health. The measurement equipment is removed after test while the system is under voltage and carrying load.

Paper Insulated Lead Covered (PILC): A cable design using paper insulation impregnated with a fluid and encased in lead to prevent the fluid from leaking out of the insulation.

Partial Discharge: A low voltage (mV or µV) signal resulting from the breakdown of gas enclosed in a dielectric cavity. The signals travel down the cable system and may be detected at the end thereby enabling location.

PE-Based: Extruded insulations that do not have an incorporated filler (Carbon Black or Clay). This class includes all types of HMWPE, PE, WTRXLPE, XLPE, etc.

Polyethylene (PE): A polymer used as electrical insulation in cables.

Power Frequency: A substantially sinusoidal waveform of constant amplitude with an alternating frequency in the range 49 Hz to 61 Hz.

Shielded Cable: A cable in which an insulated conductor is encapsulated in a conducting 'cylinder' that is connected to ground.

Simple Withstand Test: A test in which a voltage of a predetermined magnitude is applied for a predetermined time. If the test object survives the test it is deemed to have passed the test.

Space Charge: Quasi-permanent injected charge that is trapped within the insulation of a cable system. This charge is sufficient to modify the applied AC and Impulse voltage stresses.

Splice: A joint.

Tan δ (TD): The tangent of the phase angle between the voltage waveform and the resulting current waveform.

Termination: A device that manages the electric stress at the end of a cable circuit, while sealing the cable from the external environment and providing a means to access the cable conductor. Devices referred to as Elbows or Potheads are types of terminations.

Time Domain Reflectometry (TDR): A technique to determine cable system lengths and positions of joints using reflections from a rapid rise time low voltage pulse.

Very Low Frequency (VLF): AC waveform of constant magnitude with an alternating frequency in the range 0.01 Hz to 1.0 Hz.

Water Tree Retardant Crosslinked Polyethylene (WTRXLPE): A thermoset polymer used as electrical insulation in cables that is designed to retard water tree growth.

Water Trees: Dendritic pattern of electro-oxidation that can occur at stress enhancements such as protrusions, contaminants or voids in polymeric materials subjected to electrical stress and moisture. Within the water tree the insulation is degraded due to chemical modification in the presence of moisture.

1.0 INTRODUCTION

Almost all electric power utilities distribute a portion of the electric energy they sell via underground cable systems. Collectively, these systems form a vast and valuable infrastructure. Estimates indicate that underground cables represent 15 % to 20 % of installed distribution system capacity. These systems consist of many millions of feet of cable and hundreds of thousands of accessories installed under city streets, suburban developments and, in some cases, in the countryside. Utilities have a long history of using underground system with some of these cable systems installed as early as the 1920's. Very large quantities of cable circuits were installed in the 1970's and 80's due to the introduction of economical, polymer-based insulation compounds and the decreasing acceptance of overhead distribution lines. Today, the size of that infrastructure continues to increase rapidly as the majority of newly installed electric distribution lines are placed underground.

Cable systems are designed to have a long life with high reliability. However, the useful life is not infinite. These systems age and ultimately reach the end of their reliable service lives. Estimates set the design life of underground cable systems installed in the United States to be in the range of 30 to 40 years. Today, a large portion of this cable system infrastructure is reaching the end of its design life, and there is evidence that some of this infrastructure is reaching the end of its reliable service life. This is a result of natural aging phenomena as well as the fact that the immature technology used in some early cable systems is decidedly inferior compared to technologies used today. Increasing failure rates on these older systems are now adversely impacting system reliability and it is readily apparent that action is necessary to manage the consequences of this trend.

Complete replacement of old or failing cable systems is not an option. Many billions of dollars and new manufacturing facilities would be required. Electric utilities and cable/cable accessory manufacturers are simply not in a position to make this kind of investment.

However, complete replacement of these systems may not be required because cable systems do not age uniformly. Cable researchers have determined that many cable system failures are caused by isolated cable lengths or isolated defects within a specific circuit segment. Thus, the key to managing this process is to find these "bad actors" and to proactively replace them before their repeated failures degrade overall system reliability. Various cable system diagnostic testing technologies were developed to detect cable system deterioration. The results of diagnostic tests are used to identify potential failures within cable systems and then again, after repair, to verify that the repair work performed did indeed resolve the problem(s) detected.

Appropriate maintenance and repair practices enable system aging to be controlled and helps manage end of life replacements. Diagnostics to determine the health of the cable system are critical to this management program.

A number of cable diagnostic techniques are now offered by a variety of service providers and equipment vendors. Each service claims to provide a reliable method for establishing the condition of a cable circuit. However, no one service has definitively demonstrated an ability to reliably assess the condition of the wide variety of cable systems currently in service. In general, there is significant confusion and some mistrust regarding the effectiveness of these services. For these reasons, the full potential benefits of cable diagnostic technologies are unrealized.

To address this issue, Georgia Tech NEETRAC created the Cable Diagnostic Focused Initiative (CDFI). The intent of the CDFI was to provide cable diagnostic technology assessment and development via a series of tasks developed by NEETRAC with input from the Initiative participants. The primary objective was to **clarify the concerns and define the benefits of cable system diagnostic testing.**

Implementing cable system diagnostics in an effective way involves the management of a number of different issues. This includes the type of system (network, loop or radial), the load characteristics (residential, commercial, high density, government, health care, etc.), the system dielectric (XLPE, EPR, Paper, mixed), and system construction (direct buried or conduit).

The issues are better understood, but the work is made complex by the fact that most cable circuits were never installed with cable diagnostic testing in mind. Frequently, these circuits contain multiple branches or multiple cable and accessory types, each with its own aging and failure mechanisms. A natural consequence is that different diagnostic techniques are often needed to detect different bulk and localized problems. This situation can be very daunting for cable engineers.

While the need to establish the condition of underground cable systems is apparent, diagnostic tools have not been deployed extensively by electric utilities. There are several reasons why. First, it is very difficult to establish the accuracy of a diagnostic tool. When a given diagnostic test indicates that a cable system segment is "bad", there is little data to confirm that the circuit is indeed "bad" and will likely fail in the near future. Second, diagnostic testing is expensive and time consuming. In most cases, the cable system segment to be tested has to be switched out of service. In other cases, sensors have to be placed on each joint located in manholes.

The initiation of the NEETRAC Cable Diagnostic Focused Initiative (CDFI) highlighted the importance of understanding how best to deploy diagnostics on cable systems. The project was co-funded by the United States Department of Energy and a wide variety of electric utilities and companies that supply electric utilities. It began in late 2004 and ended in late 2010.

1.1 Scope

This project focused on helping electric utility engineers determine when cable circuits should be refurbished, repaired or replaced. To accomplish this goal, the document provides a brief description of how cable systems fail, a description of available diagnostic testing technologies and a discussion of how best to apply these technologies based on available information. The project scope included all diagnostic testing technologies that may be practically deployed in the field to assess the condition of service aged, medium voltage, distribution cable systems. To keep the scope manageable, the project did not include cable systems in the transmission class, newly installed systems, or unshielded systems (5 kV and below).

The range of activities for the CDFI included:

- A review of the basic details of the various cable system diagnostic approaches that were commercially available,

- A description of how these different approaches are used on cable systems, and

- An analysis of results from diagnostic tests with the goal of describing the main advantages, disadvantages, and outstanding issues for the variety of approaches currently available.

Overall, the goal of the CDFI was to combine information from a wide range of sources and develop a resource that will enable cable system engineers to make informed decisions about the most appropriate way to conduct diagnostic tests on their cable systems. It includes an examination of diagnostic technologies that were accessible at project initiation. Because a number of different approaches are available, the project did not attempt to explore the development of new technologies. However, the project did explore new methods for deploying existing technologies to maximize their effectiveness.

These discussions focused on diagnostic approaches for aged MV cable system components as defined in the ICEA S-94-649, IEEE Std. 48™, IEEE Std. 386™, and IEEE Std. 404™. HV, EHV, and pipe type systems are outside the scope of the present study, yet much of the discussion may be relevant to these cables as well.

The focus of this document is on underground systems with extruded cables (Filled Insulations - EPR and Unfilled Polyethylene based Insulations - HMWPE, WTRXLPE, and XLPE) and Paper Insulated Lead Covered (PILC) cables.

This document represents NEETRAC's assessment of the state-of-the-art cable diagnostic testing technology at the end of 2009.

1.2 Cable System Diagnostics

Cable system diagnostic technologies usually fall into two categories.

The *first* category involves techniques to assess the global or "bulk" condition of a cable system. Though a variety of techniques may be employed, the general approach is to measure electrical losses within a given cable circuit.

The *second* category involves techniques to assess localized defects within a cable circuit. Again, various techniques are used to accomplish this goal, including a withstand test to "blow out" the weak location or the measurement of localized electrical discharges within the system.

Cable system diagnostic tests usually achieve one of the following:

- Verify that a new circuit installation, or repaired circuit, is suitable to be placed into service. Thus, the engineer will have some assurance that the circuit does not contain significant workmanship problems nor was it subjected to severe mechanical damage during the repair process, which would adversely affect the design life.

- Assess the health of a cable system and thereby determine the likelihood that an aged cable system will experience failures in the near future. In this case, the testing could be part of an overall cable system asset management program or as a means of minimizing failures on highly critical or problematic circuits.

While these appear to be straightforward goals, it can be difficult to establish exactly how to employ diagnostic technologies effectively. This is due to the following:

- There are many different types of diagnostic testing technologies.

- The diagnostic testing technologies are in different stages of maturity.

- Cable circuits are often very complex with branches or multiple cable and accessory types, each with their own aging mechanisms.

- Multiple diagnostic techniques are sometimes needed to detect different problems.

- Some diagnostic technologies have not been universally accepted.

- Independently developed information on the subject is not widely available in a single document.

Cable system diagnostic testing should be considered a process (either continuous or scheduled), not a single event. Circuits must be studied to match the appropriate technology to the specific components in the circuit. For some applications, it is best to begin with an easy-to-apply technology, which provides general information that is used to select a more focused technology. In many cases, it is desirable to apply diagnostic technologies periodically over the life of the cable circuit to establish, over time, how a circuit is performing.

The basic cable diagnostic testing technologies used to assess cable circuit conditions are listed below and are discussed in more detail in Section 3.

- Time Domain Reflectometry (TDR)
- Partial Discharge (PD) at operating, elevated 60 Hz, elevated Very Low Frequencies (VLF) or Damped AC (DAC) Voltages
- Tan δ /Dielectric Spectroscopy at 60 Hz, VLF or variable frequencies
- Recovery Voltage
- DC Leakage Current
- Polarization and Depolarization Current
- Simple Withstand Tests at Elevated VLF, 60 Hz AC, or DC Voltages
- Acoustic PD Techniques
- Monitored Withstand Tests at Elevated VLF, 60 Hz AC, or DC Voltages with simultaneous monitoring of PD, Tan δ, or Leakage Current
- Combined Diagnostic Tests at 60 Hz AC, Very Low Frequencies (VLF), or Damped AC (DAC) voltages using PD and Tan δ

Different diagnostic testing technologies assess different cable system characteristics. In many cases, more than one technology should be utilized to establish a reasonably complete picture of the cable system condition. This is a particularly complex problem for hybrid cable circuits that contain more than one type of cable insulation and/or one or more types of cable joints or cable terminations. Whether a cable circuit is simple or complex, diagnostic tests must be employed carefully to assure that the results will be meaningful.

Setting realistic expectations is one of the most important considerations when using cable diagnostic testing technologies. There is no question that when applied properly, diagnostic testing can provide information essential to lowering cable system failure rates [1], [2], [4]. However, diagnostic tests do not always yield accurate results, nor are the tests able to predict exactly when a cable will fail. These issues are described in much more detail in Section 3.0. In this respect, cable diagnostic testing is much like a medical examination, in which the resulting information can be used by a patient to take corrective actions that will extend the patient's life. However, the information is rarely able to predict the patient's exact life expectancy.

1.3 Participation

The CDFI brought together utilities, equipment manufacturers, cable diagnostic providers, and other interested parties for the purpose of assessing and enhancing technologies used to diagnose the condition of underground power cable systems. The resulting consortium worked for a total of five years in an effort that was administered, coordinated, and, largely conducted by Georgia Tech NEETRAC. The project sponsoring companies are listed below:

Ameren
American Electric Power
Centerpoint
Consolidated Edison Company of New York
Cooper Power Systems
Duke Energy
Exelon - Commonwealth Edison & PECO
First Energy
Florida Power & Light
GRESCO
Hydro Quebec
NRECA
Oncor
Pacific Gas & Electric
Pacificorp
PEPCO
Prysmian Cables and Systems
Public Service Electric & Gas
Southern California Edison
Southern Company
Southwire
Tyco Electronics

Note: Companies in italic font are manufacturers/distributors; others are electric utilities.

In addition to cost sharing with the Department of Energy, many of these companies also supported the project by providing test data, technical advice, and by making their utility systems available for testing.

Six cable system diagnostic providers also participated in the project by providing in-kind cost sharing in the form of technical advice, test data, test equipment or test services. The list of participating diagnostic providers is shown below:

Cablewise/Utilx
HDW Electronics[1]
High Voltage, Inc.
HV Diagnostics[2]
HV Technologies[3]
IMCORP

[1] US representative for SEBA KMT
[2] US representative for Baur GmbH, Austria, in 2005-2006
[3] US representative for Baur GmbH, Austria, in 2007-2010

From this collaboration, significant progress was made towards the goal of understanding how to effectively deploy diagnostics to evaluate underground cable systems.

1.4 Tasks

The initial project tasks outlined below were established to accomplish the project objective:

1) **Technology Review:** Review literature to understand current diagnostic testing practices and technologies. See References section.

2) **Analyze Existing Data:** Review available cable diagnostic test data to establish the effectiveness of tests conducted to date. Analytical results appear in Section 3, Section 5, and Appendix A.

3) **Conduct Field Tests and Analyze New Data:** Work with CDFI participating utilities to conduct tests on their system, monitor cables tested and analyze results. Field test results are provided in Section 3, Section 5, and Appendix A.

4) **AC/VLF Test Level Analysis:** Establish optimal threshold voltage and time values for VLF withstand voltage application using field-aged cables tested in the laboratory. This information is provided in Section 3.8.

5) **Defect Classification:** Tests on circuits with known problems to validate the accuracy of various diagnostic technologies under controlled conditions. See comments below.

6) **Reports, Update Meetings, and Tech Transfer Seminars:** Provide progress reports as required and hold Update Meetings and Seminars when appropriate.

As the project progressed, the scope of some tasks evolved. Tasks 1-4 transpired generally as planned and the results are provided in the body of this report. Rather than focus on classifying defect types as outlined in Task 5, it became apparent that it was more important to establish the ability of a diagnostic to predict failures rather than detect a specific type of defect. For this reason, Task 5 was refocused to review thousands of test segment data records against the ultimate performance of the cable segments. This proved to be very useful in that it helped to establish that many diagnostic technologies are very good at establishing which circuits are good (do not fail within three to five years after the test is performed), but they have only a limited ability to predict which cable circuits are bad (will fail less than five years after the test is performed).

In addition to the initially proposed tasks, the project also developed:

1. An overall approach to performing diagnostic tests (SAGE). See Section 4.1.
2. An on-line Knowledge-Based System (KBS) that can be used by utilities to establish the most effective approaches for a given cable system. See Section 4.2.
3. An introductory methodology for establishing the economic benefits of performing diagnostic tests. See Section 4.3.

1.5 Findings

The collaboration between the NEETRAC team and the CDFI participants led to many interesting discoveries. In general, the CDFI established that when deploying cable diagnostic test programs, it is important to have realistic expectations. Diagnostic testing can be very useful, but it is not a perfect process. To maximize effectiveness, test programs must be carefully planned and the results must be thoroughly studied. In addition, it often takes time to see the benefits in the form of reduced failure rates. But with care and diligence, a cable diagnostic test program can help utilities improve system reliability.

It is important for the cable engineer to recognize that there are many unanswered questions regarding the effectiveness and benefits of diagnostic testing. It is a rapidly developing field and there is still much to learn.

It is useful to return to the concept of diagnostic testing in a medical context; most diagnostic tests are invasive to the cable system. Thus, they carry risks and benefits that must be carefully weighed before used. It is obvious from the medical analogy that there can be situations where some techniques do not bring sufficient value to warrant the risks to the system that they entail; therefore, the risks, benefits, and accuracy of diagnostic tests must be weighed carefully before commencing on the journey.

With a thorough understanding of the advantages and disadvantages of each technology, and with effectively applied technology enhancements, utilities are now better able to improve underground cable system reliability.

2.0 HOW A POWER CABLE SYSTEM AGES, DEGRADES, AND FAILS

A power cable system fails when *local* electrical stresses are greater than the *local* dielectric strength of dielectric material(s) [5]. The reliability, and thus, the rate of failure of the whole system depend on the difference between the *local* stress and the *local* strength. Failure of the dielectric results in an electrical puncture or flashover. The flashover can occur between two dielectric surfaces, such as the cable insulation and joint insulation. It can also occur as an external flashover at cable terminations. The failure can occur as a result of the normally applied 60 Hz voltage or during a transient voltage such as lightning or switching surges.

As time progresses and the cable system ages, the bulk dielectric strength degrades (aging). Equally, artifacts that raise the local stress (water trees, disbondment of contaminants, and voids) can develop with time. The net effect appears as aging. Aging manifests itself in many ways (three general cases are shown in Figure 1). The exact way in which the strength of a device degrades will depend upon many factors such as voltage, thermal stresses, maintenance, system age, cable system technology, and environment. In addition, as the Rapid Aging in Figure 1 shows, the aging rates change with time. Unfortunately, but not unexpectedly, the aging usually accelerates.

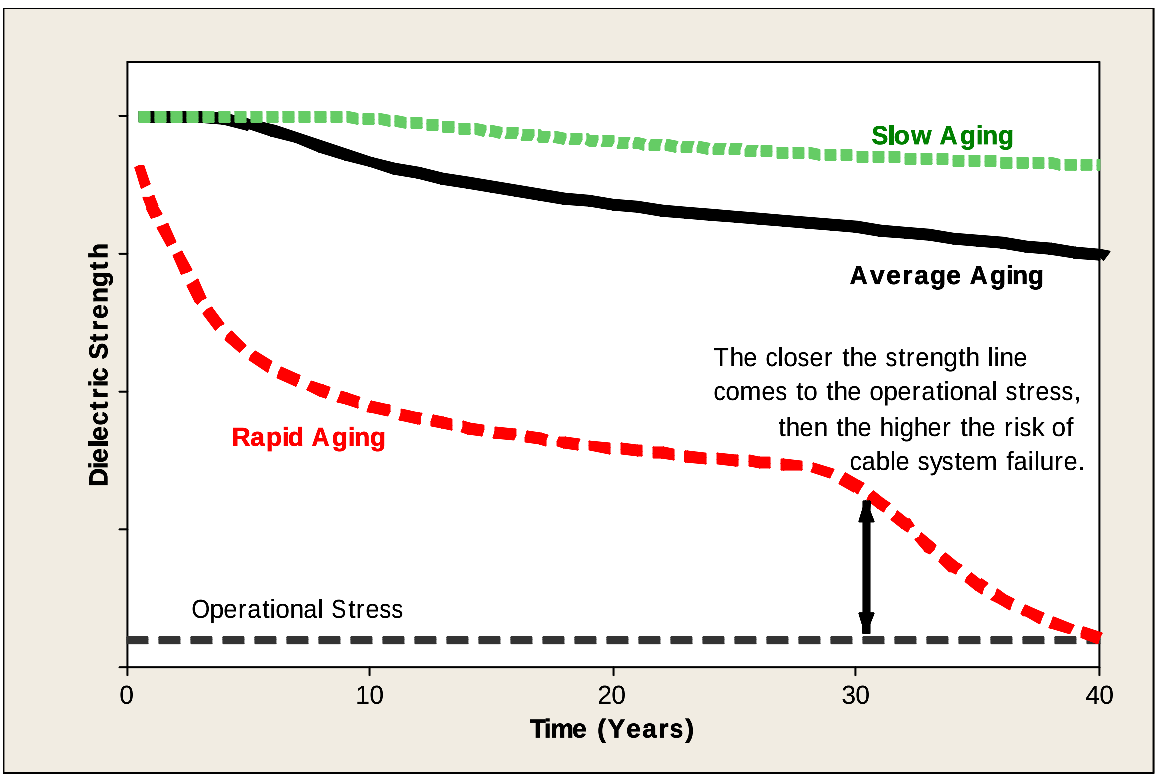


Figure 1: Cable System Aging Characteristics

Figure 2 shows the effect of different electrical stresses on the endurance (time to failure) for a dielectric in arbitrary units. It is clear that as the electric stress is increased, then the endurance or the time to failure will decrease. This is not a linear effect. It is generally accepted, as shown in Figure 2, that a 10 % increase in stress (such as increasing the stress from 15 units to 16.5 units) will cause a 60 % reduction in endurance [**Error! Reference source not found.**]. This is why so much attention focuses on cleanliness in dielectric systems – to avoid introducing contaminants that often serve as stress enhancers.

This is also why it is possible, and often common, for a system to experience aging at different rates along the cable length. In a cable with an isolated contaminant (large vented tree), there can be a low level of bulk aging but a high level of local aging at the contaminant due to the higher stress at the contaminant. Therefore, the area immediately surrounding the contaminant experiences the dual effects of higher stress and higher aging. However, in a cable with many bow tie trees distributed throughout the insulation, there will more likely be a medium level of bulk aging. The distinctions may seem arbitrary, as failure will always occur at the weakest point. However, this does have a big impact on the "repairability" of the system. In the case of an isolated defect, a repair after the failure will result in a system with dielectric strength that is very often quite high. If the failure was due to more dispersed deterioration, then repairs may not provide much benefit as the remaining system is only marginally stronger than the weakest part that failed.

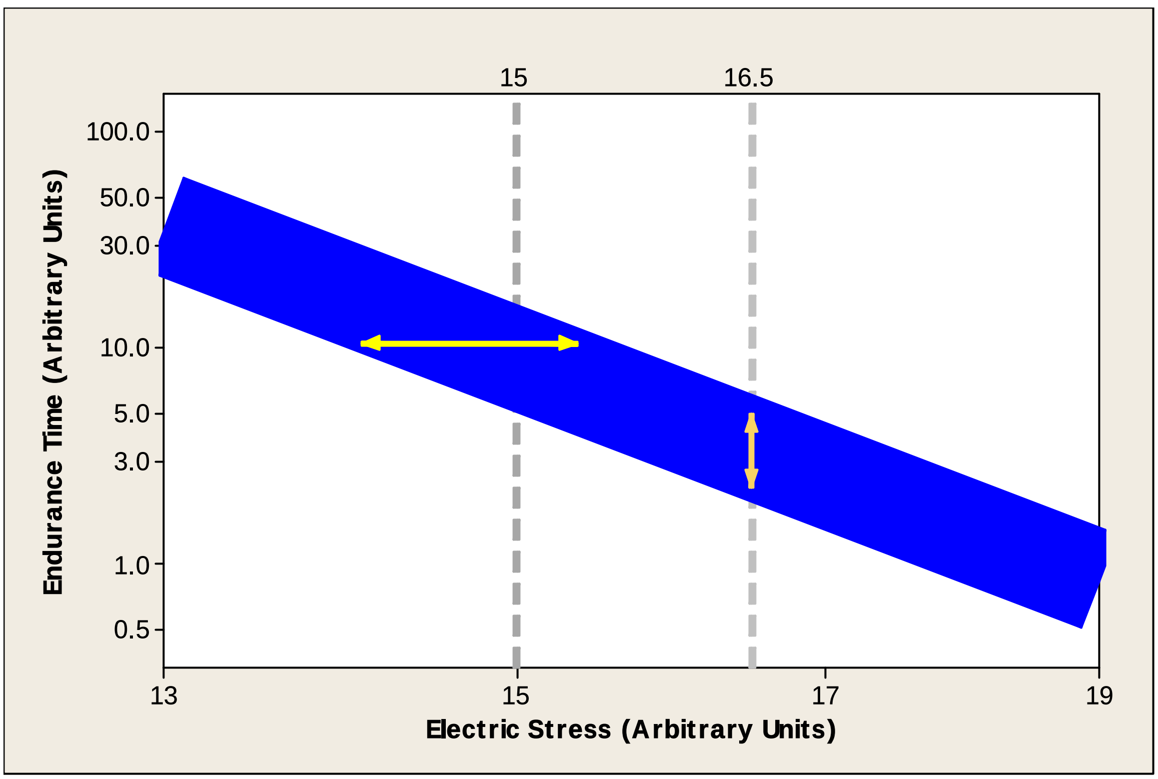


Figure 2: Endurance Reduction with Elevated Electrical Stresses (Following the Inverse Power Law $E^n t=K$ with n=12)

Figure 1, Figure 2, and most references, represent dielectric strength and endurance as lines implying that they are single valued, or deterministic, results. Nothing could be farther from the truth. Even in well controlled laboratory assessments there is considerable scatter, or randomness, in such data (Figure 3). Furthermore, this scatter is enhanced when considering the less well-controlled environment of a cable system. This is important for the engineer to bear in mind as diagnostic tests, in general, determine if there are weak locations within the cable circuit. A cable system will begin failing long before the average dielectric strength of the system is below the operating stress.

It is not only the dielectric strength that displays statistical scatter; this is common to all physical characteristics of the system measured in diagnostic tests. Furthermore, as Figure 3 shows, it is common for the characteristics of an aging system to broaden over time. This is because aging occurs at different rates at different points along the cable system length. Often, the broadening of the curve is more significant than the reduction in the mean. There is one profound consequence, namely that repeated measurements on the same cable system, with the same mean and scatter, are expected to yield different diagnostic results at different times.

After significant aging, the curve tends to again narrow about a mean value and the distributions tend to become much tighter as theoretically illustrated in Figure 3. Different mean and standard deviations are shown. The normal distribution has been selected for this visualization, yet this may not be the most appropriate for all diagnostic techniques. This effect is particularly clear for overall dielectric strength (from field tests).

Often the separation is not so clear. Consequently, there is much research to:

- Define the most appropriate metrics for each physical characteristic,
- Determine the best decision methods,
- Find the most appropriate values that accurately classify the condition of the system.

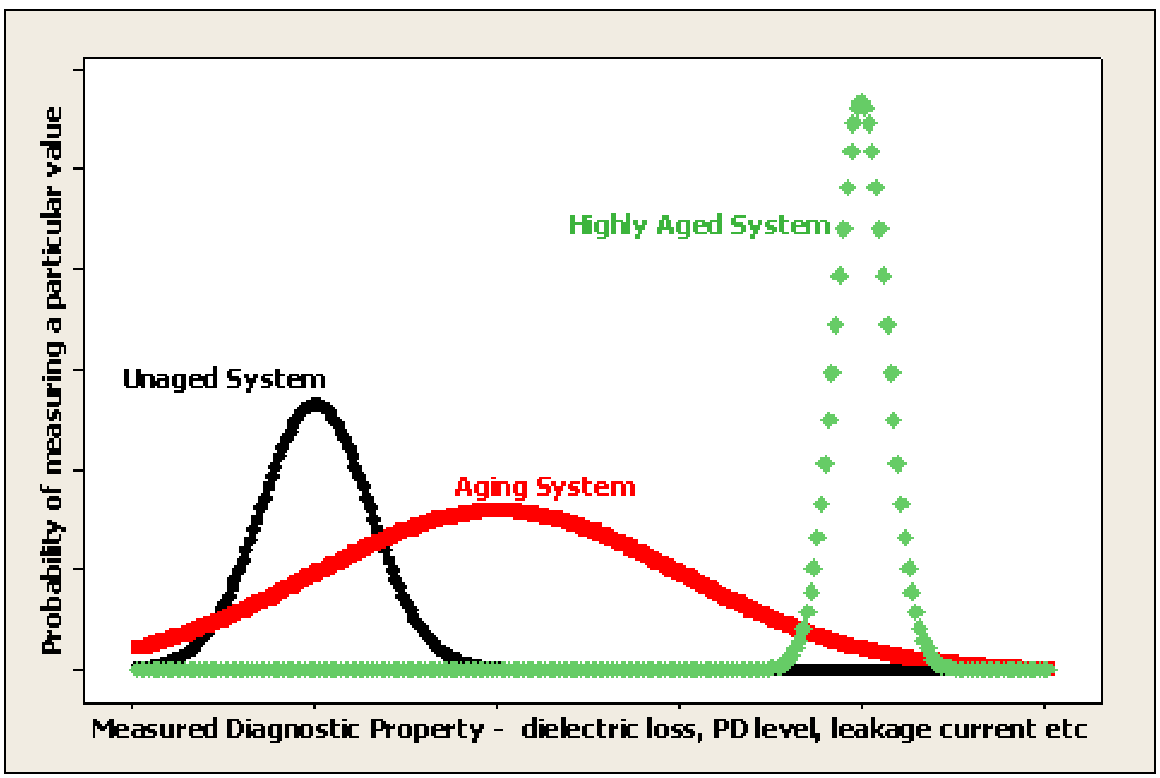


Figure 3: Schematic Distributions of Diagnostic Responses

The discussions above show why it is critically important to assess the level of performance using Diagnostic Testing **and** to understand the mechanisms of failure. The remainder of this section addresses the last point.

Turning to the specific mechanisms, the excessive electrical stress or bulk deterioration of the insulation can occur as a result of:

- Manufacturing Imperfections: Tend to increase the local stress leading to either initial failure or higher rates of aging.
  - Voids
  - Contaminants in insulations
  - Poor application of shield material
  - Protrusions on the shields
  - Poor application of jackets

- Poor Workmanship: Tends to increase the local stress leading to either early failure or higher rates of aging.
  - Cuts
  - Contamination
  - Missing applied components or connections
  - Misalignment of accessories

- Aggressive Environment: Tends to reduce the dielectric strength. The impact can be local if the environmental influence is local.
  - Chemical attack
  - Transformer oil leaks
  - Floods
  - Petrochemical spills
  - Neutral corrosion

- Wet Environment: Tends to reduce the dielectric strength and increase the local stress.
  - Bowtie trees
  - Vented water trees
  - High rates of corrosion
  - Can reduce dielectric properties

- Overheating: Tends to reduce the dielectric strength. The impact can be restricted to short lengths (local) if the adverse thermal environment is localized.
  - Excessive conductor current for a given environment and operating condition (global)
  - Proximity to other cable circuits for short distances (local)

- Mechanical: Tends to reduce the dielectric strength. The impact can be restricted to short lengths if the mechanical stress is localized.
  - Damage during transportation (usually localized)

  - Excessive pulling tensions or sidewall bearing pressures (can be localized or global)
  - Damage from dig-ins (local)

- Water Ingress: Tends to reduce the dielectric strength and increase the stress in the area surrounding the moisture.
  - Normal migration through polymeric materials
  - Breaks in seals or metallic sheaths

Defects in cables with extruded insulation that can lead to failure appear in Figure 4. These defects include protrusions, voids, cracks, delamination, conductor shield interruptions, water trees, and electrical trees [4] – [7]. Within PILC cables, areas with insufficient oil due to oil migration and water ingress can also create failures over time [7].

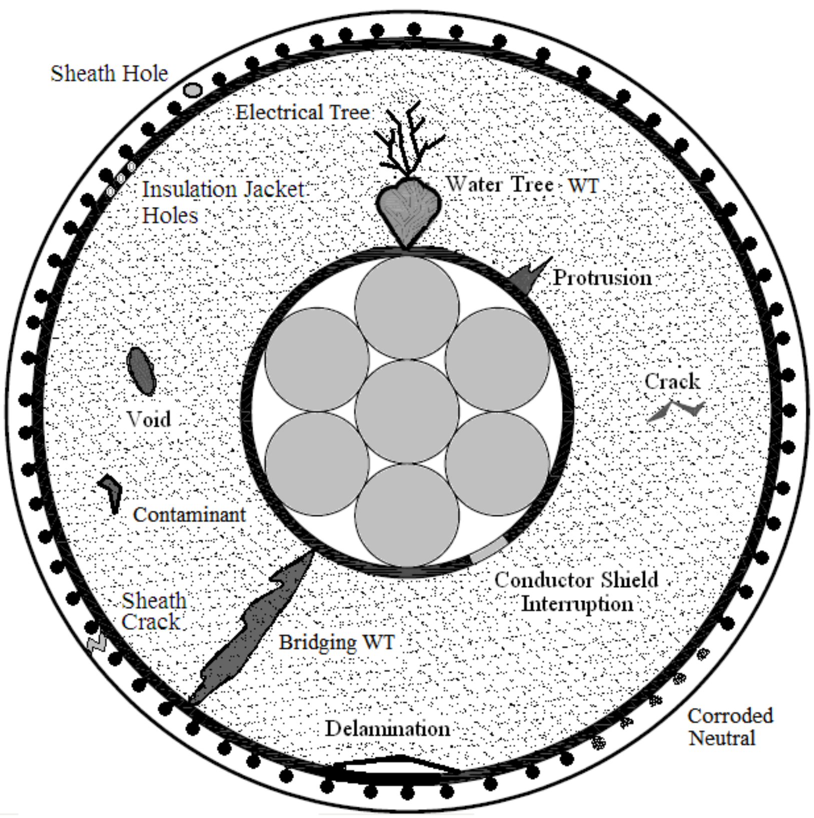


Figure 4: Typical Power Cable Defects

In addition, typical defects that can evolve into failures in a cable joint with extruded insulation are shown in Figure 5. These defects include voids, interface discharge (tracking between the interfaces of the cable insulation and the joint insulation), and knife cuts made during the shield cutback operation. The same types of defects that can occur in different joint constructions, both taped and prefabricated, can also occur in terminations.

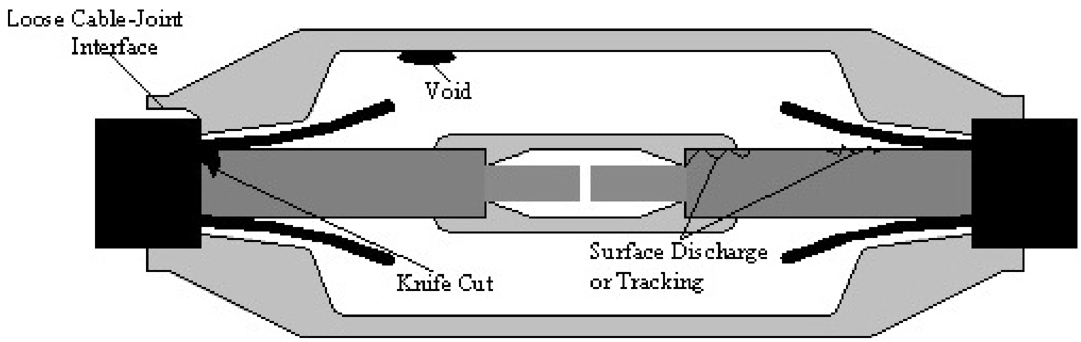


Figure 5: Typical Cable Joint Defects

As the aging mechanism depends on factors that involve the cable characteristics, accessory characteristics, and operating conditions, different power cable systems will age in different ways. As the system ages, the dielectric strength of various components tend to weaken. In fact, aging, degradation, and failure mechanisms are statistical in nature [4], [8]. Therefore, there may be substantial variations in how the mechanisms develop and evolve over time with respect to cable length and accessories. This leads to significant differences between power cable systems operating under the same conditions and exposed to similar environments. Moreover, due to the statistical behavior of these mechanisms, the power cable system properties measured through diagnostic testing will also show statistical features. As a result, when utility engineers try to estimate the statistical time to failure for a given cable segment, the data should be interpreted correctly, e.g. with a sufficient number of data points to provide a reasonable assessment of trends and predictions.

Table 2 through Table 5 list typical deterioration or aging mechanisms along with the associated causes of each for various accessory and cable types. Mechanisms that lead to rapid failure (thermal runaway and extremely high local stresses from contaminants) are omitted as they bypass the degradation step and thus do not permit intervention.

It is useful to recall that the dielectric loss within a system depends upon the electrical stress (E), frequency (ω), permittivity (ε), and Tan δ:

$$\text{Dielectric Loss} \propto \omega E^2 \varepsilon \,\text{Tan}\,\delta \quad \textbf{(1)}$$

Before any failure, there is either tracking or an electrical tree. Thus it should be noted in all of the flow diagrams in Table 2 that tracking and electrical treeing precede all failures. The only question is how long they can be observed before the failure.

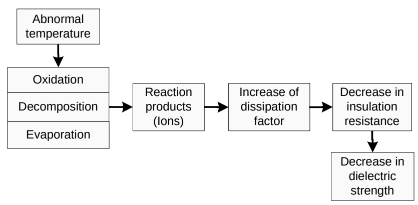
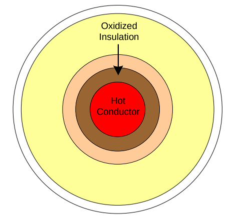
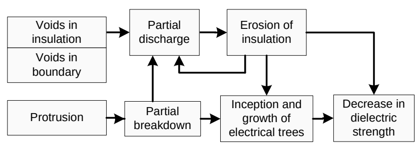
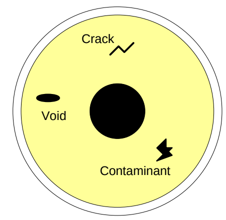
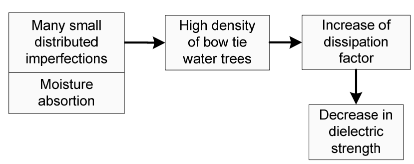
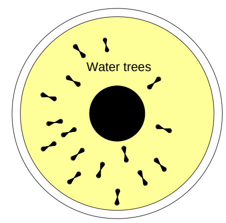
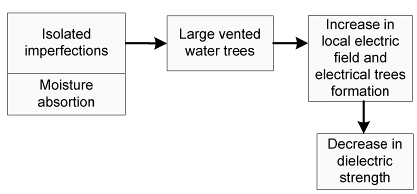
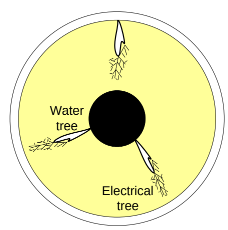
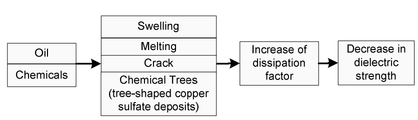
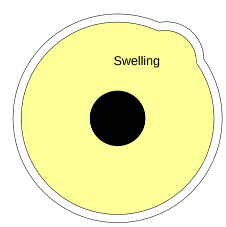
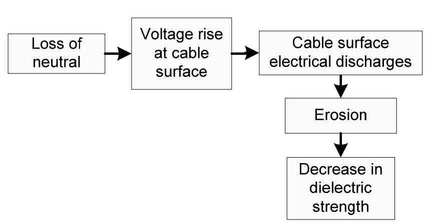
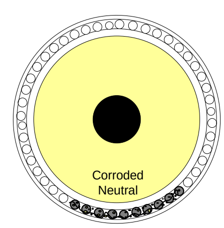
Table 2: Aging and Degradation Mechanisms for Extruded Cable			
Type of Deterioration	**Aging Process**	**Typical Causes**	**Example**
Thermal		Excessive conductor current for a given environment and operating conditions	
Dry Electrical		Manufacturing imperfections (i.e. voids, contaminants), mechanical damage	
High Density of Small Water Trees		Moisture ingress (external and via conductor)	
Large Water Trees		Moisture ingress	
Chemical		Petrochemical spills, transformer oil leaks, fertilizers	
Neutral Corrosion		Unjacketed cable in soil that enhances copper (Cu) corrosion, jacketed cable with corrosive water ingress	

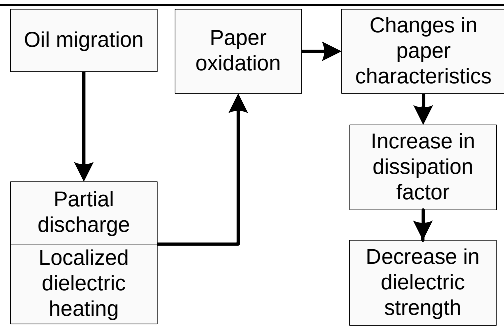
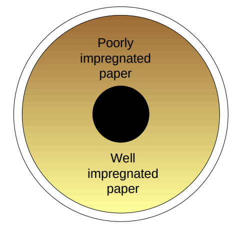
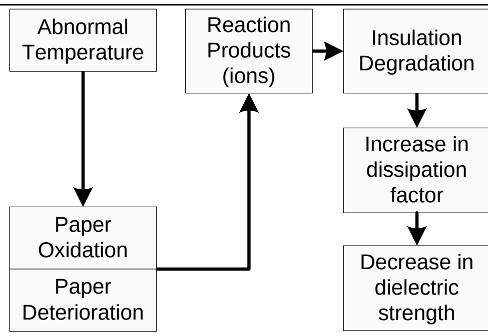
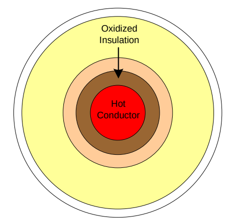
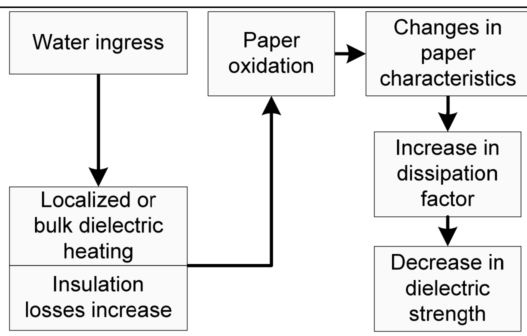
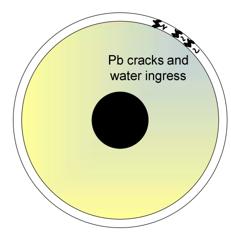
Table 3: Aging and Degradation Mechanisms for Paper Cable			
Type of Deterioration	**Aging Process**	**Typical Causes**	**Example**
Oil Starvation		Extreme elevation changes, lead (Pb) breach: cracks and corrosion	
Thermal		Excessive conductor current for a given environment and operating conditions	
Water Ingress		Lead (Pb) breach: cracks and corrosion	

Table 4: Aging and Degradation Mechanisms for Accessories of Extruded Cable

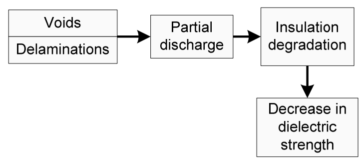
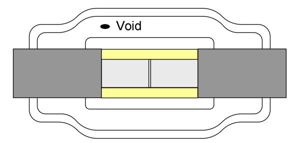
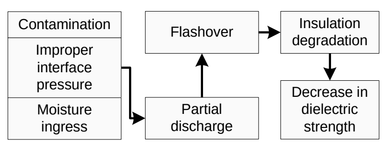
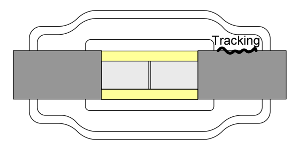
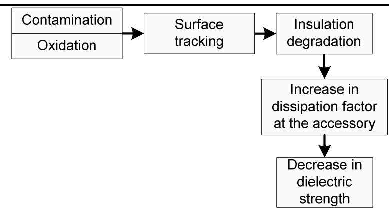
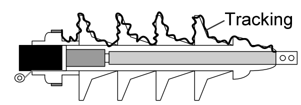
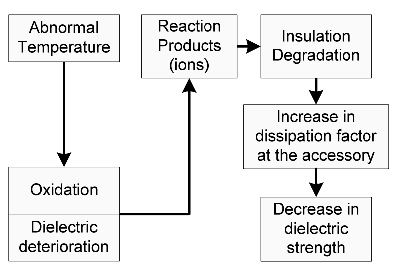
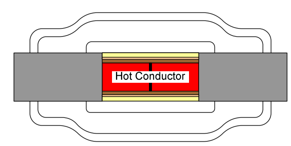
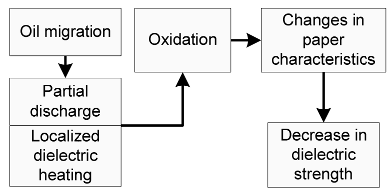
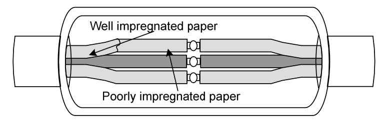
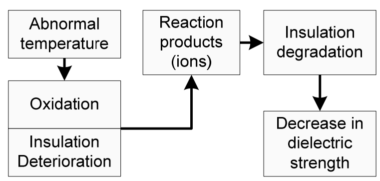
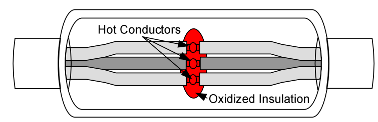
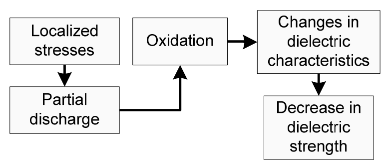
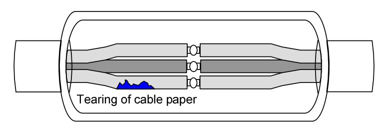
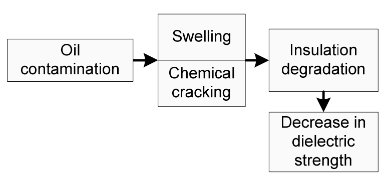
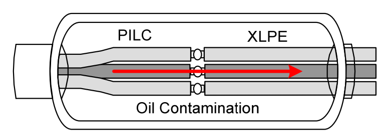
Type of Deterioration	Aging Process	Accessory Type	Typical Causes	Example
Dry Electrical		Joint, termination, separable connector	Manufacture defects, natural aging, poor workmanship	
Electrical Interface		Joint, termination, separable connector	Moisture ingress, poor workmanship	
Electrical External		Termination	Pollution, Ultra Violet (UV) degradation	
Thermal		Joint, termination, separable connector	Excessive conductor current for a given environment and operating conditions, failed connectors	

Table 5: Aging and Degradation Mechanisms for Accessories of PILC cable

Type of Deterioration	Aging Process	Typical Causes	Example
Oil Starvation		Extreme elevation changes, lead (Pb) breach: cracks and corrosion	
Thermal		Excessive conductor current for a given environment and operating conditions, poor connection design for installation	
Localized Electrical Stresses		Tearing or separation of cable paper due to poor workmanship	
Oil Contamination from Paper to Extruded Cable in Transition Joints		Poor accessory design, poor workmanship	

The diversity of cable system failure mechanisms comes not just from the different ways that a given dielectric can age and ultimately fail, but also from the broad array of different cable systems currently in service. Figure 6 provides an estimate of the quantity of different cable system insulation types used in North America. This data originates from a survey performed as a part of this project to understand the diversity of the current underground cable system infrastructure. This figure shows that the diversity is significant. Thus, it is important to understand how to match a given diagnostic technology to a specific cable system type. It is very unlikely that one diagnostic technique will be effective for assessing the true condition of each system type.

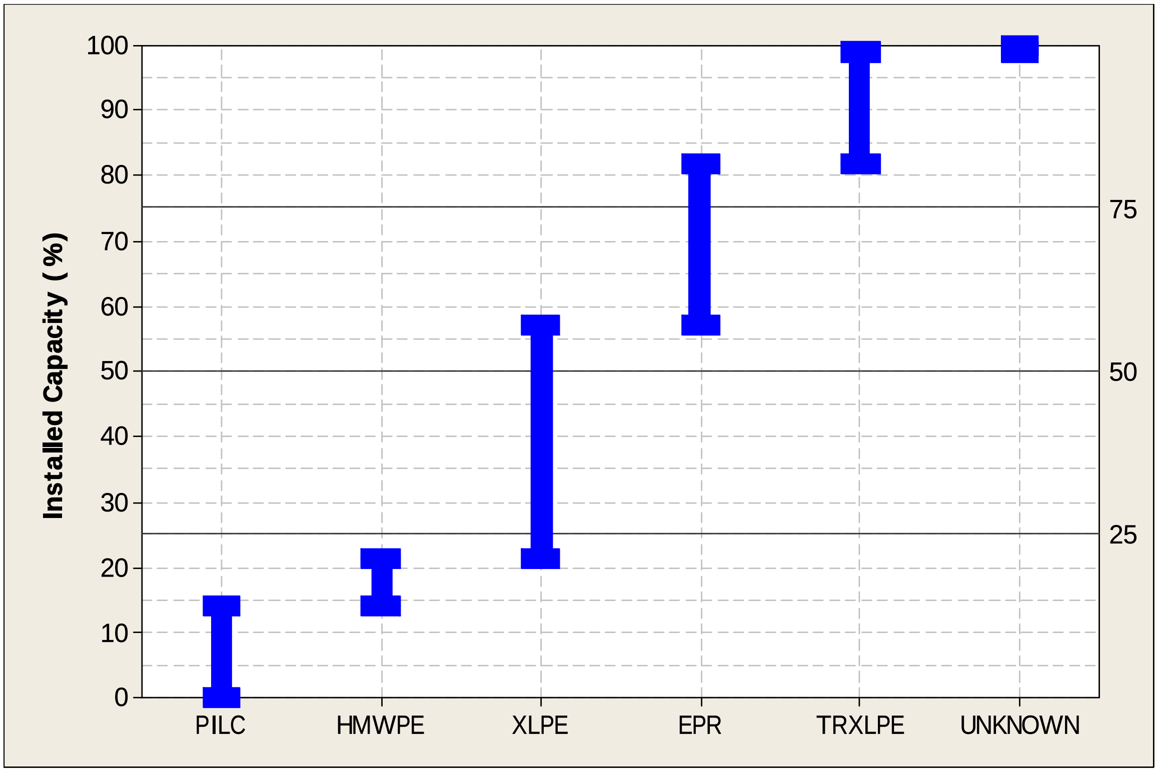


Figure 6: Estimate of North American Installed MV Cable Capacity, Segregated by Cable Insulation Type form Surveys Conducted 2006 To 2007

It is also important to understand what portion of existing cable systems are failing and at what rate. From Figure 7 it is clear that while some utilities are experiencing very high failure rates of over 100 [failures/100 miles/year], the mean is approximately 12 [failures/100 miles/year]. This information is very important because it sets the stage for understanding the economic considerations associated with diagnostic testing as well as setting expectations for improved reliability.

Figure 8 shows that failures occur not just in cable, but also in joints (splices) and terminations. Thus, diagnostic technologies must be able to detect weaknesses in all cable system components. Finally, Figure 9 shows that a significant percentage of utilities do not deploy cable system diagnostic testing programs and about half of those use one technique. This information implies that in general, utilities do not fully appreciate the potential benefits of performing diagnostic test programs on their cable systems. Note that these data come from surveys conducted in 2006 and 2007.

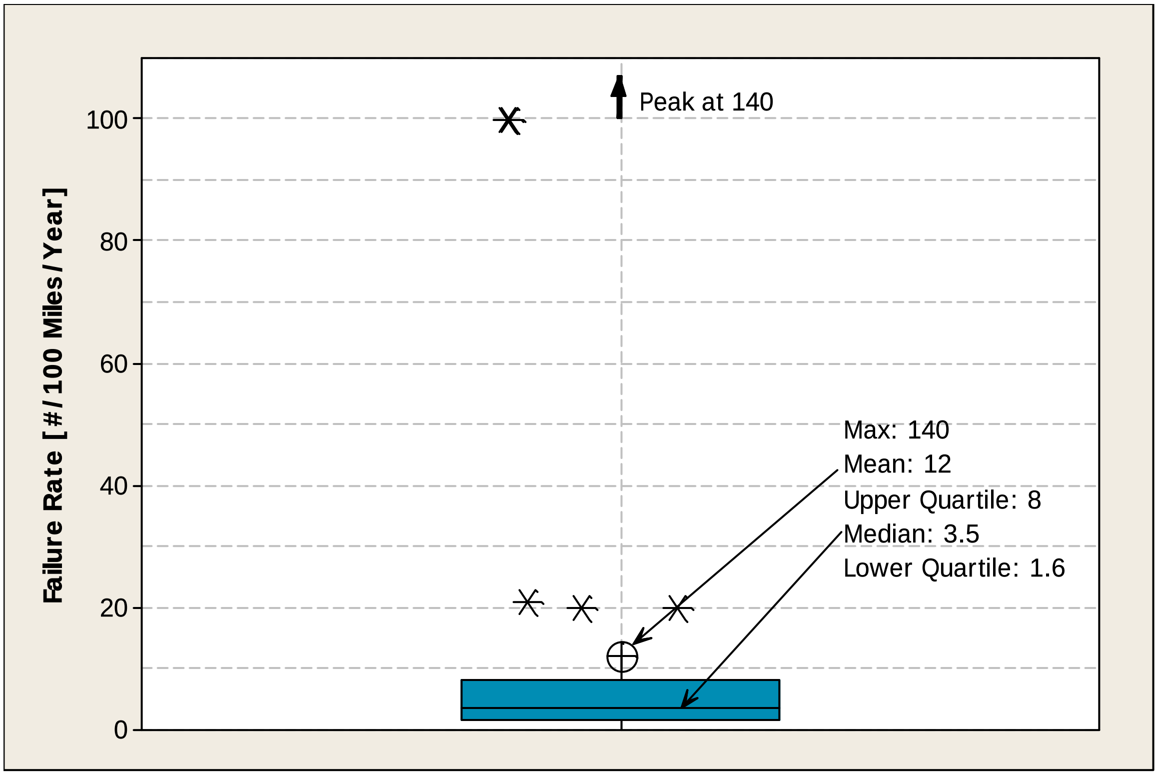


Figure 7: Estimate of North American MV Cable System Failure Rates

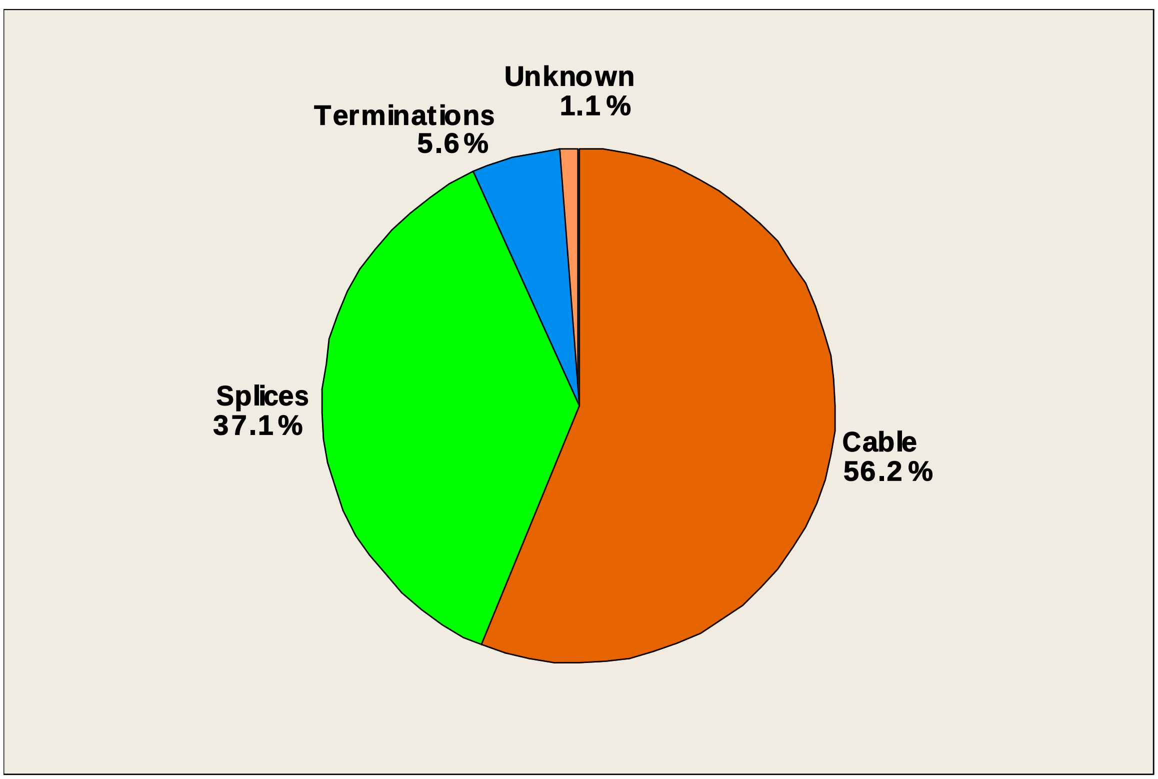


Figure 8: Estimated Dispersion of North American MV Cable System Failures by Equipment Type

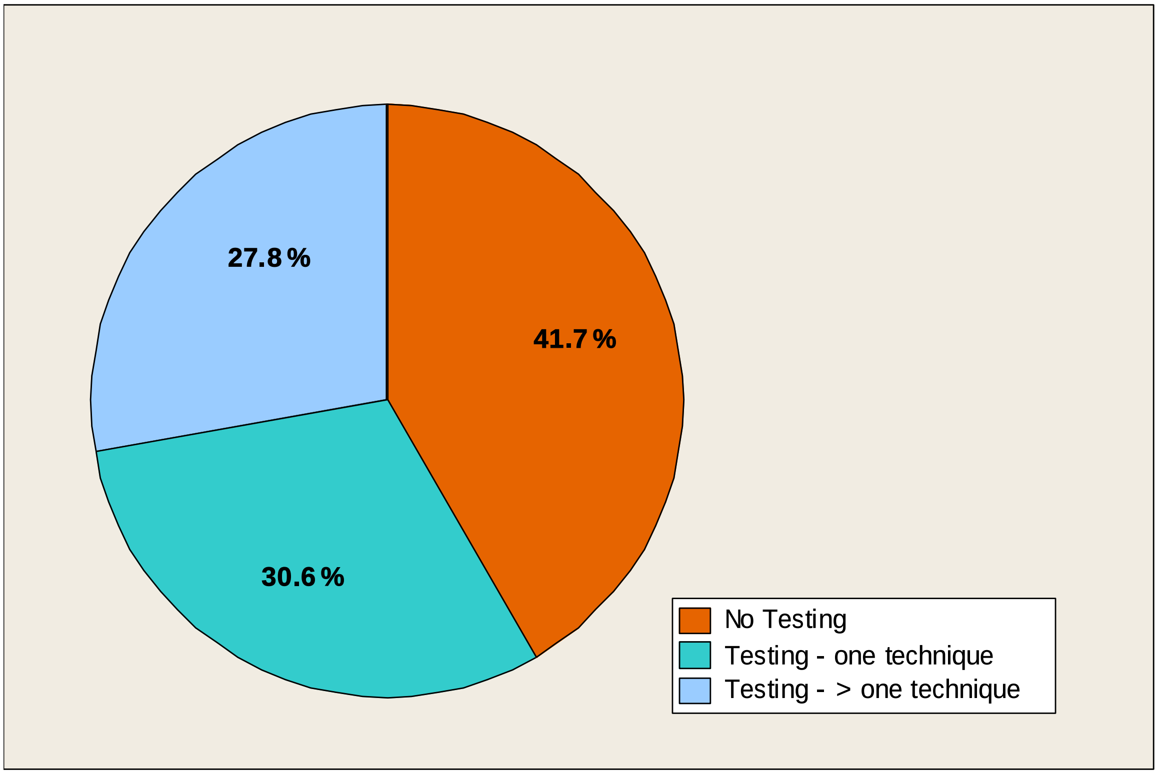


Figure 9: Estimate of North American Diagnostic Use on MV Cable Systems

3.0 AVAILABLE DIAGNOSTIC TECHNIQUES

There is a wide range of cable system diagnostic testing techniques available for evaluating the condition of underground cable systems. For many of these techniques, there are also variations on the same basic technology. To determine the correct technique for a given application, an engineer should consider:

- Effectiveness – Does the technique do what is intended?
- Maturity – Has the technique been deployed long enough to assure its effectiveness? (Much of the benefit of diagnostic testing comes from a comparison with measurements on other circuits. Useful comparative data may be unavailable for immature or changing technologies/techniques.)
- Accuracy – How often does the technique deliver the correct assessment?
- Clarity – Does the technique provide an answer that is easy to understand and actionable?

This section describes the operational details of 15 diagnostic testing techniques. Many of these techniques are used by utilities in diagnostic programs while others have yet to be adopted in the US. Figure 10 shows the results of a survey conducted in 2006 - 2008 on the use of diagnostics. As this figure shows, a number of techniques are in regular use while others are being tested or occasionally employed.

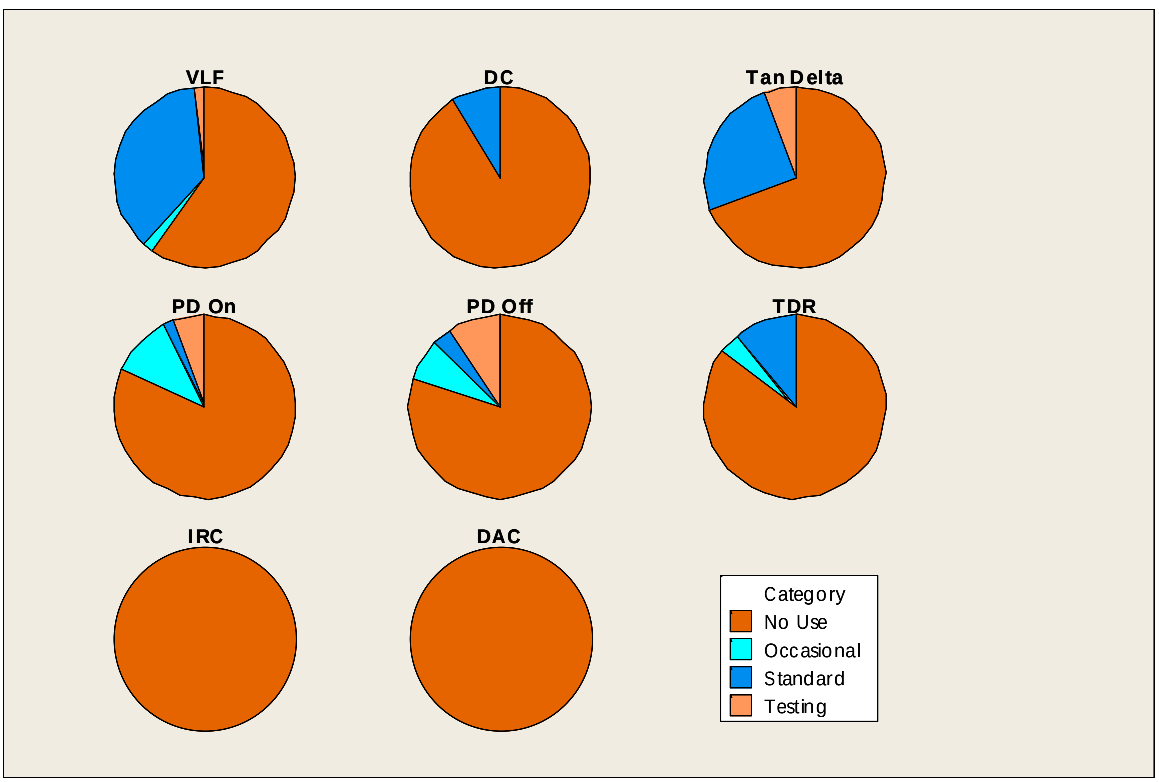


Figure 10: Estimate of North American Diagnostic Use on MV Cable Systems

The following sections provide the cable system owner/operator a basic understanding of each technique such that they can answer the questions outlined above.

Each diagnostic technique section contains a description of:

- The Technique Scope
- How it works
- How it is applied
- Advantages, disadvantages, and open issues
- Success criteria
- Estimated accuracy (described in Section 3.1)
- An overall CDFI (authors and contributors) perspective on the technique

For this report, advantages, disadvantages, and open issues are defined as follows:

- Advantages are technique characteristics that make it particularly useful for a specific application.
- Disadvantages are fundamental issues that cannot be readily overcome.
- Open Issues are drawbacks or questions about that technique that are not fundamental or insolvable and may be resolved as the technique matures or as it is studied further. Until that time, Open Issues are Disadvantages.

3.1 Diagnostic Accuracy

Accuracy is crucial to any cable system diagnostic technique. Estimated accuracies for each diagnostic testing approach are *based on the data available to the CDFI.* They are not based on Provider or Supplier claims.

To define the accuracy of a diagnostic test, circuits are sorted into two categories:

1. **Pass:** Those circuits that the diagnostic test results indicate are "Good" (do not require action or *Not Act*) and are not expected to fail within a specified time horizon.
2. **Not Pass:** Those circuits that the diagnostic test results indicate are "Bad" (do require action or *Act*) and are expected to fail within a specified time horizon.

For the CDFI, Accuracies appear in two forms:

- **Overall Accuracy** – For a set of tests performed, this accuracy is the percentage of tested segments that correctly matched the circuit's condition to its performance. In other words, this accuracy combines the number of "Good" circuits that did not fail with the number of "Bad" circuits that did fail.
- **Condition-Specific Accuracy** – For each set of diagnosed circuit conditions ("Good" or "Bad"), this accuracy is the percentage that were correctly diagnosed. In other words, what percentage of segments diagnosed as "Good" did not fail or what percentage of segments diagnosed as "Bad" did fail.

The above accuracy types are subtly different in their definitions but tremendously different in their implications. The primary difference between the two is how the group of tested circuits is subdivided. The first type, overall accuracy, considers the performance of each technique in each of the available datasets as purely the number of correct assessments out of the number of attempted assessments. It is the typical notion of accuracy. Overall accuracy looks at the general performance of the diagnostic and is the primary means of comparing one diagnostic technique with another. On the other hand, condition-specific accuracy examines the accuracies within the smaller groups (i.e. the number of *Act* circuits that went on to fail and the number that did not).

Consider the following example: suppose in a test of 100 circuits it was known before the test that 80 of them were truly "Good" (not going to fail) while the remaining 20 were actually "Bad" (going to fail). After testing the entire population the results in Table 6 were obtained.

Table 6: Summary of Diagnostic Testing Results for the 100 Circuit Example

True Condition	Circuits [#]	Circuits Diagnosed as Pass [#]	Circuits Diagnosed as Not Pass [#]
"Good"	80	64	16
"Bad"	20	2	18

Table 7 shows the resulting Overall and Condition-Specific accuracies computed using the data shown in Table 6.

Table 7: Pass and Not Pass Accuracies (100 circuit example)		
Assessment	**Overall Accuracy [%]**	**Condition-Specific Accuracy [%]**
Pass	82%	80%
Not Pass		90%

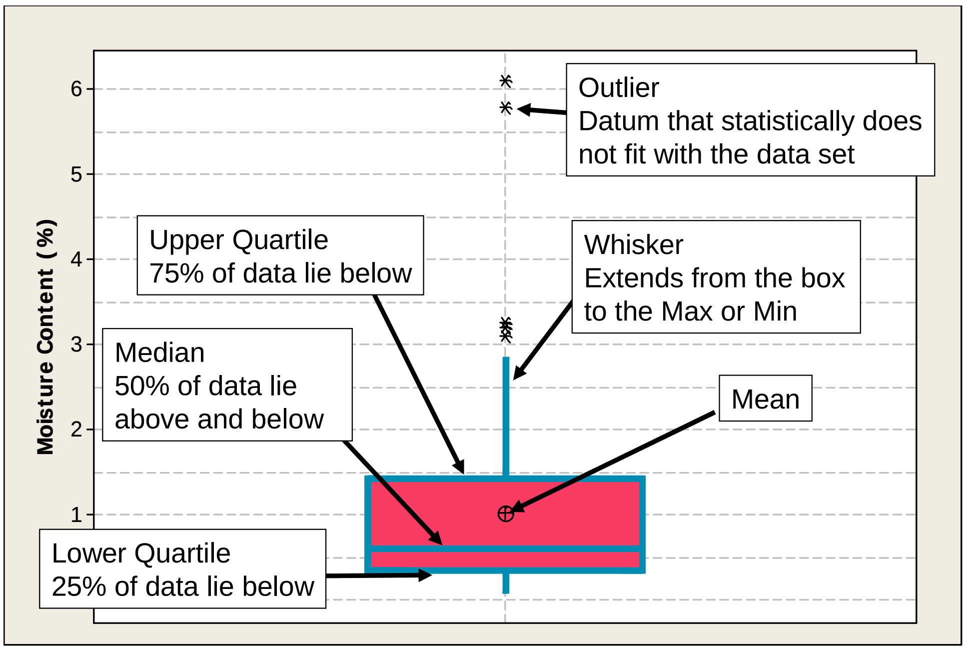
There are a number of observations that can be made about Table 6 and Table 7. First, the "Good" and "Bad" groups are different fractions of the whole population. Second, the Pass and Not Pass Conditions have different Condition-Specific accuracies and the resulting Overall Accuracy is a weighted average of the two Condition-Specific accuracies. This weighting is determined by the relative sizes of the two groups. In theory, this may be extended to any number of conditions.

Some diagnostic techniques offer more specific classifications than Pass and Not Pass. For example, they may provide a numerical ranking (1, 2, 3, 4, 5) or some may provide a semi descriptive diagnosis such as Defer, Repair, or Replace. To establish the accuracy of these diagnostic approaches, their assessments are combined to generate one of the two assessment groups above (*Act* or *Not Act*). The methodology used to combine the results is specified for each diagnostic technique.

Furthermore, when available, multiple datasets are analyzed for each diagnostic technique to obtain the general performance of that technique on different utility systems. The information appears as summary parameters that describe the distributions of accuracies resulting from the available datasets. Table 8 lists the statistics and their definitions. These statistical parameters are utilized in the graphical "box plot" representation also shown in Table 8.

Table 8: Summary of Statistical Parameters for Accuracy Distributions

Summary Parameter	Description
Median	Mid-point of distribution. 50 % of data are above and 50 % are below this value. Similar to mean although immune to the effects of very low or very high values.
Upper Quartile	75 % of data are below this value while 25 % of the data are above.
Lower Quartile	25 % of data are below this value while 75 % of the data are above.



Box plot Representation

Finally, all accuracies appear in two forms, raw and weighted. Raw accuracies refer to the number of segments regardless of length while the weighted accuracies consider the different tested lengths. That is, a result on a 10 mile section is weighted more highly that a result on a 2 mile section. Table 9 illustrates a sample accuracy table.

Table 9: Sample Accuracy Table

Accuracy Type	Diagnostic Technique		
		Raw	**Weighted**
Overall Accuracy (%)	Upper Quartile		
	Median		
	Lower Quartile		
	Number of Data Sets {possible}		
	Length (miles)		
Pass Accuracy (%)	Upper Quartile		
	Median		
	Lower Quartile		
	Number of Data Sets {possible}		
	Length (miles)		
Not Pass Accuracy (%)	Upper Quartile		
	Median		
	Lower Quartile		
	Number of Data Sets {possible}		
	Length (miles)		
Time Span (years)			
Cable Systems			

{possible} = total number of data sets available for analysis

Another important aspect of the accuracy issue is how the information is used. When a group of cable systems within a tested area is "Bad," it is virtually impossible, based on the data analyzed, to know which cable systems will fail first. Thus, some other criteria are suggested to select the "Bad" segments that should be acted on first. That decision could be based on the results from a second diagnostic parameter, the failure history of a "Bad" segment, or the sensitivity of the load supplied by that segment. Of course, another option is to act on all the "Bad" segments at one time.

Each cable system diagnostic testing technology is now described.

3.2 Time-Domain Reflectometry (TDR)

3.2.1 Test Scope

A time-domain reflectometer locates and characterizes changes in impedance in a cable system. These changes can be caused by:

- faults (shorts),
- joints (splices),
- open connections,
- taps in the circuit,
- deteriorated neutrals,
- water ingress into insulation material or joints, and
- bad (high resistance) connectors.

3.2.2 How It Works

A TDR works like radar. A fast rise time pulse is injected into the cable circuit at one end. As the pulse travels down the cable, any impedance discontinuities will cause some of the incident signal to be reflected back towards the source. The reflected pulse components will be positive or negative depending on whether the impedance is more or less than the cable's characteristic impedance. The initial pulse and the reflection are plotted against time on the instrument display, like an oscilloscope. Since the instrument can be calibrated to determine the speed of the pulse in the cable, the distance to the end of the circuit can be determined.

This information can also be used to locate discontinuities indicated by reflected pulses. In addition, the shapes of reflected pulses on the instrument display help the operator to determine the nature of the discontinuity.

The magnitude of the reflection at a discontinuity is calculated as the reflection coefficient or ρ. It is calculated as:

$$\rho = \frac{Z_d - Z_o}{Z_d + Z_o} \qquad \textbf{(2)}$$

Where

Z_o is the characteristic impedance of the cable and Z_d is the impedance of a discontinuity.

The value of ρ ranges from 1 (open circuit) to -1 (short circuit). A reflection coefficient of zero indicates there is no reflection, implying that cable circuit terminates at impedance equal to the characteristic impedance of the tested circuit.

3.2.3 How It Is Applied

Typically, this technique is performed offline. A fast rise time, low voltage pulse is applied between the conductor and the insulation shield of a cable circuit at an elbow or termination. As the pulse travels through the cable circuit, reflections are produced by discontinuities and changes in circuit impedance. The initial and reflected pulses are displayed against time on an oscilloscope type display and interpreted by the operator. Since the speed of travel of the pulse can be determined, the time can be converted to distance or location. An experienced operator can often determine the source (cause) of an impedance discontinuity by the shape of the reflected signal.

The test duration (including interpretation) is between five and ten minutes once the TDR and the cable circuit are connected.

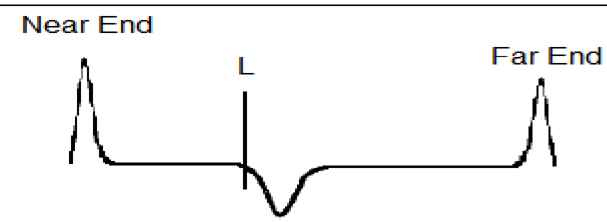
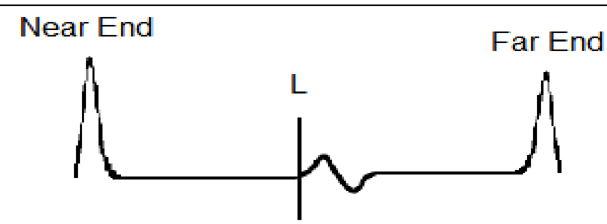
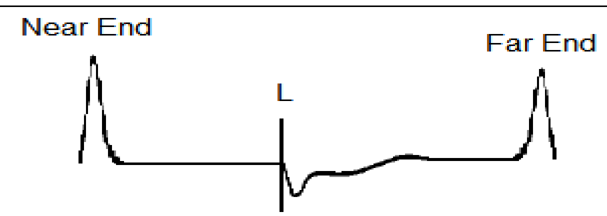
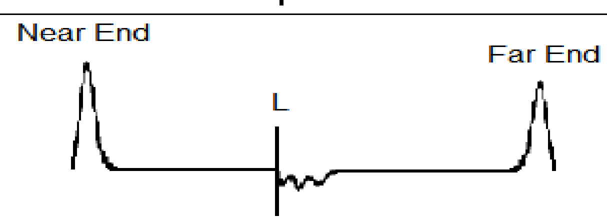
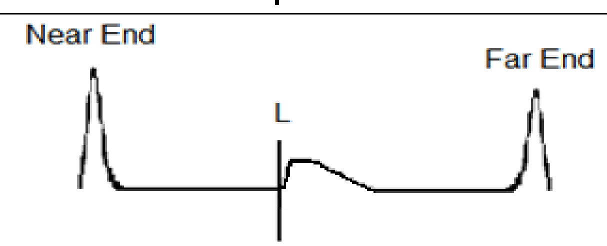
Table 10: Overall Advantages and Disadvantages of TDR Measurements

Advantages	• Testing is easy to employ. • Test equipment is small and inexpensive. • Test equipment uses low test voltage (less than U_0). • Periodic testing provides historical data that increases the value of future tests by observing changes over time (trends). Requires good data keeping. • Locates areas of the cable system with impedance related problems.
Open Issues	• The ability to perform the test online is unclear. • Proper interpretation of TDR data may require the history of cable circuit construction. • The test voltage of a low voltage TDR may not be high enough to detect some dielectric imperfections. • It is difficult to interpret some impedance discontinuities. • It is difficult to interpret results on tape-shielded cables. • Selecting the pulse width for optimal resolution and distance can be problematic. • Interpreting results on circuits with multiple taps is challenging.
Disadvantages	• Skilled operators are required for testing and post analysis. • Blind spots occur at the point where the pulse is injected. The length of cable within the blind spot depends on the applied pulse width. • Electrical noise may interfere with the low voltage TDR signal.

3.2.4 Success Criteria

Typical waveforms and their meaning appear in Table 11. The actual appearance of the waveforms varies and will not exactly match those shown in references. Therefore, there are no unified success criteria for TDR testing.

Table 11: Cable Conditions Distinguishable using TDR [64]

Case	TDR
Uniform cable segment with no joints.	
Uniform cable segment with no joints and shorted conductor at distance L from Near End.	
Cable segment with a joint at a distance L from Near End.	
Cable segment with a wet joint at a distance L from Near End.	
Uniform cable segment with water ingress at a distance L from Near End.	
Uniform cable segment with localized corroded neutrals at a distance L from Near End.	

3.2.5 Estimated Accuracy

The amount of TDR data needed to compare test results and actual findings is insufficient to calculate accuracies. In addition, most TDR results are not provided in pass/fail terms, but rather as general information concerning the tested cable circuit.

3.2.6 CDFI Perspective

TDR is a useful tool for diagnosing potential cable system problems. It is an easy, fast way to scan a cable segment and associated accessories (joints and terminations). TDR is especially valuable during field measurements where portability is essential and cable segments are often long. TDR was used here to obtain preliminary data on the cable segment to be tested, *i.e.* length and number of splices. It is also used as a diagnostic tool providing an initial condition assessment of the cable segment, *i.e.* neutral condition, possible water ingress, etc.

A TDR unit typically uses very low power. Because of the non-destructive nature and usefulness of the data provided, it is highly recommended that it be performed prior to any other diagnostic test. The TDR may even provide some information hybrid circuits. While the distances/locations would not be correct for some of the circuit, the number of joints would still be measurable. Unfortunately, branch circuits present an additional challenge that has yet to be overcome for the TDR.

As with any diagnostic tool, accurate data interpretation maximizes the value of the resulting data. TDR test results are used to:

- Examine the waveform/trace to understand the tested segment characteristics and identify anomalies,
- Compare the length of one phase of a cable circuit segment against a companion phase.

Examples of each of these appear in Sections 3.2.6.1 and 3.2.6.2.

3.2.6.1 Diagnosis via Waveform Analysis

Interpreting the signal to provide an accurate TDR condition assessment requires experience. TDR traces with similar condition assessments can look different from the examples shown here, even if the cable segment is the same type and length.

During one series of field tests, a failure occurred at a splice after testing a PILC feeder cable in an area that had experienced several failures. Upon examination, water was found in the splice. Evidence of the water appears in the TDR trace for that cable (Figure 11). The length of the cable segment tested and a rough estimate location of the water ingress given by the TDR correlated with both the actual length and the failure site location.

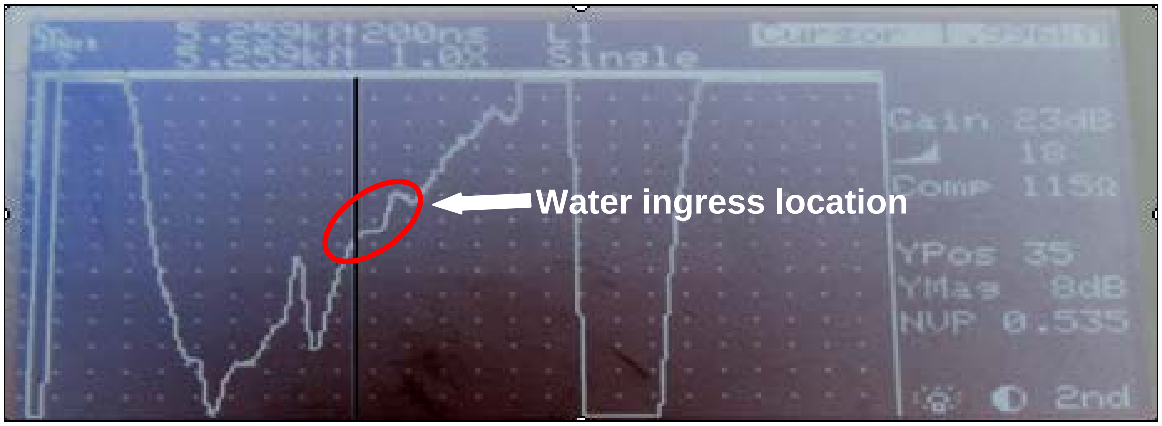


Figure 11: TDR Trace - Moisture in Splice

During another series of field tests performed on PILC cable systems, a significant change in the characteristic impedance of the cable insulation was detected at a specific location using a TDR test. Figure 12 shows a sharp negative peak on the TDR trace indicating the location of the change in insulation impedance. Examination of the circuit in that area found the manhole full of water with signs of oil leakage.

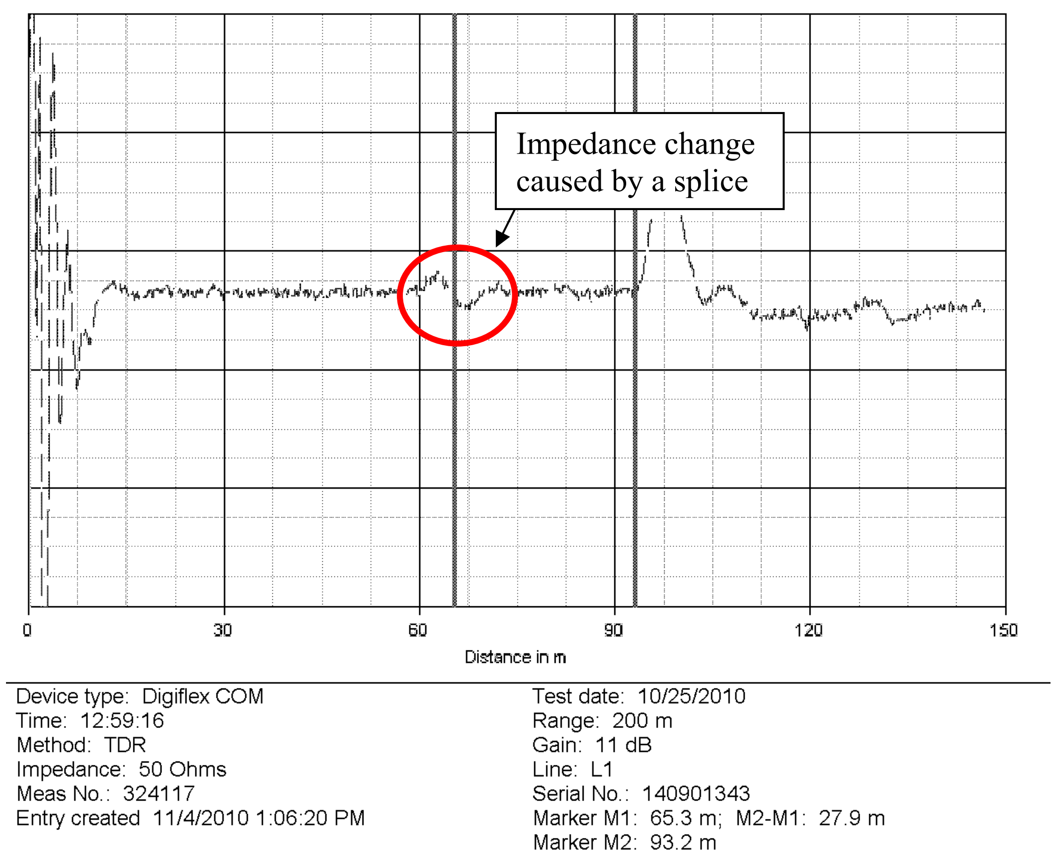


Figure 12: TDR Trace – Significant Change in Cable System Impedance

Anomalous reflections on adjacent phases of three-phase circuits suggest additional investigation. Figure 13 shows an example of how measurements made on an XLPE cable circuit are used to assess the overall characteristics of a tested cable segment. The solid circles indicate a splice location while the open circles indicate anomalous reflections.

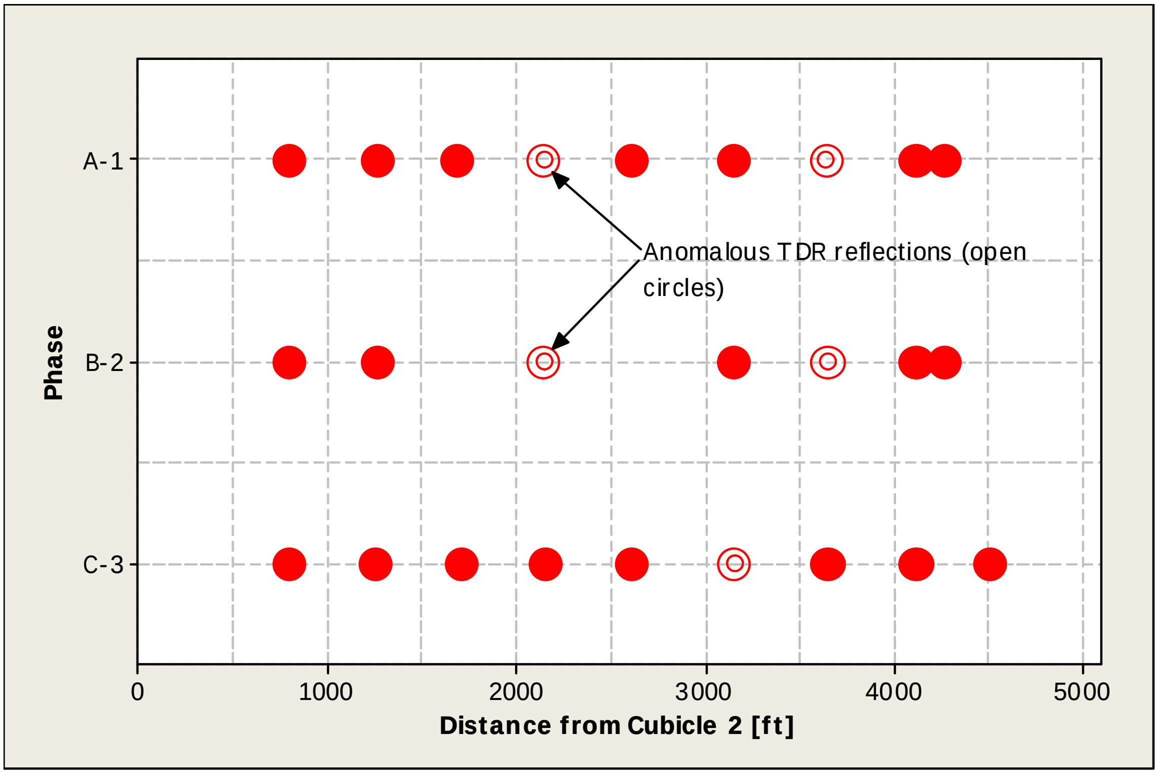


Figure 13: Example of Anomalous TDR Reflections on Adjacent Phases

3.2.6.2 Diagnosis via Length Comparison

Length comparisons are especially useful (and simple) on three-phase circuits since the length of the phases are nearly identical. Measurements made from both ends of the segment are effective for identifying single or multiple breaks in the neutral wires. For example, consider a three-phase cable circuit with a neutral wire metallic shield as shown in Figure 14.

Figure 14: Three-Phase Section under Test Using TDR

The TDR length results for all phases measured from Location 1 appear in Table 12. Note that Phases A and B measure nearly identical lengths at approximately 1,500 ft while Phase C measures only 690 ft.

Table 12: TDR Results from Location 1

Phase	Length [ft]
A	1,500
B	1,503
C	690

The TDR results clearly indicate a break/discontinuity in the Phase C metallic shield (neutral wires). A TDR measurement from Location 2 will determine if there are multiple breaks. Table 13 shows the results of these measurements.

Table 13: TDR Results from Location 2

Phase	Length [ft]
A	1,500
B	1,503
C	380

Comparing the Phase C measurements from Table 12 with Table 13 it is apparent that there are multiple (at least two) neutral wire breaks since the sum of the measured lengths is only 1,070 ft. Had the two lengths summed to approximately 1,500 ft then there is only a single break.

3.3 Partial Discharge (PD)

A large amount of research published over the past decade investigates the characterization of partial discharge sources in power cable systems. Nevertheless, the study of partial discharge in cables is empirical due to the complexity of the phenomenon [8] – [18]. However, PD is a powerful tool to evaluate the condition of a power cable system, especially at HV and for commissioning tests.

3.3.1 Test Scope

Partial Discharge detects localized 'void type' defects, primarily in the form of voids in cable or accessories. Voids in this context can be:

- Quasi-spherical (most often due to manufacturing process problems),
- Dendritic (often due to aging processes that lead to the development of electrical trees resulting from enhanced voltage stresses),
- Interfacial (due to the delamination of components, or a loose fit between the cable and an accessory),
- Irregular (mechanical damage either before or after installation).

PD is applicable to all cable types, although its usefulness may be limited when performed on discharge resistant cables (as defined in ICEA S-94-649 and S-97-682) or on oil impregnated paper insulated cables (PILC or MIND) that also have a significant resistance to partial discharge. These cables may have considerable PD when new. Mixed systems of discharge-free and discharge-resistant cable designs can be especially troublesome.

This method is attractive; as all discharge-free cable and many accessories are PD tested at the factory prior to shipping according to specified, controlled conditions. As such, they are PD free as defined in the appropriate ICEA and IEEE Standards. Therefore, any additional PD detected in service must be due to problems caused by installation or defects that develop over time. However, it is important to recognize that there are no industry recognized testing procedures or PD limits for PD tests conducted on complete cable systems installed in the field.

3.3.2 How it Works

A high voltage is applied to the cable system. If conditions are right at the void location, a partial discharge, i.e. a discharge across the void occurs. The PD equipment detects transient microvolt or microampere level signals generated at the discharge site that travel through the cable to the detection equipment. The exact shape and bandwidth of these pulses depends on the discharge source, frequency response of the cable system, and frequency response of the measurement equipment. Each of these elements alters the shape of the original PD pulse. The PD pulses themselves must then be separated from ambient noise signals. The available PD instruments are classified by bandwidth as they can have bandwidths of hundreds of kilohertz (narrow band and IEC 60270 standard) to up to 100 MHz (ultra-wide bandwidth (UWB)).

Although not precise, some practioners perform a calibration procedure at the detection end of the cable system to provide an approximate quantification of the PD pulse in terms of charge. The sensitivity of the measurement system, which includes the cable system under test, is checked via pulse injection at the far end of the cable system. This allows the operator to determine the minimum pulse charge that can reliably be detected by the measurement instrument given the cable system under test and ambient noise at the time of testing. This is usually termed a “sensitivity check”.

Figure 15 shows the commonly used equivalent circuit to describe PD measurements. The capacitances (C) are identified by the subscripts *a*, *b* and *c*. C_a represents the capacitance of an element of power cable that does not contain a defect. C_b and C_c represent an element of cable that contains a void defect, where C_c is the capacitance of the void and C_b represents the remnant cable element capacitance. S_g is the spark gap that represents the discharging defect/void.

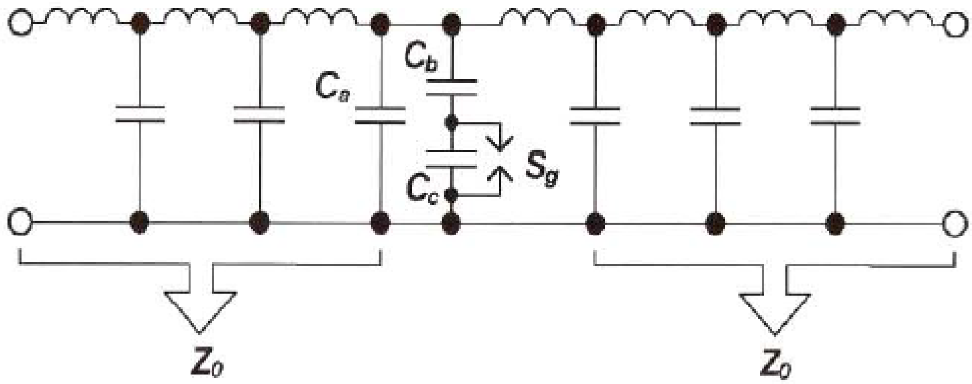


Figure 15: Equivalent Circuit for Power Cable PD [19]

Note that the capacitances *b* and *c*, and thus the charge generated in the measurement circuit, will depend upon the radial position of the void within the cable. This is because the capacitances depend upon the relative amount of insulation on either side of the defect. This is one of the reasons why PD signals are often termed “apparent charge” rather than “true charge.”

Although outside the scope of this project, a brief discussion on the physics of discharges in voids is included to help cable engineers better understand the complexity of this test. PD is a Townsend discharge in a small cavity (a gas ionization process where, initially, a small number of free electrons, accelerated by a sufficiently strong electric field, results in electrical conduction through a gas by avalanche multiplication). The stress at which the discharge initiates (V_{PD}) is described by Paschen's Law, where the critical parameter is the product of the void size [diameter *d*] and the internal pressure [*p*]; β and χ are constants related to the gas within the void.

$$V_{PD} = \frac{\beta \cdot p \cdot d}{\chi + \ln(p \cdot d)} \qquad \textbf{(3)}$$

The Paschen Equation identifies a number of fundamental issues that the cable system engineer using PD testing must understand, including:

- Discharges only occur in gaps – PD testing can only find voids, not contaminants unless they subsequently debond from the insulation, thus leaving a void.
- Voids need to satisfy three further conditions to discharge:
    - They must not be completely filled with a liquid.
    - If they are gas filled, then the gas must be at a low pressure or the discharge initiation stress may be above the test stress. See Figure 16.
    - They must be large enough; small voids require higher initiation stresses (Figure 16).

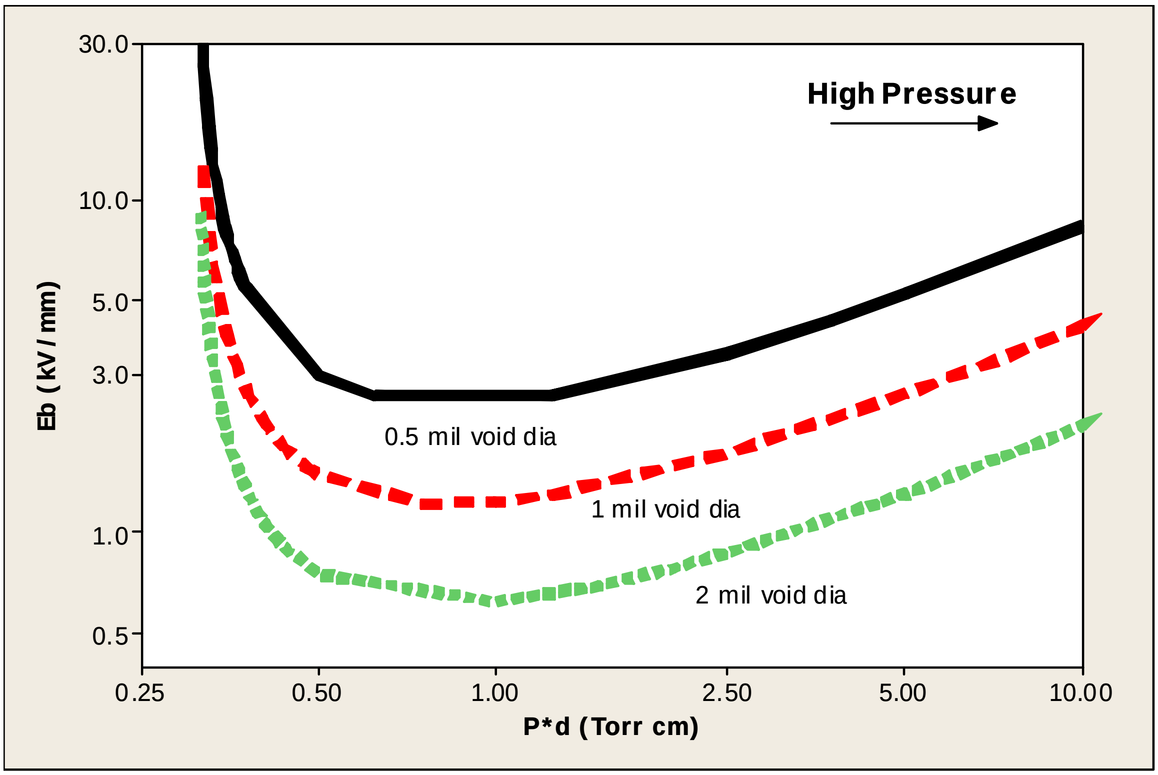


Figure 16: Theoretical Paschen Curves for Air-Filled Voids (Selected Void Sizes)

When measuring PD, three prerequisites must be satisfied:

- The voids must be in a state that allows them to discharge,
- The PD signal must reach the detector in a suitably unattenuated, undispersed state to be recognizable as PD signals with respect to the background noise, and
- The PD detection system is properly calibrated to optimally account for the length and type of cable under test.

Addressing the first point, PD is a stochastic (probabilistic) process. It may or may not be present at a void depending on all the parameters and conditions described above. Thus if no PD is detected, it can mean either that no voids are present or that a void is present but that that conditions are not right for it to discharge. This is significant for short measurement times and the risk of "false negative" results should be recognized.

A number of technical articles have described instances where PD pulses (at most a few nanoseconds wide) spread and reduce in magnitude as they propagate away from the PD source as a result of high frequency attenuation in the cable due to dispersion (frequency-dependence of the propagation velocity) [19]. The loss of high frequency energy from the PD pulse reduces its magnitude and distorts its shape. This can make it difficult to acquire the PD pulses and accurately identify the source and type of the PD. Figure 17 shows how the detection sensitivity for PD degrades as the length of the cable increases. Thus, the charge magnitude (measured in pico coulombs) measured by a PD detector for a 50 pC discharge located 5 km away from the detector would be identical in magnitude to a 10 pC discharge located only 1 km away. Note that PD diagnostic providers indicate that sensitivities lower than those shown here can be achieved on shorter cable lengths.

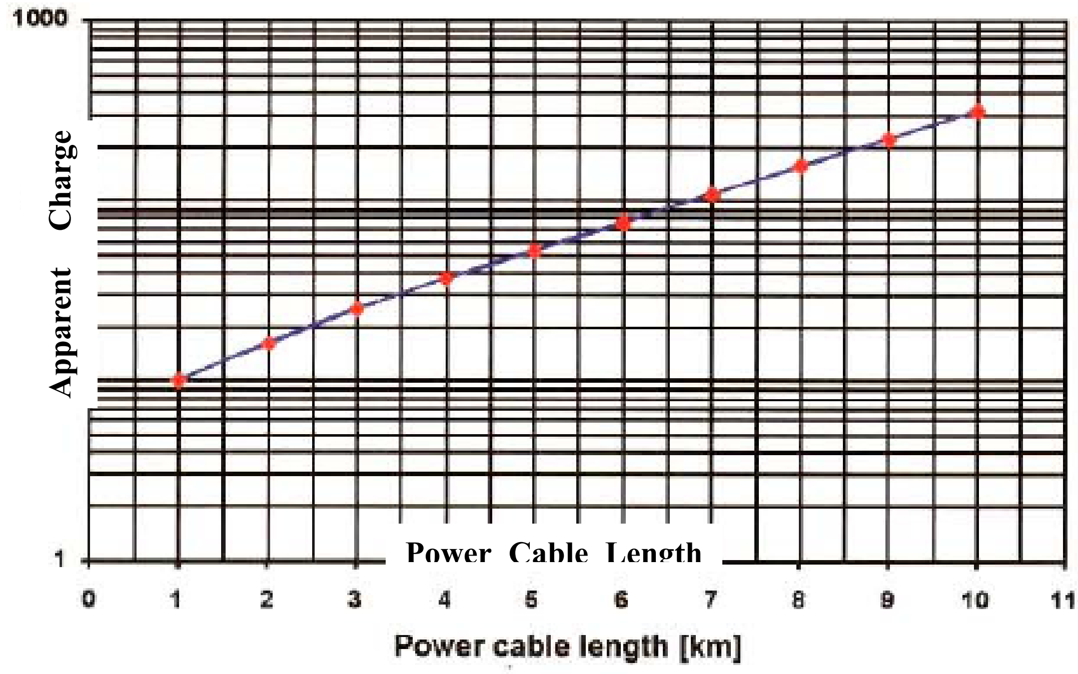


Figure 17: Relative PD Detection Sensitivity Reported by CIGRE [19]
(Relative to an apparent charge of 10 pC at 1 km)

3.3.3 How it is applied

PD testing can be performed online and offline [14]. Online techniques typically employ high frequency current transformers (CTs) or capacitively coupled voltage sensors to detect transient signals from discharges. Offline techniques most often employ voltage dividers at the voltage source or opposite end of the circuit.

Offline voltage sources can be:

- 30 – 300 Hz AC: Equipment typically consists of an excitation transformer connected in series or parallel with a variable inductance reactor. The equipment is heavy and requires a truck or van.
- 0.01 – 1 Hz (nominal) AC Offline Very Low Frequency (VLF): Equipment is relatively light and portable. Waveform used is sinusoidal.
- Damped AC (DAC): Equipment is relatively light and portable. The applied voltage is a damped sine wave with a frequency range of 30-100 Hz, though frequency varies with cable length and can, in some cases, be tuned with an external element (capacitor). This source is used only as a combined diagnostic (see Section 3.12 for details).

Most offline techniques apply 1.5 to 2.5 U_0, where U_0 is the operating phase-to-ground RMS voltage of the circuit.

PD results may be reported in terms of:

- Apparent charge magnitude at a given test voltage level,
- Extinction voltage (voltage at which the discharge extinguishes as the voltage is lowered),
- Inception voltage (voltage magnitude at which discharge initiates as the voltage is increased),
- Number of pulses per unit time,
- Frequency content of the PD pulses,
- Phase relationship of the PD pulses to the applied voltage, or
- Other customized indicators (see Section 3.3.6.2).

PD measurements are influenced by the type and location of the defect or defects, operating and testing voltage magnitude, circuit operating conditions, type of insulation material (EPR, XLPE, PILC, etc.), ambient noise, and many other factors discussed earlier. Therefore, accurate interpretation of the PD data requires sound knowledge of temporal (time dependency) PD behavior. Although simplistic PD measurements (discharge magnitude in pC and PD inception voltage) are commonly employed in the diagnostic assessment, the true impact of partial discharge on cable system performance is difficult to predict. For example, studies performed in the CDFI show that a low PD inception voltage or a high pC value does not necessarily indicate that a cable system will soon fail. Some PD diagnostic providers claim to have developed proprietary means for interpreting PD measurements to predict cable system performance.

From the CDFI perspective, the connection between a measured discharge and its impact on the cable system requires many laboratory and field tests to create a database of PD characteristics that indicate “bad” PD and “tolerable” PD. This form of PD testing could enable utility engineers to create their own criteria for evaluating the condition of a cable system. To date, the CDFI has not gathered a database large enough to establish a correlation between a given PD measurement and cable system performance. However, analyses on a number of PD field test results containing PD based recommendations (*Act* or *Not Act*) are used to establish preliminary accuracy assessments for online and offline PD diagnostic techniques.

The stochastic nature of PD measurements can create considerable variability in the measurements over time and between identical cable systems operating under similar conditions.

Any of the above can lead to potential errors in PD data interpretation; thus, the risk PD poses to the cable system should be understood. Nevertheless, as more data are collected and analyzed, engineers will gain knowledge and experience to help them improve the interpretation of PD data. The best way to accomplish this is by conducting periodic PD tests as part of a power cable testing and replacement program. If data from such tests are analyzed carefully, periodic PD measurements can, over time, be correlated with cable system performance.

The application of high voltages for a long period (cycles or time) may cause some level of further degradation of an aged cable system. See a more detailed discussion in Section 2.0. Consider this potential degradation when performing any diagnostic test requiring the application of voltage above the operating voltage. The precise degree of degradation will depend on the voltage level, frequency, and time of application. Thus, when undertaking elevated voltage PD measurements (or any other elevated voltage test), a utility should consider that a failure might occur and the resources needed to make repairs may be needed. The section on expected outcomes in the CDFI Perspective provides insight on the likelihood of failure on test.

The advantages and disadvantages of different approaches to PD testing appear in Table 14 and Table 15 as a function of voltage source used to perform the test. Table 16 shows the overall advantages, disadvantages, and open issues for PD testing.

Table 14: Advantages and Disadvantages of Online PD Measurements as a Function of Voltage Source		
Source Type	**Advantages**	**Disadvantages**
60 Hz AC Voltage Supplied by Utility System (De-energizing not needed)	• No non-system energization equipment is required. • Testing waveshape and frequency is the same as the factory test voltage. • The cable circuit is not de-energized as part of the test. • It is relatively easy to monitor over an extended period (10 to 60 minutes or longer) so that PD sites are more likely to discharge and be detectable. • Test is performed while the cable system is at normal operating temperature.	• Cannot detect PD that would occur at voltages above normal operating voltage. • Sensitivity assessment typically not possible. • Requires a skilled technician to acquire the data and a skilled engineer to interpret the results. • Results are not available for several days to weeks. • Sensors must be applied at every cable accessory (either sequentially or simultaneously) and at each end of the tested cable circuit segment. • In some approaches, PD sites in cable are not specifically located. They are only identified as occurring between two sensors or at a sensor on an accessory. • In some approaches, results are reported as levels - the specific meaning of each level is difficult to interpret. • Cannot be combined with other diagnostic tests.
60 Hz AC Supplied by Utility System (De-energized during setup)	• No non-system energization equipment is required. • Testing waveshape and frequency is the same as the factory test voltage. • It is relatively easy to monitor PD over an extended period (10 to 60 minutes or longer) so that PD sites are more likely to discharge and be detectable. • Calibration and sensitivity assessment may enhance measurement accuracy and quality.	• Cable circuit must be de-energized before PD testing to perform calibration and sensitivity assessment. • Cannot detect PD that would occur at voltages above normal operating voltage. • Requires a skilled technician to acquire the data and a skilled engineer to interpret the results. • Results are not available for several days to weeks. • Cannot be combined with other diagnostic tests.

Table 15: Advantages and Disadvantages of Offline PD Measurements as a Function of Voltage Source

Source Type	Advantages	Disadvantages
Power Frequency AC	• Testing waveshape and frequency is close to the operating voltage and factory test voltage. • Calibration and Sensitivity assessment can establish the lowest detectable partial discharge level. • Voltages above U_0 can be applied, allowing for the detection of PD that is typically not present at U_0. • PD inception and extinction voltages may be measured.	• Equipment is large, heavy, and expensive. • Application of elevated voltage (> U_0) may cause further degradation. • Cable circuit must be de-energized for testing. • Requires a skilled technician to acquire the data and a skilled engineer to interpret the results. • Short (less than a minute) data acquisition time may not capture some PD. • Results are reported in levels or voltages - the specific meaning of each level is difficult to interpret.
0.01 – 1 Hz AC Very Low Frequency (VLF) Sinusoidal External Voltage (Offline)	• Equipment is easy to handle. • Voltages above U_0 can be applied, allowing for the detection of PD that is typically not present at U_0. • PD inception and extinction voltages may be measured. • Skilled technician can interpret the results.	• Application of elevated voltage (> U_0) may cause further degradation. • Cable circuit must be de-energized for testing. • Short data acquisition time (few cycles) may not allow PD to occur. • Does not replicate operating voltage waveshape or frequency. • PD behavior is not well understood at these frequencies.
Damped AC (DAC) (30 Hz to 1 kHz)	• Equipment is small and easy to handle. • Measurements may be made at frequencies that are near the operating voltage frequency. • Can measure PD extinction voltage (PDEV)	• Cable circuit must be de-energized for testing. • Only the first voltage cycle is controlled. • Does not replicate operating voltage waveshape or frequency. • Requires skilled technician to acquire data and skilled engineer to interpret. • Application of elevated voltage (> U_0) may cause further degradation. • Comparisons between circuits are difficult because the applied voltage frequency varies as a function of the circuit impedance characteristics. • PD behavior is not well understood at these frequencies. • Few cycles during which to detect PD.

Table 16: Overall Advantages and Disadvantages of PD Measurement Techniques	
Advantages	• Identifies single or multiple localized void-type defects. • Applicable for all cable types. • If PD test interpretation indicates that cable circuit is PD-free then there is a high probability that the circuit will not fail within the next several years. See Section 3.3.6. • Offline techniques allow for the detection of PD at voltages above U_0. • Can detect electrical trees, interface tracking, voids. • Basic results available at end of test. • Test can be stopped if "unacceptable PD" is observed.
Open Issues	• It is unknown whether cycles or time at elevated voltage is the critical parameter in determining the risk of damage to the cable system. • PD results on cable systems are not directly comparable to the factory test results on the individual components. • Different providers perform calibration and sensitivity assessment differently, so results from different PD providers/equipment are difficult to compare. • Interpretation of PD signals is not straightforward (i.e. the test results can be provided as "Good/Bad", "Acceptable/Unacceptable", "Pass/Not Pass", "Defer/Repair/Replace", "1/2/3/4/5", etc.). • Locating and characterizing PD sources can be difficult due to attenuation and dispersion, especially on long cable lengths. • One large PD source could mask other potentially dangerous PD sites. • Not clear which PD features provide information on the severity (i.e. whether or not the defect will lead to failure). • Results for hybrid circuits can be difficult to interpret. • Very long cable circuits may require testing in segments. • Neutral corrosion (wire or tape) can confuse the results. • Results may be affected by cable system temperature. • Results from different PD technologies/providers cannot be readily compared because Pass/Not Pass criteria are often proprietary. • Voltage exposure (impact of voltage and time on cable system) caused by elevated 60 Hz AC, DAC, and VLF has not been established.
Disadvantages	• Cannot detect all possible cable system defects – only those that discharge. • Does not directly detect water trees. • Does not assess global degradation (high density of defects such as water trees or contaminants distributed over a significant portion of the segment length). • No uniform Pass / Not Pass criteria established for field testing. • Only a small percentage of PD sites detected actually fail in service.

3.3.4 Success Criteria

As mentioned above, PD results may be reported in a number of ways. However, many providers of partial discharge diagnostic test services prefer not to supply detailed partial discharge data. They suggest that interpretation of the test results requires an analysis of charges, voltages, pulse shapes, pulse frequencies, etc, that is best performed by the provider. Instead, they process the data to classify the tested cable circuit. In principle, there are two main classes: Pass – no action required and Not Pass – some type of action required. The Not Pass class is often subdivided into finer classes such as monitor or repair when convenient. Providing the results in the form of classes or rankings provides the customer with a straightforward interpretation of a very complex measurement. However, note that:

- The classification rules are typically proprietary and cannot be compared between PD providers.
- The classification rules often evolve with time.
- The original data may not be readily available for re-analyses or comparison with subsequent test data.

With limited guidance regarding acceptable versus unacceptable PD results, some have suggested using factory test standards as a basis for providing PD results. The basic logic is that if a cable system can meet the current factory test standards for individual new components then it is most likely in good condition. Unfortunately, this only provides guidance for cable systems that are “good” – it says nothing about those cable systems that do not meet the current factory standards. Are the circuits that do not meet these standards really “bad” or are they just “not new”?

There is an additional complication as the factory test standards have changed over time. As a result, an aged cable system could be expected to meet a more stringent test standard than was in effect was the cable system was manufactured. Figure 18 gives the evolution of the maximum permitted Factory Test PD levels defined in AEIC cable specifications [21] for discharge-free extruded cable only. This figure is helpful in that it shows the level of PD that a cable could possibly have as a function of year of manufacture. To use this information effectively, the year of manufacture of the cable must be known. An example can best illustrate this point. The presence today of 20 pC of discharge at 2 U_0 in a discharge-free cable manufactured in 1975 does not imply that discharge is developing in a worsening void defect or that an electrical tree is growing. That may have simply been the condition of the cable in 1975. However, 20 pC of discharge at 2 U_0 would be of concern for cables installed in the last 20 years. To help deal with these issues, it is useful to have the basic test data provided in addition to classification information to identify trends over time.

The only success criteria for accessory component PD tests in US standards are in IEEE Std. 48™ for cable terminations, IEEE Std. 386™ for separable connectors (elbows/bushings), and IEEE Std. 404™ for cable joints.

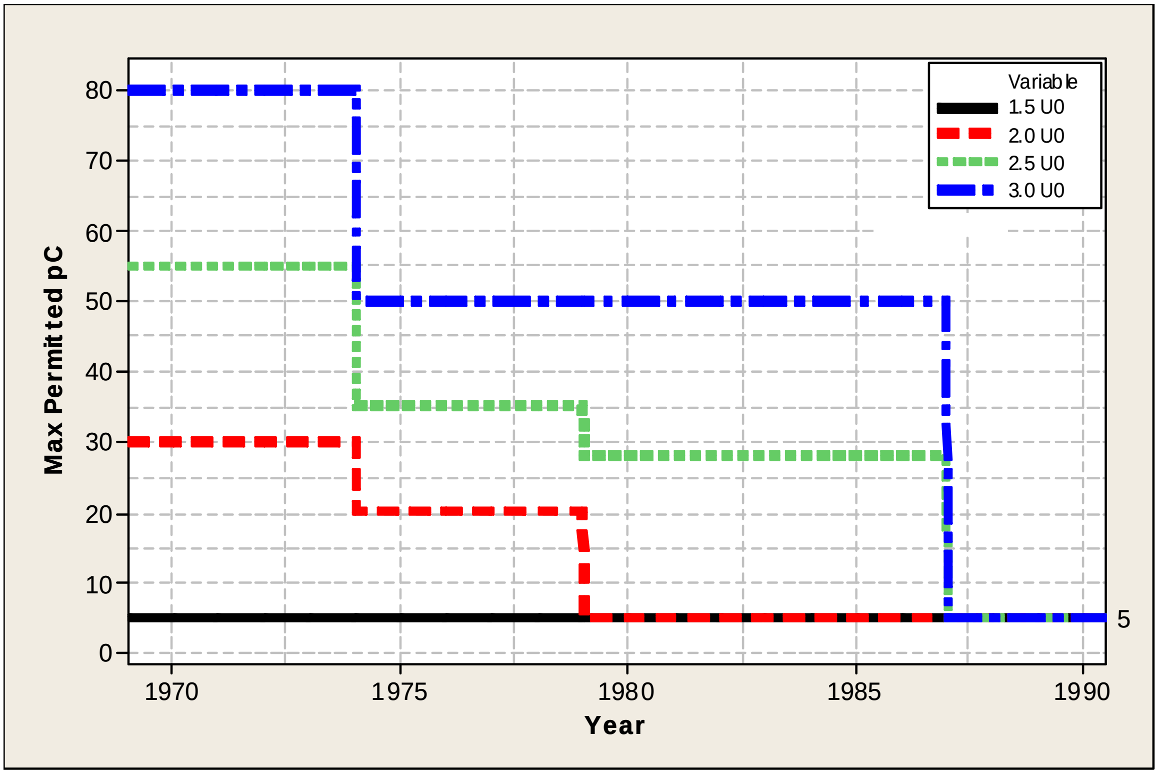


Figure 18: Maximum Permitted Factory Test PD Levels for Discharge-Free Extruded Cable Only (Accessories Excluded) [21]

General success criteria guidelines for partial discharge measurements on both cable and accessories that could be located appear in Table 17. The values listed in the table for offline PD come from the USA Standards. The only values found for offline PD are from IPEC High Voltage in Great Britain. The values that appear in the table are for 11 kV circuits in the UK.

Note that the PD criteria in these cable and accessory standards and specifications are:

- For design and production tests of new, individual components,
- Used as one of a suite of electrical and non electrical tests,
- Do not address in-service PD tests.

In some cases, partial discharge is allowed, depending on the specific standard/specification, the year of the specification, the type of product, and the test voltage. Partial discharge service providers in the USA do not make their criteria publically available; however, if used carefully, the values in Figure 18 and Table 16 can be guides for establishing acceptable field service criteria.

Table 17: Pass and Not Pass Indications for Partial Discharge Measurements
(The validity of these criteria have not been substantiated in the CDFI)

Cable System	Test Type	Pass Indication	Not Pass Indication
HMWPE WTRXLPE XLPE EPR[1]	PD Offline 60 Hz and 0.1Hz	Cable[2]: <5pC at 4 U_0	Unknown
		Accessories[3]: 3-5 pC at 1.25-1.5 U_0	
	PD Online	Cable[4]: No PD at U_0 (< 250 pC)	Cable[4]: >500 pC at U_0
		Accessories[4]: <500 pC at U_0	Accessories[4]: >2500 pC at U_0
	DAC	Unknown	Unknown
PILC	PD Offline 60 Hz and 0.1Hz	Unknown	Unknown
	PD Online	Cable[4]: PD < 3000 pC at U_0	Cable[4]: PD > 10k pC at U_0
		Accessories[4]: <5000 pC at U_0	Accessories[4]: >15k pC at U_0
	DAC	Unknown	Unknown

[1] Discharge-free designs only
[2] From ICEA Standards S-94-649 and S-97-682 (See standards for details)
[3] From IEEE Std. 48™, 386™, and 404™ (See standards for details)
[4] PD levels from IPEC High Voltage Ltd. [22]. (Data based on European cable circuits)

3.3.5 Estimated Accuracy

To estimate the accuracy for the various implementations of PD technologies it is necessary to define common criteria applicable to all technologies. The adopted definitions are:

- Pass – Cable System is defined by the PD Providers as either free of partial discharge activity or any measured PD is considered benign. The means by which the providers make this determination is typically proprietary.
- Not Pass – Cable System is defined by the PD Providers as containing partial discharge activity that requires utility action or presents a quantifiable risk to reliability. The means by which the providers make this determination (including the level of risk) is typically proprietary.

The resulting accuracies for PD technologies based on results from multiple data sets from tests performed in the field appear in Table 18. For information on the detailed calculations associated with accuracy tables, see Section 3.1. The analyzed datasets include data using Online (U_0) and Offline (1 – 2.5 U_0), using VLF and 60 Hz excitation voltages. At this time, no Damped AC (DAC) data have been provided to CDFI.

Figure 19 shows all of the available PD accuracy data in a graphical form. Of all the PD datasets analyzed thus far, the Pass accuracy is generally much higher than the Not Pass accuracy. Note that these accuracies use time horizons of 1 to 11 years depending on when the tests took place. This table combines PD Offline techniques with PD Online techniques, as data are too limited for each of these techniques to develop separate tables. Future work may allow us to separate these techniques.

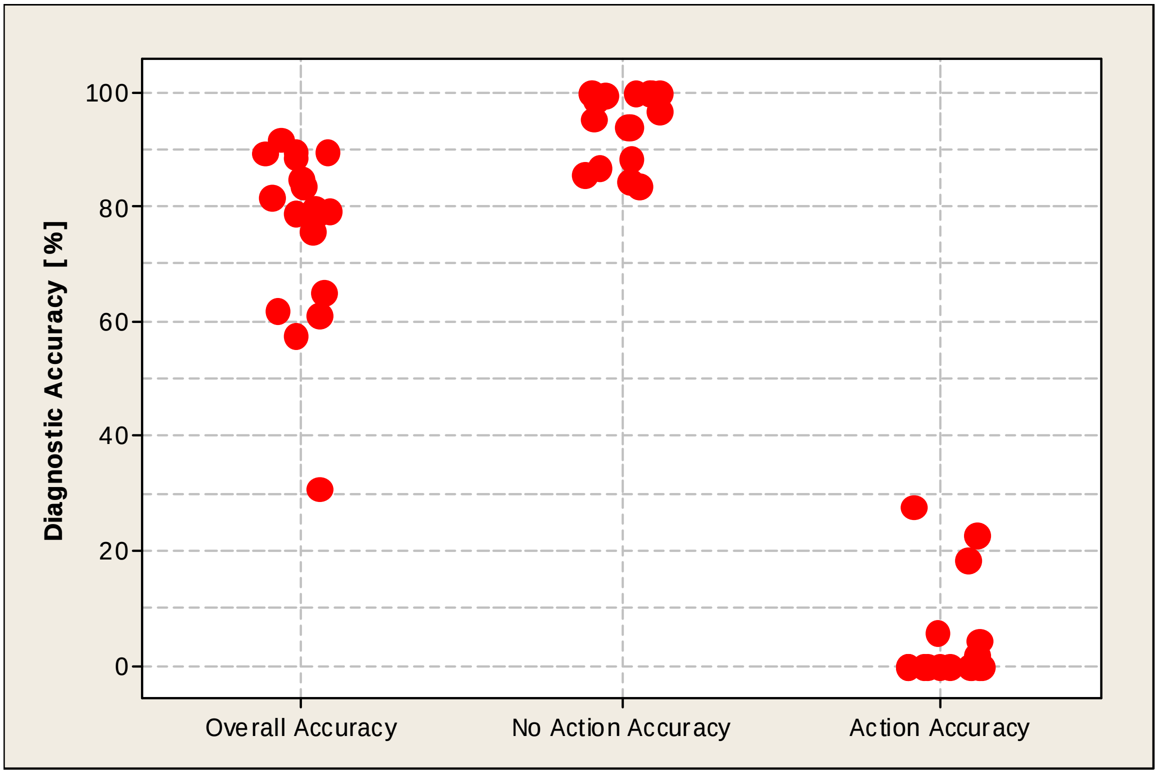


Figure 19: Estimated PD Accuracies for each Available Data Set.

The high Pass accuracy (94 % to 98 %) implies that those segments diagnosed as Pass have a very high probability of not failing for several years. If one assumes a Pass accuracy of 95%, then one segment in 20 will fail and 19 will not fail within the time horizon. On the other hand, the low Not Pass accuracy indicates that segments diagnosed as Not Pass also have a high probability of not failing for several years. Alternatively, on average, fewer than 1 in 20 Not Pass segments actually go on to fail within several years of testing.

Combining the condition-specific accuracies and weighting them according to the relative population sizes yields the Overall accuracy. This accuracy represents a weighted average that is, as expected, lower than the Pass group accuracy yet much higher than the Not Pass accuracy simply because the Pass group tends to be a much larger population. As a result, the Pass group accuracy is more influential in the Overall accuracy calculation.

Table 18: Summary of Accuracies for Partial Discharge Techniques *(See Section 3.1 for discussion on raw versus weighted accuracies)*			
Accuracy Type	**Partial Discharge**		
		Raw	**Weighted**
Overall Accuracy (%)	Upper Quartile	89.2	85.0
	Median	79.8	79.5
	Lower Quartile	64.5	79.0
	Number of Data Sets	18	18
	Length (miles)	669	669
Pass Accuracy (%)	Upper Quartile	100	99.1
	Median	98.1	94.0
	Lower Quartile	88.1	88.4
	Number of Data Sets	18	18
	Length (miles)	669	669
Not Pass Accuracy (%)	Upper Quartile	4.9	23.0
	Median	0.1	6.0
	Lower Quartile	0.1	0.1
	Number of Data Sets	18	18
	Length (miles)	669	669
Time Span (years)		1998 – 2009	
Cable Systems		Extruded Feeder, Extruded URD, Hybrid Feeder	

3.3.6 CDFI Perspective

A number of partial discharge data sets have been analyzed in the CDFI project. Although this topic required considerable effort, the extent of the analysis is less compared to that performed on other diagnostic techniques. The reasons are:

- PD measurement and analysis techniques are often proprietary technologies. Thus, detailed information that could extend and strengthen the analyses is often unavailable.
- The custom of reporting classification data rather than detailed partial discharge data does not lend itself to independent collation and analysis or interpretation.

The lack of detailed analysis does not indicate deficiencies of the technique, but merely the natural consequence of what can be done with the available data. Due to the issues above, the information in this section provides the user with an increased awareness of the issues rather than a detailed explanation of how to analyze the data.

3.3.6.1 Different Approaches to Measurement

The underlying principles of PD measurements (detection of low level voltage or current signals due to discharges in voids that are active at the time of measurement) are common to all approaches to PD detection. However, there are many ways to detect and quantify these discharge signals. This large number of approaches makes comparisons between test results from different PD diagnostic technologies so difficult that utilities are cautioned against making comparisons.

There are two basic approaches to PD detection:

Online
This approach uses PD signals captured under operating conditions of voltage and temperature. There are at least four different methods of online technology; each of which takes a different approach to quantification and interpretation of the test results.

The ability to test without disconnecting the system is often cited as an advantage. However, no less effort is required as some form of sensor needs to be attached at multiple locations of the cable system. This may be much easier for conduit systems than for direct buried systems. This entails risks, including safety risks for line crews.

In one form of this approach, the technique cannot pinpoint discharge locations between sensors. Discharges that are active only above operating voltage go undetected. The inability to locate discharges distant from the sensor may not be a serious handicap as many utilities replace cable sections or accessories rather than repair a specific location. In these cases, the ability to locate PD within a few feet is insignificant.

Providers' different approaches make it very difficult to compare quantitative measurements. Most of the online data reported within the CDFI has come from one service provider/technology, which provides the results in the form of numerical ranking.

Offline
This approach uses PD signals captured at voltages above operating voltages. When adopting this method, there might be some risk to the cable system from elevated voltage, but the risk to personnel and the customer are minimal. The ability to conduct a sensitivity assessment (i.e. assessment of the measurement system's ability to detect low magnitude signals), locate discharges, and probe for defects that discharge only above operating voltages are seen as advantageous. When making these measurements, defects that are prevalent at operating temperatures may be missed. The stochastic nature of PD can mean that the defects are not active during the short times typically employed for the measurements.

The approaches to interpretation of offline PD are complex and fluid. However, all approaches typically employ calibration procedures that should maximize the measurement sensitivity. Unfortunately, sensitivity assessments in the field are complex and conducted in many different ways. Practical comparisons of the quantitative measurements made by the different approaches are difficult to make.

Most of the data reported within the CDFI has come from two excitation technologies: 60 Hz AC and 0.1 Hz VLF AC.

3.3.6.2 Reporting and Interpretation

All signals received by a PD detector originate from a PD site. Thus, it is widely acknowledged that signal interpretation and classification are major challenges in field testing. When performing PD tests on cables in the factory, the exact cable characteristics are known, ambient electrical noise is minimized with the use of shielded rooms, and the test is performed only on cable with special laboratory type terminations. Interpretation of the PD data is relatively straightforward in this case. When performing PD tests in the field, ambient electrical noise should be separated carefully from actual PD signals. This is challenging because the cable system acts as an antenna for all types of electrical noise. Interpreting the PD signal is also a challenge because the circuit under test is often a hybrid mix of cable types and cable accessories that are of different vintages with different amounts of aging. Thus, PD measurements in the field are generally more difficult to interpret than factory-made measurements.

The basic goals of PD interpretation are to:

- Distinguish true PD signals from background noise,
- Establish that the PD signals are located within the devices being tested,
- Confirm that the PD poses a risk to the cable system.

Partial discharge data are reported in a variety of forms. They may be a simple report of one PD parameter such as PD magnitude as a function of applied voltage, or may include an analysis of multiple parameters that are embedded in PD signals such phase, density, inception voltage, etc. Some practitioners believe that a detailed analysis provides little benefit to the customer. They benefit most by indicating that PD is present, often by quoting a discharge magnitude (pC) and/or an inception voltage and an approximate location. Others consider that the traditional PD metrics are insufficient indicators and have developed customized and, thus, proprietary indicators. Both approaches are effective: however, they each have advantages and disadvantages.

Traditional Indicators (PD magnitude and inception voltage)

The advantages of this approach are:

- This type of data is commonly understood and available from providers.
- Once the measurement equipment is appropriately calibrated and the sensitivity has been confirmed, PD discharge magnitudes are comparable between technologies.
- Performance criteria based on these indicators can be uniformly established and updated as new performance information becomes available.

The disadvantages of this approach are:

- These parameters on their own are generally insufficient to classify accurately the severity of the discharge. In fact, highly detailed analyses within the CDFI show this is the case (Figure 33 and Figure 34).
- Traditional parameters do not provide the user with actionable information.
- Without an indication of severity, it is impossible to know if the presence of PD is a problem.
- PD magnitude is highly dependent on calibration and service providers have not standardized calibration procedures.

Customized Indicators (recommended actions or level codes)

The advantages of this approach are:

- They have the potential to consider more information in their classification of discharges than magnitude and inception voltage alone.
- The more detailed analysis of the PD has the potential to highlight the impact of the discharge on performance.
- The recommended actions or level codes derived from the detailed analysis provide a user with actionable information.

The disadvantages of this approach are:

- It is difficult to verify that the more detailed classification is accurate as the algorithms and personnel knowledge used to make the classifications are proprietary.
- When classes are updated, it is difficult to establish the relationship between the old and new classes. This is particularly challenging when the number of classification levels changes.
- Level indicators are essentially ranks (e.g. “1, 2, or 3,” “a, b, or c,” or “replace, repair, or OK”) and, thus, do not convey the relative differences between levels. In other words, we can say (a) is more severe than (b) but not by how much.

3.3.6.3 Expected Outcomes

Several PD data sets were collected and analyzed from both lab and field PD tests. The distribution of the data between lab and field data appears in Table 19. Figure 20 shows the individual lengths of cable systems tested using PD measurement techniques.

Table 19: PD Measurement Lengths

Technique	Laboratory [Conductor miles]	Field [Conductor miles]
PD Offline	2	490
PD Online	-	262

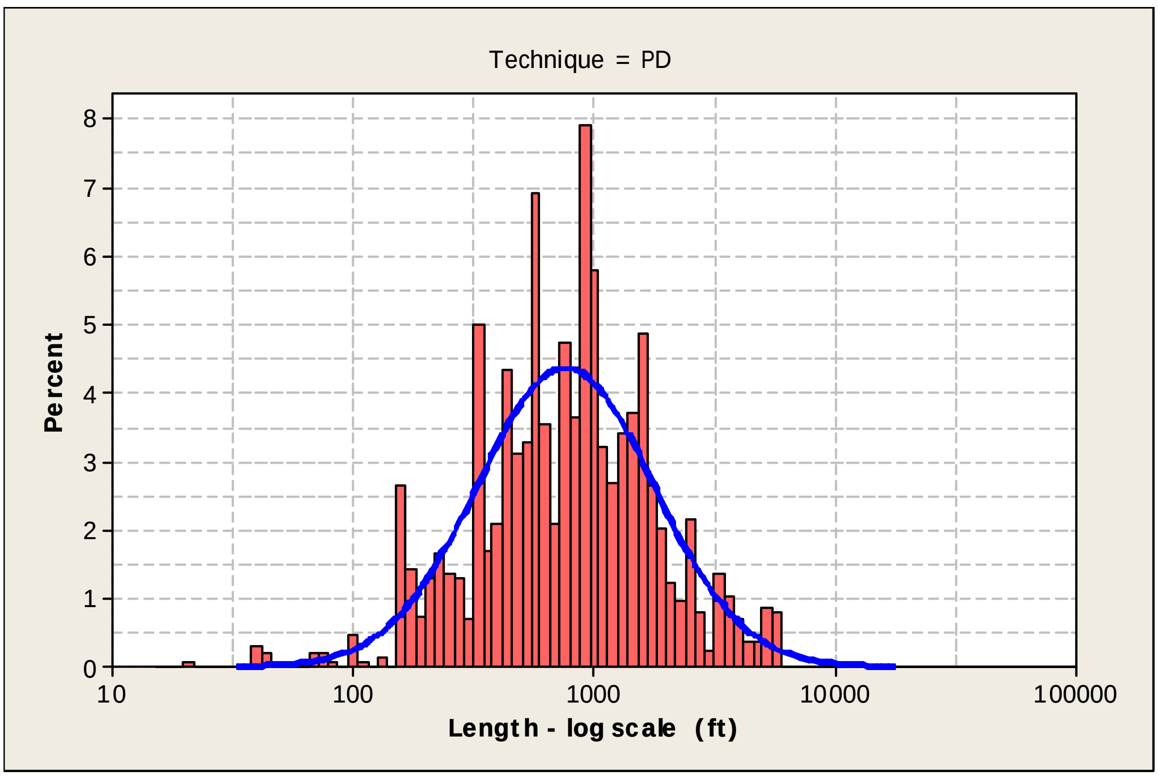


Figure 20: Tested Cable System Lengths – PD

Analyzing the reported data is useful in two ways:

- To estimate potential scenarios that would result from the use of different PD measurement techniques.
- To establish trends to identify test results that are uncharacteristically high or low

Analyses were compiled for field data from the two main PD approaches:

- Online – one of four techniques were analyzed
- Offline – two of four techniques were analyzed

The use of customized indicators in some of the offline and online measurement techniques makes it difficult to compare results. However, they can be used to analyze general outcomes / scenarios.

Offline

Figure 21 shows how all of the Offline PD data analyzed in the CDFI are distributed as a whole amongst the custom indicators. For example, 62.2 % of the total population of circuits tested were classified as “Defer” by the diagnostic provider. The data are from one Offline PD technique. The diagnostic provider has verified that the custom indicators have evolved over time, but the extremes appear to be consistent (“Replace” and “Defer”). The “Repair” category consolidates a number of generational steps (indicators).

Figure 22 shows how the individual data sets are distributed amongst the custom indicators (used in Figure 21): each solid symbol represents a single dataset. For example, for the “Replace” indicators one data set had 25 % its tested circuits classified as “Replace” while another data set had only 2.5 % of circuits classified as “Replace”.

Figure 23 shows how all of the detected PD site data analyzed in the CDFI were distributed as a whole amongst the cable system components. For example, overall approximately 39 % of all PD sites were found in the cable portions of the tested circuits.

Figure 24 shows how detected PD sites from the individual data sets were distributed amongst the cable system components: each solid symbol represents a single dataset. For example, 5 – 44 % of all PD sites identified within a particular dataset were located in splices.

Figure 25 relates the occurrence of PD sites to the length of cable system tested: based on the mean and median, respectively, we would expect 19 and 8 PD sites per 10,000 ft of system tested.

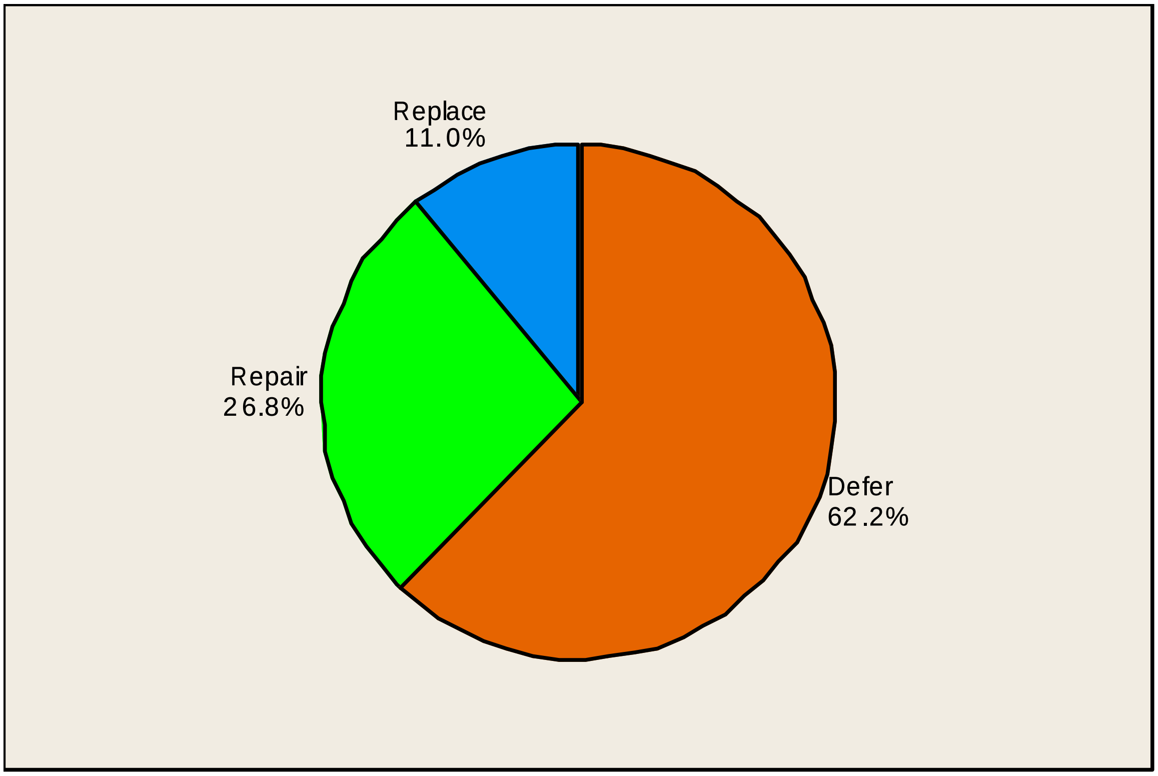


Figure 21: Split between Action Classes – Offline

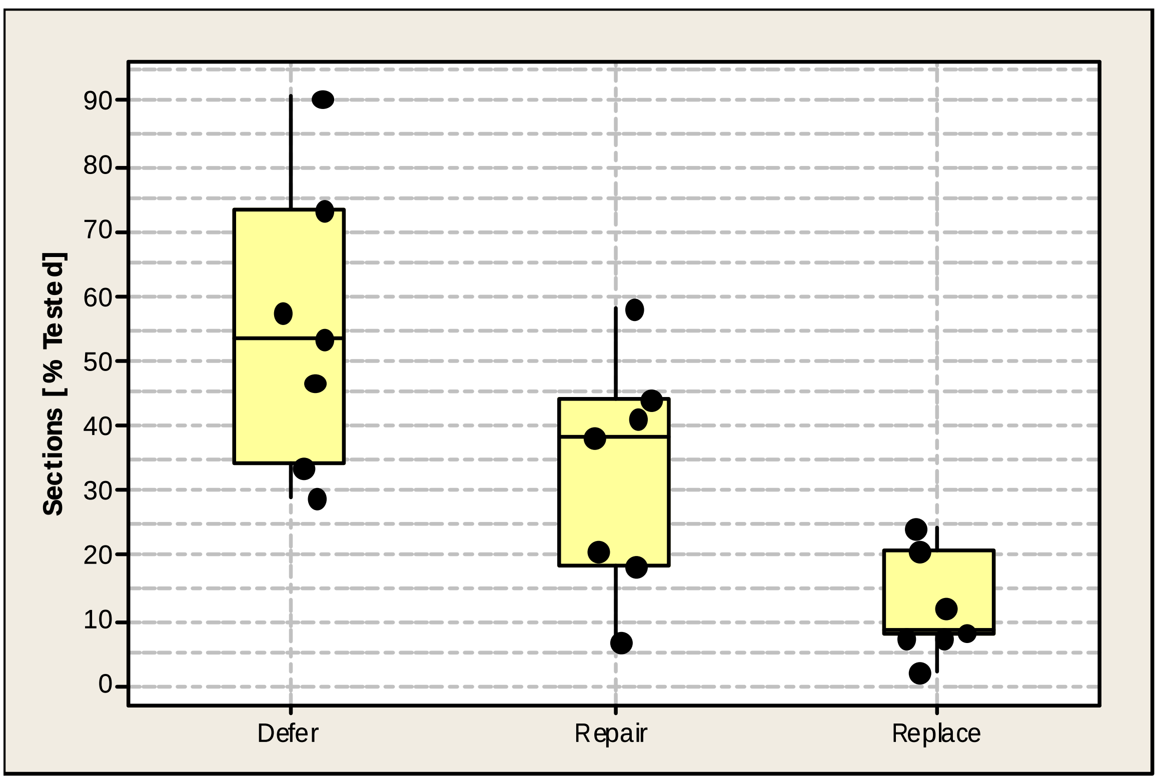


Figure 22: Range within Classes - Offline

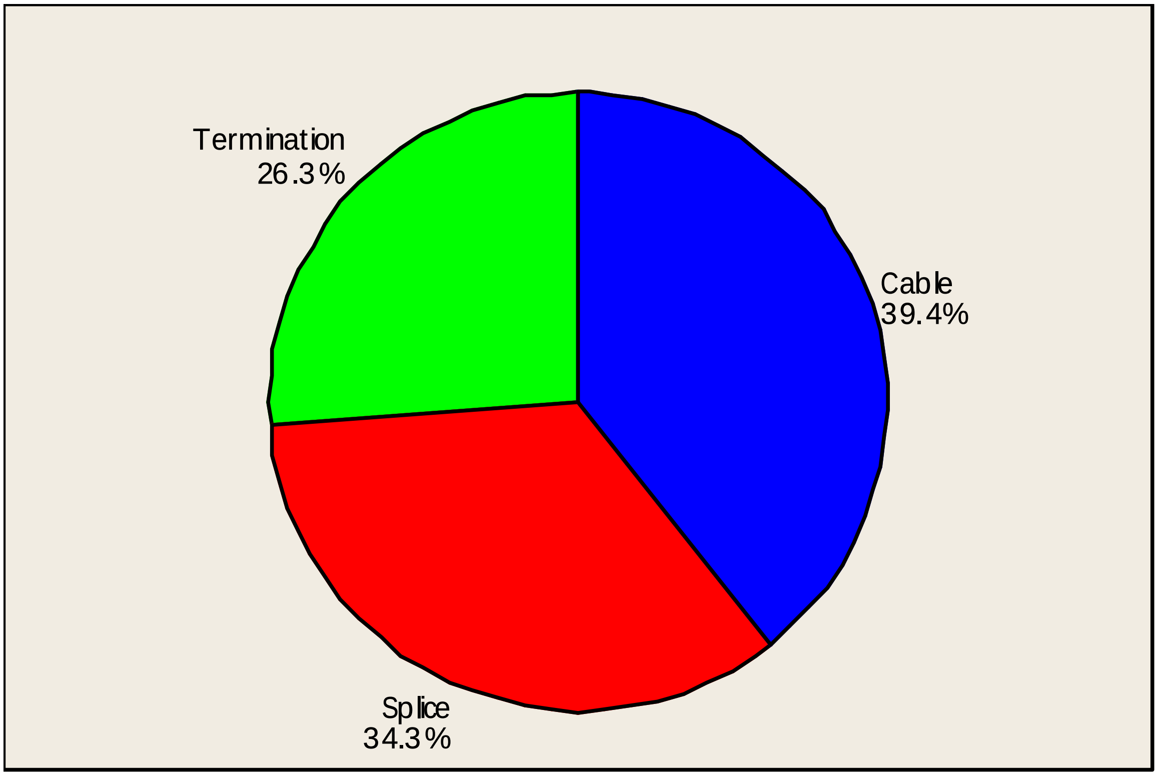


Figure 23: Split between PD Sources – Offline

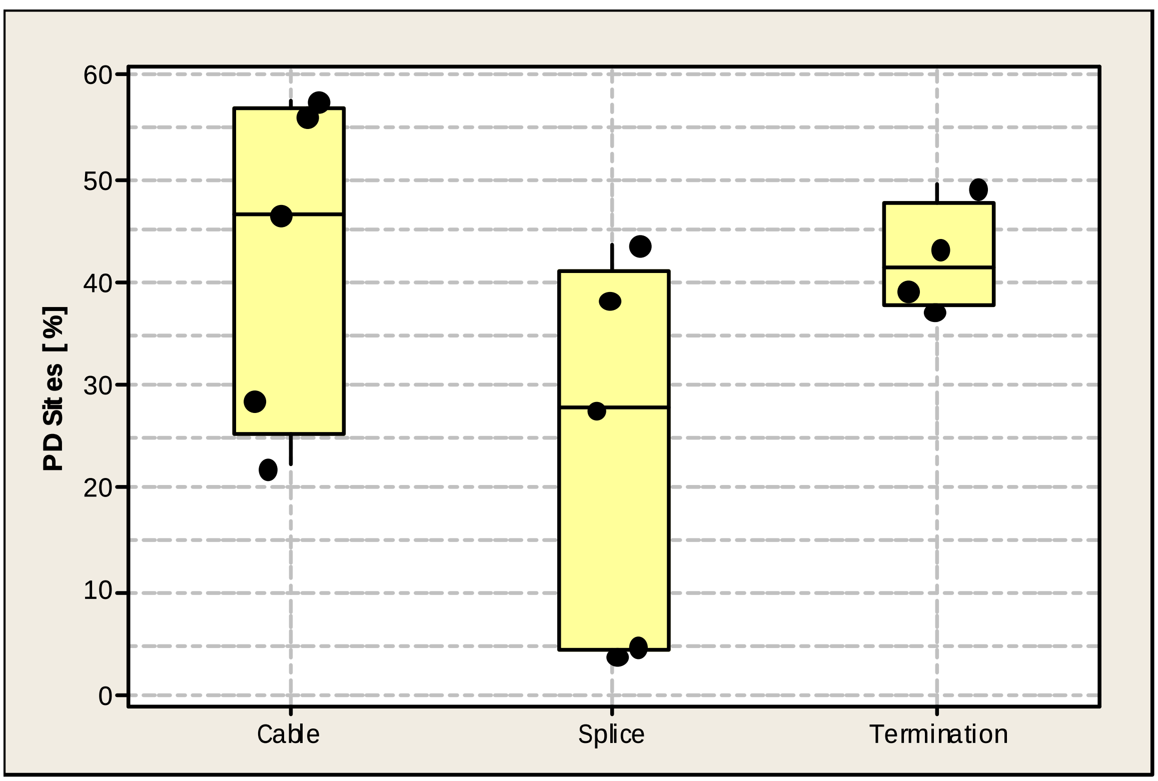


Figure 24: Range within PD Sources – Offline

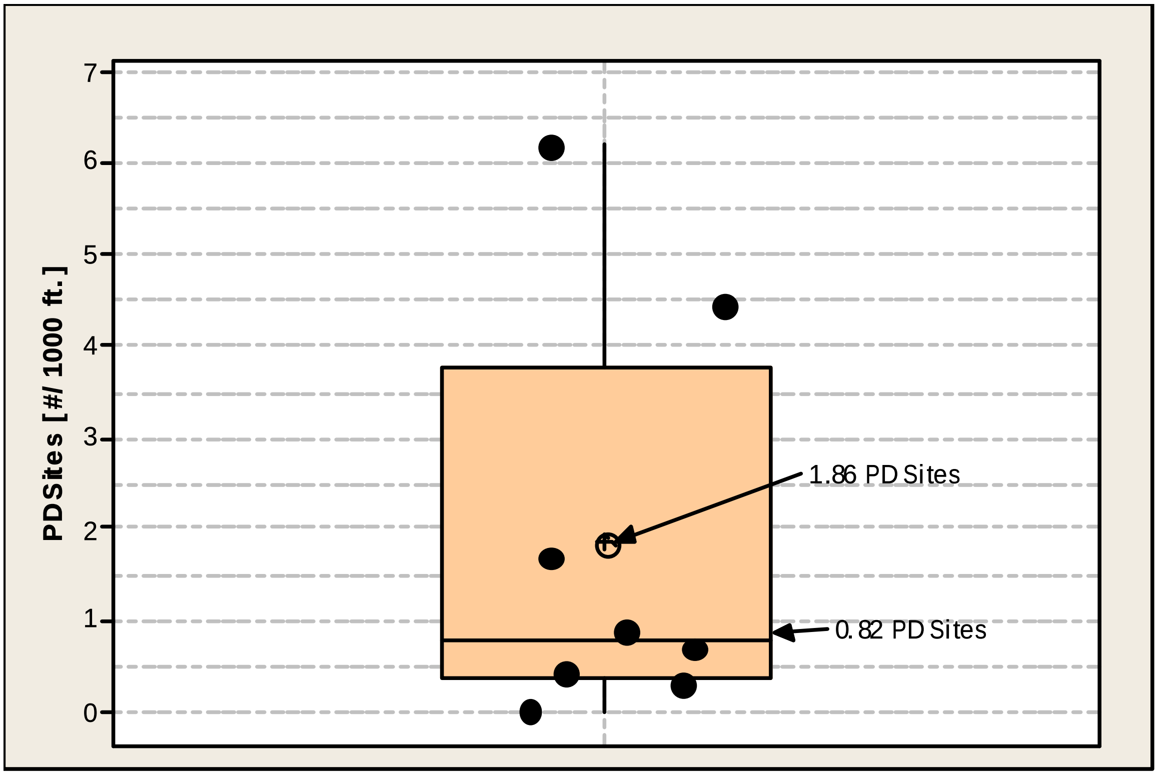


Figure 25: Range of PD Occurrence per 1,000 ft - Offline

Online

Figure 26 shows how all of the Online PD data analyzed in the CDFI are distributed as a whole amongst the custom indicators. The data are from a single method of the Online PD technique. The diagnostic provider has reported that the custom indicators have not evolved over time. For example, 62.2 % of accessories and 68 % of cable sections tested are classified as Level 2 by the diagnostic provider.

Figure 27 shows the individual data sets are distributed amongst the custom indicators (used in Figure 26): each solid symbol represents the dispersion for a single dataset. For example, the individual datasets indicate that 45 – 90 % of tested accessories were classified as Level 2.

Figure 28 shows how all of the Level 4 and Level 5 (indicating presence of PD) data analyzed in the CDFI were distributed as a whole amongst the cable system components. This technology embodiment does not permit the separation of joints and terminations, thus the data only pertain to accessories.

Figure 29 shows how the Level 4 and Level 5 data from the individual data sets were distributed amongst the cable system components: each solid symbol represents the dispersion for a single dataset. For example, 0 – 80 % of tested cable sections within a particular dataset were classified as Level 4 or Level 5 by the diagnostic provider.

Figure 30 relates the occurrence of Level 4 and Level 5 to the length of cable system tested, these data are segregated for cables and accessories as well as the grouped approach for all: based on the median we would expect 1 PD site per 4,000 ft of system tested.

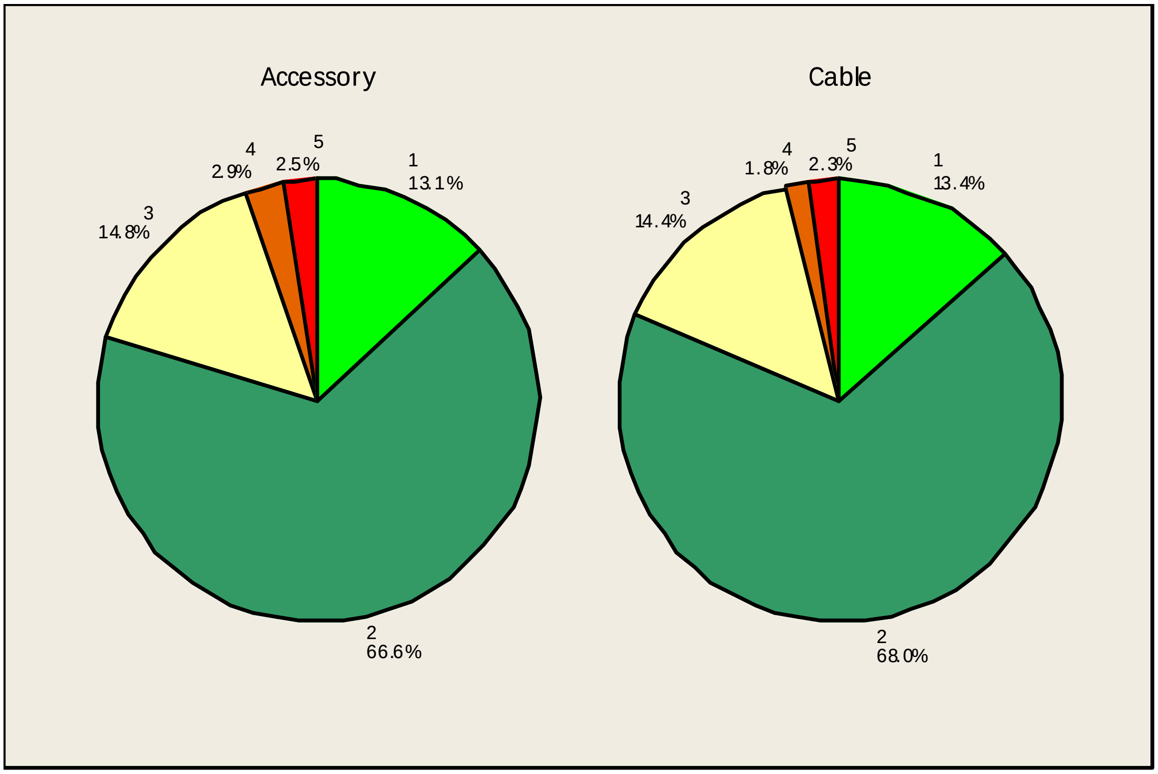


Figure 26: Split between Assessment Classes – Online

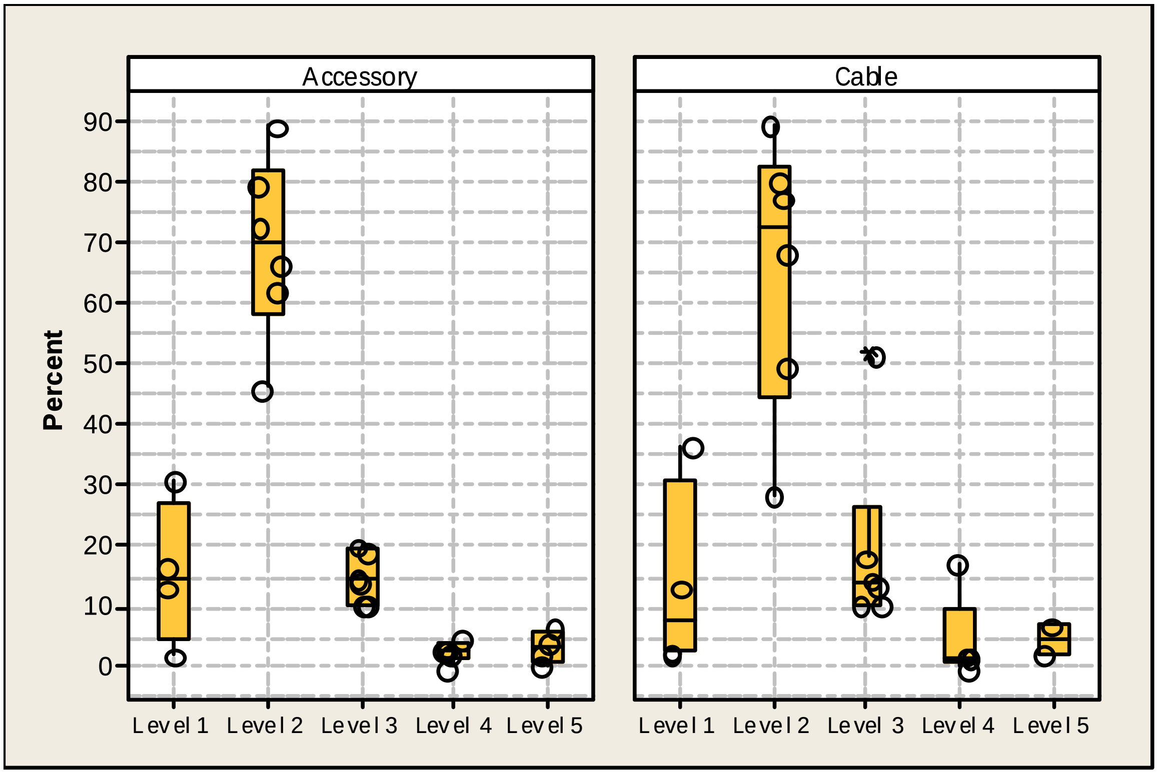


Figure 27: Range within Classes - Online

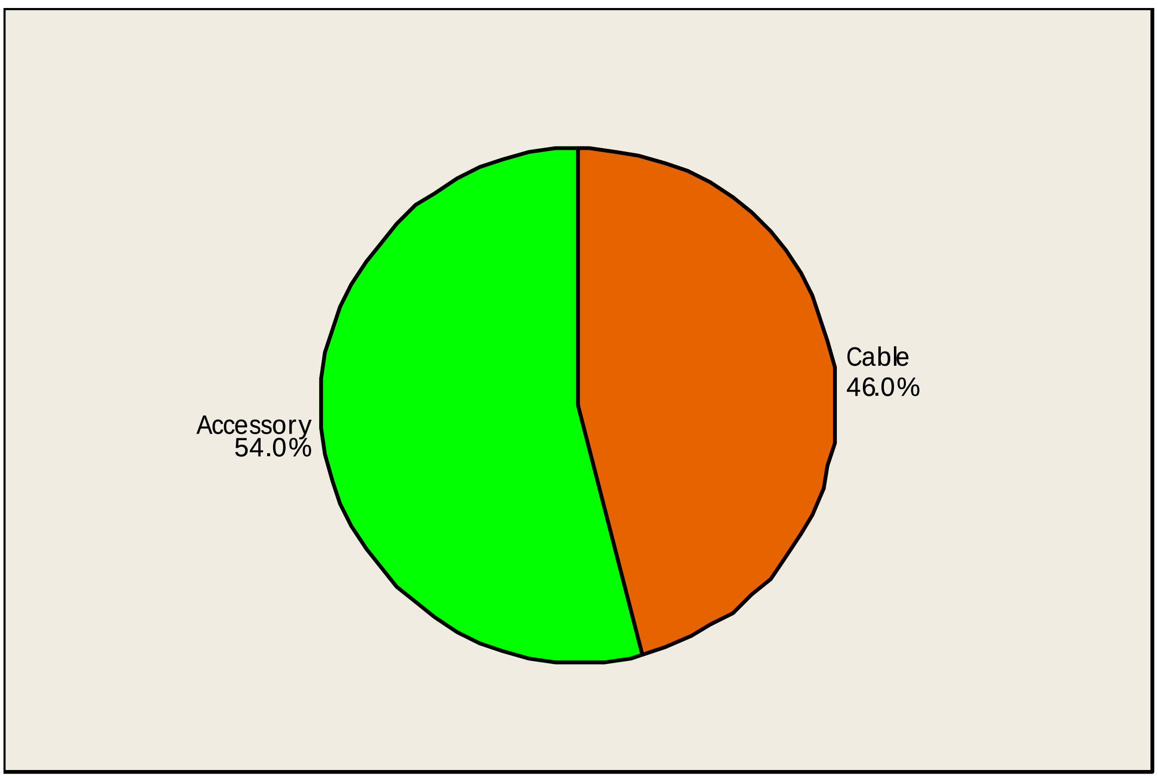


Figure 28: Split between PD Sources – Online

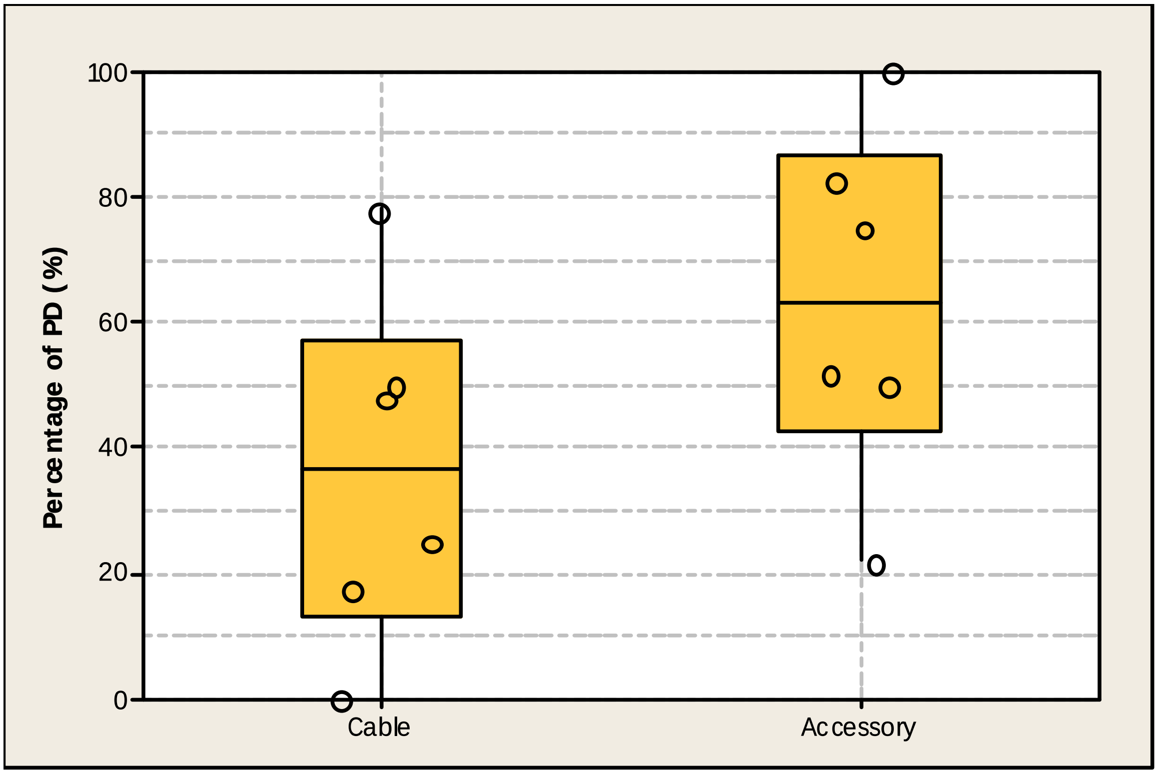


Figure 29: Range of within PD Sources – Online

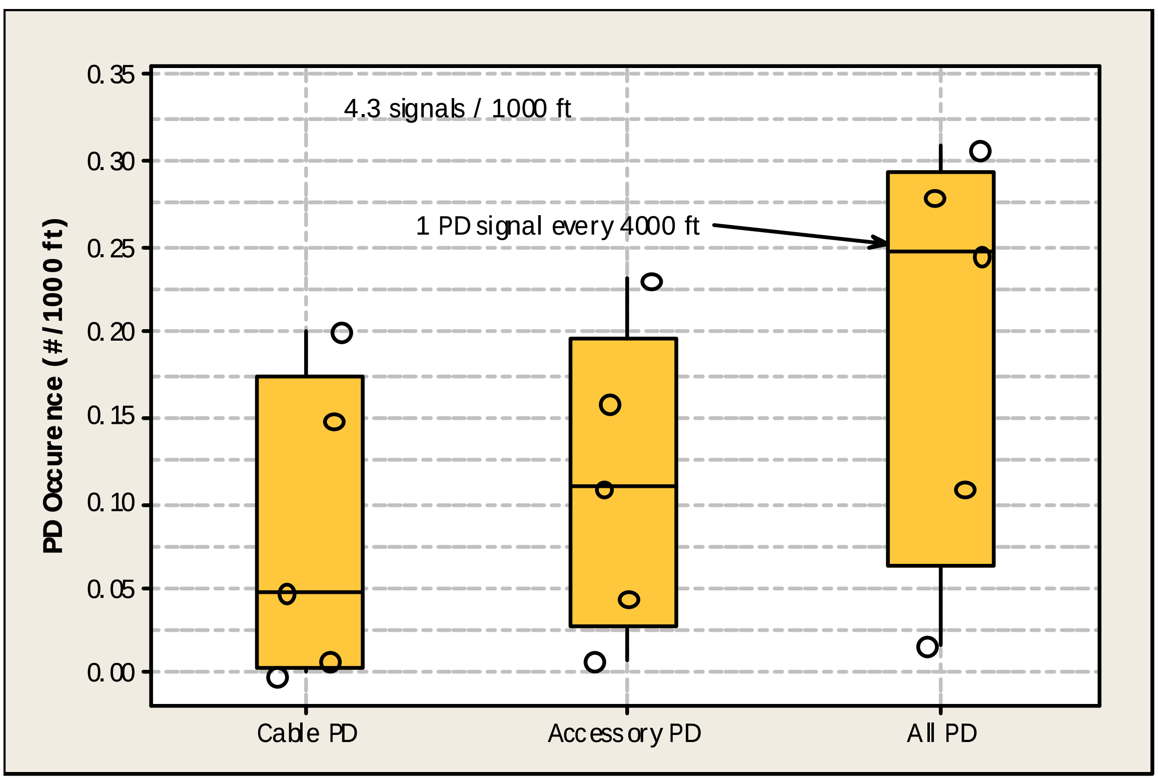


Figure 30: Range of PD Occurrence per 1,000 ft – Online

When pilot studies were undertaken (with the diagnosed cable systems left in service) and the service performance after test has been followed, it is then possible to determine Diagnostic Performance Curves. These curves show how failures have accumulated within circuits in the same classification group. Figure 31 shows Diagnostic Performance Curves for one of the Online PD technologies. This approach uses the provider's custom classifications for discharges (1 to 5, Levels 4 and 5 refer to "discharge" signals while it is not clear what Levels 1, 2, and 3 represent). The collated service failures recorded after the test enable a probability of failure (shown as Percent on the y-axis) for Levels 3, 4 and 5 to be estimated since the segments were left untreated. Interpreting these curves is achieved by estimating the probability of service failure for selected times. As an example, segments classified as Level 5 have a failure probability of 40 % within one year after the test and greater than 99 % within 2.5 years after the test.

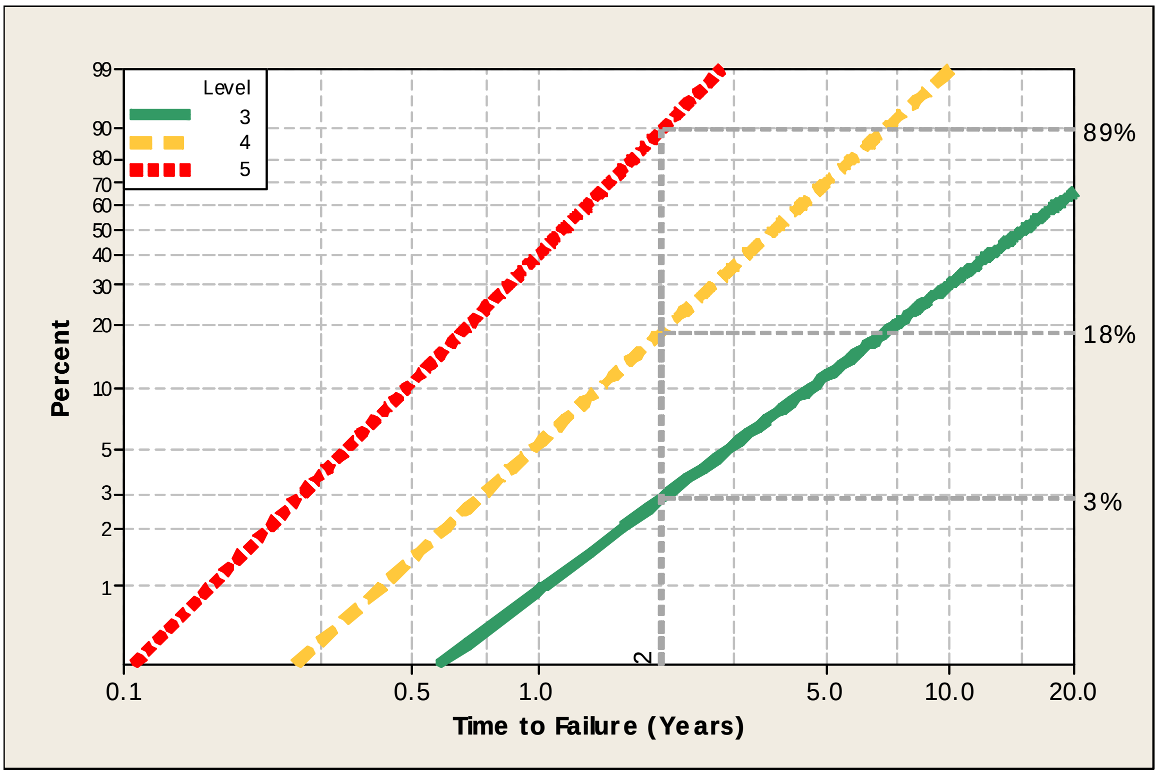


Figure 31: Diagnostic Performance Curves for One Online PD Test Technique

Figure 32 shows the Diagnostic Performance Curves for PD sites detected using one Offline PD technique. The curves originate from failure data supplied by a participating utility. Note that these curves are for individual PD sites located in cables and splices.

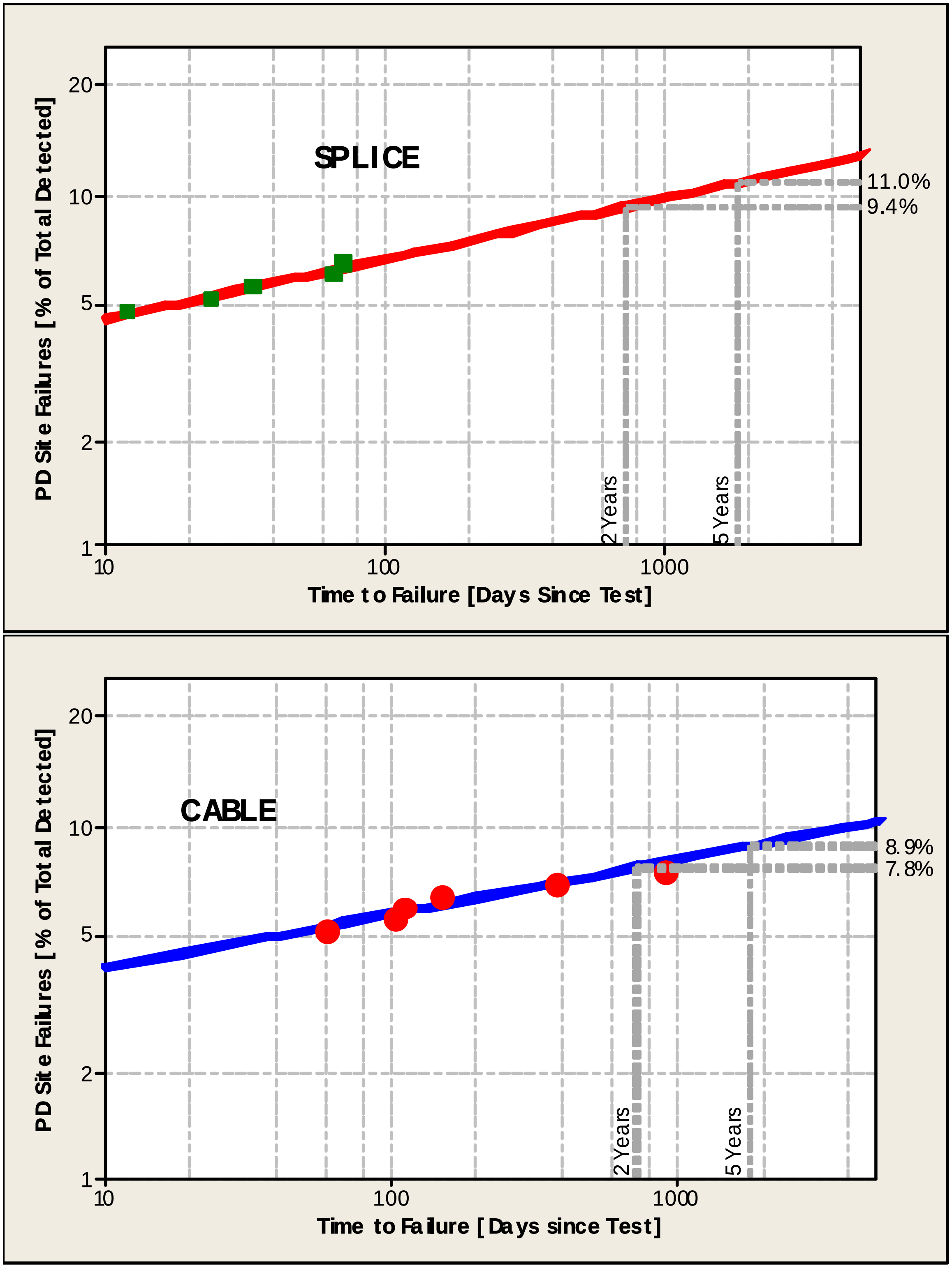


Figure 32: Diagnostic Performance Curves from a Cable System in Service for One Offline PD Test Technique, Segregated for Cable (bottom) and Splices (top)

The Diagnostic Performance Curves of the type shown in Figure 31 and Figure 32 are very useful as they help utilities interpret diagnostic test results by showing what type of results to expect. A number of these benefits appear below:

As noted previously, one of the aspects of custom indicators is that the level codes are ranks that do not convey the relative differences between levels. Performance Curves enable level interpretation or renaming as shown in Table 20. Levels are based on the probability of failure for circuits classified at each level shown in Figure 15 within two years after the test. The alternate codes show that the separations between Level 3 and Level 4 are different as compared to the difference between Level 4 and Level 5. The available data in Figure 31 do not include information on Level 1 or Level 2. Thus, these levels only indicate a lower probability of failure than Level 3.

Table 20: Interpretation or Alternate Codes for Custom Level Assessments from Figure 31

PD Level Code	Alternate Code
Level 1	<< 3
Level 2	< 3
Level 3	3
Level 4	18
Level 5	90

The Diagnostic Performance Curves also enable utilities to estimate the potential number of failures with time and, thus, make an informed economic evaluation of potential actions to take based on the test results. Table 21 shows a computation for a 14 mile MV cable system segregated into 100 segments (the dispersion of PD sites is shown in Figure 23 and the occurrence of PD is shown in Figure 25). The estimates show that approximately 12 % of the defects will have failed within 5 years. It is important to recognize that all defects need to be treated, repaired, or replaced to improve reliability because it is not known which ones will fail first.

Table 21: Example Scenario Evaluation for an Offline PD Program

PD Location	Sites [#]	Predicted Failures	
		After 2 Years	After 5 Years
Cable	31	3	3
Accessories	47	5	6
TOTAL	78	8 [10.2%]	9 [11.5%]

3.3.6.4 Data Classification

Traditionally, the magnitude and inception voltage of PD signals were used to classify discharges as to whether or not they would cause a failure in service. Analytical work on pilot studies have shown that, even if advanced classification tools are used, PD magnitude and inception voltage cannot be used to accurately identify the defects that cause cables or accessories to fail. The objective of any classifier used in this fashion is to correctly predict a cable system's performance based solely on the available diagnostic feature data. This amounts to assigning a Pass or Not Pass assessment to each tested cable system. The most critical performance metric for any classifier is the success rate of its classification, in other words, whether it correctly assesses each cable system. Similar to the discussion in Section 3.1, there are fundamentally two forms of success rates for classifiers:

- **Overall Success Rate** – For a complete set of cable segments, this success rate is based on the percentage of the segments that performed as predicted by the classifier (i.e. the number of "Good" segments that did not fail plus the number of "Bad" circuits that did fail) when tested using a training dataset.
- **Group Success Rate –** For each group (Pass and Not Pass), this success rate is based on the percentage of the segments that perform as predicted by the classifier. In other words, what percentage of segments the classifier assesses as "Pass" did not fail and what percentage of segments classified as "Not Pass" did fail.

Because of the above definitions, there are three classifier success rates that must be considered in examining a technique's performance with different diagnostic features. It is important to understand, however, that different classification techniques are more efficient in exploiting elements of the diagnostic features. Unfortunately, classifiers are only successful if the diagnostic features they use are the right ones to make the classification. For example, one cannot use the sound of a car engine to classify the color of its body. Engine sound simply has little or no connection to the color of the car. This analogy is also true in classification using diagnostic features.

Figure 33 shows an example of the accuracies of one classifier, k-Nearest Neighbor, when used with PD magnitude and inception voltage to classify sites as those that will fail (Not Pass) and those that will not (Pass). This classifier has one adjustable parameter that may be used to improve the classification success rate: the number of neighbors to use in the classification. The objective is to choose the number of neighbors (neighborhood size) that achieves the best balance between the group success rates. In this example, 13 neighbors represents the best balance between the two groups.

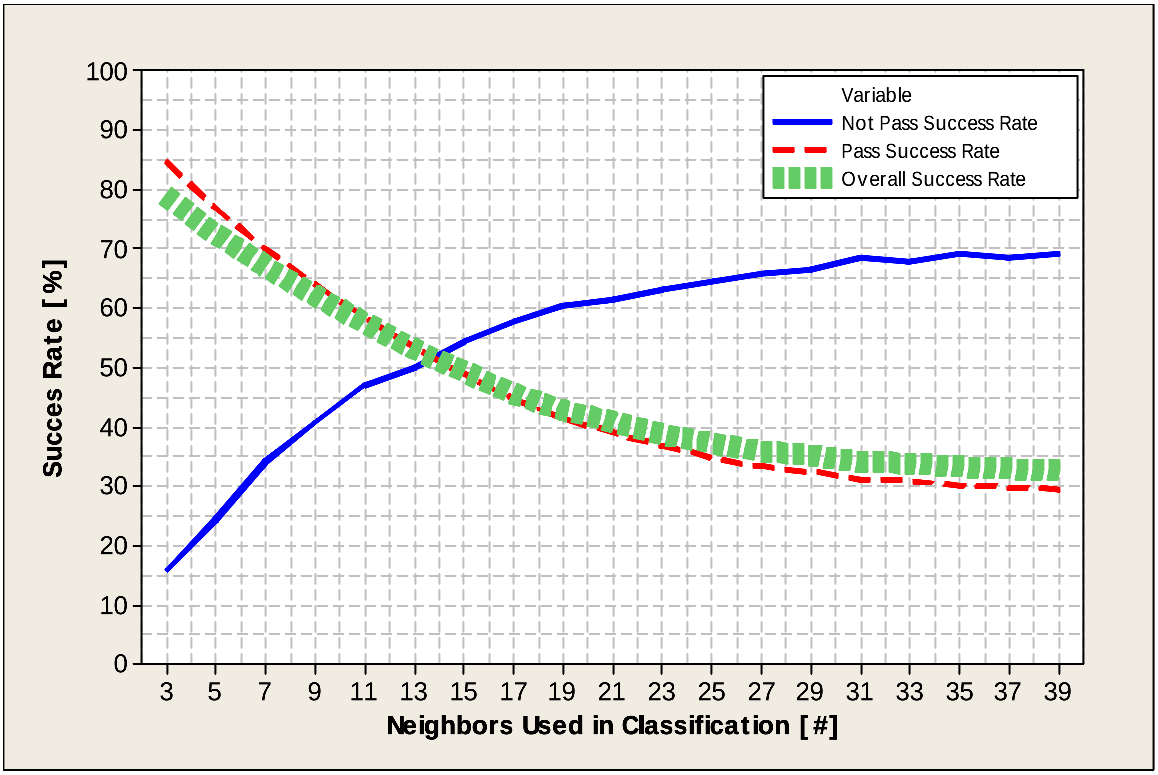


Figure 33: k-NN Success Rates for Different Sized Neighborhoods

For 13 neighbors, the overall success rate for this classifier is only 52 %. This implies that PD magnitude and inception voltage are unsuitable for classification since the accuracy is only slightly better than flipping a fair coin.

The k-NN analysis raises a number of rarely addressed issues:

- What are the appropriate diagnostic features to use for classification? (If not PD magnitude and inception voltage, then what?)
- How many diagnostic features are required?
- What is the best way to use these features?

These questions are addressed for both laboratory and field measurements in the CDFI. The approach is to use a multivariate clustering algorithm that combines similar variables into groups or clusters. These clusters indicate, in principle, the number of features required and what features might be chosen. Figure 34 shows the analysis of laboratory data that initially contains 56 different PD diagnostic features. The goal of this graph is to identify how dissimilar different features are – the more dissimilar the better, since dissimilar features provide unique information on the PD signal. A low value of similarity reflects this (Figure 34). Successive use of clustering reduces the original 56 features down to 15. These remaining 15 features naturally arrange themselves into 7 clusters. Clusters 1, 2, and 7 each have a single member while Cluster 3, for example, contains 8 features. This means that a single diagnostic feature from within that cluster can represent the information in Cluster 3. This is important since adding more features from Cluster 3 will not improve a classifier's ability to make the classification, as these additional features do not contain additional information. Therefore, there is no reason to include them.

As mentioned above, the key to any classification problem is to choose the right features. Figure 34 represents one approach to solving this problem.

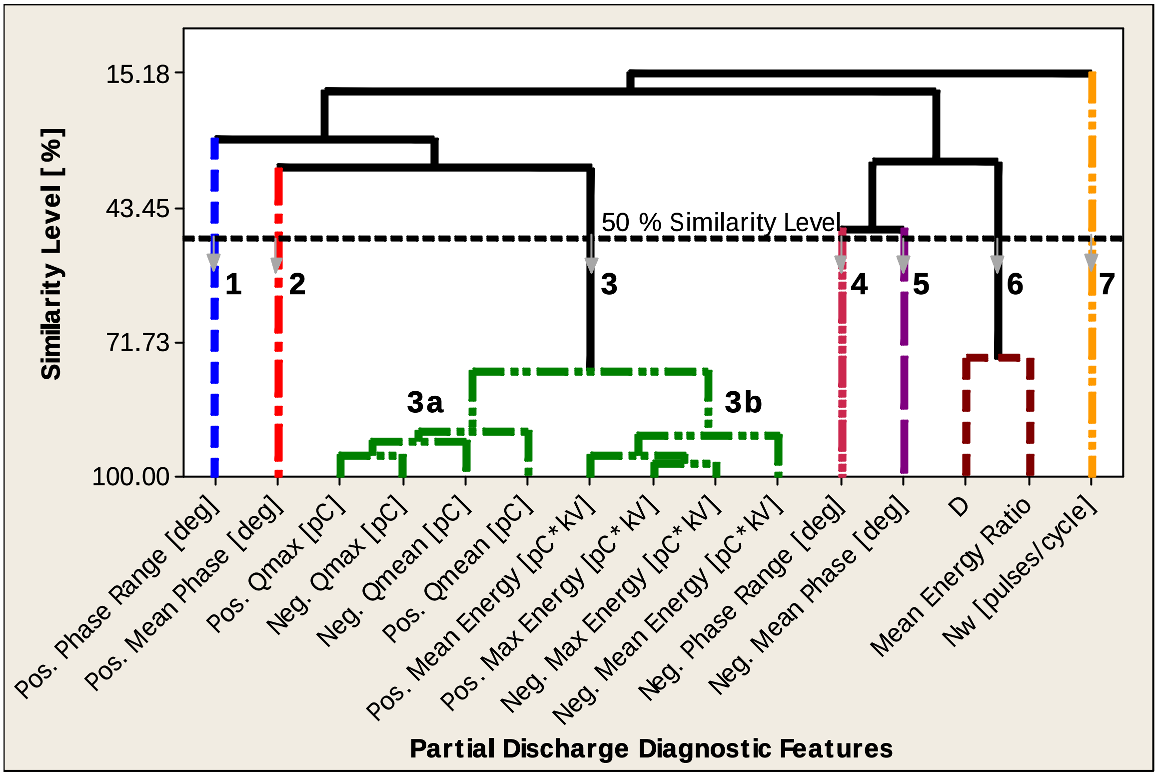


Figure 34: Dendrogram Representation of PD Features

With the right features selected, a classifier such as the k-NN classifier described above can be implemented and used to enhance diagnosis using PD.

3.4 Partial Discharge – Acoustic Measurements

3.4.1 How It Works

When partial discharge occurs, it produces an almost instantaneous release of energy. This energy release results in a mechanical wave, which propagates through the materials of the device in which it occurred. Thus, the PD site acts like an acoustic wave source. The waves propagate from the PD location and can be externally detected using acoustic wave detection equipment. This is the basis of acoustic partial discharge detection.

An important advantage of acoustic PD techniques compared to conventional PD methods is the immunity of the acoustic measurements to electromagnetic interference; therefore, acoustic techniques could be applicable to situations in which electrical methods are ineffective [17], [18].

However, the literature reports [17], [18] that acoustic techniques are ill-suited for discharge detection in cables because the acoustic signal is significantly attenuated as it travels through a cable. As a result, the acoustic sensor must be in contact with the cable to provide any hope of reasonable sensitivity. Acoustic techniques are usually applied to the detection of PD in terminations, joints, and cable sections that are accessible so that direct contact with the device can be achieved.

It is difficult to perform a sensitivity assessment for acoustic partial discharge detection. Consequently, acoustic PD measurements are limited to the detection of the presence (not the magnitude) of PD where possible and are ineffective at indicating that no PD is present.

3.4.2 Estimated Accuracy

Very little information is available on acoustic PD detection so accuracy estimations are not possible.

3.4.3 CDFI Perspective

The lack of available information does not provide for a CDFI perspective on this topic.

3.5 Tan δ Measurement

3.5.1 Test Scope

Tan δ measurements determine the degree of real power dissipation in a dielectric material. A comparison relates this measurement to a known reference value for the type of dielectric measured. A judgment establishes the condition of the tested circuit based on how much the dielectric loss differs from the reference value. Reference values can be based on:

- Values measured on adjacent phases (A, B, C),
- Values measured on cables of the same design and vintage within the same location,
- Values when new,
- Industry standards, or
- An experience library.

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

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

3.5.2 How it Works

Applying an AC voltage and measuring the phase difference between the voltage waveform and the resulting current waveform provides the Tan δ. This phase angle is used to resolve the total current (I) into its charging (I_C) and loss (I_R) components. The Tan δ is the ratio of the loss current to the charging current, as shown in (4).

$$DF = \frac{I_R}{I_C} = \frac{\sqrt{I^2 - I_C^2}}{I_C} \quad \textbf{(4)}$$

The angle δ appears in a phasor diagram in Figure 35.

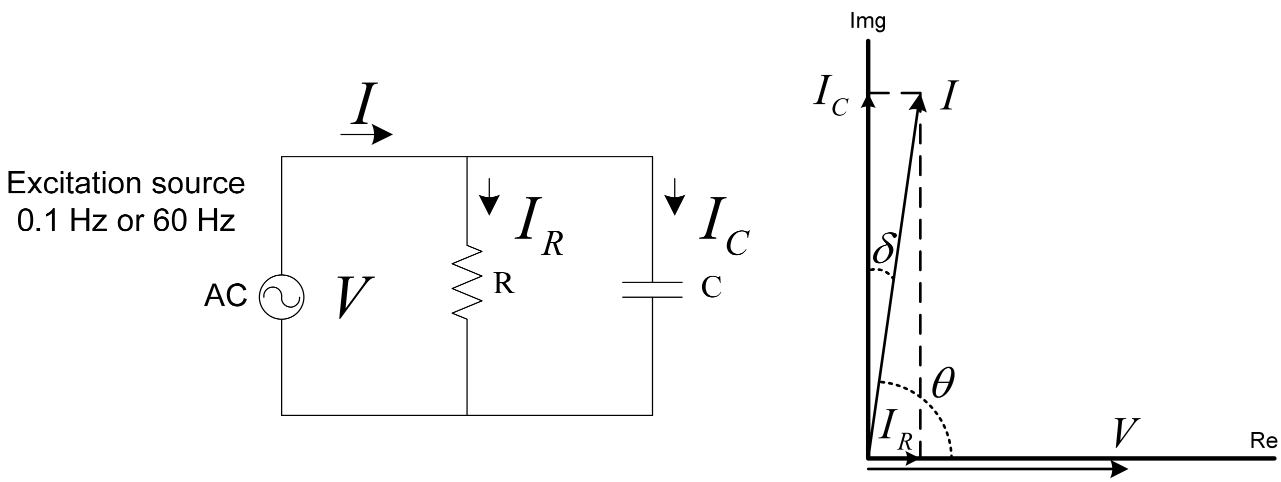


Figure 35: Equivalent Circuit for Tan δ Measurement and Phasor Diagram

Figure 35 shows an equivalent circuit for a cable, consisting of a parallel connected capacitance (*C*) and a voltage dependent resistance (*R*). The Tan δ measured, at a frequency ω and voltage V, is the ratio of the resistive (I_R) and the capacitive (I_C) currents according to (5).

$$DF = \tan(\delta) = \frac{I_R}{I_C} = \frac{V/R}{V/(1/\omega C)} = \frac{1}{\omega RC} \quad \textbf{(5)}$$

The terms “Tan δ” and dissipation factor are used interchangeably.

3.5.3 How it is Applied

The cable segment under test is disconnected from the grid and energized from a separate power supply with a fixed AC frequency (e.g. 60 Hz or VLF AC). The segment is typically energized using a voltage level of 0.5 to 2 U_0. Summaries of the advantages and disadvantages of using Tan δ as a cable system diagnostic appear in Table 22 and Table 23.

Table 22: Advantages and Disadvantages of Tan δ Measurements as a function of Voltage Source		
Source Type	**Advantages**	**Disadvantages**
60 Hz AC Offline	• Testing voltage waveform is the same as the operating voltage. • Voltages higher or lower than the operating voltage can be applied.	• Energizing test equipment is large, heavy, and expensive. • Tan δ is less sensitive at 60 Hz than at lower frequencies due to the increased magnitude of the capacitive current (5).
0.01 – 1 Hz AC Offline Very Low Frequency (VLF)	• Energizing test equipment is small and easy to handle. • Frequency dependency of Tan δ can be established. • Tan δ is more sensitive at lower frequencies than at 60 Hz due to the reduced magnitude of the capacitive current (3). • Can test long circuits.	• Testing voltage waveform is not the same as the operating voltage. • Frequencies lower than 0.01 Hz may cause space charge formation. • Reference test times are typically for 0.1 Hz, so lower frequencies require longer test times. • When using a Cosine-rectangular waveform, tan δ has to be approximated.
Damped AC (DAC) (30 to 100 Hz)	• Energizing testing equipment is small and easy to handle. • Results may be comparable to those obtained from 60 Hz AC.	• Testing voltage waveform is not the same as the operating voltage. • Accuracy is limited because ac waveform varies in RMS magnitude over time. • Resolution is limited ($1x10^{-3}$).

Table 23: Overall Advantages and Disadvantages of Tan δ Measurement Techniques	
Advantages	• Test results provided as simple numerical values can easily and quickly be compared to other measurements or reference values. • Three basic Tan δ features can be ranked in order of importance in making an assessment. • Provides an overall condition assessment. • Measurements on a given phase can be compared to adjacent phases, so long as the phases have the same configuration. (Also applies to T-branched or other complex circuit configurations.) • Can be performed using a variety of different ac power supplies. • Indicator for the overall degree of water treeing in XLPE cable. • There is minimal influence from external electric fields / noise. • Periodic testing provides numerical data that may be compared with future measurements to establish trends. • Data obtained at lower voltages (U_0 versus 2 U_0) are generally as useful as data obtained at higher voltages. • Measured values that change as a function of test segment length can be indicative of problems such as corroded neutrals. • When measured values change (are unstable) during a test, it may indicate that a component is progressing to failure. • Simple numeric results enable a quick risk assessment prior to testing at higher voltage levels.
Open Issues	• The relationship between the measured loss on the entire system and the loss at a specific location (such as an accessory or cable defect) needs to be established. • The importance of differentiating between the loss characteristics of different EPR insulation materials needs to be established. • Methods to interpret results for hybrid circuits need to be established. • Initial data indicate that loss measurements can detect problems with corroded neutrals, further exploration to establish the relationship is necessary. • How different applied VLF voltage frequencies affect the measured loss criteria is not yet determined. • How temperature affects loss measurements, especially for high loss cables, needs further exploration. • Voltage exposure (impact of voltage on cable system) caused by 60 Hz AC, DAC, and VLF has not been established. • Effect of single or isolated long water trees on the Tan δ. • Usefulness of commissioning tests for comparison with future tests.
Disadvantages	• Cannot locate discrete defects. • Cable circuit must be taken out of service for testing. • Not an effective test for commissioning newly installed cable systems. • Precise Pass / Not Pass levels are not yet established.

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

To enhance the effectiveness of a Tan δ test in assessing cable degradation, the dielectric loss should be periodically observed, preferably over a period of several years. In general, an increase in the Tan δ in comparison to previously measured values indicates additional degradation has occurred [26 - 32].

Dielectric loss is also measureable as a function of frequency. This approach, Dielectric Spectroscopy, appears in more detail in Section 3.6.

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

Therefore, the best practice is to perform periodic testing at the same voltage level(s) while observing the general trend in Tan δ over time.

3.5.4 Success Criteria

Tan δ results appear in terms of the specific loss measurement or the increase of loss ("tip up") at selected applied voltages (electrical stresses). The tip up is more correctly a voltage gradient, however in present day Tan δ terminology it is the difference between the dielectric loss measured at U_0 and 2 U_0. The results are often interpreted using rules such as those in Table 24 and Table 25 where test values fall into two classes: "Pass" and "Not Pass." However, the basic data are usually reported. This feature is powerful and valuable as it makes it possible to:

- Reinterpret data in the light of new knowledge,
- Track trends, and
- Compare with adjacent cable lengths.

Establishing the success criteria for dielectric loss measurements is complicated in that the values depend not only on the cable system quality, but also on the cable and accessory technologies employed on the tested cable circuit.

IEEE Std. 400™ - 2001 initially has established broad performance categories for 0.1 Hz Tan δ measurements (Table 24 and Table 25). However, recent work has lead to an expansion and revision of these levels, thus users should be cautious in the direct application of these earlier values. The values are based on cables tested in various countries. These newer criteria serve to show how an assessment protocol might be constructed after a suitable analysis is performed. It is also important to recognize that data at 60 Hz cannot be compared with those at 0.1 Hz – compare Figure 60 and Table 25.

Table 24: Pass and Not Pass Indications for Tan δ Measurements

Test Type	Cable System	Pass Indication	Not Pass Indication
0.1 Hz	XLPE	Table 25 for IEEE Std. 400™-2001 Criteria See CDFI Perspective Section for 2010 CDFI Criteria	
	HMWPE WTRXLPE		
	EPR		
	PILC		
>0.1Hz, <60 Hz	XLPE	No unified criteria.	
	HMWPE WTRXLPE		
	EPR		
	PILC		
60 Hz	XLPE		
	HMWPE WTRXLPE		
	EPR		
	PILC		
DAC	XLPE		
	HMWPE WTRXLPE		
	EPR		
	PILC		

Table 25: Tan δ and Cable Condition Assessments in IEEE Std. 400™ - 2001 (All Cable Designs)
Included for historical reference but not recommended for current use.

Assessment	Tan δ [E-3]		Tip Up [E-3]
	U_0	2 U_0	2 U_0 to U_0
Clause 8.4			
Good	-	<1.2	<0.6
Aged	-	>1.2 <2.2	>0.6 <1
Highly Degraded	-	>2.2	>1
Clause 9.7			
OK	<4	-	-
Replace Eventually	>4	-	-

One important point shown in Table 25 (Clause 8.4) is the fact that the Tan δ should only vary slightly between different voltage levels. An increase in Tan δ with increasing voltage can indicate the presence of a severe problem, which may include partial discharge. The values presented in Table 25 are approximate guidelines only.

3.5.5 Estimated Accuracy

Since Tan δ data are available in numeric form, multiple criteria leverage the accuracy of Tan δ measurements. In this section, accuracy considers the IEEE Std. 400™ criteria described below.

IEEE Std. 400™ - 2001 Criteria

As mentioned earlier, according to IEEE Std. 400™ - 2001, the success criteria for the Tan δ diagnostic measurement technique are:

- Pass – Tan δ value at 2 U_0 of less than 1.2 and a tip up (difference in Tan δ between $2U_0$ and U_0) of less than 0.6
- Not Pass – Tan δ value at 2 U_0 of more than 1.2 and a tip up (difference in Tan δ between $2U_0$ and U_0) of more than 0.6

In the CDFI, a number of Tan δ data sets were analyzed and the resulting calculated accuracies were established in Table 26 based on the IEEE Std. 400™ - 2001 Pass/Not Pass criteria.

Table 26: Summary of Tan δ Accuracies *(See Section 3.1 for discussion on raw versus weighted accuracies)* *(Pass and Not Pass Criteria are based on IEEE Std. 400™ - 2001)*			
Accuracy Type	**Tan δ**		
		Raw	**Weighted**
Overall Accuracy (%)	Upper Quartile	74.8	59
	Median	60.0	59
	Lower Quartile	45.8	59
	Number of Data Sets	8	8
	Length (miles)	136	136
Pass Accuracy (%)	Upper Quartile	100	98.7
	Median	100	98.7
	Lower Quartile	92.0	98.7
	Number of Data Sets	7	7
	Length (miles)	134	134
Not Pass Accuracy (%)	Upper Quartile	53.5	9.8
	Median	7.9	9.8
	Lower Quartile	0.1	9.8
	Number of Data Sets	8	8
	Length (miles)	136	136
Time Span (years)		2000 - 2008	
Cable Systems		XLPE, WTRXLPE, PAPER, HMWPE	

The CDFI is exploring other success criteria, but they are incomplete. See Table 27 through Table 29 in Section 3.5.6.5. The IEEE Std. 400.2™ Working Group is considering some of these criteria as they revise/update IEEE Std. 400.2™. Therefore, accuracies for these new, proposed criteria have not been computed. However, available data indicate an improvement in accuracies over those appearing in Table 26.

3.5.6 CDFI Perspective

Participating utilities provided several extensive Tan δ data sets to the CDFI. Because all the data provided was numerical and represented a physical property measurement, it lent itself to extensive analysis and processing. Although a significant amount of this data was analyzed and reported in the CDFI, this is not an endorsement of the technique, but the natural consequence of having large volumes of analyzable numeric data from utilities willing to make it available for analysis.

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

3.5.6.1 Measurement Approaches

The underlying principle of Dielectric Loss measurements is common to all approaches to Dielectric Loss assessment. However, there are two primary means of measuring dielectric loss: VLF AC, and Damped AC (DAC). These two basic approaches appear below:

Approach 1: Constant RMS Voltage

These approaches include 60 Hz AC, VLF AC – sinusoidal, and VLF AC – cosine-rectangular voltage sources. They both measure capacitive and resistive currents to determine the system dielectric loss. The 60 Hz AC and VLF AC – sinusoidal approaches use relatively conventional measurement algorithms. However, the VLF AC – cosine rectangular approach is to measure the time dependent (polarization) current for the DC portion of the waveform and then employ the Hamon approximation [33] to provide a loss estimate. (The efficacy of this approach has not been investigated in the CDFI.)

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

Most of the data reported within the CDFI has come from the VLF AC – sinusoidal version of the technology.

Approach 2: Decaying Voltage

In this approach, the voltage source uses the resonance between the cable capacitance and external inductances to create a decaying ac waveform. The level of the dielectric loss determines the rate at which each subsequent “period” of the waveform decays. Thus, measuring the rate of decay is directly proportional to the overall circuit dielectric loss.

Different versions of this basic approach use different algorithms and portions of the wave to estimate the loss.

All of the approaches using this technology report numeric data. The loss is reported as Tan δ. The variability of the loss with time cannot be quantified. It can be quantified in terms of excitations.

This technique reportedly widely used outside the US, though no data sets were made available to the CDFI.

3.5.6.2 Reporting and Interpretation

In principle, there are three types of dielectric loss data:

- Tan δ – normally reported as the mean of a number of sequential measurements (the median of these measurements may also be used).
- Differential Tan δ or Tip Up - normally reported as the simple algebraic difference between the means of a number of sequential assessments taken at two different voltages. The difference between medians may also be used.
- Tan δ stability - normally reported as a standard deviation of sequential measurements. The inter-quartile range (span of middle 50 % of the data) may also be used.

Figure 36 shows the entire Dielectric Loss data collected in the CDFI project in a box and whisker format. This excludes the data from the Monitored Withstand technique that is covered in Section 3.9. Figure 36 includes three graphs:

- "TD" – mean Tan δ measured at U_0,
- "TU 1.5-.5" – differential Tan δ measured at $1.5U_0$ and $0.5U_0$, and
- "Std Dev" – standard deviation for sequential measurements made at U_0.

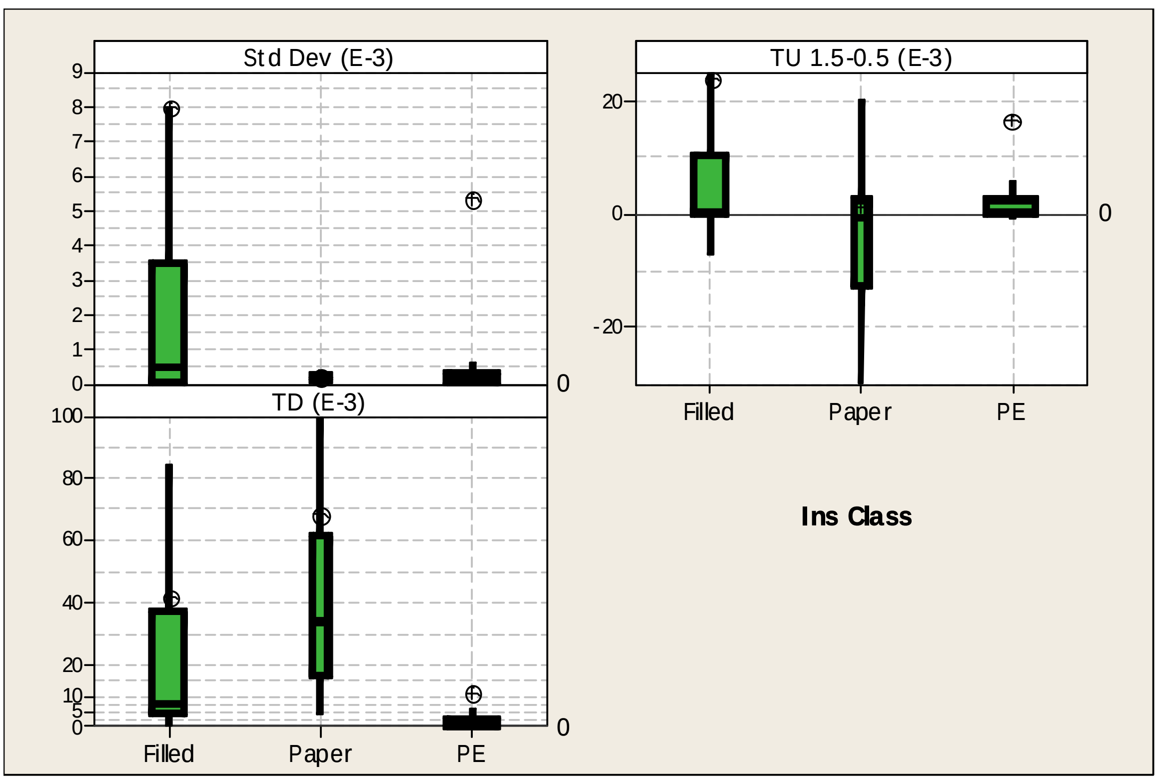


Figure 36: Dielectric Loss Feature Data segmented for Insulation Class

The data in Figure 36 represent more than 3,300 segments with a mean length of 1,070 ft. The total length for this population exceeds 700 conductor miles. The open circles represent the mean of the data sets. The horizontal lines within the boxes represent the median.

3.5.6.3 Traditional Success Levels

In many instances, a condition assessment is attempted using Dielectric Loss Tan δ as the primary metric. This approach appears in the current data from IEEE Std. 400™. The results of this approach are frequently problematic as the interpretation may be influenced by the length of the cable and the presence and dispersion of high loss elements (terminations, highly water treed regions, or splices). Applying the criteria suggested in IEEE Std. 400™ to the collated data available within the CDFI clearly demonstrates this. The standard suggests that cable systems with Tan δ > 4E-3 need to be replaced. However, inspection of the data shows that this implies that 40% of the systems measured require replacement. Not only does this appear to be an unreasonably high percentage of "bad" circuits, the fact that most of these systems are in service and have not failed supports this conclusion. Thus, we conclude that the present IEEE Std. 400™ criteria are too conservative.

IEEE Std. 400™ also notes that the critical levels will depend upon the insulation types used for the system. This contention is supported within Figure 36 for the basic insulation classes.

The update of IEEE Std. 400.2™ will address the critical levels, features, and insulation dependencies. It will revise much of the guidance presently in IEEE Std. 400™.

3.5.6.4 Multiple Success Features

While many engineers focus on a Tan δ level, IEEE Std. 400™ also suggests that multiple Tan δ features should be considered (i.e. Tan δ and Tip Up) in the assessment. Unfortunately, the standard does not provide guidance regarding how to make a decision. Are the suggested criteria either/or or and? For example, for a segment to be judged "highly degraded" does it need to have both high Tan δ and high Differential Tan δ or does it only need one? The use of multiple features, say Tan δ and Differential Tan δ, has proven useful in the CDFI analyses (Figure 36). In such a scheme, clarity and consistency in determining the critical levels is important.

3.5.6.5 Establishing Critical Levels with Multiple Features

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

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

As an alternative to this approach, NEETRAC has developed a database for Dielectric Loss data from the field and augmented with data provided by the participating CDFI utilities (AEP, Duke Energy, Intermountain REA, National Grid, and PG&E). As a result, knowledge rules for Tan δ can now be further refined. The following sections describe the current database and its use in determining Tan δ critical diagnostic levels. This work relies on a hierarchy for Dielectric Loss features:

- First Tier – Stability
- Second Tier – Tip Up or Differential Tan δ
- Third Tier –Tan δ

The database covers at least 22 discrete test areas and more than 3,700 data entries. The number of data with the associated circuit lengths and the percentage of data as a function of circuit segment lengths appear in Figure 37 and Figure 38, respectively. Note that "filled" refers to all cables with EPR or Vulkene insulation, "paper" refers to PILC cables, and "PE" refers to all cable with polyethylene based insulations, including HMWPE, XLPE, and WTRXLPE insulations.

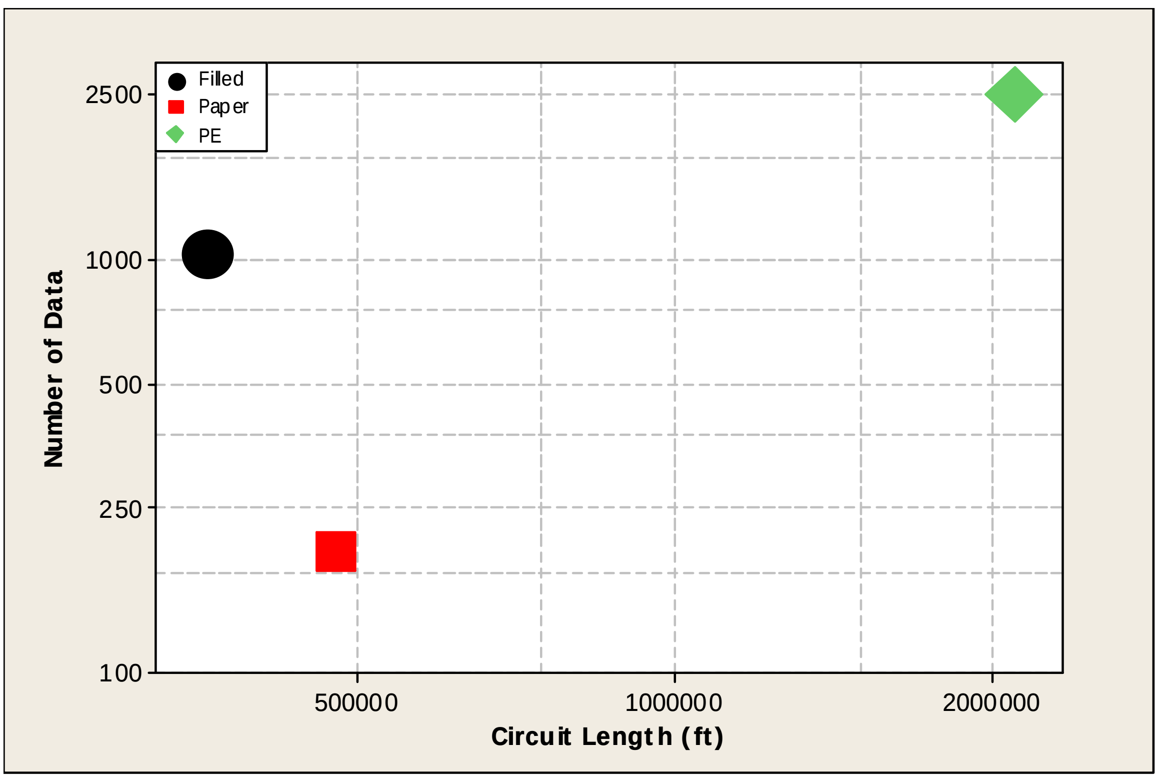


Figure 37: Tan δ Data and Corresponding Circuit Length (2.9 Million Feet)

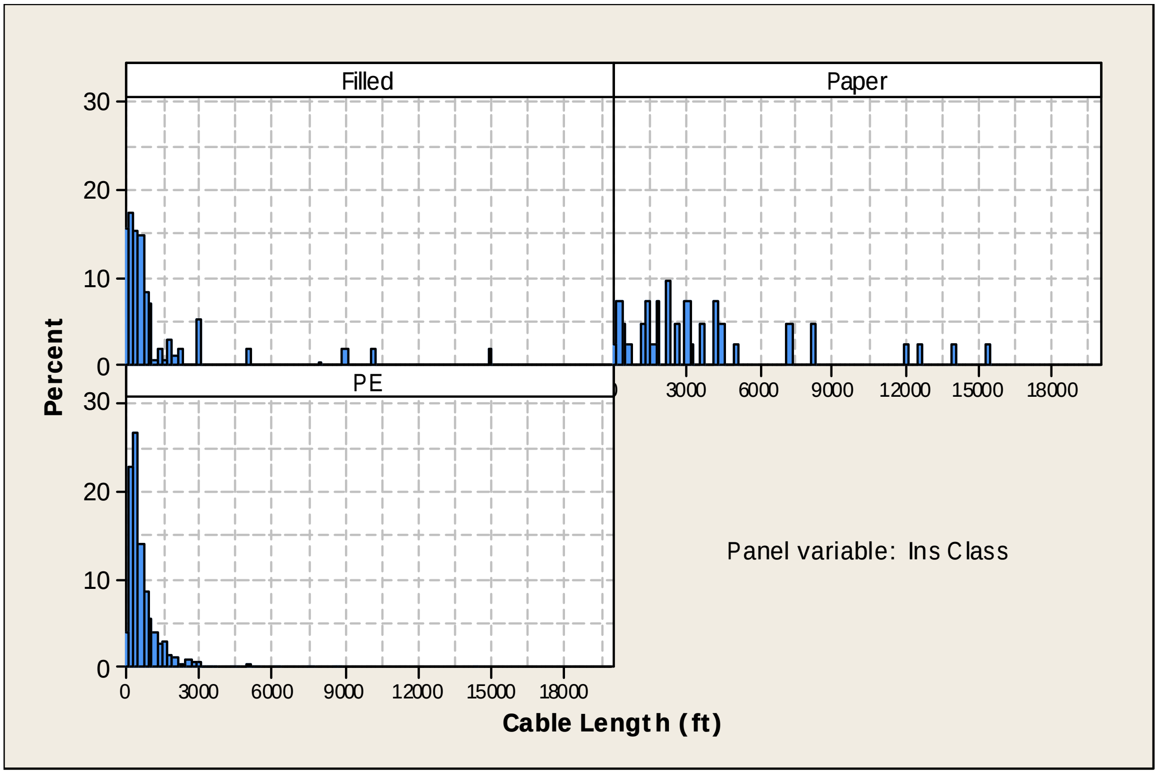


Figure 38: Histograms of Tested Lengths by Insulation Type

Figure 39 shows the distribution of Tan δ stability measurements at U_0 for each insulation class (PE, Filled, and Paper). Stability, in this case, is assessed by the standard deviation of the data. As this figure shows, 80 % of the stability measurements are less than 5 E-3, 0.3 E-3, and 0.8 E-3 for Filled, Paper, and PE insulations, respectively. The choice of the 80th percentile relies on the Pareto Principle, which says that 80 % of the problems come from the worst 20 % of the population.

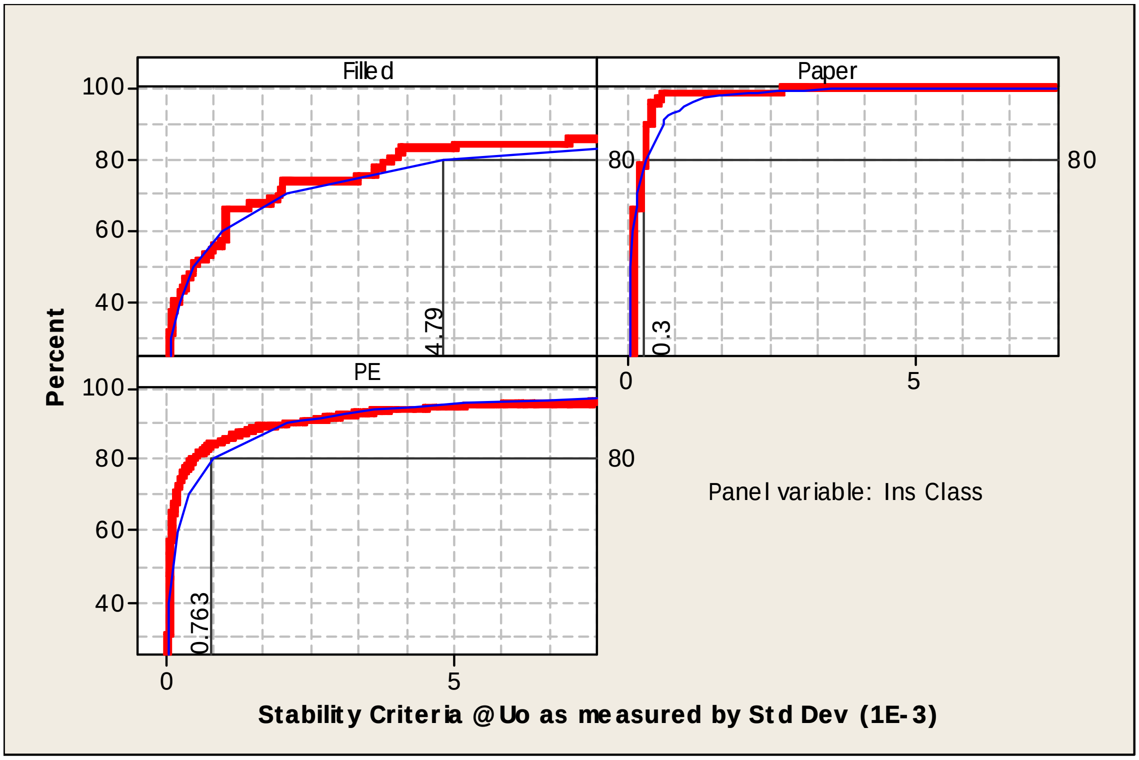


Figure 39: Cumulative Distribution of all Cable System Stability Values at U_0

Figure 40 and Figure 41 show the distributions of Tip Up data for different ranges of Tip Up where Tip Up is the difference in Tan δ measured at $1.5U_0$ and $0.5U_0$.

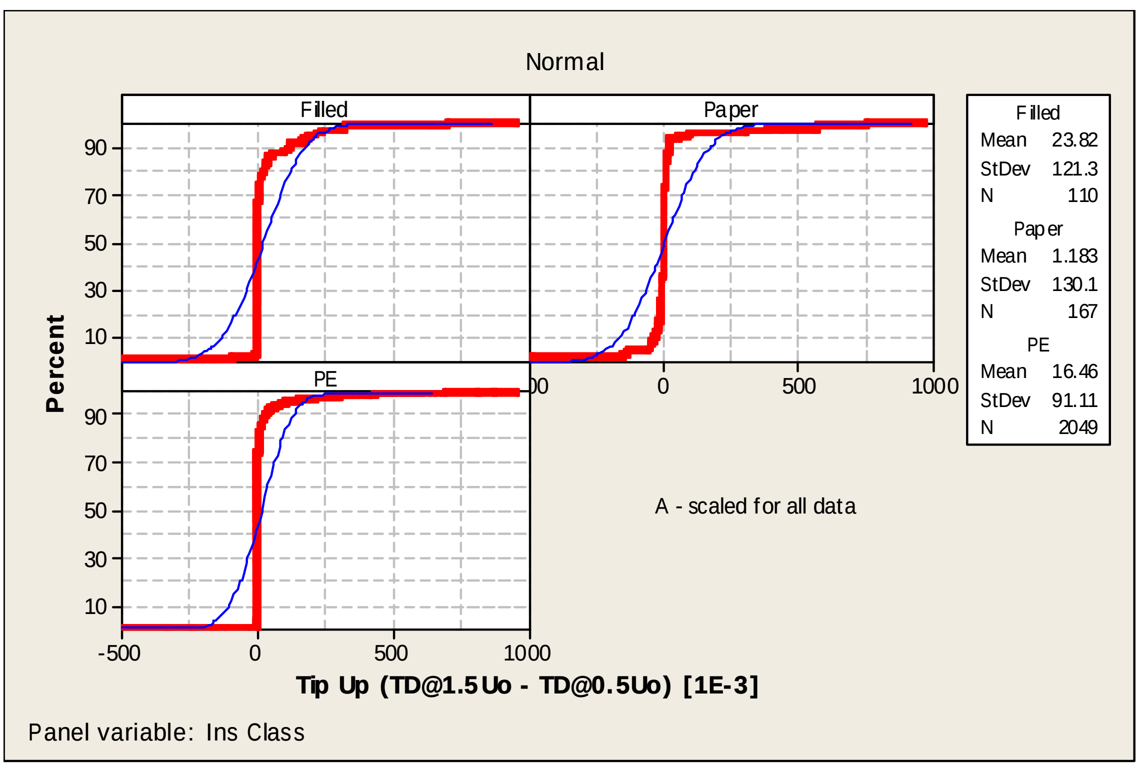


Figure 40: Cumulative Distribution of all Cable System Tip Up Criteria

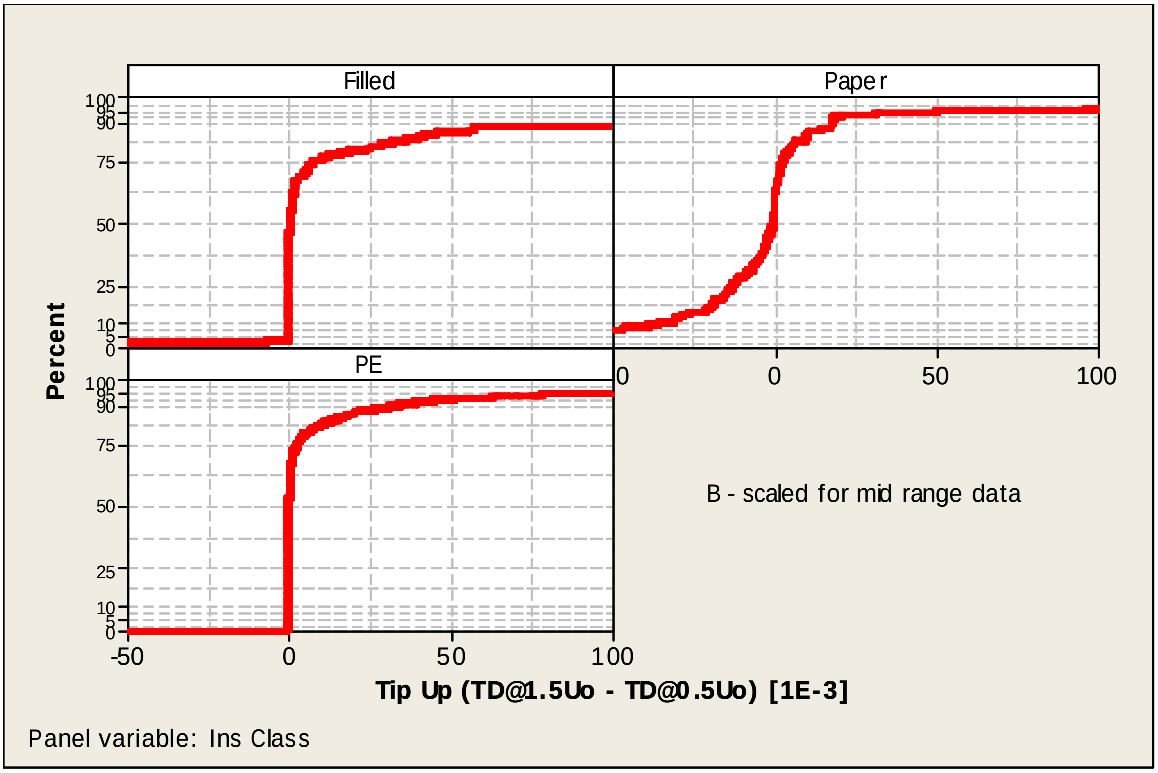


Figure 41: Expanded Version of Figure 40

Figure 42 shows the distributions of Tan δ measured at U_0. In this case, the 80th percentile corresponds to Tan δ values of 45 E-3, 86 E-3, and 4 E-3 for Filled, Paper, and PE-based insulations, respectively. Note that the distribution of Filled and Paper Tan δ measurements are well modeled by single distributions while PE clearly requires a more complicated model. In previous efforts to develop criteria, the same behavior appeared with PE and was assumed to occur with the other insulations. The data available at the time for Filled and Paper cables systems appeared to behave similarly; however, the expanded database indicates that these insulations behave in fundamentally different ways.

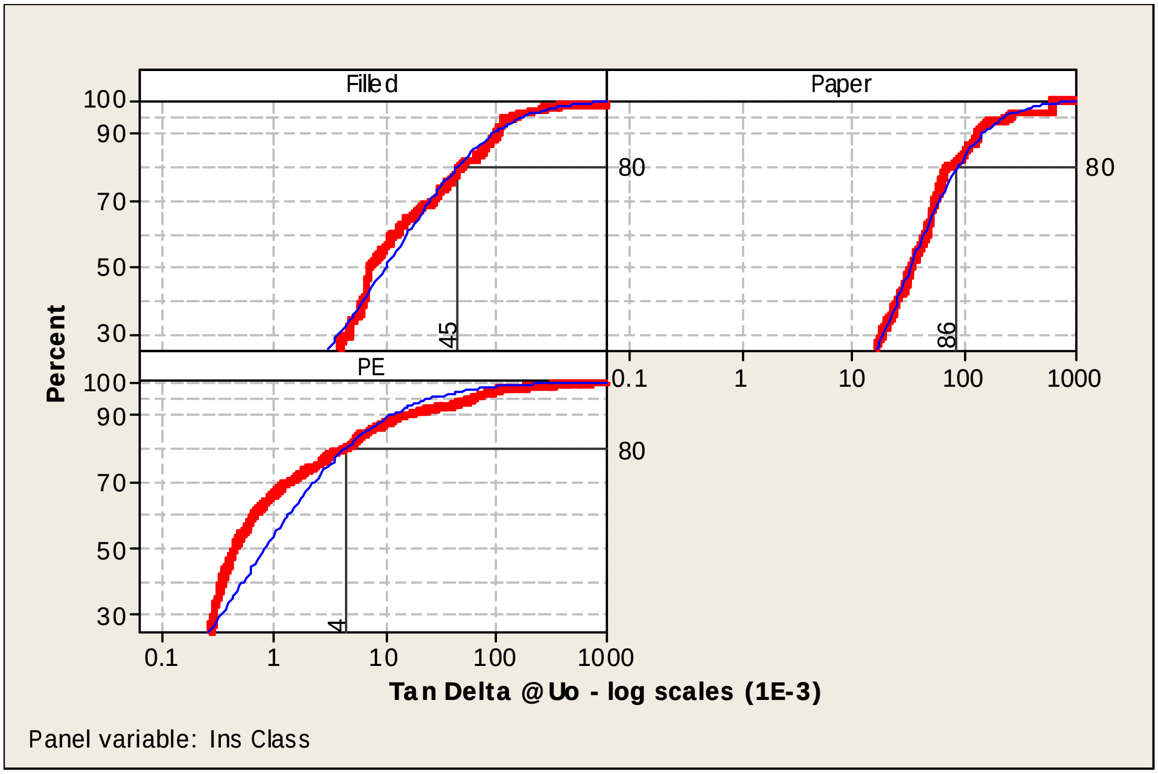


Figure 42: Cumulative distribution of all the Cable System Tan δ at U_0

The approach used to determine the critical levels for diagnostic features from these data relies on the collated field data as of the end December 2009. Figure 39 through Figure 42 show that in most of the cases (the exception being Tan δ at U_0 for Paper and Filled insulation) the data are not well modeled by simple distributions. In fact, the largest available data set (PE with >2,000 entries) indicates that there are suitable "breakpoints" between the distributions. By coincidence, these breakpoints are associated with probability levels of 80 % and 95 %, which are the same probability levels as found using other analysis techniques such as Pareto Analysis. Given this observation, these probabilities guide the Condition Assessments as shown below:

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

These definitions appear graphically in Figure 43.

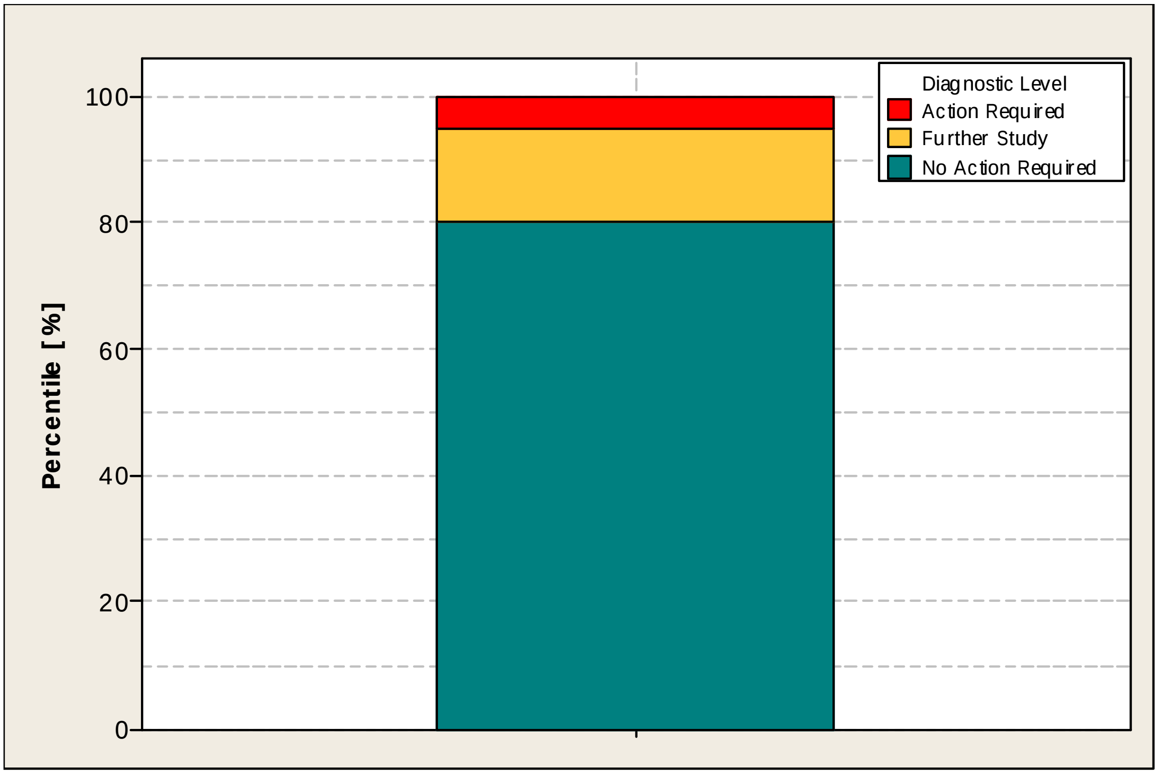


Figure 43: Percentiles Included in Each Diagnostic Level

Table 27 through Table 29 are based on these guidelines. As part of the ongoing dissemination of information from the CDFI, NEETRAC has made these tables available to the IEEE Std. 400.2™ working group for inclusion in the forthcoming update. The hierarchy for diagnosis using Tan δ is as follows:

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

Table 27: 2010 CDFI Criteria for Condition Assessment of PE-based Insulations (PE, HMWPE, XLPE, & WTRXLPE)

Condition Assessment	Tan δ Stability at U_0 [E-3]		Tip Up ($1.5U_0 - 0.5U_0$) [E-3]		Tan δ at U_0 [E-3]
No Action Required	<0.8	or	<8	or	<5
Further Study Advised	0.8 to 5		8 to 80		5 to 50
Action Required	>5		>80		>50

Table 28: 2010 CDFI Criteria for Condition Assessment of Filled Insulations (EPR & Vulkene)

Condition Assessment	Tan δ Stability at U_0 [E-3]		Tip Up ($1.5U_0 - 0.5U_0$) [E-3]		Tan δ at U_0 [E-3]
No Action Required	<5	or	<25	or	<50
Further Study Advised	5 to 20		25 to 200		50 to 125
Action Required	>20		>200		>125

Table 29: 2010 CDFI Criteria for Condition Assessment of Paper Insulations (PILC)

Condition Assessment	Tan δ Stability at U_0 [E-3]		Tip Up ($1.5U_0 - 0.5U_0$) [E-3]		Tan δ at U_0 [E-3]
No Action Required	<0.3	or	-40 to 20	or	<75
Further Study Advised	0.3 to 0.4		-40 to -60 or 20 to 100		75 to 250
Action Required	>0.4		<-60 or >100		>250

The overall condition assessment of the circuit is defined by the most “serious” condition of any of the dielectric loss features. In other words, if any one criterion indicates the circuit is “Action Required,” then the assessment is “Action Required” regardless of what the other two criteria indicate. See Table 30 for examples. Prioritizing or differentiating between circuits with the same overall assessment requires looking at the remaining two criteria. This scheme is very similar to the level-based systems used for other diagnostic techniques. However, in this case, the knowledge rules (i.e. the critical levels, the level criteria (80 % and 95 %), and the data base) are available to the user.

Table 30 shows the overall condition assessments resulting from each of the possible combinations of Stability, Tip Up, and Tan δ assessments made using the above criteria. As Table 30 shows, there is one way to produce a “No Action Required” overall assessment while there are seven and 21 combinations that would produce “Further Study Advised” and “Action Required,” respectively. Fortunately, in practice the most common condition assessments are “No Action Required.”

Table 30: Overall Assessments for all Stability, Tip Up, and Tan δ Combinations

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

This approach uses the most severe feature assessment to generate the overall condition assessment. A more sophisticated approach would recognize the extra information held within the 2nd and 3rd features. This is explored in the next phases of work where a fuzzy logic system may be used to determine a more precise assessment.

As mentioned in the above tables, the criteria in Table 27 through Table 29 were generated in 2010. It is useful to examine the evolution of these criteria over the course of the CDFI. It is important to note that IEEE Std. 400™ - 2001provided the starting point for the CDFI and several utilities.

Table 31: Evolution of CDFI Tan δ Criteria

Version	Assessment Hierarchy	Criteria
2001 IEEE Std. 400™	Tan δ Tip Up ($2U_0$ & U_0)	PE criteria only
2007	Tan δ Stability (U_0) Tip Up ($1.5U_0$ & $0.5U_0$) Mean Tan δ (U_0)	Qualitative – all insulations
2008		PE - criteria based on data Filled - estimates for criteria PILC - estimates for criteria
2010		PE - criteria based on data (Table 27) Filled - criteria based on data (Table 28) PILC - criteria based on data (Table 29)

It is important to note the use of the term “qualitative” to describe some of criteria in 2007. This term is used because the understanding in CDFI at the time was limited to which measurement values were “really good” and those that were “really bad” but there was not a defined threshold to separate the two. These thresholds/criteria were developed once data were available or reasonable estimates could be made using data from other insulation materials.

An update to the 2010 CDFI Criteria is planned as future work in CDFI Phase II.

3.5.6.6 Feature Selection

The methodology described in Section 3.5.6.5 is applicable to any multi-modal data (i.e. data that cannot be modeled with a single probability distribution). In the case of Tan δ, the available features include Tan δ at different voltages, Differential Tan δ, and Tan δ Stability. Ideally, one would prefer to use as few features as possible to make a condition assessment but then the question becomes: What features to use?

There are a number of ways to approach the problem of feature selection when there are only a few features available. One of the methods adopted by the CDFI is Performance Ranking. This method looks at the diagnostic feature’s ability to correctly rank a group of tested segments as to their relative performance in service. This work took place in the laboratory and the metric used to evaluate service performance is the breakdown strength. Figure 44 shows the results of the first laboratory assessment of the breakdown strength of highly aged XLPE cables under VLF excitation. As this figure shows, there can be significant differences in the breakdown performance of aged cable segments. See Figure 58 for field verification of this approach.

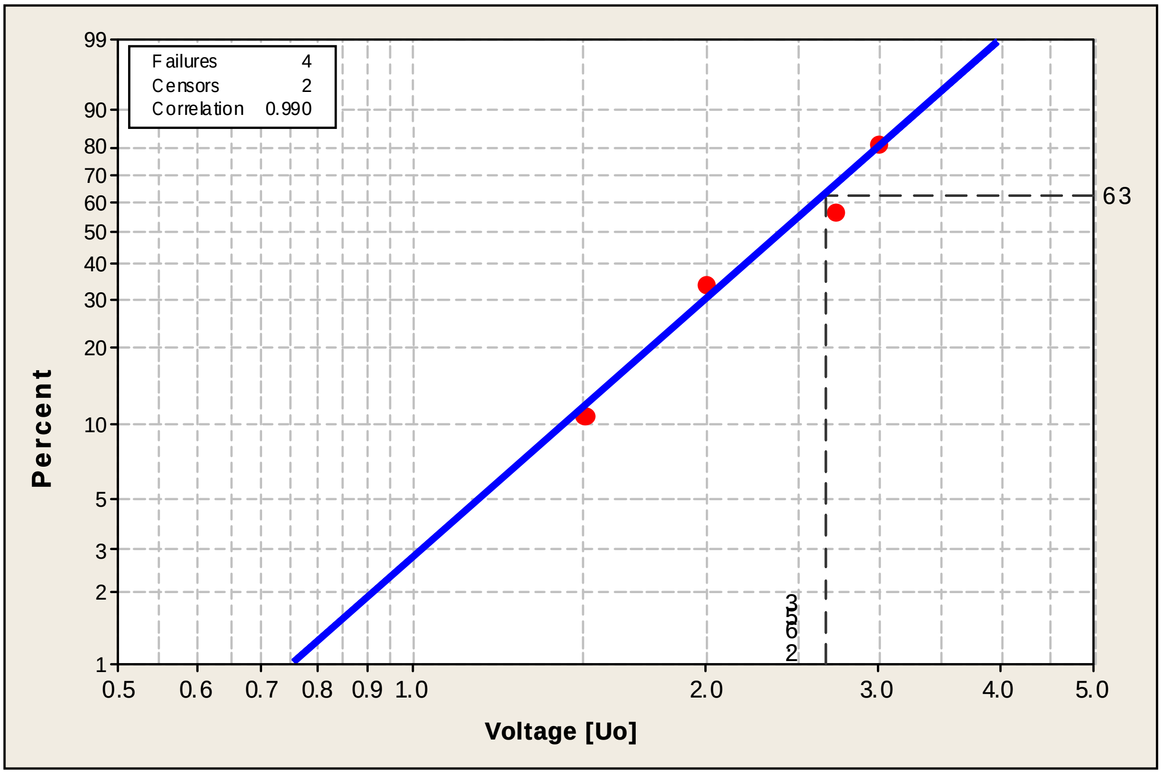


Figure 44: VLF Breakdown Voltage of Highly Aged XLPE Cables in Weibull Format

Prior to determining these breakdown strengths, all three of the dielectric loss features were measured. Thus after failure it was possible to examine which of these pre-mortem features best predicted the final breakdown strength outcome. The Performance Ranking approach involves identifying the best predictor of the breakdown strength using a Performance / Diagnostic Rank correlation plot as shown in Figure 45.

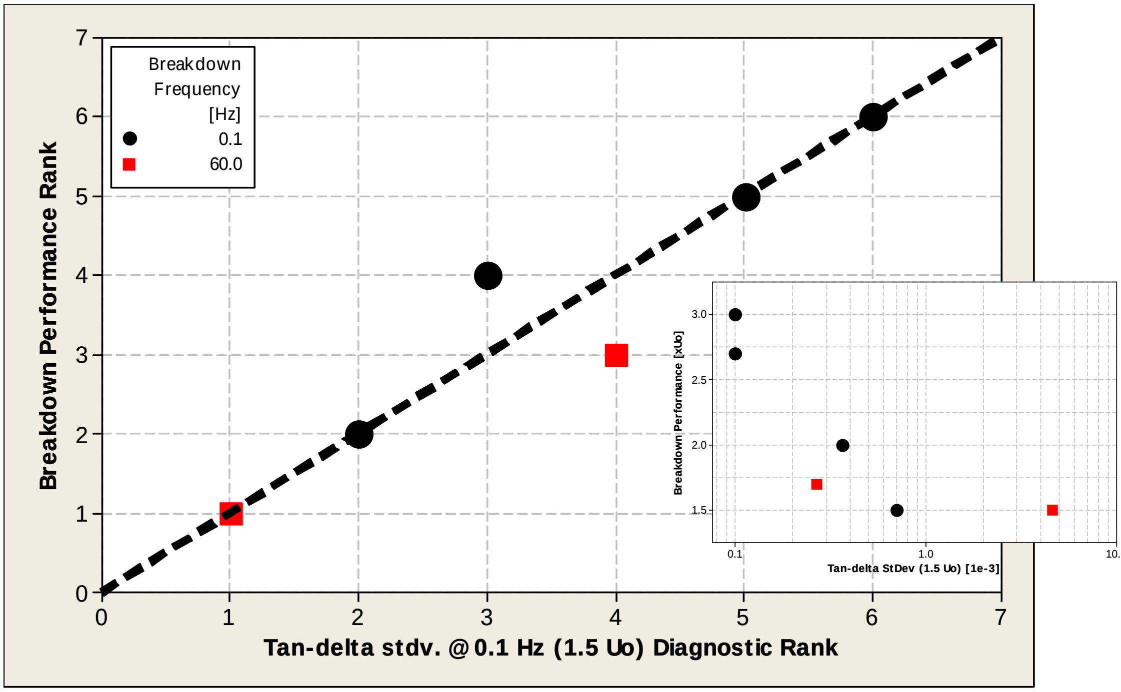


Figure 45: Rank Correlation of VLF Breakdown with Tan δ Stability (Standard Deviation) at 1.5 U_0. Inset is the Data Correlation of VLF Breakdown with Stability (Standard Deviation)

The graphical results in Figure 45 may then be analyzed numerically using the Pearson Correlation Coefficient (Table 32) [63].

Table 32: Performance and Diagnostic Rank Correlations

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

Table 32 shows that the feature with the highest significance (i.e. 1 – *P*-Value) is Tan δ Stability. This feature quantifies how the measured Tan δ values change throughout the measurement period. The smaller this value, the greater the stability. Since a stable dielectric loss is indicative of a “good” dielectric, it makes sense that this would be a primary indicator of a cable system condition. Analysis of all the available features indicates that an alternative hierarchy to the traditional Dielectric Loss/Tan δ approach in IEEE Std. 400™ may be more appropriate. This hierarchy is as follows:

First Order Feature:	Tan δ Stability – paper cables are in general more stable
Second Order Feature:	Differential Tan δ or Tip Up – paper cables typically have negative tip ups where as PE cables have positive values
Third Order Feature:	Dielectric Loss Tan δ – although overlapping the typical levels of loss are different for the insulation systems

3.5.6.7 Mitigating the Risk of Failure on Test

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

Figure 44 above shows the breakdown performance of aged XLPE cables. This analysis shows that the data fits a Weibull probability distribution and confirms that there are no "extra" failure modes for test voltages up to 3 U_0. This enables risk estimates to be made for various test voltages. IEEE Std. 400™ suggests the use of 2 U_0 for measuring Dielectric Loss and the Tip Up. As can be seen from Figure 44, this voltage does not introduce an excessively high probability of failure, even on these highly aged cables (the risk of failure would be commensurately lower on less aged cables).

On the other hand, the probability of failure could be reduced by 70 % (30 % probability down to 10 % probability) if the test voltage was reduced from 2 U_0 to 1.5 U_0. Of course, this is only useful if measurements at lower voltages provide the same level of information as measurements at higher voltages. This effect is studied in Figure 46 and Figure 47 using data correlation plots. The key finding is that both for Tan δ and Tip Up, the values are different at the different voltages. However, the *same rankings* occur. In other words, the lowest value at 2 U_0 is still the lowest value at 1.5 U_0. This shows that the lower (reduced risk) test voltages may be used without any loss in resolution. It should be noted that criteria established using higher voltages should not be directly used for measurements made at lower voltages, but the correlation curves (the fitted line in Figure 46) provides a means to translate the criteria from one voltage to another.

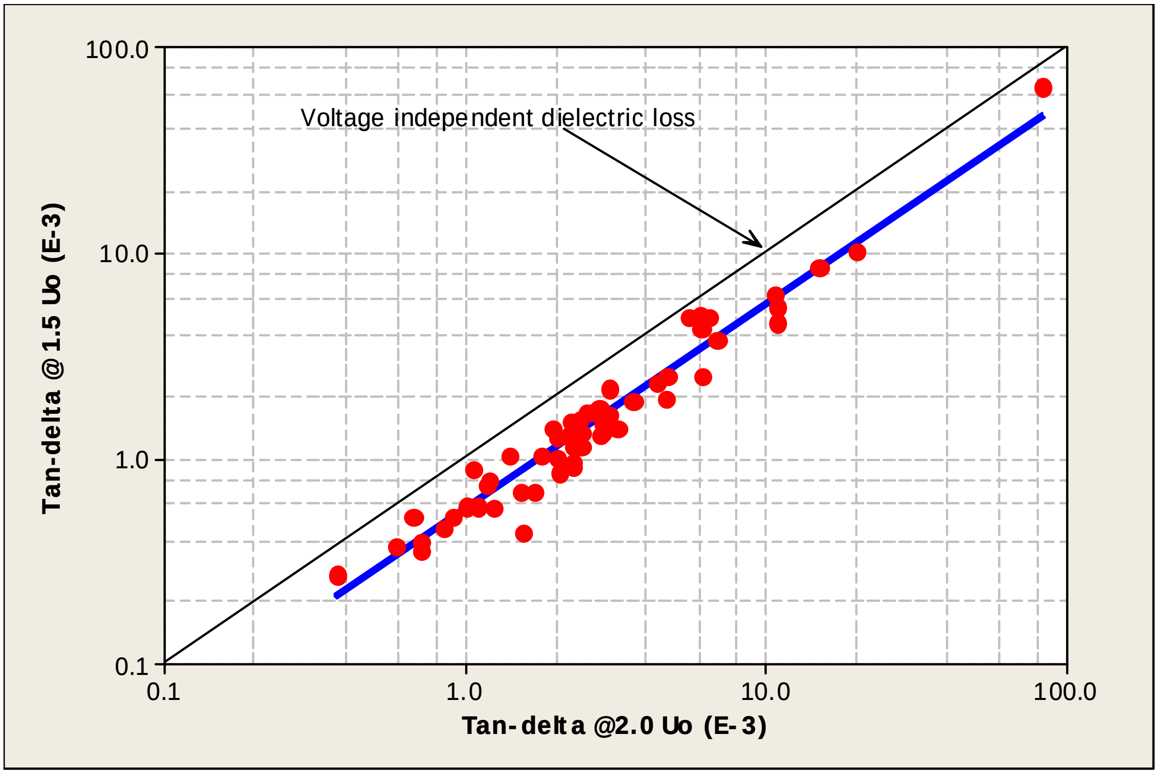


Figure 46: Correlation of Dielectric Loss Data Collected at Different VLF Test Voltages

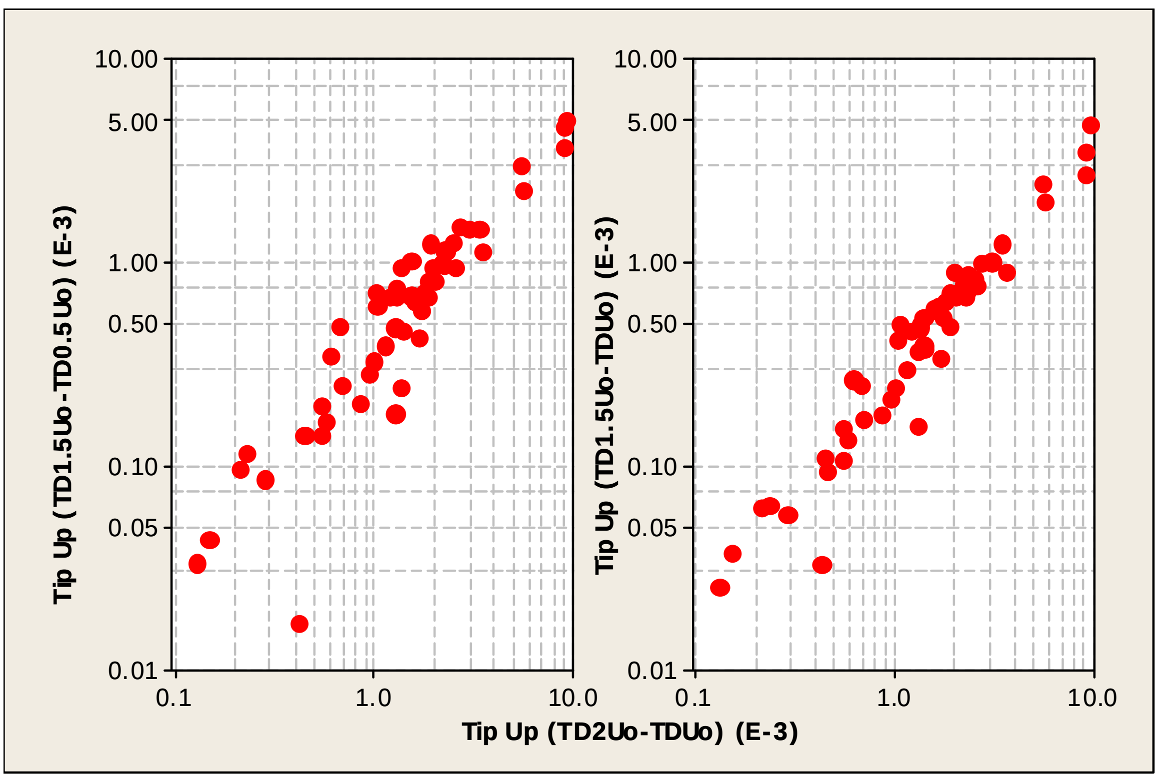


Figure 47: Correlation of Differential Loss (Tip Up) Data Collected at Different VLF Test Voltages

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

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

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

3.5.6.8 Importance of Context

Sometimes testing is performed on an individual cable segment in isolation. When this is done, the utility has to judge the condition of the segment by comparing the measured values to values outlined in documents such as IEEE Std. 400™. However, as discussed earlier, there is significant value in comparing the results to results on other, similar cable segments. In this case, the measured features (Tan δ, Tip Up and Stability) are considered in a hierarchical manner but the condition assessment levels are derived from comparison with other local measurements rather than (or in addition to) external data sources such as IEEE Std. 400™. This approach appears in Figure 48 where data for adjacent subdivisions are segregated. Through inspection of these data, it is possible to select a subdivision (say Cambridge Highlands) and then identify the segments that have results that are noticeably different from the majority of the segments in that subdivision. These are likely the segments requiring the most urgent attention within that subdivision. However, this approach does not identify which segments need immediate attention.

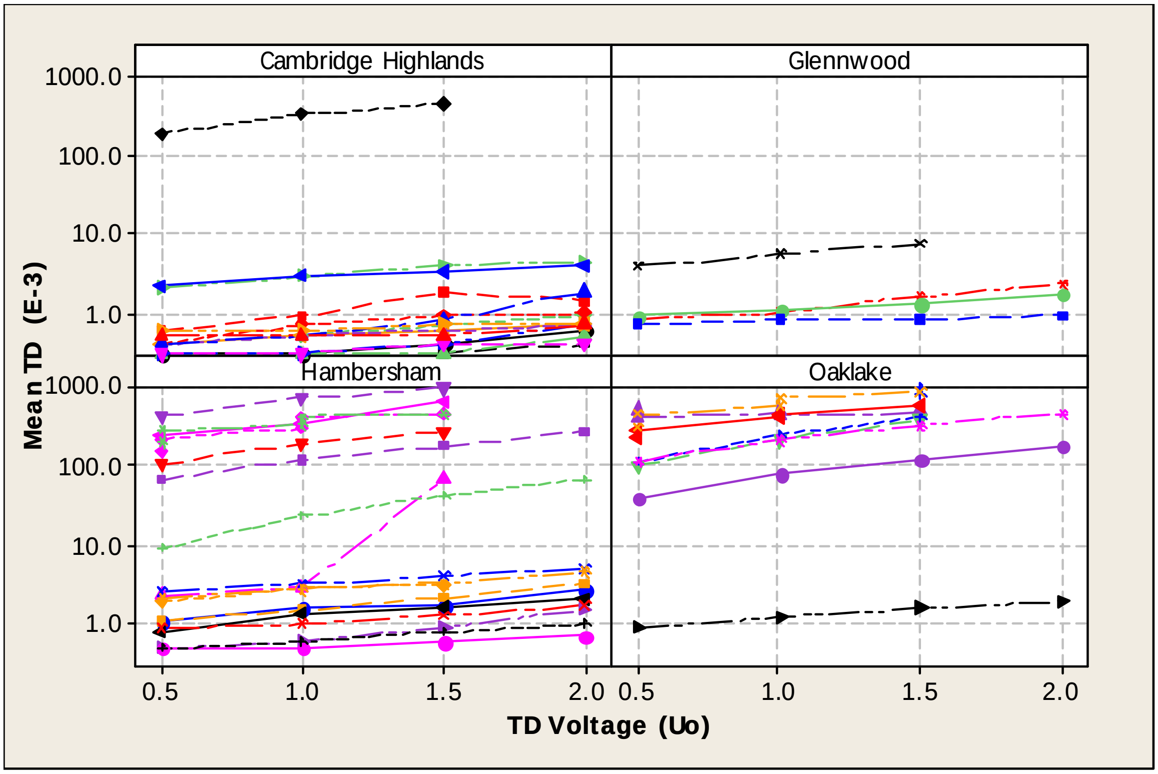


Figure 48: Dielectric Loss Data for Aged XLPE Cable Systems

3.5.6.9 Usefulness of Length Analyses / Correlations

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

Simulations where cable systems are modeled as a series of parallel resistors and capacitors show that the dielectric loss of a circuit sometimes varies as a function of the circuit length when the loss measurement is affected by factors such as corroded neutral wires. The most convenient way to visualize this is in a log-log plot. Figure 49 shows typical field data that demonstrate how the condition of the neutrals can affect dielectric loss measurements. In general, Tan δ should be independent of the tested length except in the case of corroded neutrals where the Tan δ tends to increase with length.

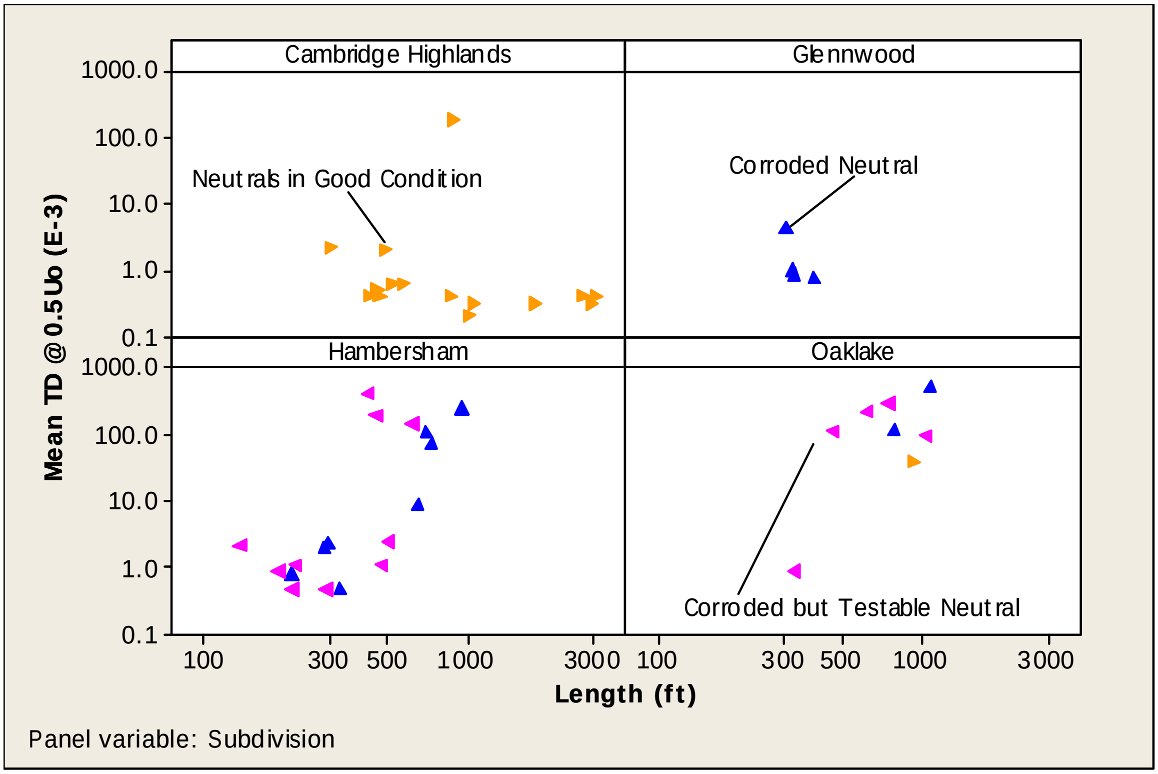


Figure 49: Dielectric Loss versus Length Representation for the Data shown in Figure 48

Similar observations apply to Figure 50. In this case, each circuit was first tested using Tan δ and then tested using a VLF Simple Withstand (see Section 3.8). Those circuits that failed during the VLF Withstand show a length dependence as compared to those circuits that went on to pass the VLF Withstand. Data are available for both Filled and PE based insulations.

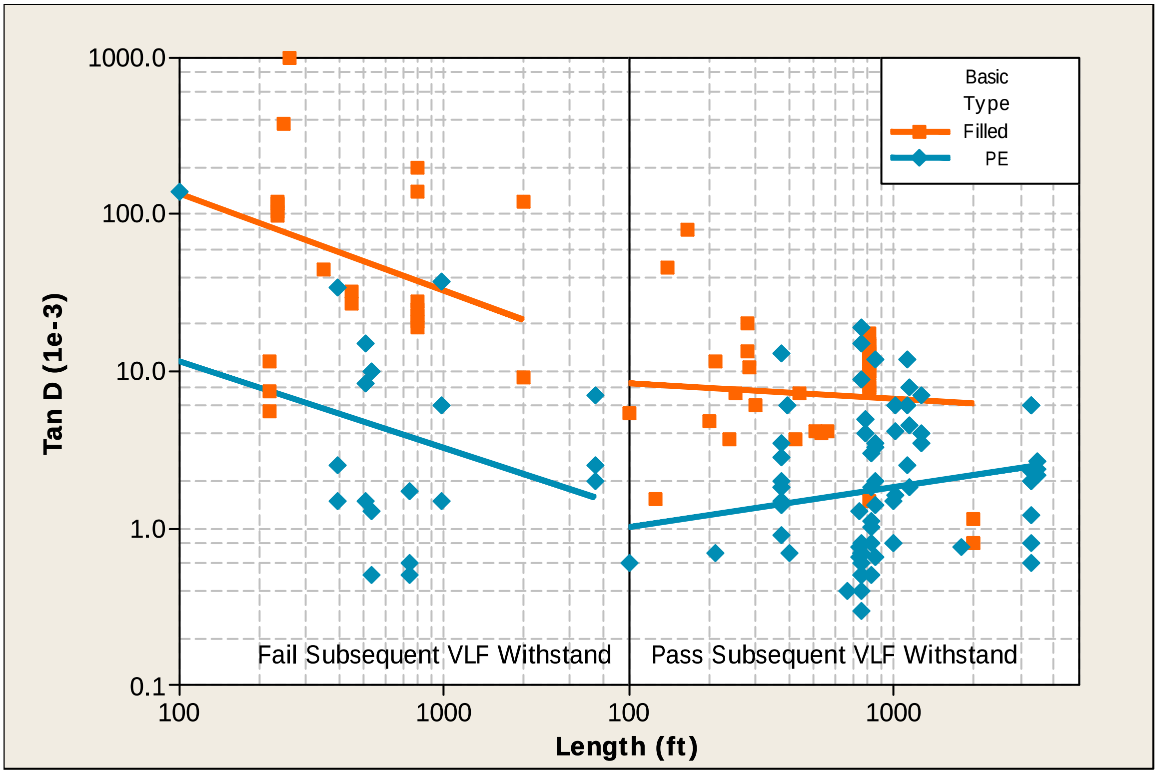


Figure 50: Dielectric Loss versus Length Segregated by Insulation Type (Filled and PE) with Performance in Subsequent VLF Withstand tests

The forms of the curves shown in Figure 49 and Figure 50 may be interpreted using the descriptions in Table 33.

Table 33: Interpretation of the Slopes of the Dielectric Loss versus Length Graphs

Graph Form	Diagnosis	Example
Flat (Loss independent of length)	Uniform level of loss for all parts of the cable system.	Figure 49 (Cambridge Highlands)
Random (No clear length dependence)	No clear pattern of loss for the cable system (as compared to Figure 49 – Cambridge Highlands). Each segment tested is different from others in the area/group.	Figure 50 (Cables pass subsequent VLF Withstand tests)
Upward Slope (Loss increases with length)	Neutral issues (the equivalent circuit is not a simple parallel representation of a resistor and a capacitor, but has a series resistance too). Either corroded neutrals or poor contact between the neutral and the insulation screen can potentially cause this to occur.	Figure 49 (Hambersham)
Downward Slope (Loss decreases with length)	Isolated high loss portions (bad accessories or heavily water treed regions) within a large proportion of low loss cable can cause this to occur.	Figure 50 (Cables fail subsequent VLF Withstand tests)

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

3.5.6.10 Expected Outcomes

The distribution of the dielectric loss data as a function of voltage source appears in Table 34. Figure 51 shows the individual lengths of cable systems tested using dielectric loss techniques.

Table 34: Dispersion of Dielectric Loss Measurements

Technique	Laboratory [Conductor Miles]	Field [Conductor Miles]
60 Hz AC	0.3	--
Damped AC	--	--
VLF AC	1.5	550

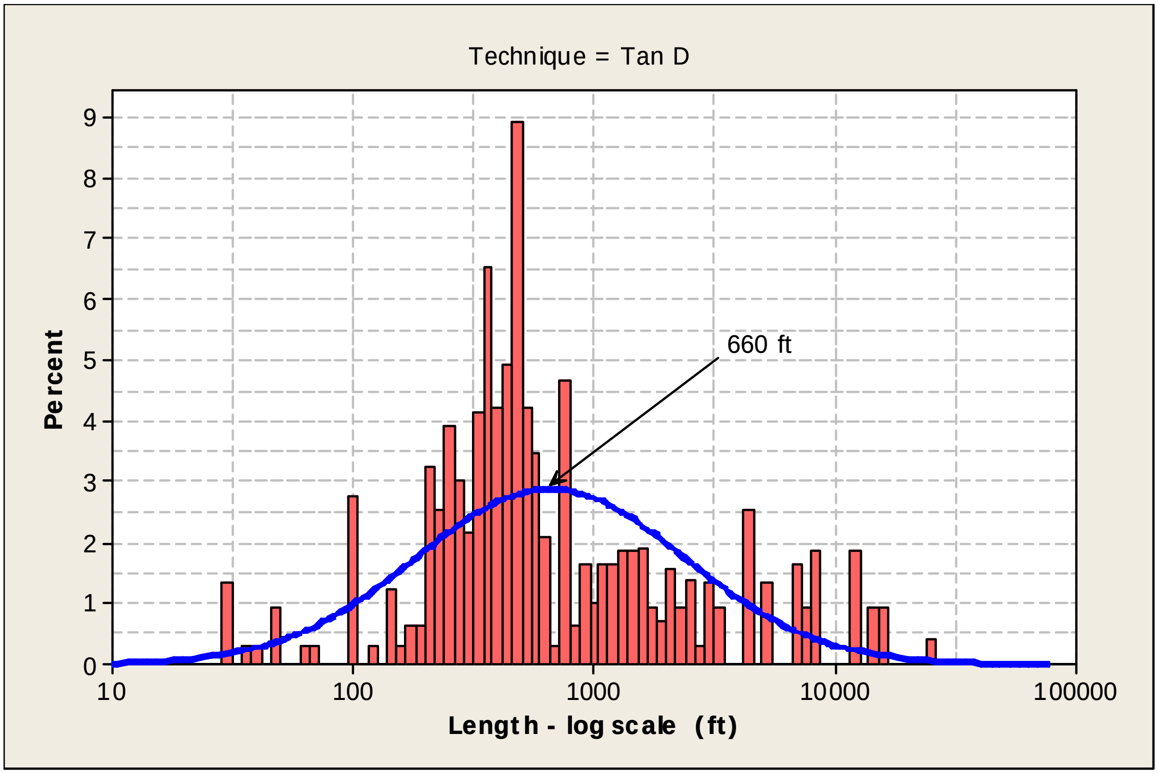


Figure 51: Cable System Lengths Tested with Dielectric Loss Techniques

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

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

An analysis of a large body of Tan δ field measurements gathered using a sinusoidal VLF voltage source established how the data correlates to both the IEEE Std. 400™ performance requirements and the performance requirements developed in the CDFI.

Figure 52 and Figure 53 classify the data according to IEEE Std. 400™, using Tan δ and Tip Up criteria as "either / or" requirements. Thus, a segment with Tan δ of 1.5E-3 and a Tip Up of 2E-3 is classified as "Highly Degraded" based on the Tip Up whereas the Tan δ would suggest a classification of "Aged." Note that the standard does not have criteria for paper or filled systems.

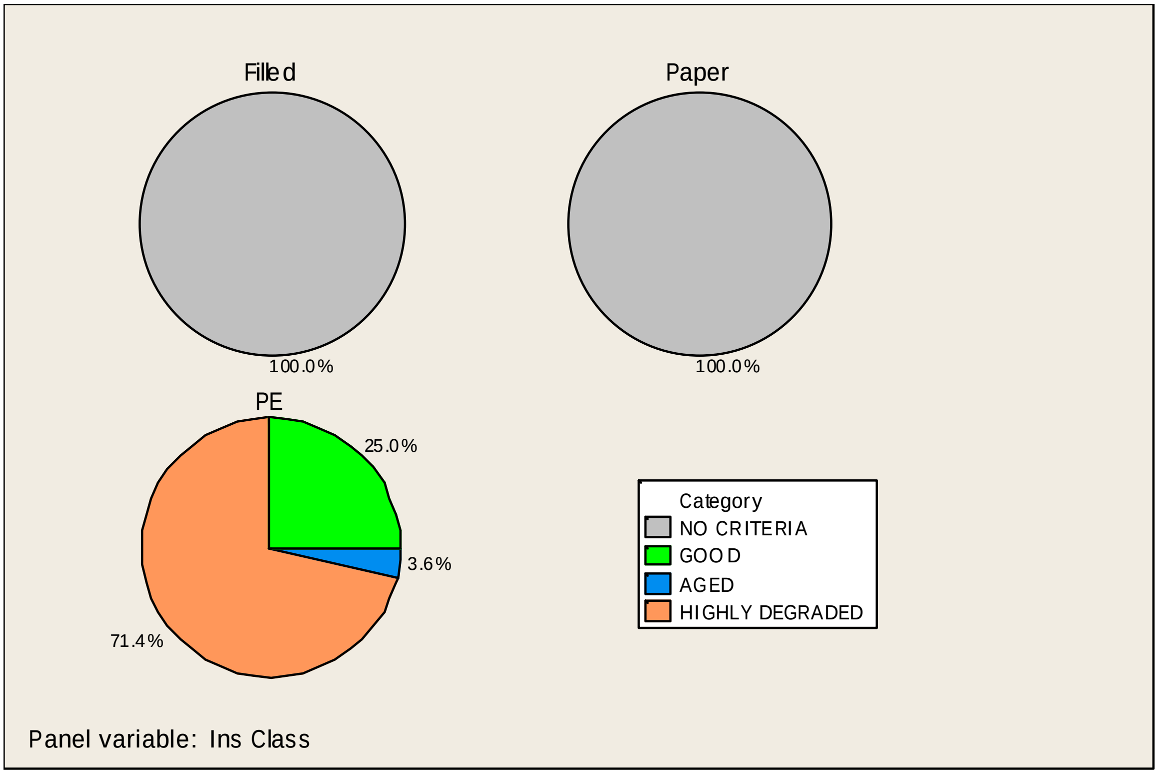


Figure 52: Distribution of Dielectric Loss Classifications Based on IEEE Std. 400™

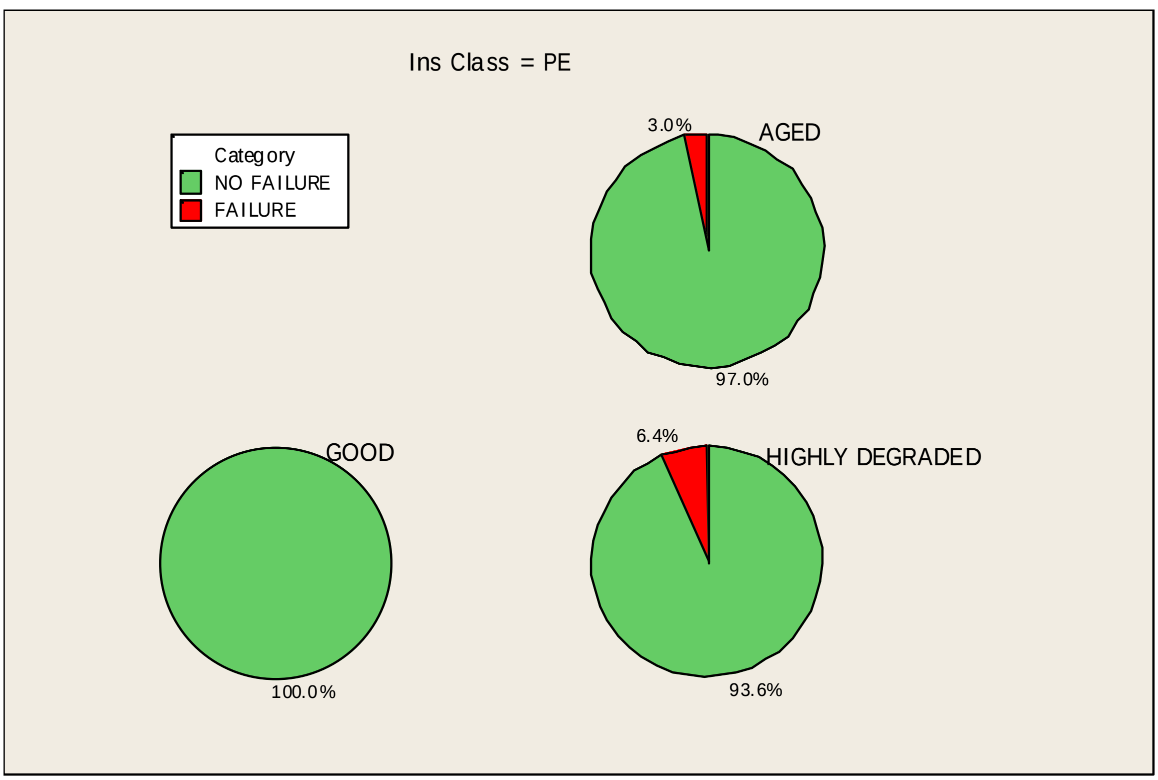


Figure 53: Correlation of Actual Performance (Failure on Test or in Service) with the IEEE Std. 400™ Classification Approach

Figure 52 clearly shows the concerns with IEEE Std. 400™ in that these levels classify more than 70 % of the segments as "Highly Degraded" while Figure 53 shows that only 7% of these segments actually went on to fail either in service or on test.

Figure 54 shows the same dielectric loss data used in Figure 52 but classified using the "atypical" approach developed in the CDFI for the Differential Tan δ and Tan δ, with the values being derived from the analyses shown in Figure 39, Figure 40, and Figure 42. In this approach, filled and paper insulations may be addressed. The resulting service performance appears in Figure 55.

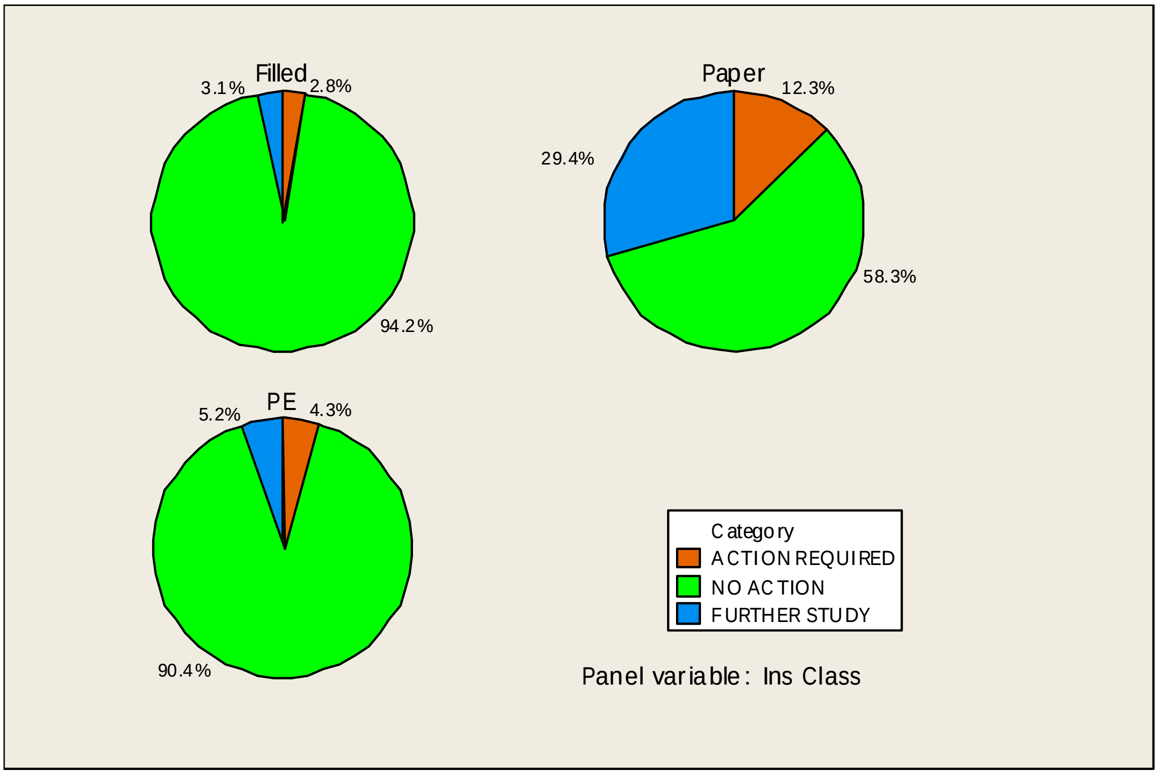


Figure 54: Distribution of Dielectric Loss Classifications Using Criteria based on Identifying "Atypical" Data

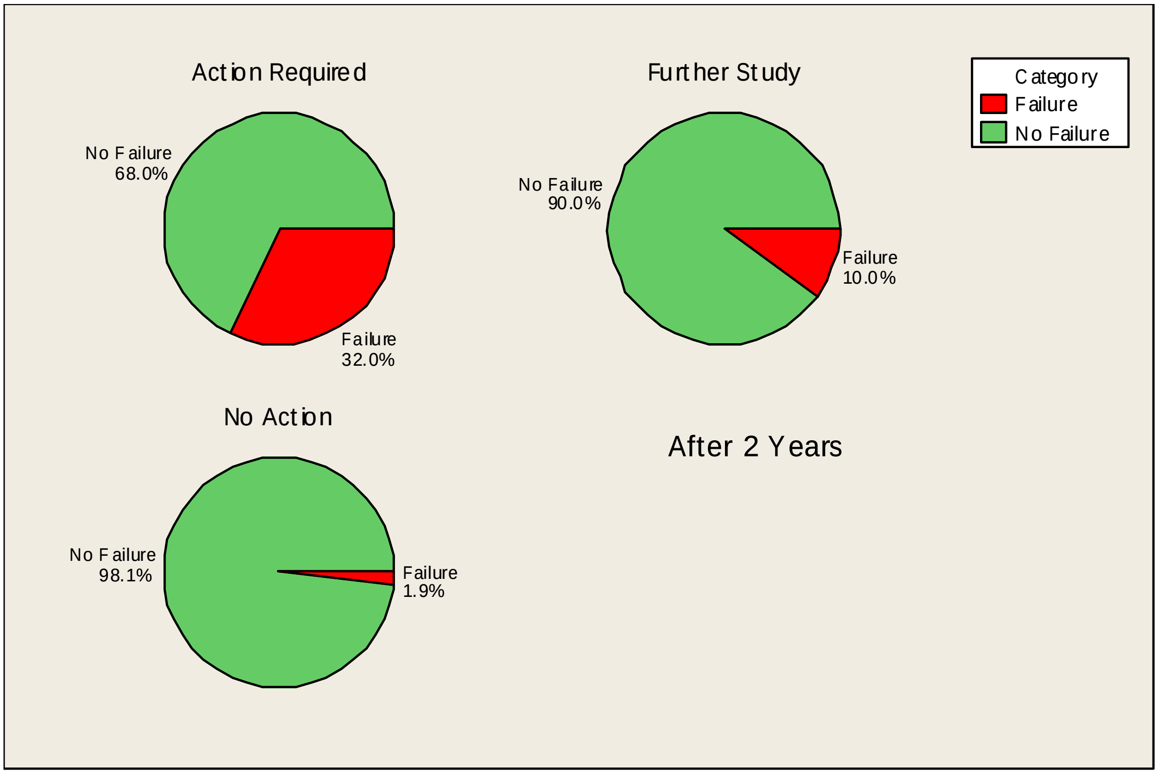


Figure 55: Correlation of Actual Performance (Failure on Test or in Service) with the "Atypical" Data Approach

Figure 55 shows that a much higher percentage of the segments classified as either "Further Study" or "Action Required" do go on to fail as compared to the levels in IEEE Std. 400™ (Figure 53). Furthermore, the percentage of segments classified as requiring some sort of action represents less than 10 % of the population as compared to more than 70 % for PE using IEEE Std. 400™. The less conservative levels in the "atypical" approach do have a downside in that there are failures in the "No Action" group as well, albeit a small percentage. Still one must bear in mind that no diagnostic will give a correct diagnosis every time. The choice of levels affects the risk the utility assumes and the number of actions the utility needs to perform. More actions lead to higher costs but less risk.

Figure 54 considers all the Tan δ data combined as one data set. It is also useful to examine how different utility data sets distribute among the condition classes. Figure 56 shows the distribution for each insulation type and class for the "atypical" approach using the box and whisker format. Figure 56 allows a utility to determine how similar its measurements are to other utilities. Figure 57 gives the length-adjusted occurrence of the classes for the different data sets in Figure 56, also in box and whisker format. Not surprisingly, the distribution for each utility (shown by the individual data points) is different but the median occurrences for the action classifications (i.e. all classes except "No Action") are all less than 0.7 per 1,000 ft.

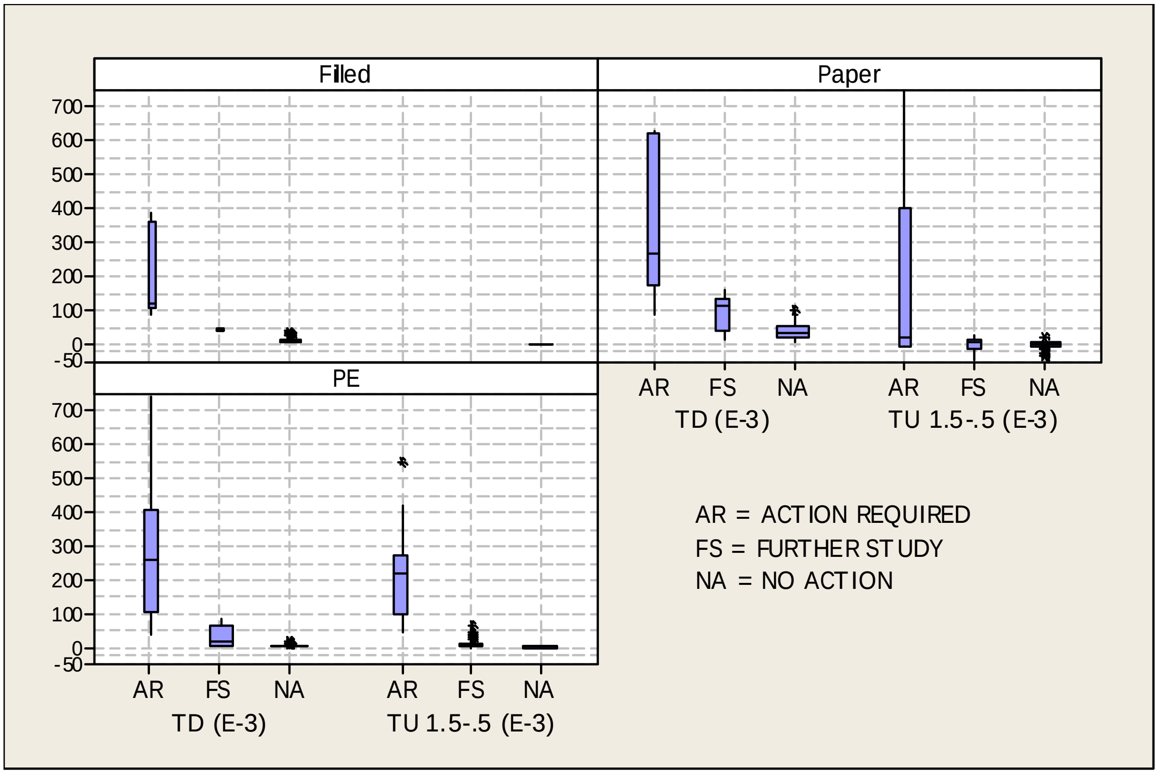


Figure 56: Tan δ and Differential Tan δ Data for the Dielectric Loss Classifications based on Identifying “Atypical” Data (Figure 54)

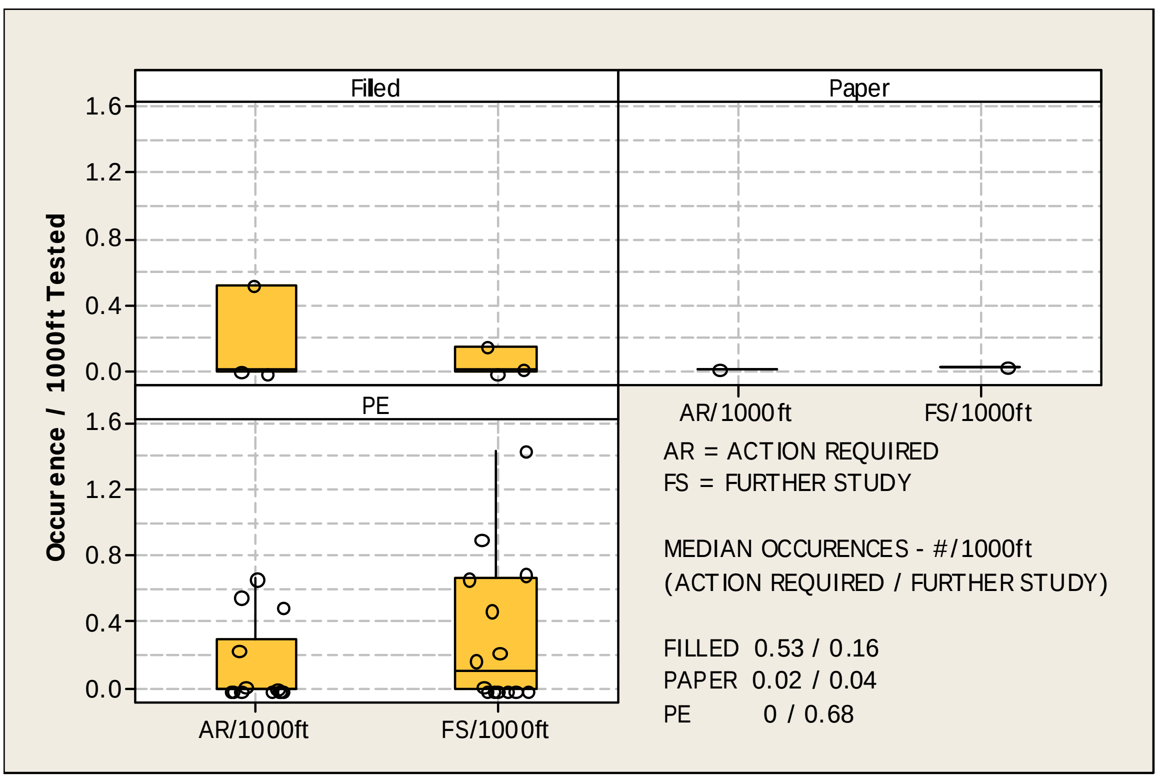


Figure 57: Occurrence of Dielectric Loss Classifications based on “Atypical” Data

Figure 54 shows that using the "atypical" levels and multiple features give a distribution much closer to what a utility might expect. Failure data are also available for these classifications and the usual Weibull time analysis of these data is shown in Figure 58. These data result from measurements made by or supplied to CDFI. These systems were left in service and their performance (measured by service failures) was tracked. The lower times correspond to the failures on dielectric test (FOT). The quality of the fit is also worth noting since the distribution fits the available data well, which leads to several significant conclusions.

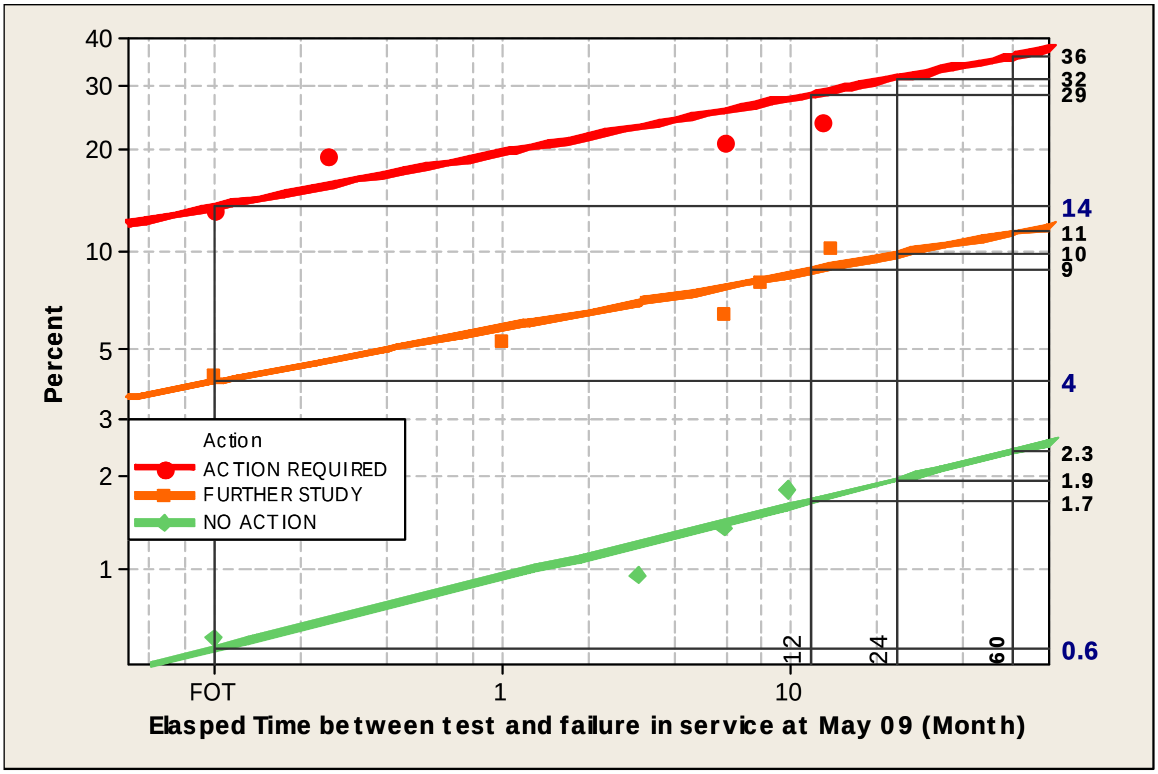


Figure 58: Diagnostic Performance Curves for Tan δ

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

One of the major issues with different diagnostic techniques and implementations is how to compare the different recommendation hierarchies. The Performance Curves in Figure 58 allow the conversion of any class designation into a probability of failure for any chosen time. For example, in the “atypical” approach for Tan δ, Table 35 shows how these data may be renamed.

Table 35: Diagnostic Class Renaming Example

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

In addition to the correlation between dielectric loss and service performance shown in Figure 58, similar and complementary evidence is shown in Figure 59. In this figure, the performance of power cables installed in an industrial environment were first tested for dielectric loss and then subjected to a VLF (generally 0.1Hz sinusoidal) withstand test. These data are the same as those used for Figure 50 but appear here in a box and whisker format. These data show that for both the filled and unfilled (PE) cable cases, cable systems possessing elevated Tan δ (the Tip Up and Stability were not measured for these systems) had a much higher chance of failing the subsequent VLF test. Although it is difficult to correlate failures on withstand with service performance, it is clear that the cable systems with the higher loss are electrically weaker and this normally correlates with shorter life.

Another conclusion from Figure 59 is that filled and unfilled systems that have Tan δ > 20E-3 or 10E-3, respectively, have a much lower likelihood of passing a VLF withstand test.

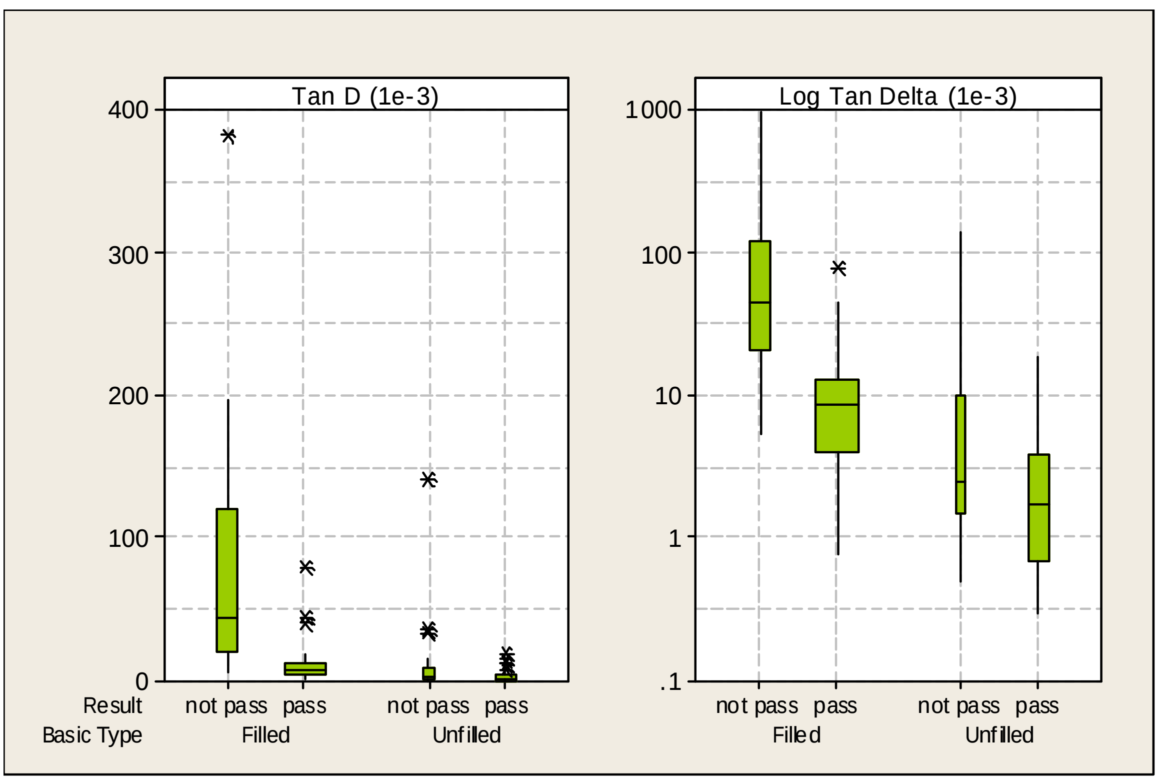


Figure 59: Relationship between VLF Withstand Performance and Dielectric Loss

The Diagnostic Performance Curves in Figure 58 and box and whisker plot in Figure 57 are very useful as they enable utilities to make an informed interpretation of the dielectric loss diagnostic data and assess what is likely to occur for different action scenarios. Table 36 demonstrates how a utility might use these collated data to develop a scenario prior to the start of the testing and thereby be better prepared for any consequences. This scenario uses 14 miles of MV cable system with 80 segments. It is important to recognize that these data originate from the available field data and these have generally followed the IEEE Std. 400™ $2U_0$ testing philosophy rather than the reduced risk approach described earlier. Thus, the estimated failures for segments after 5 years (26 %, 4 %, and 11 % for Filled, Paper, and PE, respectively) are likely to be high or conservative estimates if the reduced-risk scheme is used.

Table 36: Example Scenario Evaluation

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

3.6 Dielectric Spectroscopy

3.6.1 Test Scope

Dielectric Spectroscopy is a similar technique to Tan δ; however, the Tan δ is established by measuring the real and imaginary components of a cable system current (Figure 35) at a range of applied voltage frequencies, typically 0.001 to 100 Hz [26], [33] – [39]. The benefit of this process is that it supplies additional information about the cable system insulation. In general, the Tan δ varies inversely with frequency (since the capacitive current is directly proportional to the applied AC frequency) and will therefore be larger and more easily measured at lower frequencies (Figure 60 [28] and Figure 61 [36]). The loss current, on the other hand, remains constant with frequency unless there is degradation present in the cable system.

The data that result from dielectric spectroscopy measurements are essentially frequency spectra that contain considerable information, and consequently require more careful interpretation than Tan δ measurements made at one frequency. Note the strong frequency and voltage stress dependencies in Figure 60 and the strong frequency and age dependencies (Cable 1 – 20 yrs, Cable 2 – 50 yrs) [36] in Figure 61.

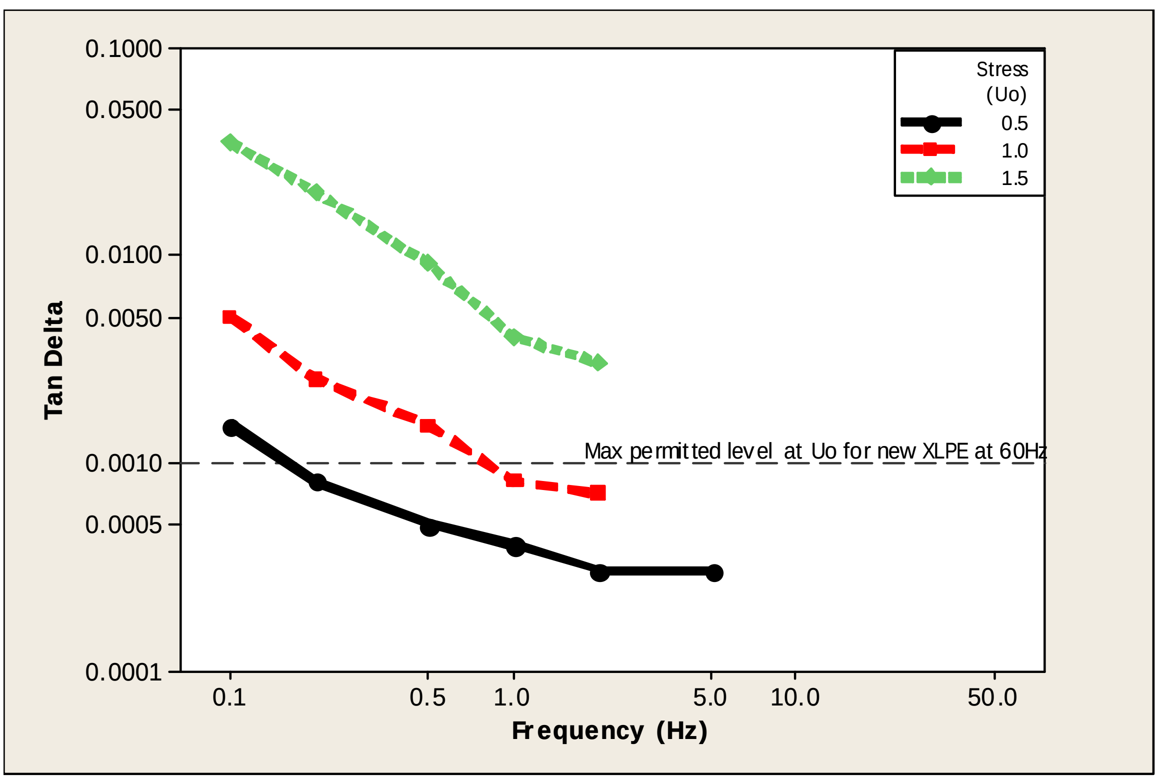


Figure 60: Dielectric Spectroscopy of Aged XLPE Cables

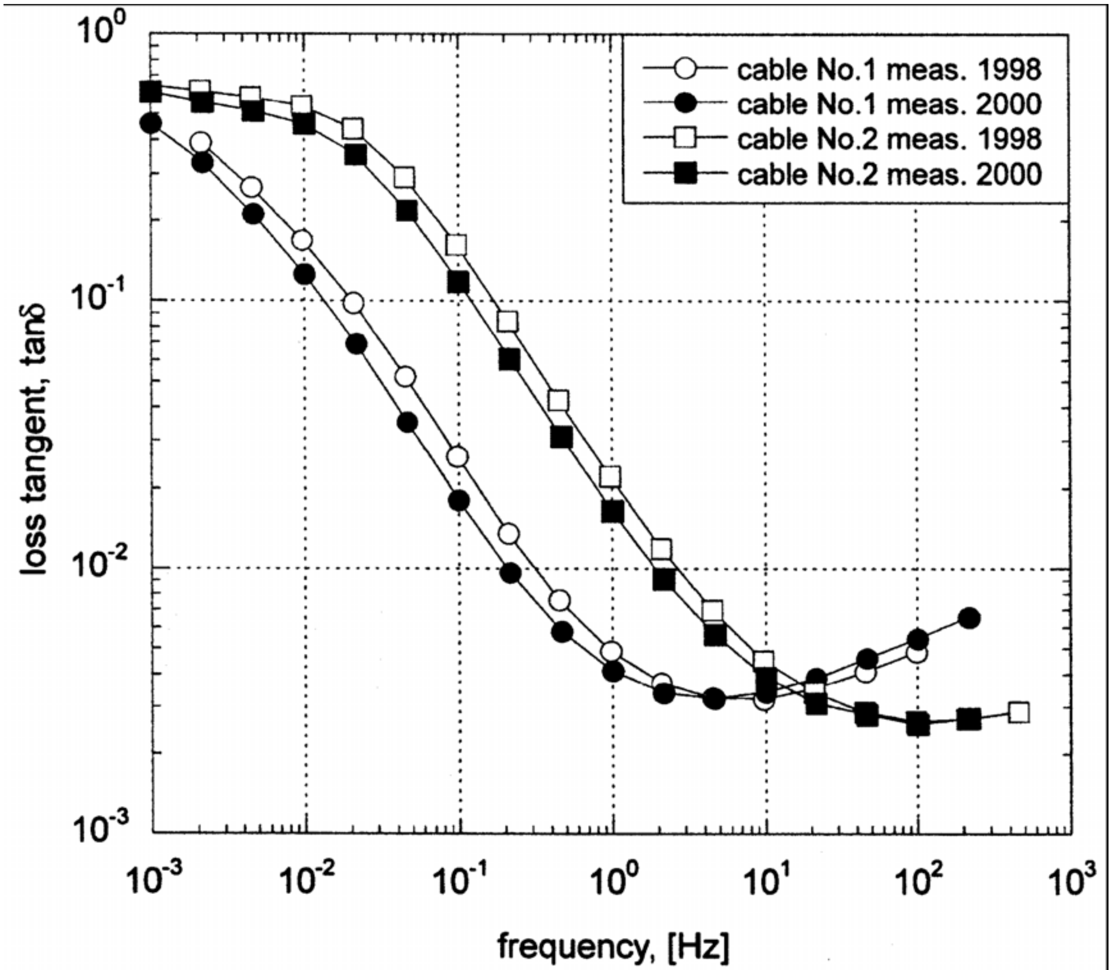


Figure 61: Dielectric Spectroscopy of Aged Paper Cables

3.6.2 How it Works

There are two ways to obtain the dielectric loss spectra:

- Frequency Domain Spectroscopy (FDS) – Employ a variable frequency source and perform conventional current measurement and phase angle calculation.
- Time-Domain Spectroscopy (TDS) – Measure a number of DC currents as a function of time and then transform to the frequency domain using the Hamon Approximation [35].

The variable frequency / conventional data (FDS approach) are obtained by applying voltages at discrete frequencies and then calculating the real and imaginary parts of the current at that frequency. The Tan δ is then the ratio of these two parts. The frequency is then stepped to cover the complete frequency range. The data may be interpreted as frequency spectra [28] or via equivalent circuit models [33, 39]. The equivalent circuit model translates the measured "complex" current into a "complex" permittivity where the real part of the permittivity represents the direct capacitance and the imaginary part represents the resistive or loss component. The Tan δ then becomes the ratio of the imaginary permittivity to the real permittivity. The effects of age, moisture, and temperature can then be analyzed using either of these approaches. Figure 62 shows examples of frequency domain permittivity measurements on paper cables with different moisture contents.

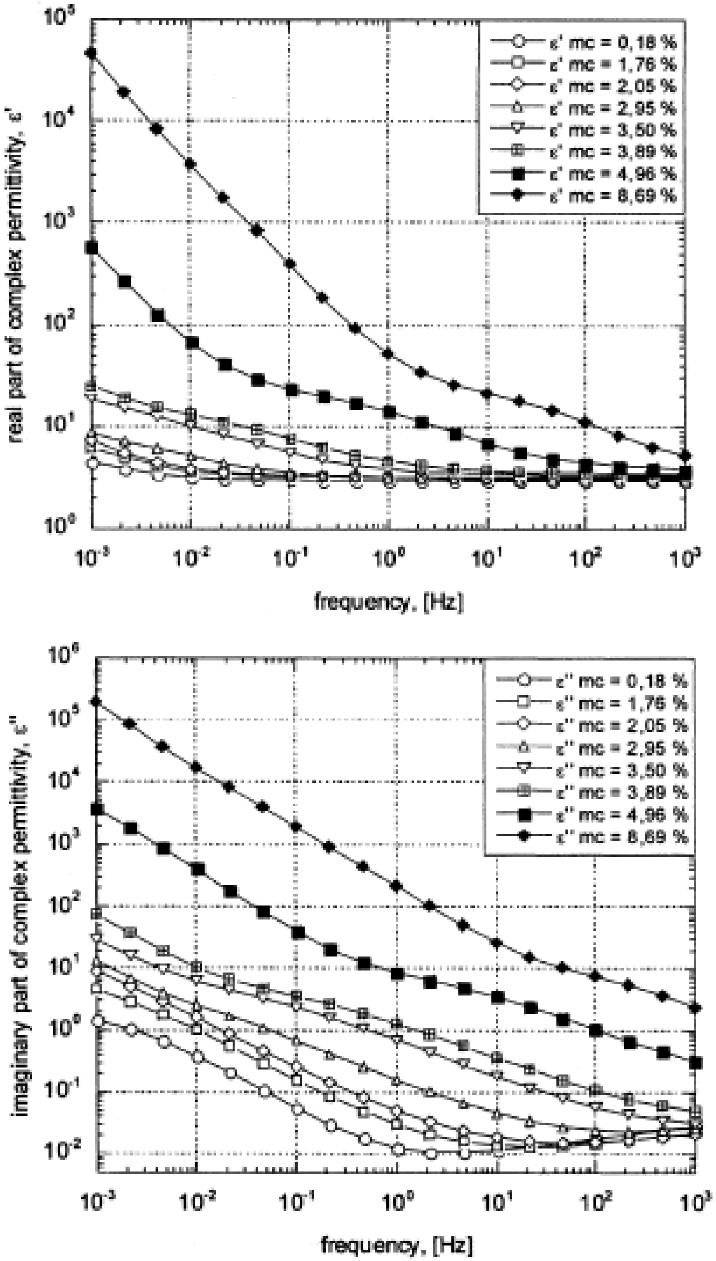


Figure 62: Real (top) and Imaginary (bottom) Parts of Complex Relative Permittivity for Paper Cables with Different Moisture Contents

The TDS approach, as compared to the FDS approach, uses a DC voltage applied for sufficient time to obtain measurements of the cable system loss current as a function of time. These measurements are subsequently transformed to the frequency domain using the Hamon Approximation. The basic approach to TDS with the contributing currents is set out in Figure 63. As this figure shows, measurements are made both with voltage (polarization mode) and without voltage (depolarization mode) applied. Three current components make up the currents measured with voltage (i_{pol}) and without voltage (i_{depol}):

- i_{cap} – Capacitive current (charging current)
- i_{abs} – Absorption current (loss current)
- i_{qc} – Space charge / quasi-conduction current

Equation (6) shows i_{pol} and i_{depol} as functions of the above current components.

$$\begin{aligned} i_{pol} &= i_{cap}(t) + i_{abs}(t) + i_{qc}(t) \\ i_{depol} &= -i_{cap}(t) - i_{abs}(t) \end{aligned} \quad \textbf{(6)}$$

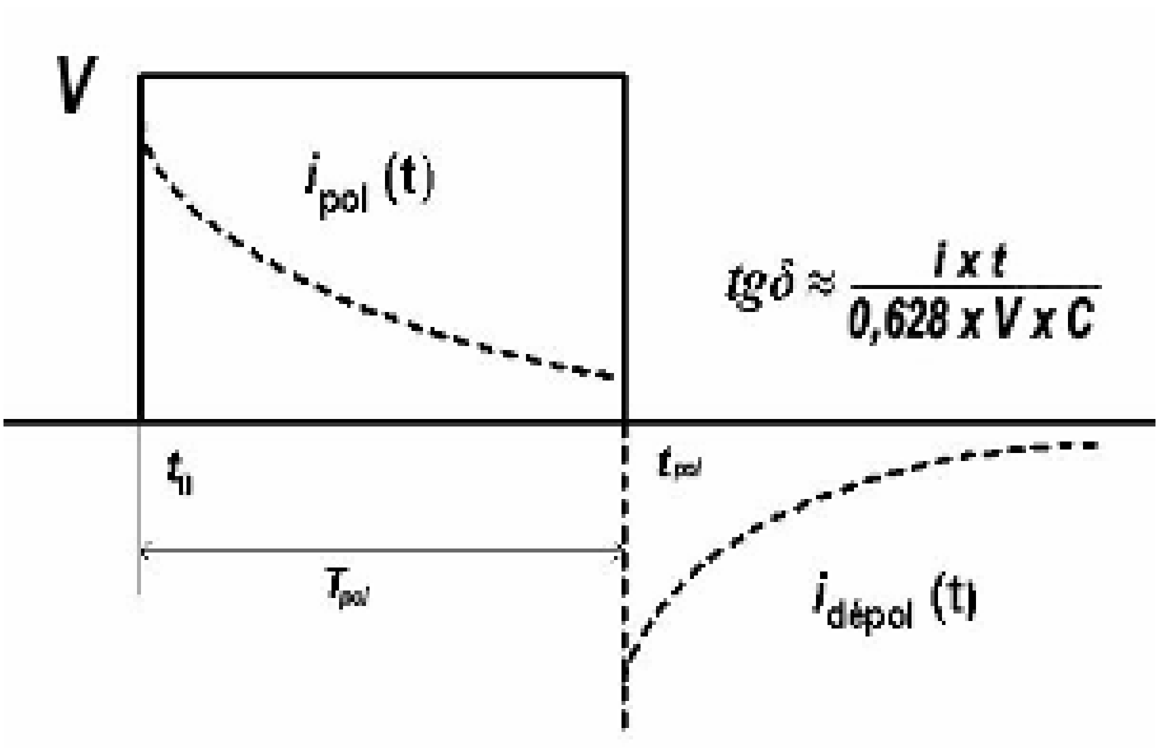


Figure 63 Currents and Voltages for Tan δ Estimation using TDS

An estimate of the Tan δ is given by the Hamon Approximation once the capacitance (C) and the absorption (i_{abs}) current are measured. Figure 63 shows that two currents can be derived from the application of DC (polarization and depolarization) thus giving two ways to estimate Tan δ via the two formulas shown in Figure 63. In theory, the polarization and depolarization absorption currents should be equal for the case where the charging time is infinitely long. Such long test times are not practical and so the charging and discharging times are selected to allow for reasonably complete charging and discharging of the dielectric, the actual charging and discharging currents end up appearing similar in shape but different.

3.6.3 How it is Applied

Figure 64 shows a TDS unit with the typical voltage application protocol used in the field. Note that the voltage protocol uses a polarization and depolarization period for each voltage step. Furthermore, the time duration of the depolarization phase is significantly longer than that of the polarization phase.

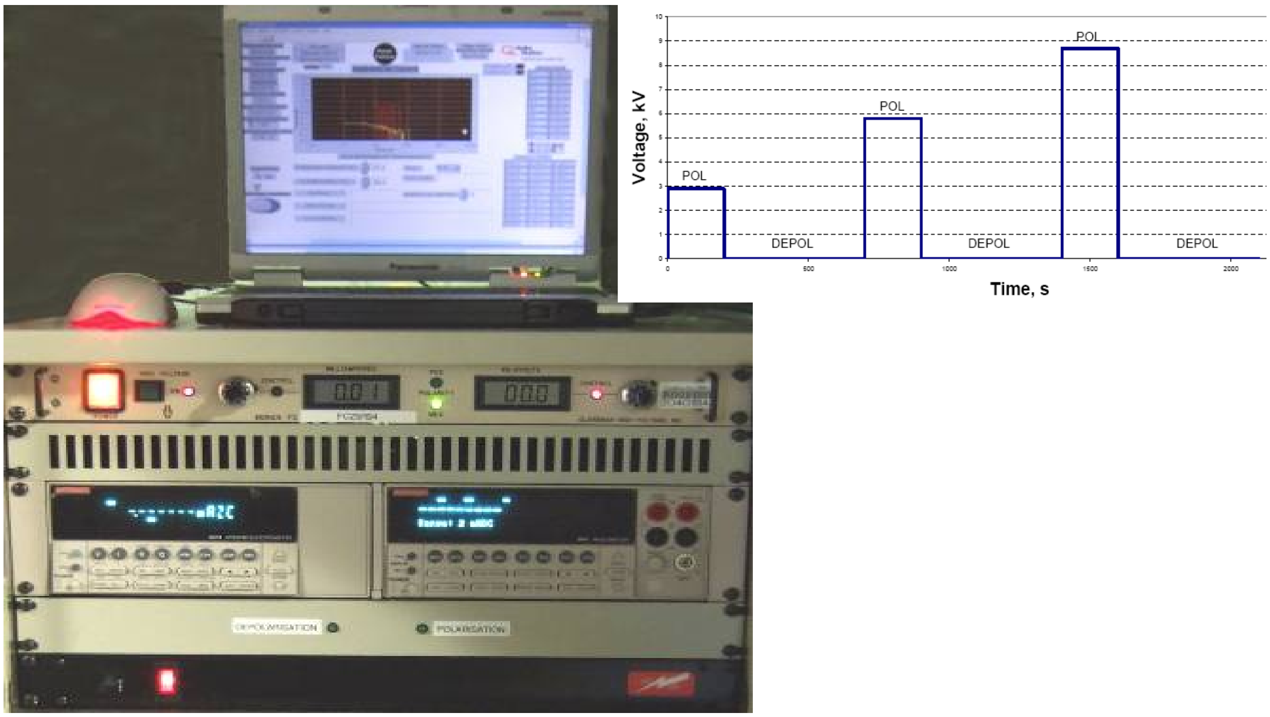


Figure 64: TDS Unit and Voltages Used for the step tests

Figure 64 shows the set up of power supply (top) and digital meters (bottom) for the measurements; not shown is a Capacitance Meter. The data obtained using the TDS approach are presented as current versus time and Tan δ versus frequency graphs as shown in Figure 65 and Figure 66. These figures show the measurements made during both polarization and depolarization modes.

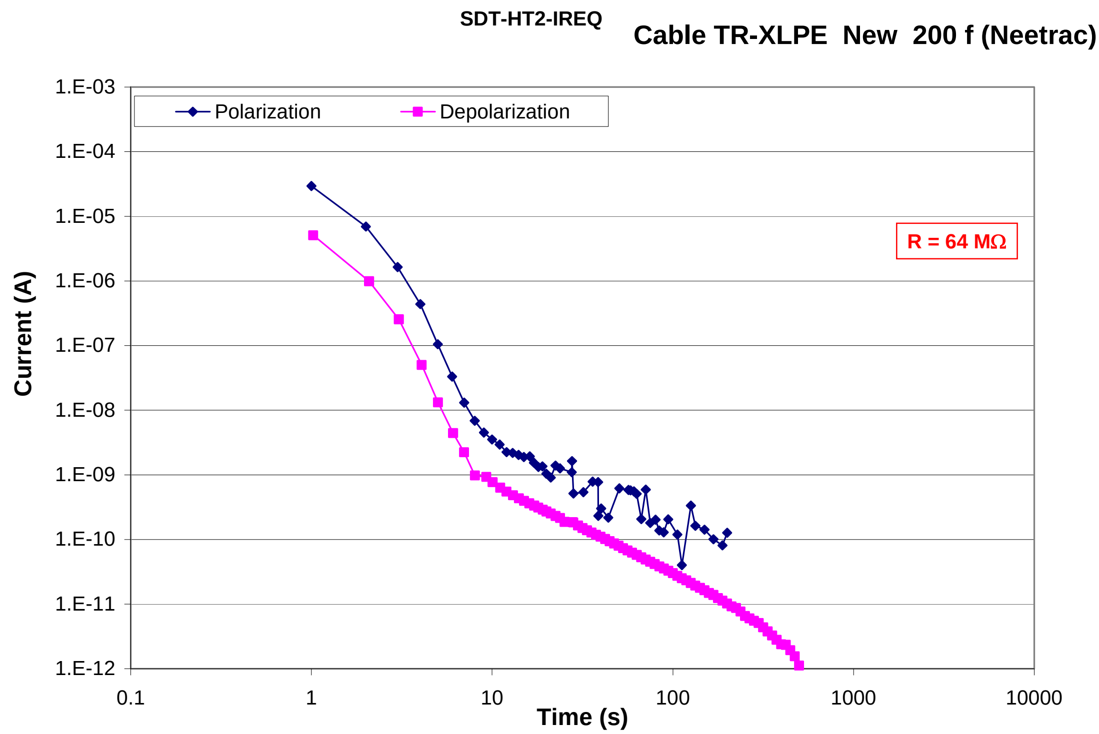


Figure 65: Time-Domain Current Measurements Using TDS Approach

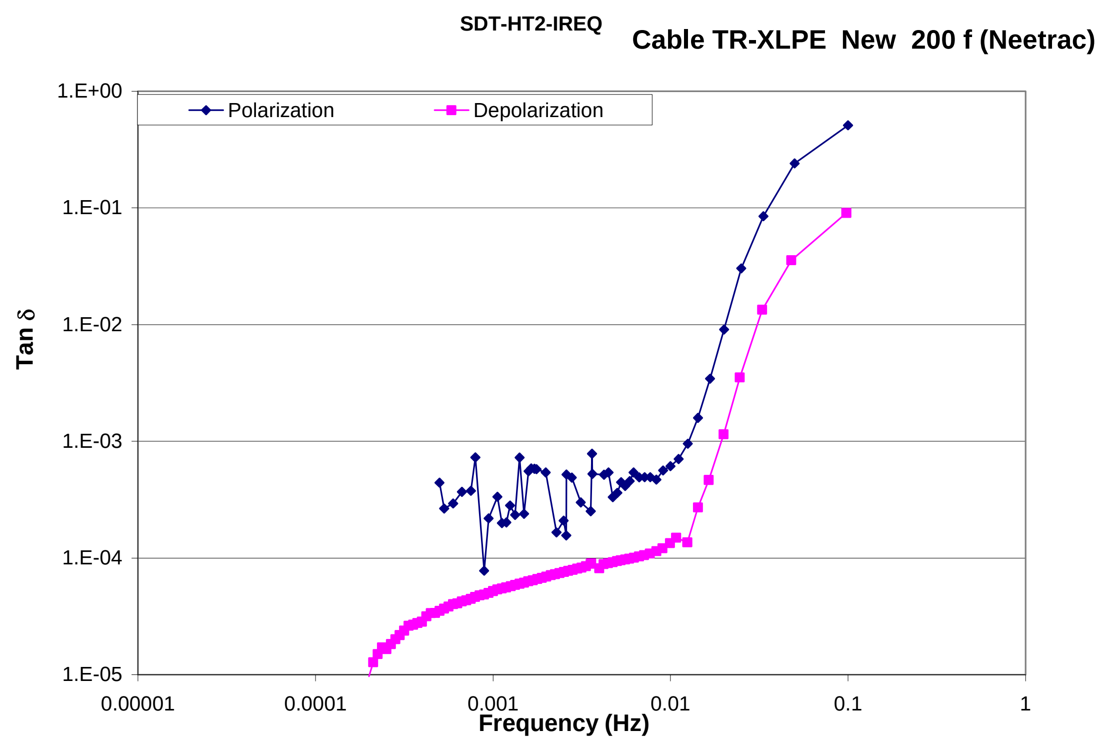


Figure 66: Transformed Tan δ Spectra from Figure 65

As the above figures show, the transformation from the time-domain to the frequency-domain is a one-to-one mapping of the data points. The currents and their components appear in Figure 65. Currents measured at short times (< 10 sec in Figure 65) are dominated by the capacitive current (i_{cap}) while currents measured at long times (>10 sec) are dominated by the absorption current (i_{abs}). The absorption current is the current that is of interest for determining the Tan δ. When these currents are transformed to the frequency domain using the Hamon Approximation ($f = 0.1/t$), shorter times correspond to higher frequencies and longer times to low frequencies so the absorption current becomes dominant at frequencies generally below 0.01 Hz. The practical consequence is that currents at higher frequencies have considerable capacitive components that mask the absorption current. This means that Tan δ measurements using the Hamon Approximation at higher frequencies (>0.01 Hz) and shorter times may not be accurate estimations of the Tan δ since the capacitive current is likely still masking the absorption current. Cable system length (capacitance) determines the precise cut off frequency for the capacitive current.

The advantages and disadvantages of Dielectric Spectroscopy appear in Table 37 and Table 38.

Table 37: Advantages and Disadvantages of Dielectric Spectroscopy for Different Voltage Sources

Source Type	Advantages	Disadvantages
DC (Time Domain)	• Testing equipment is small and easy to handle. • Multiple voltage levels up to and above U_0 can be applied. • Tip Up can be easily computed. • Comparing Polarization and Depolarization Tan δ provides an additional diagnostic feature not available in other Tan δ diagnostics.	• Long Test Times (> 10 minutes per voltage step) are required to charge and discharge the cable circuit. • Requires very low current measurements on the order of nano and pico amps. • May inject space charge at the higher voltages (>20 kV/mm and times longer than 100 sec). • The polarization and depolarization estimates of Tan δ complicate interpretation since there two estimates of Tan δ for every frequency.
Variable Frequency AC Sinewave (Frequency Domain)	• Testing equipment is small and easy to handle. • Waveform is the same shape as the operating voltage waveform.	• Test voltages may be limited to a fraction of U_0 due to the difficulty of synthesizing frequencies >0.1 Hz. • Long test times are associated with frequencies below 0.01 Hz (i.e. times >100 sec per cycle) • May inject space charge at low frequencies (<0.01 Hz) and higher voltages

The application of voltages above U_0 for a long period (defined by either cycles or time) may cause further degradation of an aged cable system. See a more detailed discussion in Section 2.0. The impact of this effect warrants consideration for all the methods of Dielectric Spectroscopy described in this section. The precise degree of degradation will depend upon the voltage level, frequency, and time of application. Thus, when undertaking spectroscopic measurements, a utility should consider that a circuit can fail during the test and may want to have a repair crew on standby.

To enhance the effectiveness of Tan δ measurements at variable frequencies, the measurements should be made periodically, preferably over several years. In general, an increase or shift in the spectra in comparison to previously measured values indicates that additional degradation has occurred.

Note that some accessories employ stress relief materials with non-linear loss characteristics (dielectric loss changes nonlinearly as a function of voltage). Some have suggested that these materials might have an influence on the measured loss values. However, the evidence available indicates that the type of stress relief may have a smaller effect on the overall loss measurement for the circuit than losses associated with severely degraded or improperly installed accessories. Therefore, the best practice is to perform periodic testing at the same voltage level(s) while observing the general trend in Tan δ over time.

Table 38: Overall Advantages and Disadvantages of Tan δ Dielectric Spectroscopy Techniques	
Advantages	• Adds Tan δ frequency dependence as a diagnostic feature • Measurements on a given phase are comparable to adjacent phases, so long as the phases have the same configuration. (Also applies to T-branched or other complex circuit configurations.) • Periodic testing provides numerical data that can be compared with future measurements to establish trends. • Indicator for the overall degree of water treeing in XLPE cable. • Data obtained at lower voltages ($<U_0$) are generally as useful as data at higher voltages. • Test results are simple numerical values that can easily and quickly be compared to other measurements or reference values. • Simple numeric results enable a quick risk assessment to be made prior to proceeding to higher test voltage levels.
Open Issues	• The relationship between the measured loss on the entire system and the loss at a specific location (such as an accessory or cable defect) needs to be established. • Development of the equivalent circuit from the data • Identification of defects from the loss measurements. • The importance of differentiating between the loss characteristics of different EPR insulation materials needs to be established. • Methods to interpret results for hybrid circuits need to be established. • How temperature affects loss measurements, especially for high loss cables, needs further exploration. • May be possible to determine the equivalent electrical circuit. • Voltage exposure (impact of voltage on cable system) caused by 60 Hz AC has not been established. • Effect of single or isolated long water trees on the Tan δ. • Usefulness of commissioning tests for comparison with future tests.
Disadvantages	• Cannot locate discrete defects. • Cable must be taken out of service for testing. • Not an effective test for commissioning newly installed cable systems. • Few data sets are available to determine the usefulness of this approach • Accurate Pass / Not Pass levels not yet established.

3.6.4 Success Criteria

There is insufficient data to provide definitive success criteria. However, the success criteria provided earlier for measurements made at 0.1 Hz are applicable for data developed at the same frequency. However, there are no guidelines on how to interpret frequency dependent Tan δ data.

3.6.5 Estimated Accuracy

The CDFI lacks sufficient dielectric spectroscopy data to estimate the accuracy of this measurement technique.

3.6.6 CDFI Perspective

3.6.6.1 Comparison with other Techniques

Collaborative work between NEETRAC and IREQ [38] has shown that, within comparable frequency ranges, 0.1 Hz VLF-sinusoidal Tan δ and DC dielectric spectroscopy (TDS) give very comparable data. Figure 67 shows results from the TDS and standard variable frequency VLF Tan δ measurement techniques on a heat shrink joint. The upper group of curves comes from the TDS polarization current measurement whereas the lower group comes from the depolarization current measurement. This finding held true for EPR, WTRXLPE, and XLPE cables and for joints as well. The data developed in the CDFI show that the Tan δ values estimated using the TDS polarization technique agree with measurements made on the same cable using the standard VLF Tan δ measurement technique. It is also possible to derive Tip Up (or differential dielectric loss data) by applying different polarization voltage levels. Note that dielectric loss estimates from depolarization (discharge measurements) do not directly follow the polarization results. In fact, this difference can be used as a diagnostic feature because the depolarization loss is a "voltage off" estimate. In a lightly degraded and, hence, linear cable system the two measurements should be in close agreement. If these measurements differ from each other, then this indicates a non-linear cable system that must have some form of degradation present to generate this behavior.

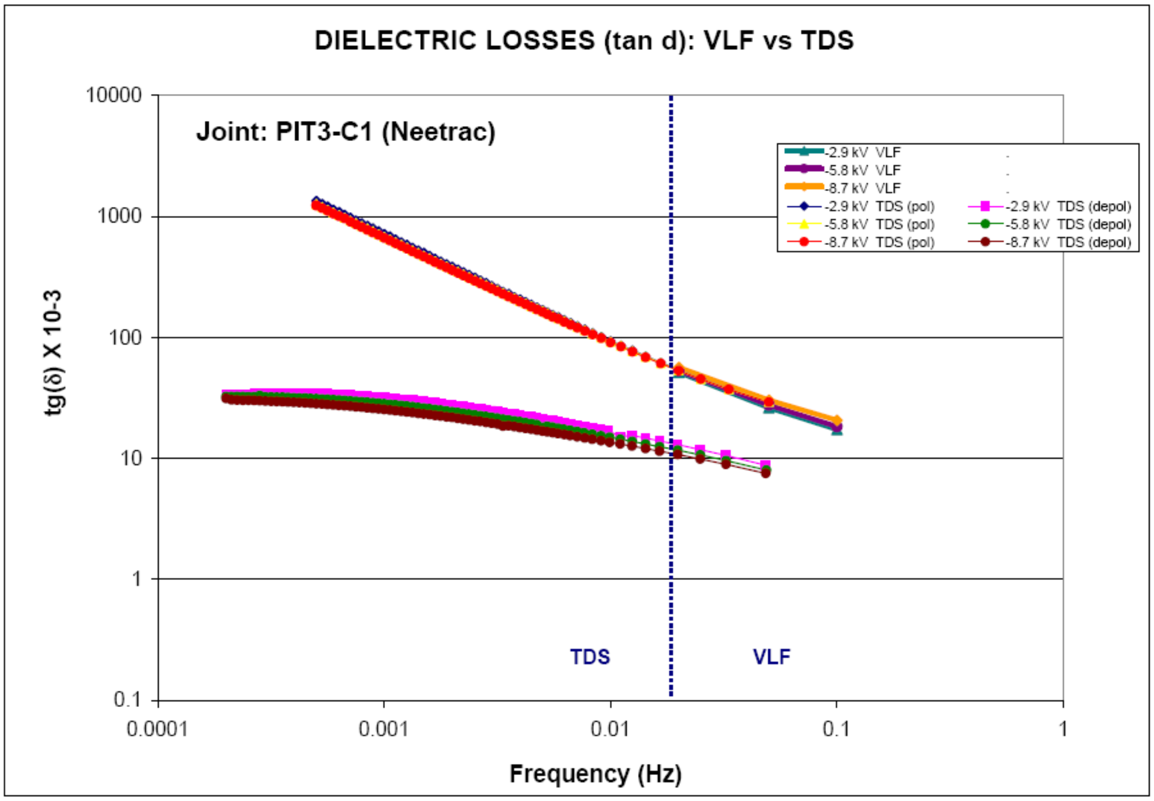


Figure 67: Frequency Spectroscopy on a Heat Shrink Joint using Variable Frequency VLF and TDS Dielectric Loss Measurement Equipment

3.6.6.2 Diagnosis for Paper Cable

Work undertaken in Sweden [36] using variable frequency Dielectric Spectroscopy provides data for paper insulated cables as shown in Figure 68. The authors of this work have suggested that the loss results are correlated to the moisture content of the cables to the extent that the loss measurements may be used to determine the moisture content directly. In this case, the magnitude of the minimum loss, measured over a wide frequency band (0.001 Hz to 1 kHz), is determined, and related to the moisture content via (7).

$$Moisture = \alpha + \beta \ln(Tan\delta_{Min}) \quad \textbf{(7)}$$

where,

α,β – Constants to be determined empirically

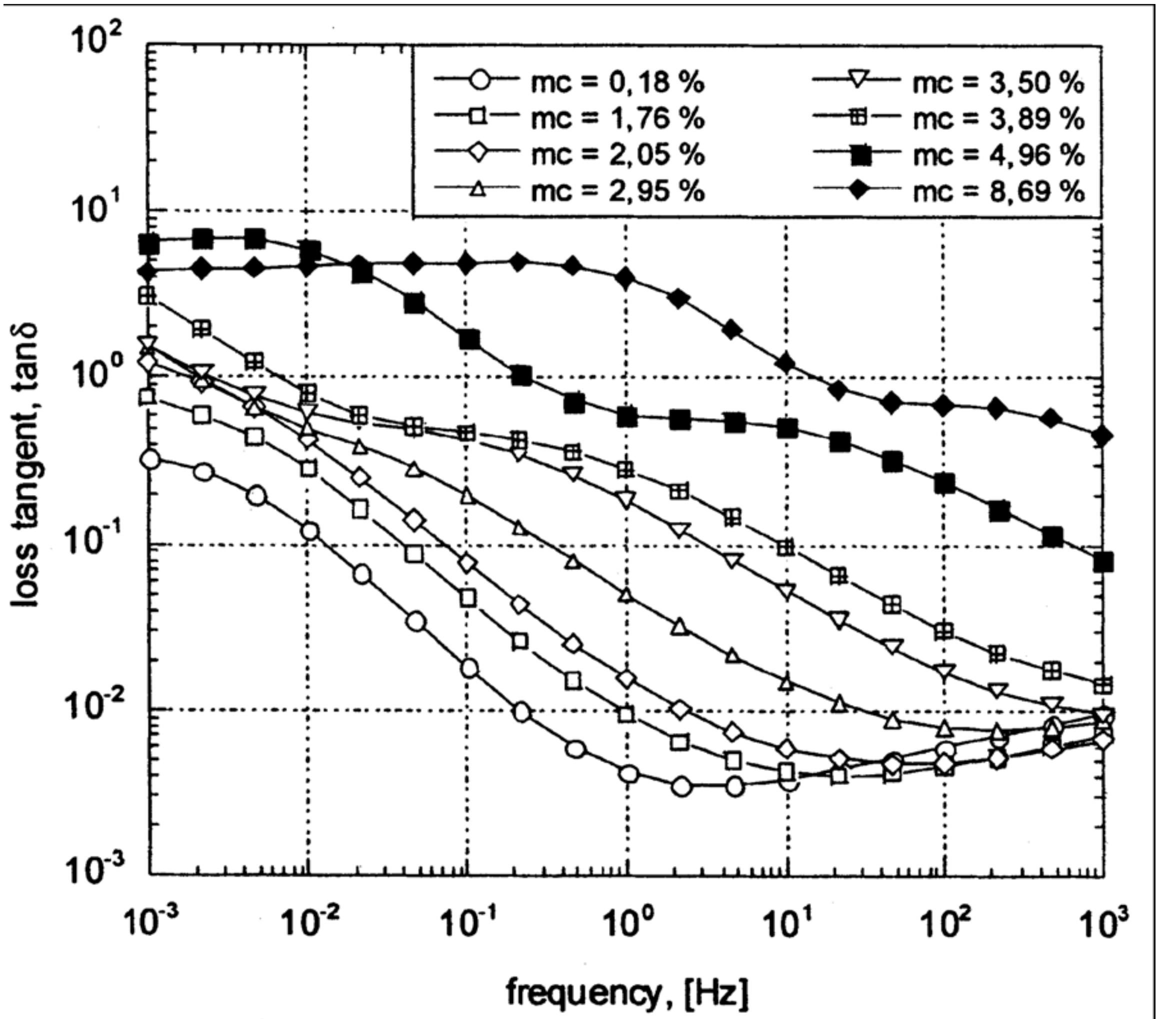


Figure 68: Relationship between Loss and Frequency for Selected Moisture Contents

This proposed correlation [36] may be practical at low moisture contents as the minima are expected to be within the low frequency range. This is not the case for higher moisture contents. Thus, it was decided to investigate the relationship of the absolute loss measured at 0.1 Hz since this frequency is commonly employed in field measurements of Tan δ. It was found that the Tan δ versus moisture data could be modeled such that Tan δ could be used to ascertain the average moisture content of the cable system. Using the data shown in Figure 68, the corresponding Tan δ / moisture content model appears in Figure 69. The data in Figure 61 were then used to test the usefulness of this model since these measurements were made on different cable systems. The reference lines on Figure 69 show the Tan δ and moisture contents measured for Cable 1 and Cable 2 from Figure 61. The model appears to be valid since these data points fall right on the curve.

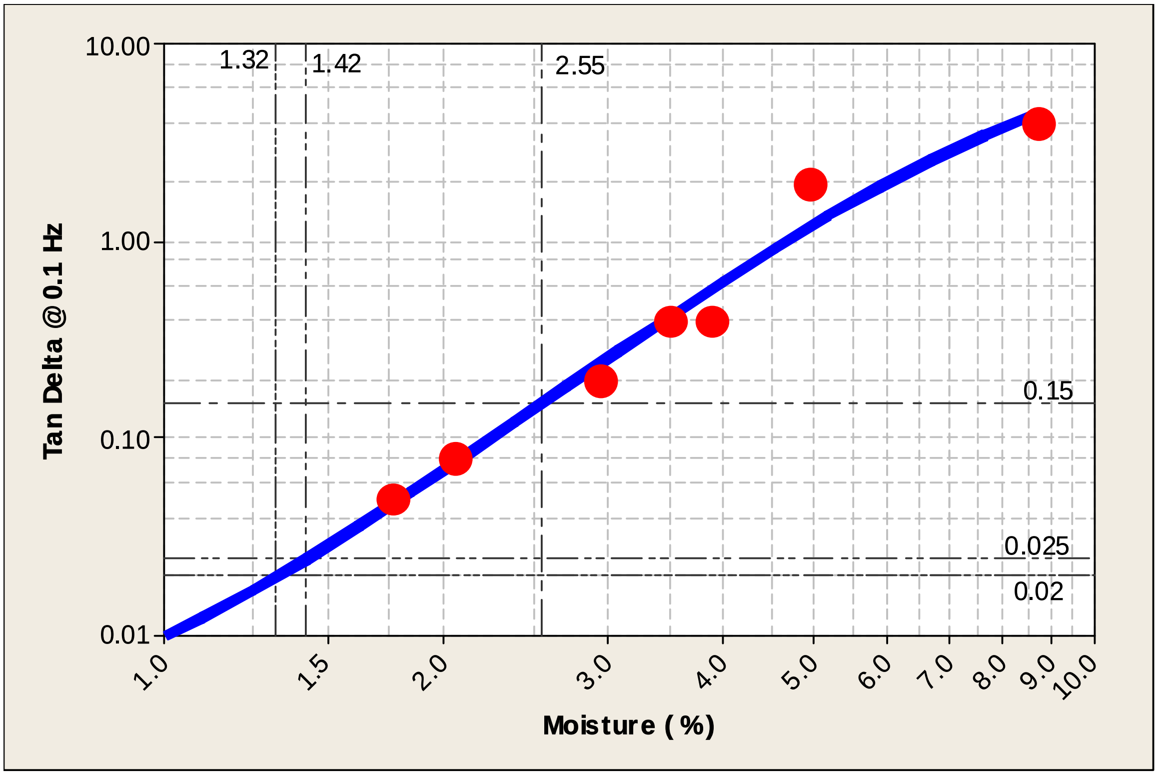


Figure 69: Relationship between Tan δ at 0.1 Hz (from Figure 68) with Moisture Content

3.7 DC Leakage Current Measurement Technique

3.7.1 Test Scope

DC leakage current tests consist of the application of DC voltage (lower than that used in DC withstand tests described in Section 3.8) with the simultaneous measurement of leakage current. It can be applied to all cable circuits. However, research has shown that the application of DC voltage to aged XLPE insulated cables can cause premature failure by injecting space charge into degraded regions of the insulation [43], [65], [66]. This trapped charge, if not discharged from the cable system leads to enhanced stress within the insulation once the circuit is re-energized with 60 Hz AC.

3.7.2 How it Works

A DC voltage is applied to the circuit. Once at steady state, the DC current required to maintain a given cable circuit at a specified voltage is measured.

3.7.3 How it is Applied

This technique is performed offline. Its intent is to measure the global condition of the cable system insulation, but it can also be useful for measuring tracking currents at insulation interfaces or on the external surface of terminations. A DC test voltage is applied between the conductor and the insulation shield and the resulting current is measured. The test voltage is increased stepwise. Each step usually takes 30 seconds. The total test duration is approximately 10 minutes. The maximum voltage is typically twice the peak value of the rated line-to-ground voltage of the cable. For new circuits, as an acceptance test, the voltage may be as high as 6 U_0.

The advantages and disadvantages of the DC Leakage Current Measurement Technique appear in Table 39.

The application of high voltages for a long period (defined by either cycles or time) may cause further degradation of an aged cable system (see more detailed discussion in Section 2.0). The impact of this effect warrants consideration for all the methods of DC Leakage Current described in this section. The precise degree of degradation will depend upon the voltage level and time of application. However, there are numerous studies that show that the rate of degradation is heightened when DC voltages are used – see discussion in Section 3.8.2. Thus, when applying elevated voltage to a cable system, a utility should have a repair crew on standby to address possible failures.

Note that some accessories employ stress relief materials with non-linear loss characteristics. There have been suggestions that these materials might influence the measured values. CDFI has not explored DC leakage testing or data analysis to any significant degree, so the true impact of these materials on DC leakage measurements is unknown.

Table 39: Overall Advantages and Disadvantages of Leakage Current Technique	
Advantages	• Provides a general (though simplistic) condition assessment of a cable system. • The technique can be automated. • Test equipment is small, inexpensive, and easy to deploy. • Periodic testing provides historical data that enhances future testing by establishing trends.
Open Issues	• DC Leakage tests may not be able to detect dirty terminations.
Disadvantages	• DC voltages (>U_0) create space charge accumulation that can cause aged XLPE insulated cables to fail prematurely after returning to service. • Before and after each test, cable must be completely discharged – these times can be long; > 4 times the length of the test. • The duration of voltage application is not well established. Typical times range from 15-60 minutes. • The cable system must be taken out of service for testing. • DC only detects severe cable system defects.

DC leakage testing has been deployed for many years and it is still used today, though mostly for industrial cable applications. In many cases, this appears to be a legacy issue from the previous common practice of DC Hipot Testing, rather than the proven efficacy of the technique.

3.7.4 Success Criteria

Leakage Current results are reported in terms of the basic data.

Table 40: Pass and Not Pass Indications for Leakage Current Measurements

Cable System	Pass Indication	Not Pass Indication
HMWPE WTRXLPE XLPE	No uniform criteria established.	No uniform criteria established.
EPR		
PILC		

There are no unified success criteria for leakage current measurements (Table 40). Establishing such criteria is complicated in that the values depend not only on the cable system quality, but also on the cable / accessory technologies employed, the applied voltage, the circuit length, and the humidity (which may impact the measurement equipment and terminations) at the time of the test.

Although no unified criteria are available, a number of references indicate some useful features that form a basis for diagnostic conclusions (Table 41).

Table 41: Useful Judgment Criteria for the DC Leakage Current Technique [40]

Observed Characteristic	Judgment		
	No signs of deterioration	**Middle signs of deterioration**	**Marked signs of deterioration**
Leakage Current changes with time during test	Current tends to decrease.	Current tends to decrease.	Current tends to increase.
Rate of Change of current changes during test	Rate of change decreases.	Constant Rate.	Rate of change increases.
Leakage Current (relative to reference cable)	Same as reference.	2 to 10 times reference.	>10 times reference.

3.7.5 Estimated Accuracy

The CDFI does not have sufficient DC leakage current data to estimate the accuracy of this measurement technique.

3.7.6 CDFI Perspective

The CDFI does not have sufficient DC leakage current data to establish a CDFI perspective.

3.8 Simple Dielectric Withstand Techniques

3.8.1 Test Scope

Simple dielectric withstand tests require the application of continuous RMS voltage at levels above the normal operating voltage for a prescribed time period. The result of these tests is either Pass or Not Pass. This approach is valid for all cable and accessory types. An alternative use of the Simple Withstand test, called Monitored Withstand, appears in a separate section.

IEEE Std. 400™ - 2001 does not consider withstand testing as a diagnostic because the result is either Pass or Not Pass. However, it is regarded as a diagnostic in the CDFI because the results can and do help engineers make cable circuit repair and replacement decisions. In addition, the details of the test result (voltage at failure, if this occurs during the ramp up, or the time of failure within the test period) may be used to categorize the performance. For example, failure 2 minutes into a 2 U_0 Simple Withstand test would be viewed as having poorer performance than a failure 20 minutes into the same test. Thus, this approach is included in this handbook because of the foregoing discussion and because many practitioners and utilities use it to determine the "health" of their cable systems.

3.8.2 How it Works

The applied voltage is raised to a prescribed level, usually between 1.5 and three times the nominal circuit operating voltage. The purpose is to cause weak points in the circuit to fail during an elevated voltage application, rather than failing while in service. Testing takes place when the impact of the failure is low and repairs can be made quickly and cost effectively [40 - 49].

3.8.3 How it is applied

This technique is conducted offline. The applied voltage can be DC, VLF, or 60 Hz AC. Typical testing voltages range from 1.5 U_0 to 3.0 U_0. If a failure occurs during the test, it is good practice to make a repair and retest the circuit **for the full test time**. See Section 3.8.6 for a cautionary discussion on the use of DC as a withstand voltage source.

The key to a successful withstand test is to apply the voltage long enough to cause electrical trees or other significant defects present in the insulation system to fail without leaving behind electrical trees that can cause the cable system to fail after it is returned to service. Because of this objective, utilities should have a Repair Crew on standby to address any possible failures.

Providers of VLF test equipment advocate [48] the use of VLF withstand voltage magnitudes shown in Figure 70 and Table 42 for a recommended period of 30 minutes. These are also the test voltages indicated in IEEE Std. 400.2™. These values are based on electrical tree growth rate data obtained from laboratory tests conducted on molded plaques imbedded with sharp needles. How this laboratory data relates to electrical tree growth rates in actual cables is unknown. However, VLF providers caution that VLF withstand tests must be performed carefully (at the proper voltage level and duration) to avoid having weak spots remain in the cable system after it is tested.

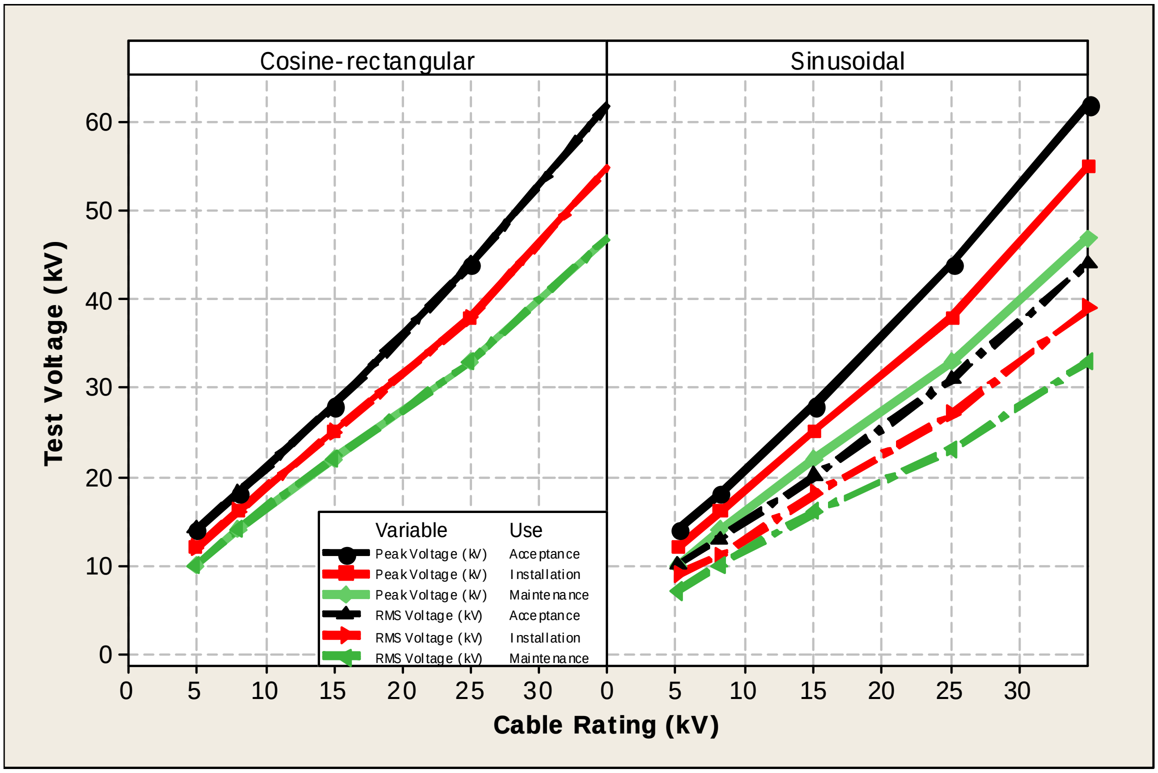


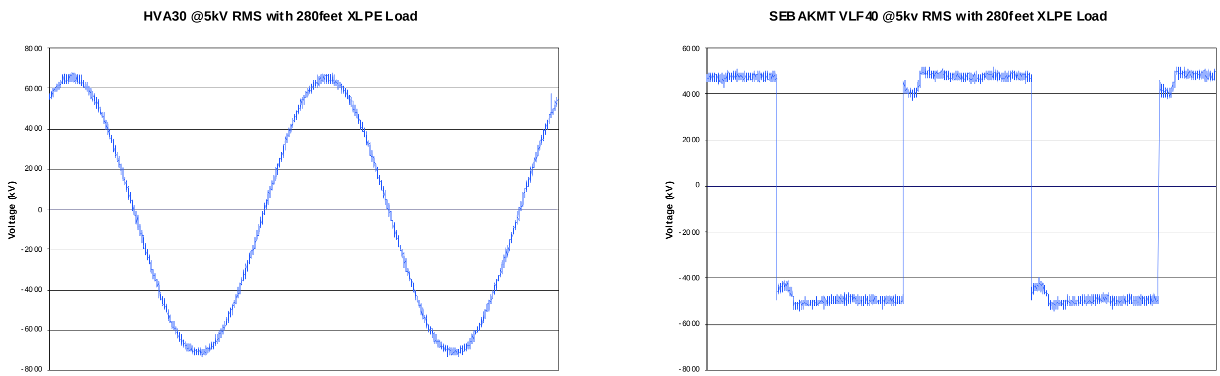
Figure 70: Cosine-Rectangular and Sinusoidal Waveforms (Table 42) VLF Withstand Voltages (IEEE Std. 400.2™ Clause 5.1)

Table 42: VLF Maintenance[1] Test Voltages for Cosine-Rectangular and Sinusoidal Waveforms (IEEE Std. 400.2™ - 2001, Clause 5.1)

Cable Rating phase to phase rms voltage (kV)	Sinusoidal				Cosine Rectangular			
	rms		peak		rms		peak	
	kV	U_0 (rms)	kV	U_0 (rms)	kV	U_0 (rms)	kV	U_0 (rms)
5	7	2.4	10	3.5	10	3.5	10	3.5
8	10	2.2	14	3.0	14	3.0	14	3.0
15	16	1.8	22	2.5	22	2.5	22	2.5
25	23	1.6	33	2.3	33	2.3	33	2.3
35	33	1.6	47	2.3	47	2.3	47	2.3

[1]- field tests made during the operating life of the cable

Waveforms for the most commonly employed VLF test devices are shown in Figure 71.



Sinusoidal Waveform **Cosine Rectangular Waveform**

Figure 71: Withstand Voltages Waveforms (IEEE Std. 400.2™, Clause 5.1)

The advantages and disadvantages of simple withstand testing are summarized in Table 43 and Table 44.

Table 43: Advantages and Disadvantages of Simple Withstand Tests for Different Voltage Sources		
Source Type	**Advantages**	**Disadvantages**
60 Hz System Voltage (Online)	• No extra equipment needed. • Serves as an easy-to-deploy commissioning test at U_0. • Able to test long lengths.	• Not able to test at elevated voltages. • Will find only the most blatant defects. • Failure on test exposes circuit to full system fault current.
30 - 300 Hz AC Offline (Series Resonant Test Systems)	• Test voltage frequency is close to the system voltage frequency. • Allows for the application of test voltages above the operating voltage.	• Testing equipment is large, heavy, expensive, and rare. • Large equipment size limits accessibility.
AC Offline Very Low Frequency (VLF 0.1 Hz) Cosine Rectangular	• Equipment is small and easy to handle. • Can test longer lengths at 0.1 Hz than sinusoidal VLF for the same size test equipment.	• Periods of elevated DC voltage reversing each cycle raises concerns over space charge injection. • Does not replicate normal operating or factory test voltage waveform or frequency.
AC Offline Very Low Frequency (VLF 0.01 – 1 Hz) Sinusoidal	• Equipment is small and easy to handle. • The test voltage waveform is the same as the operating voltage waveform.	• Does not replicate normal operating or factory test voltage frequency. • Longer circuit lengths require reducing either the frequency or voltage.
Direct Current (DC)	• Equipment is small and easy to handle. • Able to test long lengths using small equipment.	• Injects space charges, which are known to accelerate failures in cables with aged HMWPE and XLPE insulations. • Does not replicate electric stress conditions that are present under normal operating voltage. • No evidence that it provides significant benefits for extruded cable circuits. • Cascading failures can occur, which can be time consuming to address.

Table 44: Overall Advantages and Disadvantages of Simple Withstand Techniques	
Advantages	• Easy to employ. • Clear recommendations for test voltages and times in Edition 2 of IEEE Std. 400.2™. • Results for the simple withstand test are unambiguous – Pass / Not Pass. • The required action is clear (repair or replace circuit). • Can be used to test any circuit type: extruded, paper insulated, or hybrid.
Open Issues	• Some voltage-time conditions may weaken the dielectric but not cause failure, resulting in failures soon after the circuit is returned to service. • Frequency-time relationship is unclear (should the number of cycles be increased if the frequency is reduced?) • Retest procedure after failure and repair are well specified in standards but inconsistently applied by utilities. • Voltage exposure (impact of voltage on cable system) caused by 60 Hz AC and VLF has not been established.
Disadvantages	• Significantly elevated DC voltages may create space charge accumulation that can cause HMWPE, XLPE and, possibly other extruded cables to fail prematurely after returning to service. • Cable must be taken out of service for testing. • An inexperienced test operator can cause damage by applying a voltage that is either too high or for too long. • Cannot detect all possible cable system defects.

3.8.4 Success Criteria

Withstand results are placed into two classes: Pass – no action required; Not Pass – action required. Table 45 shows the requirements for Pass and Not Pass indications for simple withstand.

Table 45: Pass and Not Pass Indications for Simple Withstand *(See Section 3.1 for discussion on raw versus weighted accuracies)*			
Test Type	**Cable System**	**Pass**	**Not Pass**
0.1 Hz & 60 Hz AC	HMWPE	No Failure.	Voltage cannot be held on cable system.
	XLPE		
	WTRXLPE		
	EPR	No signs of distress[1].	Any signs of distress[1].
	PILC		
DC	PILC		

[1]Distress is defined as excessive power required to energize the tested segment, audible arcing or discharge, or any other unusual observations during the test.

3.8.5 Estimated Accuracy

The criteria for the simple withstand technique are:

- **Pass** – Circuit survives entire withstand test duration
- **Not Pass** – Circuit experiences a failure during withstand test

In both cases, the desired outcome is for there to be no failures for an undefined time in service after the test. For purposes of the CDFI, the overall diagnostic accuracy is computed for a two-year horizon. Note that in the case of a simple withstand test, the required action is integrated with the test for those circuits that fail, as they experience a failure during the test. Since the result from the test is a failure, not a condition assessment, there is no way to determine how close to failure a circuit was prior to the test. As a result, the condition-specific accuracies cannot be computed for simple dielectric withstand.

Table 46 summarizes the accuracies for the simple withstand technique. As an example, for the seven data sets investigated, 93 % of the tested circuits did not fail within two years after the test. On a weighted basis, 87 % of the cable tested did not fail. These data correspond to the median overall accuracy obtained from the distribution of all seven available accuracies. The median represents the middle data point if all data are ordered from smallest to largest. In other words, 50 % of the data points have values greater than the median and 50 % of the data points have values that are less than the median.

Table 46: Summary of Simple Withstand Accuracies			
Accuracy Type	**Simple Withstand**		
		Raw	**Weighted**
Overall Accuracy (%)	Upper Quartile	100	87
	Median	93.0	87
	Lower Quartile	87.0	87
	Number of Data Sets	7	7
	Length (miles)	7875	7875
Time Span (years)		2001 - 2008	
Cable Systems		XLPE, PAPER, EPR	

3.8.6 CDFI Perspective

A comprehensive analysis of simple withstand testing was performed with respect to circuit performance, both on test and in service after testing. This detailed analysis is possible because:

- Utilities provided the CDFI with a large number of sizeable datasets,
- Several of the datasets represent multi-year diagnostic programs,
- Results of withstand tests are easy to interpret – Pass/Not Pass,
- Some datasets include additional information (circuit ID, length, age, component that failed, etc.) that enables collation, comparison, and re-analysis / re-interpretation.

The large amount of detailed analysis performed should not be taken as an approval or endorsement of the withstand technique.

3.8.6.1 DC Withstand

The use of DC voltages to assess the condition of extruded cables has been the source of much discussion and significant work. From this work [43], [65], [66], it is clear that the application of DC withstand voltages generally does not provide very useful information about the condition of a cable circuit. This appears to be true for all cable MV cable types. In fact, for the most part, it is no longer used as a factory production test.

As discussed earlier, the application of DC voltage causes premature failures in aged, XLPE insulated cables. However, the effect of DC voltage on WTRXLPE and EPR insulations is unclear. Discussions on this topic continue in industry technical committees as experiments show that DC can inject space charges into these insulation materials, just as it does in XLPE insulation [67]. ICEA S-94-649-2004, Section 5.3 limits the voltages and times used for DC testing of new cables. Furthermore, it does not recommend DC testing on **any cables** more than 5 years old.

Therefore, since:

(a) the type of cable is generally not known at the time of testing and
(b) diagnostic tests are carried out on cables much older than 5 years

The prudent approach is not to use DC voltage for withstand testing of any aged MV cables.

3.8.6.2 Damped AC Withstand

Damped AC has been discussed in the industry as being used for withstand testing. However, it does not fit the definition of Simple Withstand used in this document, for a valid source for withstand testing. As defined in Section 3.8.1, DAC does not meet the constant RMS voltage or prescribed time criteria. To verify the effectiveness of a source data are required showing the pass and fail of components. As far as the CDFI can ascertain no such data are available for DAC. Section 3.12.6.1 contains a more detailed discussion of the issues associated with DAC.

3.8.6.3 Different Approaches to Measurement

The underlying principles of withstand (proof) measurements are common to all approaches. However, there are many ways that the required voltage stress may be applied to the system. The variety of approaches (60 Hz AC, DC, VLF AC – sinusoidal, VLF AC – cosine-rectangular) and cable system makeup makes direct comparison of withstand data difficult. In fact, utilities are cautioned not to attempt such comparisons. Fortunately, there are techniques available that can be used to overcome the difficulties such that an industry-wide perspective on withstand testing can be constructed. The following sections describe the details of the analysis undertaken by the CDFI.

3.8.6.4 Reporting and Interpretation

All variations of withstand tests report the outcome of the test as either Pass or Not Pass. However, many other data are often recorded about the tested circuit.. Table 47 is an extract from a typical withstand test data sheet received from a utility.

Table 47: Test Log (VLF AC – sinusoidal)											
Note	**Date**	**Feeder**	**Cable Type**	**Ckt Voltage**	**fs**	**Conductor Length**	**Test Voltage & Duration**	**Failure Yes / No**	**What failed?**	**Time to Fail**	**Comments**
A	5/2/2005	Y71465	PL	12	3	12,481	30min. @ 16kV rms	Yes		1:00 & 8:00	AØ fail @ 10kV BØ fail @ 8kV
	5/3/2005	H706	EX	12	1	300		No			
A	5/3/2005	Y1932	PL	12	3			Yes		11:00 & 6:00	AØ fail @ 18.1kV CØ fail @ 20.2kV
B	5/3/2005	Y71465	PL	12	3	12,481		No			Pass retest AØ & BØ
	5/5/2005	A619	EX	12	1	450		Yes	CABLE	5:00	AØ fail @ 13.7kV
	5/5/2005	E021	EX	12	1	500		Yes	CABLE	0:07	AØ fail@ 2.1kV
B	5/5/2005	Y1932	PL	12	3	20,000		No			Pass retest after 5/3/05 VLF failure.
	5/6/2005	Y1935	PL	12	3			No			
	5/9/2005	Y84048	PL	12	3			No			
	5/11/2005	Y1960	PL	12	3	32,136		No			
	5/16/2005	E2012	EX	12	1	300		Yes	CABLE	3:00	AØ fail @ =22.5kV
C	5/17/2005	L1675	EX	12	3	1,750		Yes		16:00	BØ fail @ =22.4kV
	5/17/2005	W6011	EX	12	1	1,000		No			
	5/18/2005	C1314	EX	12	3	800		No			
C	5/18/2005	L1675	EX	12	3	1,750		Yes		17:00	BØ fail 2nd VLF test @ =22.5kV
	5/20/2005	A872	EX	12	1	400		No			
	5/20/2005	E2012	EX	12	1	400		Yes	CABLE	8:00	AØ fail @ -16kV

A number of observations are worth noting in Table 47:

- These are proactive tests that were carried out using the times and voltages (30 min at 16 kV RMS) recommended for maintenance testing in IEEE Std. 400.2™.
- Failures occurred during some of the tests. However, not all of these failures were repaired and retested (see A – failures on first test and B – full retest after failure on test to confirm

that a successful repair was made). It is conceivable that some circuits were short enough that the utility chose to replace them rather than repair them.

- Although a circuit that fails the first test, is repaired, and then passes the retest (a common outcome), there are instances (see C) where more than one failure on test may occur. This is most likely to take place on longer length cable circuits where multiple defects might exist.

- There are a significant number of failures on test (see C) at times greater than 15 minutes (the lower limit presently allowed in IEEE Std. 400.2™).

As regards the last bullet above, Figure 72 shows the collated results of VLF tests from two utilities for a one-year period.

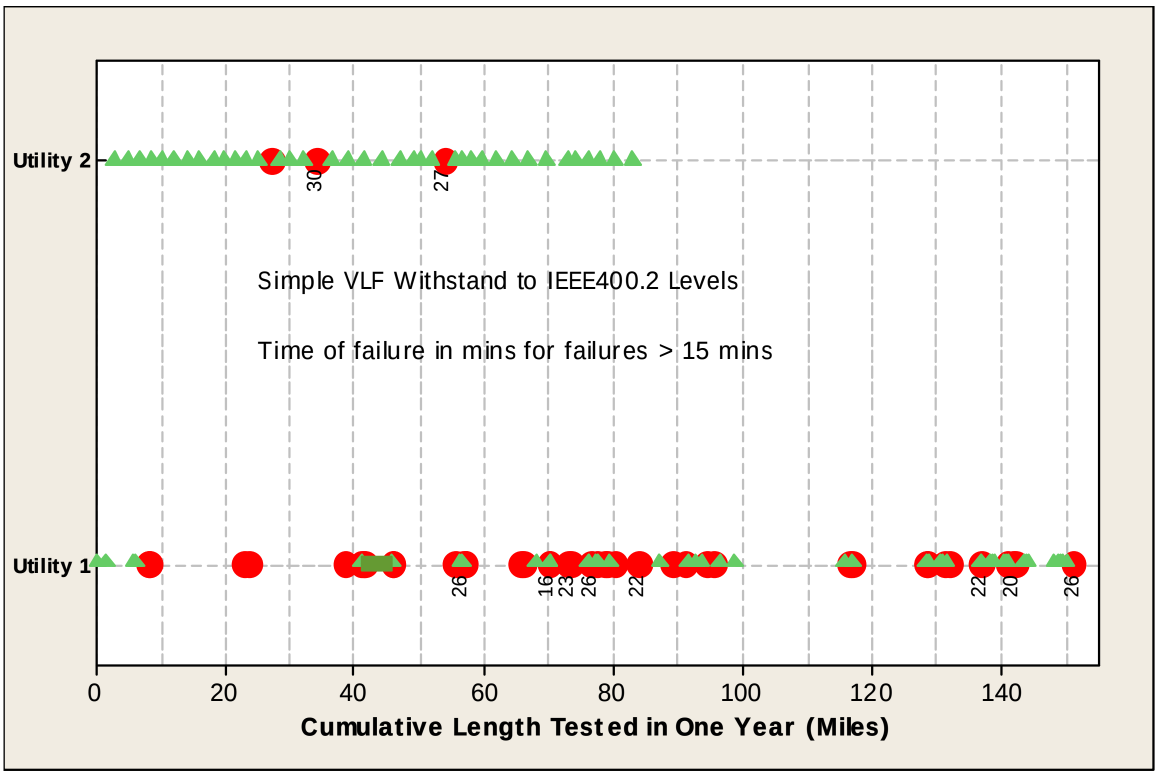


Figure 72: Collated VLF Test Results from Two Utilities over a One-year Period (IEEE Std. 400.2™ recommended 30-minute tests)

The test results shown in Figure 72 were completed using the times and voltages recommended in IEEE Std. 400.2™ (30 minute tests). The X-axis is the cumulative circuit length tested. The red symbols identify the tests resulting in Not Pass while the green symbols show the tests that resulted in Pass. The distance between two successive points represents the length of an individual cable system test. The time to failure is shown for only failures that occurred after the 15 minute lower limit allowed in IEEE Std. 400.2™ (those failures without times occurred at 15 minutes or less). The test results in Figure 72 come from data of the type recorded in Table 47.

A number of points are noteworthy:

- The majority of circuits tested result in Pass (see later discussion).
- Most failures are associated with longer test circuit lengths (see later discussion).
- IEEE Std. 400.2™ recommends a test time of 30 minutes. However, the 15-minute test time allowed in IEEE Std. 400.2™ has found favor with a few utilities. Inspection of the failure times shown above for these two utilities indicates ten failures in more than 230 conductor miles that would have gone undetected. More detail is contained in the later discussion.

A critical issue for withstand testing is the application time for the test. If the time is too short, then degraded cables may be put back into service without failing under test. Traditionally, the outcomes of simple withstand tests have been discussed in terms of the number (or proportion) of failures that occur using different test durations and voltage levels (see IEEE Std. 400™ and IEEE Std. 400.2™). The disadvantage of this approach is that it focuses on the small minority of failures rather than on the overwhelming majority of circuits that pass. A convenient way, pioneered in CDFI, to address this deficiency is to perform a Survivor Analysis. The resulting survivor curves show how the survival rate of a defined area (utility, subdivision, county, or country) declines during the simple withstand test. Figure 73 shows the data for cable circuits tested as long as 60 minutes for two utilities. It is based on data from two non-US utility studies) [42, 45, 48]

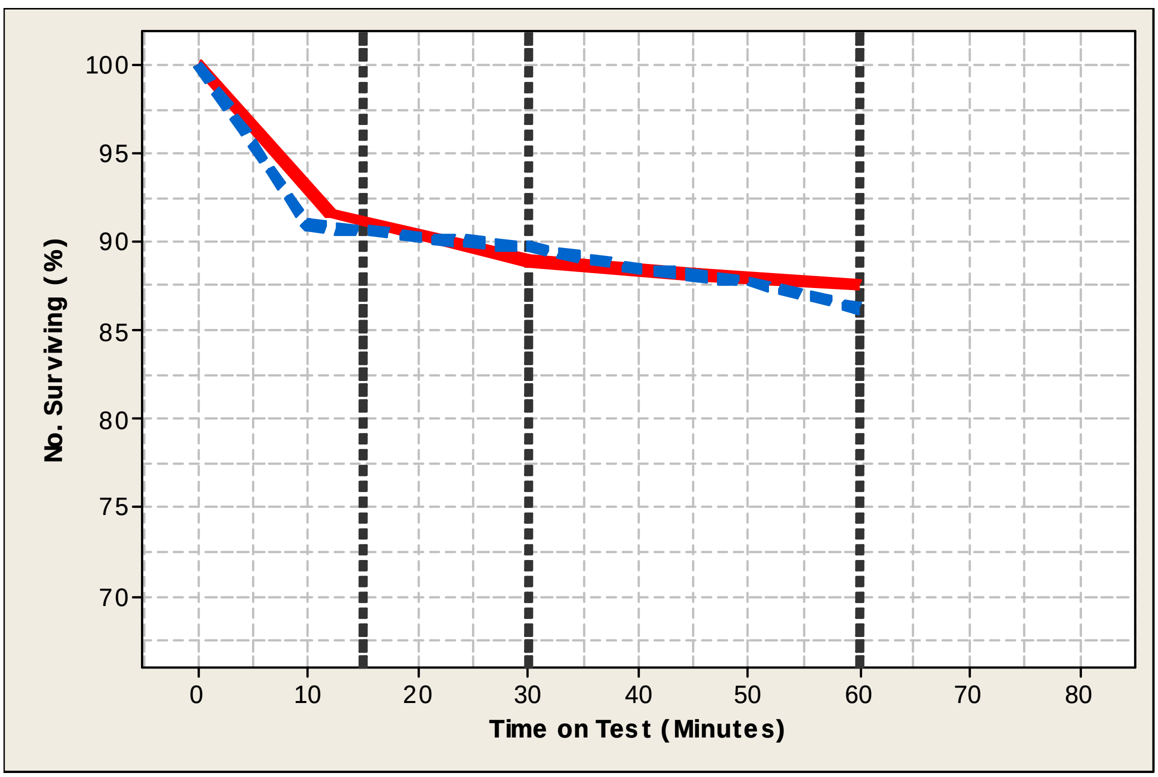


Figure 73: Percentage of Cable Survival for Selected AC VLF Voltage Application Times

Figure 73 shows that the survival curves are very similar for these two datasets. However, they are not asymptotic at either 15 or 30, or even 60 minutes. This implies:

- The test time of 15 minutes may lead to a decision to place back in service circuit segments that would have failed during a longer test.
- A test time of 60 minutes will likely capture a larger number of failures and there is still a small but finite chance of failure on test at times longer than 60 minutes.
- The absence of data for test times longer than 60 minutes makes it impossible to quantify the degree of risk (missed failures) in using test times of 60 minutes or more.

Although a longer test time would be more accurate, there could likely be a significant penalty on testing for 60 minutes.

Several US utilities initiated Simple Withstand diagnostic programs after the publication of initial test protocol recommendations in IEEE Std. 400.2™. These datasets are collated together within the CDFI. Analyses for both DC and VLF withstand tests were performed, though it is only the more extensive VLF data that are presented in Figure 74.

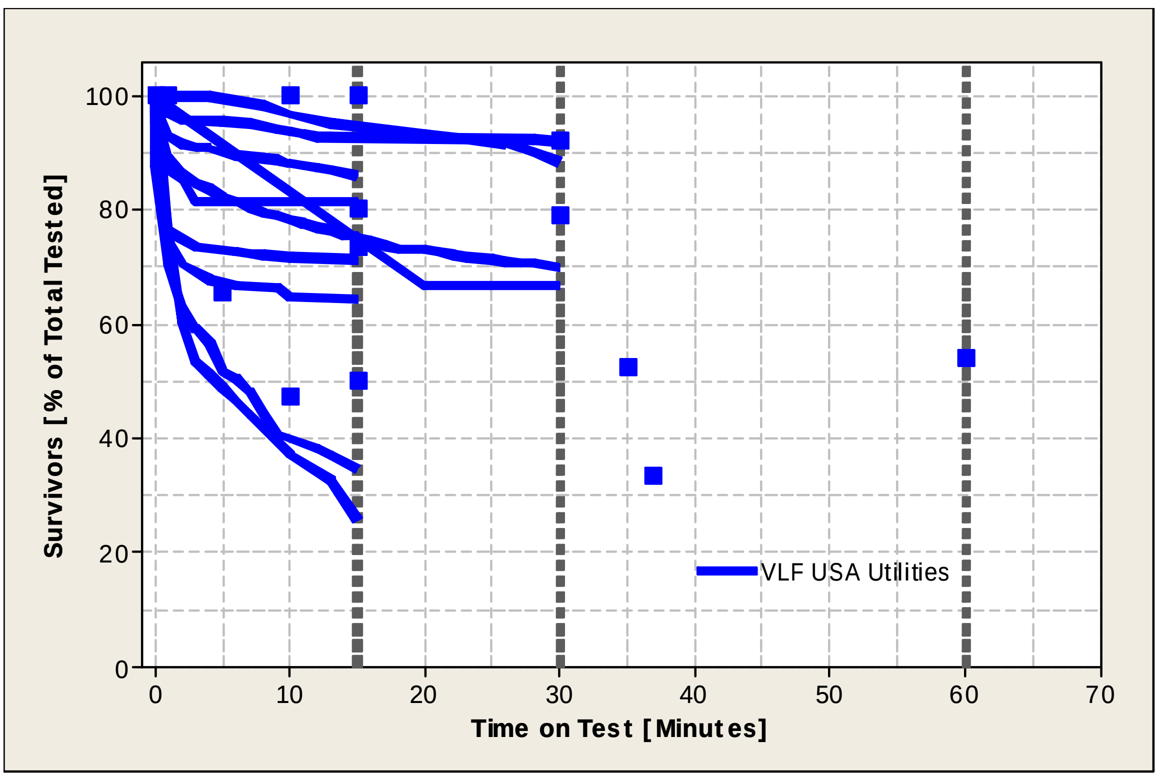


Figure 74: Survivor Curves for Collated US Experience with VLF Withstand Tests [47]

Figure 74 shows all of the simple VLF withstand data collated by the CDFI for US utilities. Again, this figure came from data of the type recorded in Table 47 in which the time to failure was recorded for each circuit that resulted in a Not Pass. The curves all follow the same general trend with 100 % survival at the start of the test and differing rates of decline down to some final levels.

Prior to this work under the CDFI, no central repository of US data existed. Engineers were required to rely on studies from Germany and Malaysia to interpret test results (data shown in Figure 72). A number of particularly noteworthy observations are:

- The median survival rate at the end of a 15-minute test is 77% of the circuits tested. However, there was no allowance for the high variability of circuit lengths included in each dataset (see later discussion).

- Although IEEE Std. 400.2™ recommends a test time of 30 minutes, most of the reporting US utilities choose to use the shorter 15-minute test time discussed in the standard.

- In principle, at the end of a simple withstand test, the survivor curve should have decayed to a stable value with a slope of zero. However, it is clear that in 50 % of the cases shown in Figure 74, at both 15 and 30-minute test times, this is not the case.

3.8.6.5 Failure Modes

Closer inspection of the survivor curves in Figure 74 reveals two important observations:

1. The number of survivors decreases rapidly early in the test for all datasets and

2. Only a few of the curves show the flattening that would indicate they were approaching an asymptote.

Traditionally, it was believed that these curves could be modeled by a single failure mode. However, the fact that the survivor curves do not approach asymptotes suggests that there is more than a single failure mode at work during the withstand test.

An analysis of the occurrence of Failures on Test (FOT) for both DC and VLF withstand tests (Figure 75) shows that there are at least two failure modes present in datasets representing a range of cable system voltages, components (accessories and cable), and insulation materials (EPR, PILC, and XLPE). In these tests, the same stresses were applied using both sinusoidal and cosine-rectangular waveforms. An allowance was made for the tests that did not result in a failure using censored data points. In addition, length adjustments (see later discussion in Section 3.8.6.4) were made to allow the cable system populations to be comparable. Most of the difference between the performance of VLF and DC tests comes from the Early (ramp) portions of the test (see Figure 75). This finding is only apparent once the failure modes are separated and length adjustments made.

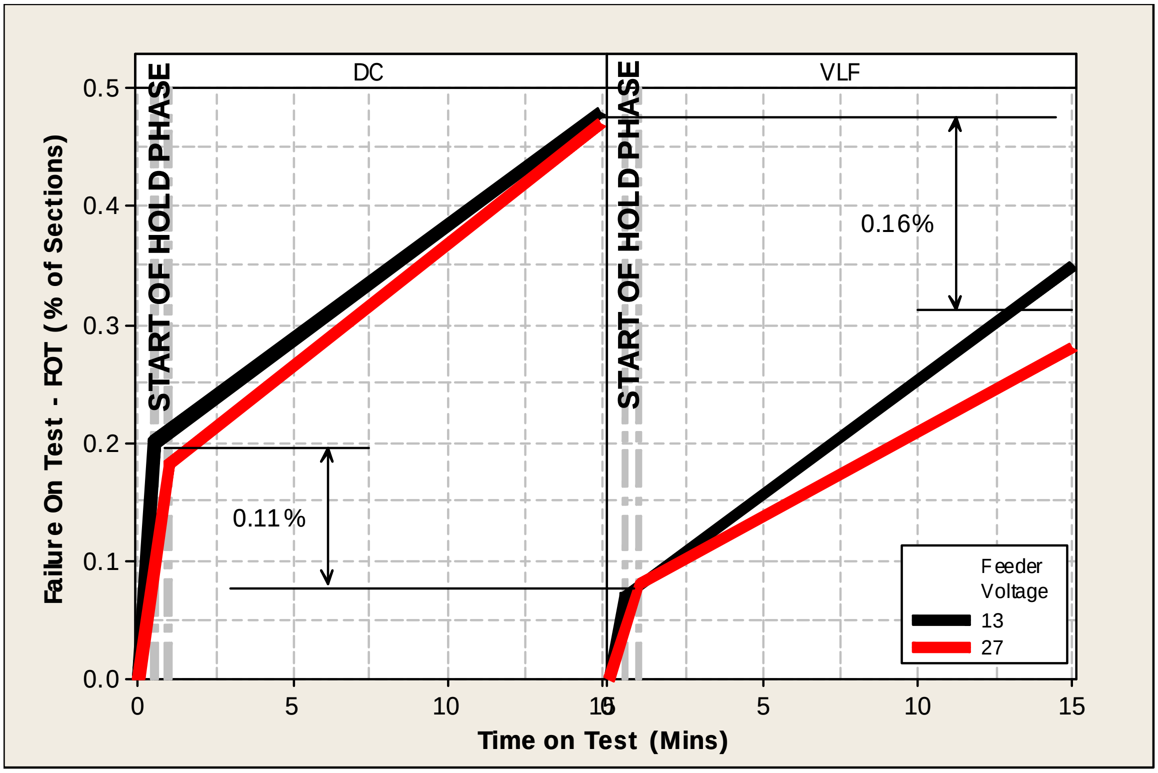


Figure 75: Distribution of Failures on Test as a Function of Test Time for DC and VLF Tests at One Utility

In analyzing the datasets available to the CDFI, it turns out to be common (Figure 76) to see two failure modes present in withstand data. Generally, these data follow the pattern of one or two modes for Early failures (Ramp or <1 minute into the test) and a different mode for failures during the constant voltage (Hold) portion of the test.

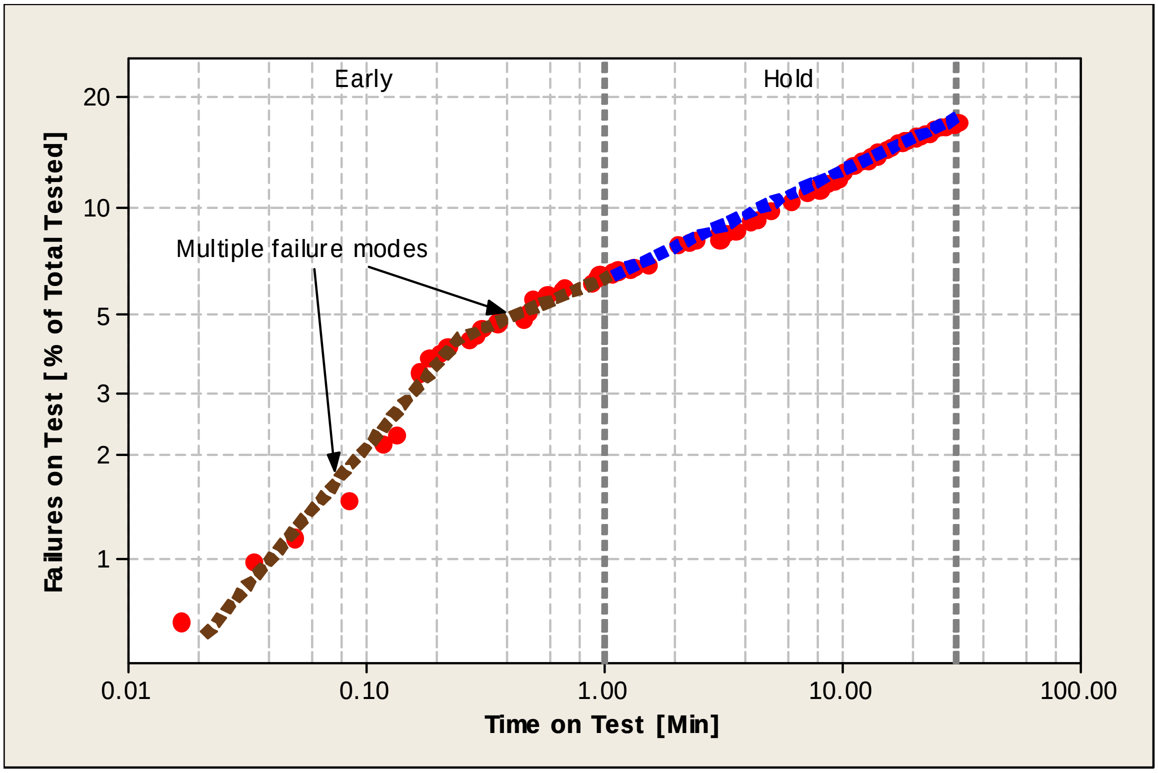


Figure 76: Distribution of Failures on Test as a Function of VLF Test Time (Direct application of test voltage without ramp phase)

Hold failure modes from different datasets appear to be similar while the Early failure modes can differ significantly between different utility data sets and voltage sources (Figure 77). The differences in the Early failure modes likely arise from the two subclasses that exist for this phase of the test. These result from the two ways voltage can be brought up to the intended test level:

- Ramp / Step Up – the test voltage is raised in steps over 30 sec to 1 min to the final Hold voltage, the test time commences once the Hold voltage is achieved.

- Hold Entry – the Hold voltage is directly applied. The voltage application is instantaneous for DC and VLF AC – Cosine-Rectangular but requires some time for the VLF AC – Sinusoidal approach (one quarter cycle).

Identifying and separating failure modes is important, especially when considering the appropriateness of test times and the expectation for the overall test outcome. Both of these elements are critical when considering the potential economic benefits of withstand test programs.

Figure 77 shows the data on DC and VLF tests where, in both cases, the voltage is raised in steps to the Hold (constant voltage) phase. The peak voltage of the failures within the Early phase was recorded and plotted using a Weibull format. This representation clearly shows that:

- There are failures at surprisingly low voltages.
- The risk of failure changes and increases rapidly above a critical stress.

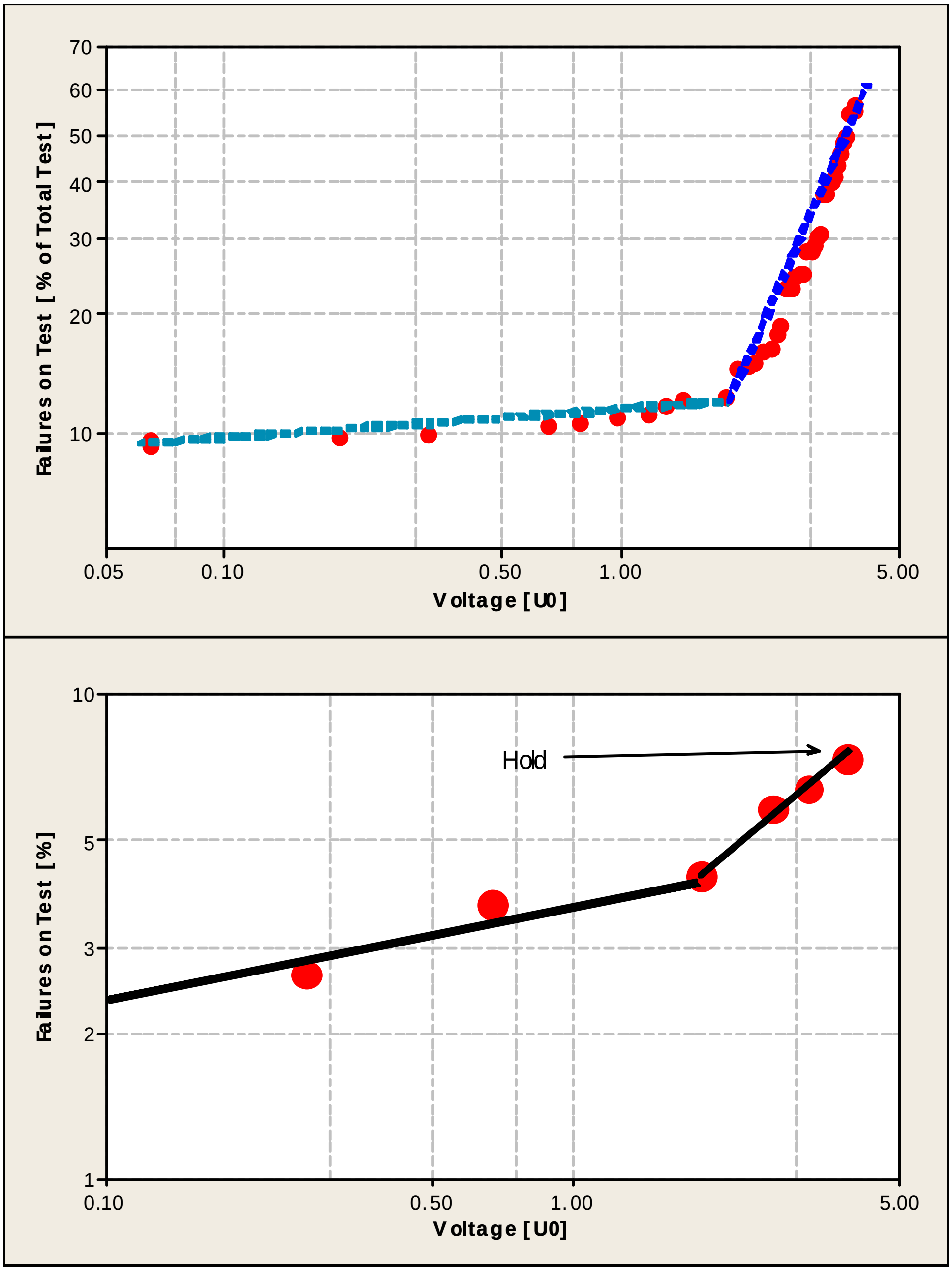


Figure 77: Dispersion of Failures on Test as a Function of Test Voltage during Ramp Phase for DC (Top) and VLF (Bottom)
(Note that the highest VLF test voltages used exceed the IEEE Std. 400.2™ recommendations)

This finding is a consequence of the simple withstand procedure itself as essentially identical features are seen when the data are separated by Voltage Type (DC, VLF), Voltage Class (Figure 78), Insulation (EPR, Paper, XLPE), or Component (Cable, Accessory). In Figure 78, where Voltage Class separates the data, the data show the mode separation of Early from Hold, and the two sub-modes within the Early failures.

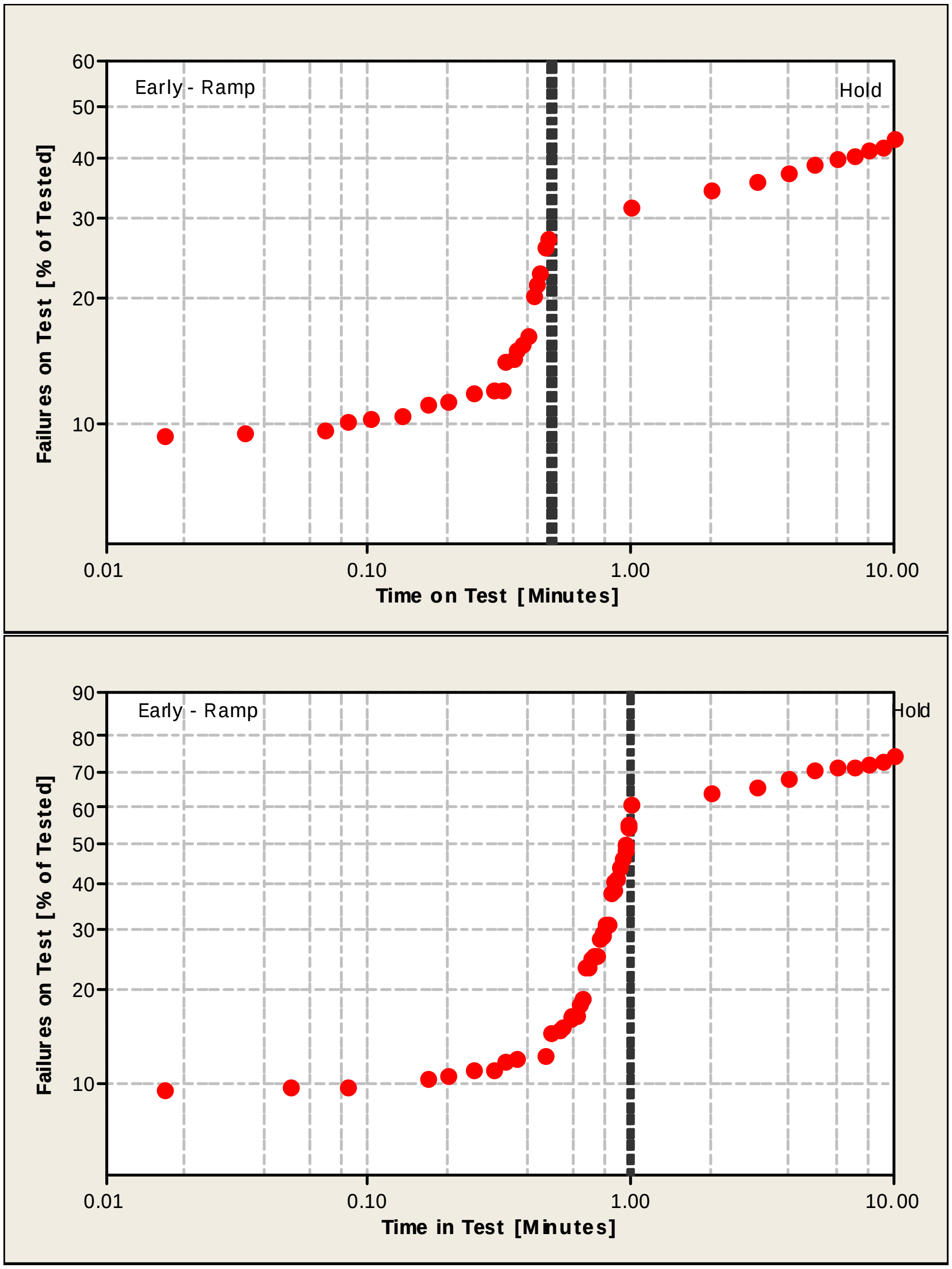


Figure 78: Dispersion of Failures on Test as a Function of DC Test Time 13 kV System (Top) and 27 kV System (Bottom) (After a Linear Increase in Voltage to the Hold Phase)

3.8.6.6 Length Analyses

Inspection of utility test data shows that simple withstand techniques are the most widely used diagnostic technique and encompass an extremely broad range of cable system lengths as shown in Figure 79 [47]. The extreme range of lengths presents a number of challenges when attempting a quantitative analysis of a withstand diagnostic as the likelihood of a long length containing a weak spot is higher than a shorter length. In other words, it is unreasonable to treat a 1,000 ft segment the same as a 50,000 ft segment. Figure 74, which shows results for survivor analysis, does not consider whether some groups of tests were conducted on different length circuits. All circuits are treated the same in this approach.

Where the lengths of each tested circuit are known, an adjustment to a common length base can be made. Dividing long lengths into consistent smaller sets is an obvious approach. However, this step, on its own, is insufficient for meaningful quantitative analysis. Five steps are necessary:

1. Selection of a meaningful and appropriate reference length – A 10,000 foot test length could be subdivided into 100 ft, 5,000 ft, or 1,000 ft lengths, but how meaningful (Figure 79) are 100 ft and 5,000 ft lengths in the context of a utility feeder. In the CDFI, we have used 500 ft and 1,000 ft lengths, but most utilities commonly report data in 1,000 ft lengths.

2. Censoring of non-failed segments where we recognize that there are two subsets of censoring:
   a. The large number of those which survive to the end of the test – five 10,000 ft lengths surviving a 30 minute test would provide 50 censors (5×10) at 30 minutes.
   b. Those that are a part of a circuit where a failure occurs and, thus, have survival times lower than the target test time. For example, using a 1,000 ft reference length, a failure of a 10,000 ft long circuit at 20 minutes into a 30-minute test would provide one failure at 20 minutes and nine censors at 20 minutes (all we know is that these nine have survived 20 minutes, we do not know nor can assume that they would have survived 30 minutes).

3. The precise logic and mathematical approach is outside the scope of this guide but appears in all reputable Weibull analysis texts.

4. These data are not standard continuous variables, but are essentially “inspection” of “binned data. Consequently, the analysis needs to accommodate these “non-standard” data.

5. The appropriate mode for the Weibull analysis must be selected; this analysis is accomplished one mode at a time. For simple withstand, the Early and Hold modes need to be separated. Most of the CDFI analyses employing length adjustment have focused on the Hold mode.

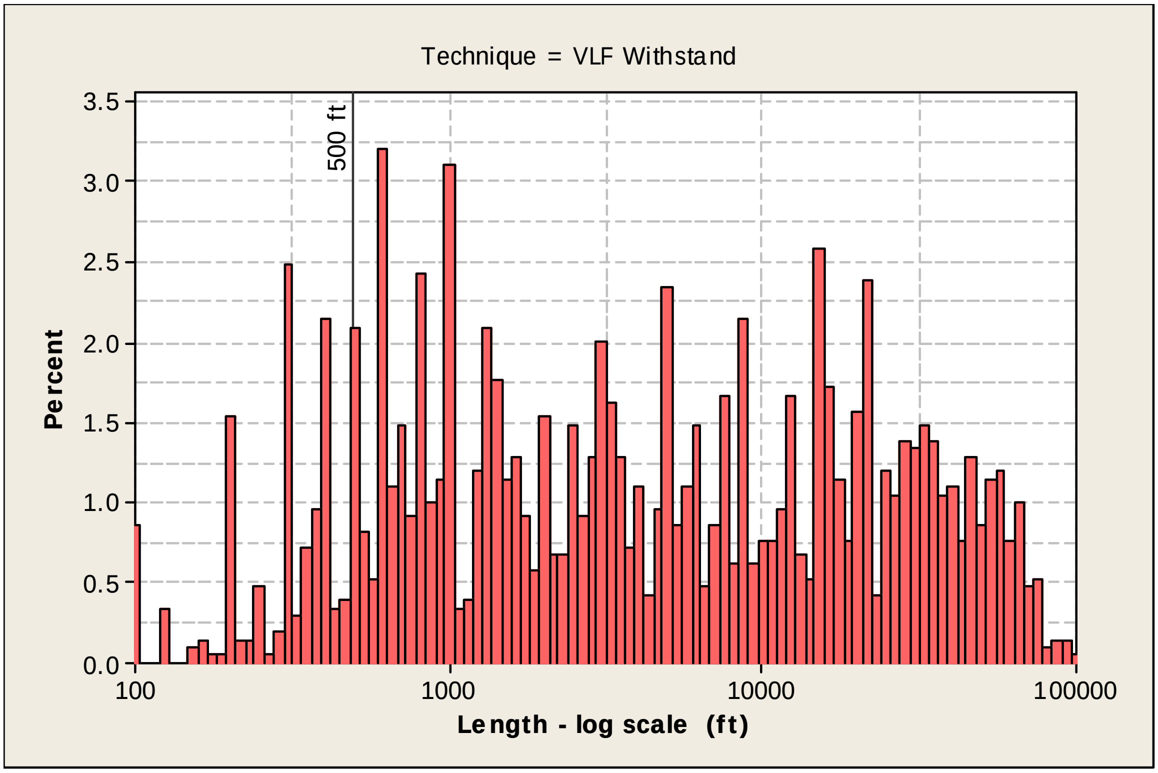


Figure 79: Distribution of Test Lengths for the VLF Withstand Technique [47]

Figure 80 shows the impact of reference circuit length on probability of failure for the Hold phase of a VLF withstand test. Early failures are treated as “left” censors. In other words, the assumption is that their times to failure are less than, in this case, 1 min. In this analysis, two reference lengths were used, 500 and 1,000 ft. As the reference length shortens, the probability of failure diminishes since there are more and more censored data points. Thus, it is clear that a too short reference length provides unrealistically optimistic estimates.

An analysis of the data shown in Figure 80 also demonstrates that the data can be well fit by a simple two-parameter Weibull curve. This means that there is only a single mode of failure. If there were more than a single mode then there would be curvature, cusps, or breaks in the data that would cause a separation between the data and the fit lines. As this figure shows, the data do not exhibit this sort of behavior.

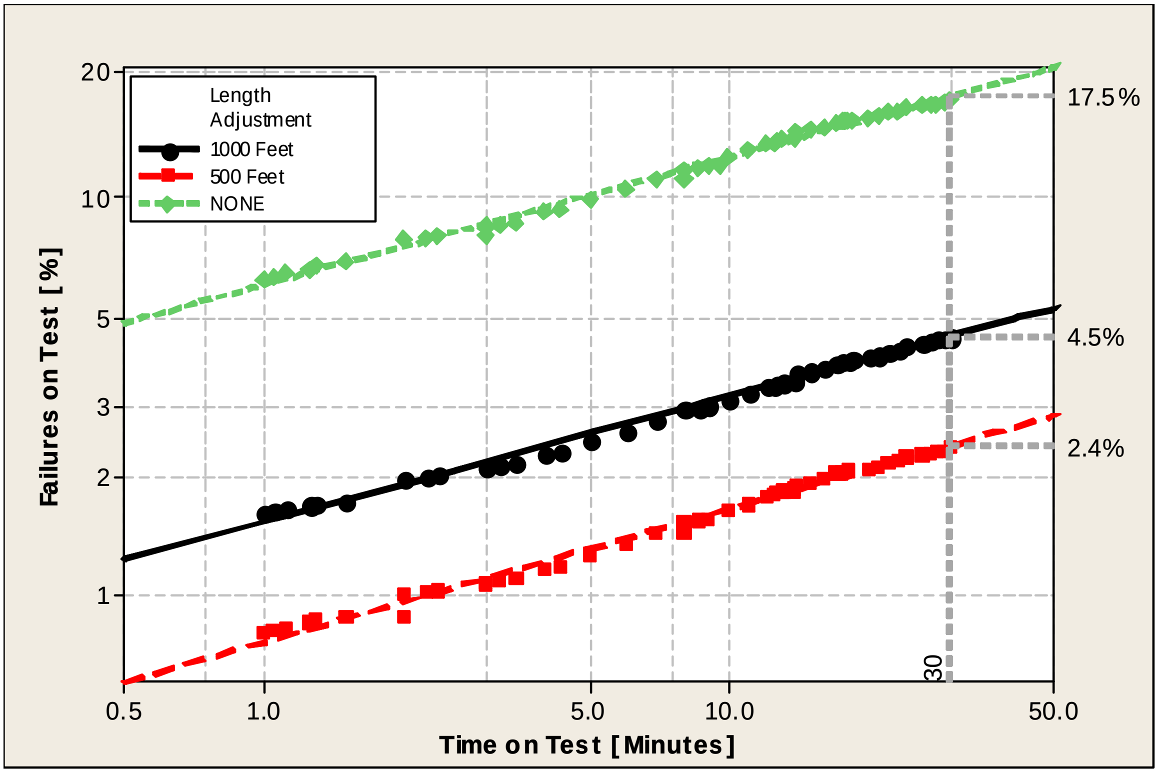


Figure 80: Impact of Reference Circuit Length on Probability of Failure for Hold Phase of VLF Test

Figure 81 shows this same approach applied to cable systems of two different voltage classes (within one utility). The top figure graph shows the data for a 13 kV system; the bottom graph is for a 27 kV system. It is instructive to note that once the length adjustments are made and the Early phase failure mode is properly censored, the two systems fail during tests at nearly identical rates.

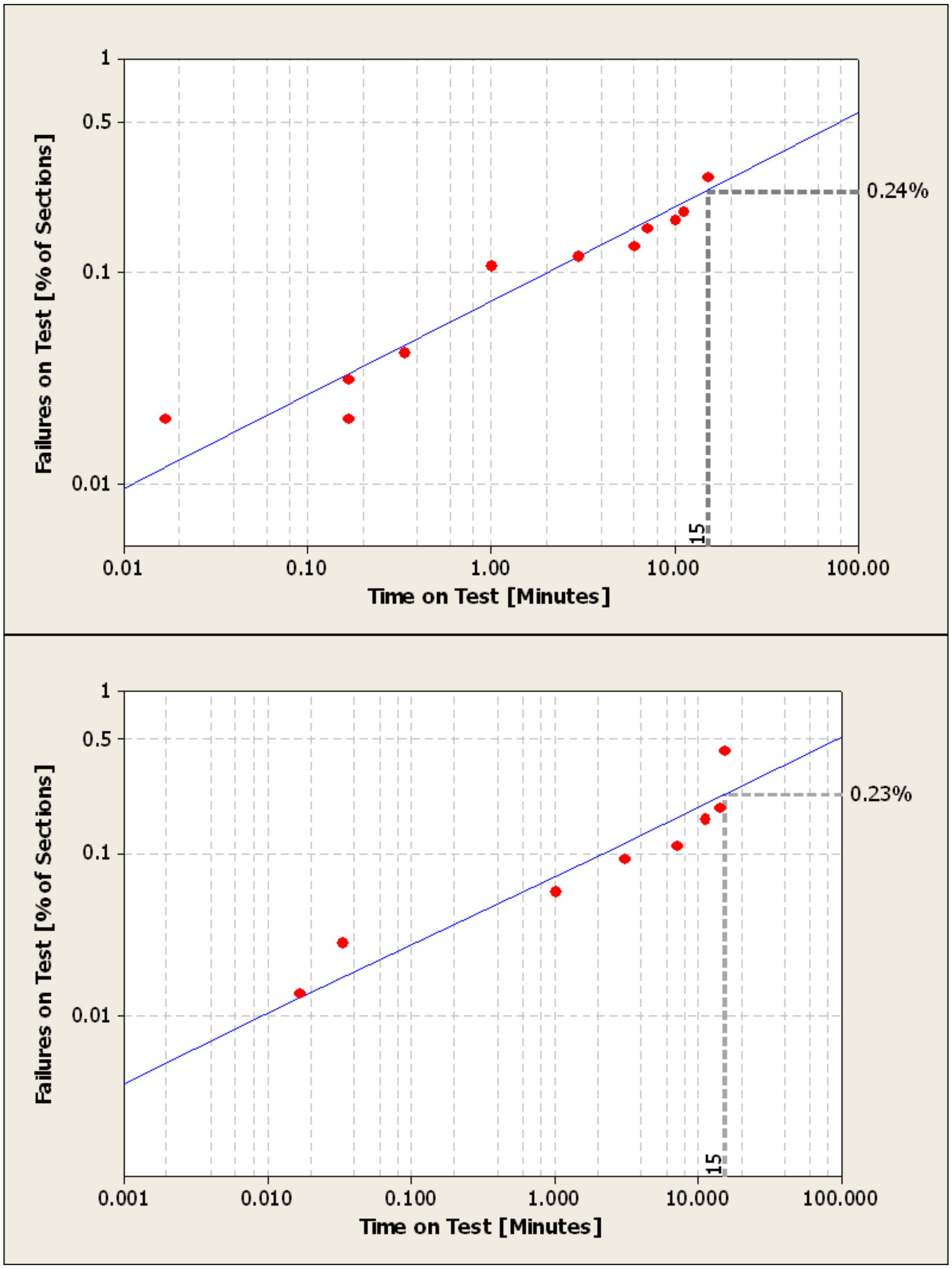


Figure 81: Distributions of Length Adjusted Failures on Test by Time for VLF Tests Length Adjustment Based on Number of Feeder Sections 13 kV System (Top) and 27 kV System (Bottom)

The results shown in Figure 80 and Figure 81 apply to other utilities as well. Figure 82 shows five of the survivor curves shown originally in Figure 74. These curves appear substantially different from one another in terms of shape and Failure on Test rate.

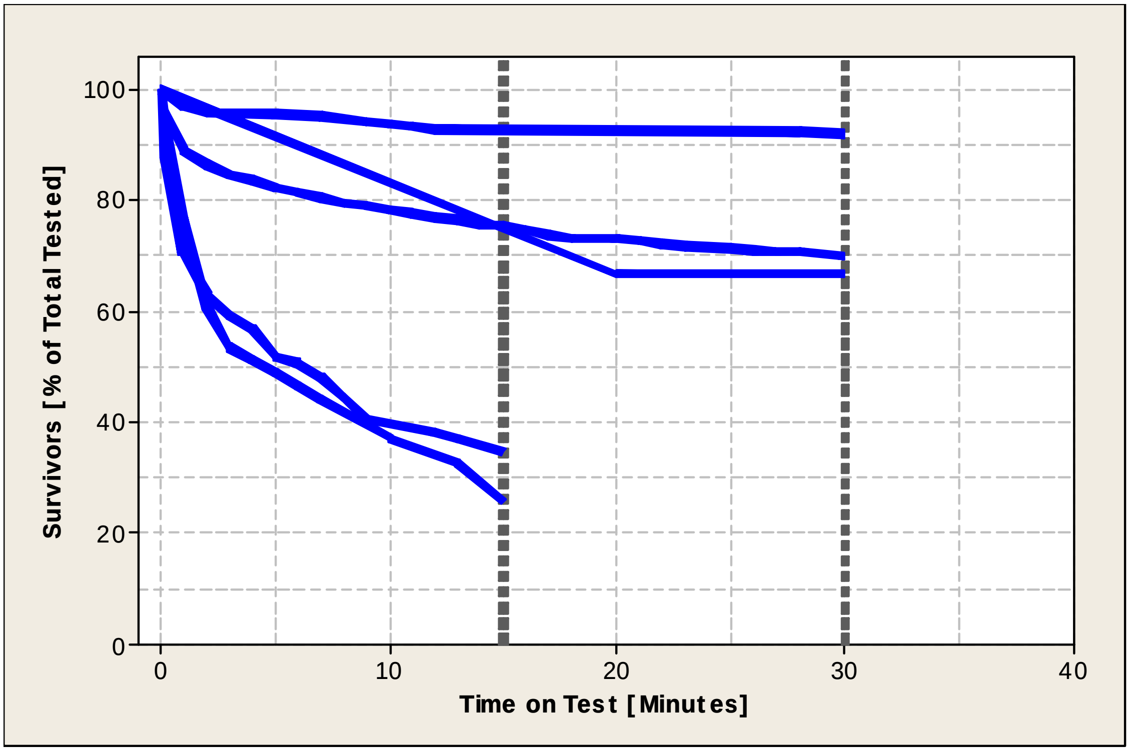


Figure 82: Survivor Curves for Five Datasets

However, by applying the length adjustments (using a base length of 1,000 ft) and censoring the Early phase failures, the survivor curves in Figure 82 may be transformed into the Weibull curves shown in Figure 83.

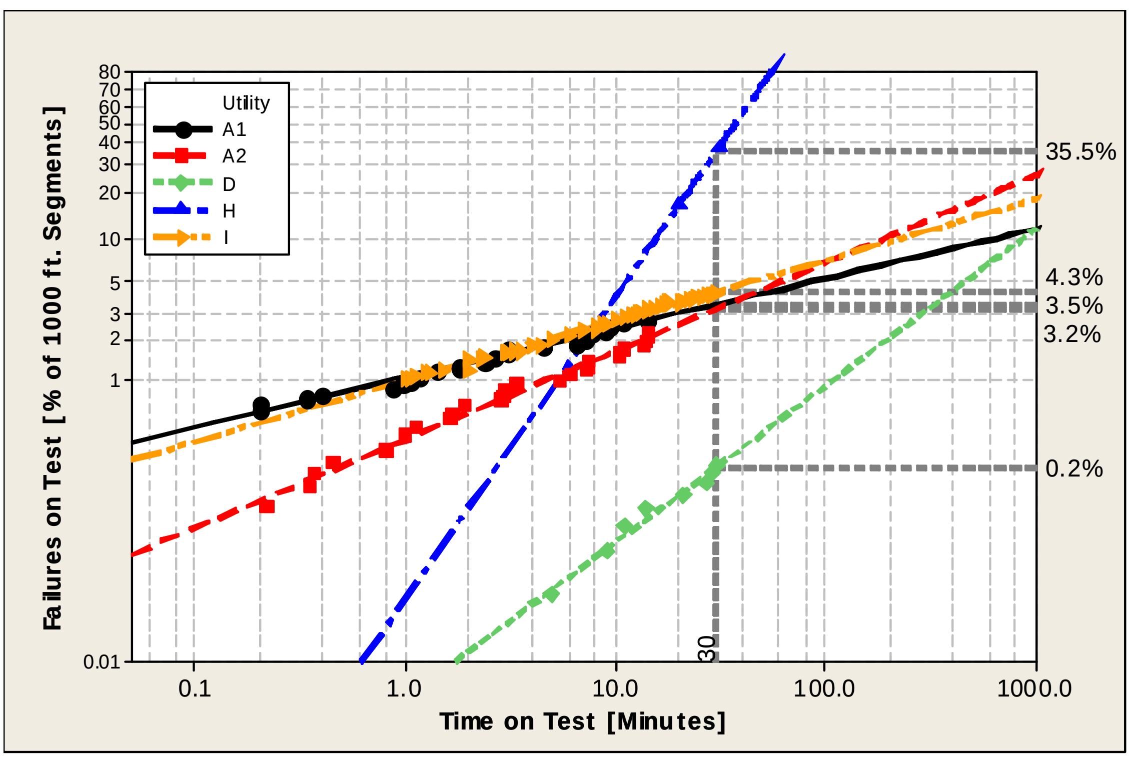


Figure 83: VLF Withstand Test Data Sets Referenced to 1,000 ft Circuit Length [47]

As Figure 83 shows, what appeared to be very different rates of failure on test actually become much more similar once the data are length adjusted. This is more apparent in Figure 84 where the replotted survivor curves use the length-adjusted data. As these figures show, four out of the five datasets have FOT rates of 4.5% or less for 1,000 ft segments.

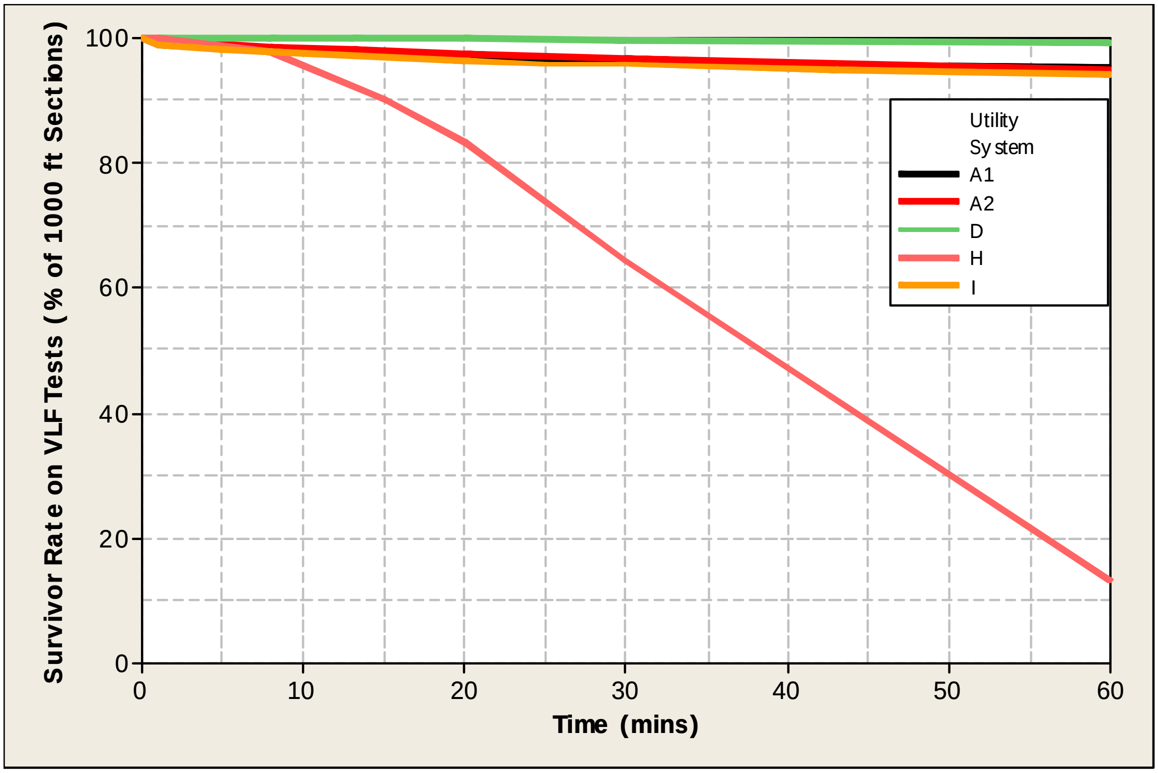


Figure 84: Length Adjusted Survivor Curves

As Figure 85 demonstrates, the high Failure on Test rate for the one outlier dataset (represented as ■) in Figure 84 is a result of the short length tested. The other datasets each represent 250 to 850 miles of tested cable system while the outlier dataset encompasses only one mile of tested cable system.

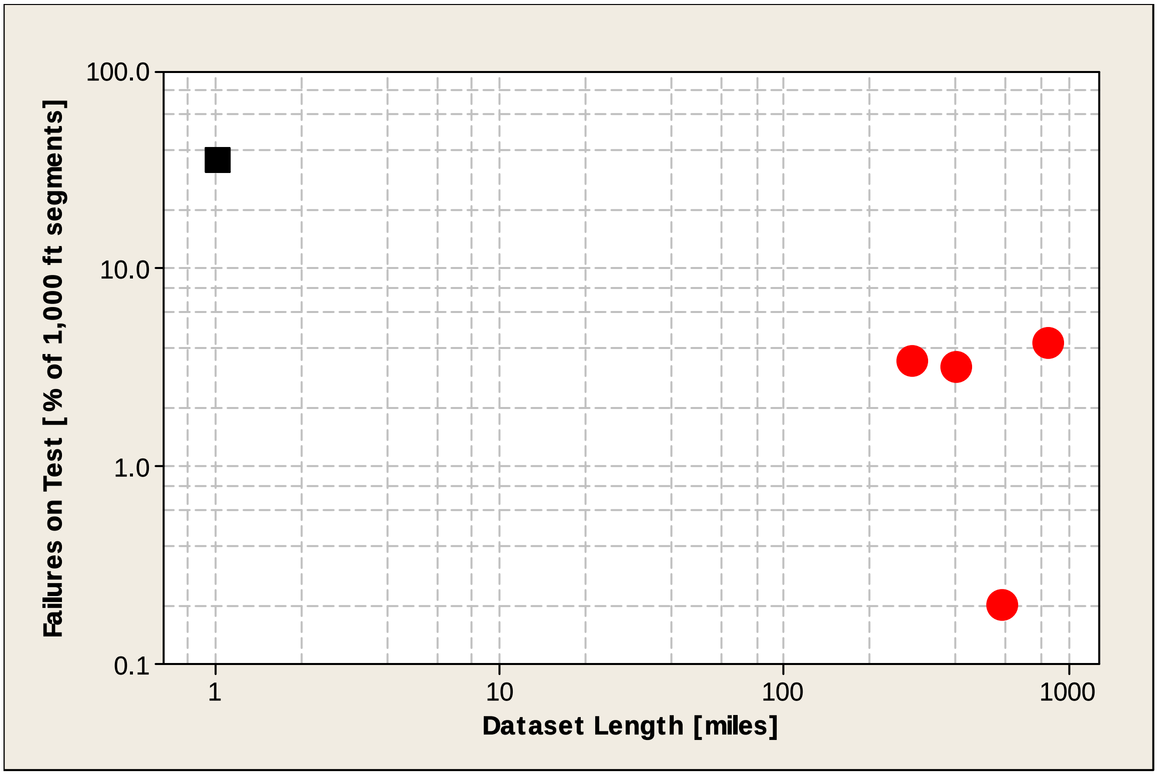


Figure 85: FOT Rates and Total Lengths of Datasets in Figure 82.

A number of observations from this analysis are noteworthy:

- There is a single mode of failure in the Hold phase for all of these data sets. This allows for reasonable predictions of the performance on test.
- The failure modes are remarkably consistent across the data, as evidenced by the similar gradients. This implies that utilities initiating Simple Withstand programs could confidently expect the performance shown above.
- The analysis has provided a robust framework for the analysis of data acquired from both 15 and 30-minute tests, thus showing that the 30-minute tests provide better performance both on test and in service.
- It is possible to extrapolate the curves to estimate the failures on test at times longer than 30 minutes. Estimates out to 120 minutes may be possible. This is useful if a utility wishes to perform non-standard Simple Withstand tests (i.e. longer than 30 minutes).
- The overall likelihood of failure, as evidenced by the likelihood of failure of 1,000 ft sections tested for 30 minutes, is approximately 4 % for populations of significant length.
- These five datasets include both hybrid (paper and extruded) and single insulation cable systems.

As the above observations suggest, there is remarkable consistency in the performance of cable systems tested using VLF Simple Withstand. This consistency holds for different system compositions, locations, lengths, and voltage classes and is based on 2,100 miles of tested cable systems. The above analysis allows predictions as to the expected number of failures a utility should be prepared to address given a certain size test population. For example, for every 100,000 conductor feet tested (100 - 1,000 ft segments), a utility could reasonably expect to see four failures on test. Taking the approach in IEEE Std. 400.2™ of combining all datasets, Figure 86 shows that the Failure on Test rate for 30 minute test protocols is 2.7 % (based on 1,000 ft segments).

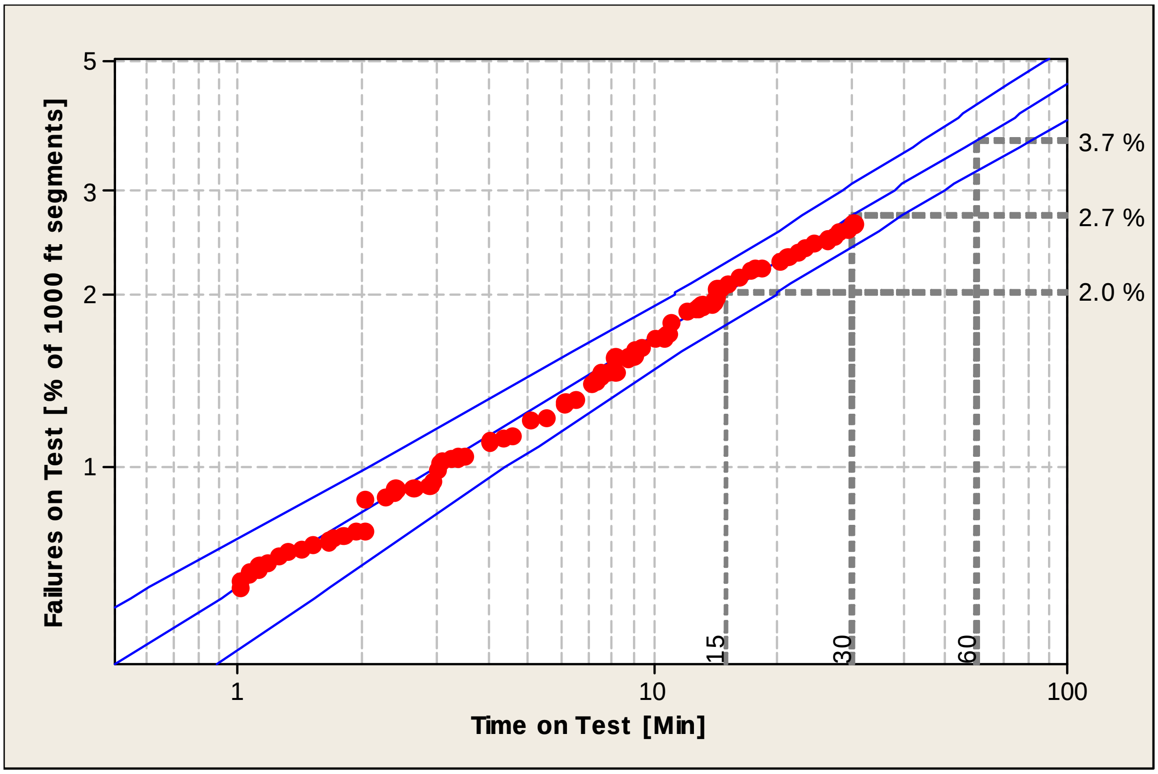


Figure 86: Combined Weibull Curve for all VLF Data in Figure 83

3.8.6.7 Laboratory Studies of Test Times

Although simple VLF withstand tests are routinely employed in the field, very few laboratory studies have studied the effects of the main test variables: test voltage and test duration. To address this issue, the CDFI undertook a test program [49] with a number of unique features that included:

- Long cable lengths (140 ft)
- Field aged, triplexed XLPE insulated, unjacketed, concentric neutral cables (circa 1970's) made by one manufacturer and removed from conduit in one service area.
- A wide range of selected test times and voltages
- Sequential application of VLF test and 60 Hz aging voltages. Figure 87 shows the general test plan. 60 Hz partial discharge measurements were made at the "field aging voltage" both before and after each elevated withstand test voltage application.

The primary observation (test metric) was the survival of the test cables during the elevated voltage application and the 60 Hz aging periods. Figure 87 schematically illustrates the test program schedule.

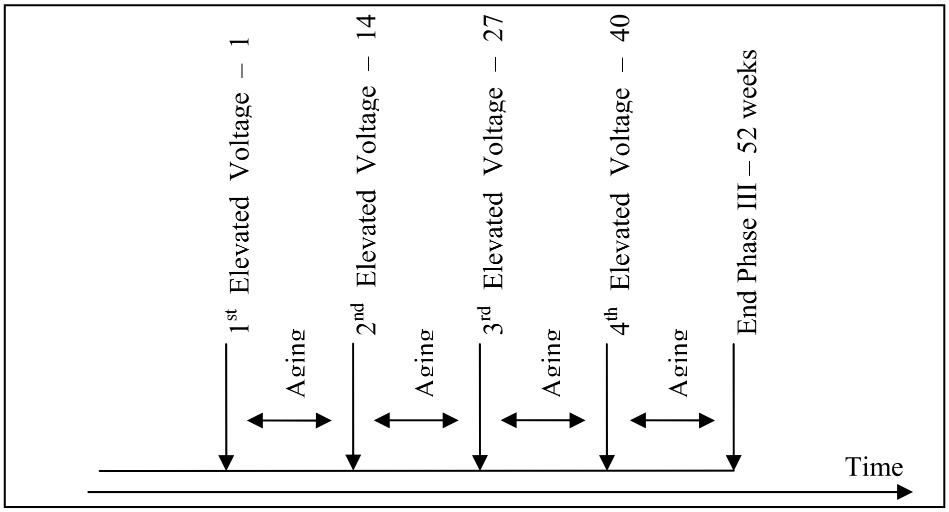


Figure 87: Laboratory Test Schedule for Impact of VLF Withstand Tests

The VLF High Voltage Withstand test program was originally designed to be conducted in two phases. Phase II of the test program took place six months after Phase I to allow for adjustments in the Phase II test matrix based upon information obtained in Phase I. Phase III was added because most of the test samples survived both earlier phases. Results of these studies appear in Table 48 and Table 49.

Table 48: U_0 Ambient Aging Test Program Results (Phase I and Phase II) VLF Sinusoidal Withstand Tests)

Sample Set	Initial Length [ft]	Elevated Voltage Application (EV) Multiple of Rated Voltage	Elevated Voltage Application (EV) Multiple of Op Voltage	Actual RMS [kV]	Test Freq [Hz]	Test Duration [min, *cycles]*	Failures Aging [#]	Failures Failure Time [day]	Failures Total Failures [#]	Failures Time on Test [min]
1	280	None	None	--	--	--	0	NA	NA	NA
2	280	1.8	2.2	16	0.1	15, 90	0	NA	0	NA
3	280	3.0	3.6	26	0.1	120, 720	0	NA	3	51, 59, 78
4	280	2.1	2.5	18	0.1	60, 360	0	NA	2	17, 28
5	280	1.8	2.2	16	0.1	120, 720	0	NA	0	NA
6	280	3.0	3.6	26	60	0.25, 900	0	NA	2	On Ramp

[1] - Each sample set includes two 140 ft lengths of cable that was divided into 14, 20 ft test samples.

Table 49: 2 U_0 and 45 °C Aging Test Program Results (Phase III) VLF Cosine Rectangular Withstand Tests

Sample Set	Initial Length [ft]	Elevated Voltage Application (EV) Multiple of Rated Voltage	Elevated Voltage Application (EV) Multiple of Op Voltage	Actual RMS [kV]	Test Freq [Hz]	Test Duration [min, *cycles]*	Failures Aging [#]	Failures Failure Time [day]	Failures Total Failures [#]	Failures Time on Test [min]
1	280	None	None	--	--	--	0	NA	NA	NA
2	280	1.8	2.2	16	0.1	15, 90	0	NA	0	NA
3	220	3.0	3.6	26	0.1	120, 720	0	NA	10	8, 11, 22, 23, 26, 28, 43, 43, 61, 91
4	240	2.1	2.5	18	0.1	60, 360	0	NA	2	26, 59
5	280	1.8	2.2	16	0.1	120, 720	0	NA	0	NA
6	240	3.0	3.6	26	60	0.25, 900	2	0, 54	0	NA

A number of useful results are noted:

- No samples exposed to an elevated VLF withstand test voltage failed during any of the U_0/Ambient or 2 U_0/45 °C “aging” periods (i.e. no failures during aging). All samples exposed to a VLF withstand voltage that failed did so during the VLF withstand voltage application.

- No “failures on test” occurred during elevated voltage applications using a 2.2U_0 test voltage. This applies to both sinusoidal and cosine-rectangular waveforms. This is the current maximum IEEE Std. 400.2™ voltage magnitude recommendation.

- Out of 17 VLF failures on test, only two failures occurred within the first 15 minutes of testing. Three failures occurred after 60 minutes on test.

- The absence of failures in the aging phase indicates that the VLF test conditions used here do not appear to have allowed defects to remain that subsequently degraded the service performance.

- Some of the test conditions used in the study fell considerably outside the ranges recommended by IEEE Std. 400.2™ (i.e. 120 minutes test time and 3.6U_0 test voltage). None of these conditions caused incipient defects that led to failure during the aging (or service replicating) periods. This was true even when the aging period used twice the normal operating voltage.

The failures that occurred during the application of the elevated voltage VLF withstand test appear in Figure 88 using a Weibull Analysis for the different VLF test voltages. For comparison, the time for 10 % of tested 20 ft samples to fail appears on each subplot. It is noteworthy that:

- Only two of the 17 failures occurred at times in the range 0 to 15 minutes.

- Only three of the 17 failures occurred at times in the range 60 to 120 minutes.

- More failures occurred using the cosine-rectangular waveform and 2 U_0 aging (Table 49) than occurred with the sinusoidal waveform and U_0 aging (Table 48).

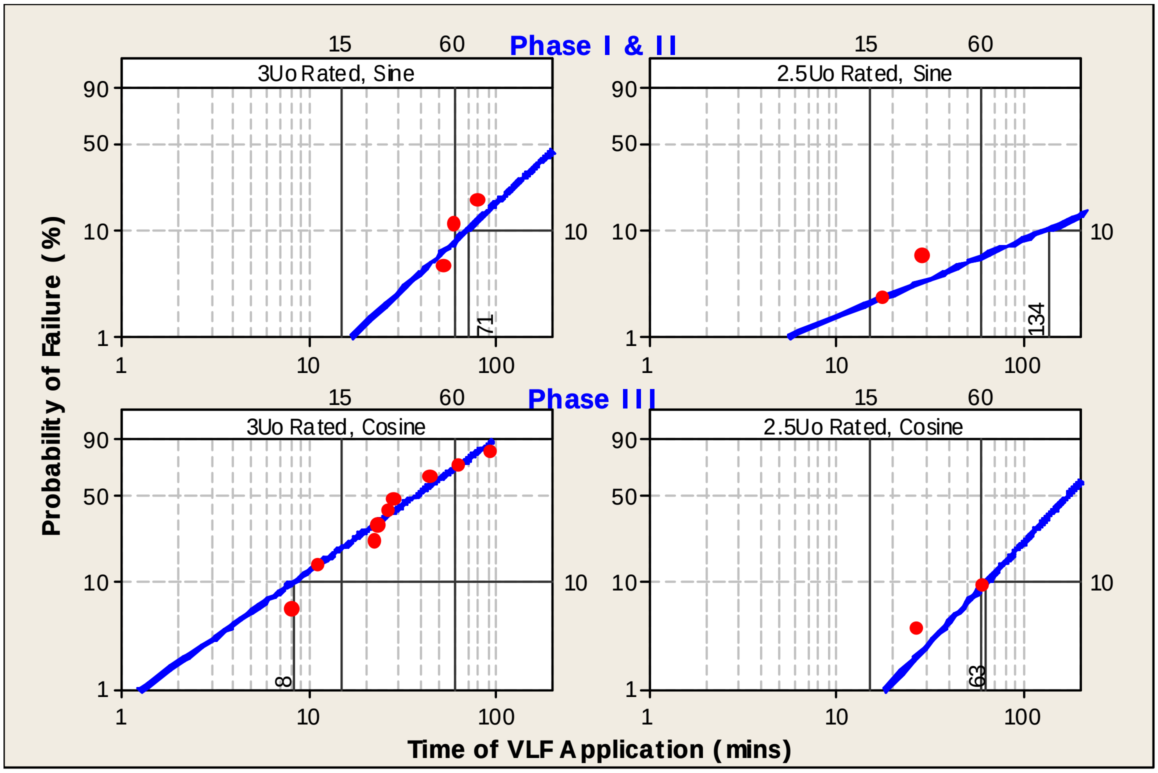


Figure 88: Weibull Analysis of Failures on Test for Phases I, II, and III [49]

Since no failures have occurred on samples tested at $2.2U_0$, the performance of these sample sets are estimated using censoring and assuming a Weibull shape parameter that is less than the cases shown in Figure 88. This corresponds to a standard Bayesian type analysis, commonly used in the aerospace and automobile industries. The resulting lower confidence limit for the Weibull curve appears in Figure 89. This is a limit rather than an estimate. Given the limitations of this analysis technique, all that one can say with any certainty is that the correct result is in the near vicinity to the right side of the line.

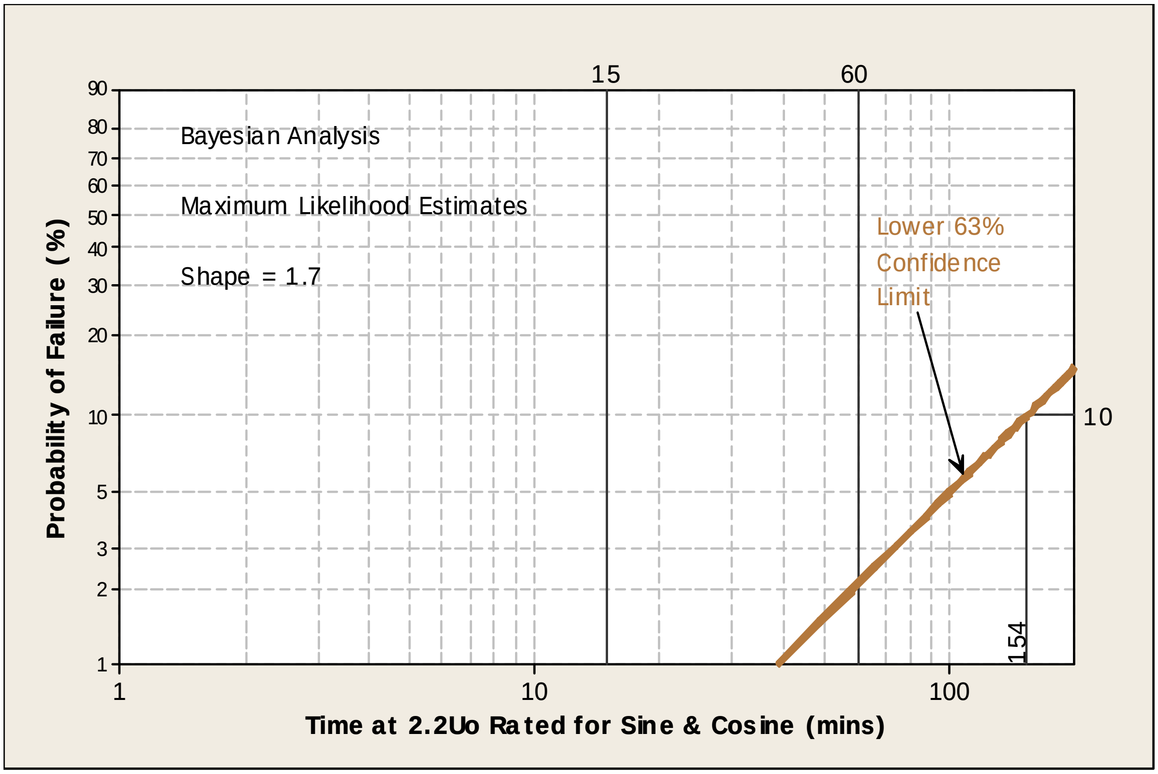


Figure 89: Bayesian Estimate of Weibull Curve for VLF Samples Tested at $2.2U_0$

Using the times on test for the 10 % failure rate from Figure 88 and Figure 89, it is possible to plot time on test as a function of the test voltage for all three test phases. Figure 90 shows the results of this analysis. For all phases, the increasing test voltage clearly translates into a shorter time on test (i.e. higher failure rate). Note that these curves are not comparable numerically to one another since the aging conditions for the tests conducted in Phase III are more aggressive.

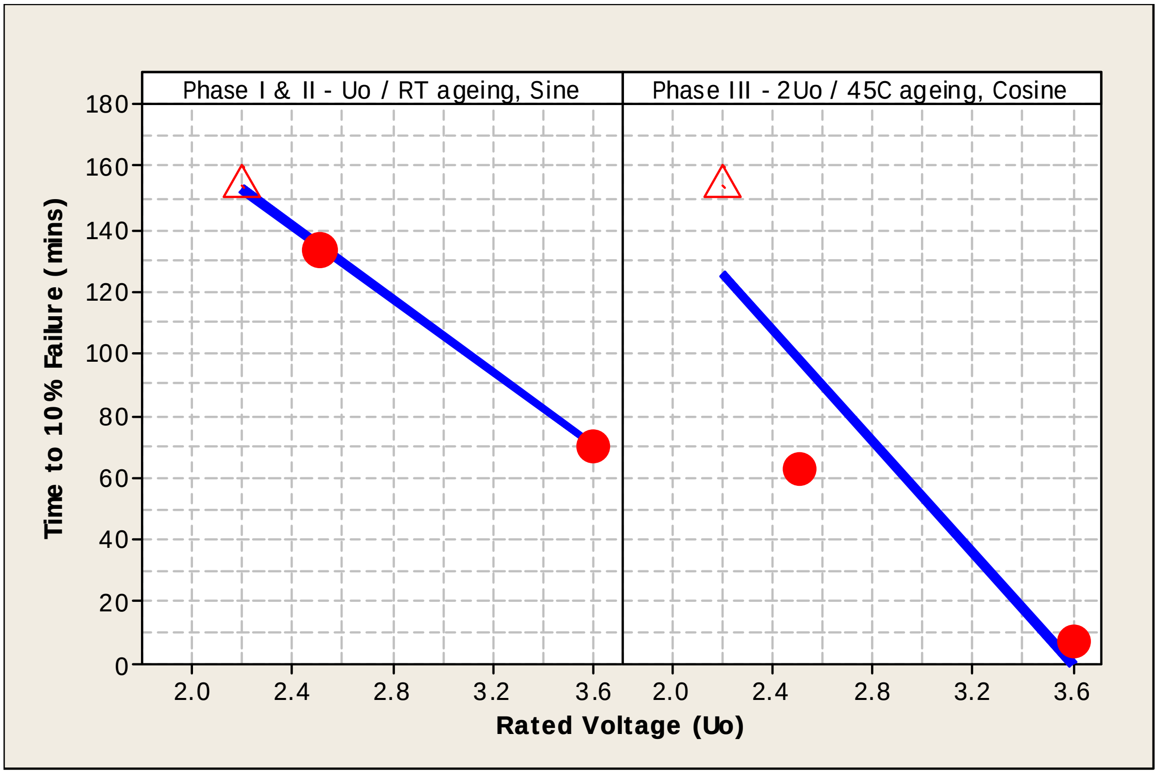


Figure 90: Failures on Test as a Function of Test Voltage [49]
(The Open Upward Arrow Shows that the True Estimate Lies Somewhere Above this Estimate)

It is apparent from this test program that higher test voltages lead to more failures on test. However, the increased stress does not translate to degraded service performance, at least within the first 13 weeks after testing, which is the duration of the aging periods between elevated voltage applications. Ideally, a utility would like to fail as few segments as possible on test while maintaining a low post-test failure rate in service. This means that the goal is to "grow" to failure only those defects that would ultimately have failed in service. The key is to select the right voltage and test duration to accomplish this goal. Given the available data, these two parameters (time and voltage) are treated as a pair.

3.8.6.8 Performance of Cable Systems after Field Tests

The study described in the previous section was unique in that, for a laboratory study, it employed relatively long cable lengths. However, such lengths are still much shorter than those typically seen in the field. Thus, there is a benefit in conducting a parallel analysis on field data. These data also allow for DC withstand and VLF withstand data to be included along with cable system accessory performance data.

Figure 91 shows an analysis of simple DC withstand tests for two types of tests, a regular withstand of 15 minutes, and a "partial" withstand test that employs a shorter time and lower voltage conducted after a repair was completed. Note that this cable system is a hybrid system with PILC, EPR, and XLPE. The data for a number of different locations within this single utility appear on this graph as different curves.

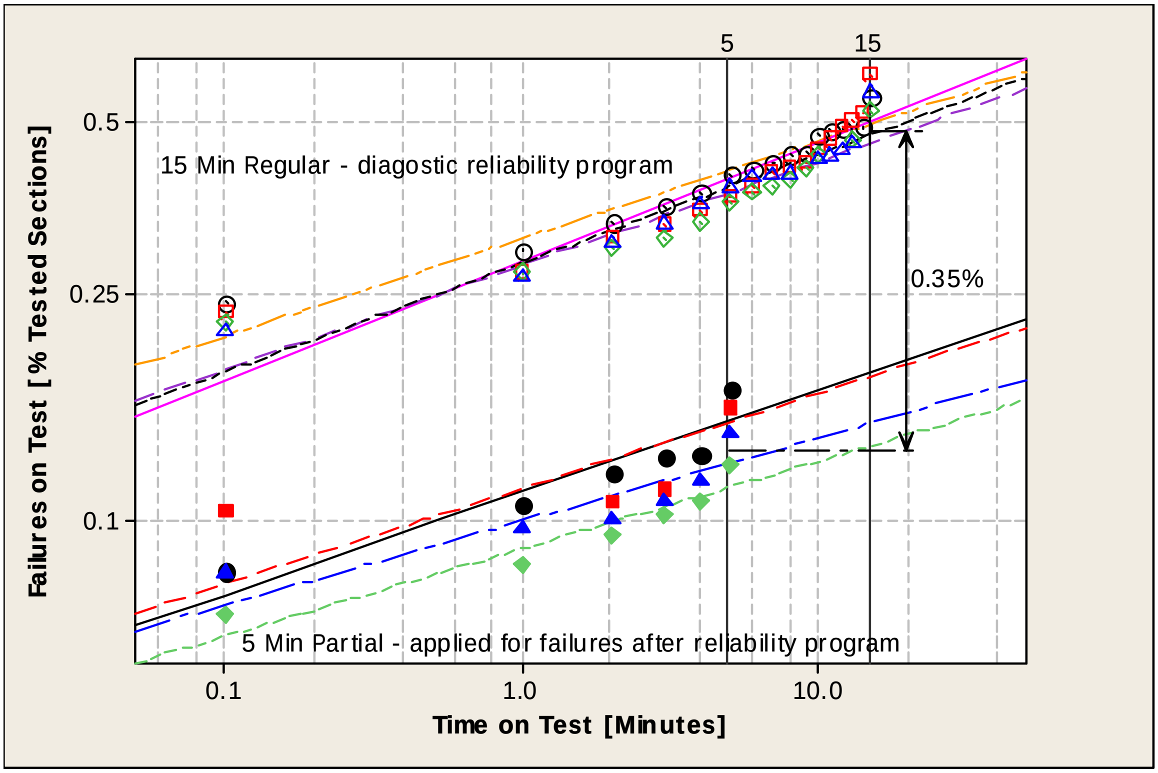


Figure 91: Failures on Test for Regular (15 min) and Partial (5 min) DC Field Tests (Data are Size-Adjusted by the Number of Feeder Sections)

The analysis shown in Figure 91 provides an estimate of the effectiveness of each diagnostic test program. A number of points emerge in this analysis:

- The likelihood of failure is much less (0.12 % for 5 min test vs. 0.47 % for the 15 min) after the cable section failed in a controlled manner and was then repaired.
- In this case, the analysis does not provide any indication that DC is creating weak spots in the cable system since the curve for the 5-minute retest data has the same gradient and lower failure rate than the 15-minute test.
- The regular 15 min tests do not cause all of the defects present to fail because the 5 min "partial" test failure rate is not zero.
- Single failure modes are associated with the failures occurring during both tests within the constant voltage "hold" phase of the test.
- The mechanisms of failure are similar between the before and after repair tests.

Figure 92 shows the results of a post-VLF test service performance audit for one utility system. The figure shows the distribution of the time to in-service failure after a simple VLF withstand test. The data were segregated for two types of VLF test: 15 minutes at 2.5 U_0 and 30 minutes at 1.8 U_0. The analysis uses censoring for the tests that have not resulted in service failures.

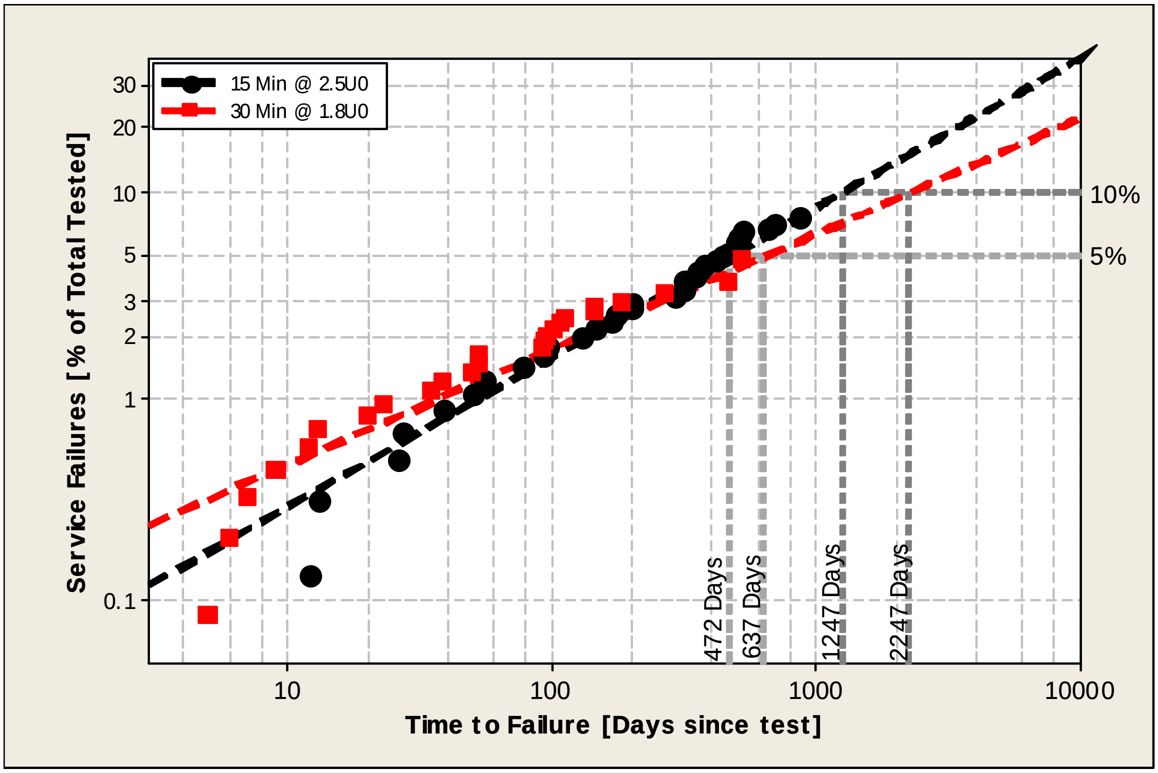


Figure 92: Distribution of Times to In-service Failure after a Simple VLF Withstand Test [47]

The results in Figure 92 show the percentage of tests that are likely to result in service failures. Inspection shows that for short times, less than 200 days after test, the lower voltage (1.8 U_0) withstand test yield more failures, but the failure rate is lower than those for the 2.5 U_0 tests. Furthermore, the failures begin to occur less than 12 days after test in both cases. Therefore, there is no "grace" period in which the tested circuits are failure-free. At 500 days, the 30-minute 1.8 U_0 test results in fewer service failures than the 15 minute, 2.5 U_0 test. The magnitude of this difference can conveniently be expressed as the estimated time to reach a specific level of failures as shown in Table 50.

Table 50: Times to Failure for Different VLF Withstand Protocols

Test Conditions	Time to Failure [Days] at Selected Levels of Failure	
	5 % of Circuits	10 % of Circuits
15 Minutes @ 2.5 U_0	472	1247
30 Minutes @ 1.8 U_0	637	2247

The analysis in Figure 92 shows that in the long term the highest reliability results from a test of 1.8 U_0 for 30 minutes (the current IEEE Std. 400.2™ recommended test voltage and duration).

However, the approach used for this analysis does not show which test provides the greatest benefits. The benefits are investigated in the analysis shown in Figure 93. The data shown in Figure 92 are segregated for cable sections that completed the VLF tests without failures and sections that failed and were subsequently remediated. Thus, there are four data sets in Figure 93:

a) 15 minute test, no failures on test (left)

b) 30 minute test, no failures on test (right)

c) 15 minute test, failure on test and repair (left)

d) 30 minute test, failure on test and repair (right)

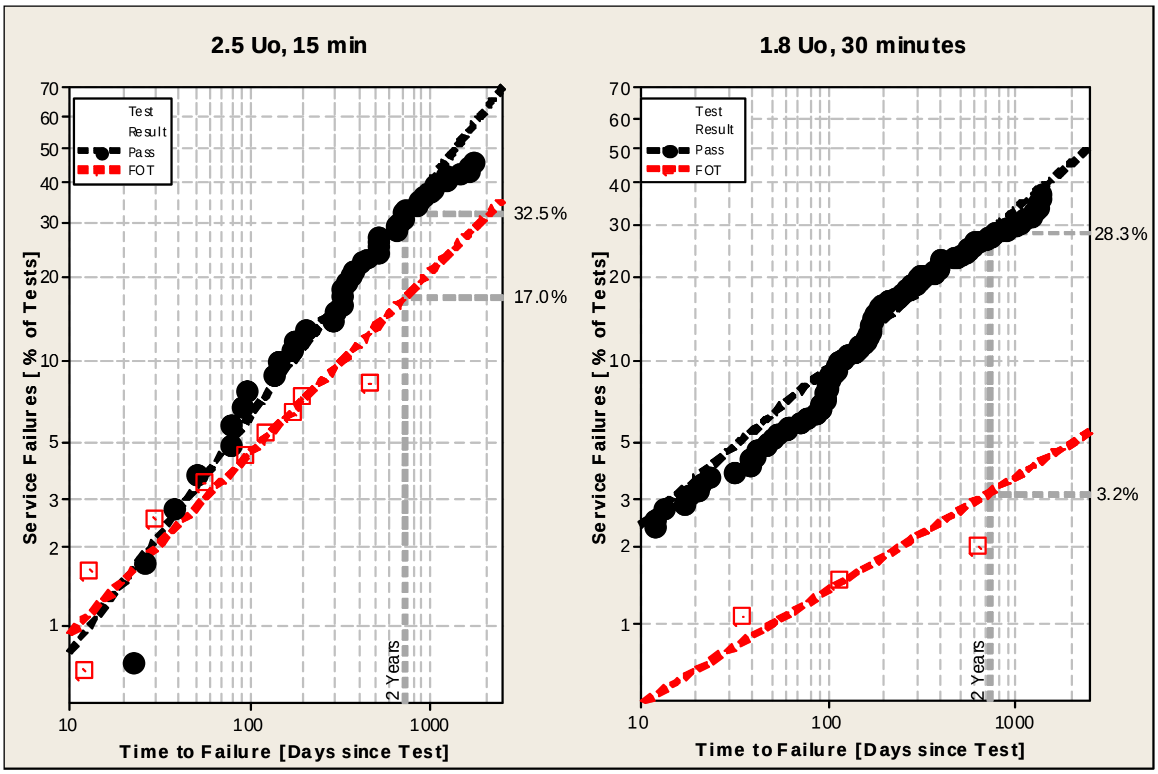


Figure 93: Time to In-Service Failure After Simple VLF Withstand Tests (3-Phase Sections) [47]

The in-service performance of cable segments after 15 and 30-minute tests that did not result in failure on test (solid symbols) are very similar. They have similar modes of failure and failure rates. In principle, it suggests that when cable systems are in acceptable health, the applied voltage and test duration have a small influence on the in-service performance (note that this is not the case for performance on test). The data variations are probably due to seasonal influence on utility failure rates. On the other hand, the open symbols in Figure 93 represent the tests that failed and were subsequently remediated. A number of points emerge:

- The likelihood of failure is much less (3 % – 17 % vs. 28 % – 33 % after 2 years) when the cable section fails in a controlled manner and is then repaired.

- The test does not appear to leave weak spots that would later cause failure in service. If this were the case, we would expect the likelihood (percent) of in-service failure to be similar or even higher than where the cable section passes the withstand test.
- The initial tests do not capture all of the defects, as there is a nonzero (albeit lower) failure rate for the cable segments that fail their first withstand test.
- Single and essentially identical failure modes are associated with the subsequent in-service failures occurring for both 15 and 30-minute tests.
- The levels of failure after repair are much lower for the 1.8 U_0, 30-min test than for the 2.5 U_0, 15 min test (3 % and 17 %, respectively, after 2 years).

Thus, it is possible to conclude that the improved performance of circuits after the 1.8 U_0, 30 min test, as compared to the 2.5 U_0, 15 min, test, is the result of improvement of the circuits that failed on test and were then remediated.

3.8.6.9 Performance Assessment

Withstand tests are described as non-diagnostic as a metric is not provided by the test. However, utilities use them for diagnosis. An important issue is if the Pass / Not Pass result is a valid metric. These results are valid for diagnostics if engineers collate and review them, a requirement common for all techniques. Figure 94 through Figure 96 show an example of withstand data being used diagnostically.

The overall Failure on Test (FOT) rates were approximately 1 % and 4.5 % for the Early and Hold phases, respectively (Figure 78 and Figure 80). Figure 94 shows the situation for a combination of four regions from within a single utility system (the Early failures are not shown in Figure 94 but are accounted for using censoring). The combined Failure on Test rate for these four areas is different from those mentioned above. Figure 96 shows that higher FOT rates were experienced in three areas, Areas 2, 3, and 4, and that Area 1 had significantly better performance. From such analysis a utility could proactively prioritize test programs by focusing on those areas that experienced poorer performance on test.

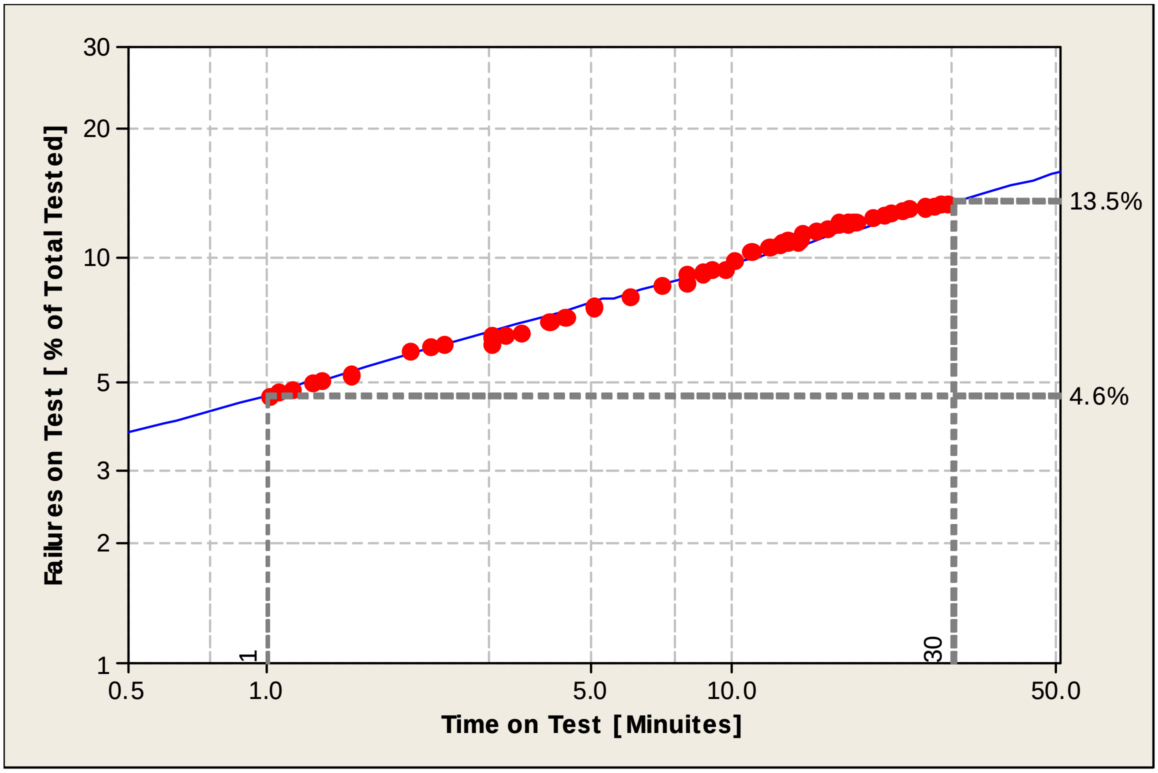


Figure 94: Failures on Test for Four Regions (Combined) within a Utility System (Data Adjusted for a Length of 1,000 feet)

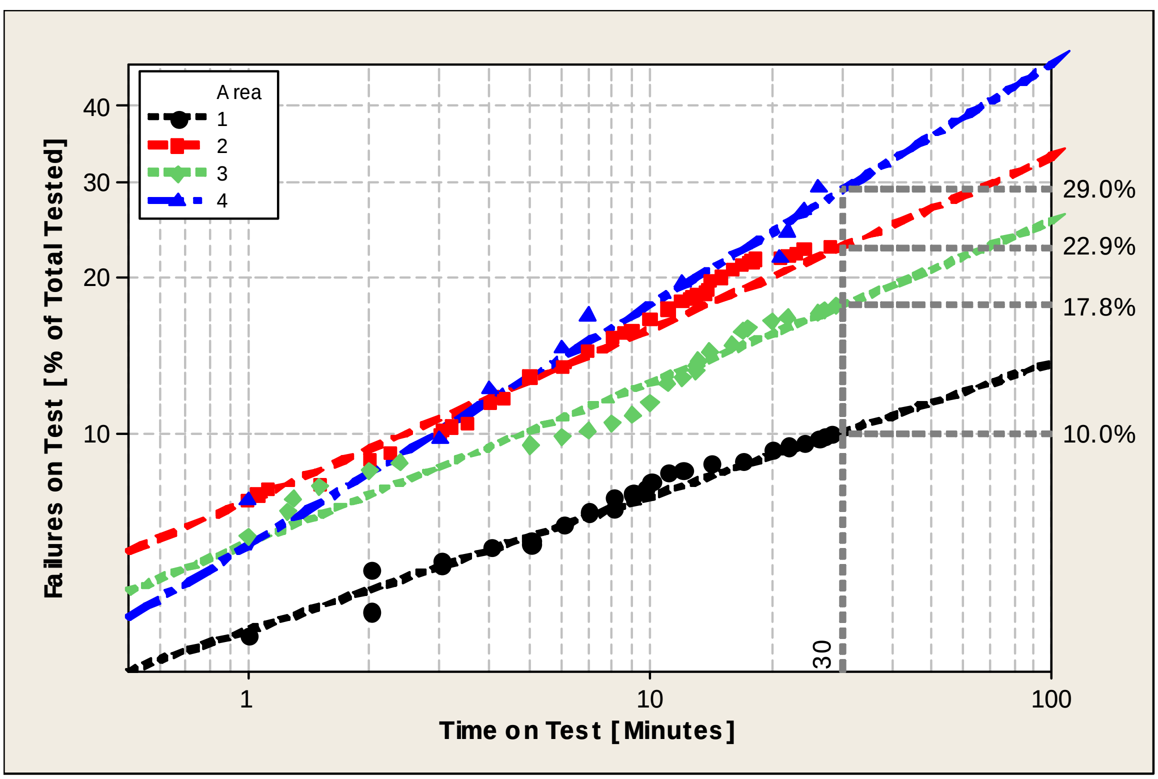


Figure 95: Failures on Test for Four Regions (Segregated) within a Utility System (Data Adjusted for a Length of 1,000 feet)

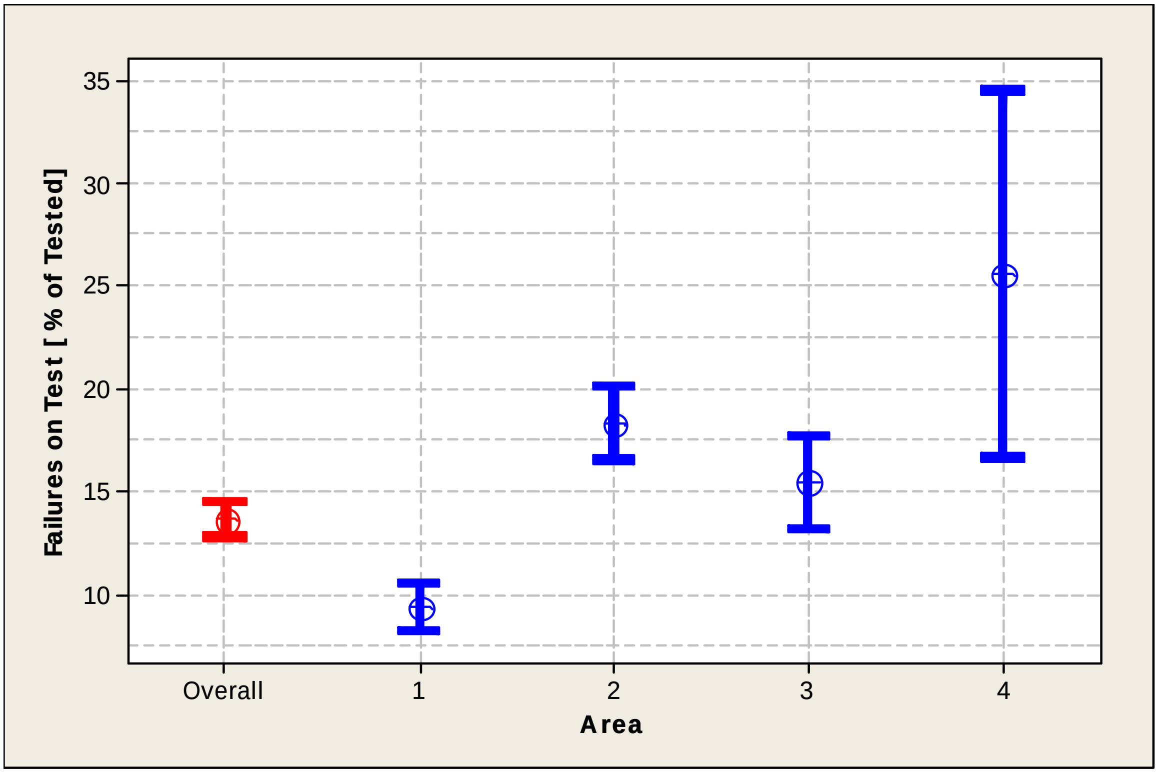


Figure 96: FOT Estimate at 30 minutes for Four Regions (Segregated) within a Utility System (Data Adjusted for a Length of 1,000 feet, 95% Confidence Limits Shown)

3.8.6.10 General Summary

An analysis and assessment of the Simple Withstand Test approach is complicated by the diversity of the environments and the ways in which utilities deploy the technique. Consequently, it is impossible to consider a single test or single facet of utility experience when making this assessment.

However, there is a considerable body of knowledge upon which an assessment can be made. Thus, given this experience, it seems reasonable to conclude that the current levels of voltage and time (30 min) recommended by IEEE Std. 400.2™ are:

- Reasonable at finding defects in a wide range of utility cable systems.
- Do not pose an unreasonably high failure risk for cable systems either during tests or afterwards

The evidence also supports the assertion that voltage levels in excess of those recommended by IEEE Std. 400.2™ can increase this reasonable risk of failure (2.7% per 1,000 ft tested), even at shorter test times. This statement is based on the large number of failures associated with the Early modes of failure (Figure 75 through Figure 78).

3.9 Monitored Dielectric Withstand Techniques

3.9.1 Test Scope

Simple Withstand tests are proof tests that apply voltage above the normal operating voltage to stress the cable system in a prescribed manner for a set time. These tests are similar to those applied to new accessories or cables in the factory where they 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 its surviving the voltage stress, a property of the system be measured and monitored. This implementation of a withstand test, called Monitored Withstand, is discussed in this section.

One of the drawbacks of Simple Withstand tests is that there is no straightforward way to estimate the "Pass" margin – once a test (say 30 min at 2 U_0) is completed, it is impossible to differentiate among those passing segments. That is, it is impossible to distinguish the segments that would survive 120 min from those that would have only survived 40 min.

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. Provide an estimate of the "Pass" margin.
2. Enable a utility to stop a test after a short time if the monitored property appeared close to imminent failure on test, thereby allowing the required remediation work to take place at a convenient (lowest cost) time.
3. Enable a utility to stop a test early if the monitored property provided definitive evidence of good performance, thereby increasing the number of tests that could be completed and improving the overall efficiency of field testing.
4. Enable a utility to extend a test if the monitored property provided indications that the "Pass" margin was not sufficiently large, thereby focusing test resources on sections that present the most concern.

3.9.2 How it Works

In a Simple Withstand test, the applied voltage is raised to a prescribed level, usually 1.5 to 2.5 times the nominal circuit operating voltage for a prescribed time. The purpose is to cause weak points in the circuit to fail during the elevated voltage application when the circuit is not supplying customers. Testing occurs at a time when the impact of a failure (if it occurs) is low and repairs can be made quickly and cost effectively.

When performing a Monitored Withstand test, a dielectric or discharge property is monitored during the withstand period (Figure 97). The data and interpretation are available in real time during the test so that the decisions outlined above might be made. The dielectric or discharge values monitored are similar to those described in earlier sections. However, their implementation and interpretation differs due to the requirement of a fixed voltage and a relatively long period of voltage application. Within these constraints, Leakage Current, Partial Discharge (magnitude and repetition rate) and Tan δ (stability and magnitude) [27] might readily be used as monitors.

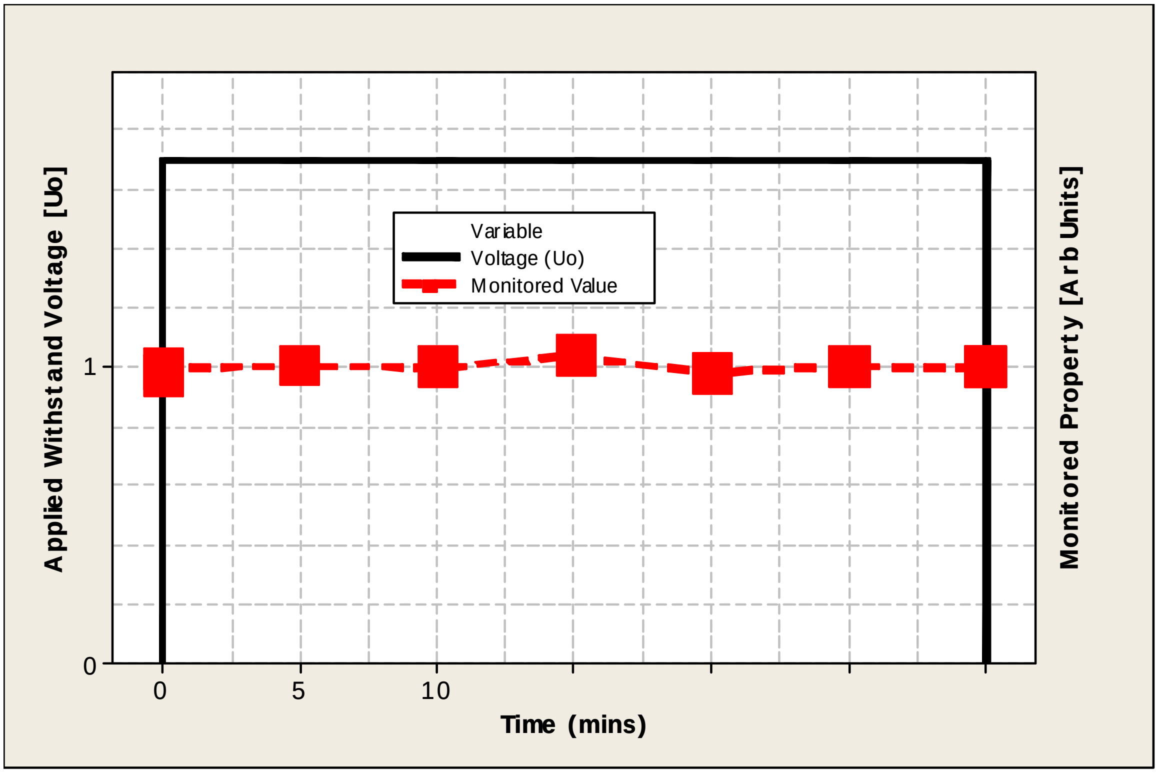


Figure 97: Schematic Representation of a Monitored Withstand Test

3.9.3 How it is applied

This technique is conducted offline with the circuit disconnected from the rest of the system. The applied voltage may be DC (not recommended for most applications), VLF, or 60 Hz AC. Typical testing voltages range from 1.5 - 4.0 U_0 [19] 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.

Damped AC is often discussed in the industry for use in withstand testing. However, for the definition of Monitored Withstand used in this document and project, it is not a valid source for withstand testing. As defined in Section 3.8.1, DAC does not meet the constant RMS voltage or prescribed time criteria. The duration of each shot, the voltage frequency, and the voltage magnitude (cycle to cycle) are not controlled or prescribed as they are in the sources mentioned above. See Section 3.12.6.1 for additional information.

In Figure 97, the schematic represents a Monitored Withstand test. The critical part of the test is the measurement and interpretation during the withstand phase. However, it is clear that the simple scheme in Figure 97 could be modified to allow an evaluation before the start of the withstand test as shown schematically in Figure 98. 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.

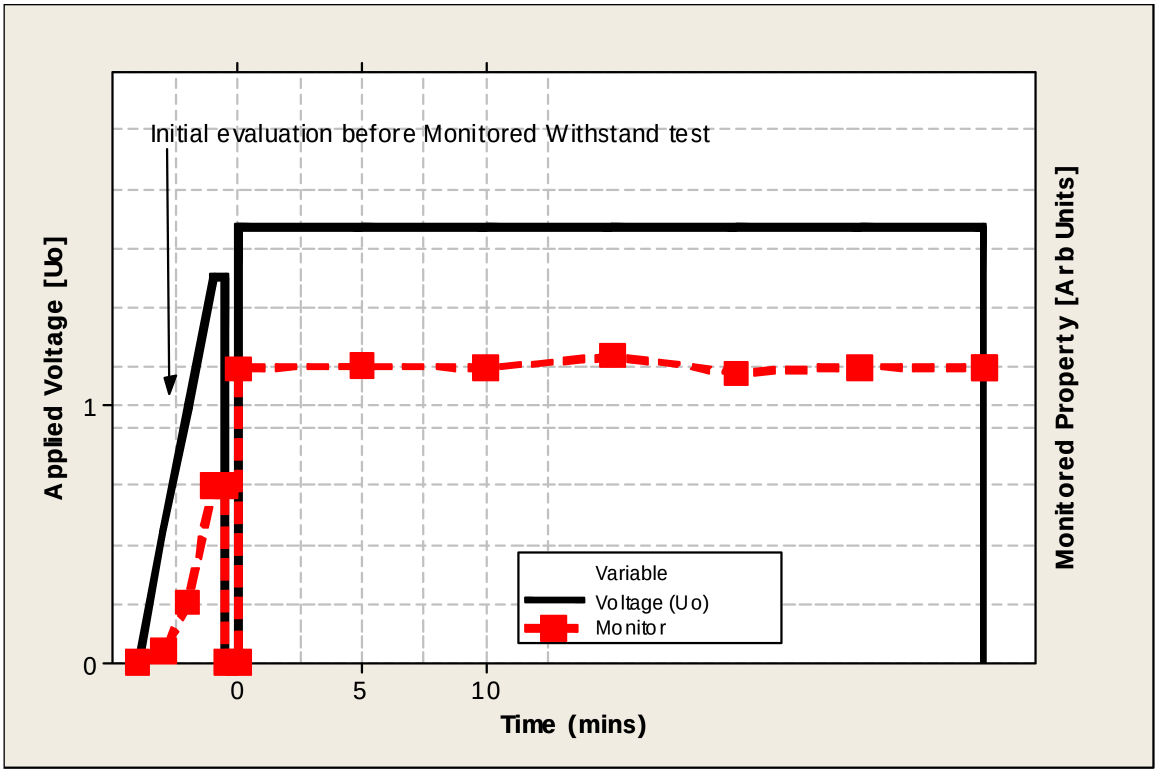


Figure 98: Schematic of a Monitored Withstand Test with Optional Diagnostic Measurement

Like other diagnostic techniques, Simple and Monitored Withstand tests require the application of voltages in excess of the service voltage. However, unlike many other diagnostic test techniques, a utility should acknowledge the potential to cause a failure during testing. In fact, a Failure on Test (FOT), as opposed to a service failure, is a 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 Failures on Test through undue degradation of the strong elements is reduced by using voltages closer to the service level and limited length of application. Either the number of cycles or time may readily 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 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 section of this document.

The advantages and disadvantages of withstand testing are summarized in Table 51 and Table 52. It should be noted that this table focuses on the issues associated with the long term (15 minutes 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 sections. 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 51: Advantages and Disadvantages of Monitored Withstand for Different Voltage Sources and Diagnostics			
Source	**Diagnostic**	**Advantages**	**Disadvantages**
60 Hz AC Offline	Leakage	Not Applicable	
	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 some concern that the long-term application of elevated voltage will damage the cable system, though the evidence for this is limited. • There is little or no guidance in industry standards on how to interpret results from a long term PD test
	Tan δ	• Interpretation may be performed during the withstand test.	• None
AC Offline Very Low Frequency (0.1 Hz) Cosine Rectangular	Leakage	• No unique advantages for withstand monitoring mode.	• Interpretation impossible during withstand test – data only available at end.
	Partial Discharge	No Field Experience	
	Tan δ	No Field Experience Underlying technical assumptions not yet validated	
AC Offline Very Low Frequency (0.01 – 1 Hz) Sinusoidal	Leakage	Not Applicable	
	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. • Some level of guidance on interpretation will soon be available in industry standards.	• No unique disadvantages for withstand monitoring mode.

Table 52: Overall Advantages and Disadvantages of Monitored Withstand Techniques	
Advantages	• Provides additional information over the simple "Pass" or "Not Pass" obtained from a 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 such that the test may be altered (test time increased or decreased) to fit utility objectives. • Allows for the integration of outcomes from Simple Withstand test with those from other diagnostic techniques.
Open Issues	• Selection of monitored property (i.e. PD, Tan δ, or Leakage). • Interpretation of diagnostic data when used in monitored mode – not the same as in a typical single diagnostic test. • Implementation where only level-based assessments are available is unclear and may not be useful. • Voltage exposure (impact of voltage on cable system) caused by 60 Hz AC and VLF has not been established.
Disadvantages	• Adds complexity (interpretation, set up, and data recording) to Simple Withstand test. • Highly skilled engineers required.

A critical issue for Monitored Withstand testing, like Simple Withstand testing, is the application time for the test. If the time is too short, then cables with localized defects that could cause failures may be returned to service before the defect is taken to failure or with insufficient opportunity for the monitored feature to provide useful information. For 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 section suggests that 30 minutes should be the usual target test time. 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..

3.9.4 Success Criteria

Monitored Withstand results fall into two classes:

- Pass – no action required
- Not Pass – action required that may include "Further Study"

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

1. Dielectric puncture
2. No dielectric puncture AND non-compliant information from the monitored property:
    - Rapid increase anytime during the test
    - Steady upward trend at a moderate level
    - Instability (widely varying data)
    - High magnitude

On the other hand, there is only one way in which a cable system may "Pass" a Monitored Withstand test: no dielectric puncture and compliant information from the monitored property:

- Stable (narrowly varying data)
- Low magnitude

Figure 99 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 99 would lead to a "Not Pass" result.

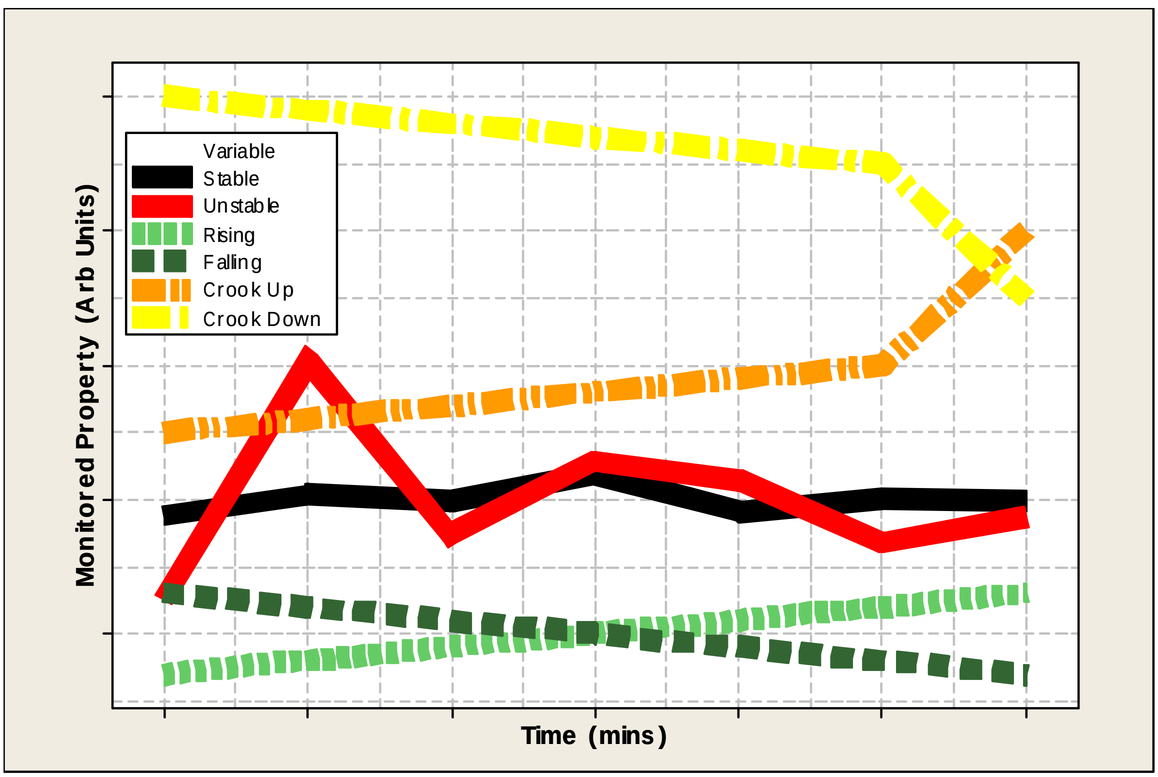


Figure 99: Possible Characteristic Shapes of Monitored Responses

3.9.5 Estimated Accuracy

The Pass / Not Pass criteria for the Monitored Withstand technique are defined previously.

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, no data are available to assess the accuracy of Monitored Withstand testing.

3.9.6 CDFI Perspective

Although often discussed, there is limited information on the application of a Monitored Withstand program. There are a number of "accidental" Monitored Withstand tests on which to draw anecdotal information. For example, PD tests at elevated voltage for significant times will include a withstand element resulting from the elevated voltage. However, in the course of the CDFI project, a number of similar programs have begun and data from these tests were provided to the CDFI.

3.9.6.1 Damped AC Withstand

Damped AC has been discussed in the industry as being used for withstand testing. However, it does not fit the definition of Monitored Withstand used in this document for a valid source for withstand testing. As defined in Section 3.8.1, DAC does not meet the constant RMS voltage or prescribed time criteria. To verify the effectiveness of a source, field data are required showing the pass and fail of components. As far as the CDFI can ascertain, no such data are available for DAC. Section 3.12.6.1 contains a more detailed discussion of the issues associated with DAC.

3.9.6.2 Interpretation and Hierarchy – Tan δ, PD, and Leakage Current

At this stage, it is instructive to examine the differences between the interpretations of standard Dielectric Loss measurements compared to the assessment of the same property in a Monitored Withstand test. Work within the CDFI has suggested the following hierarchy for Dielectric Loss measurement interpretation, when not used in the Monitored Withstand mode is (ranked from most important to least important):

1. Stability within a voltage step. In the CDFI, stability is assessed by the standard deviation on Tan δ measured during each step. Other methods for stability assessment methods may also be used.
2. Tip Up (difference in the mean value of Tan δ at two selected voltages).
3. Tan δ (mean value at U_0).

When used in the Monitoring mode, the constant voltage employed does not permit the assessment of the Tip Up. However, this information can be available if a voltage ramp is used on the way to the withstand voltage level (Figure 98). Otherwise, Tip Up cannot form part of the standard hierarchy for Monitored Withstand.

There are similar issues with the mean Tan δ. A mean Tan δ can be computed for the entire withstand period of the test. However, since this is a Monitored Withstand test, testing occurs at voltages above U_0, the voltage commonly used for standard Tan δ assessments. The concept of mean Tan δ is useful even at this higher voltage, but the critical values for assessment cannot be the same as those used for Tan δ at U_0. In fact, these values are likely to be higher than those used for the standard Tan δ assessment (Table 53). If one examines the criteria for Tip Up, segments can have non-zero voltage dependence (i.e. non-zero Tip Up) and still be considered as "No Action Required". This means that these circuits have a voltage dependence and are still okay. In fact, the Tip Up criteria for PE-based insulations indicates an acceptable Tip Up of 8E-3. Therefore, from the criteria for standard Tan δ assessments, the acceptable mean Tan δ at withstand voltages must be no less than 8E-3 (Tip Up criterion of 8E-3). Criteria for Monitored Withstand tests will emerge with additional testing.

Generally, stability is the most useful of the three dielectric loss features. Unfortunately, the use of standard deviation is not likely to be sufficient for this purpose. The need to improve the approach is driven by the long times used for the monitored test and because the user is more likely to be interested in the trend (increasing or decreasing) of the instability rather than its absolute value.

Thus, the following hierarchy for Dielectric Loss in a Monitored Withstand is suggested:

1. Trend within the monitored period. These are likely to be categorical attributes: flat, upward trend, downward trend, etc. See Figure 99.

2. Stability (standard deviation on the mean value) within the monitored period.

3. Tan δ (mean at withstand voltage).

Anecdotal feedback (not yet confirmed by data) indicates that this hierarchy is a standard approach for those using Monitored Withstand programs employing Dielectric Loss. Consequently, we believe it is likely that the above hierarchy for assessment of Tan δ can be generalized for any monitored property:

1. Trend within the monitored period. These are likely to be categorical attributes: flat, upward trend, downward trend, etc. See Figure 99.

2. Stability (by how much did it change) within the monitored period.

3. Monitored property (mean value at withstand voltage).

This hierarchy is applicable to Leakage Current and PD for all voltage sources except Damped AC.

3.9.6.3 Establishing Critical Levels with Multiple Features

This section describes the preliminary effort to develop knowledge rules to help interpret Monitored Withstand/Dielectric Loss results. This is accomplished in the same manner as the individual monitored properties. Figure 100 shows the distributions (fitted – 3 parameter Weibull and empirical) for the Standard Deviation (overall for 30 minutes) for field tests on PILC cables.

Convenient percentiles such as 80 % and 90 % are suggested as critical values. In practice, the values at these percentiles can be rounded to 1.4 E-3 and 2.8 E-3.

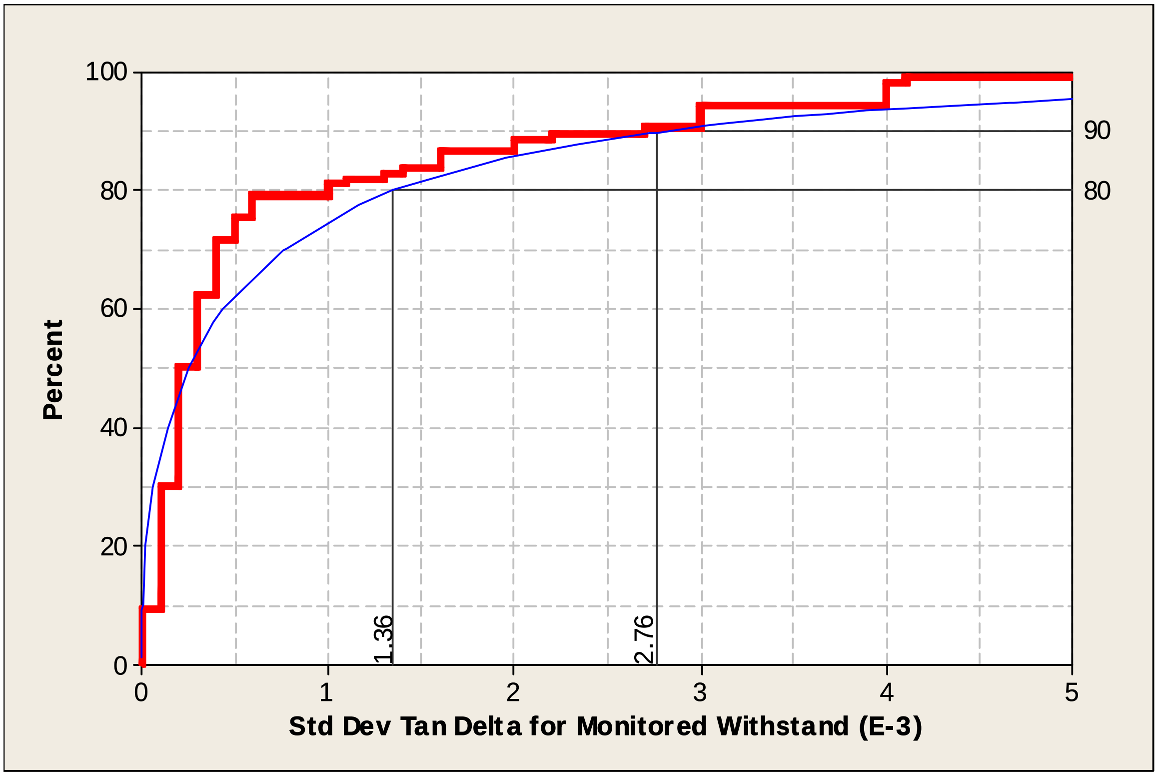


Figure 100: Empirical Distribution of Standard Deviation (Overall for 30 minutes) for Field Tests on PILC Cables at IEEE Std. 400.2™ Voltage Levels

Table 53 shows a comparison of the criteria for stability in a standard Tan δ measurement and the resulting criteria obtained from Figure 100 for the Monitored Withstand mode. Note that the limits are higher for the Monitored Withstand mode.

Table 53: 2010 CDFI Criteria for Condition Assessment Criteria of Paper Insulations (PILC) for Dielectric Loss and Monitored Withstand Modes		
Condition Assessment	**Tan δ Stability Measured at U_0 (Dielectric Loss Mode) (Table 29) [E-3]**	**Tan δ Stability Measured at IEEE Std. 400.2™ Withstand levels (Monitored Withstand Mode) (Figure 100) [E-3]**
No Action Required	<0.3	<1.4
Further Study Advised	0.3 to 0.4	1.4 to 2.8
Action Required	>0.4	>2.8

As in the case of Tan δ, the Tan δ Monitored Withstand criteria in Table 53 represent the latest version developed within the CDFI. It is useful to review the basis for the evolution of the criteria shown in Table 54. These criteria will be updated during CDFI Phase II.

Table 54: Evolution of Tan δ Monitored Withstand Criteria			
Version	**Trend**	**Stability**	**Mean Tan δ**
2008	Qualitative Assessment Flat/Up/Down/Unstable	Standard Deviation Qualitative Criteria All Insulations	Qualitative Criteria All Insulations
2010		Qualitative Criteria **PE & Filled** **PILC** criteria based on data (Table 53)	Qualitative Criteria **PE & Filled** **PILC** criteria based on data (Table 53)

It is important to note the use of the term "qualitative" to describe some of criteria in 2008 and 2010. This term is used because the understanding in CDFI at the time was limited to which measurement values were "really good" and those that were "really bad" but there was not a defined threshold to separate the two. These thresholds/criteria were developed once data were available.

3.9.6.4 Field Data

The results of a VLF AC - Sinusoidal Monitored Withstand test in which the Tan δ was monitored continuously for the first 30 minutes appear in Figure 101.

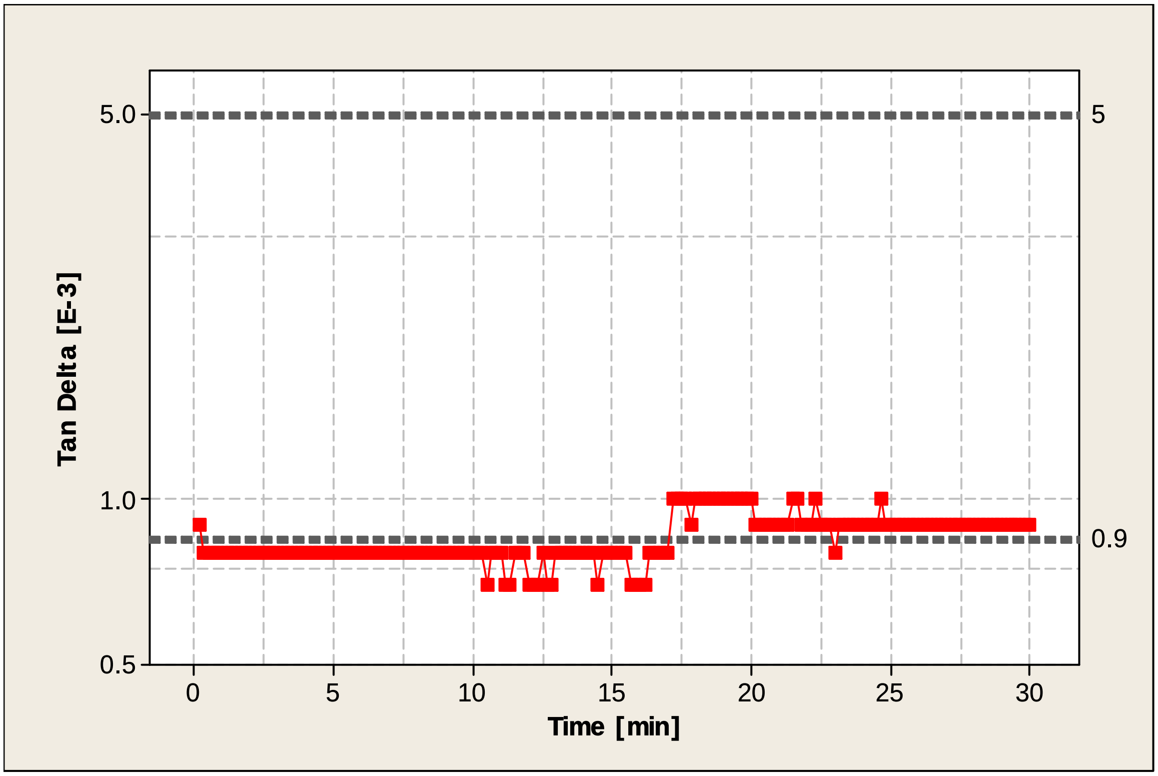


Figure 101: Tan δ Monitored Withstand Data on service aged XLPE cables

These results lead to the following assessment:

1. The tested segment did not experience a dielectric puncture
2. Trend: Flat
3. Stability (standard deviation on the mean at the withstand voltage): 0.79E-3
4. Tan δ (mean at withstand voltage): 0.9E-3

The Monitored Withstand assessment of this performance would likely be "No Action Required." Based on the most recent analysis for the pure Tan δ diagnostic, this sample set lies on the border of the "No Action Required" and "Further Study" classes. The Monitored and Tan δ diagnostic differ in their outcomes because the third level of the hierarchy uses data obtained at U_0, which has lower critical levels than would be appropriate at the withstand voltages.

Results of a VLF AC - Sinusoidal Monitored Withstand test with Tan δ on EPR insulated cables (30 minutes) appear in Figure 102. The 190 individual data points have been compressed to the Mean and Standard Deviations (Std Dev) for each minute of testing. The open symbols are the initial test values and would be the only data available had this been a standard, short term Tan δ diagnostic test. It is interesting to see that the dielectric loss increases and becomes less scattered (lower Std

Dev) as time progresses. This provides further evidence that the critical levels from the standard diagnostic test need to be redefined for a Monitored Withstand.

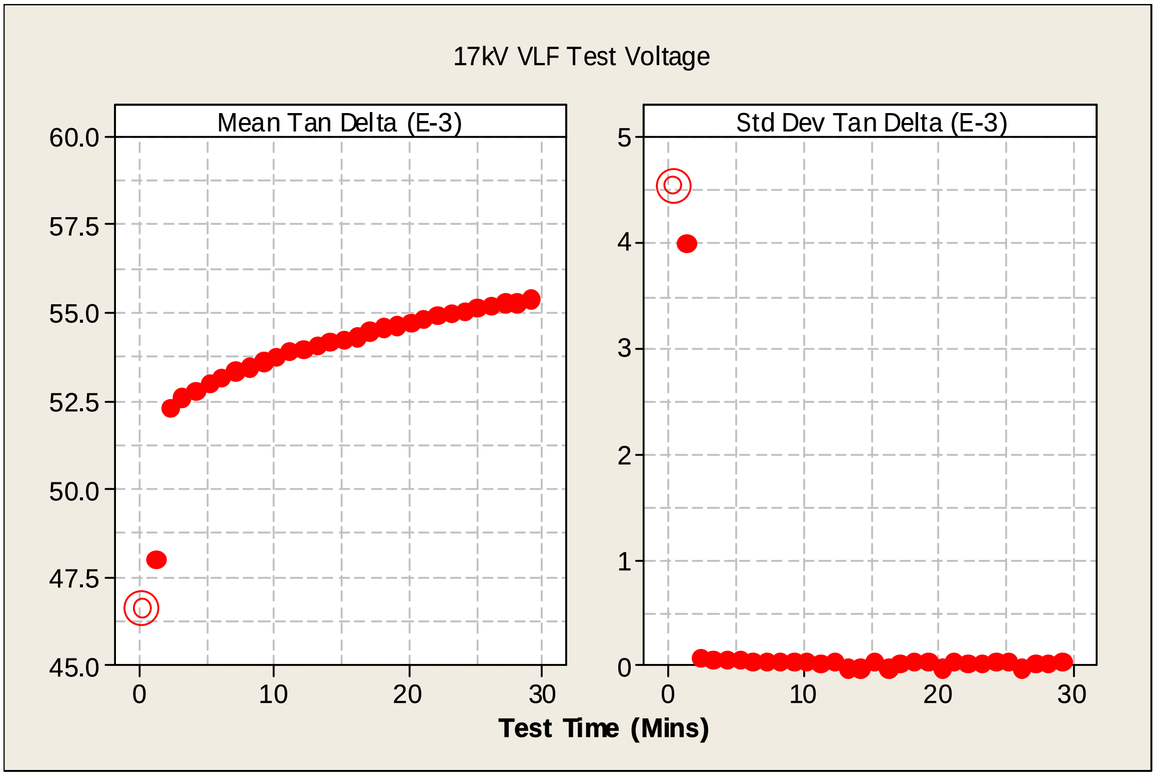


Figure 102: Tan δ Monitored Withstand Data from Service Aged EPR Insulated Cables

Figure 102 shows the Tan δ Monitored Withstand data. Numerical criteria are have not yet been established but the following observations can be made with an assessment based on the authors' experience:

1. No Dielectric Failure
2. Trend: Upward
3. Stability (standard deviation on the mean at the withstand voltage): 2.6 E-3 (range of 0 to 4.55 E-3).
4. Tan δ (mean at withstand voltage): 53.3 E-3 (range of 46 to 55 E-3).
5. Test Result: Unknown – criteria not yet established.

A challenging example appears in Figure 103. In this case, the extended period of monitoring reveals the instability in the standard deviation and the median Dielectric Loss. Neither of these features would have been revealed by a standard diagnostic test.

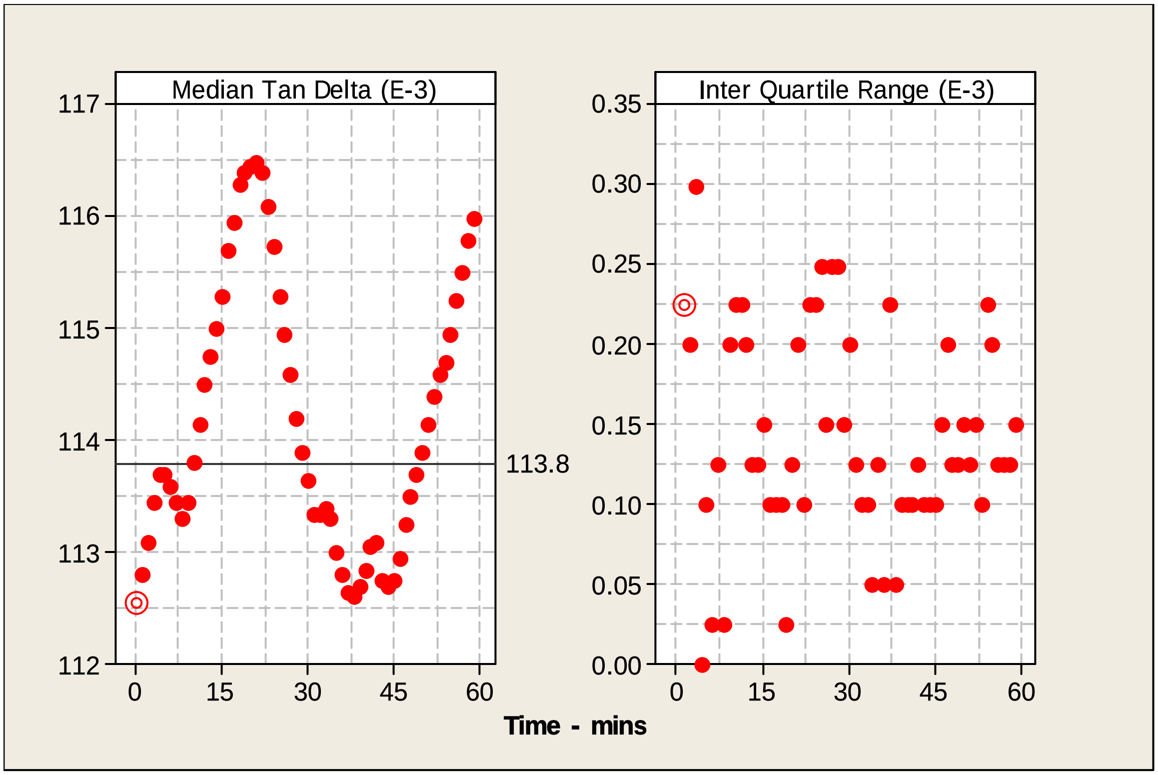


Figure 103: Tan δ Monitored Withstand Data on Service Aged Cable with Filled Insulation Tested at IEEE Std. 400.2™ Voltage Level

Figure 103 shows that the Tan δ Monitored Withstand data would be classified as:

1. No Dielectric Failure
2. Trend: Unstable
3. Stability (Inter Quartile Range at the withstand voltage): 0.125 E-3 (range of 0-0.3 E-3)
4. Tan δ (median at withstand voltage): 113.8 E-3 (range of 112.5-116.5 E-3).
5. Test Result – Unknown – criteria not yet established

It is interesting that in this test the interim interpretation at 15 minutes led the test crew to extend the test to 60 minutes. If the test had been curtailed at 15 minutes, the trend would have been classified as: Upward.

3.10 Recovery Voltage Technique

3.10.1 Test Scope

This diagnostic technique can be applied to any single cable insulation type (not hybrid circuits) with conventional or non-linear stress relief accessories. However, the availability of success criteria has effectively limited its use to paper insulated cables.

3.10.2 How it Works

This technique is sensitive to the level of water tree degradation in the insulation [51 - 54], or moisture ingress in PILC cables. It measures the increase in voltage caused by the release of trapped charges within the insulation. Absorbed moisture within the insulation likely causes charges to be trapped. The voltage measured across the cable system dielectric after the applied test voltage is removed is called the recovery voltage.

3.10.3 How it is applied

This technique is conducted offline and measures the global condition of the insulation. Very little Recovery Voltage testing was performed in the CDFI so the following discussion is based on information from the literature.

The procedure follows the scheme shown in Figure 104. The cable circuit is charged using DC voltage for a given time. Typical values range from 1 to 2 kV. Charging time is usually 15 minutes. After the circuit is charged, it is discharged for 2 to 5 seconds through a ground resistor. The open circuit voltage is then measured. This voltage is known as the recovery voltage.

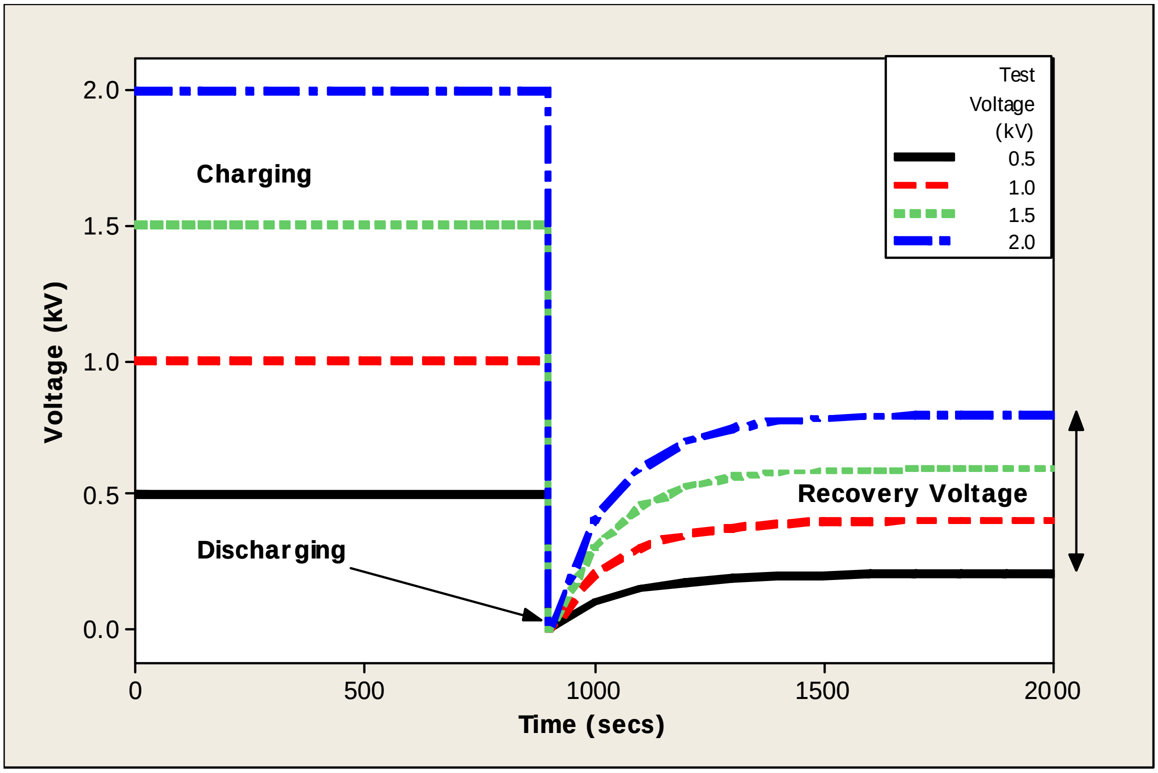


Figure 104: Schematic Representation of the Recovery Voltage Measurement Technique

Data from Kuschel et al. [42] (Figure 105) display the magnitudes expected from tests on new (unaged) cables. Note the different discharging characteristics and that the Recovery Voltages are in the range of 0.1 % to 0.2 % of the DC charging Voltage. These data used the following test protocol: :

- Charging Voltage: 3 kV DC
- Charging Time: 15 min (900 sec)
- Discharge time: 5 sec

The data appear in Figure 105 for the maximum measured voltage and the result after a decay time of 10,000 sec.

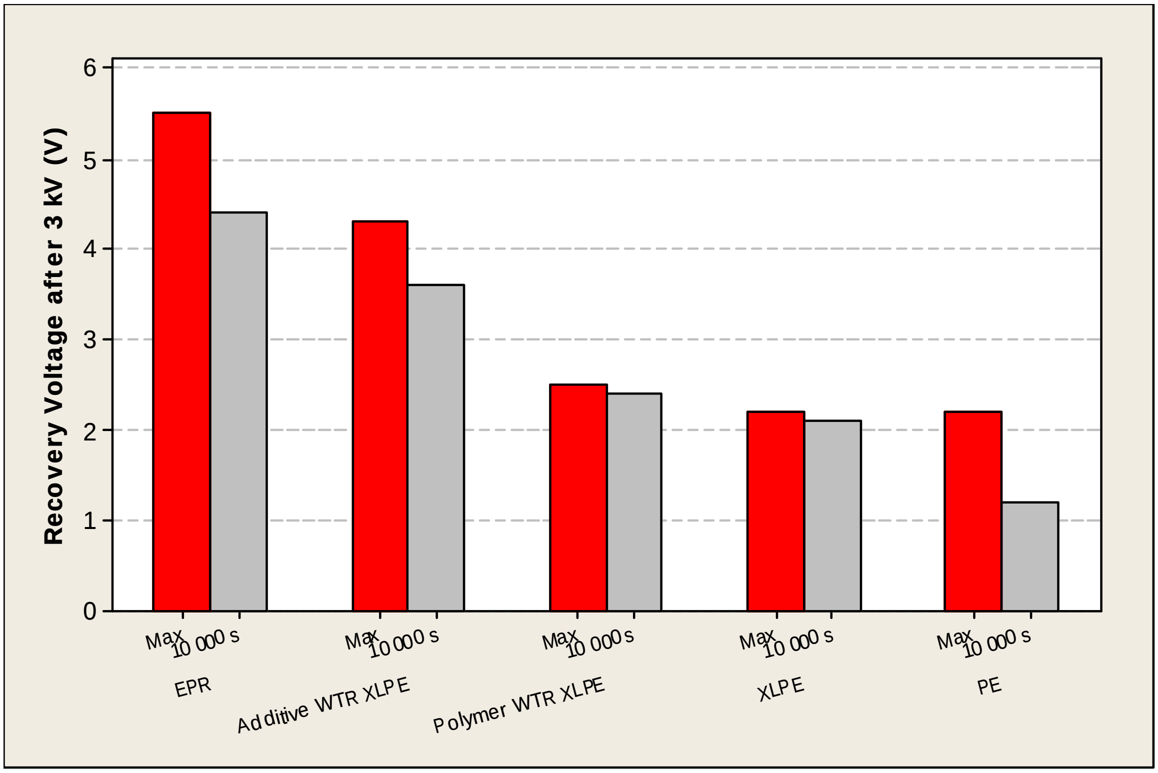


Figure 105: Recovery Voltage Data [42]

In the recovery voltage technique, the diagnostic factor D describes the level of damage to the cable. The diagnostic factor D is the ratio between the maximum recovery voltage with U_0 as the charging voltage and the maximum recovery voltage with 2 U_0 as the charging voltage [23]. This ratio appears in (8).

$$D = \frac{\text{Recovery Voltage}_{\text{Max}}(2\text{U}_0)}{\text{Recovery Voltage}_{\text{Max}}(\text{U}_0)} \quad \textbf{(8)}$$

Where:

D - Diagnostic factor
Recovery Voltage$_{Max}$ *(2*U_0*)* - Maximum recovery voltage recorded for 2 U_0
Recovery Voltage$_{Max}$ *(*U_0*)* - Maximum recovery voltage recorded for U_0

The standard diagnostic criterion is the “non-linearity” of the return voltage at its maximum value. For unaged (undamaged) cables, D should equal two. That is, if the charging voltage doubles then the recovery voltage should also double as there is a one-to-one correspondence between the recovery and charging voltages. A heavily aged cable system will not behave linearly and so the diagnostic factor (D) for such a system would different from the ratio of the two charging voltages [52, 53].

Although the nonlinearity of the dielectric response seems to be a good diagnostic parameter for water tree detection, a false diagnosis is possible if the degree of non-linearity is exclusively described by a single numerical value, i.e. the value of D established using measurements at U_0 and

$2U_0$. Thus, better discrimination may be attained if D is computed for a range of voltages and thus shown to be linear or near-linear.

Advantages and disadvantages for the Recovery Voltage technique appear in Table 55.

Table 55: Overall Advantages and Disadvantages of Recovery Voltage Technique

Advantages	• Provides a general condition assessment of cable system insulation. • Test equipment is small.
Open Issues	• Historically applied to all cable types but currently recommended only for paper cables. No data on paper cables are available. • Accessory behavior must be considered to properly assess cable system insulation condition. • Cable must be completely discharged after each test.
Disadvantages	• No application guidelines are available. • Cannot detect localized defects. • Cannot be applied to hybrid circuits due to the responses of different insulation materials. • Cable must be removed from service for testing.

Note that some accessories specifically employ stress relief materials with non-linear loss characteristics, that is, their dielectric loss does not vary linearly with the applied test voltage. There have been a few suggestions that these materials might have an influence on the measured values when low levels of current and voltage are involved. However, the evidence available to date for dielectric loss measurements (Section 3.5), which are related to Recovery Voltage, shows that the type of stress relief is likely to show a smaller effect than either:

a) the aging of the accessory or

b) incorrect installation depending on the tested segment length.

Therefore, the best practice is to perform periodic testing at the same voltage level(s) while observing the general trend in Recovery Voltage values.

3.10.4 Success Criteria

Recovery Voltage results are reported in terms of basic recovery voltage measurements as a function of charging voltage.

There are some success criteria for recovery measurements (Table 56) that provide a hierarchy of levels. General criteria for all cable types are used but it is expected that the criteria depend on not only the quality of the cable system, but also on the cable and accessory technologies employed and the stress associated with the application (charging) voltage.

Table 56: Pass and Not Pass Indications for Recovery Voltage Measurements		
Cable System	**Pass Indication**	**Not Pass Indication**
HMWPE WTRXLPE XLPE	No unified criteria.	No unified criteria.
EPR		
PILC		

Although no unified criteria are available, a number of references indicate some useful features to form a basis for diagnostic conclusions (Table 57).

Table 57: Interpretation Rule of Diagnostic Factor D Obtained From Maximum Recovery Voltages at U_0 and 2 U_0 [52]		
Diagnostic Factor D	**Evaluation**	**Action**
2.0 – 2.5	Insulation in good condition.	No action.
2.5 – 3.0	Insulation in fair condition.	Other tests are recommended to identify isolated weak areas.
> 3.0	Severely damaged.	Replace cable.

Figure 106 graphically illustrates the criteria shown in Table 57.

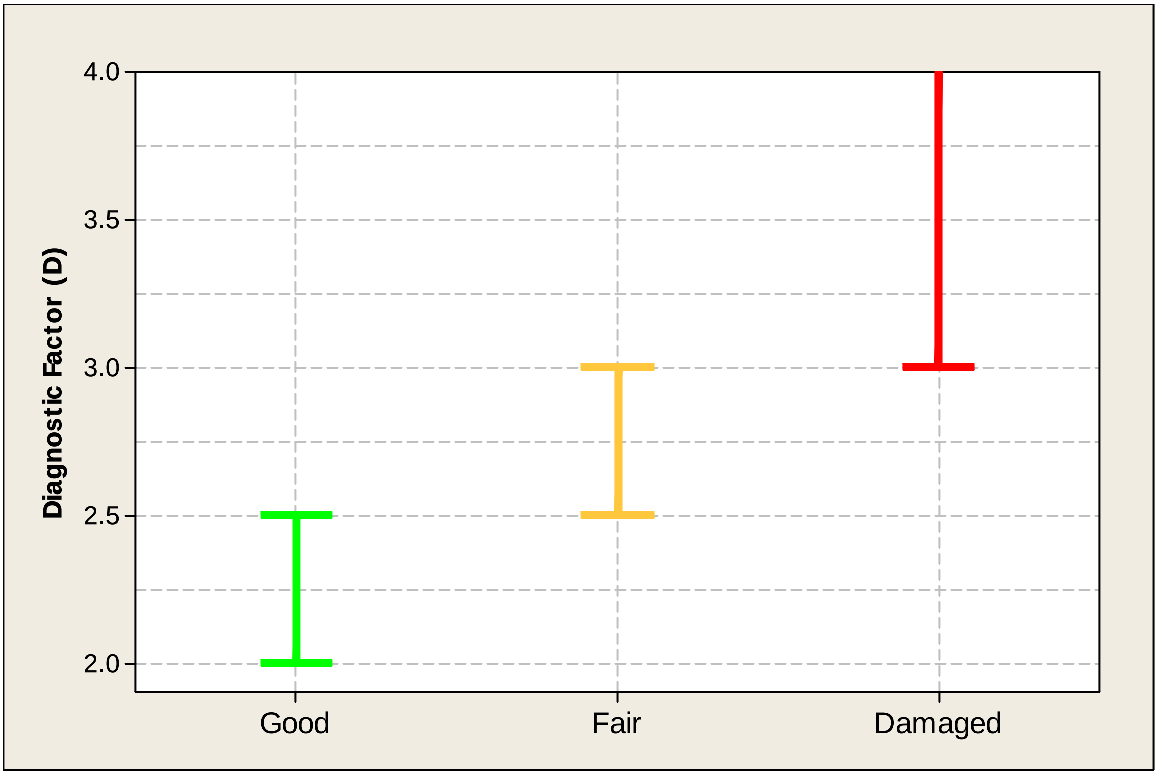


Figure 106: Interpretation of the Diagnostic Factor D

3.10.5 Estimated Accuracy

No information is available to CDFI to make this assessment.

3.10.6 CDFI Perspective

This technique is not used in the US or Canada so no significant data have been provided to the CDFI. Thus no perspective on this technology was developed.

3.11 Polarization/Depolarization Current or Isothermal Relaxation Current (IRC) Technique

3.11.1 Test Scope

This test involves the short-term application of low DC voltages to extruded cable circuits having only one type of insulation material. Very little IRC testing was performed in the CDFI so the following discussion is based on information from the literature.

3.11.2 How it Works

It measures the time constant of trapped charges within the insulation as they relax by measuring the discharge current over time after the application of a prescribed DC voltage [55], [56].

3.11.3 How it is applied

This technique is performed offline. The measured results relate to the global condition of the insulation and the presence of water trees. The procedure is as follows: The cable circuit is charged using DC voltage (1 kV) for a given time. The charging time is usually 5 to 30 minutes. After the circuit is charged, it is discharged for 2 to 5 seconds through a resistor to ground. The discharge current is then measured for 15 to 30 minutes. This current is known as the depolarization or Isothermal Relaxation Current (IRC). The voltage application is similar to that described for Recovery Voltage in Figure 104, but the measured parameter is a current, not a voltage. The measured current appears schematically in Figure 107.

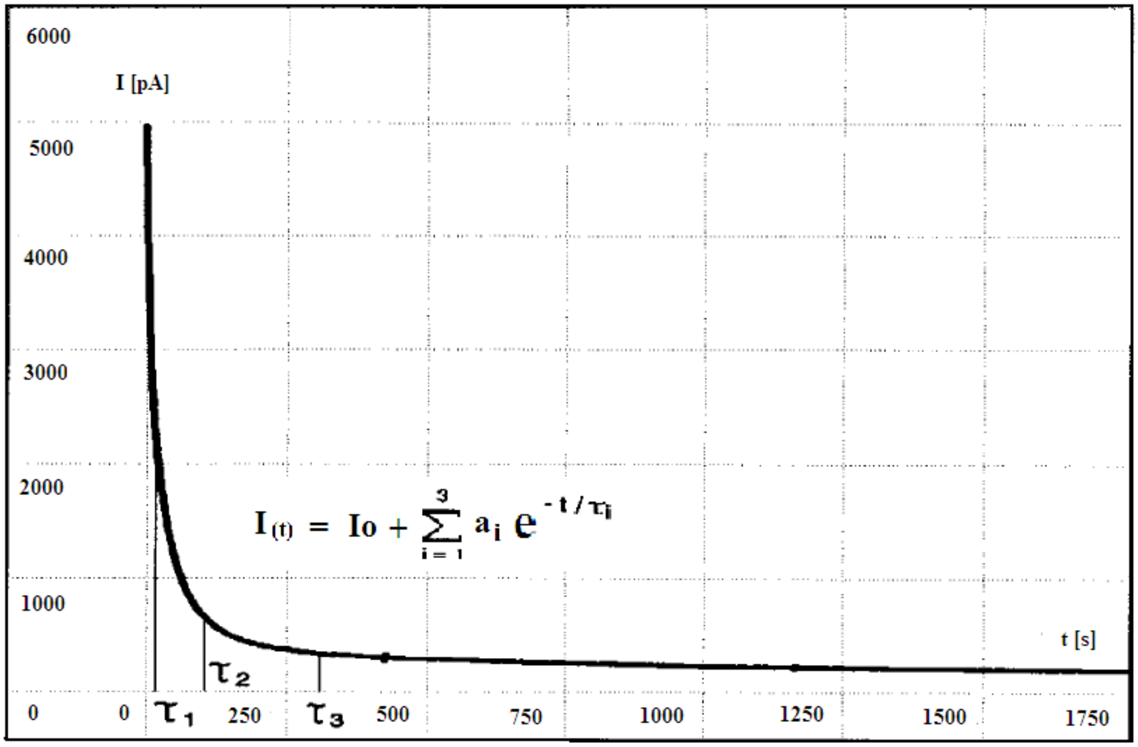


Figure 107: Schematic Representation of Measured Current from the IRC Technique [55]

It is assumed that the measured discharge current is comprised of three current components (similar to the discussion on Dielectric Spectroscopy in Section 3.6.2), which must be separated and compared. The separation applies an assumed model that considers three exponential currents, each with a different time constant. These three currents are computed and identified as:

a) Current related with the cable insulation,
b) Current related with the semi conductive layer, and
c) Current related with insulation defects.

Each current has a corresponding duration and, thus, represents a certain amount of charge: Q1, Q2, and Q3. The current of most concern is that which generates Q3. In fact, the larger the peak of Q3 as compared to Q2 or Q1, the worse the condition of the cable insulation [54]. Figure 108 shows these principles graphically. See [55] for definitions of the terms used in this figure.

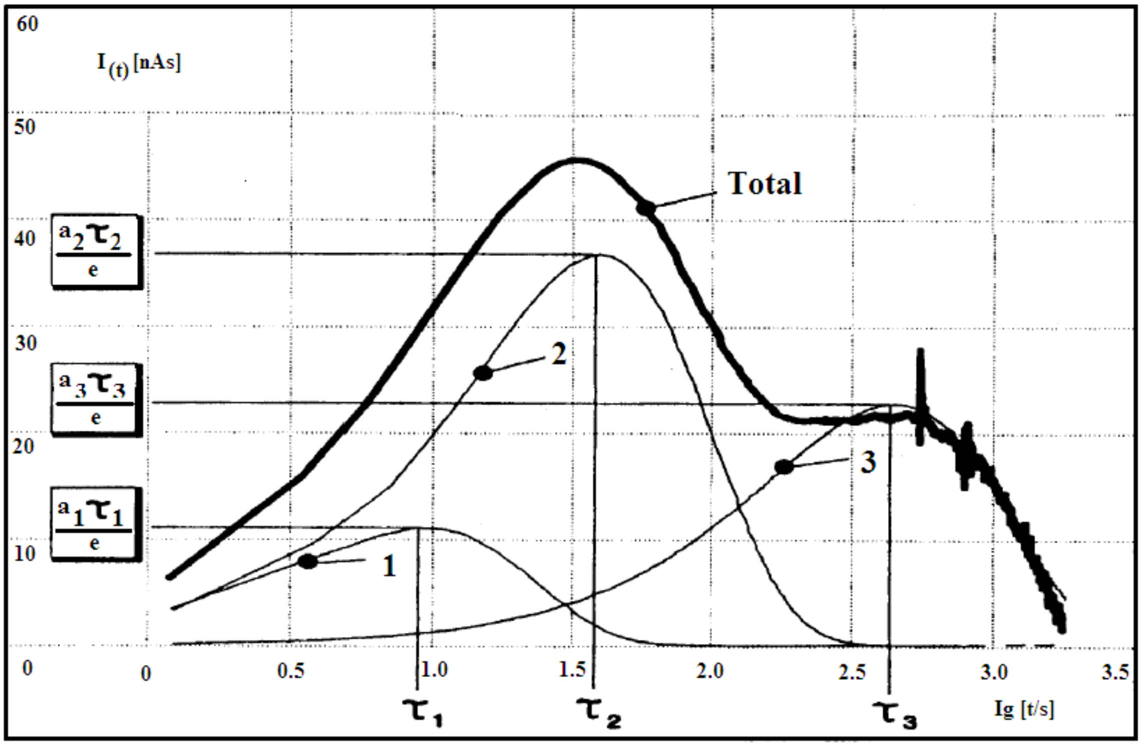


Figure 108: Principles of IRC Current Separation and Charge Calculation [55]

Advantages and disadvantages for the IRC approach to diagnostic testing appear in Table 58.

Note that some accessories specifically employ stress relief materials with non-linear loss characteristics. There have been a few suggestions that these materials might have an influence on the measured values when low levels of current and voltage are involved. However, the evidence available for dielectric loss, which is related to the IRC measurement, shows that the type of stress relief is likely to show a smaller effect than either:

a) the aging of the accessory or
b) incorrect installation depending on the tested segment length.

Therefore, the best practice is to perform periodic tests at the same voltage level(s) while observing the general trend in IRC values.

Table 58: Overall Advantages and Disadvantages of Polarization/Depolarization Current Technique	
Advantages	• There are well-established criteria for evaluating German XLPE cable systems against accelerated laboratory endurance tests. • Test equipment is small.
Open Issues	• No assessment criteria for US cables. • Criteria not established for WTRXLPE or EPR cable systems. • Accessory behavior may need to be included to properly assess cable system condition. • Assumes a three time constant model. This model may not be appropriate. • Reproducibility of measurement for very small currents on the order of nano amps. • Stability of the mathematical separation techniques for the current. • Cables need to be energized prior to testing to ensure adequate polarization. • The technique is apparently sensitive to the presence of water trees.
Disadvantages	• Difficult to measure new extruded cables due to presence of crosslinking byproducts. • The small currents measured are very sensitive to the test environment. • Cannot detect localized defects. • Cable must be completely discharged after each test. • Cable must be taken out of service for testing. • Cable neutral must be ungrounded. • Computationally difficult to extract model parameters. • Long length required to get sufficiently large signal.

In the IRC technique, the aging factor (IRCA) describes the level of damage to the cable. The aging factor is the ratio between the trapped charge in the insulation defects and the trapped charge in the semiconductor layers of the cable [55]. This ratio appears in (9).

$$IRCA = \frac{Q_3}{Q_2} \qquad \textbf{(9)}$$

Where:

$IRCA$ - Aging factor

Q_3 - Trapped charge in the insulation

Q_2 - Trapped charge in the semiconductor layers

3.11.4 Success Criteria

General criteria depend on the cable system quality, the cable and accessory technologies employed, and the stress associated with the application voltage. . Table 59 and Table 60 show the interpretation of IRCA.

<table>
<tr><th colspan="3">Table 59: Pass and Not Pass Indications for Recovery Voltage Measurements</th></tr>
<tr><th>Cable System</th><th>Pass Indication</th><th>Not Pass Indication</th></tr>
<tr><td>XLPE</td><td>See Table 60</td><td>See Table 60</td></tr>
<tr><td>HMWPE
WTRXLPE</td><td rowspan="3">No unified criteria.</td><td rowspan="3">No unified criteria.</td></tr>
<tr><td>EPR</td></tr>
<tr><td>PILC</td></tr>
</table>

Table 60: Correlation Between Aging Class and Aging Factor for XLPE Cables [55]

IRCA	Aging Class
Less than 1.75	Good
Between 1.75 and 1.90	Middle
Between 1.90 and 2.10	Aged
More than 2.10	Critical

3.11.5 Estimated Accuracy

This technique is not used in the US or Canada and thus no extensive data are available for analysis.

3.11.6 CDFI Perspective

No CDFI perspective exists due to the limited information available on this technology.

3.12 Combined Diagnostics

3.12.1 Test Scope

One of the drawbacks of a single diagnostic test is that each diagnostic examines one particular degradation mode while being less sensitive to other modes. This is important as it is possible that more than one degradation mode might be concurrently affecting a cable system. Thus, there is considerable benefit to making simultaneous, non-conflicting measurements of two or more diagnostic properties/characteristics.

Note: Before reading or consulting this section, the reader should review the previous sections on the individual diagnostic techniques.

3.12.2 How it Works

The outcome of this approach considers two or more diagnostic responses, each of which requires interpretation to determine the result. This differs from the Monitored Withstand approach in three ways:

1. In a Monitored Withstand test, only one diagnostic response requires interpretation.

2. In a Monitored Withstand test, the test conditions (time, voltage, etc) for the measured diagnostic have to match the requirements of the withstand test.

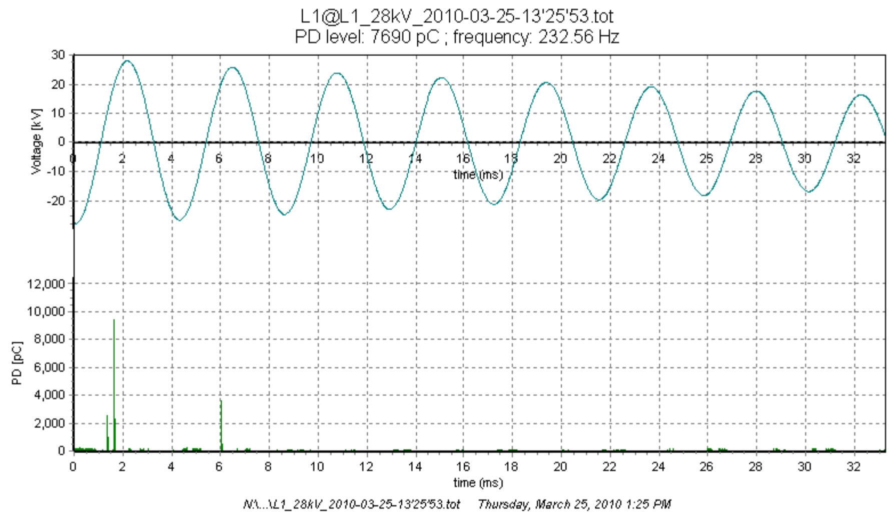
3. Unlike a Monitored Withstand test, there is no opportunity for the test to be modified, in terms of time or voltage, because of the diagnostic results.

The most promising combined diagnostic is the simultaneous measurement of dielectric loss and partial discharge. Damped AC is a commercially available Partial Discharge and Dielectric Loss combined diagnostic technology. The measurement of Tan δ and Partial Discharge using controlled, VLF AC sinusoidal sources is being explored.

3.12.3 How it is applied

The Combined Diagnostic approaches are conducted offline, i.e. with the cables disconnected from the system. The applied voltage may be Damped AC (DAC) or Very Low Frequency (VLF) AC. Typical testing voltages tend to be $<1.7\ U_0$ as the goal is to avoid a withstand style test.

The only commercially available combined diagnostic uses the Damped AC approach. The decaying oscillations enable the measurement of Partial Discharge magnitude and extinction voltage. The rate of voltage decay is proportional to the dielectric loss of the cable system. The PD pulse is captured as a function of time, which enables the position of the discharge along the measured circuit length to be established. In field units, the rate-of-decay method of loss estimation, which averages the loss over the entire voltage range, so, although possible in theory, in practice it is not possible to establish the stability of the Tan δ measurement as a function of voltage. Figure 109 shows an example of simultaneous PD (top graph) and Tan δ (bottom graph) using DAC. Note that the voltage waveform for the one shot appears along with the measurement data.



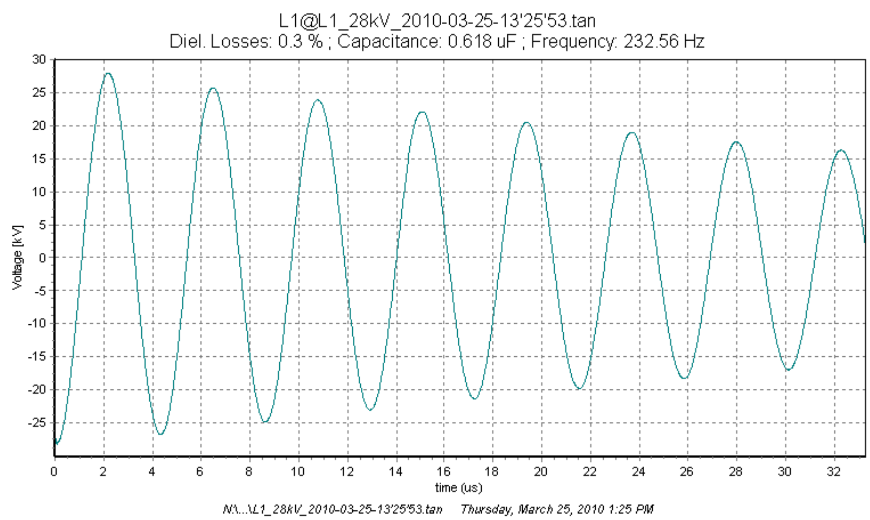


Figure 109: Simultaneous PD (Top) and Dielectric Loss (Bottom – See Text Above Waveform) Measurement Using DAC – Roswell March 2010

The frequency and the number of cycles above U_0 are not explicitly controlled for a DAC test. However, some level of dielectric loss and partial discharge stability can be established through multiple DAC applications. Currently, the partial discharge measurement using DAC is based upon Ultra Wide bandwidth (UWB) technique, which captures information from frequencies up to 100 MHz rather than from a narrow band as described by IEC 60270.

Typical results using DAC are shown for four shots at different voltages (top graph of Figure 110) and 50 shots at one voltage (bottom graph of Figure 110) for tests conducted at Roswell, GA. The

50-shot data in this figure shows PD charge magnitude and dielectric loss measurements averaged over 10 consecutive shots. A shot-by-shot example of DAC testing appears in Figure 111.

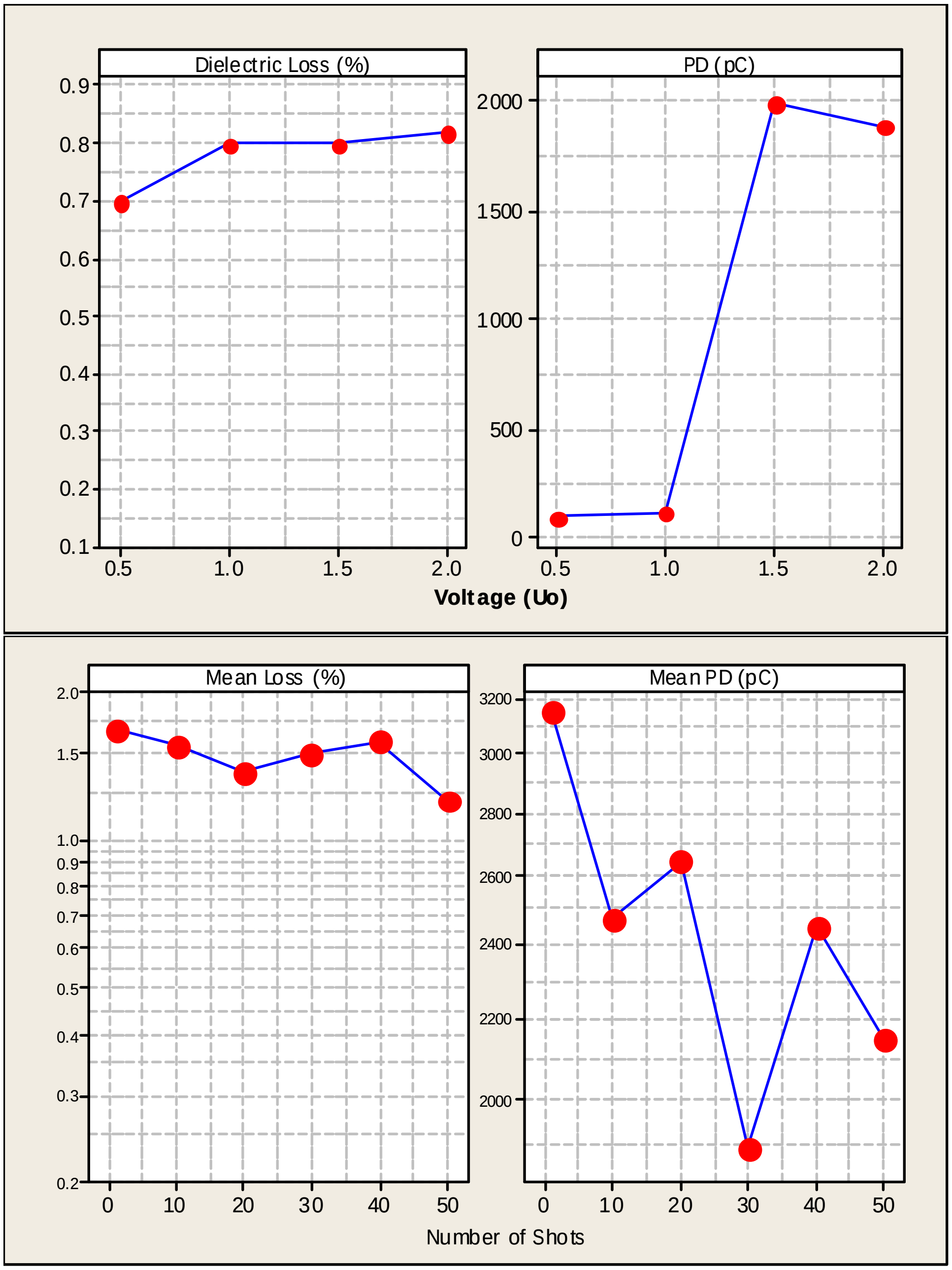


Figure 110: Combined Damped AC PD and Dielectric Loss Testing Voltage Ramp (Top) and Multi-Shot Constant Voltage Magnitude (Bottom)

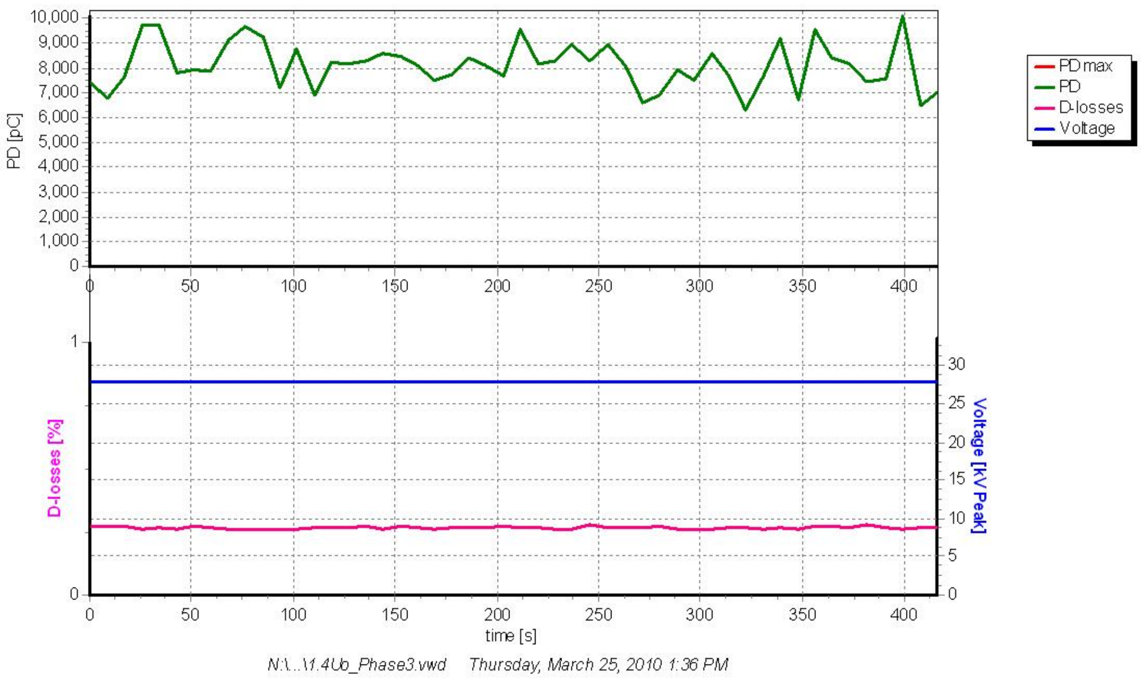


Figure 111: 50 Shots Combined Tan δ and PD Testing using DAC Roswell, March 2010

The simultaneous PD and Tan δ measurement using a sinewave VLF voltage source is not fully developed, so very limited data has been collected. However, the issues associated with this technology are included in the following discussion.

The approaches to combined diagnostics tend to discuss a hierarchy of diagnostics i.e. one diagnostic takes precedence in the design, operation, and interpretation. Table 61 shows the current understanding of the diagnostic hierarchy and the features that might be considered.

Table 61: Combined Diagnostics for Different Voltage Sources		
	Primary	**Secondary**
DAC	**PD**	**Dielectric Loss**
	Magnitude Location Inception Number If appropriate • Time Stability	Magnitude Time Stability If appropriate • Voltage Stability • Time Stability
VLF	**Tan Delta**	**PD**
	Magnitude If appropriate • Voltage Stability • Time Stability	Magnitude Location Inception Number If appropriate • Voltage Stability • Time Stability

Table 62 and Table 63 show the advantages and disadvantages of Combined Diagnostics.

Table 62: Overall Advantages and Disadvantages of Combined Diagnostic Techniques	
Advantages	• Provides additional information over single diagnostic results. • Allows for the development of trending information for more than one phenomenon. • The simultaneous collection of data allows the test engineer to establish how one measured parameter affects the other.
Open Issues	• Selection of monitored properties. • Implementation using level-based diagnostic techniques. • Voltage exposure (impact of voltage on cable system) caused by 60 Hz AC, DAC, and VLF is not established.
Disadvantages	• Adds complexity (interpretation, and data recording) to a single diagnostic test. • Highly skilled operators required.

Table 63: Advantages and Disadvantages of Combined Diagnostics for Different Voltage Sources

Source	Advantages	Disadvantages
Damped AC (PD & Dielectric Loss)	• Envelope method for loss estimation ensures minimal interference from discharge pulses. • Single integrated unit. • Ultra wide bandwidth (UWB) enhances the detectability of discharges. • May localize the sources of partial discharge.	• Apparent charge magnitude cannot be interpreted using IEC calibration norms. • Comparison of PD results with other methods of estimation may be difficult due to UWB approach. • Comparison of loss estimates with established 60 Hz criteria may be difficult unless the oscillation frequencies are close to the operating frequency. • Comparison of results with other measurements (other segments) may be difficult due to different and uncontrolled frequencies.
AC Offline Very Low Frequency (0.01 – 1 Hz) Sinusoidal (PD & Tan δ)	• Some level of guidance on interpretation of Tan δ data available in standards/literature. • Signals are acquired at a slow enough rate to allow for real time interpretation. • Ultra wide bandwidth of the PD unit enhances the detectability of discharges.	• Apparent PD charge magnitude cannot be interpreted using IEC calibration norms. • Comparison of PD results with other methods of estimation may be difficult due to UWB approach. • Requires the user to integrate the individual PD, Tan δ, and voltage components. • Localization requires an additional procedure.

3.12.4 Success Criteria

No specific success criteria for combined diagnostics can be provided due to the limited amount of available information.

3.12.5 Estimated Accuracy

It is possible to estimate accuracies for Combined Diagnostics. However, these techniques are not used in the US or Canada and thus no extensive data are available for analysis.

3.12.6 CDFI Perspective

Little practical work has been undertaken in this area. However, discussions at the IEEE Insulated Conductors Committee (ICC) have identified a number of outstanding issues with suggestions on how they might be addressed.

3.12.6.1 Voltage Exposure

An important issue for all off-line diagnostic techniques is the concept of "voltage exposure". The voltage exposure that a cable system experiences depends on the voltage magnitude, number of cycles, total duration, voltage frequency, and waveshape. It characterizes the impact of applied voltage on a cable system designed to operate at U_0 and 60 Hz sinusoidal AC. There are two fundamental concerns:

> a) a lower than anticipated voltage exposure such that the "proof" applied to the system is lower than expected and, thus,
> b) a higher than anticipated voltage exposure such that the "proof" applied to the system is higher than expected and thus potentially more damaging.

The way currently preferred by CDFI is to use a form of the Inverse Power Law (IPL): $V^n t = Constant$ to create a semi quantitative estimate. In the case of MV insulations, a reasonable estimate of n could be of the order of 5 to 10.

As an example, consider the use of DAC in diagnostic testing. The voltage waveform in a DAC shot is an exponentially decaying sinusoidal voltage. The frequency of the AC portion for each shot depends on the cable system capacitance while the exponential envelope depends on the cable system dielectric loss. As a result, segments with different lengths and insulations will produce different frequencies and voltage envelopes. Equally important is that tests conducted at different times on the same circuit may produce different decay rates as the dielectric loss changes over time. Degraded segments will have faster decay rates than circuits in good condition. Using the concept described above, then it is possible to consider a metric that would be termed Effective Voltage Exposure and this would help to account for differences in applied voltage waveforms. For example, in the case shown in Figure 109, using purely cycles, the EVE for this test would be 7.5 cycles (modified by the IPL) rather than the 8.0 shown, the reduced exposure coming from the decaying amplitude. Furthermore, the 50 shots shown in Figure 111 would have 375 (50*7.5) effective cycles rather than the 400 at first sight.

Similar arguments examining the effects of VLF – Sinusoidal, VLF – Cosine-Rectangular, and elevated 60 Hz AC can and should be made. Additional work in this area is needed to relate the various voltage waveforms, frequencies, durations, and magnitudes used in diagnostic testing.

3.12.6.2 Success Criteria

It has been suggested that the interpretation of the Combined Diagnostics should follow the approaches for each individual diagnostic, i.e., there might be a problem if, for example, the PD magnitude is greater than 50 pC or if the Tan δ is greater than 100 E-3.

Where action is required, the diagnosis is straightforward. However, it is much less clear when:

- The diagnoses are intermediate i.e., PD = 7 pC or Tan δ = 4 E-3.
- The diagnoses conflict i.e., PD = < 5 pC, but the Tan δ = 60 E-3.

In these cases, some form of a combined weighting scheme could be applied. One possible approach is a combination based on the rank positions of each diagnostic technique within their own hierarchies. This has not been investigated.

3.13 Diagnostic Voltages and Diagnostic Test Times

The test voltages and times are described in the preceding technique sections. However, for the convenience of the cable engineer, they appear here in Table 64 and Table 65. Note that:

- New and aged cable systems must be considered as separate entities for testing. Generally, the test voltage for aged systems should be lower than for new systems. This is because the risk of causing unwanted / undetected damage by applying the test is much higher in such systems.
- The numbers provided below give the reader an appreciation of the times and voltages involved in each diagnostic technique and may differ between providers of the same diagnostic technique.

Table 64: Diagnostic Voltages and Diagnostic Times

Technique		Voltage	Test Duration excl set up
Time Domain Reflectometry (TDR)		Pulse voltage is a few volts for handheld units.	5 to 15 minutes.
Offline Partial Discharge (60 Hz)		Aged cables: ramp / step to 2.5 U_0. Newer Cables: ramp / step to 3 U_0.	Less than 15 seconds.
Offline Partial Discharge (VLF)			Less than 5 min
Offline Partial Discharge (DAC)			Less than 3 min
Online Partial Discharge		Operating Voltage U_0.	Min. 15 min.
Tan δ (VLF)		Step up to 2 U_0.	5 to 10 min
Dielectric Spectroscopy		Freq 0.0001Hz-1Hz up to 2 U_0.	Depends upon frequency.
Withstand	AC 60 Hz	Aged cables: up to 2 U_0. Newer Cables: 3 U_0.	15 to 60 min.
	VLF Sinusoidal	Maintenance test Phs / Phs voltage / kV 8, 15, 25, 35 Pk /Pk voltage / U_0 3, 2.5, 2.3, 2.3.	30 min. IEEE Std. 400.2™ Ed 2
	VLF Cos Rect		
	DC (PILC Only)	Aged cables: up to 2.5 U_0. Newer Cables: 3 U_0.	15 min.
Recovery Voltage		Cable circuit is charged up to 3 kV. (Not for aged XLPE cables.)	Charging time 15 min discharge for 2-5 seconds through resistor.
Polarization/Depolarization Current or Isothermal Relaxation Current (IRC)		Circuit is charged with DC voltage up to 0.5 U_0. (This is not recommended for new XLPE cables as polar byproducts affect the measurements.)	Charge 5-30 min, discharge 2 sec, current measured for 15-30 min.[1]
PD Acoustic		No information available	
DC Leakage			

[1] Some providers have asked to ground the segment hours prior to the test.

Table 65: Time to Obtain Diagnostic Results (Test + Interpretation)			
Technique		**Initial Appreciation**	**Complete Documented Analysis including local context**
Time Domain Reflectometry (TDR)		10 Minutes	1 Day
Offline Partial Discharge (60 Hz)		1 Day	2-14 Days
Offline Partial Discharge (VLF)		1 Day	2-14 Days
Offline Partial Discharge (DAC)		End of Test	2-14 Days
Online Partial Discharge		1 Day	14-30 Days
Tan δ (VLF)		End of Test	1 Day
Dielectric Loss (DAC)		End of Test	1 Day
Dielectric Spectroscopy		End of Test	3 Days
Withstand	AC 60 Hz	End of Test	1 Day
	VLF Sinusoidal	End of Test	1 Day
	VLF Cos Rect	End of Test	1 Day
	DC (PILC Only)	End of Test	1 Day
Monitored Withstand	PD	End of Test - 1 Day	2-14 Days
	Tan δ	End of Test	1 Day
Combined Diagnostic	DAC – PD & Tan δ	End of Test	2-14 Days
	VLF – Tan δ & PD	1 Day	2-14 Days
Recovery Voltage		No Data Available	
Isothermal Relaxation Current			
PD Acoustic			
DC Leakage			

3.14 Local vs. Global Assessments

As discussed earlier, the assessment provided by diagnostic testing technologies generally falls into two location categories: global and local. Table 66 describes which diagnostic tests are most commonly used for global and local assessments.

Table 66: Local vs. Global Assessments for Diagnostic Techniques

Technique		Identifies Local Defects	Identifies Global Degradation
Time Domain Reflectometry (TDR)		X	
Offline Partial Discharge (60 Hz)		X	
Offline Partial Discharge (VLF)		X	
Offline Partial Discharge (DAC)		X	
Online Partial Discharge		X[1]	X[1]
Tan δ (VLF)			X
Dielectric Loss (DAC)			X
Dielectric Spectroscopy			X
Withstand	AC 60 Hz	X	
	VLF Sinusoidal	X	
	VLF Cos Rect	X	
	DC (PILC Only)	X	
Monitored Withstand	PD	X	
	Tan δ	X	X
Combined Diagnostic	DAC – PD & Tan δ	X	X
	VLF – Tan δ & PD	X	X
Recovery Voltage[2]			X
Isothermal Relaxation Current[2]			X
PD Acoustic[2]		X	
DC Leakage[2]			X

[1] There are two versions of Online PD, one provider identifies local defects and one provider identifies global degradation.
[2] No data are available, however, their fundamental principles of measurement do indicate global versus local assessment.

3.15 Typical Deployment

Utility engineers have voiced a desire for guidance on the qualifications necessary for conducting tests and interpreting test results. Table 67 provides some basic information on typical deployment.

Table 67: Typical Diagnostic Technique Deployment

<table>
<tr><th colspan="2">Technique</th><th>Testing performed by</th><th>Interpretation of Raw Data by</th><th>Form of Output to end user</th><th>Condition Assessment performed by</th></tr>
<tr><td colspan="2">Time Domain Reflectometry (TDR)</td><td>Utility or Provider Technician</td><td>Utility or Provider Technician or Engineer</td><td>Trace</td><td>Utility or Provider by comparison with library of curves</td></tr>
<tr><td colspan="2">Offline Partial Discharge (60 Hz)</td><td>Provider Engineer</td><td>Provider Engineer</td><td>Report with classification data [1]</td><td>Provider using Proprietary Criteria [4]</td></tr>
<tr><td colspan="2">Offline Partial Discharge (VLF)</td><td>Utility Technician or Engineer</td><td rowspan="2">Utility or Provider Engineer</td><td rowspan="2">Data or Report with numeric data [2]</td><td>Utility or Provider using Knowledge Rules [5]</td></tr>
<tr><td colspan="2">Offline Partial Discharge (DAC)</td><td>Utility or Provider Technician or Engineer</td><td>Utility or Provider using Knowledge Rules [5]</td></tr>
<tr><td colspan="2">Online Partial Discharge</td><td>Provider Engineer</td><td>Provider Engineer</td><td>Report with classification data [1]</td><td>Provider using Proprietary Criteria [4]</td></tr>
<tr><td colspan="2">Tan δ (VLF)</td><td rowspan="2">Utility Technician</td><td rowspan="2">Utility Technician or Engineer</td><td rowspan="3">Numeric data [2]</td><td>Utility using IEEE Std. 400.2™</td></tr>
<tr><td colspan="2">Dielectric Loss (DAC)</td><td rowspan="9">Utility using Knowledge Rules [5]</td></tr>
<tr><td colspan="2">Dielectric Spectroscopy</td><td>Provider Engineer</td><td>Provider Engineer</td></tr>
<tr><td rowspan="4">Withstand</td><td>AC 60 Hz</td><td rowspan="4">Utility Technician</td><td rowspan="4">Utility Technician or Engineer</td><td rowspan="4">Survival data [3] (Pass / Fail)</td></tr>
<tr><td>VLF Sinusoidal</td></tr>
<tr><td>VLF Cos Rect</td></tr>
<tr><td>DC (PILC Only)</td></tr>
<tr><td rowspan="2">Monitored Withstand</td><td>PD</td><td>Provider or Utility</td><td>Provider or Utility</td><td rowspan="2">Survival data [3] (Pass / Fail) & numeric data [2]</td></tr>
<tr><td>Tan δ</td><td>Utility Technician</td><td>Utility Technician or Engineer</td></tr>
<tr><td rowspan="2">Combined Diagnostics</td><td>DAC – PD & Tan δ</td><td rowspan="4">Provider or Utility Not used in USA</td><td rowspan="4">Provider or Utility Not used in USA</td><td rowspan="5">Numeric data [2]</td></tr>
<tr><td>VLF – Tan δ & PD</td><td>Utility using Knowledge Rules and IEE400.2</td></tr>
<tr><td colspan="2">Recovery Voltage</td><td rowspan="3">Utility using supplier furnished Knowledge Rules [5]</td></tr>
<tr><td colspan="2">Isothermal Relaxation Current</td></tr>
<tr><td colspan="2">PD Acoustic</td><td>Provider or Utility Engineer</td><td>Provider or Utility Engineer</td></tr>
</table>

Technique	Testing performed by	Interpretation of Raw Data by	Form of Output to end user	Condition Assessment performed by
DC Leakage	Utility Technician	Utility Technician or Engineer	Numeric data [2]	Utility using Knowledge Rules [5]

[1] Classification Data – results are described in terms of the membership of a number of classes ranging from good to poor performance (A, B, C; Repair, Replace, etc); no information is conveyed about the relative position within a class (it is impossible to prioritize within a class); class membership can be determined by either Proprietary Criteria or Knowledge Rules.
[2] Numeric Data – results are described in terms of a continuous variable (inception voltage, loss, count etc).
[3] Survival Data – two classes Pass / Not Pass; no information is conveyed about the margin of any Pass / Not Pass.
[4] Proprietary Criteria – the membership of a class (see footnote 1 above) is determined by multiple criteria for the measured and system data which are not open to scrutiny; the receiver of the classification data (see footnote 1 above) is unable to reassess the class membership as they do not (generally) have access to the measured data or the criteria; the receiver of the data has no means to verify whether the criteria have changed (improved of degraded).
[5] Knowledge Rules – the membership of a class (see footnote 1 above) is determined by multiple criteria for the measured and system data which are open to scrutiny; the receiver of the classification data (see footnote 1 above) is able to reassess the class membership as they have access to the measured data and the criteria; the receiver of the data has a means to verify that the criteria have remained unchanged over time.

4.0 PRACTICAL APPLICATION OF DIAGNOSTIC TECHNOLOGIES

This section examines three important tools for the deployment of diagnostics:

- SAGE – Conceptual map of the phases of diagnostic programs (Section 4.1)
- Knowledge-Based System (KBS) for Selection of Diagnostics – Software system that provides users with a short list of diagnostic techniques to consider for their particular application. The KBS is based on the expert opinions of 35 industry experts (Section 4.2).
- Diagnostic Program Economics – Mathematical framework for developing the cost-benefit case for a diagnostic program (Section 4.3)

Each of these tool is discussed in detail in the following sections.

4.1 Diagnostic Program Stages – SAGE

Diagnostic techniques are generally used either to ensure the performance of newly installed equipment (commissioning tests) or to assess the state / health of older components or systems. Diagnostics are employed to increase the efficiency of reliability improvement programs. The acronym SAGE is used to describe the four basic elements of an effective diagnostic program.

<u>Selection</u> – Choose the cable circuits for testing that will significantly improve reliability. Typically, this is based on age, failure rate, load sensitivity (hospitals, public buildings, industrial customers, etc.)or other engineering judgment.

<u>Action</u> – What actions are likely to be taken as the result of certain diagnostic outcomes or interpretations? The actions are in two groups (Act or Not Act) and may include replacement, defer action, rejuvenation, and/or repair. These actions are based on those most suitable for the system topology and most prevalent failure mechanisms (local or global degradation).

<u>Generation</u> – Diagnostic tests generate data that dictate the type of corrective actions and prevalent failure mechanisms.

<u>Evaluation</u> – Are the methods employed for Selection, Action, and Generation giving the expected results: lower rates of failure and increased times between failures? Can the diagnostic elements be improved?

Figure 112 illustrates how the four components function together over time to produce (if implemented properly) a reduction in the failure rate. Note that this benefit is not realized immediately nor does it cease once the program has ended: there is a lag before the benefit is fully realized. Furthermore, failure rates do not begin to change until the actions directed by the diagnostic testing (Generation) are well underway. Selection, Generation, and Action are each defined stages in time while the Evaluation component is ongoing throughout the entire test program and beyond.

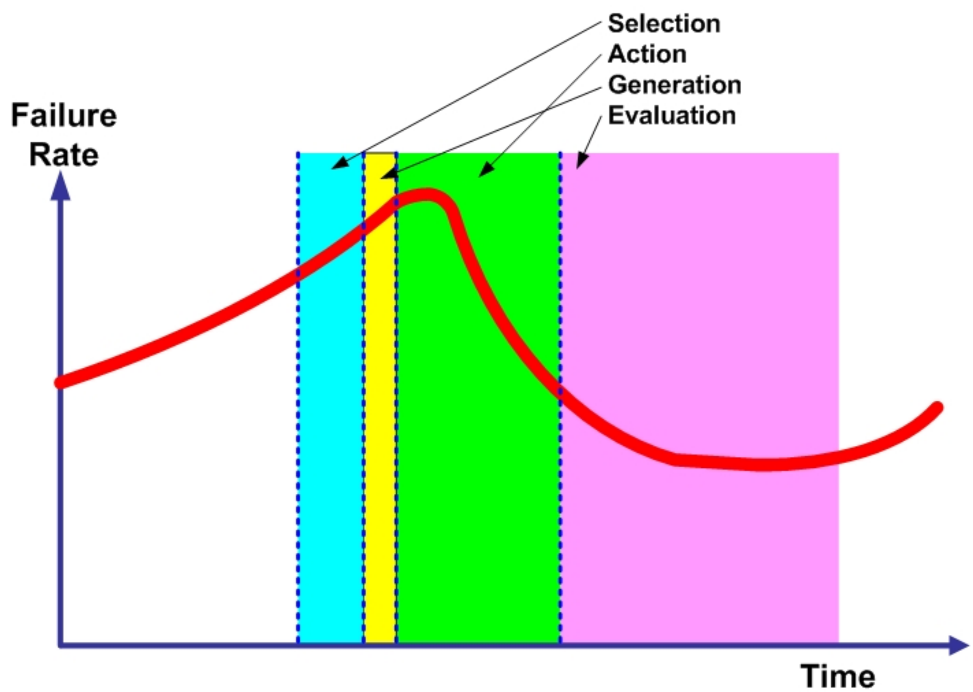


Figure 112: Effect of SAGE on the Failure Rate of a Target Population

Note that the failure rate in Figure 112 continues to increase during the Selection and Generation phases. Only after the actions are completed does the failure rate start to decrease. After some time, the failure rate will begin to increase again (Evaluation phase) and this would retrigger the whole SAGE process.

These phases are discussed in the following sections.

4.1.1 Selection

The selection phase represents the first stage of the SAGE process. The utility uses all available data to identify those circuits that may be susceptible to failure within a chosen time horizon, generally 5-10 years. These circuits may be in areas that have historically experienced higher than usual failure rates or may simply be of critical importance to system operation. Regardless of the criteria used, the size and composition of this population greatly affects potential reliability improvements and economic savings resulting from the program. These circuits constitute the "target population" that will be tested and acted on using one or more diagnostic tests.

In theory, selection begins by assessing the information available within the utility and should address each of the following:

System Construction – How are the circuits used in the system? Is the system a radial or network system? What level of redundancy is present? Can circuits be easily isolated from the network without impacting customers?

Acceptability of Failure During Testing – Is a failure tolerable during testing if circuits are subjected to elevated test voltages?

Available Historical Data – Number of circuits of the same type in service, their ages, and failure histories.

Failure Projections – How fast are failure rates increasing? If there are cable or accessory designs in use, in which are the failure rates increasing fastest?

Prevalent Failure Mechanism – What causes the most failures? Is the mechanism electrical, mechanical, or thermal in nature?

Objective – Is the objective to improve reliability, reduce costs, or both? Has a budget been allocated to attain this?

The above information is invaluable in determining which circuits to test. However, the relative importance of circuits is also essential since these circuits will often supply important customers where an outage would result in high economic consequences for the utility.

The following example illustrates how the selection process must consider both local failure rates and circuit importance. Figure 113 shows the local failure rates for different areas of a single utility. According to this figure, the area labeled as χ has historically experienced the highest failure rate.

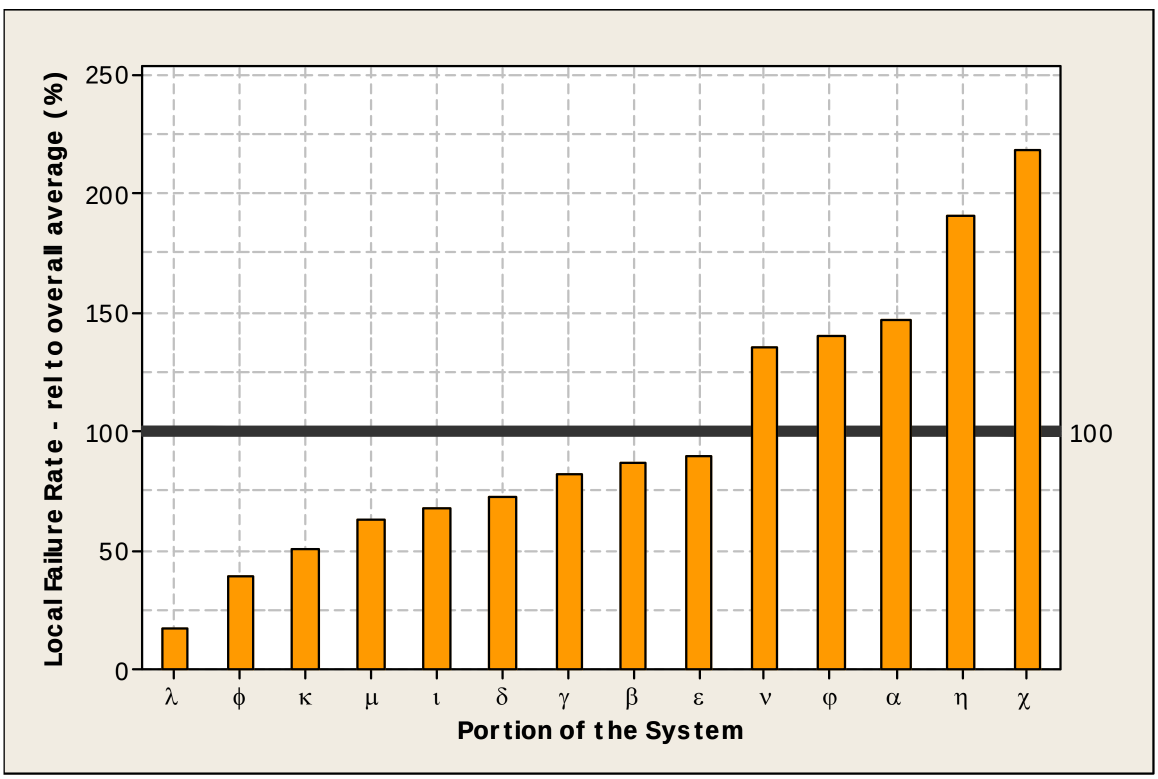


Figure 113: Examples of Local Failure Rates for Different Areas

Considering only the local failure rates (as shown in Figure 113) the areas the utility should focus its diagnostic program on are χ, η, α, φ, and υ. However, when the utility also considers the importance of each area, as shown in Figure 114, the resulting priority list can change dramatically.

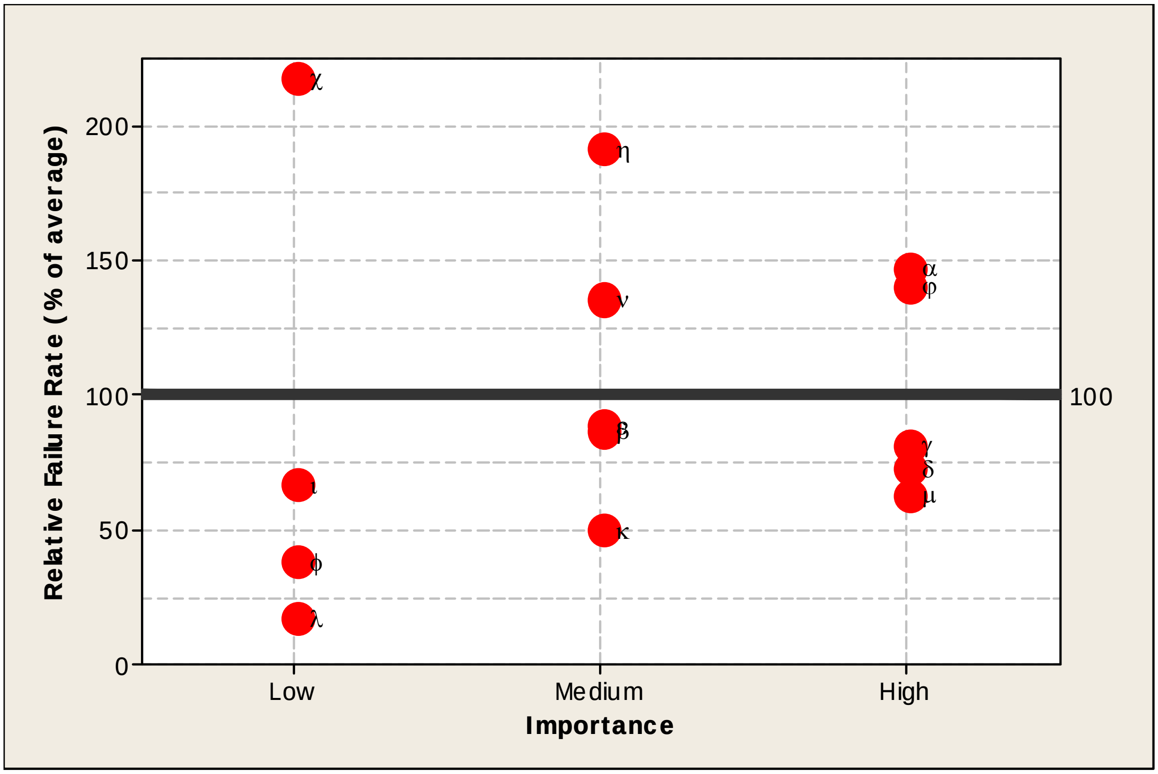


Figure 114: Failure Rates and Relative Importance to Utility

In Figure 114, the highest failure rate area (χ) is of low importance to the utility. Therefore, the utility might be less inclined to include it as part of the diagnostic program or might save it for last if funds are available. On the other hand, there are several highly important areas with above average failure rates (α and φ) that should be addressed as the "first choices" for the diagnostic program. The primary consideration in how many areas to include in the program is the size of the allocated budget.

In many utilities, the criticality/importance of different areas is basic information for the cable engineers operating these systems. Unfortunately, the availability of historical records can be an obstacle to the selection process since these records may not exist. In the past, the utilities were not as careful as they could have been to maintain detailed failure and installation records. This has changed only in the last few years. However, an engineer or regional operator with several years of experience within the particular utility can guide this process in the absence of suitable records. In addition, other criteria may be chosen in addition to local failure rates. These can include cable age, design, operating stresses, or any other criteria (based on engineering judgment) that would adversely affect a circuit's reliability. If sufficient information exists within the records then the utility may utilize failure projections in the selection process. These can aid the utility in defining where the system is heading in terms of failure rates as well as the amount of action required to curtail an unacceptably high failure rate.

Regardless of the methods used to select the target population, this population will include both circuits (segments, sections, runs, etc.) that will fail in the near future ("bad" circuits) and those circuits that will not ("good" circuits). The analysis of historical records is simply the first step in identifying the problem areas. Utilities must also consider the size of each area. Larger target populations will require more time for testing and possibly longer delays between testing and completion of the required corrective actions and replacements. This time delay can be long enough to allow for additional service failures to occur either before the circuit is tested or between the time testing is completed and the completion of the corrective action. On the other hand, too small a target population may not be economically justifiable if there are either too few "good" circuits or too few "bad" ones. One may define the "good to bad" ratio, or G/B, as the percentage of "good" circuits as compared to the percentage of "bad" circuits in the population. A G/B ratio of 10/90 leads to low benefit (if any) as the cost of diagnostic testing is simply added to the cost of replacement of virtually the entire population. On the other hand, the case of G/B ratio equal to 95/5 produces only small improvements in system reliability so the utility would probably need to look elsewhere to improve reliability.

There is no universal G/B ratio that is applicable to all diagnostic programs. However, based on experiments and studies of diagnostic programs operating in US utilities, a system that is at best 85/15 is suitable for inclusion in a diagnostic program. Unfortunately, the diagnostic accuracy must be in the range of 95% for systems with higher G/B ratios to realize economic benefits.

Once the selection process is complete, the utility must then examine options to correct degraded circuits identified by the diagnostic test. This corresponds to the action phase.

4.1.2 Action

The Action stage of the SAGE process refers to the establishment of possible repair and replacement actions that are based on the results of diagnostic testing. Ideally, specific action is taken for each possible circuit condition. The goal is to perform the minimum level of action that will restore the circuit to reliable operation for the next several years. Each action has an associated cost and level of reliability improvement that it will deliver. For example, the cost of replacing a bad splice in a 500 ft. segment is very different from the cost of replacing the entire segment. On the other hand, the reliability of the repaired segment is not likely to be as high as the reliability of the replaced segment. An economic analysis quantifies the value for one action compared to another.

For cable systems, the list of available actions is relatively short and includes:

- Wholesale Replacement – complete replacement of the entire target population
- Targeted Replacement – replace only the segments that are degraded
- Repair – remove short length(s) of cable and replace with two joints and a piece of cable or replace problematic accessories
- Rejuvenation – liquid injection (PE-based insulations)
- Do Nothing

The choice of actions will affect the choice of diagnostic technique(s) since some diagnostics are unable to locate specific points of degradation within a given segment. Furthermore, the composition of the target population might limit actions.

Once a suitable maintenance policy for each diagnosis exists, work may be performed in the target population to generate the diagnostic data. This constitutes the Generation phase.

4.1.3 Generation

The generation stage of the SAGE process starts with the choice of a suitable diagnostic followed by testing on the target population of circuits. By definition, the diagnostic techniques measure specific characteristics of the circuit thought to be symptomatic of the known failure mechanisms. These symptoms generally fall into two categories: (1) global and (2) local. Global symptoms cannot be fixed to a specific location within the circuit or segment. Dielectric loss is an example of a global characteristic since the diagnostic cannot identify where the loss is generated. On the other hand, local symptoms can be attributed to specific locations within the circuit. Partial discharge is an example of a diagnostic that detects local degradation.

The following factors should be considered during the generation phase:

Prevalent Failure Mechanism: Global (corroded neutrals, water treeing, etc.) or local (voids, contaminants, electrical treeing, etc.) degradation? Can the diagnostic measure a characteristic of the circuit from which its condition may be reliability ascertained?

Accuracy of the Diagnostic: How often does the diagnostic correctly classify the circuit's condition?

Cost of the Diagnostic: Does the cost of the diagnostic represent a large portion of the replacement cost of the component?

Resolution of the Diagnostic: Does the diagnostic provide enough information to classify the components into the number of desired subpopulations?

Reliability: Can the diagnostic produce useful results in the field??

Risk: What is the risk of failing the component during the test?

The above list of issues is summarized as follows: Is the diagnostic able to diagnose the prevalent problem in the target population and do so with high enough accuracy to provide an advantage to the program? The accuracy of the diagnostic is a critical factor. As part of the CDFI, accuracies for each diagnostic technology were computed and are summarized in Section 3. Methods for extracting diagnostic accuracy from diagnostic and performance data are described in Appendix A.

4.1.4 Evaluation

The final stage of the SAGE process is the evaluation stage. This is the stage where utility engineers ask themselves: Are we getting what we expected? A question such as this covers many issues; however, these can be summarized by two key topics: (1) Cost and (2) Reliability. A diagnostic program must deliver improved reliability at a lower cost as compared to other maintenance strategies to be considered effective. Evaluation tools, such as those presented in Appendix A, can assess the impact the program has made on system reliability. Furthermore, the utility can then adjust the program in real time to improve the program's performance. The evaluation phase represents an ongoing process that remains in place until the need again arises to conduct another diagnostic program.

Bear in mind that diagnostic testing techniques should not be performed independently of other information about the cable circuit in question. They are tools that are applicable to a variety of cable systems at different points in their lives.

There are two basic ways to use the Cable Diagnostic techniques: Commissioning Diagnostics and Condition Assessment Diagnostics. In general, all diagnostics techniques may be used in either mode. Figure 115 shows the distinction in the tests with reference to the potential aging curves for three different cable systems (Circuit 1, Circuit 2, and Circuit 3).

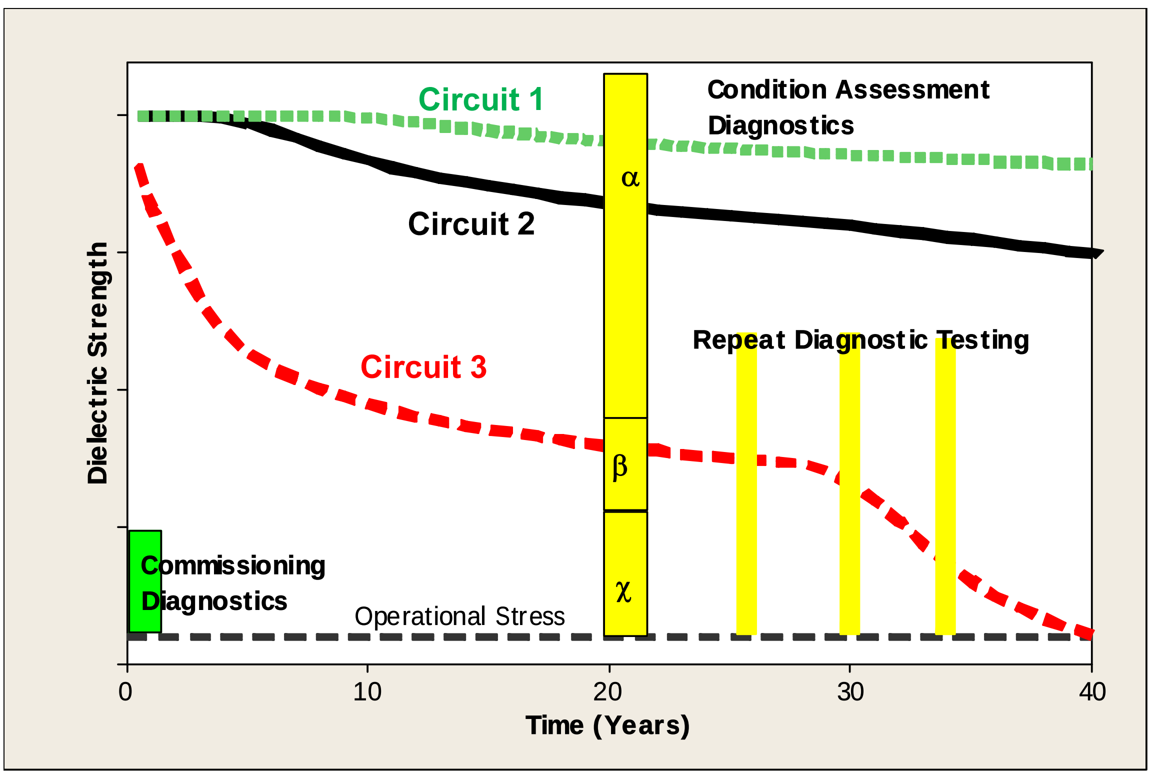


Figure 115: Cable System Aging and the Application of Basic Diagnostics
Commissioning [Single Use – Pass / Fail]
Condition Assessment [Multiple Uses After Years of Service]
Classification – α, β χ are Arbitrary Condition Assessment Classes

Commissioning Diagnostics are used at the start of a cable system's life or after a repair. In this mode, the health (classification) of the system is not of primary interest. The engineer wants to know if there are any significant defects caused by installation workmanship (generally, most new components are factory-tested). Thus, the tests (voltages and times) ensure that the system is free from gross defects. Importantly, these test conditions are generally not designed for aged systems and should not be applied to aged systems. Furthermore, when testing a new system that is attached to aged components, modifications are needed during the test.

Condition assessment diagnostics are applied to aged cables (Figure 115) on a regular basis. Thus, this is much more of a process rather than spot check assessment using a Pass/Fail criterion. Consequently, it is important to focus on classification and avoidance of doing the system harm (further weakening). In essence, the techniques attempt to discern the rate at which the diagnostic features approach the operating stress. In the examples in Figure 115, Circuit 1 ages the slowest while Circuit 3 ages the fastest since Circuit 3 reaches the operational stress the soonest.

4.2 CDFI Knowledge-Based System (KBS)

A Knowledge-Based System (KBS) for the selection of an appropriate diagnostic technology was developed during the CDFI. A working version has been made available to the CDFI participants. The KBS is a way of integrating expert opinion into a software system that can then be used by individuals to obtain what amounts to as the consensus for the expert base. In other words, instead of contacting each expert separately to obtain his or her opinion, a cable engineer can use the KBS to query all the experts at once. The resulting output shows the extent of agreement between the experts as to which diagnostic techniques the cable engineer should consider using in his or her situation.

The Knowledge Module of the KBS contains input collected through detailed surveys from NEETRAC engineers, industry experts, utility engineers, and diagnostic providers. Figure 116 shows the contributions from each group of experts.

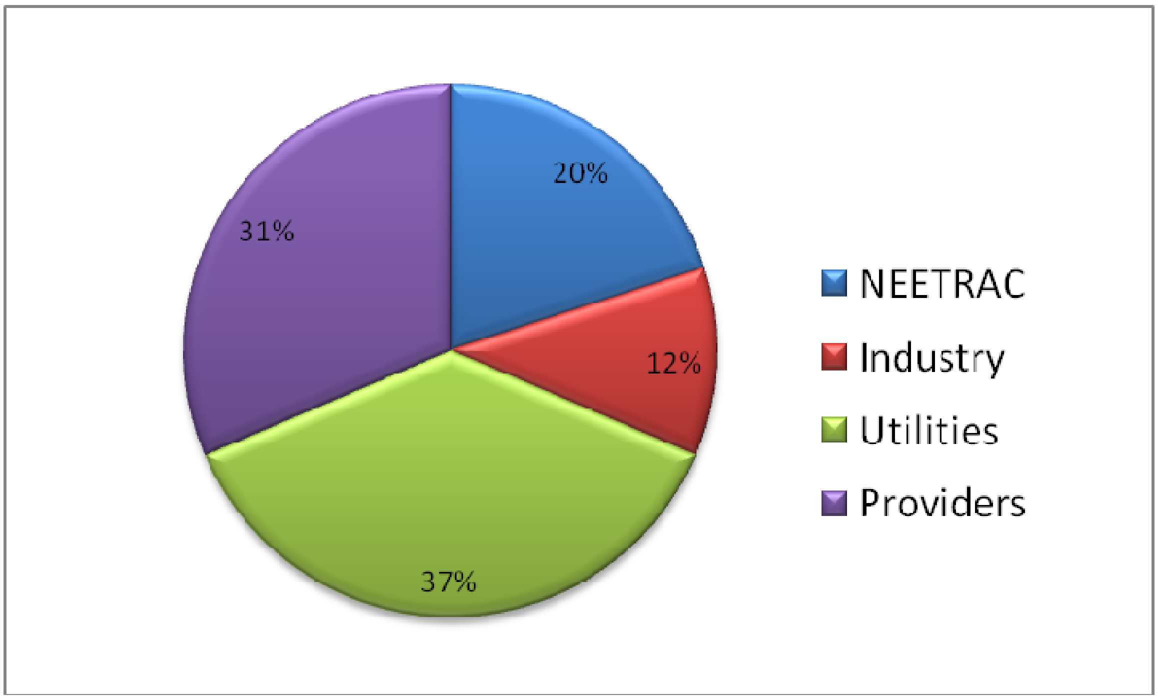


Figure 116: Expert Knowledge Base

These data are then collated together and made accessible via a graphical user interface (GUI).

4.2.1 User Inputs

To query the Knowledge Module, the cable engineer must provide a series of basic data on the cable system in question. These data include:

- Type of insulation system
    - PE (HMWPE, XLPE, WTRXLPE)
    - Paper

    - EPR
    - Hybrid (any combination of PE, Paper, or EPR)
- Cable jacketing
    - No
    - Yes
- Approximate age of cable system
    - 0-10
    - 10-20
    - 20-30
    - 30-40
    - 40-50
    - >50 years
- User's planned/preferred approach to remediation
    - Replace large area
    - Replace cable segment
    - Replace small section (> 6 ft length)
    - Replace accessories only
    - Liquid rejuvenation
    - Unknown

4.2.2 Sample Output of KBS

Once the data are input to the KBS, the KBS outputs a graph showing the collated recommendations from the expert base. Figure 117 shows an example of KBS output for a 10 – 20 year old EPR Jacketed cable system where the preferred remediation approach would be to replace the accessories. The main plot shows four different graphs, each of which shows the recommendations considering different constraints: technical (main), cost (top right), time required in the field (center right), and time for results to be available (bottom right). The data on each of these graphs show the percent of experts who recommend that the user consider each of the diagnostics considering the corresponding criterion.

For simplicity, the diagnostic technologies are represented with generic designations of 1 – 10 (a reference key is provided). The red and green lines are statistical measures of the recommendation level and degree of agreement between diagnostics. The techniques that are above the green line are those that have strong consensus from the experts as being good choices to consider. On the other hand, techniques that are below the red line have a weak consensus and the experts do not recommend them for this application. Note that as the criterion changes, the recommendation levels for each technique and the corresponding locations of the green and red lines also change. In this example, the unconstrained (i.e. test time, cost, and time for results to be available are not considered in these recommendations) diagnostic approach with the highest recommendation is Diagnostic 8, whereas Diagnostic 3 has the highest recommendation in all of the constrained cases.

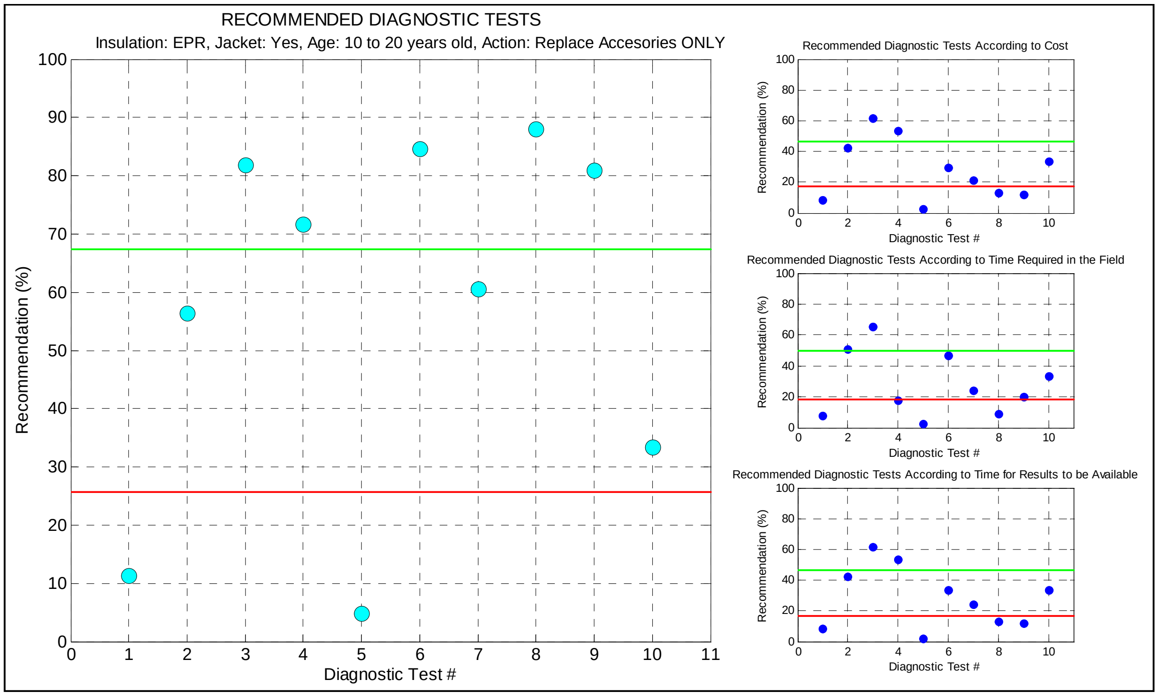


Figure 117: Example KBS Output

4.2.3 Hybrid Module

The KBS handles both single insulation systems and hybrid systems where two or more insulation types are present in the same cable system (e.g. Paper and PE, PE and EPR, or Paper, PE, and EPR). To generate the hybrid cable system recommendations, the KBS requires additional information on the system in the form of:

- Percentage of each type of insulation (0-99 %)
- Approximate age of each cable type
  - 0-10
  - 10-20
  - 20-30
  - 30-40
  - 40-50
  - >50 years
- Failure rate for each insulation class
  - Low
  - Medium
  - High
  - Unknown

Figure 118 illustrates the methodology used in the KBS to produce results for hybrid cases.

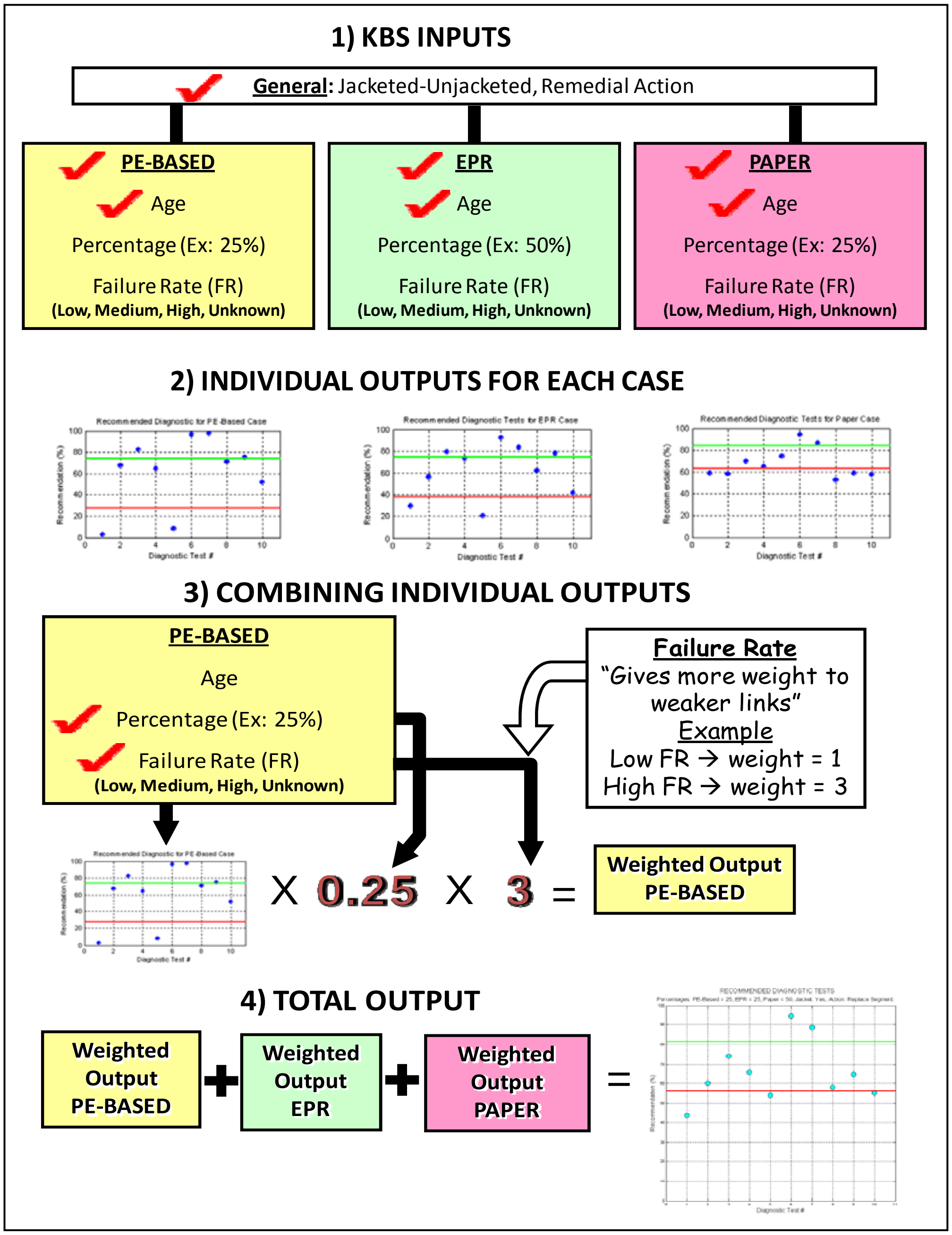


Figure 118: Hybrid Case Methodology

Once the required information is entered into the KBS, the first step is to generate recommendations for each individual insulation type. For each of these outputs, the KBS utilizes the type of insulation, age, jacket, and remedial action to compute the expert recommendations for the diagnostic tests.

The next step is to combine the outputs for each insulation type into the hybrid case. For this case, the KBS considers the percentage of each insulation type and the failure rate. The goal is to give priority to the type of insulation that makes up the largest portion of the cable system while also to taking into account its weakest link – the part of the system that is more critical and prone to fail.

The final output of the hybrid module is the weighted sum of expert opinions for all diagnostic tests (Figure 119). The individual recommendations for the component cable system designs are computed and displayed as the three side graphs (PE – top, EPR – center, and Paper – bottom). The main recommendation (large figure) is estimated using a weighted contribution from these side graphs.

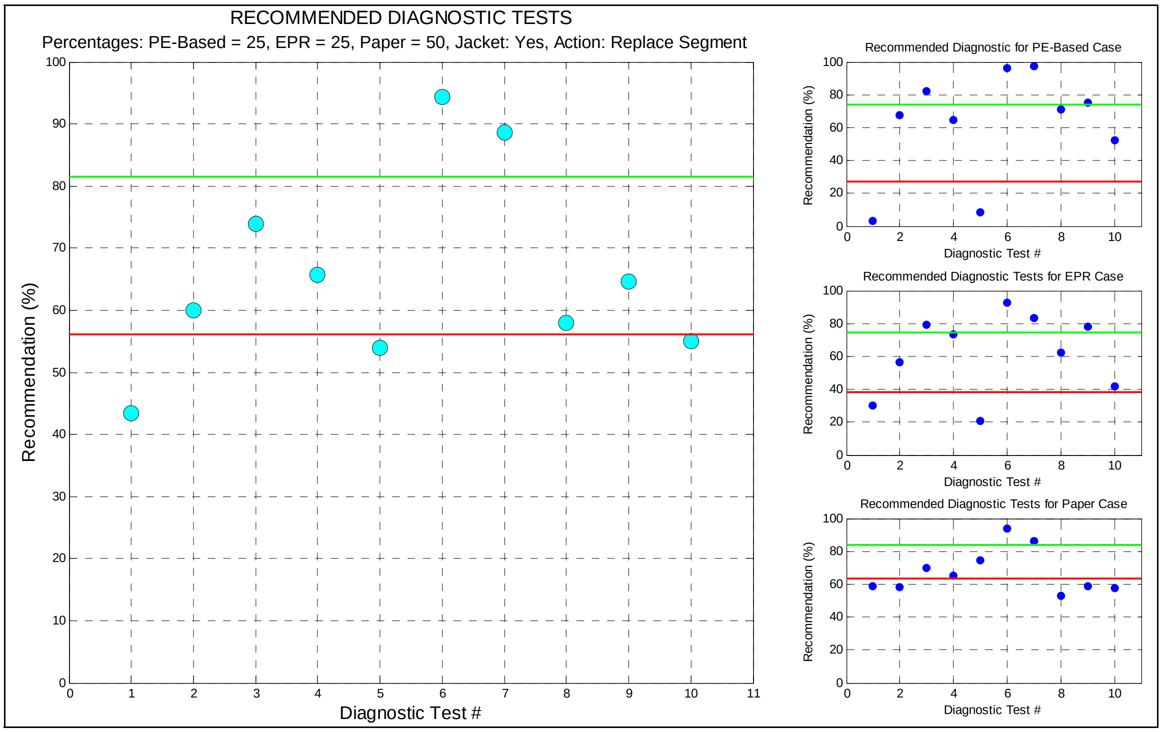


Figure 119: Expert Recommendations for Hybrid Circuit Outlined in Figure 118

With the KBS recommendations in hand, a cable engineer then has the information to begin developing a diagnostic program.

4.3 Diagnostic Program Economics

This section introduces the cost model used in the economic modeling of diagnostic programs. The ultimate goal is the calculation of the economic benefit, where the benefit is the financial savings resulting from a lower total cost as compared to an alternative. The following sections describe the model details.

4.3.1 Short-Term Diagnostic Program Cost

This section describes the calculation of short-term cost elements associated with the diagnostic program. The true values of each of the following cost elements contain some uncertainty. However, every effort should be made to minimize that uncertainty given the specific details of the scenario under consideration.

4.3.1.1 Cost of Selection

The utility incurs selection cost (C_S) as it collects and analyzes available system data to choose which circuits to include in the target population. This is one of the most important steps in the process as the target population composition is critical to the diagnostic program's performance.

4.3.1.2 Cost of Diagnostic Testing

Diagnostic programs require an upfront investment from utilities to cover the costs of testing and the data analysis needed to generate the recommended corrective action(s) for each tested circuit.

The costs of diagnostic testing the entire target population are:

$$C_D = X_{AR}\left(C_T + C_{SW}\right) \quad \textbf{(10)}$$

where,

C_D = Total cost of performing the diagnostic test on the at-risk population $[\$]$

C_T = Cost of diagnostic equipment and personnel $[\$/\text{Test}]$ or $[\$ / \text{Circuit}]$

C_{SW} = Cost of line crew for switching the circuit out of service, if needed $[\$/\text{Test}]$

X_{AR} = Number of circuits or tests required to test the target population [Circuits or Tests]

These costs should be known prior to the initiation of the diagnostic program. The cost of the testing equipment and personnel can vary significantly between the diagnostic techniques. Furthermore, utility safety regulations generally require all connections and switching be performed by either a utility line crew or their approved contractors. The cost of these additional resources must be included in the cost of testing.

4.3.1.3 Cost of Corrective Actions

Diagnostic techniques generate multiple recommendation levels, each having a corresponding level of corrective action (i.e. Do Nothing, Repair, or Replace). This corresponds to a multi-tiered approach into which each circuit is classified by the diagnostic. The resulting corrective action cost is as follows:

$$C_M = \sum_{i=1}^{k} C_{M,i} \left| \underset{\sim}{X}_i \right| \tag{11}$$

where,

C_M = Total cost of corrective actions performed using multi-tiered approach
$C_{M,i}$ = Cost of performing the required corrective action for circuits in condition i
$\left| X_i \right|$ = Number of circuits in condition i

The costs shown in (11) only reflect the cost of performing a particular level of corrective action on all circuits or defects diagnosed as requiring it. In addition, the summation starts at $i = 1$ since the $i = 0$ subpopulation is defined as the set of circuits that do not require action. Therefore, the cost $C_{M,0}$ is zero while $C_{M,k}$ represents the cost to replace the circuit (the most expensive option).

4.3.1.4 Total Short-Term Costs

The cost of the corrective actions and testing were defined in (10) and (11), respectively. They are combined as:

$$\begin{aligned} C_{AR} &= C_S + C_D + C_M \\ &= C_S + X_{AR}\left(C_T + C_{SW}\right) + \sum_{i=1}^{k} C_{M,i} X_i \end{aligned} \tag{12}$$

where,

C_S = Selection cost [$]
C_D = Cost of performing the diagnostic testing [$]
C_M = Total cost of completing the corrective actions recommended by the diagnostic [$]
C_{AR} = Total short-term cost of diagnostic program in target population [$].

In (12) C_D is a fixed cost incurred regardless of the results of the actions performed. The simplest diagnostic program considers two levels – “Pass” and “Not Pass.” One could imagine this corresponding to a Simple Withstand diagnostic program in which the two actions are “Do Nothing” and “Repair.” It is also possible, depending on the cable system configuration, to have a “Do Nothing” and “Replace” approach.

Using the cost elements developed above, it is possible to construct a cost diagram that shows the accumulation of these costs. The cost elements discussed thus far represent the upfront or short-term costs the utility would incur to complete the testing and perform the necessary corrective actions on their target population. Figure 120 shows these elements graphically (as described mathematically in (12)).

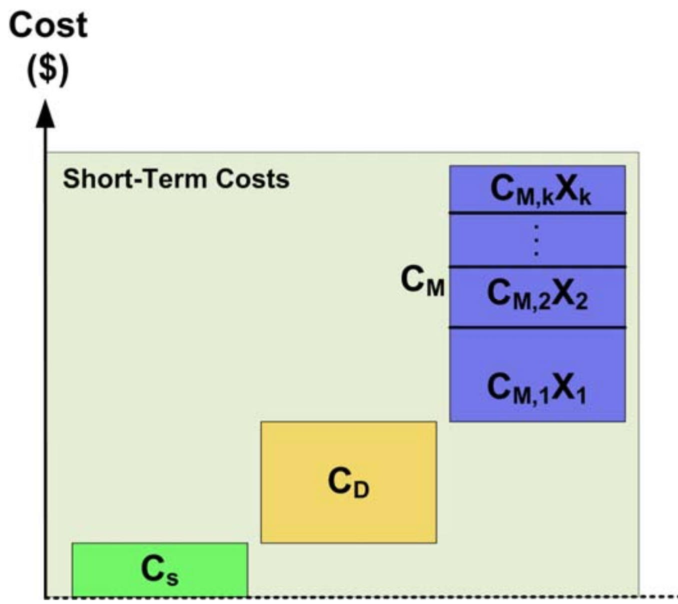


Figure 120: Summary of Short-Term Diagnostic Program Costs

An additional cost related to reliability (or un-reliability) must be added to those shown in Figure 120 as it also contributes to the total program cost. This cost, however, represents a long-term expenditure that would accumulate over the years following the completion of the corrective actions. This cost is, in general, the most difficult to define because it requires assigning a dollar value to reliability. In other words, the true cost of a service failure must be estimated. The following section describes how to estimate the long-term diagnostic program cost and difficulty of performing this task.

4.3.2 Long-Term Diagnostic Program Cost

The long-term costs of a diagnostics program result from service failures that occur on circuits diagnosed incorrectly as "good" and circuits where the recommended repair was not properly completed. The resulting cost of a service failure is not simply the labor and materials needed to complete the repair. This cost also includes a "Consequence" element that accounts for the intangible costs associated with poor reliability. Unfortunately, these costs are difficult to determine but, based on discussions with CDFI participants, are significant with respect to the repair cost. Section 4.3.2.1 describes one method of formulating the cost of a service failure.

4.3.2.1 Cost of a Service Failure

The cost of a single service failure is by far the most difficult cost to compute. In the CDFI, attempts to quantify this cost were made. However, utilities are unable to define a precise dollar amount for this cost. With this uncertainty in mind, the total cost per failure is:

$$C_F = C_{FR} + C_{SW} + \sum_{i \in Customer\ Type} C_{Cust,i} N_i \qquad \textbf{(13)}$$

where,

C_F = Total cost of failure [\$/Failure]

C_{FR} = Cost of repairing the circuit when it has failed [\$/Failure]

C_{SW} = Switching cost of outage [\$/Failure]

$C_{Cust,i}$= Penalty resulting from customer relations issues associated with different customers [\$ / Customer / Failure]

N_i = Number of each type of customer impacted by the outage

The parameter, C_{Cust}, will be different depending on the type of customer involved in the outage. For example, an industrial customer is likely to have a higher customer penalty since the outage likely affects their production. A residential customer, on the other hand, will not be as affected as the industrial customer will and should, have a lower $C_{Cust.}$ As (13) shows, the total customer penalty includes the per customer penalty rate for each customer type and the number of each customer type affected.

Equation (13) can be separated into two distinct parts as:

$$\begin{aligned} C_F &= C_{FR} + C_{SW} + C_{Cust,total} \\ &= C_{RS} + C_{Cust,total} \end{aligned} \qquad \textbf{(14)}$$

where,

C_{RS} = Total cost of restoring service [\$]

$C_{Cust,\ total}$ = Total consequence cost incurred from all affected customers [\$]

The first portion of (14) represents the cost of material and labor needed to repair the failure as part of the service restoration process. This cost would be incurred by the utility regardless of whether the repair resulted from a service failure or a defect that was identified through diagnostic testing.

On the other hand, the second set of terms in (14), the "Failure Consequence," represent additional financial losses incurred because the failure happened while the circuit was in service. These include the losses resulting from unserved load and emergency off-hours switching activities, as well as penalties both from the local regulator (Public Service Commission or Public Utility Commission) and possibly from large industrial customers. Even collateral damage can result from a service failure. The penalty costs together are significant with respect to the costs associated with restoring service and repairing the failed circuit. Unfortunately, utilities and their respective regulatory agencies keep the details of this information confidential. The regulator cost depends on many factors including past performance of the utility and current failure rates. These are measured through various reliability indices such as SAIFI, CAIDI, etc. [60] – [62].

The primary objective of diagnostics is to avoid service failures. Unfortunately, as Section 3 describes, no diagnostic is 100 % accurate nor is every repair perfect. The following section discusses the various paths for service failures to occur even though a utility uses a diagnostic program.

4.3.2.2 Undiagnosed Failures

Sometimes "bad" circuits are not recognized or go undetected during each phase of the diagnostic program (SAGE):

- Selection – "bad" circuits that were not included in the target population and would subsequently not have been tested or acted upon.
- Action – failures that result because either the corrective action was not adequate or the repair/replacement was performed incorrectly on suspected "bad" circuits.
- Generation – "bad" circuits were misdiagnosed as "good" by the diagnostic and thus did not receive the required corrective action.

These "bad" circuits ultimately produce service failures, each of which has a cost to the utility. The nature and reasons behind the occurrence of these undetected "bad" circuits are discussed below.

Failures Missed During Selection

Unless the target population includes all the circuits in the system, the utility should expect failures to occur. As mentioned earlier, during the selection phase of the program it is important to select the circuits that are at-risk of failure in the near future. Unfortunately, for any target population the utility identifies, it is likely that circuits outside of the target population will unexpectedly fail. This situation is illustrated in Figure 121.

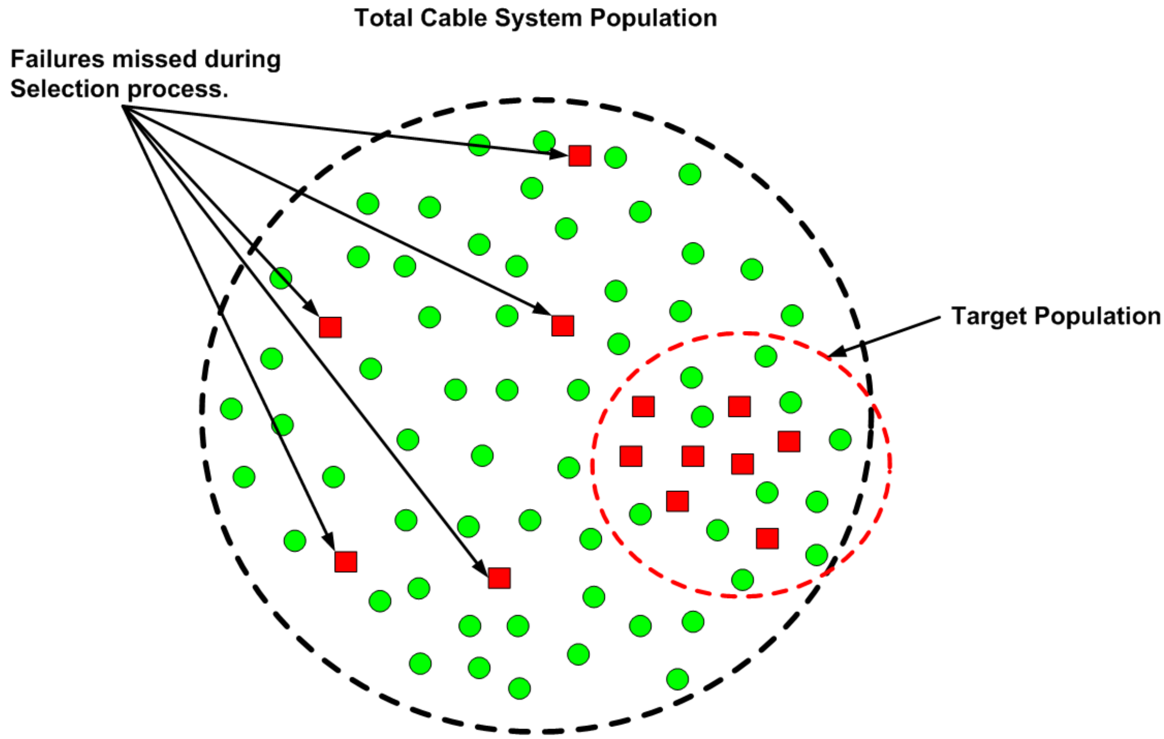


Figure 121: Example Scenario – Failures Occurring Outside Target Population

The scenario portrayed in Figure 121 is likely to occur, as the records and models are never sufficiently detailed to allow for perfect identification, hence the reason for employing diagnostics. On the other hand, one way to ensure that all the failures are included in the target population is to consider the entire population as being at-risk for failure. However, this approach is prohibitive given the sizes of most cable systems. It is commonly suggested that 80 % of a system's problems come from 20 % of the population. The key objective is to select the target population such that it includes circuits with historically poorer reliability that are vital to the operation of the system.

Failures Missed and Created During Action Phase

The chosen set of corrective actions (e.g. repair, replace, and rejuvenate) allow for the possibility that an incorrect or inadequate action may be performed on a circuit (a repair instead of a replace, for example). The goal is to perform only the minimum action needed to make the circuit reliable for the desired time horizon. However, this goal carries the risk that a circuit could less action than required. The effect would ultimately be a service failure.

A service failure might also result from an incorrectly completed action. Cable system components (cable and accessories) follow the well-known Weibull "bathtub" curve as shown in Figure 122.

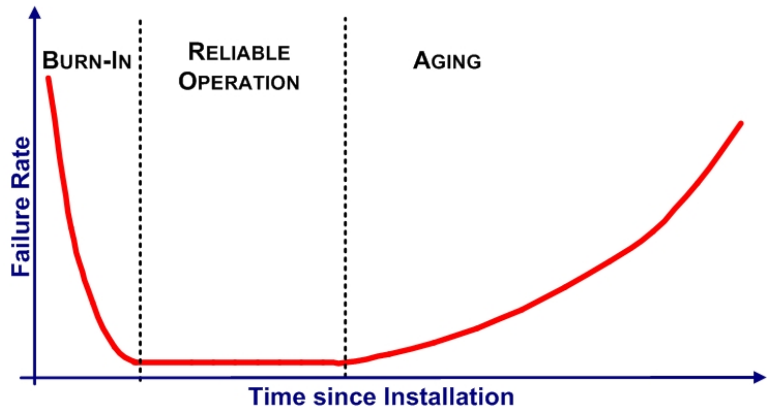


Figure 122: Illustrative Weibull “bathtub” Curve for Cable System Components

Using Figure 122, the goal of the diagnostic program is defined as follows: identify the components that are farthest into the *aging* region and then perform the necessary corrective action to return them to the *reliable operation* region. Unfortunately, the “bathtub” curve shows that new components can experience higher than normal failure rates for a short period following installation. This stage is termed *infant mortality* or *burn-in*. Failures during this stage are usually due to manufacturing or workmanship defects.

One possible scenario that could occur involves replacing a circuit that is not far enough into the *aging* region. This process could, if the infant mortality mode is significant, precipitate a failure sooner than it would have occurred had the circuit remained undisturbed. This appears in Figure 123. Eventually this circuit would move into the reliable operation region and, thus, be highly reliable but the early failure could be damaging to the perception of the diagnostic program.

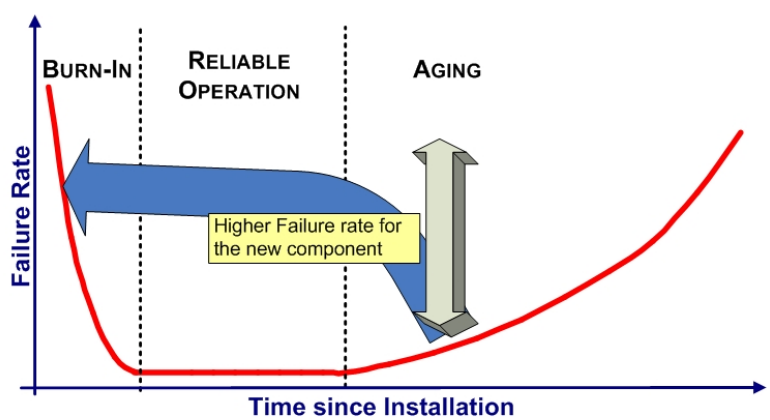


Figure 123: Graphical Interpretation of High Infant Mortality After Incorrectly Executed Action

In addition to the failures that occur during the “*infant mortality”* stage, there is also the possibility in diagnostic programs that employ more than two action levels that the chosen corrective action may not be aggressive enough to bring the circuit back to *reliable operation*. Thus, the circuit receives a partial reduction in its failure rate. In this case, the circuit simply returns to an earlier point within the *aging* region, as depicted in Figure 124.

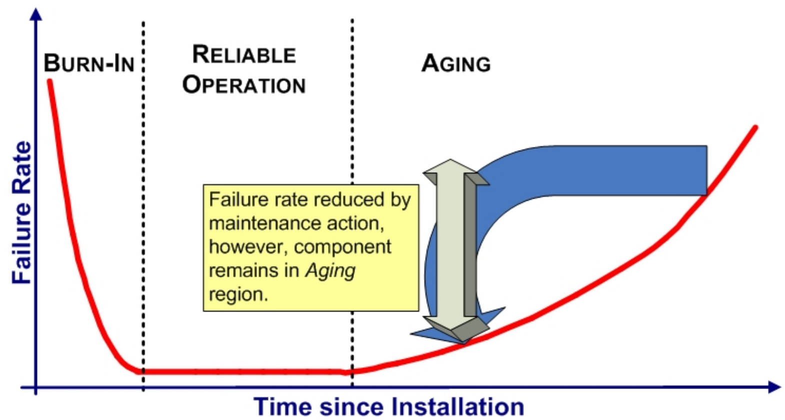


Figure 124: Graphical Interpretation of an Inadequate Corrective Action

The situation depicted in Figure 124 still produces a benefit for the utility in terms of a reduced failure rate. However, this reliability improvement is reduced from what could have been achieved had the correct level of corrective action been performed.

Failures Missed During Generation Phase

Diagnostic tests are not 100 % accurate. This means that a portion of their diagnoses will be incorrect. For a *k* level diagnostic test, the following consequences can result from misdiagnoses:

- If the diagnostic test places a circuit into the “good” class when its true condition is “bad,” then the circuit will produce a service failure.
- If the diagnostic test classifies a circuit as “bad” when it is only marginally “bad” then a more expensive action will be performed than is necessary.
- If the diagnostic test classifies a circuit as “marginally bad” when it is “bad” then a less aggressive action will be performed and a service failure may occur (see above discussion).

Each of the above consequences incurs a cost. In the first case, a service failure occurs incurring the cost of the failure plus any additional customer penalties. In the second case, an unneeded corrective action will increase the initial cost of the diagnostic program. Figure 125 shows an example of how a target population may be classified into two groups: Pass and Not Pass. Note that the squares (■) in Figure 125 represent circuits that will fail while the dots (●) represent those that will not.

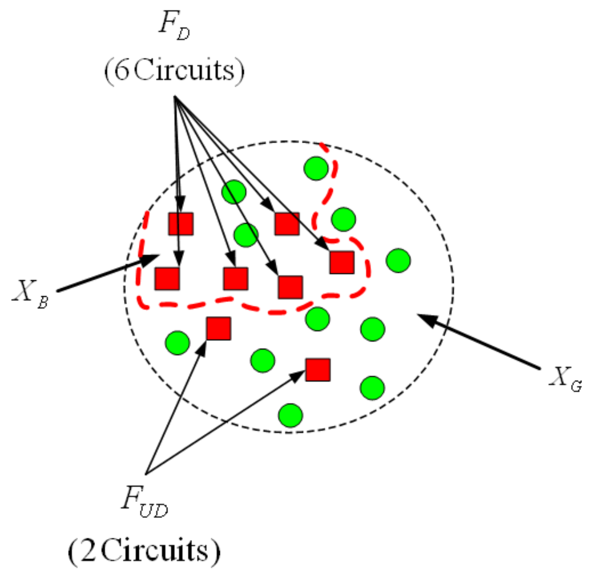


Figure 125: Sample Results of Diagnostic Testing

The number of "bad" circuits that the diagnostic correctly identifies as requiring corrective actions is shown in Figure 125 as F_D. This is number of avoided failures in the target population. Since the diagnostic is not 100 % accurate, there will still be incorrectly diagnosed circuits within the target population.. The number of overlooked "bad" circuits is shown in Figure 125 as F_{UD}. These circuits or undiagnosed failures reduce the net benefit of the diagnostic program.

Returning to the example presented earlier in Figure 121, Figure 125 shows a possible classification of a target population using a diagnostic test. The resulting yield calculation is as follows:

$$\begin{aligned} F_D &= 6 \text{ Failures} \\ F_{UD} &= 2 \text{ Failures} \\ F_{SR} &= 100\% \cdot \frac{F_D}{F_D + F_{UD}} = 75\% \\ \text{Yield} &= \frac{6}{19} = 0.316 \,[\text{Failures / Test}] \end{aligned} \quad \textbf{(15)}$$

According to the above scenario, the utility would experience a savings of six failures because of its diagnostic program. This equates to a 75 % "success rate" in identifying the circuits that would fail within the diagnostic time horizon. Two failures would still occur in this example. This translates to a yield of 0.316 [Failures/Test]. Furthermore, the number of corrective actions required to achieve this reduction is:

$$X_b = 8 \Rightarrow \frac{X_b}{X_{AR}} = \frac{8}{19} = 0.421$$

$$\frac{F_D}{X_b} = \frac{6}{8} = 0.750 \text{ [Avoided Failures / Corrective Action]} \qquad \textbf{(16)}$$

Where,

X_b = Total number of truly "bad" circuits in the target population

Therefore, the scenario in Figure 125 requires that corrective actions be performed on 42.1 % of the target population. This translates into a reduction in failures of 0.75 [Failures/Corrective Action]. On the other hand, had the utility chosen to act on the entire target population, the following results would have been obtained:

$$\begin{aligned} F_D &= 8 \\ F_{UD} &= 0 \\ F_{SR} &= 100\% \cdot \frac{8}{8} = 100\% \\ \frac{F_D}{X_{AR}} &= \frac{8}{19} = 0.421 \text{ [Avoided Failures / Corrective Action]} \end{aligned} \qquad \textbf{(17)}$$

This data shows that a greater number of failures would have been avoided by performing corrective actions on the entire population. However, in the case of the diagnostic program, the corrective actions are more targeted and so the resulting efficiency is greater for the diagnostic program (0.750 [Avoided Failures/Corrective Action] versus 0.421 [Avoided Failures/Corrective Action]). The question is: how much are the two failures that were missed by the diagnostic worth to the utility? By assessing their respective costs, the utility can decide which option to select.

4.3.3 Total Cost of a General Diagnostic Program

The total cost of a diagnostic program includes both the short-term and long-term costs described in Sections 4.3.1 and 4.3.2. Figure 126 shows that diagnostic programs have four primary costs:

- Selection Cost
- Diagnostic Testing Cost
- Corrective Action Cost
- Consequence Cost (C_F)

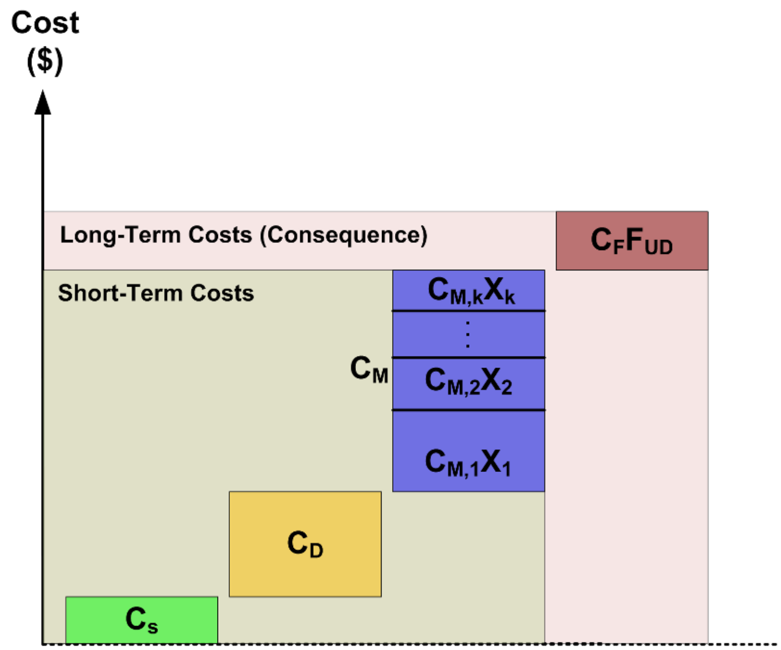


Figure 126: Total Diagnostic Program Cost

The variables that appear in Figure 126 were defined above, but are reproduced below for clarity:

C_s = Total cost to complete the "selection" of the target population
C_D = Total cost of performing the diagnostic test on the at-risk population $[\$]$
C_M = Total cost of corrective actions performed
C_F = Total cost of failure $[\$/\text{Failure}]$
F_{UD} = Total number of undiagnosed "Bad" circuits in the target population that would subsequently produce service failures

Section 4.3.1 and Section 4.3.2 demonstrated the calculation steps needed to compute the total cost of a diagnostic program over a period of T_H years. This can be rewritten in the following basic form:

$$C_{Total}^{DP} = C_S + X_{AR}\left(C_T + C_{SW}\right) + \sum_{i=1}^{k} C_{M,i}X_i + F_R X_{AR} T_H \left(1-P\right)\left(C_{M,1} + \sum_i C_{Cust,i} N_i\right) \quad \textbf{(18)}$$

Where,
$C_{Total}{}^{DP}$ = Total cost of diagnostic program [\$]
F_R = Average failure rate of target population [Failures/Circuit/Year]
T_H = Target time horizon [Years]
P = Overall accuracy of diagnostic test

Equation (18) can be broken down into the four cost elements shown in Figure 126:

$$C_{Total}^{DP} = \underbrace{C_S}_{\text{Selection}} + \underbrace{X_{AR}\left(C_T + C_{SW}\right)}_{\text{Diagnostic Testing}} + \underbrace{\sum_{i=1}^{k} C_{M,i} X_i}_{\text{Corrective Actions}} + \underbrace{F_R X_{AR} T_H \left(1-P\right)\left(C_{M,k} + \sum_i C_{Cust,i} N_i\right)}_{\text{Consequence}} \quad \textbf{(19)}$$

Equation (19) can be used to determine the cost of a diagnostic program provided reasonable values could be assigned to each of the variables. The following observations can be made:

- Diagnostic program cost is not simple to calculate – information on both the utility system and diagnostic test are required.
- Failure predictions are required.
- The cost of performing the diagnostic testing is only one piece of the program cost.
- Additional options for the corrective actions substantially increase complexity.

Diagnostic programs will always carry a cost to conduct. Cost should not be the driving factor when deciding whether to conduct a diagnostic program. Rather, the cable engineer must compare the diagnostic cost to an alternative program (run-to-failure, complete replacement, etc.) to determine the *benefit* the diagnostic program could deliver. Potential benefit should drive the decision process. This is discussed in Section 4.3.4.

4.3.4 Economic Benefit

A diagnostic program can produce benefit for a utility through:

(1) Reduced spending on corrective actions
(2) Improved reliability through avoided failures
(3) Less costly diagnostic techniques (if comparing different diagnostic programs)

The economic benefit arises from the cost difference between the diagnostic program and any alternative program. Examples of alternative programs include other diagnostic programs, complete replacement of the target population, and "run-to-failure." It turns out that the complete replacement and run-to-failure programs represent limiting cases for each of the bullet points above. These programs are discussed in Sections 4.3.4.1 and 4.3.4.2.

4.3.4.1 Complete Replacement Program

This section demonstrates the economic savings a utility could obtain from a diagnostic program as compared to a complete replacement program. The total cost of a complete replacement program is:

$$C_{Total}^{CR} = C_S + C_{M,k} X_{AR} \quad \textbf{(20)}$$

Where,

C_S = Total cost to complete the "selection" of the target population [$]
$C_{M,k}$ = Total cost to replace a circuit [$/Circuit]
X_{AR} = Number of circuits in the target population [Circuits]

The savings that a diagnostic program would produce is computed as:

$$\begin{aligned} S &= C_{Total}^{CR} - C_{Total}^{DP} \\ &= C_S + C_{M,k} X_{AR} - C_S - X_{AR}\left(C_T + C_{SW}\right) - C_{M,k} X_1 \\ &\quad - F_R X_{AR} T_H \left(1-P\right)\left(C_{M,k} + \sum_i C_{Cust,i} N_i\right) \end{aligned} \quad \textbf{(21)}$$

Rearranging the terms slightly in (21) leads to:

$$S = C_{M,k}\left(X_{AR} - X_k\right) - \sum_{i=1}^{k-1} C_{M,i} X_i - X_{AR}\left(C_T + C_{SW}\right) - F_R X_{AR} T_H \left(1-P\right)\left(C_{M,1} + \sum_i C_{Cust,i} N_i\right) \quad \textbf{(22)}$$

As in (19), two elements to the savings can be readily seen:

$$S = \underbrace{C_{M,k}\left(X_{AR} - X_k\right) - \sum_{i=1}^{k-1} C_{M,i} X_i}_{\text{Corrective Action Savings}} - \underbrace{X_{AR}\left(C_T + C_{SW}\right) - F_R X_{AR} T_H \left(1-P\right)\left(C_{M,1} + \sum_i C_{Cust,i} N_i\right)}_{\text{Diagnostic Program Cost}} \quad \textbf{(23)}$$

The first element, corrective action savings, represents the reduction in replacement spending by utilizing the diagnostic program. The remaining terms constitute the remaining cost of the diagnostic program. For there to be a savings, the diagnostic program cost must be less than the corrective action savings. This implies that as compared to the complete replacement scenario, the diagnostic program generates its savings from reduced spending on corrective actions.

4.3.4.2 "Run-to-Failure" Program

The "run-to-failure" program is similar to the complete replacement case in Section 4.3.4.1. The total cost of a "run-to-failure" program can be defined as:

$$C_{Total}^{RF} = C_S + F_R X_{AR} T_H \left(C_{M,k} + \sum_i C_{Cust,i} N_i\right) \quad \textbf{(24)}$$

where,

C_{Total}^{RF} = Total cost of the "run to failure" program [$].

Similar to the complete replacement case, the cost difference between the diagnostic program and the "run-to-failure" program is computed as:

$$S = C_{Total}^{RF} - C_{Total}^{DP}$$

$$= F_R X_{AR} T_H \left(C_{M,k} + \sum_i C_{Cust,i} N_i \right) - X_{AR} \left(C_T + C_{SW} \right) - \sum_{i=1}^{k} C_{M,i} X_i - F_R X_{AR} T_H \left(1 - P\right) \left(C_{M,k} + \sum_i C_{Cust,i} N_i \right) \quad \textbf{(25)}$$

Rearranging the terms slightly in (25) leads to:

$$S = F_R X_{AR} T_H P \left(C_{M,k} + \sum_i C_{Cust,i} N_i \right) - X_{AR} \left(C_T + C_{SW} \right) - \sum_{i=1}^{k} C_{M,i} X_i \quad \textbf{(26)}$$

As in (23), two components to the savings can be readily seen:

$$S = \underbrace{F_R X_{AR} T_H P \left(C_{M,k} + \sum_i C_{Cust,i} N_i \right)}_{\text{Reliability Savings}} - \underbrace{X_{AR} \left(C_T + C_{SW} \right) - \sum_{i=1}^{k} C_{M,i} X_i}_{\text{Diagnostic Program Cost}} \quad \textbf{(27)}$$

Note that in this example the savings component of (27) is now the result of improved reliability rather than reduced spending on corrective actions. Once again, the diagnostic program produces a savings when the diagnostic program cost is less than the reliability savings it produces.

4.3.4.3 Alternative Diagnostic Program

The two programs described in Sections 4.3.4.1 and 4.3.4.2 demonstrate two extreme cases:

(1) Savings exclusively from reduced spending on corrective actions as in the complete replacement example.
(2) Savings exclusively from improved reliability as in the “run to failure” example.

Comparing two diagnostic programs would yield a mixture between reliability, corrective action, and testing savings as shown in (28).

$$\begin{aligned} S = &\underbrace{X_{AR} \left(C_{T,2} - C_{T,1} + C_{SW,2} - C_{SW,1} \right)}_{\text{Diagnostic Testing Savings}} \\ &+ \underbrace{\sum_{i=1}^{k} C_{M,i} \left(X_{i,2} - X_{i,1} \right)}_{\text{Corrective Action Savings}} \\ &+ \underbrace{F_R X_{AR} \left[T_{H,2} \left(1 - P_2\right) \left(C_{M,k} + \sum_{i \in \text{Cust Type}} C_{cust,i} N_i \right) - T_{H,1} \left(1 - P_1\right) \left(C_{M,k} + \sum_{i \in \text{Cust Type}} C_{cust,i} N_i \right) \right]}_{\text{Reliability Savings}} \end{aligned} \quad \textbf{(28)}$$

where,

$C_{T,d}$ = Cost of diagnostic d equipment and personnel $[\$/\text{Test}]$ or $[\$ / \text{Circuit}]$

$C_{SW,d}$ = Cost of line crew to perform switching for diagnostic d, if needed $[\$/\text{Test}]$

$X_{j,d}$ = Number diagnosed by diagnostic d as requiring corrective action j [Circuit]

$T_{H,d}$ = Diagnostic time horizon of diagnostic d [Year]

P_d = Overall diagnostic accuracy of diagnostic d

As (28) shows, the comparison of two diagnostic programs is complex but possible.

The above scenarios represent the possible benefits a utility would consider in assessing a diagnostic program. The greatest challenge in modeling these situations is obtaining the data needed to complete the calculation. Unfortunately, these data are not readily available. Section 4.3.5 describes one method of dealing with this uncertainty.

4.3.5 Simulation Studies

The focus of this section is to demonstrate the effect of different scenarios on the likelihood of obtaining economic savings. To that end, this section will illustrate the model described in Sections 4.3.1 through 4.3.4 using stochastic simulation techniques. These case studies rely on artificial data (that have been selected to be as realistic as possible) that are used to illustrate the relative behavior and effect of the different inputs. The goal is to show basic characteristics and not to focus on the numbers themselves as these data would be different for each utility and target population.

The simulations utilize the input data shown in Table 68.

Table 68: Artificial Input Data Used in Simulation Studies			
Cost Component	**Input Parameter**	**Description**	**Assumed Values**
Selection	Time Horizon	Time period for which the diagnostic is assumed valid.	5 Years
	X_{AR}	Size of target population	100 Circuits
	Circuit Length	Average circuit length in target population	1000 ft
	Failure Rate	Local failure rate of target population	0.001 – 0.10 [Failures/Circuit/Year] 0.53 – 53 [Failures/100 Miles/Year]
Diagnostic	Diagnostic Test	Total cost of performing diagnostic testing on each segment (includes switching crew if needed).	0.5 Cost Units
	Failure on Test Rate (FOT)	Percentage of segments that fail during diagnostic testing.	2.5%
	Overall Diagnostic Accuracy	Percentage of correct diagnoses made during the time horizon.	51 – 99%
Corrective Action	Installation Cost	Total cost to install a repair splice.	2 Cost Units
Consequence	Average # of Customers	The average number of customers affected by the failure of one circuit.	20 Residential Customers 200 Residential Customers
	Time of Failure	Day of week and time of day when failure occurs. Outside of normal business hours produces overtime factor.	0 – 168 hours
	Failure Penalty Cost	Total amount utility is charged resulting from service interruptions.	0.1 – 0.5 [Cost Units/Customer/Failure]
	Normal Repair Cost	Cost of crew and parts to repair a segment (does not include impact to customers or reliability indices).	2 Cost Units 2.5 Cost Units (Overtime)

Given the difficulty of obtaining precise values for the inputs in Table 68, the approach here will be to treat them as random variables with uniform distributions.

As discussed above, to determine the benefit of any program, it must be compared to an alternative program. For these simulation studies, the alternative program is run-to-failure.

4.3.5.1 Failure Rate Transformation

Failure rates are generally discussed in terms of number per length per year. This makes understanding the target population composition more difficult than it needs to be. A useful transformation for failure rate information is the Good-Bad (G/B) ratio of the population. This ratio essentially describes the percentages of the population can be thought of as "good" and "bad." The failure rate used in conjunction with the target population data generates the G/B ratio.

Figure 127 shows the percentage of a target population that is expected to fail over a specific time horizon for the failure rate range and circuit length in Table 68. Note that this figure refers only the performance of the aged population and does not account for infant mortality failure modes resulting from newly installed components.

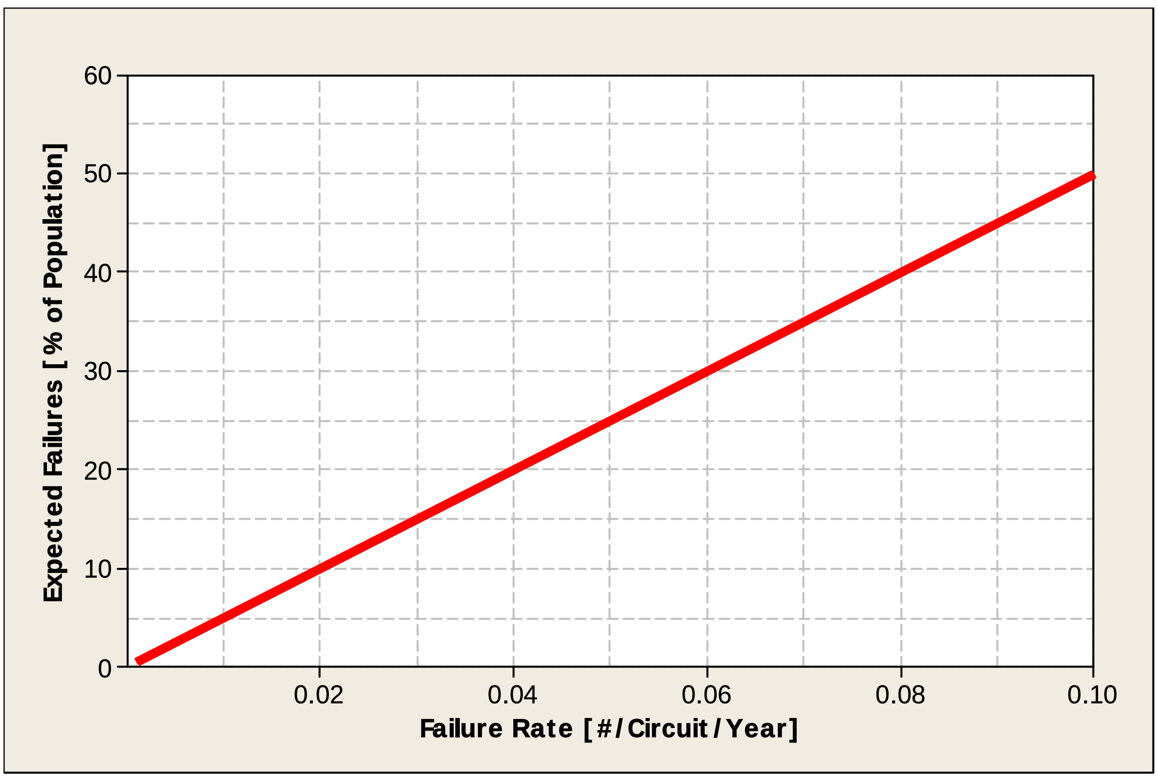


Figure 127: Population Composition as a Function of Failure Rate (Assumes Population of 100 Circuits Each 1,000 ft in Length and 5 Year Time Horizon)

From Figure 127, it is straightforward to extract the G/B ratios for a selected group of failure rates as shown in Table 69.

Table 69: G/B Ratios for Selected Failure Rates	
Failure Rate [#/1000 ft Circuit/Year]	**Good/Bad Circuit Ratio [G/B]**
0.01	95/5
0.02	90/10
0.03	85/15
0.04	80/20
0.05	75/25
0.06	70/30
0.07	65/35
0.08	60/40
0.09	55/45
0.10	50/50

In the datasets analyzed in the CDFI, no cable system has exhibited a G/B ratio worse than 50/50. It is common to find diagnostic tests used in systems that are closer to a G/B ratio of 85/15.

4.3.5.2 Simulation Results

As mentioned above, stochastic simulation techniques are used because the values for the inputs are, for the most part, uncertain. The results of these simulations are presented in terms of G/B ratio and overall diagnostic accuracy. However, all inputs shown in Table 68are used in each simulation. A sensitivity analysis showed that G/B ratio and overall diagnostic accuracy are the two inputs with the greatest impact on the simulation results.

The simulation results are presented as a Benefit-Loss map. This map uses green and red coloring to indicate G/B ratio and accuracy combinations that are likely (with greater than 90 % probability) to produce benefit (green) and loss (red). Figure 128 shows the Benefit-Loss map for a cable system located in a rural area (few customers).

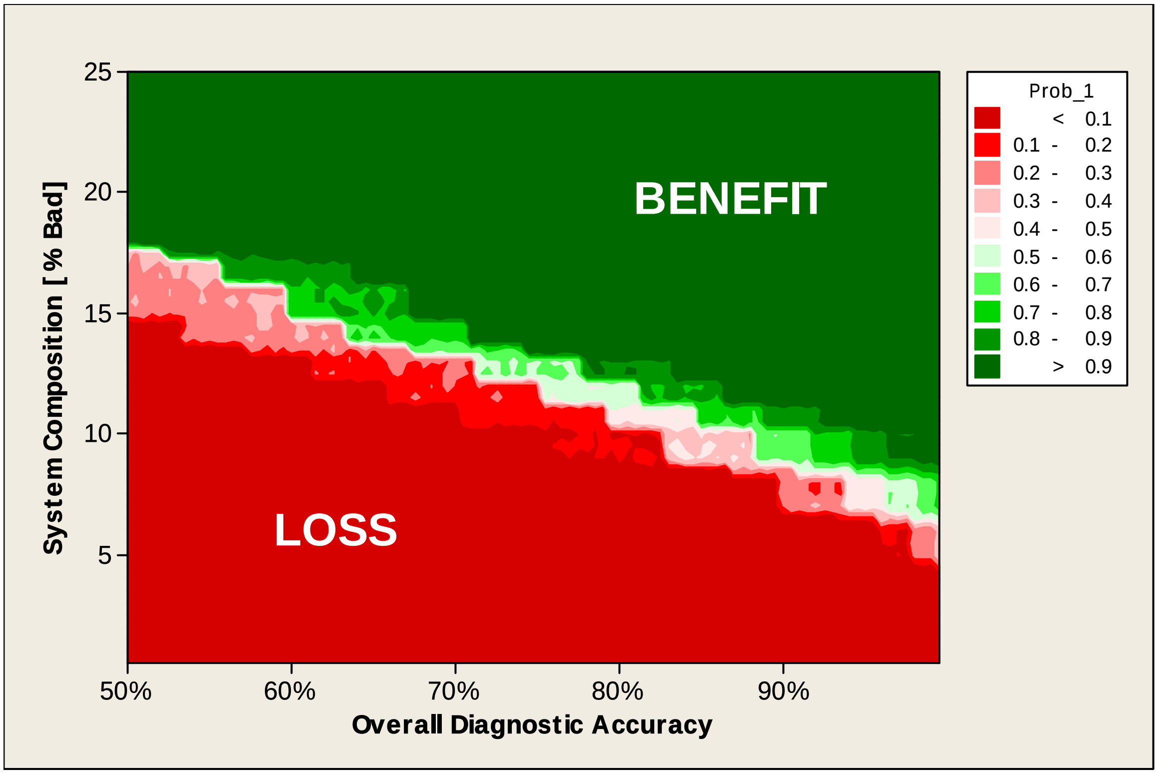


Figure 128: Benefit-Loss Map for Rural Region

Figure 128 clearly shows a region of benefit and a region of loss. Not surprisingly, the loss region is located where the G/B ratio is better than 85/15 (for low diagnostic accuracies). In other words, there are very few failures in these target populations for the diagnostic to find. This makes sense since the run-to-failure program cost includes minimal corrective actions and maximum failure consequence cost. A diagnostic program should require more corrective actions than run-to-failure and this should produce a reduction in the failure consequence cost. For G/B ratios better than 85/15, the target population is simply “too good” for most diagnostics. A more accurate diagnostic test can allow a target population of up to 95/5 to be used but even a 100 % accurate diagnostic would not yield a benefit for a system with a G/B ratio better than 95/5.

The same simulation can be run for a suburban region where the number of customers affected is substantially higher than in the case shown in Figure 128. The Benefit-Loss map for a suburban region appears in Figure 129.

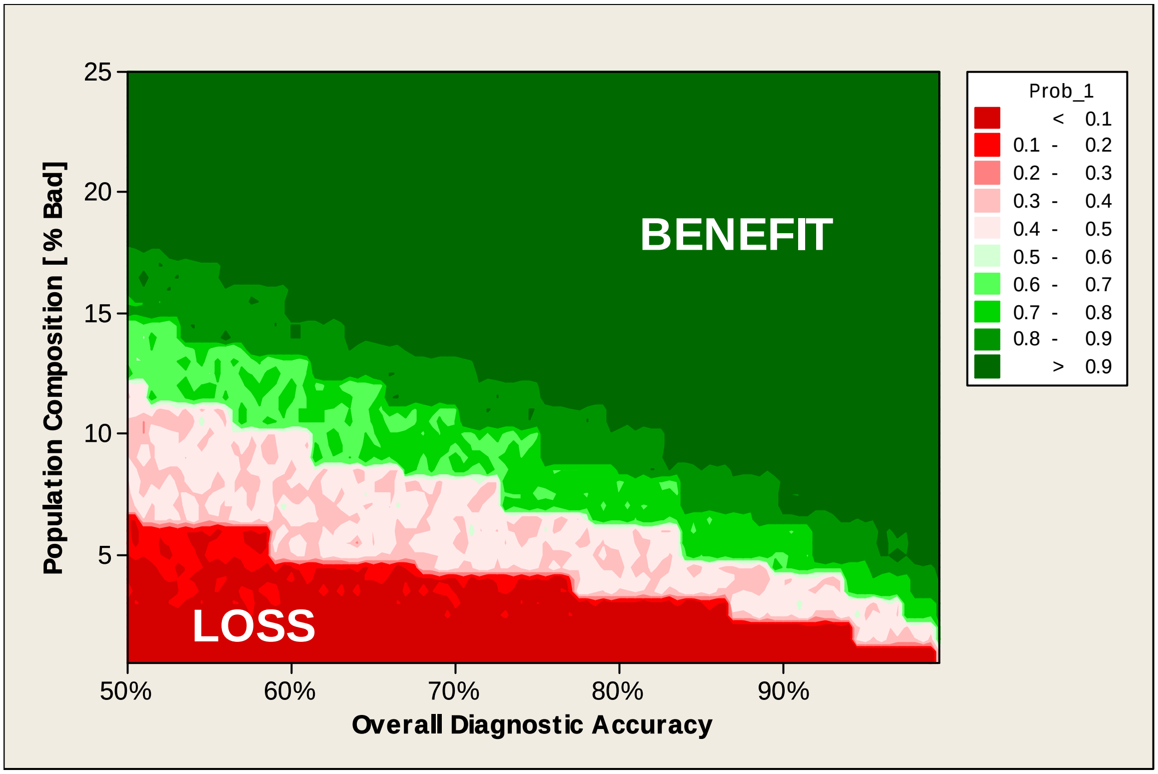


Figure 129: Benefit-Loss Map for Suburban Region

As Figure 129 shows, the basic structures and positions of the benefit and loss regions are the same as those in Figure 128. Again, for target populations that are in good condition, the likelihood of loss is high. On the other hand, the area of the loss region is substantially less than the rural case because the cost of each failure is more for a suburban region. A high cost per failure allows diagnostics to provide benefit over a broader range of target population compositions.

Simulation studies such as those described above allow a utility to assess the risk of experiencing a loss with a proposed diagnostic program. This information should be considered when making any decision regarding the use of cable system diagnostics.

4.3.6 Implementation

The mathematical framework described in the preceding sections can be used as the basis for a software program that would enable utilities to perform the cost-benefit analyses. The challenge in developing such a tool is that the calculations depend heavily on the availability of accurate cost information. Unfortunately, these data have been difficult to quantify. The example calculations presented in Section 4.3.5 made several assumptions in order to make the calculations possible. Unfortunately, these assumed values for the input parameters would be different for each utility participant in the CDFI. Future work in CDFI Phase II will include developing an approach, perhaps like the KBS in Section 4.2, to a software tool that would allow for such calculations to be completed.

5.0 CASE STUDIES

A significant portion of the work in CDFI focused on the compilation and analysis of data from both historical diagnostic programs as well as newly launched programs. These data sets were provided by both utility participants and other utility supporters outside of the CDFI. These data were used extensively to develop the material presented in Section 3 and Section 4 and forms the foundation for the CDFI Perspectives on each of the diagnostic techniques. A summary of the data sets examined in the CDFI appears in Table 70. In total, the diagnostic data examined by the CDFI covers over 40 diagnostic programs and 83,000 conductor miles of diagnostic testing.

Table 70: Summary of Diagnostic Programs Examined During the CDFI

Utility Reference	Diagnostic Technique	Length [Miles]	Cable System Type	Year of Testing	Service Performance Monitored
A	Simple Withstand	120	XLPE	2000-2001	X
A	PD	120	XLPE	2000-2001	X
A	None	100	XLPE	2001-2007	X
A	PD	210	XLPE	2002-2006	X
B	PD	114	Hybrid	2001-2008	X
B	Simple Withstand	78,000	Hybrid	2001-2008	X
B	Simple Withstand	1,092	Hybrid	2001-2008	X
C	PD	22	Hybrid	2006	
C	Simple Withstand	2,100	Hybrid	2003-2008	X
D	Combined	126	XLPE	2001-2006	X
E	PD	9	XLPE	2001-2007	
E	Tan δ	76	XLPE	2002-2007	
F	Simple Withstand	368	Paper	2004-2006	X
F	PD	91	Hybrid	1999-2000	X
F	PD	8	Hybrid	1999-2000	X
F	PD	9	Hybrid	1999-2000	X
G	PD	22	Paper	2000-2001	
H	PD	74	XLPE	1999	
H	PD	--	XLPE	2006	
H	PD	82	XLPE	2008	
Mooresville	Tan δ	6	XLPE	2006	X
Clemson	Tan δ	2	XLPE	2007	X
Charlotte	Tan δ	3	XLPE	2007	X
Cincinnati	Tan δ	180	Paper	2007-2008	X
M	Combined	55	Paper	2008	

Utility Reference	Diagnostic Technique	Length [Miles]	Cable System Type	Year of Testing	Service Performance Monitored
Evans	Tan δ	7	XLPE	2006	X
Macon	Tan δ	4	XLPE	2006	X
Mooresville	PD	6	XLPE	2006	X
Charlotte	Monitored Withstand	3	XLPE	2007	X
Cincinnati	Monitored Withstand	180	Paper	2007-2010	X
Evans	PD	7	XLPE	2006	X
Roswell	Tan δ	10	XLPE	2008	X
Roswell	PD	3	XLPE	2009	X
Roswell	Monitored Withstand	10	XLPE	2008	X
I	PD	2	XLPE	2007	
J	PD	3	XLPE	2007	X
J	PD	8	XLPE	2007	X
J	Tan δ	20	XLPE	2008	X
J	PD	14	Hybrid	2000	X
K	Simple Withstand	--	--	--	
L	Tan δ	18	Mixed	--	
L	Simple Withstand	108	Mixed	--	

The details of each of the data sets in Table 70 were not directly discussed in either Section 3 or Section 4 as this would be quite protracted. It is, on the other hand, useful to review the details of a select group of these data sets as case studies. Sections 5.1 through 5.4 review in detail four of the diagnostic programs appearing in Table 70:

- Utility A Offline PD Pilot Study
- Duke Energy – Mooresville, NC
- Duke Energy – Cincinnati, OH
- Georgia Power – Roswell, GA

These case studies were selected because they provided the CDFI with many useful insights regarding the different diagnostic techniques. They are discussed in chronological order (oldest program to most recent program) to show the evolution of the diagnostics and the understanding within the CDFI. These insights are summarized in Table 71 and discussed in more detail in the sections that follow.

Table 71: Summary of Selected Case Studies				
Diagnostic Program	**Testing by**	**Diagnostics Employed**	**Test Date**	**Insights**
Utility A	Diagnostic Provider	PD Offline	2000-2001	• Classic metrics of charge magnitude and inception voltage (factory test standards) are not sufficient PD features for diagnosis of field testing. • Diagnosis of accessories is challenging. • Most circuits diagnosed as "bad" did not fail. • Circuits with PD in the cable portions are five times more likely to fail in service within 3 years than circuits without PD in cable. • A small number of cables diagnosed as "good" failed in service.
Duke Energy *Mooresville*	CDFI	Tan δ PD Offline	2006	• IEEE Std. 400™-2001 VLF Tan δ criteria found to be unclear and too conservative. • Tan δ and PD Offline not inherently destructive with respect to service failures after testing. • Failures on test removed the weak spots as none of the circuits failed within 4 years. • No circuits diagnosed as "bad" using 2001 CDFI Criteria failed within 4 years of testing. • No circuits diagnosed as "good" failed within 4 years of testing.

Duke Energy
 	
Cincinnati
	CDFI
	&
	Utility
		Simple Withstand
		
		Tan δ
		
		Monitored Withstand
			2007-2010	• First implementation of Monitored Withstand.
				• Program used CDFI Tan δ and Monitored Withstand criteria.
				• Combined diagnostics are often be complimentary and improve the diagnostic program's performance.
				  o 11 % "Not Pass" using only Simple Withstand
				  o 8 % additional "Not Pass" using Tan δ and Tan δ monitoring
				  o 19 % Total "Not Pass" using combined diagnostics approach
				• Failure rate of target population in service reduced by 46 % due to diagnostic guided actions.

Georgia Power *Roswell*	CDFI	Tan δ Monitored Withstand PD Offline	2008-2009	• Used KBS to obtain short list of diagnostic techniques. • Used economics model to assess benefit of diagnostic techniques obtained from KBS. • Multiple diagnostics employed – Tan δ (2008 CDFI criteria), Monitored Withstand (2008 CDFI criteria), and PD Offline.

5.1 Utility A Offline PD Pilot Study

A pilot study consisting of 120 miles of direct buried unjacketed XLPE feeder cable was tested using Offline PD. These circuits were either 15 kV or 25 kV class. The service performance of these circuits as well as the locations of the failures within the circuits was followed for seven years after testing. Figure 130 shows the lengths of the circuits that were tested as part of this diagnostic program. It is useful to note that the median length is 687 ft for this population of 195 3-phase sections.

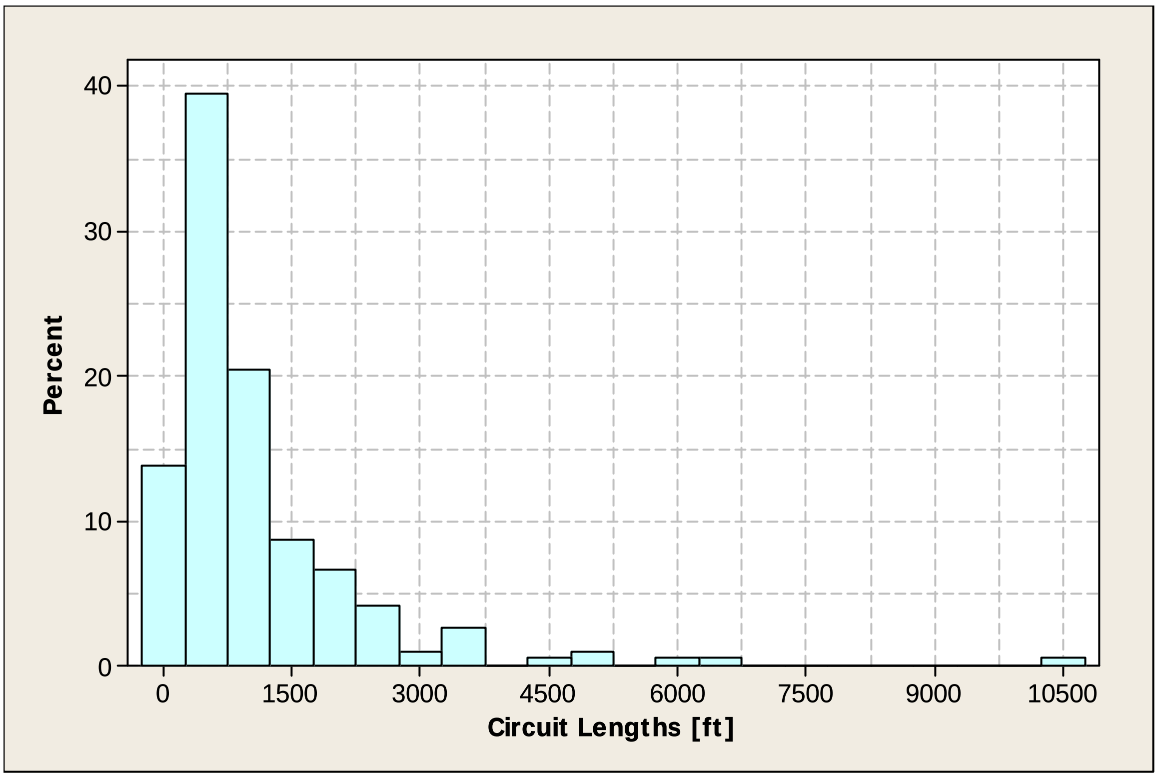


Figure 130: Tested Circuit Lengths

Table 72 summarizes the service performance of cable segments where PD sites were identified. Note that for this analysis PD sites identified in the accessories have been excluded.

Table 72: Service Performance of PD Sites Detected in Cable (Accessory PD Sites Excluded)

Voltage Class [kV]	Failed PD Sites [#]	Not Failed PD Sites [#]	Total PD Sites [#]	PD Sites Failed [%]	PD Sites Not Failed [%]
15	23	252	275	8%	92%
25	5	117	122	4%	96%

As Table 72 shows, 4 – 8 % of the cable PD sites generated service failures within the 7 year time horizon. The measurement data on the PD sites includes both charge magnitude and inception voltage. The distributions of the data are shown in Figure 131 and have been segregated by the resulting service performance of the site (i.e. "failed" and "not failed").

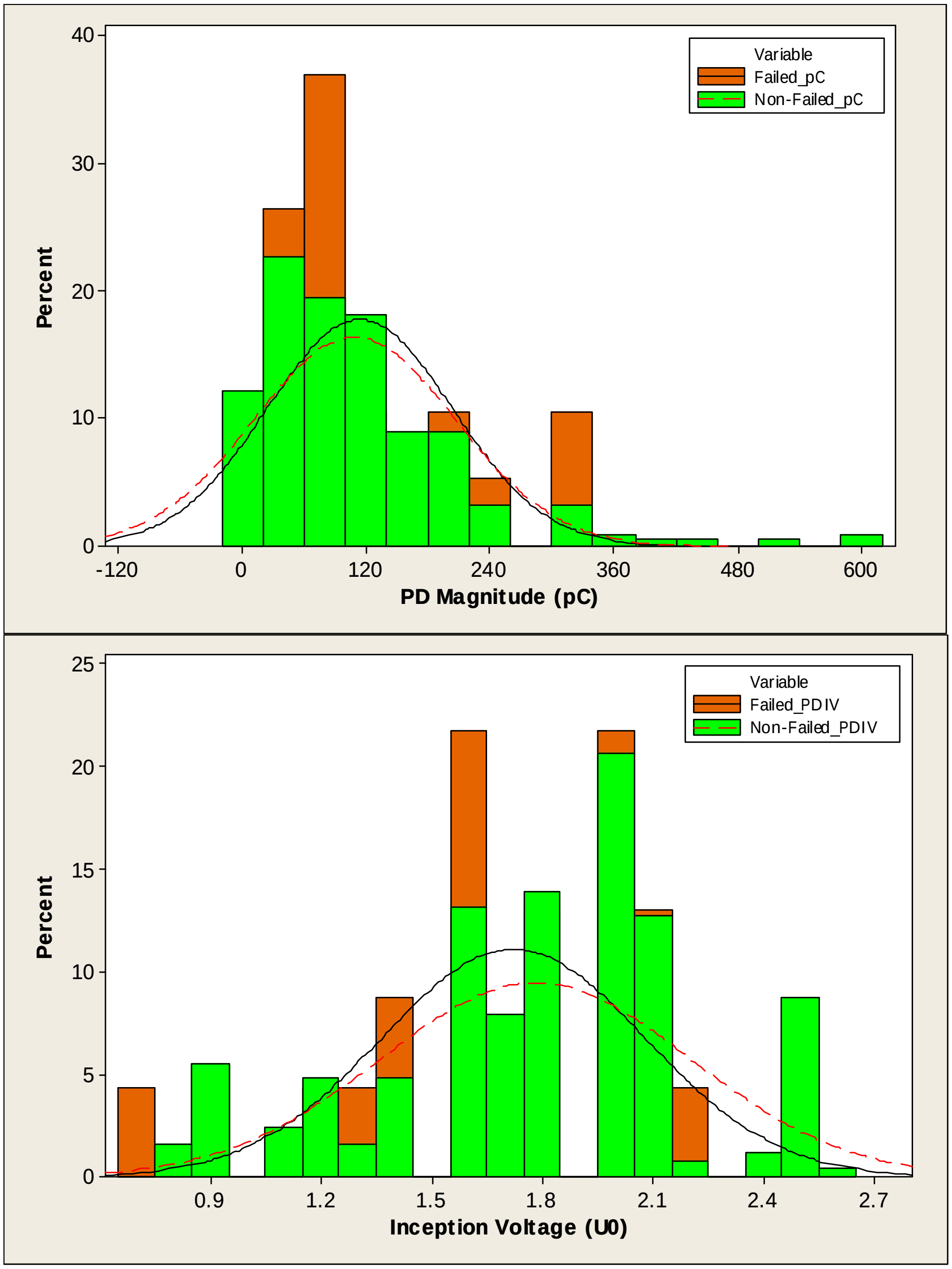


Figure 131: Cable PD Data Distributions Segregated According to Service Performance After Test - Charge Magnitude (top) and Inception Voltage (bottom). Note Overlap of Failed and Non-Failed Data

Figure 131 illustrates the current challenge with PD measurements – determining which PD sites will cause service failures and which will not. The two sets of distributions show little or no difference between those sites that yielded failures and those that did not. Given the data in Table 72, this is a critical distinction to make since less than 10 % of the sites went on to fail within seven years.

The two types of measurements may also be combined to generate Figure 132. The charge magnitudes and inception voltages corresponding to PD sites that failed in service are shown as a blue circle. As in Figure 131, there is no clear separation between the two groups.

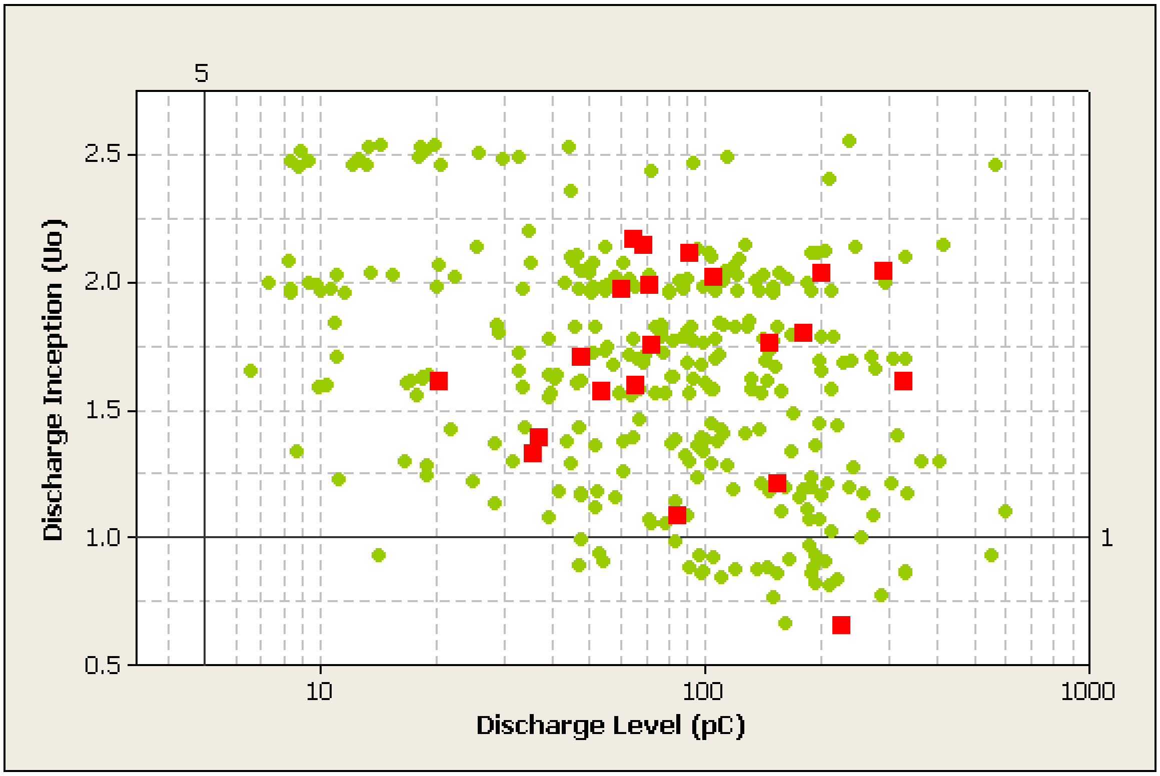


Figure 132: Cable PD Magnitude vs. PD Inception Voltage Segregated by the Failure Outcome in Service After Testing
(■ – PD sites that failed and ● – PD sites that did not fail in service)
(Only Includes Cables with Detectable PD)

While the PD site data collected during this test program cannot be used to differentiate PD sites that fail from those that do not, the presence of PD can be shown to reduce the service life of cable systems. Figure 133 shows the time to failure performance of circuits with PD (“No Pass”) and those with no detectable PD (“Pass”).

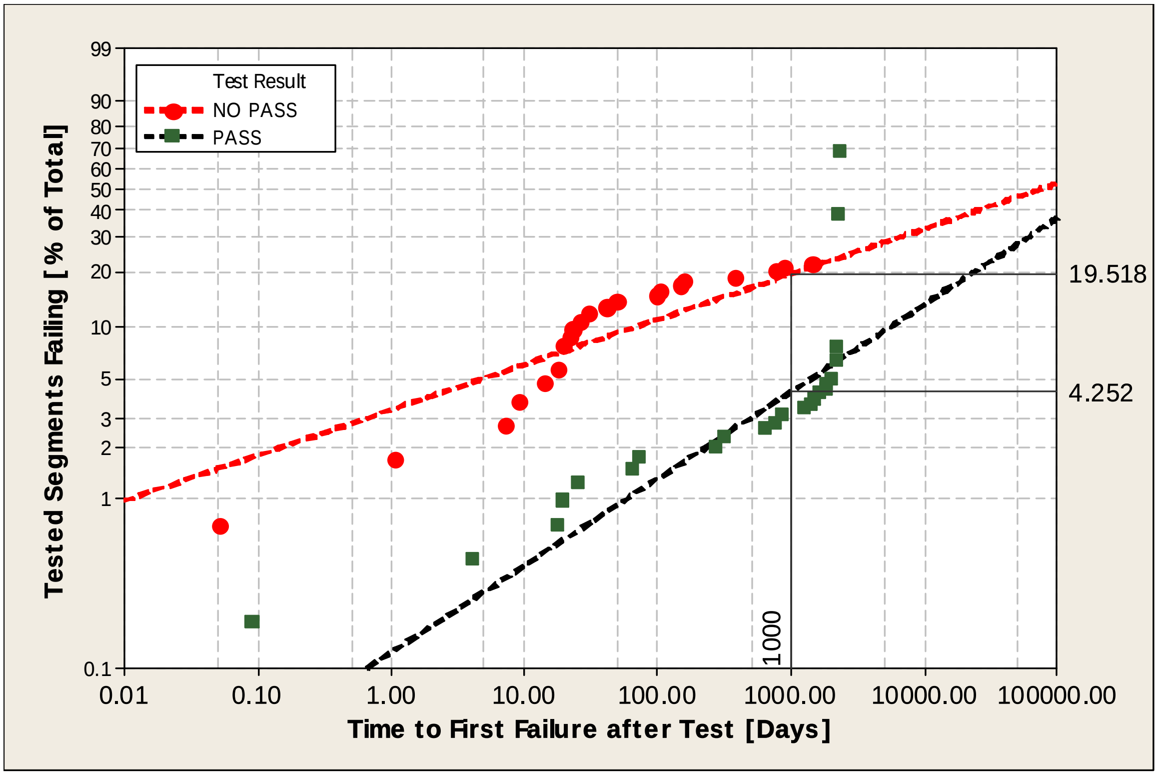


Figure 133: Time Evolution of Cable Failures in Service Segregated by PD Diagnosis "No Pass" - Cable PD Detected (PD Data Shown in Figure 132) "Pass" – No Cable PD Detected (Not Shown in Figure 132) Circuits Replaced Upon Failure

Comparing the time to failure for circuits with and without PD using Figure 133 shows the reduction in service life a utility could expect. At 1,000 days (~ 3 years) from test, the failure rate for circuits with PD is approximately 19.5 % while the failure rate for those circuits without PD is only 4.3 %. In other words, 1 in 5 circuits with PD will fail within 1,000 days while only 1 in 25 circuits without PD would fail within the same time period.

5.1.1 Diagnostic Program Benefit

This Pilot Study was not designed to be a proactive program in which the results of the diagnostic testing were then used to direct corrective actions. The purpose of this program was to examine the performance of an Offline PD diagnostic on this utility's system. The data that was generated by this program was used by the CDFI to determine if the classic PD features of charge magnitude and inception voltage could be used to accurately separate PD sites that would fail in service from those that would not. As discussed in Section 3.3.6.4, these two features are not sufficient for this purpose. Other measurement data (features) are needed in order to determine if this is, in fact, viable.

Pilot studies of this type are vital to verifying the accuracy of diagnostic programs.

5.2 Duke Energy – Mooresville, NC

The Mooresville area of the Duke cable system located north of Charlotte, NC, was selected for testing as it displayed some very interesting characteristics. The cables were mid-generation XLPE cables with jackets which had given good performance for a number of years when operated at 15 kV. However, when upgraded to their rated voltage of 25 kV after a number of years, some service failures were experienced. After these initial upgrade failures, the "normal" performance returned. These cable circuits are single phase URD runs. This testing was completed in 2006 and a retest is scheduled for 2010-2011 as part of CDFI Phase II.

This system was tested using VLF Tan δ and VLF Partial Discharge. Figure 134 shows the connection of the voltage divider (yellow cylinder) for PD measurement to the cable circuit. The connections for VLF Tan δ are similar but exclude the voltage divider.

Figure 134: Test arrangement for VLF PD measurements

Prior to both diagnostic tests, the circuits were each measured using a TDR to determine the total length and splice locations. The distribution of tested lengths is shown in Figure 135. The median length is approximately 400 ft.

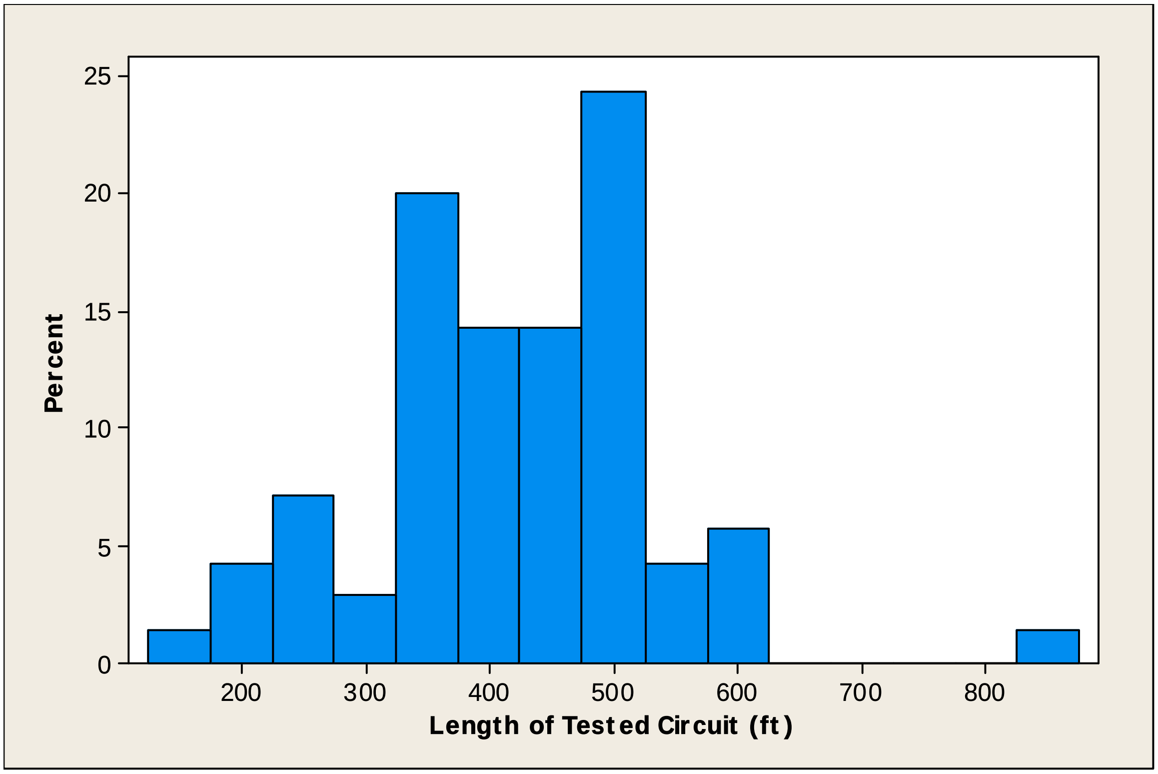


Figure 135: Disbursement of Circuit Lengths Tested

5.2.1 Test Results

Tests were made on circuits located in several subdivisions throughout the Mooresville area. In addition, these tests were made up to $2U_0$ according to IEEE Std. 400™ - 2001. The mean Tan δ results as a function of test voltage for each of these subdivisions are shown in Figure 136. Note that IEEE Std. 400™ - 2001 critical levels are also shown (2001 CDFI Criteria - Table 31).

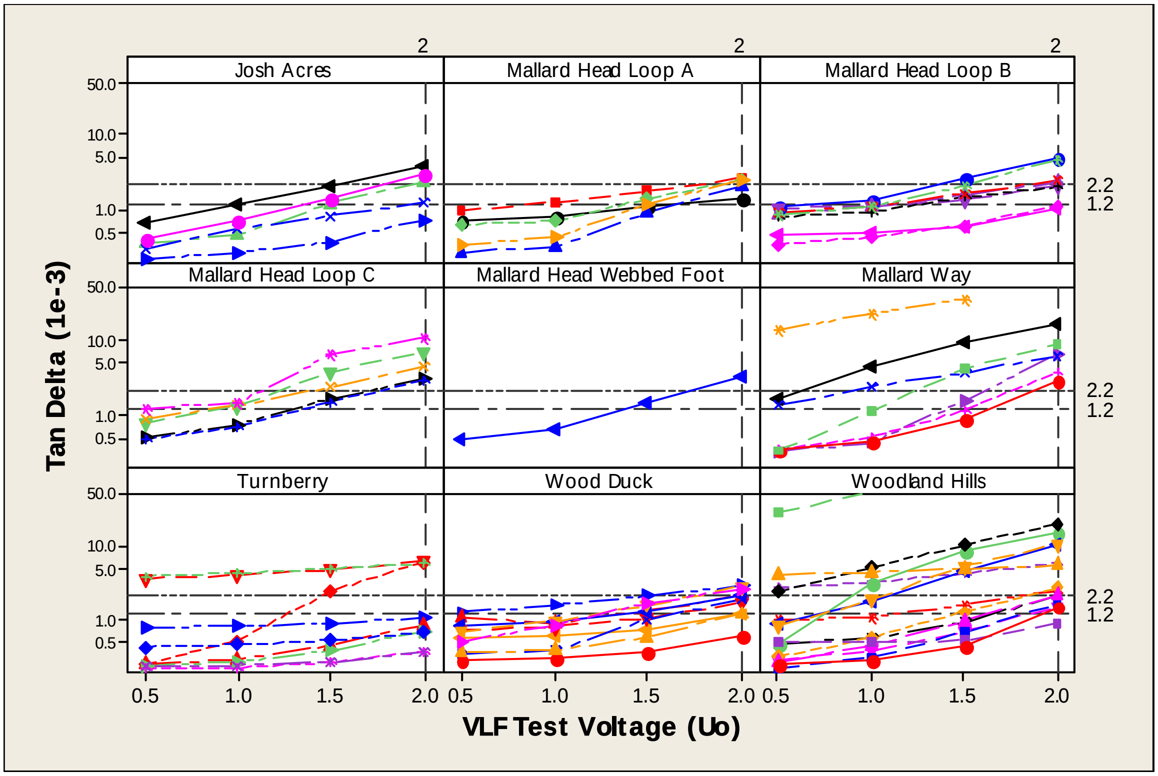


Figure 136: Tan δ Results at Selected Voltages (units of U_0) Segregated by Subdivision

A similar summary for PD inception voltages appears in Figure 137. Note that criteria are shown for both 15 kV and 25 kV system voltages. The maximum test voltage was $2U_0$ or 28 kV.

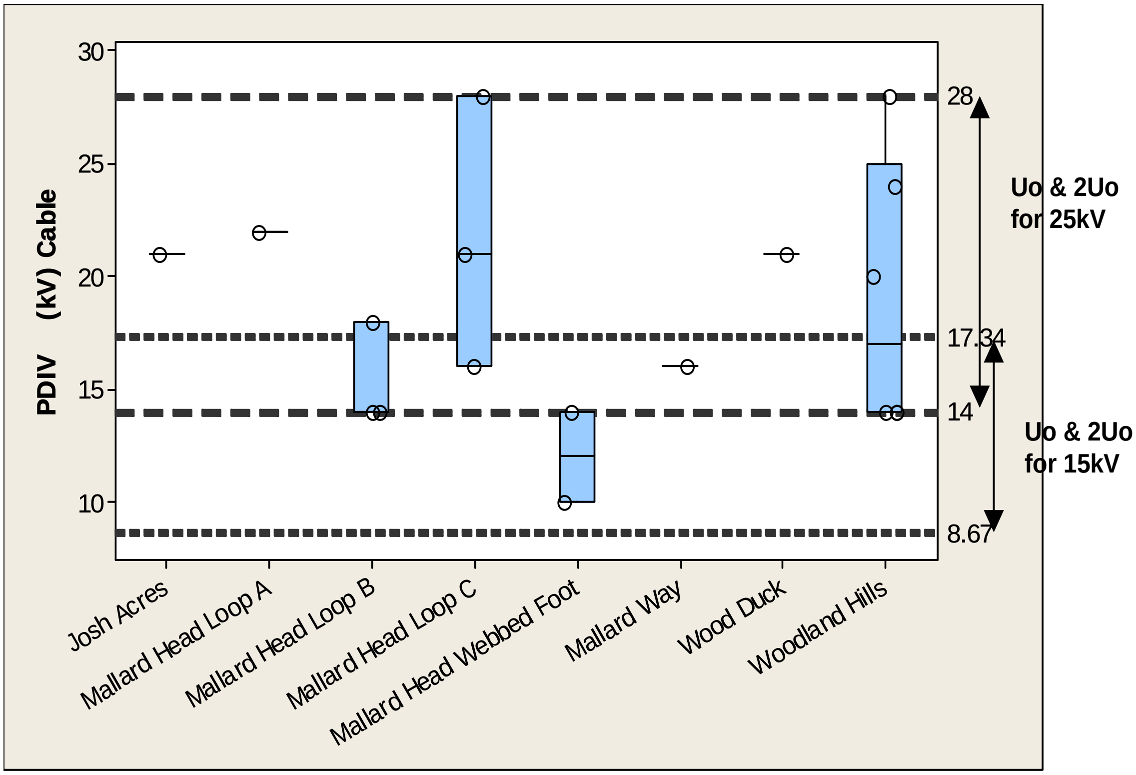


Figure 137: Dispersion of PD Inception Voltage (Circuits with Detectable PD) by Subdivision

As Figure 137 shows, several circuits were found to have discharge in the cable sections (accessory PD is excluded for this analysis). The majority of circuits with discharge had inception voltages greater than the 25 kV system operating voltage (14.4 kV). In fact, six out of the 17 circuits with discharge had inception voltages at or below 14.4 kV but above 8.7 kV (15 kV system operating voltage). This implies that these circuits would discharge during normal 25 kV system operation but not when these circuits were operated at 8.7 kV. Note that none of these circuits have failed since the testing was completed.

An overall summary of the Tan δ and PD assessments appears in Figure 138. Using the Tan δ criteria in IEEE Std. 400™ - 2001, up to 80 % of the tested circuits were classified as requiring action as they were assessed as either "aged" or "highly degraded". This is a conservative view as compared to the criteria discussed in Section 3.5.6 and is quite different from the PD results that indicate only 8 % of the circuits require action.

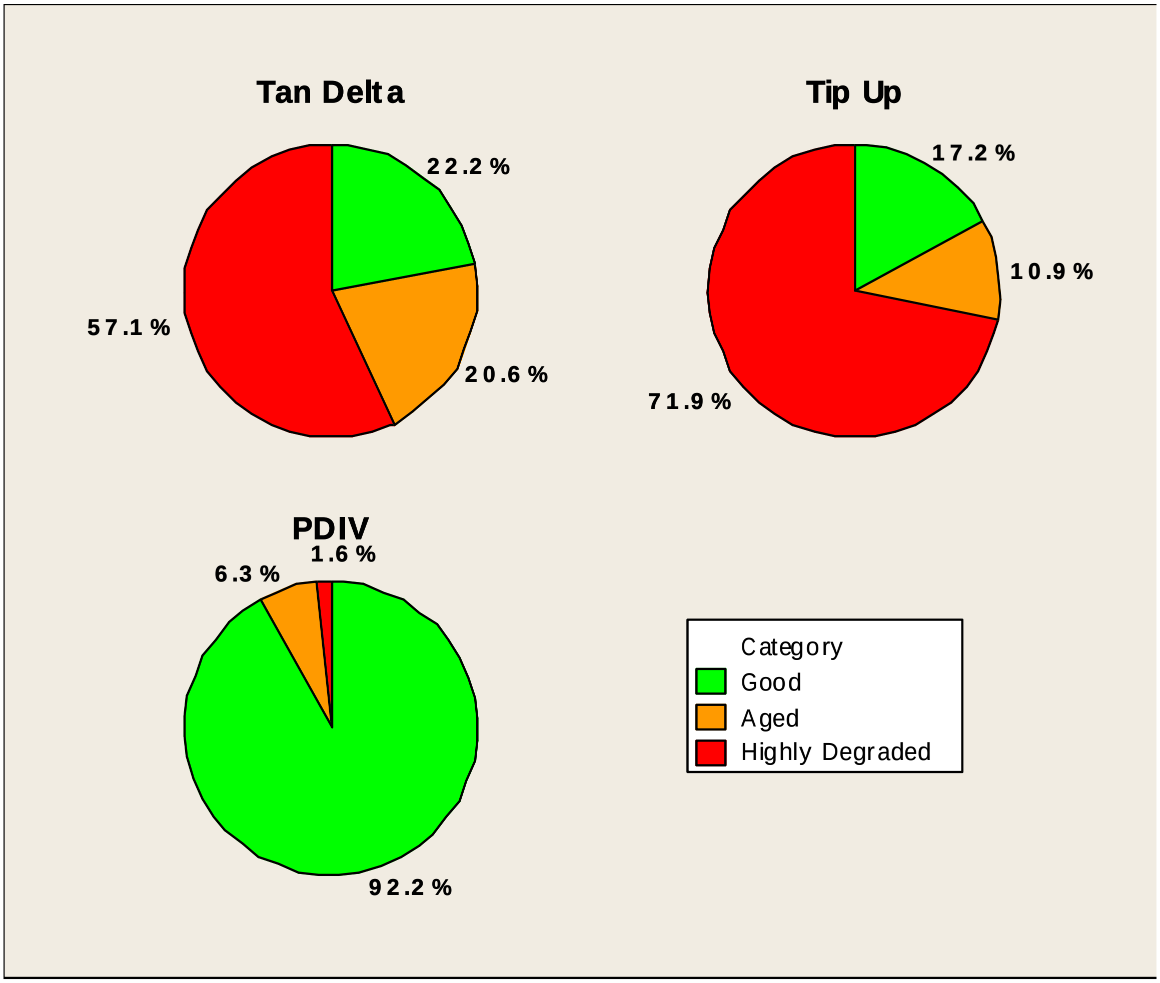


Figure 138: Outcome Assessments for Tan δ (2001 CDFI Criteria - Table 31) and Partial Discharge Measurements

For the PDIV results in Figure 138, the following criteria were used:

- "Good" – No detectable PD up to 14.4 kV
- "Aged" – PD detected at test voltages between 8.7 kV and 14.4 kV
- "Highly Degraded" – PD detected at test voltages less than 8.7 kV

It is anticipated that in future CDFI work, these circuits will be revisited to determine how these results differ following several years of 25 kV operation.

5.2.2 Diagnostic Program Benefit

This system experienced a sufficiently high failure rate prior to testing to require Duke to replace the entire population of 31,000 ft. The replacement cost was estimated at $1,100,000. The total cost of testing and replacement of splice failures that occurred during testing was approximately $60,000. As a result of the testing, Duke did not need to replace the population (no failures in 4 years after testing) and this generated an estimated savings of $1,040,000.

5.3 Duke Energy – Cincinnati, OH

Duke Energy initiated a pro-active diagnostic program in 2007 in Cincinnati, OH, to examine their PILC substation get-away cable circuits. This program uses a VLF Tan δ diagnostic ramp and VLF Tan δ Monitored Withstand to assess the cable circuits. The program reached full scale implementation in 2009 and is ongoing.

Figure 139 shows the dispersion of tested lengths. The median tested length is approximately 3,100 ft while the maximum length is approximately 25,000 ft.

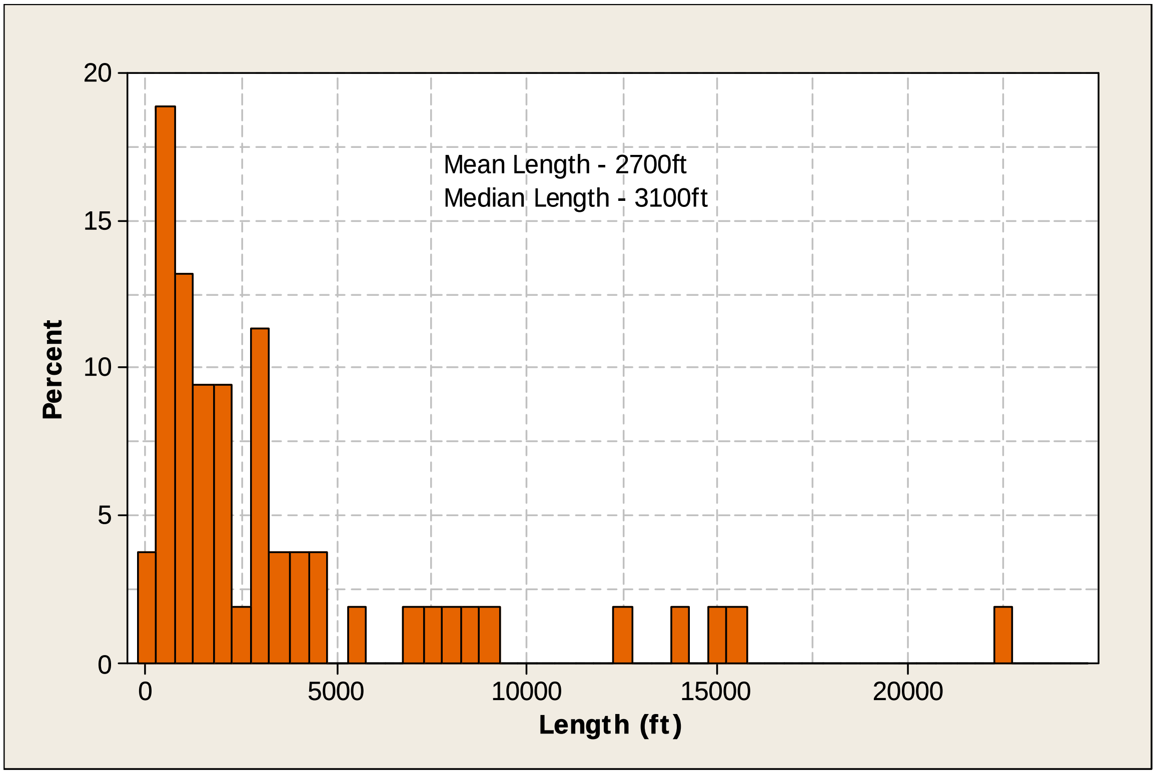


Figure 139: Disbursement of Tested Lengths

Given the combined nature of the diagnostic employed in this program, there are several issues to consider when examining the Pass and Not Pass results:

- "Not Pass" results if ANY of the following occur:
  1. Tan δ Ramp (2007 CDFI Criteria – Table 31)
     a. Unacceptable Tan δ Stability
     b. Unacceptable Tip Up
     c. Unacceptable Mean Tan δ
  2. Monitored Withstand (assuming acceptable Tan δ Ramp test)
     a. Dielectric puncture
     b. No dielectric puncture AND non-compliant Tan δ:
        - Rapid increase anytime during the test
        - Steady upward trend at a moderate level

        - Instability (widely varying data)
        - High magnitude
- "Pass" results if ALL of the following occur:
    3. Tan δ Ramp (2007 CDFI Criteria – Table 31)
        a. Acceptable Tan δ Stability
        b. Acceptable Tip Up
        c. Acceptable Mean Tan δ
    1. Monitored Withstand
        a. No dielectric puncture
        b. No dielectric puncture AND compliant Tan δ:
            - Stable with time
            - Low magnitude

Considering the above definitions of "Pass" and "Not Pass", Figure 141 shows the split between circuits that resulted in a "Not Pass" on either the Tan δ Ramp or Monitored Withstand and those that resulted in a "Pass" on both tests. Note that approximately 19 % of the tested circuits were assessed as "Not Pass" using this test protocol.

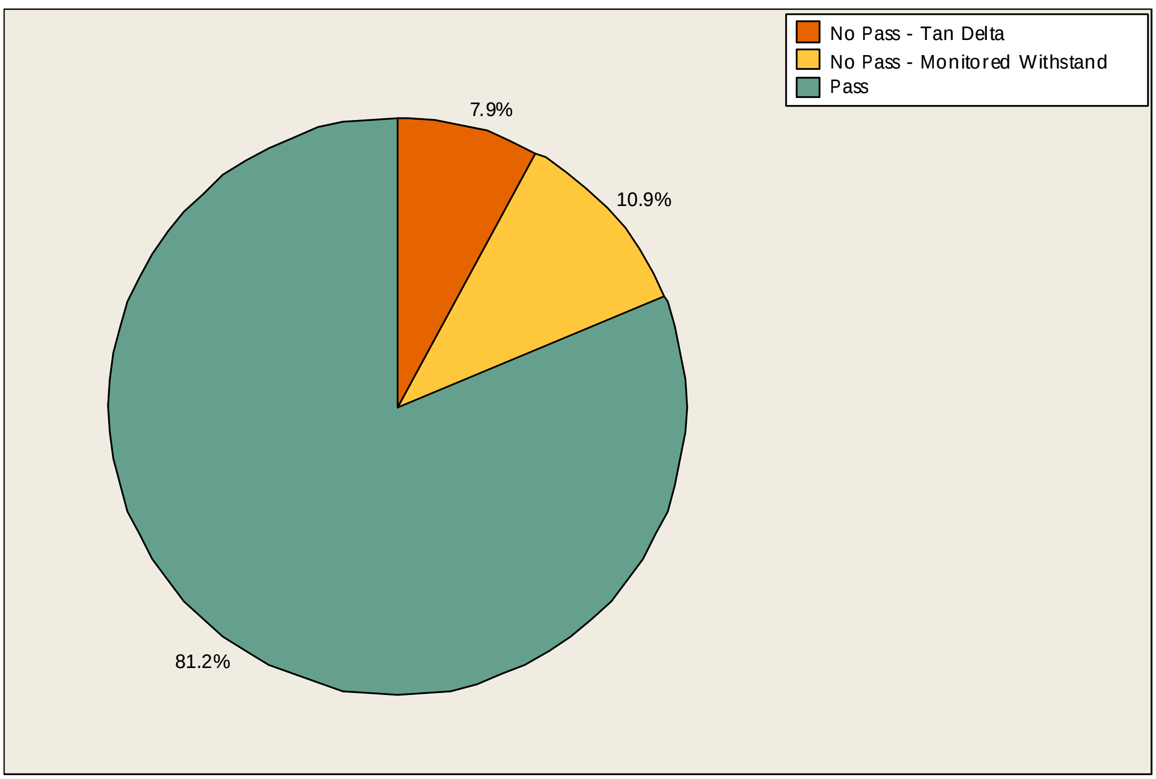


Figure 140: Results of Combined Diagnostic Program

The Tan δ measurements from the Tan δ Ramp and Monitored Withstand appear in Figure 141. Note that the different shapes/colors indicate the performance of individual circuits (i.e. ■ indicate "Not Pass" on the Monitored Withstand test while ● indicates "Not Pass" on the Tan δ Ramp test).

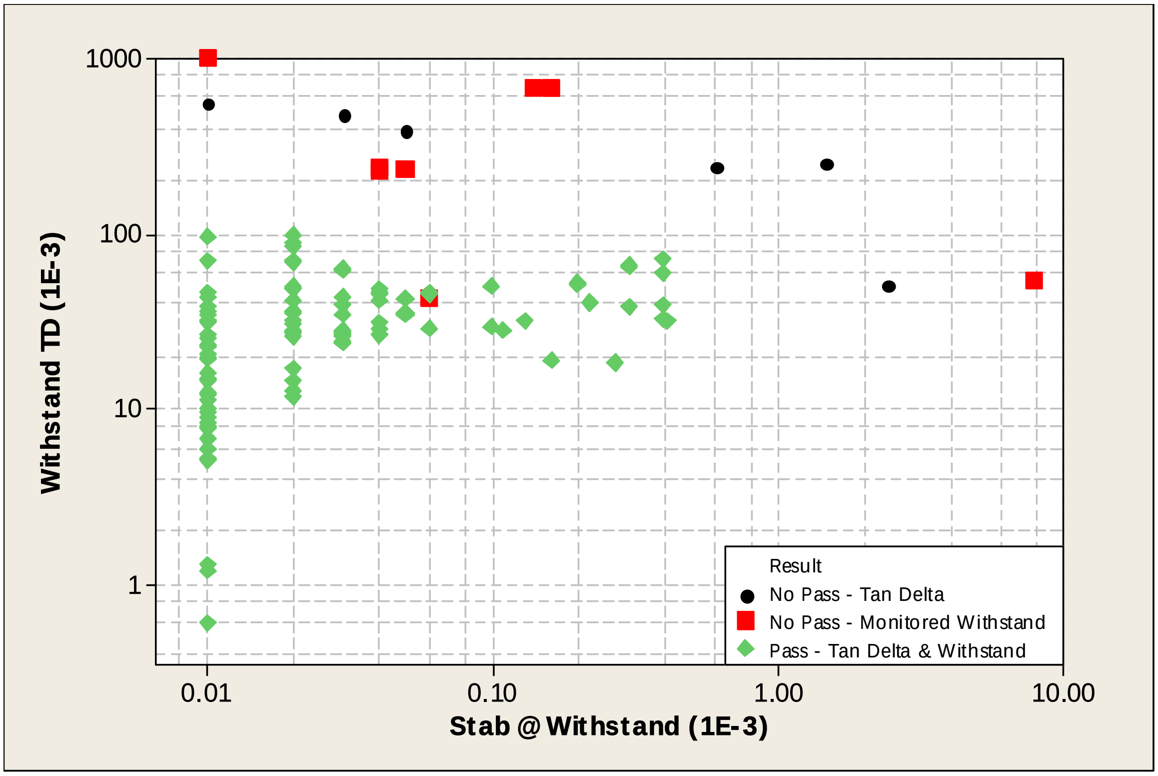


Figure 141: Monitored Withstand Tan δ and Tan δ Stability (Standard Deviation) Results

It is useful to compare the above analysis with what would have resulted from a Simple Withstand test. Considering only the circuits that experienced a dielectric puncture, approximately 6.1 % of the tested circuits would have been assessed as "Not Pass" as shown in Figure 142. Note that on a 1,000 ft standard length basis, the industry experience indicates a failure on test rate of 1.5 %.

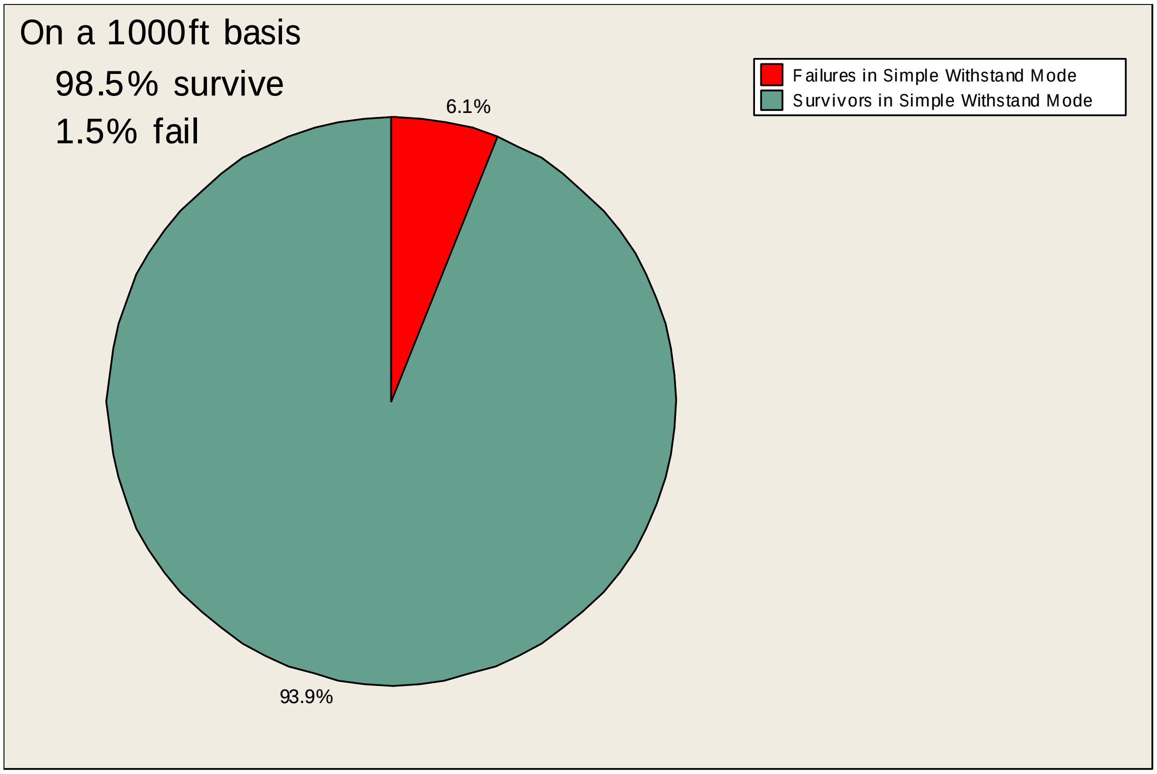


Figure 142: Results of Hypothetical Simple Withstand Test

5.3.1 Diagnostic Program Benefit

The above test results are important as one considers the effect the test program has had on the failure rate this circuit population. The annual failure rates for 2007 through 2009 appear in Figure 143. This figure shows that the failure rate has decreased from approximately 59 [Failures/100 miles/year] in 2007 to 32 [Failures/100 miles/year] in 2009, a reduction of 46 %.

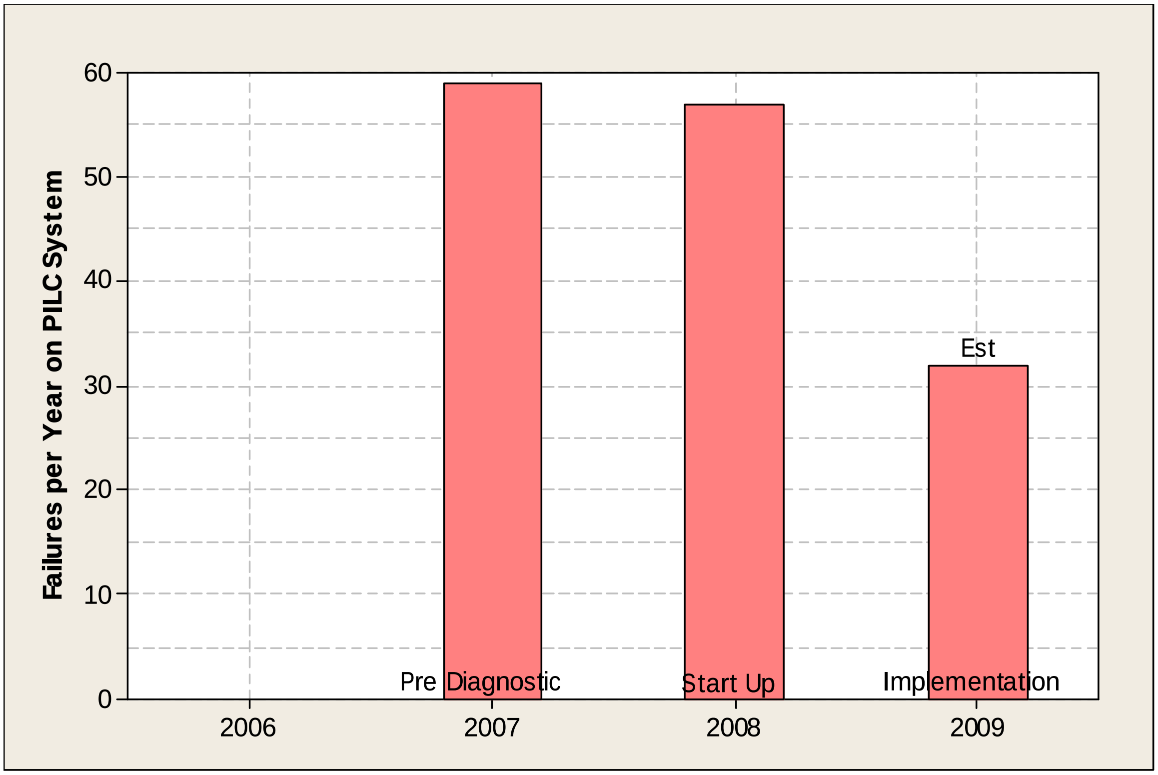


Figure 143: Evolution of PILC Cable System Service Failure Rate

This diagnostic program is ongoing and additional analysis is expected to be conducted during the next phase of the CDFI.

5.4 Georgia Power – Roswell, GA

A portion of the Georgia Power system located just outside the Atlanta area was offered for testing by GPC (Figure 144). The feeder circuit consists of 25 kV XLPE jacketed cable installed in the early 1980's with a total circuit length of 17,000 ft. (51,000 conductor feet). This circuit experienced a higher-than-normal failure rate in the six months prior to testing and was under consideration by GPC for replacement. These recent failures were all in accessories – heat-shrink joints that were likely not installed properly. The diagnostic testing work was completed in 2009.

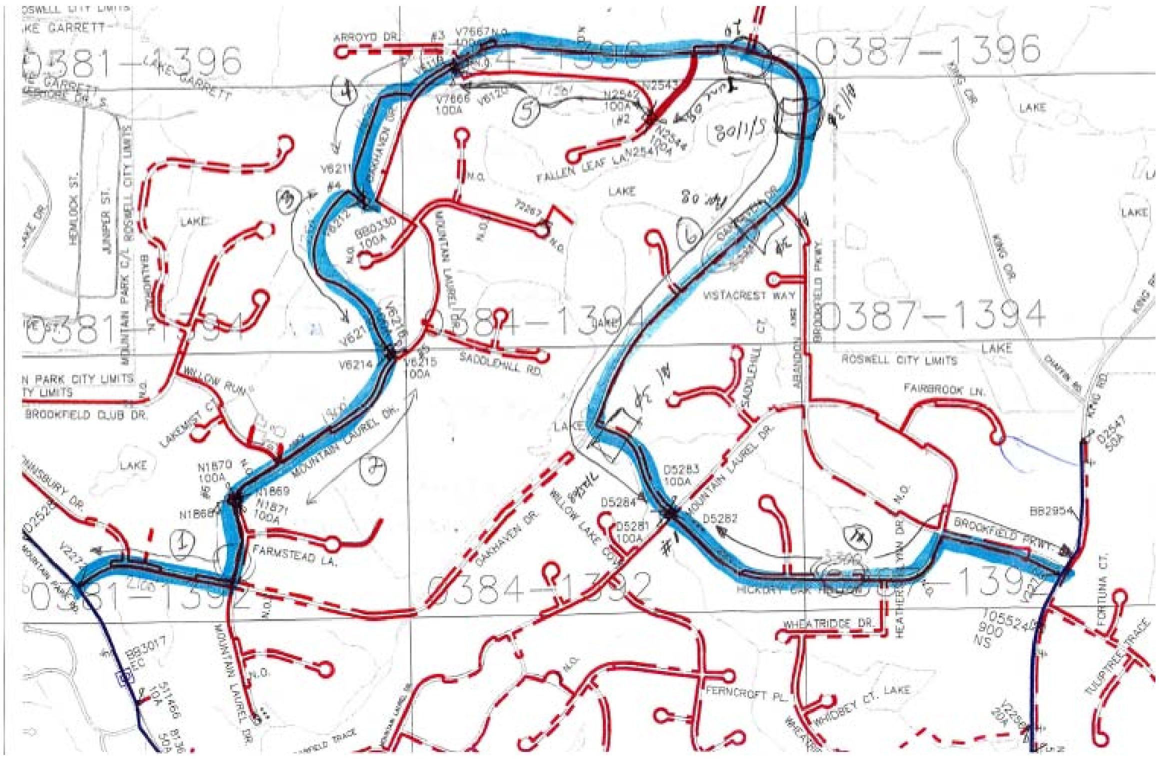


Figure 144: Roswell feeder route – blue line

The main features of this circuit are:

- 1980 vintage XLPE feeder cable
- 1000 kcmil, 260 mils wall, jacketed
- Recently experienced high failure rates of splices on this section: 32 fails / 100 miles / yr
- Overall there have been 10 -15 failures of these splices in last two years
- Intense Area and customer pressure to do something, complete replacement being considered at $1,000,000 approximately
- Splice replacement **<u>may</u>** be accepted if there is a technical basis
- Complete splice replacement estimated at $60,000
- Test time (determined by switching) 4 - 5 Days
- Selection Costs – Cost for Georgia Power staff to research the necessary records and collate the failure data is estimated at $5,000
- Retest after remediation 1 Day

Using the initial versions of the CDFI Knowledge-Based System (KBS) (Section 4.2) and the Economic Model (Section 4.3), the situation in Roswell was analyzed to determine what routes to pursue. The KBS was used to generate a list of diagnostic tests for three corrective action scenarios. These scenarios are:

- Replace a small portion (< 6 ft)
- Replace segment
- Replace accessories only

A summary of the outputs from the KBS is shown in Table 73. The colors indicate the recommendation level computed by the KBS:

- Highest recommendation level – Green
- Middle recommendation level – Yellow
- Low recommendation level – Red

Table 73: Summary of KBS recommendations by action scenario.

Scenario	Diagnostic Technique									
	DC	VLF 15 min	VLF 30 min	VLF 60 min	Monitored DC	Monitored VLF	Tan δ	PD Online	PD Offline	Historical Analysis
Replace Small Portion	Red	Green	Green	Green	Red	Green	Yellow	Yellow	Green	Yellow
Replace Segment	Red	Yellow	Green	Yellow	Red	Green	Green	Yellow	Green	Yellow
Replace Accessories	Red	Yellow	Green	Green	Red	Green	Yellow	Green	Green	Yellow

Based on the data shown in Table 73, three diagnostic techniques received the highest recommendation level for all three of the proposed corrective action scenario:

- VLF 30 Min
- Monitored VLF
- PD Offline

The Economics Model (Section 4.3) also showed that all three of the above diagnostic tests could generate a benefit for Georgia Power over the alternative of wholesale replacement.

Considering both the recommendations of the KBS and the economic analysis it was decided to use a monitored VLF withstand technique as the initial approach. The monitoring was performed using the Tan δ technique. However, prior to the selection of this technique, Georgia Power was presented with the expectations (based on historical review) of testing as predicted by the available data on both Offline PD and Monitored VLF Withstand. This information is summarized in Table 74.

Table 74: Historical Results of Offline PD and Monitored Withstand

Data	Offline PD	Monitored Withstand
Typical Observations	• 0.5 % fails on test, no customer interrupted • 1 PD site / 1,000ft • 40 % of discharges in cable	• < 4 % (1,000 ft sections) fails on test, no customer interrupted • 70 % of loss tests indicate no further action
Qualitative Prediction	• 0-1 fails on test • 51 discharge sites • 15 splices • 1-2 failure within 12 months after test	• 1-2 fails on test • 3 assessed for further consideration 0-1 failure within 12 months after test
Historical Outcomes	• 1-3 failures overall	• 1-3 failures overall

According to the data above, the historical performance of Offline PD and Monitored Withstand indicate that similar cable system performance would result (assuming no action is performed). The primary difference between the two techniques is when the failures would occur; on test or in service, again assuming no actions are performed.

5.4.1 Standard Tan δ Assessment

The approach adopted within the CDFI prior to performing a Tan δ Monitored Withstand test is to perform a standard Tan δ assessment since this essentially requires no additional effort. The protocol uses Tan δ measurements made as $0.5U_0$, $1.0U_0$, and $1.5U_0$ and the criteria in Section 3.5.6 to formulate an assessment. The test set up for both the standard Tan δ test and Monitored Withstand is shown in Figure 145.

Figure 145: Tan δ and Tan δ Monitored Withstand Test Set Up

The resulting Tan δ assessments for the six sections (3-phases each) are shown in Figure 146.

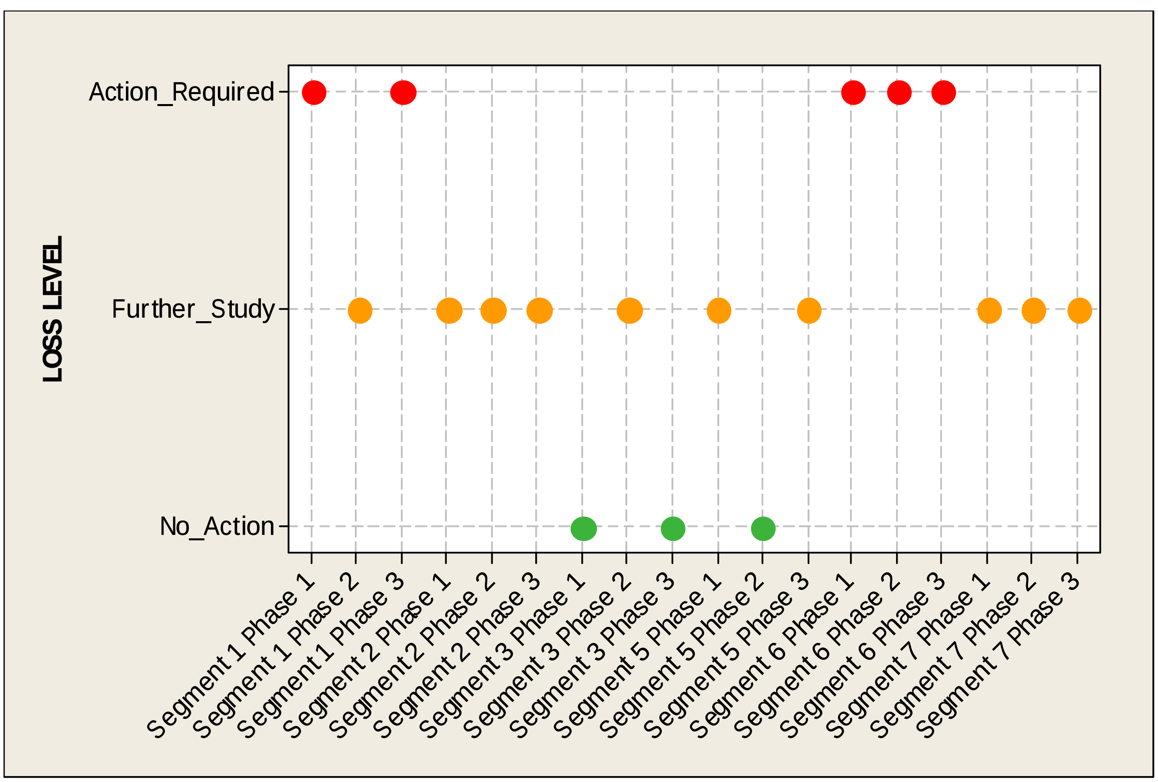


Figure 146: Tan δ Assessment of each Segment Considering 2008 CDFI Criteria (Table 31)

The overall assessment for this population of 18 segments is summarized in Table 75.

Table 75: Summary of Condition Assessments Using Standard Tan δ

Condition Assessment	Segments [#]	Segments [%]
No Action Required	3	17 %
Further Study Advised	10	55 %
Action Required	5	28 %

5.4.2 Tan δ Monitored Withstand Assessment

Following the standard Tan δ testing described in the previous section, a Tan δ Monitored withstand test was performed on each of the segments. The test protocol is adaptive and starts as a 30 minute duration test. If there is significant instability in the Tan δ during the course of the test, the test may be extended to 60 minutes. Figure 147 shows the results of the Monitored Withstand tests – no segment experienced a dielectric failure during these tests. The dots indicate the individual segments and the results of the Monitored Withstand. The lines in between show the length of each segment (i.e. the distance between two successive dots is the length of the tested segment associated with the right dot). The colors reflect the assessment and are the same as those used in Figure 146.

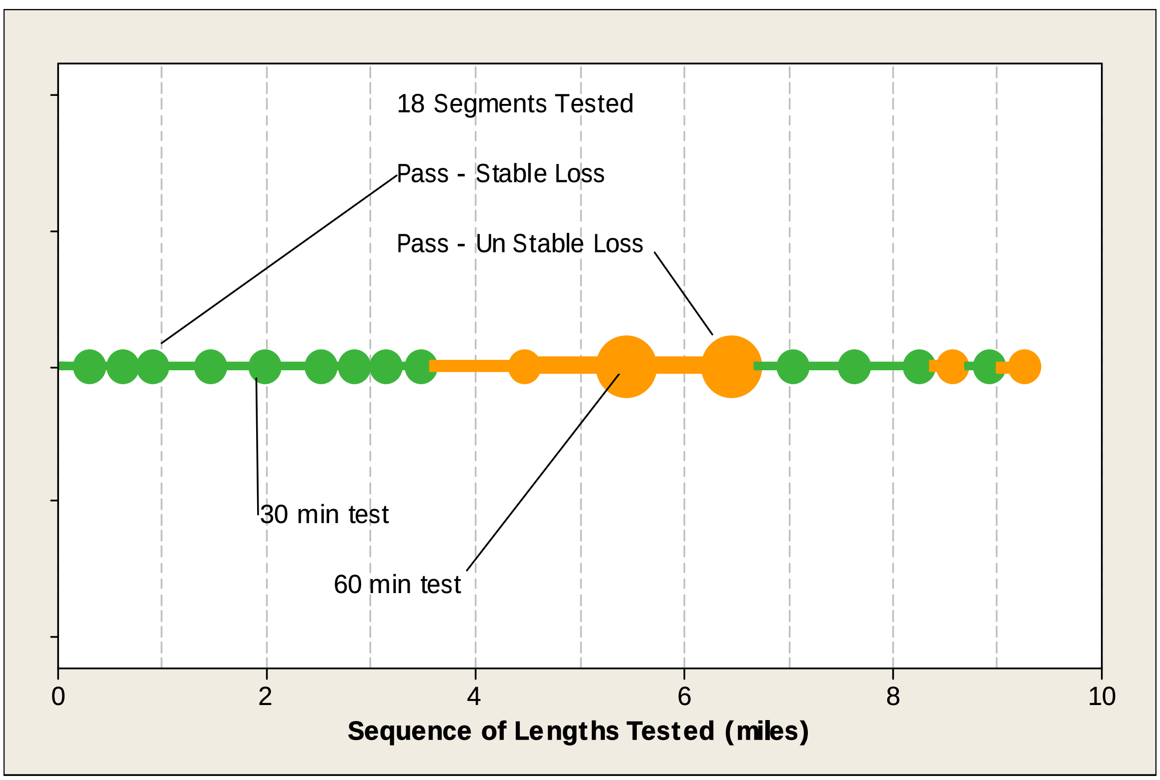


Figure 147: Results of Monitored Withstand (Cumulative Conductor Length)
Size of the Symbol Represents Test Time

As Figure 147 shows, some of the dots are larger than others. The larger sized dots represent tests where the Monitored Withstand test was extended to 60 minutes because of the observed instability in the Tan δ. This occurred for Phases 2 and 3 of Segment 6.. In fact, this section is the longest of those tested at approximately 1 mile. As this figure shows, six of the tested segments showed high instability in Tan δ. This experience shows the need for Monitored Withstand guidance as will be developed in CDFI Phase II.

The question of what level of instability should be of concern is a question on the Tan δ criteria. Like all the diagnostics, these criteria have evolved over time as shown in Table 31. As this table illustrates, the criteria began with those published in IEEE Std. 400™-2001 have developed during the CDFI to the current 2010 CDFI Criteria. This latest version includes data-based criteria for PE, Filled, and PILC cable systems as well as Tan δ Monitored Withstand stability criteria.

5.4.3 Targeted Offline Partial Discharge

The Monitored Withstand (Figure 147) and TDR (Figure 148) data both indicated that one three phase section was unusual and worth exploring with a targeted partial discharge test. Segment 6 was then retested using an offline PD with a VLF voltage source.

Figure 148 shows a comparison of the TDR results and PD location results following the targeted offline PD testing. It was anticipated, based on the standard Georgia Power reel length at the time this circuit was installed, that approximately two splices would be present in each phase. The blue dots in Figure 148 (upper portion) show the locations of TDR reflections that are indicative of cable splices. As this figure shows, there are 7 – 9 splice locations in each of the three phases in this segment. The TDR data indicate, therefore, that the installation was made using remnant reel lengths. In addition, several of these reflections had unusual shapes and are noted as anomalous in the figure.

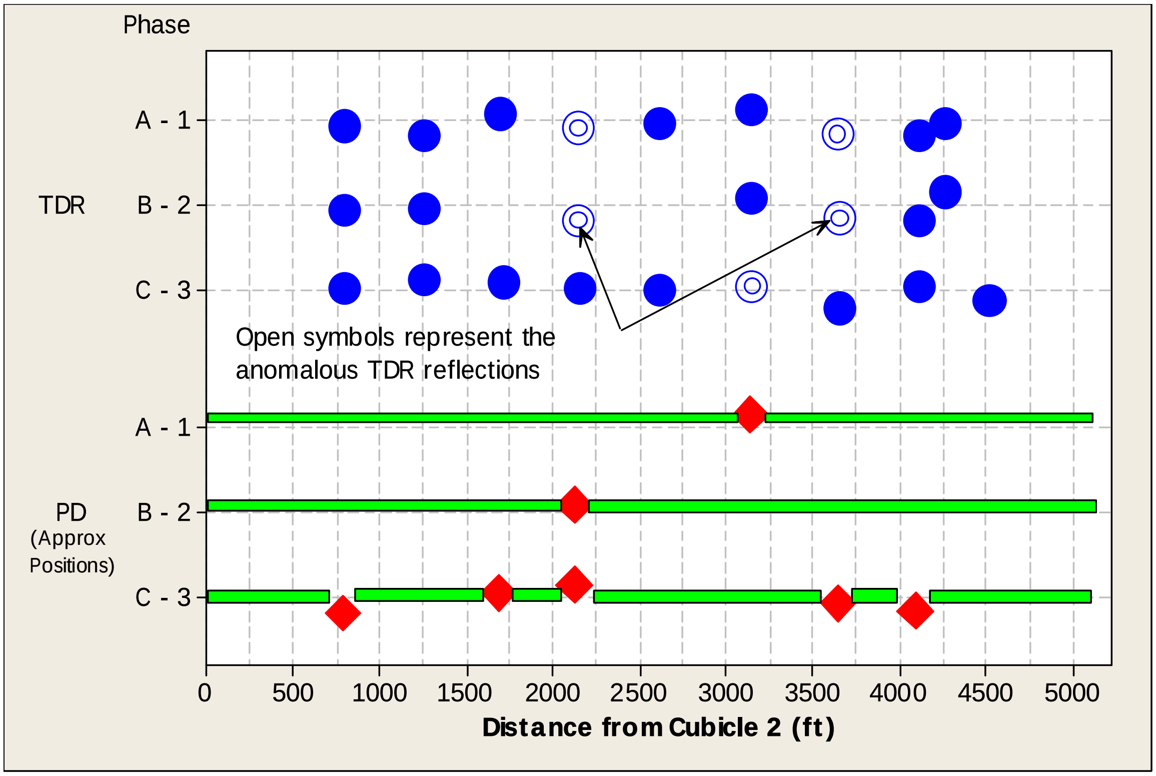


Figure 148: TDR and PD results for Segment 6
Red Diamond Indicates PD Site
Green Indicates No PD Detected

The PD results in Figure 148 shows several correlations between the sources of observed discharge signals and the splice locations indicated by the TDR. However, only one of the discharge sources could be correlated with the unusual TDR measurements. This segment remains in service and is under further investigation.

5.4.4 Diagnostic Program Benefit

Complete replacement of the cable system in this subdivision in Roswell we estimated at $1,000,000. An acceptable alternative to this approach was replacement of the splices, estimated at $60,000. Unfortunately, the testing revealed that replacing only the splices would not remove eliminate the problem areas. As a result, Georgia Power developed a third option that involved reinforcing the feeder with a new overhead line, estimated at $400,000. This third option was implemented and Georgia Power was able to achieve a savings of approximately $600,000 or eight times the cost of diagnostic testing.

6.0 SUMMARY AND CONCLUSION

Over the course of the CDFI, a number of significant accomplishments were achieved:

- Assembled and interacted with a broad consortium of utilities, manufacturers, diagnostic providers, and equipment manufacturers to conduct a large-scale, five-year, independent study of the performance of diagnostic technologies in the field and laboratory.

- Developed diagnostic program concept (SAGE – Selection, Action, Generation, and Evaluation) that addresses the complete implementation of a diagnostic program.

- Developed and deployed a Knowledge-Based System (KBS) to enable users to select a short list of diagnostic techniques based on their specific circumstances.

- Developed an economic framework for performing cost/benefit analysis of diagnostic programs.

- Encouraged utilities to utilize diagnostic technologies (field tests).

- Compiled an independent analysis of large-scale and diverse datasets covering all commonly used diagnostic techniques generated outside of the CDFI by utilities. See Table 76.

Table 76: Data Analysis by Diagnostic Technique

Diagnostic Technique	Field Performance [Conductor miles] Approx
DC Withstand	78,105
Monitored Withstand	149
PD Offline	490
PD Online	262
Tan δ	550
VLF Withstand	9,810

- Developed/improved methods for analyzing diagnostic test data.

- Developed and deployed techniques for analyzing performance data.

- Developed and updated (three versions) a reference guide, handbook, and pocket reference on cable system degradation and diagnostic testing technologies.

- Expanded the understanding of diagnostics through laboratory tests conducted on field-aged cables (including long lengths).
- Developed new means of deployment for diagnostic technologies.
- Helped define when and where diagnostics can be effective.

6.1 International Standards Activities

CDFI has supported significant work within IEEE Insulated Conductors Committee on the revision of IEEE Std. 400™ Omnibus and IEEE Std. 400.2™ on VLF testing. The project has assisted the working group chair persons as these revisions are completed. A brief summary of each of these contributions is included in the following sections.

IEEE Std. 400™ Omnibus

The latest draft of this guide was provided to the working members for comment before the Spring 2010 ICC meeting held in March. CDFI supported comments to the working group vice-chairman, Jacques Cote. The most significant support was the inclusion by the utility writing group of a diagnostic testing recommendation table. This table provides guidance as to which diagnostic tests are useful for different situations. CDFI developed the Knowledge-Based System (KBS) for the selection of diagnostic tests to fulfill this same objective. NEETRAC suggested completing the table using a portion of the output from the KBS. This essentially amounts to a similar approach as that of the utility writing group but provides the same information using a broader expert base (35 experts).

IEEE Std. 400.2™ VLF Field Testing

The working group is preparing a revision to IEEE Std. 400.2™ on VLF field testing also presented its latest draft during the Spring 2010 ICC meeting in March. The approach used by NEETRAC for extracting the thresholds for Dielectric Loss measurements based on the available data will be applied to produce criteria in the revised format. To date, NEETRAC holds the largest collation of Tan δ available in the industry.

6.2 Discussions

During the course of the project detailed discussions / dissemination / technology transfer on practical cable system diagnostics took place with the following CDFI participants

Participant	Number of Interactions (Approximately)
Alabama Power	3
Cablewise / Utilx	2
CenterPoint Energy	1
Consolidated Edison Company of New York	5
Duke Energy	8
Commonwealth Edison and PECO	2
FirstEnergy	1
Florida Power & Light	3
Georgia Power	8
HDW Electronics	3
High Voltage, Inc.	3
HV Diagnostics	8
Hydro Quebec	5
IMCORP	8
NRECA	3
Oncor (TXU)	2
Pacific Gas & Electric	3
PEPCO	3
Southern California Edison	3
Southwire	2
TycoElectronics	1

6.3 Future Work

The impact of the CDFI on the electric utility industry is significant. Utilities such as the Alabama Power Company, Georgia Power Company and Hydro Quebec are now receptive to the use of diagnostic testing programs for improving system reliability. Companies such as Duke Energy. Pacific Gas and Electric, and Consolidated Edison have initiated diagnostic programs or demonstrably modified their approach to diagnostic testing because of their participation in this project.

In short, a great deal was learned and a greater appreciation of the benefits and limitations of diagnostic testing was established. However, as with most complex issues, there is more to learn. The economic benefits of performing cable system diagnostic test programs are still not easy to establish. Part of the problem is that utilities have a difficult time assigning a value to the consequence of a system failure. A routine failure that puts a few houses in the dark may not have a significant impact – economically or politically. The impact of multiple failures could be more significant. A failure on a feeder circuit that supplies electric energy to a critical load may have large economic and political implications. These issues need clarification to appreciate the economic value of performing a diagnostic test.

Much work also remains in the area of establishing the accuracy of diagnostic test programs. In the view of the CDFI, it is insufficient to find an anomaly. Many anomalies do not lead to a cable system failure. Repairing or replacing all detected anomalies is neither feasible nor prudent. The key is to find an anomaly that is highly likely to lead to a failure in the near future. To do this requires much more data gathering and analysis to classify diagnostic results for the wide variety of cable system types used by utilities.

The potential value of continued work in this area is high. New approaches to diagnostic testing appear promising. In the past, utilities have not typically monitored dielectric loss (tan δ) or partial discharge during an elevated voltage withstand test. The work in the CDFI showed that much can be learned from performing a test in this manner. In fact, there is even greater value in monitoring both Tan δ and Partial Discharge during a withstand test. The CDFI has worked with diagnostic test equipment providers to modify their equipment such that this technically complex test can be performed. Technologies that have not typically been employed in the United States such as oscillating wave partial discharge, dielectric spectroscopy, and cosine VLF withstand also appear promising.

The United States Department of Energy recognized the potential benefits of continued work by awarding Georgia Tech NEETRAC with a project to conduct Phase II of the CDFI. This project is expected to be extensively supported by the electric utility industry in the same manner as Phase I. The project will address the topics described above. In addition, Phase II will help define the optimal approach to testing newly installed distribution circuits (commissioning tests) as well as testing transmission class underground cable circuits. The overarching objective is to continue the quest of establishing how best to deploy diagnostic testing technologies to improve underground cable system reliability.

With these goals in mind, the following tasks are planned for Phase II:

1. Diagnostic Data Set Analysis – Clarifying Accuracy

The data received in Phase I came in a vast array of formats, some more complete than others. This required the application of unique data analysis techniques that had were new to cable system diagnostic data, including performance ranking, k-nearest neighbor classifier, probabilistic failure predictions, and anomalous data identification. By using these data analysis techniques, it was possible to establish the accuracy of the diagnostic predictions from the data sets provided. One of the extremely important conclusions from Phase I was that most diagnostic technologies are reasonably accurate when they predict that a cable segment is good (not likely to fail in the near future). However, they are not as accurate when they predict that a cable segment is bad (likely to fail in the near future).

This discovery has very positive consequences in that knowing what is “good” provides very important information to utility system asset managers. This is a fundamental change in emphasis, as most previous work focused on finding the “bad” portions. With this information on “good” performance, replacing these cable segments is avoidable. However, to improve reliability, they must fix or replace segments that are bad. Because the accuracy of "bad" predictions is low, it is impossible to know which segments designated as "bad" will fail in the near future. This means that utilities must replace ALL "bad" segments even though only a few of them are likely to fail in the near-term.

In Phase II, NEETRAC will continue to encourage utilities to provide diagnostic data sets so that an analysis can establish appropriate pass/fail criteria and improve the ability of these technologies to predict accurately which segments are actually "bad".

2. Field Tests/Circuit Monitoring

The large number of data sets analyzed in Phase I provided very useful information as described earlier. However, only a few cable types and diagnostic test technologies were included in these data sets. Much more data needs to be gathered and analyzed to establish the accuracies/efficacy of a wider variety of technologies on a greater number of cable types. In particular, it is important to construct "control populations" of tested cable segments that are carefully monitored to establish the performance of the circuits after they are tested. In addition, there is much more to learn about appropriate test levels and pass/fail criteria for all types of cable circuits. There is also more to learn about the advantages of using multiple diagnostic technologies and the various ways to optimally deploy these technologies.

In this task, NEETRAC will work with utilities to design and conduct diagnostic test programs for their cable systems to learn more about the protocols (diagnostic technologies and test voltage levels and durations) that best predict the true condition of the system. In some cases, NEETRAC will perform the test using diagnostic test equipment procured in Phase I or equipment acquired in Phase II. In other cases, NEETRAC will coordinate with utilities and diagnostic providers to deploy commercially available testing services.

A variety of technologies will be deployed in this task, including:

- online partial discharge/signal assessment
- offline partial discharge (60 Hz and very low frequencies)
- dielectric loss (at selected frequencies (60 – 0.02 Hz) and voltages)
- monitored withstand
- dielectric withstand at different voltages and times

3. Assessment of Diagnostic Technologies under Controlled Conditions

In Phase I, a laboratory test was designed and performed to assess a common concern that an elevated withstand voltage applied to aged cable will cause damage, primarily in the form of an electrical tree. This damage would then initiate partial discharge that would lead to subsequent failure while the cable was operating under normal service conditions.

To address this concern, long lengths of XLPE insulated cable that had been aged in the field for many years were brought into the lab and aged under normal field conditions. Periodically, they were subjected to different elevated withstand voltage tests. Partial discharge measurements were also made periodically during the test.

In this program, the cables subjected to both high and moderate elevated withstand voltage levels did not fail during the application of normal operating conditions. In addition, there was no evidence that the withstand voltage led to the initiation of partial discharge.

These findings are very useful, but there is much more to learn from testing in a controlled environment. This study only examined one cable type and it did not include accessories. To learn more about the capabilities of all diagnostic technologies, various types of insulated cables with lengths typically found in service will be connected together in a variety of configurations using standard cable accessories (joints, terminations, and separable connectors) in an outdoor laboratory setting to explore some of the complex issues listed below:

- The effect of corroded concentric neutrals on PD and dielectric loss measurements.
- The ability of various diagnostics to assess cable condition when a circuit consists of various cable insulation types, including HMWPE, EPR, XLPE, and PILC.
- The ability of various diagnostic technologies to detect bad accessories on different cable types and lengths.
- Pass/fail conditions for complex circuit configurations.

While results from tests conducted in the field provide the primary data needed to establish pass/fail conditions, field tests are limited in that utilities often do not know the details of a given circuit construction (cable type, accessory type, number of accessories). Also, cables in the field can only be tested for short time periods. Thus, a controlled laboratory environment will help clarify the issues listed above. Existing test fixtures will be modified as required to perform these tasks.

4. Diagnostic Assessment of Transmission Cables

Phase I of the CDFI focused strictly on assessing the performance of diagnostic technologies on aged distribution class cables. However, there is significant 46 and 69 kV transmission cable system infrastructure installed in the US that is over 30 years old. In addition, utilities throughout the US are installing 115 kV – 345 kV circuits at an increasing rate. Many are interested in deploying diagnostic technologies to assess the condition of the older circuits. They are also interested in using these technologies to help assure the correct installation of new circuits, with no manufacturing imperfections.

It is anticipated that partial discharge testing will be the primary diagnostic technology used on HV cables. However, the effectiveness of using this technology is not well documented and the use of other technologies has not been explored in any detail. In this project, NEETRAC will begin the process of gathering diagnostic test data on transmission cable circuits for analysis in a manner similar to that used to analyze data from distribution circuits. New test data will be generated as practical.

This work will be coordinated with the ongoing international activities by way of CIGRE Working Group B1.28, *On-site Partial Discharge Assessment of HV and EHV Cable Systems.*

5. Expansion of the Knowledge-Based System Developed in Phase I

The Knowledge-Based System (KBS) developed in Phase I serves as a valuable tool for helping utilities determine the most appropriate diagnostic technology to use for a given application. As additional information about the performance of each diagnostic technology is learned, the KBS will be updated and refined as needed to increase its usefulness and accuracy.

The modified version will:

- Include commissioning as well as diagnostic tests
- Extend estimates to HV cable systems

6. Economic Benefits Model

An important, economic benefits model was developed in Phase I. In this model, the general economic benefits of performing a diagnostic test are compared to various options such as partial replacement, total replacement, repair, or restoration. However, its deployment was not possible in Phase I because:

- It was not possible to develop a common platform for the different remedial actions that a utility might contemplate prior to testing.
- There are uncertainties in the input costs for the economic analysis. The largest uncertainty is currently termed "consequence costs". Consequence costs incorporate knowledge about the accuracy of a given diagnostic technology and the outcomes associated with failures after testing.
- It also includes hard-to-define costs associated with utility asset management priorities.

Many utilities have asked that the economic model be expanded or converted to a broader asset management tool that would allow the benefits of performing diagnostic testing in one area with testing in another area.

As a result, an enhanced economic model with asset management capabilities will be explored in Phase II. It is important to note that utilities must be directly involved by providing input into exactly how the asset management tool could benefit different utilities with different asset management approaches and priorities.

7. Handbook (5%)

A handbook outlining the overall approach to diagnostic testing was developed in Phase I and was well received by utilities. This book will require updating to address transmission class cables, expand on the use of diagnostics for commissioning (not just maintenance) activities and to include additional diagnostic accuracy and application discoveries made in Phase II.

8. Project Reports and Reviews (10%)

Quarterly reports detailing the project progress will be prepared and submitted to the DoE as well as the project participants. A comprehensive final report will also be prepared at the end of the project. Periodic project review meetings (net meetings and workshops) will review CDFI Phase II activities with the project participants.

9. Technology Transfer (5%)

To inform utilities and other interested parties of the work performed under the auspices of the CDFI, a series of regional 1.5 to 2 day seminars are planned. The seminars will inform potential users of cable system diagnostic testing technology of the available techniques and their relative effectiveness.

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RELEVANT STANDARDS

- ICEA S-94-649 – 2004: *Standard for Concentric Neutral Cables Rated 5 Through 46 kV*
- ICEA S-97-682 – 2007: *Standards for Utility Shielded Power Cables Rated 5 Through 46 kV*
- IEC 60270 - 2000: *High-voltage test techniques – Partial discharge measurements*
- IEEE Std. 48™ – 2009: *IEEE Standard for Test Procedures and Requirements for Alternating-Current Cable Terminations Used on Shielded Cables Having Laminated Insulation Rated 2.5 kV through 765 kV or Extruded Insulation Rated 2.5 kV through 500 kV*
- IEEE Std. 386™ – 2006: *IEEE Standard for Separable Insulated Connector Systems for Power Distribution Systems Above 600 V*
- IEEE Std. 400™ – 2001 Omnibus: *IEEE Guide for Field Testing and Evaluation of the Insulation of Shielded Power Cable Systems*
- 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. 400.3™ – 2006: *IEEE Guide for Partial Discharge Testing of Shielded Power Cable Systems in a Field Environment*
- IEEE Std. 404™ – 2006: *IEEE Standard for Extruded and Laminated Dielectric Shielded Cable Joints Rated 2500 V to 500 000 V*

APPENDIX A – DATA ANALYSIS TECHNIQUES

This appendix reviews the details of some of the analysis techniques employed in the CDFI to analyze diagnostic and performance data. In addition, a more in depth discussion on diagnostic accuracy is presented.

A.1 Techniques for Analyzing Diagnostic Data

A.1.1 Classification

The fundamental task of diagnostic testing corresponds to the classification of the tested segments into those that require corrective actions (i.e. repairs or replacement) and those that do not. The process of classification may be approached a number of ways. The process involves three primary tasks:

1. Define the different subgroups into which the population of segments will be classified.
2. Define rules to base the classification on.
3. Develop a procedure for evaluating segments based on the set of rules.

With cable systems, the groupings may be defined as “Action Required” (“bad” segments) and “No Action Required” (“good” segments). Before the remaining two tasks can begin, a set of data known as the training set is needed. This data must include measurements made on segments whose true group membership is known. In other words, the measurement data are needed for both segments that did not fail in service and for those that did fail. Therefore, the training set must answer two questions:

1. What was measured?
2. What happened to the circuit afterwards?

With such a training set in hand, it is possible to develop the rules and the procedure for evaluating those rules.

A.1.1.1 Classification Rules

The classification rules in the case of diagnostic testing are based on the measurements made on each tested segment. Data from PD, Tan δ, IRC, or any other diagnostic test may be used for this purpose. The inclusion of multiple features (types of measurements) will tend to increase the accuracy of the classification. The goal is to use as few features as are necessary to perform an accurate classification. Figure 149 shows how multi-feature classification may be approached considering two features. Note that the benefit of multiple features is best realized in cases where the features are uncorrelated or unrelated to each other. Unfortunately, this is rarely the case, especially when only one diagnostic test is employed.

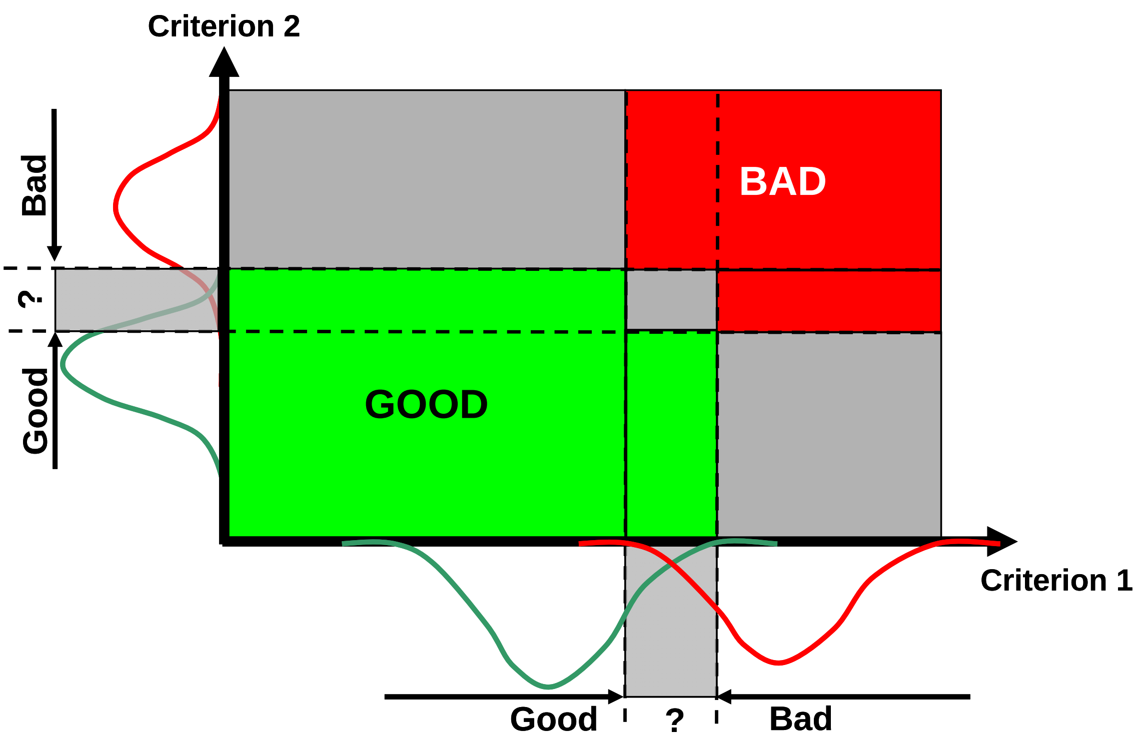

Figure 149: Example of Multi-Feature Classification Using Two Uncorrelated Features.

Note in Figure 149 that neither feature on its own is able to provide successful classification for those segments with measurements that lie in the overlap region between groups. Combining features can increase the odds of successful classification. In these cases, classification is simple when the features agree – both features indicate action required or no action required. Things are far more difficult when one feature indicates action required while the other says no action required. Regardless of the number of features one includes, grey areas will always occur where classification is not possible. The objective is to minimize these areas.

A.1.1.2 Classification Procedures

A number of procedures are available for classification including Bayesian, nearest-neighbor, and Heuristic classifiers. These procedures either utilize the statistical characteristics of the data or other hidden properties that are identified through heuristic procedures such as self-organizing maps and neural networks. Regardless of the procedure, the classifier's goal is to define the boundary (illustrated in Figure 149) between classification groups that will enable the classification of a new data point that possesses a measurement for each feature.

As part of the CDFI, a nearest-neighbor classifier has been implemented in order to classify partial discharge measurements. The nearest-neighbor (k-NN) method is a nonparametric method that classifies a data point as belonging to one group or another based on its distance from other samples whose group memberships are known. The basic procedure requires identifying the k (an odd integer) nearest samples to the data point that is being classified. In the classical k-NN algorithm, once these k samples are determined it is only necessary to determine which set the majority of the k samples belong to. The new data point is then classified as belonging to this same set.

A.1.1.3 Classification Example

This example represents a two-feature type classification as two measurements are available: (1) charge magnitude (pC) and (2) inception voltage (U_0). In this case, the actual classification for all samples is known. Therefore, it is possible to test this classifier using a subset of data as the training set and the remaining data as the testing set. The success rates for the two groups, "fail" ("bad") and "no fail" ("good"), are shown in Figure 150 for different numbers of neighbors.

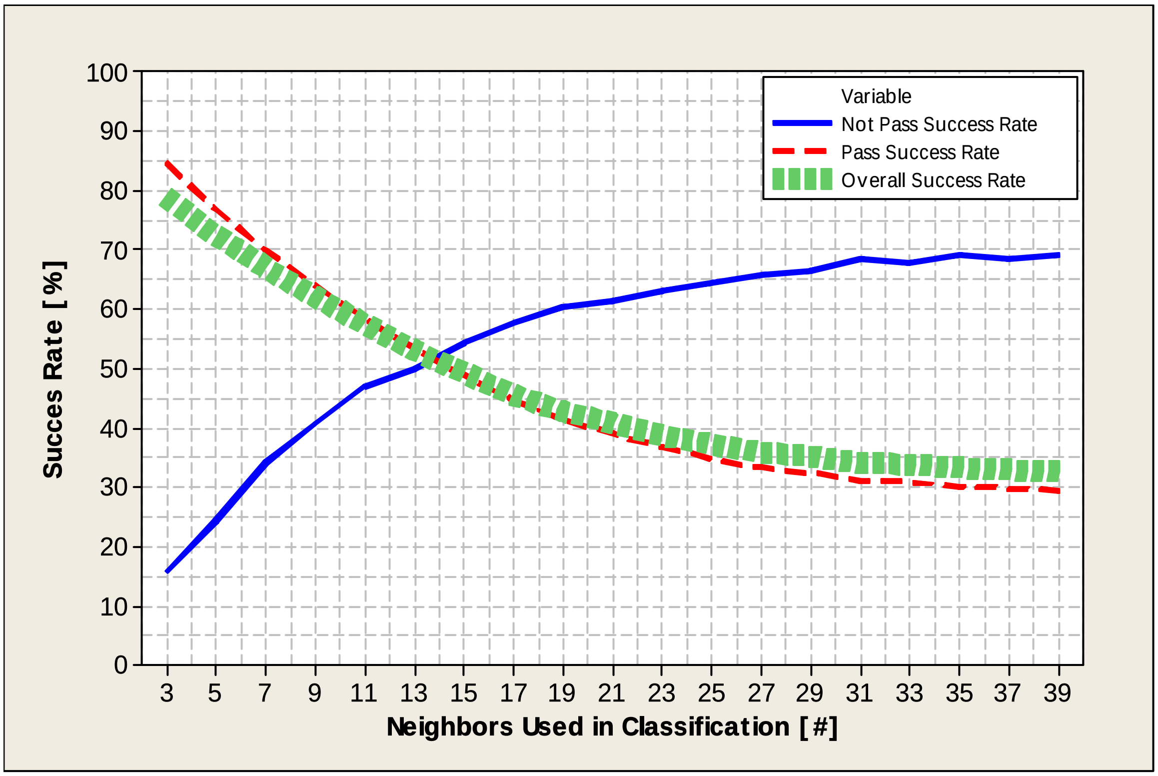

Figure 150: Sample Feature Classification Success Using Two Partial Discharge Features

For this example, a balance in success rates for the two groups is achieved for 15 neighbors and a resulting success rate of approximately 50%. This is equivalent to an overall diagnostic accuracy of 50%. However, it is important to note that the two groups respond in opposite ways to changes in the number of neighbors. This is due to the substantial difference in population size. The "no fail" group is approximately 10 times larger than the "fail" group. In the field this is a good thing since the target populations that are generally tested have turned out to be largely in good shape. With this mix, high overall diagnostic accuracy can be achieved by classifying all data as "good" but this provides little help for reliability. Note that the maximum diagnostic accuracy is approximately 80% with very high accuracy of "good" PD sites and low accuracy on "bad" PD sites. As discussed in later sections, this tends to be the case for all diagnostic techniques.

A.1.2 Cluster Variable Analysis

Cluster variable analysis is a technique for organizing large numbers of diagnostic features into meaningful structures (taxonomies). For example, before a meaningful description of differences between animals is possible, biologists must organize the different animal species into groups or clusters. In the case of the diagnostic features the organization can be accomplished by performing a cluster variable analysis of the features. This technique has been used in the CDFI to analyze partial discharge data since the number and variety of features is quite high. This technique may be used with any diagnostic data that contains a relatively high number of features. Researchers have typically used cluster variable analysis to process individual PD measurements [1-4]. In the CDFI, this technique is used to cluster the features themselves in order to identify which are the most critical and useful for classification.

The process of generating the clusters is as follows:

1. Initially each feature is declared as 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. The group average method is used to calculate the average distance between clusters.
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 distance measure used in Step 2 above is the similarity level as shown in (29),

$$S_{ij} = \frac{100(1-d_{ij})}{d_{\max}} \qquad \textbf{(29)}$$

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 straight forward. The level of similarity is a number that ranges from 0 to 100 %. A similarity level around 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 can be seen as not adding much to solving an eventual classification problem. In contrast, a level of similarity around 0% indicates that the features or clusters under investigation are complimentary or uncorrelated. Thus, the likelihood of using these features or clusters in an eventual classification problem with good classification results is higher than using the redundant features or clusters.

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. Figure 151 shows an example of a dendrogram for 15 PD features for which measurements were performed in the laboratory. Note that the objective of classification is to separate PD sites into those found in cable and those in accessories.

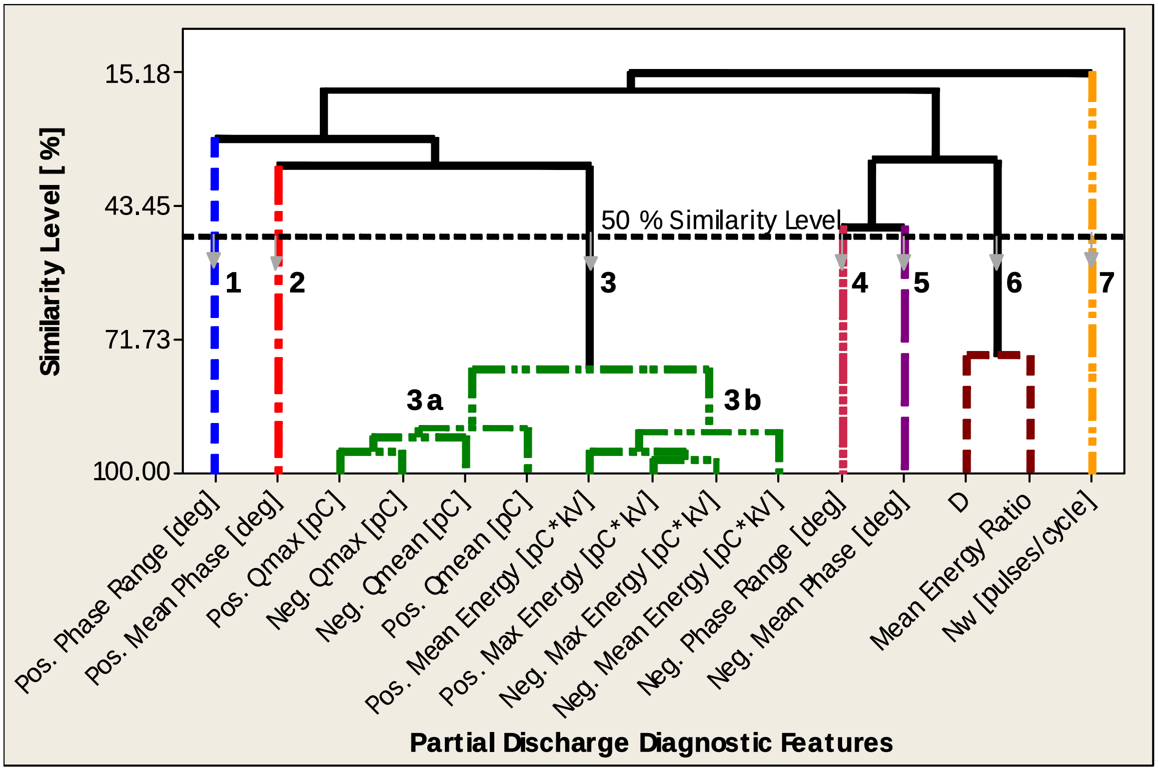

Figure 151: Sample dendrogram of 15 PD features.

As Figure 151 shows, several of the features have similarity levels that are greater than 71 %. The mean and maximum charge magnitudes contain very similar information (cluster 3a) and they can constitute a separate cluster. The same situation is also observed for the energies (cluster 3b) as well as the symmetry factor (D) and mean energy ratio (cluster 6). Note that the clusters formed by the charge magnitudes and energy levels can be also combined into one cluster (cluster 3) when comparing their similarity level with the other diagnostic features. The remaining question is how to determine the final reduced clusters of variables.

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. In Figure 151 this line has been chosen to be 50 %. The result of cutting the dendrogram at the 50 % similarity level is shown in Table 77.

Table 77: Cluster Variable Analysis Results

Cluster No.	Feature No. (Table 8)	Feature Name
1	6	Pos. Phase Range [deg]
2	5	Pos. Mean Phase [deg]
3	4	Pos. Qmax [pC]
	16	Neg. Qmax [pC]
	15	Neg. Qmean [pC]
	3	Pos. Qmean [pC]
	7	Pos. Mean Energy [pC*V]
	8	Pos. Max Energy [pC*V]
	20	Neg. Max Energy [pC*V]
	19	Neg. Mean Energy [pC*V]
4	18	Neg. Phase Range [deg]
5	17	Neg. Mean Phase [deg]
6	25	D
	27	Mean Energy Ratio
7	26	Nw [pulses/cycle]

There is no pre-established procedure on choosing the similarity level for cutting the dendrogram; however, the pattern of how similarity or distance values change from step to step in the agglomerative procedure can help in choosing the final grouping. Therefore, the step where the number of cluster changes abruptly may be a good starting point for cutting the dendrogram. The final point for cutting the dendrogram is usually given by the physical sense of the taxonomy of the data, *i.e.* the final point is determined by the lowest similarity level at which the features can be clustered keeping their taxonomy.

As seen in Table 77, the initial set of 32 variables from Table 8 can be reduced to seven clusters. Clusters 1, 2, 4, 5, and 7 have only one feature. In contrast, cluster 3 is formed by the features regarding the discharge magnitudes and energies and cluster 6 is formed by the symmetry factor (D) and mean energy ratio.

Once the key features have been selected using the cluster variable procedure then the significance of each feature may be determined using Recursive Feature Elimination (RFE).

A.1.3 Recursive Feature Elimination

Once the initial set diagnostic features is appropriately grouped by cluster variable analysis the next question one could ask is which of the features are more relevant if they are used for classification. The answer to this question can be found using RFE. This technique involves the use of an RFE algorithm that is based on a Support Vector Machine (SVM) classifier [76]. The overall process is shown in Figure 152.

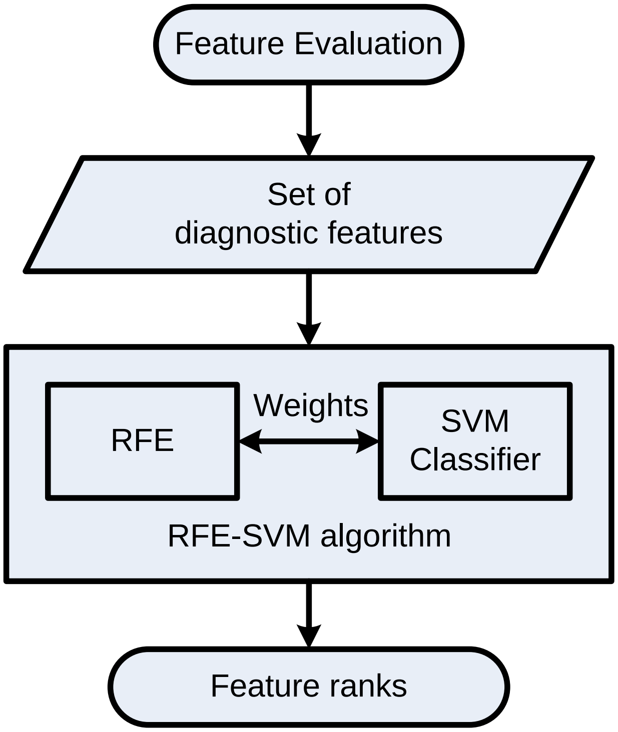

Figure 152: Diagnostic Feature Evaluation Procedure

From the flow chart shown in Figure 152, the evaluation procedure begins with the set of diagnostic features resulting from the cluster variable analysis and determines the ranking of each procedure in terms of significance. In this case, the term "significance" refers to the relative importance of the feature in classifying the available data. The rank is based on the potential for each diagnostic feature to classify the data between the groups of interest, such as cable and accessory, good and bad, or any other grouping of interest.

Table 78 shows the results for the ranking of the PD diagnostic features shown in Figure 151. The ranks are the results of the feature evaluation process using RFE. As seen in Table 78, the Pos. mean phase is the most important feature followed by the Neg. Phase Range, D (Symmetry Factor), Pos. Qmean, Neg. Mean Phase, Pos. Phase Range, and Nw (average number of PD pulses per cycle) respectively.

Table 78: Ranking of the PD diagnostic Features from Laboratory Data

Feature Name	Cluster No (Table 9)	Feature No (Table 9)	Feature Rank
Pos. Phase Range [deg]	1	6	6
Pos. Mean Phase [deg]	2	5	1
Pos. Qmean [pC]	3	3	4
Neg. Phase Range [deg]	4	18	2
Neg. Mean Phase [deg]	5	17	5
D	6	25	3
Nw [pulses/cycle]	7	26	7

To grasp the significance of the ranked PD features in an easy to understand visual manner, Figure 153shows the matrix image plot of the ranked PD diagnostic features and component groups. In Figure 153, the columns 1 to 7 on the left represent the ranked PD diagnostic features with 1 corresponding to the feature ranked as the first (Pos. mean phase) and 7 corresponding to the features ranked as the last (Nw) as shown in Table 78. The last column in Figure 153 represents the grouping by component. In the component column the accessory group is represented by the black color while the cable group is represented by the white color. The lines (rows) in the figure represent the different data points. The first 64 lines, starting from the top-down, are the data points that belong to the accessory group and the remaining 96 lines represent the data points that belong to the cable group.

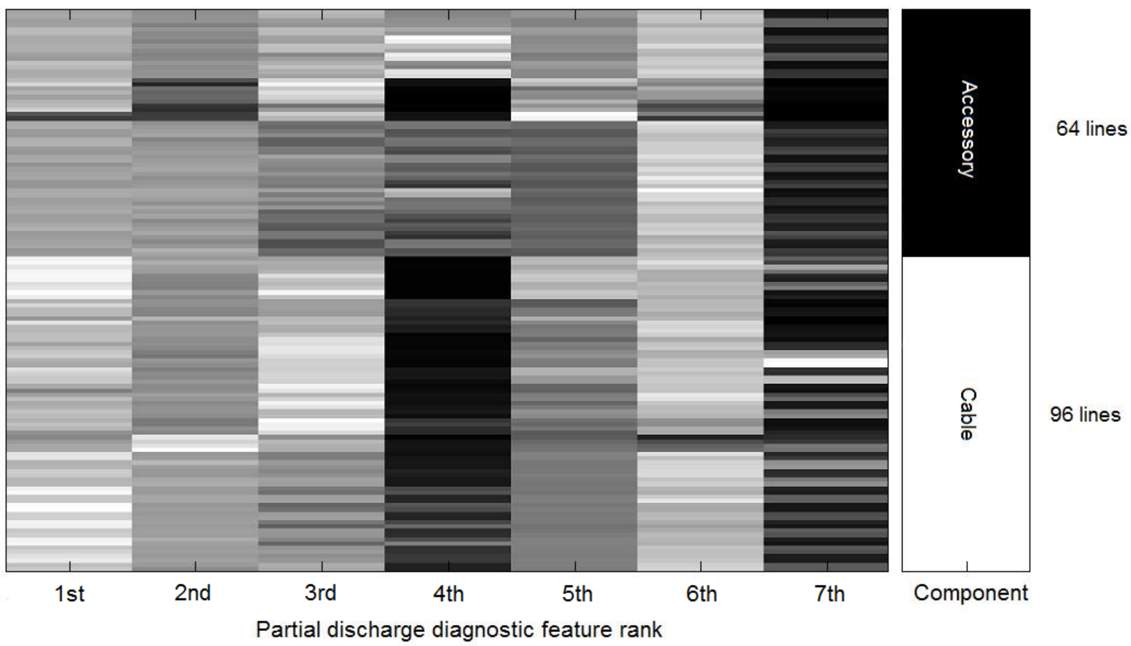

Figure 153: Matrix Image Plot of Ranked PD Diagnostic Features

The two dimensional matrix image of Figure 153 is useful because it provides a visual way of relating the ranked PD diagnostic features to the grouping or component column. The features whose columns appear most like the far right component column are the most useful for classification. As seen in the figure, the features are ranked from the left to the right. The most significant feature is located at the extreme left column while the least significant feature is at the right column just before the column representing the components grouping. The image is built using the feature values as color reference for expression in a gray scale. The gray shading indicates the feature expression related to the classification groups. Specifically, lighter colors indicate stronger correlations to the cable group while the darker colors represent stronger correlations to the accessory group.

It can be seen in Figure 153 that the most relevant feature (Pos. mean phase) is also the most visually correlated with the component column in the sense that the feature expression is generally darker for the first 64 lines and generally lighter for the remaining 96 lines. In addition, it can also be observed in the figure that the least relevant feature (Nw) is also the least visually correlated with the component column in the sense that the feature expression generally alternates between dark and light for both component. These results are in accordance with the RFE results in the sense that the most visually relevant feature is ranked the first and the least visually relevant feature is ranked the last.

Another way to grasp the significance of the diagnostic feature relevance is by looking at the SVM classifier performance. The classifier performance, using the ranked features shown in Table 78, is presented in Figure 154. The classifier performance is assessed by the class loss. The class loss is the total number of incorrectly classified data points for the cable and accessory groups over the total number of data points. Thirty two (32) data points are considered for each cable and 16 data points are considered for each joint sample. Therefore, a total of 160 data points (64 for the accessory group and 96 for the cable group) are considered in the evaluation process. A data point can be thought as one set of the seven diagnostic features used in the evaluation process each of which represents a phase-resolved pattern for a PD data acquisition.

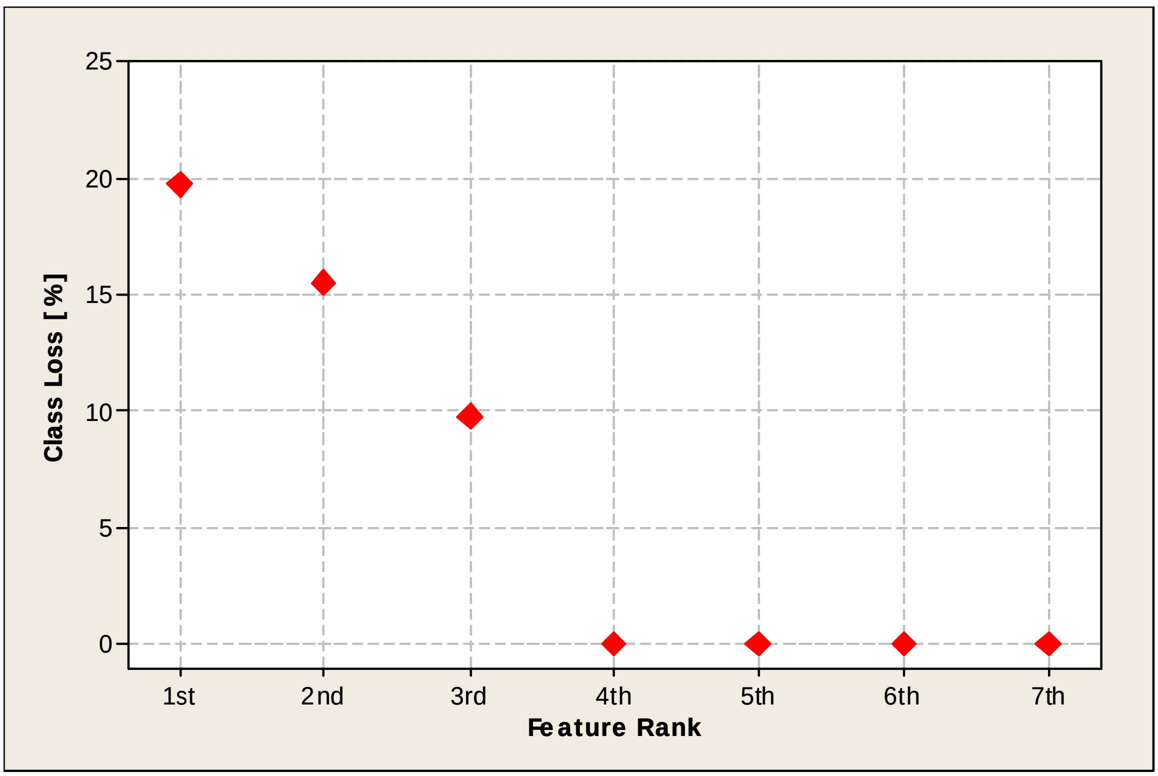

Figure 154: Class Loss as Function of Feature Rank for Laboratory PD Data

As seen in Figure 154, the class loss for the SVM classifier when using the first ranked PD diagnostic feature is 19.7 %. If the first and the second ranked features are used in the classification, the class loss improves to a value of 15.5 %. Similarly, if the first three ranked PD features are used in the classification, the class loss also improves to a value of 9.8 %. Finally, if four or more of the ranked PD features are used in the classification, the class loss becomes zero. In other words, the SVM is able to completely group the PD data between the cable and the accessory groups when the four (or more) highest ranked PD diagnostic features are used.

The first three PD diagnostic features may be mapped as shown in Figure 155. Visually there is a discernable boundary between the two groups (accessory and cable). Adding one additional feature improves this separation even further.

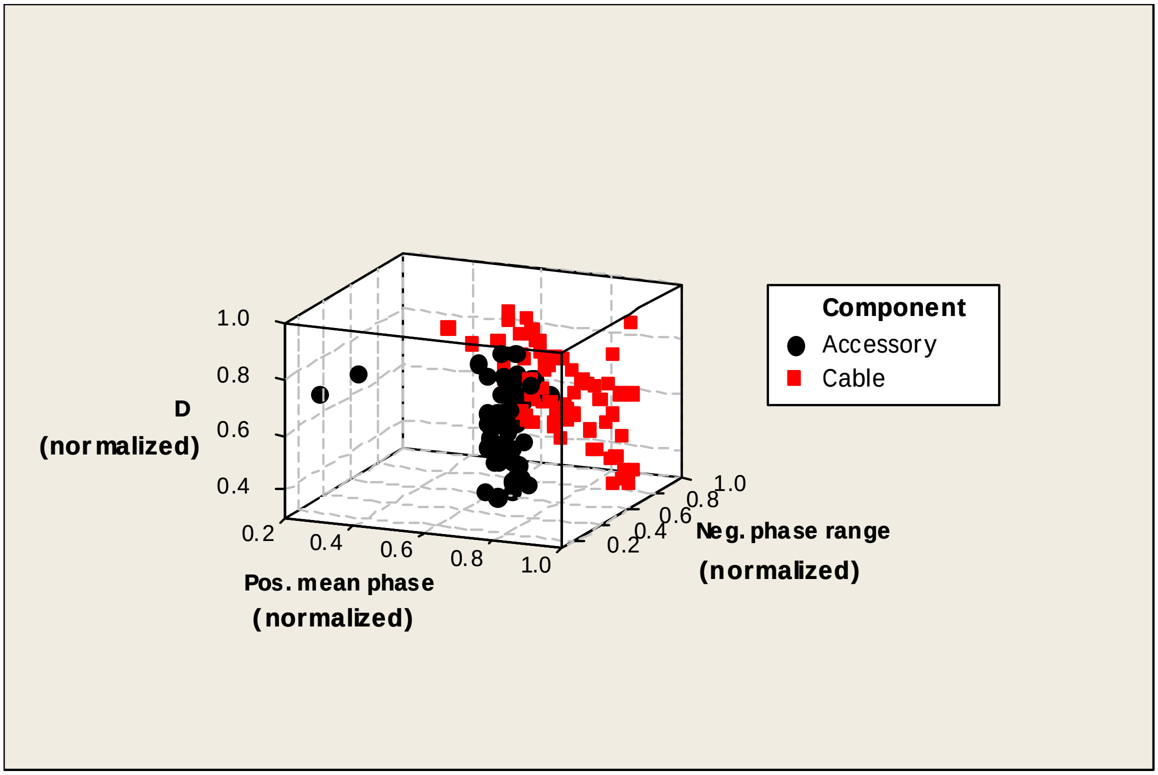

Figure 155: Classification Map Considering Top Three Features

A.1.4 Survivor Analysis

The survivor technique has been used extensively to determine appropriate duration for simple withstand tests in which segments are stressed beyond their normal operating regions for a period of time. The main concerns with withstand tests have been the voltage level and duration that the utility should test at to ensure that critical defects fail during the test while avoiding damage to otherwise healthy cables and accessories.

The greatest value of the survivor technique is that the method does not exclude data. Traditional analyses of withstand type data only examine the failures that occur during the test while completely ignoring the segments that did not fail. In analyses conducted as part of the CDFI, this can equate to ignoring almost 90 % of the tested segments.

To examine the data, one constructs a survivor curve that shows the percentage of segments that survive (i.e. did not fail) as a function of the elapsed time on test. Figure 156 shows several survivor curves for different US utilities employing withstand tests on their cable systems. Note that these systems are composed of different insulation types and are tested using different durations and test voltages.

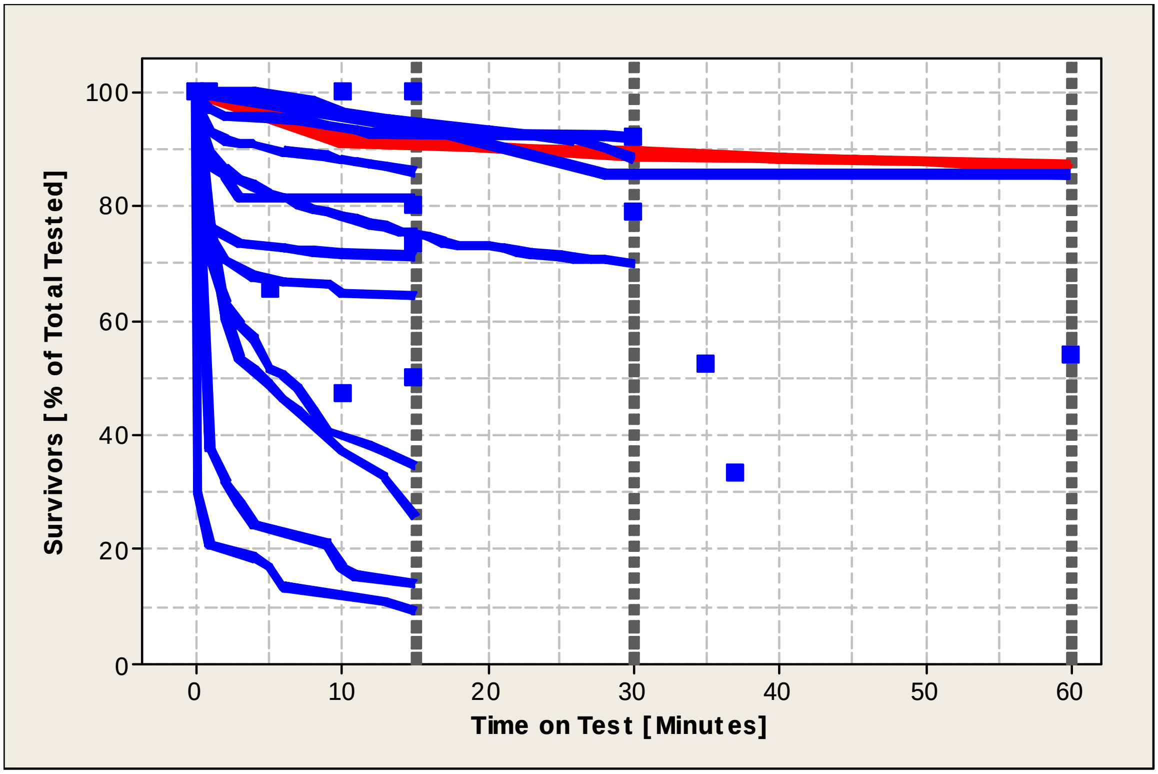

Figure 156: Sample Survival Curves for US utilities (—), Malaysia (—), and Germany (—) [45]

As Figure 156 shows, even the 60 minute long test does not cause all segments to fail during testing. In fact, only 15 % of the tested components failed during this test program. As each of the survivor curves shows, as time passes fewer and fewer segments fail. This is a desirable effect as one would expect that as more and more "bad" segments fail there are fewer "bad" segments to for the test to find. This corresponds graphically to a decrease in the magnitude of the gradient. Theoretically there is a point at which the gradient will reach zero and no additional failures would occur. Practically speaking, this point is generally at a much longer time than the durations used in the field. However, the survivor curves can be used to estimate the number of failures that a utility would "miss" if it chose to test for a shorter time.

The fact that the gradients do not increase in magnitude provides additional information. An increasing gradient would indicate that the test is more degrading the longer its duration is. The absence of such gradients implies that the withstand tests are not so degrading.

A.1.5 Censoring

The survivor technique described relies on the statistical concept of censoring. Censoring is what allowed all the segments tested to be included in the survivor analysis. The censoring technique allows one to include data for which only boundaries on their values are known. For example, in the 60 minute test mentioned in Figure 156, only 15 % of the tested population failed during the test while 85 % did not fail. It is not known exactly when this 85 % of the population would have failed had the test continued but it is sometime longer than 60 minutes. In this case, a lower bound on the times to failure for these segments can be identified. This is often termed as "right censoring" since the unknown true times to failure are greater than (to the right on a number line) of a known point [68]. Cases may also occur where it is possible to assign a maximum or upper bound on the failure time. This is termed as "left censoring" since the actual failure time is said to occur before or no later than the specified censored time.

The concept of censoring is vitally important to the analysis of any failure data and will be revisited on several occasions throughout the remainder of this document.

A.2 Techniques for Analyzing Performance Data

A.2.1 Performance Ranking

Performance ranking was developed as a means of evaluating the effectiveness of diagnostic testing by comparing the diagnostic data with service performance. This comparison provides a measure of the accuracy of the diagnostic. Ranking itself is a known procedure in statistics. In fact, a specialized version of the correlation coefficient exists for ranked data [29]. The key aspect of the development of this method is the process for generating the ranks (interpretation of diagnostic and service performance data) and the calculation of diagnostic accuracy from the ranks themselves.

Performance ranking is the only technique that looks at the entire spectrum of data from the best to the worst. In addition, it may be used with any diagnostic test was well as with data provided in any form. This is especially advantageous when comparing diagnostic technologies that do not provide measurement data.

The performance ranking technique is based on the generation of two distinct ranks, the performance rank and diagnostic rank, for each tested segment or circuit. Each of these ranks is a number that gives the relative performance of each segment compared to all other segments in the group. There cannot be duplicate ranks within either rank type. Furthermore, all segments must be assigned both a performance and diagnostic rank to be included in the analysis. In other words, if a test group consists of 10 segments, then there will be at most a single first rank, second rank, etc., for the performance rank as well as for the diagnostic rank.

The basic procedure can be summarized as follows:

1. Determine the performance rank using the available failure and segment information.
2. Determine the diagnostic rank using the available diagnostic data and the segment information.
3. Plot diagnostic rank versus performance rank.
4. Analyze the ranks for accuracy using statistical techniques.

The concept of ranking the segments is quite simple. However, with test groups containing more than a few segments, there will likely be cases where the ranking criteria produce ties. As one of the requirements of this technique is to assign a single rank to each segment, breaking these ties becomes critical. A hierarchy has been developed for cables to address this issue for both ranks, each of which is discussed in detail in the following sections in conjunction with the steps outlined above.

A.2.1.1 Performance Rank

The performance rank is based on the failure data from either before or after testing. It is determined by comparing the failure rates (annual or cumulative) for all tested segments with one another and ranking from worst (highest failure rate or shortest time to failure) to best (lowest failure rate or longest time to failure). The task can be complicated by the availability (or lack thereof) of failure information. For example, failures are typically recorded for a complete feeder circuit that includes multiple cable segments. On the other hand, several of the diagnostic technologies test each cable segment separately. In these cases, one must ensure that the diagnostic data and failure data are at the same level of detail for the analysis to be valid. It is important to note that the ranking approach is able to cope with whatever detail is provided in the available data, the analysis is simply limited to the coarsest level of detail. Typically, between performance and diagnostic data, the performance data is the coarser of the two.

It must be noted that the performance rank is highly dependent on the amount of time that has elapsed since the diagnostic tests were carried out. Depending on the local failure rate, it may take several years for enough data to be accumulated.

A.2.1.2 Diagnostic Rank

The diagnostic rank is far more complicated to determine than the performance rank because different diagnostic technologies provide their assessments in different ways. The data may be quantitative measures of the degradation that has occurred in the segment or may simply be qualitative such as “good,” “bad,” or “okay.” Furthermore, as with the performance rank this data may be as specific as by individual segment or may cover an entire feeder. Whatever the level of detail may be, it is necessary to evaluate the diagnostic data in the same groupings as the performance data.

Listed below are some examples of available cable diagnostic data that has been successfully analyzed using performance ranking as part of the CDFI:

- Recommended sections of circuit for replacement.
- Partial discharge magnitude and count.
- Dielectric loss.
- Severity.

It must be emphasized that the only requirement for diagnostic data is that it be capable of providing some level of distinction between different segments or feeders.

A.2.1.3 Ranking Tie Breaks

As mentioned above, it is common to see situations where ties can arise, especially in the case of the performance rank since many segments only experience one or two failures. Most ties may be dealt with by normalizing by the length of the segment. In target populations with similar lengths, it is also possible that multiple criteria could be needed to break all the ties. For cables, the following hierarchy was developed based on the circuit information that is typically available at utilities:

- Circuit length: Average per unit length. Also, longer circuits should be more prone to failure so give higher rank to longer circuits.
- Number of accessories: More accessories lead to more opportunities for failure thus give higher rank to circuits with more accessories.
- Age: Older circuits receive a higher rank, as these are logically more prone to failure.
- Construction: Primarily, insulation type; however, this should also include jacketing, whether the cable was direct-buried or installed in conduit, and type of neutral.

In the absence of all the above data, the utility may use other engineering judgment to rank the different segments. It is important, however, that this judgment approach be used cautiously and not be biased by the diagnostic testing results.

A.2.1.4 Analyzing the Ranks

Once the two ranks have been computed, they may be analyzed either graphically (qualitatively) or statistically (quantitatively). In the former case, a plot of diagnostic rank versus performance rank is generated. A sample of such a plot is shown in Figure 157.

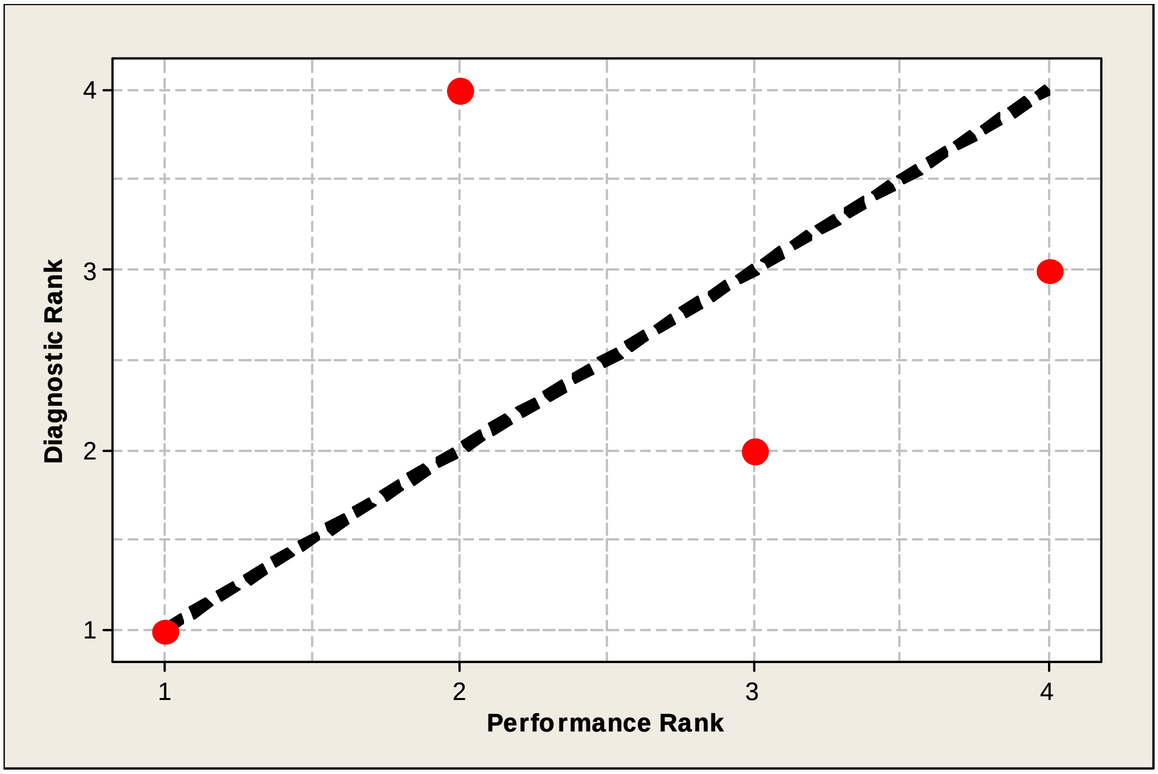

Figure 157: Sample Performance Ranking Plot for Four Circuits

The interpretation of Figure 157 is as follows: Segments (dots) in the lower left corner are the worst performers (highest failure rate and classified as "bad" by the diagnostic test) while the upper right corner contains the best performing segments (low failure rate and classified as "good" by the diagnostic test). This is further illustrated in Figure 158. The closer the ranking points are to the hypothetical perfection line (dashed line in Figure 157 and Figure 158), the more accurate the diagnostic was at evaluating the particular target population.

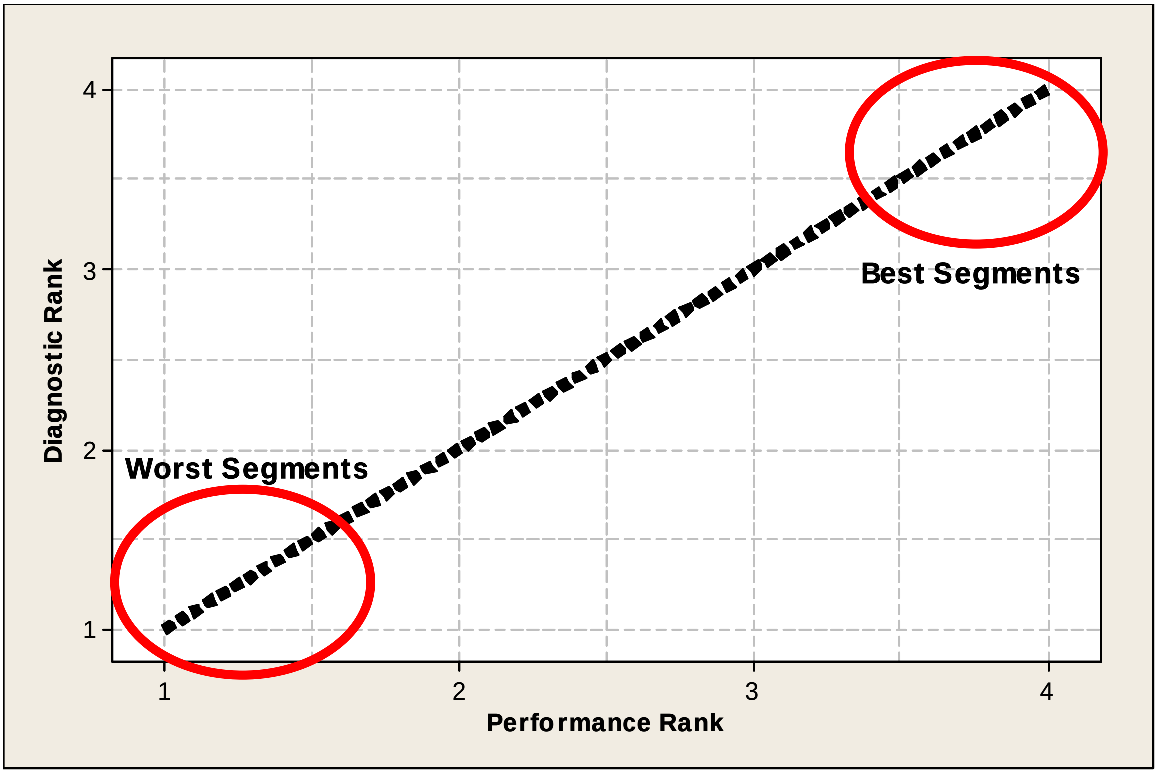

Figure 158: Performance Ranking Plot with Interpretation

The dashed line can be thought of as perfect correlation between the performance and diagnostic ranks. Therefore, the obvious statistical approach is to examine the Pearson correlation coefficient between the two ranks as,

$$r_{DP} = \frac{n\sum D_i P_i - \sum D_i \sum P_i}{\sqrt{n\sum D_i^2 - \left(\sum D_i\right)^2}\sqrt{n\sum P_i^2 - \left(\sum P_i\right)^2}}, \quad (30)$$

where,

r_{DP} = Pearson correlation coefficient,
n = number of samples,
$D_i = i^{th}$ Diagnostic Rank,
$P_i = i^{th}$ Performance Rank.

For the example shown in Figure 157, the Pearson correlation coefficient is 0.40. In addition, the correlation coefficient carries with it a specified level of significance (p-value) based on the correlation value and number of samples. This p-value represents the probability of obtaining the observed correlation coefficient at random given the same number of samples.

The resulting p-value for the example in Figure 157 is greater than 0.1 and indicating that the obtained correlation coefficient would occur randomly with probability greater than 0.1 (10 %). Typically, p-values should be less than 0.05 for the correlation to be considered significant.

A.2.2 Diagnostic Outcome Mapping

The Diagnostic Outcome Mapping (DOM) technique is useful for identifying improvements or reductions in reliability and whether or not they are coincident with actions resulting from diagnostic tests. This technique only requires basic temporal data including dates for the following:

- Testing
- Action (if needed) completed
- Pre-test failures
- Post-test failures

No data is needed on the diagnostic testing measurements as this would be implied in the decision making that led to a corrective action.

A.2.2.1 DOM Basics

DOM relies on the Crow-AMSAA or Reliability Growth technique [70]. Crow-AMSAA is a plotting technique that plots cumulative failures versus time on log-log scales. An example of such a plot is shown in Figure 159.

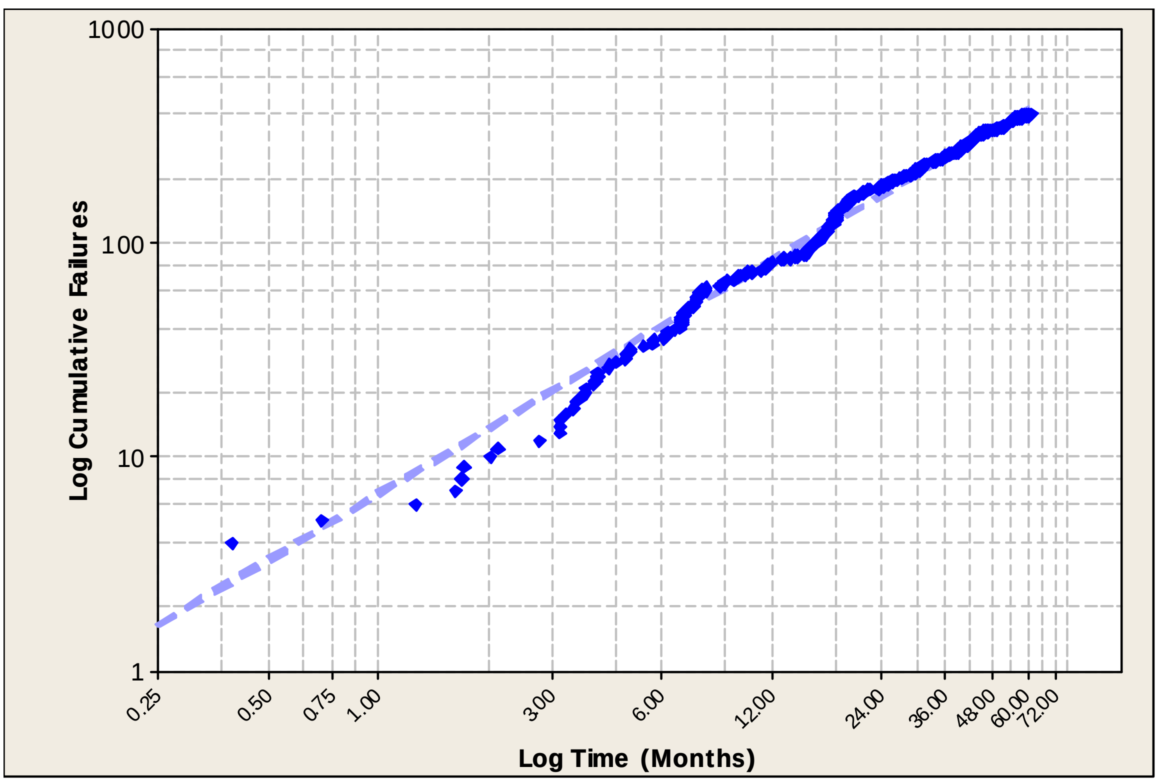

Figure 159: Sample Crow-AMSAA (Cumulative Failures versus Time).

The instantaneous failure rate is found by computing the slope, or gradient, of the curve. A decreasing gradient is associated with a decreasing failure rate while an increasing gradient is, similarly, indicative of an increasing failure rate. Constant gradients imply no change in failure rate.

By overlaying testing and corrective action events on the same plot, it is simple to see whether those tests and actions correspond to changes in the gradients and, hence, the failure rate.

A.2.2.2 DOM Examples

Figure 160 shows how a reduction in failure rate would appear following testing and action in a cable system. This figure shows that the failure following the testing and action events occurs later than would have been predicted by the line fitting the previous three failures (i.e. if the failure rate had remained constant).

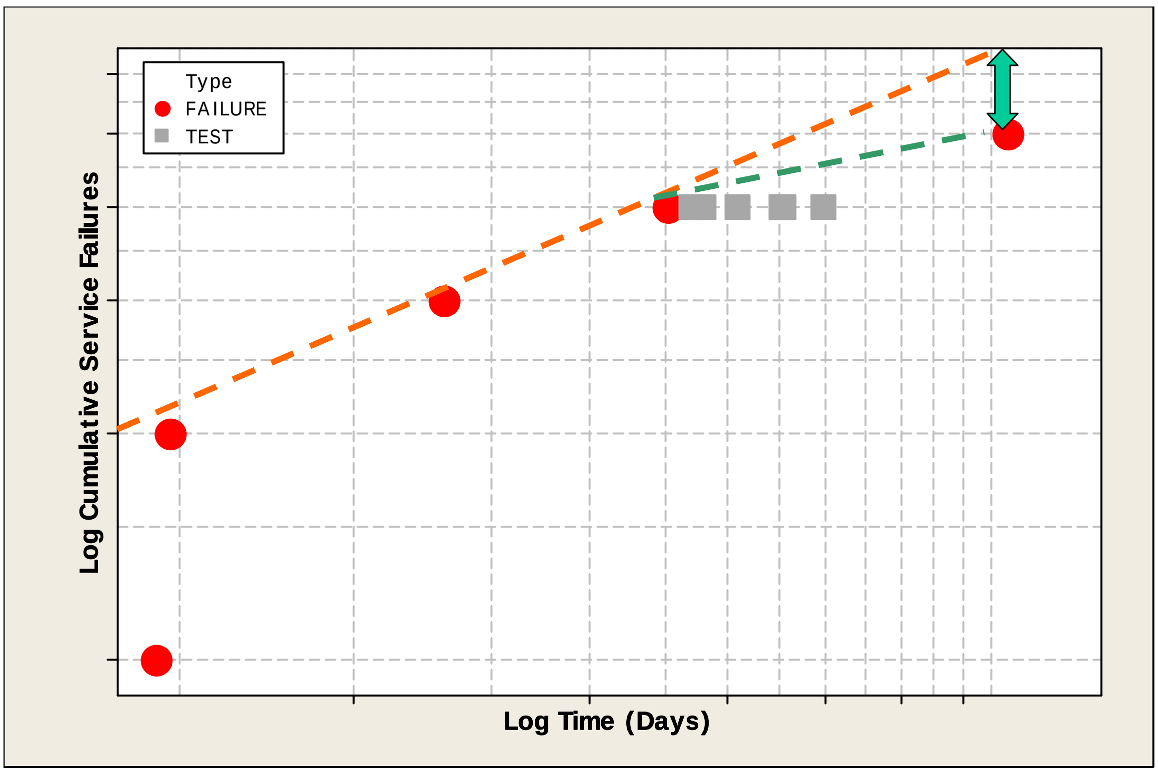

Figure 160: Sample DOM Plot for Decreasing Failure Rate Scenario

Figure 161 shows the same concept as Figure 160 except this example shows the testing program has not yet made an impact on the failure rate.

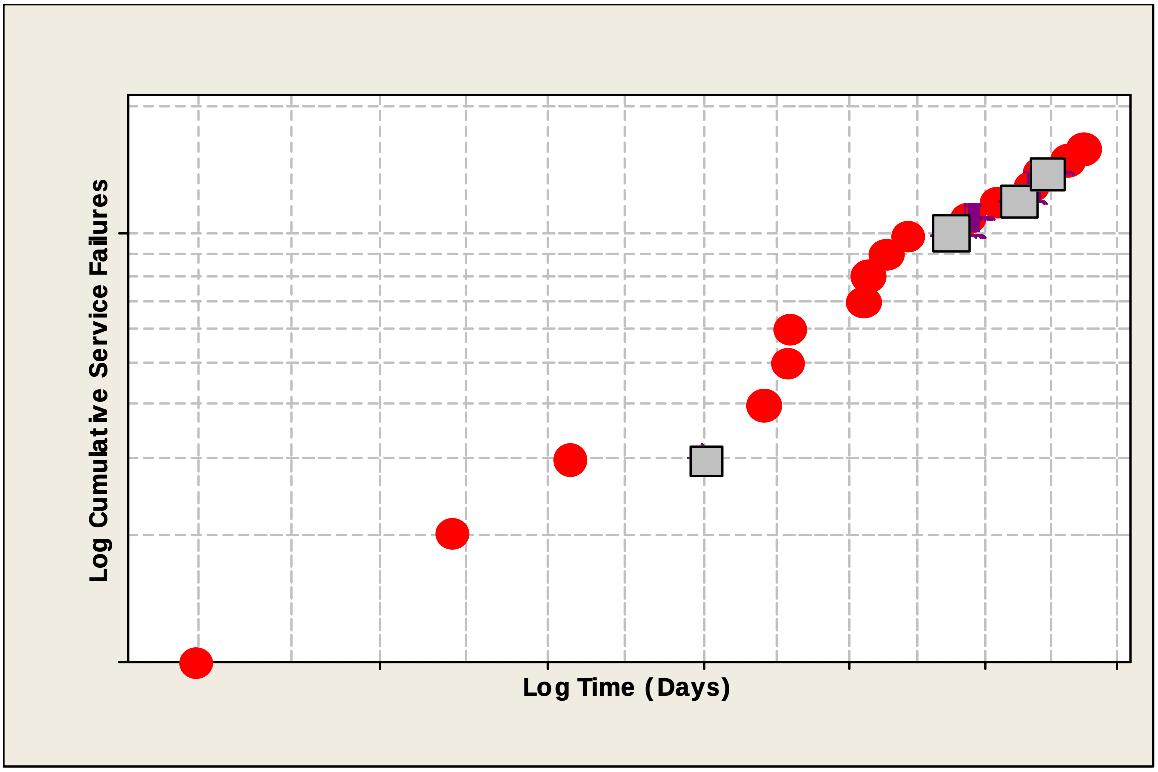

Figure 161: Sample DOM Plot for "No Change" Scenario

Using an outcome map, one can easily show if improvements in reliability are, indeed, the result of the combination of diagnostic tests and corrective actions. This process may be applied to individual segments, areas, or the entire system. Note that the length of the target population is assumed to remain constant.

Over a long enough period of time, the annual gradients can be examined to determine whether or not reliability has improved. Figure 162 shows an example of a multi-year diagnostic program. Note that after the third year, the gradients decrease until at year six they are 40% lower than at the start. This indicates a reduction in failure rate of 40% as compared to Year 0.

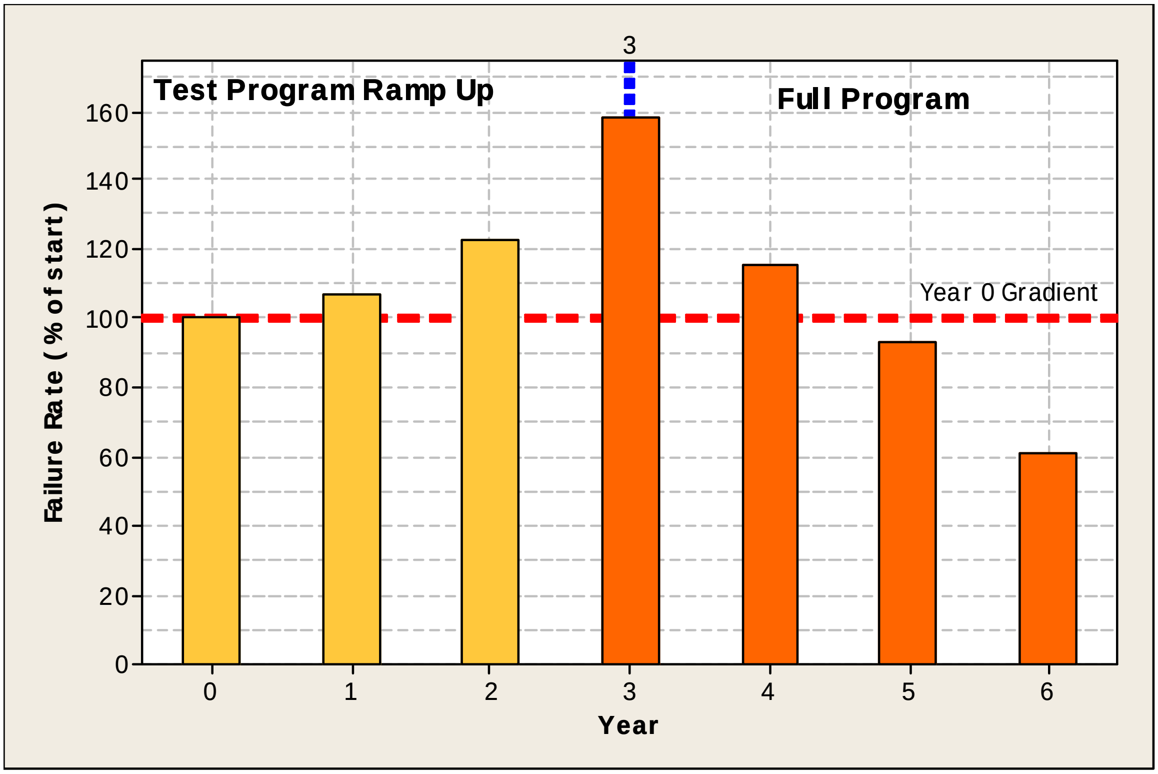

Figure 162: Sample Gradients from a Multi-Year Diagnostic Testing and Action Program.

A.3 Additional Discussion on Diagnostic Accuracy

Diagnostic accuracy is the measure of a diagnostic's ability to correctly diagnose the true condition of a cable segment. In the CDFI the primary interest is in determining which cable segments will fail and those that will not for some defined time horizon. Diagnostics accuracies are obtained from the analysis of diagnostic and performance data from utility pilot studies in which no actions are performed based on the results of the testing. The segments are tested and then monitored for a period of at least two years (five years or more is preferred).

There are two types of accuracies that are of interest:

- Overall Diagnostic Accuracy – Characterizes overall how frequently the diagnostic makes a correct assessment and is used to compare diagnostic techniques.
- Condition-Specific Accuracies – Characterize the ability of the diagnostic to make correct assessments within each diagnostic class (i.e. "good" and "bad"). These accuracies are used in the economic analysis.

The need for condition-specific accuracies is the fact that most pilot programs do not include equal portions of "good" and "bad" segments. Typically, fewer than 10 % of the tested segments are actually "bad" and this population imbalance affects the overall diagnostic accuracy. If this imbalance is known ahead of time (estimated from the failure rate) then the overall diagnostic accuracy may be used to compute the condition-specific accuracies and vice versa.

The condition-specific accuracies are primarily used in the economic analysis since the consequences from the incorrect diagnosis of a "good" or "bad" segment are different. For example, the inaccuracy in diagnosing a "bad" segment as "good" results in a service failure while the inaccuracy in diagnosing a "good" segment as "bad" leads to some unnecessary spending on additional corrective actions. Clearly these two scenarios have different implications for the utility, hence the need for condition-specific accuracies.

A major issue with all accuracy calculations is time. Cables and accessories rarely fail immediately after testing, it takes time. As a result, all accuracy calculations also have a time element since they depend on the number of failures that have occurred. All segments will eventually fail; the diagnostic test is simply a way of identifying those segments that will fail sooner. The question that arises is: how long to wait for the failure to occur? There is no universal answer. In reality, there is a probability of failure associated with each "bad" segment that is a function of time. As time passes, the probability of failure for each "bad" segment increases. The same applies to segments diagnosed as "good" but their probabilities are substantially lower than those segments diagnosed as "bad." Depending on the time of analysis, be it one year, two years, or more, after testing, the expected number of segments that would fail will be different. Equally, there are an expected number of segments that should not fail within the chosen time frame. There are two methods of dealing with this issue in the calculation of diagnostic accuracies:

"Bad Means Failure" Approach– This method ignores the time element and computes the diagnostic accuracies according to two assumptions:

- All segments diagnosed as "bad" should have already failed.
- No segment diagnosed as "good" should have failed.

"Probabilistic" Approach– This method provides the probability of failure as a function of time for the different diagnostic classes. Segments diagnosed as "bad" are assumed to have a higher probability of failure at any given time as compared to those segments diagnosed as "good."

No diagnostic test exists that can tell the utility exactly how long a particular segment will last in service before failing. The best the utility can hope for is to have some probabilistic estimate of the number of failures a target population will generate within a specified time frame. Unfortunately, this requires a significant amount of pilot study data over a long period of time (several years). NEETRAC has worked with the diagnostic providers to assemble the data for this purpose.

To establish the accuracies of the various diagnostic techniques, NEETRAC has utilized all available pilot study data from both CDFI member and non-member utilities. Some of these utilities have pilot studies that last one year while others have monitoring programs in place for several years. For datasets submitted to the CDFI, most pilot programs are in the range of 2-7 years.

For illustration purposes, each will consider the following scenario: Suppose 100 segments are tested as part of utility sponsored pilot study and the data in Table 79 are obtained.

Table 79: Diagnostic test results for a 100 segment population.

Diagnostic Class	Segments [#]
No Action ("good")	80
Action Required ("bad")	20

Following testing, the utility plans to monitor the segments for three years to be able to evaluate the diagnostic accuracy and records the failure data shown in Table 80.

Table 80: Three years of failure data for 100 segment population.

Diagnostic Class	Year 1 Failures [#]	Year 2 Failures [#]	Year 3 Failures [#]
No Action	1	1	2
Action Required	1	2	2

A.3.1 "Bad Means Failure" Approach

As mentioned above, the "Bad Means Failure" approach assumes that all "bad" segments should fail and that no "good" segments should fail. Based on these assumptions, the calculation of the diagnostic accuracies is straightforward and the results are shown in Table 81.

Table 81: Year by year diagnostic accuracies using "Bad Means Failure" approach.

Diagnostic Class	Diagnostic Accuracy			
	Year 0 (Immediately after test) [%]	Year 1 [%]	Year 2 [%]	Year 3 [%]
No Action	100	98.8	97.5	95
Action Required	0	5	15	25
Overall	80	80	81	81

Table 81 illustrates a number of important observations regarding this approach to computing diagnostic accuracies:

- No Action (i.e. "Good") accuracy only decreases with time.
- Action (i.e. "Bad") accuracy only increases with time.
- The overall accuracy is driven by the large No Action population.

The first two observations can be explained simply by the fact the failures take time to develop and that all segments will eventually fail. The last observation is a key issue with diagnostic accuracy as utilities have tended to misinterpret the meaning of "overall" accuracy. The overall accuracy is simply a measure of the number of segments the diagnostic was able to correctly diagnose considering all the segments in the population. This is not equivalent to the statement "an overall accuracy of 80 % implies that 80 % of the Action Required segments will fail." This misunderstanding has caused many utilities to avoid diagnostics because very few of the Action Required segments failed in service shortly after testing. The key point is that the population of No Action segments is much larger than the population of Action segments.

A.3.2 "Probabilistic" Approach

The "Probabilistic" approach requires additional information either from the diagnostic provider or previous pilot studies in order to establish probability curves that will be used in the accuracy calculation. Figure 163 shows an example of probability curves for No Action and Action populations generated using Weibull techniques.

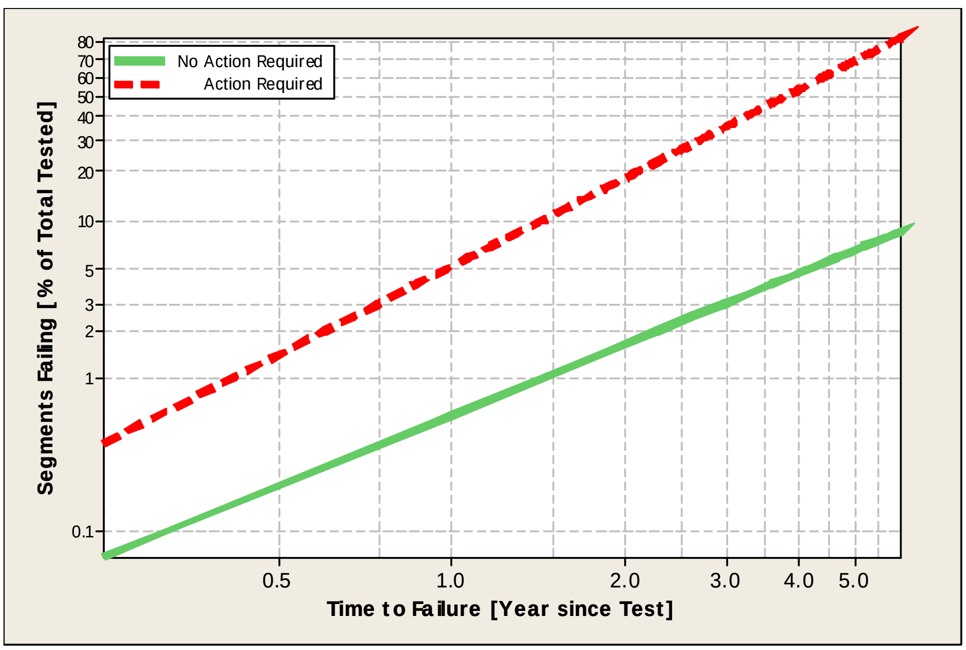

Figure 163: Example Weibull Probability Curve Showing the Percentage of Segments Versus the Time to Failure for No Action (—) and Action Required (---).

As Figure 163 shows, the probability of failure is much higher for segments diagnosed as Action Required as compared to those diagnosed as No Action. Furthermore, the probability of failure for Action Required segments in this example is not 100 % even as long as five years after testing. Similarly, the probability of failure for No Action segments is not 0 % after five years. These are important points that the Bad Means Failure approach does not consider.

Unfortunately, the probability curves cannot be used to identify which segments within a particular group of "bad" segments will fail but they can give an idea of the magnitude of failures to expect.

This may then be compared to the numbers of service failures that actually occurred to obtain the diagnostic accuracies. Table 82 shows the failure predictions for the sample target population

Table 82: Failure predictions for sample diagnostic data.

Year	No Action – 80 Segments		Action Required – 20 Segments	
	Cumulative Probability [%]	Predicted Cumulative Failures [#]	Cumulative Probability [%]	Predicted Cumulative Failures [#]
1	0.5	1	5.0	1
2	1.9	2	15.0	3
3	3.9	3	33.9	7

Considering the actual numbers of failures that occurred, Table 83 shows the resulting condition-specific accuracy calculations using the Probabilistic approach. These accuracies consider the cumulative performance of the diagnostic if one were to evaluate the accuracies after testing at Years 1, 2, and 3.

Table 83: Condition-specific accuracies for sample diagnostic data.

Class	Year	Cumulative Segments Failing [#]		Cumulative Segments Not Failing [#]		Accuracy [%]
		Actual	Predicted	Actual	Predicted	
No Action (80 Segments)	0	0	1	80	79	98.8
	1	1	1	79	79	100.0
	2	2	2	78	78	100.0
	3	4	3	76	77	98.8
Action Required (20 Segments)	0	0	1	20	19	95.0
	1	1	1	19	19	100.0
	2	3	3	17	17	100.0
	3	5	7	15	13	90.0
Overall	0	0	2	100	98	98
	1	2	2	98	98	100
	2	5	5	95	95	100
	3	9	10	91	90	99

As Table 83 shows, the condition-specific accuracies remain high and relatively stable. It is important to note that since the probability curve for each diagnostic class is available each class includes a prediction of the number of segments that will fail and the number that should not fail. As noted above, these curves cannot be used to classify a specific segment as being one of the ones that will fail or one that will not. The diagnostic has, in reality, reduced the original target population in which the utility would have been concerned about all 100 segments to a group of only 20 segments. Furthermore, the probability curves provide an indication of how long the population of segments will continue to operate before it begins to generate too many failures.

A.3.3 Comparison of Methods

Figure 164 shows the time evolution of diagnostic accuracies considering both the “Bad Means Failure” and Probabilistic approaches.

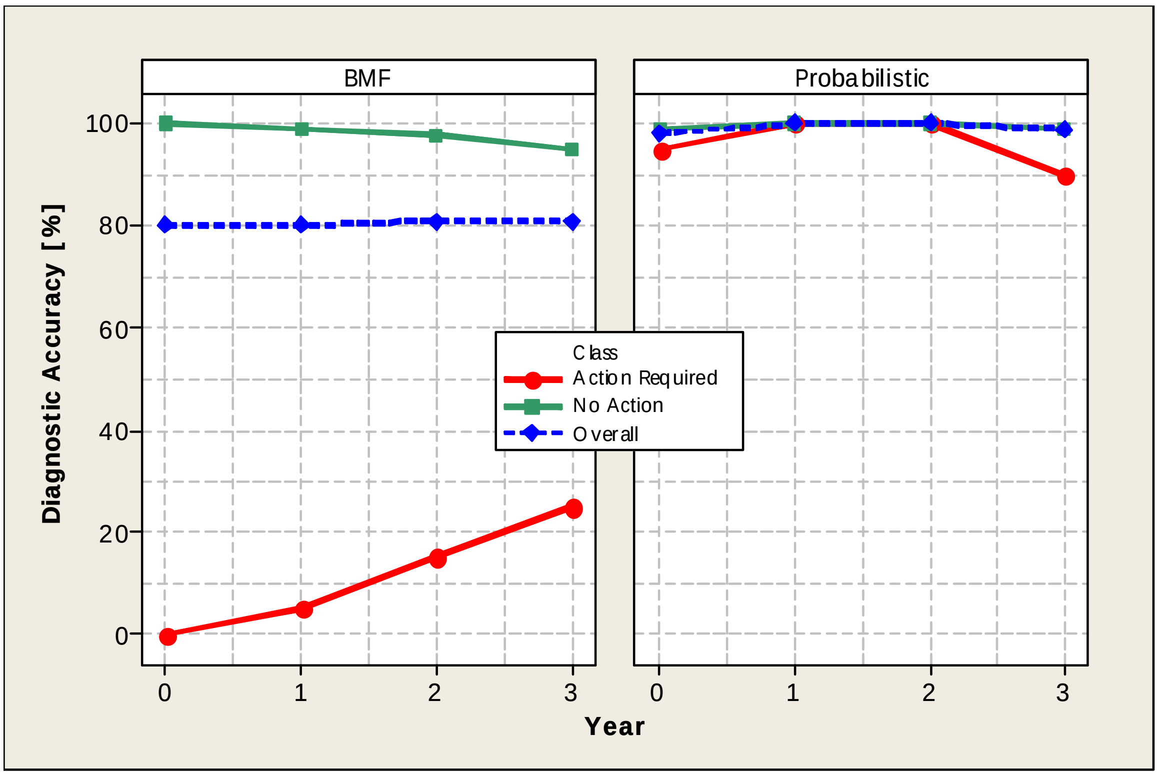

Figure 164: Diagnostic Accuracies as a Function of Elapsed Time Since Test for “Bad Means Failure” (BMF, left) and “Probabilistic” (right)

Figure 164 illustrates the effect of time on the calculation of diagnostic accuracies. Clearly, time has a great effect on the results when using the “Bad Means Failure” approach, hence it is important to bear in mind that accuracy computed using this method must be considered in the context of the monitoring period that follows the testing. To be most meaningful, comparisons between different diagnostics and/or utility systems must be made considering similar monitoring periods. On the other hand, the accuracies computed using the “Probabilistic” approach do not display a significant dependence the duration of the program, therefore, comparisons can be made between diagnostics whose monitoring periods are different.

As part of the CDFI, NEETRAC has worked to compute diagnostic accuracies using both methods (whenever possible) for each diagnostic technology used in the USA.

APPENDIX B – REVISION HISTORY FOR DIAGNOSTIC HANDBOOK

B.1 First Revision
Correction of typographical errors
Addition of comments to PD Section 4.1
Calibration / Sensitivity
Attenuation & Dispersion
Apparent Charge
Clarified metrics of success
Identified issues associated with the cable performance when first installed
Addition of comments to Tan δ Section 4.2
Additional data
Update on Success Criteria
Addition of comments on VLF Withstand Section 4.5
Clarification of Test Voltages
Discussion of appropriate test times
Survival functions
Addition of comments on Recovery Voltage Section 4.7
Additional data
Addition of comments on Relaxation Current Section 4.8
Update of Summary Voltages and Times Section 4.9
Added section on Global vs Local use of diagnostics Section 4.10
Added section 5.3 to aid in selection of appropriate diagnostic techniques
11 new figures
3 new tables
4 new references

B.2 Second Revision – December 2007 to March 2008
Correction of typographical errors
Revised existing tables and figures
Added section on SAGE, Section 2.3
Added section on Diagnostic Accuracy, Section 4.1
Added section on TDR, Section 4.2
Added section on Typical Deployment of Diagnostics, Section 4.13
Added Estimated Accuracy section for each technique discussed, Sections 4.2 through 4.10 – participants requested analysis commenced with PD
Added CDFI Perspective section for each technique discussed, Sections 4.2 through 4.10 - participants requested perspective commenced with Withstand to support IEEE Std. 400.2™
16 new tables
6 new figures
7 new references
Correction of Headings Assigned to Assist in Cross-references and Table of Contents

B.3 Third Revision – November 2008 to June 2009

Correction of typographical errors
Revised existing tables and figures

Added section on Knowledge Based System, Section 6.0
Added section on DC Leakage
Separated Withstand section into:

- Simple Withstand,
- Monitored Withstand,

Correction of headings assigned to assist in cross-references and table of contents

B.4 Fourth Revision – October 2009 to May 2010

Correction of typographical errors
Revised existing tables and figures
Added section on Dielectric Spectroscopy
Added section on Combined Diagnostics
Updated Simple Withstand & Monitored Withstand sections with information garnered from field testing
Correction of references