CHAPTER 9

Simple Dielectric Withstand

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Chapter 4: How to Start

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9.0 SIMPLE DIELECTRIC WITHSTAND TECHNIQUES

9.1 Test Scope

Simple dielectric withstand tests require the application of continuous voltage at levels above the normal operating voltage for a prescribed time period. The result of these tests is either Pass (no failure during the test) or Not Pass (failure during the test). This approach is valid for all cable and accessory types and is used for MV, HV, and EHV cable systems, albeit at different applied voltage levels. An alternative use of the Simple Withstand test, called Monitored Withstand, is covered in Chapter 10.

The *CDFI* considers Simple Withstand as a diagnostic 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 it occurs during the ramp up or the time of failure within the test period) may be used to categorize the performance. As an example, a failure 2 min into a 2 U_0 Simple Withstand test would be viewed as having poorer performance than a failure 20 min into the same test. Thus many practitioners and utilities use it to determine the "health" of their cable systems.

9.2 How it Works

The applied voltage is raised to a prescribed level, usually between 1.5 and 3.0 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 having a failure is low and repairs can be made quickly and cost effectively [7 - 16].

HV and EHV cable systems may utilize Simple Withstand tests as part of a commissioning test although this practice is becoming less commonly employed. These tests are more often now performed in conjunction with partial discharge measurements as discussed in Chapter 8.

9.3 How it is applied

This test technique is conducted with the cable system removed from service (offline). The applied voltage can be dc, VLF, or resonant ac. Test 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 prescribed test time**.

A withstand test is carefully designed to overstress a cable system to an acceptable risk level and thus to be effective it must include the following three elements:

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

Considering these three elements, dc, VLF, and Resonant ac voltage application techniques have these three elements.

DAC voltage sources, on the other hand, only comply with the first two. See Section 9.6.2. A detailed review of all of the literature references provided as technical justification in the recent version of IEEE 400.4 has failed to identify any case where any component of a MV or HV cable system, tested in the field or the laboratory, has suffered a dielectric failure. Such data are readily available for Resonant ac, VLF, and dc. As a result, DAC voltage sources will not be considered further in this chapter.

The key to a successful withstand test is to apply the voltage long enough to cause electrical trees or other significant insulation system defects that could potentially cause failure in service to grow to failure during the test. The voltage should be high enough to grow significant defects but no so high as to cause benign defects to fail. With these objectives in mind, utilities should have a repair crew on standby to make repairs as needed should test failures occur.

Simple Withstand tests are conducted on MV, HV, and EHV systems. For MV systems they are typically used as a maintenance test. For HV or EHV systems they are typically used as a commissioning test. Sections 9.3.1 and 9.3.2 discuss these different approaches in more detail.

9.3.1 MV Cable Withstand Tests

The most commonly deployed voltage source for Simple Withstand tests on MV cable systems is 0.1 Hz VLF (either sinusoidal or cosine-rectangular). Resonant ac sources and dc sources are less often employed on MV systems. DC is not recommended for aged, extruded systems due to the effects of space charge injection, which increase the potential for service failures after a dc test is performed. (Note: This has been shown for HMWPE and XLPE insulated systems, but the impact on TRXLPE and EPR insulated systems is uncertain.) Resonant ac voltage systems are generally not deployed for Simple Withstands tests on MV systems but are more commonly used for HV and EHV systems.

Historically, dc was used exclusively for MV systems but the issue with aged extruded systems mentioned above has led many utilities to switch to VLF sources. Much of the early focus within *CDFI* was on the comparison of the effectiveness of dc versus VLF withstand (hi-pot) tests.

Providers of VLF test equipment advocate [15] the use of VLF withstand voltage magnitudes shown in Figure 1 and Table 1 for a recommended period of 30 min. These are also the test voltages indicated in IEEE Std. 400.2 and 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 correct voltage level and duration) to avoid leaving weak spots that remain in the cable system after it is tested.

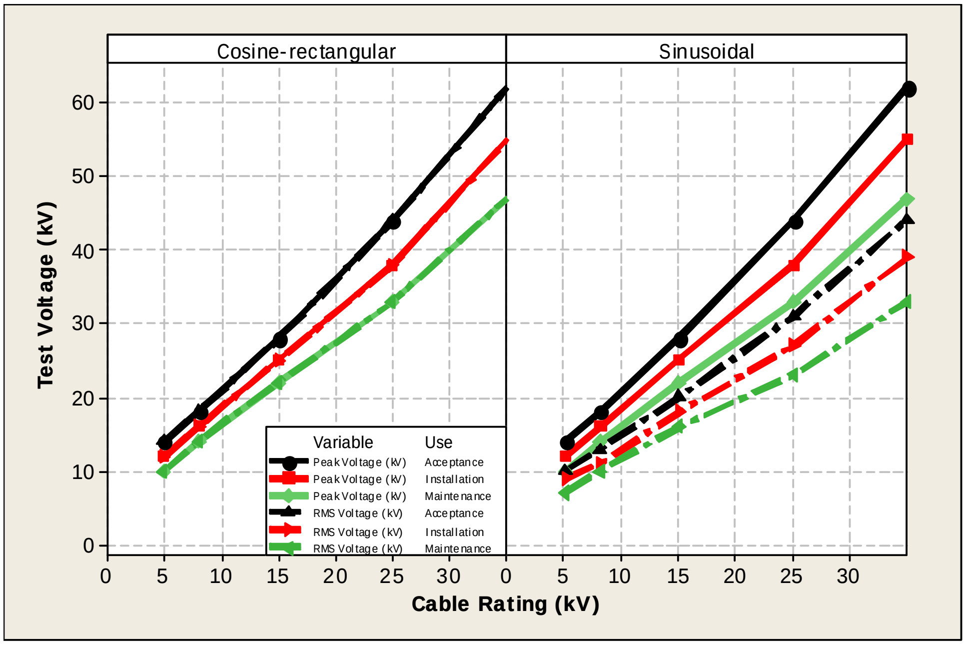


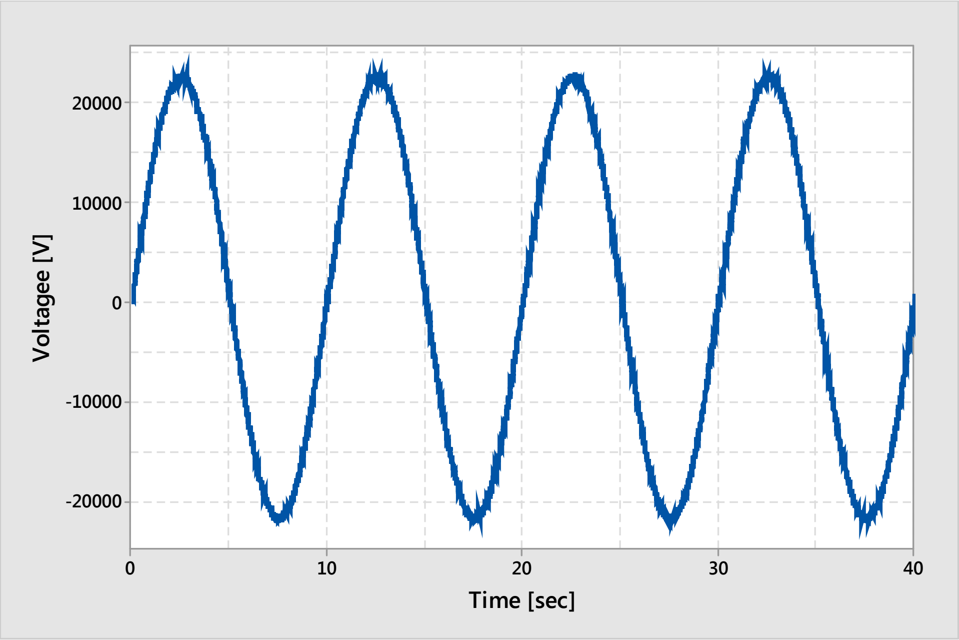
Figure 1: Cosine-Rectangular and Sinusoidal Waveforms (Table 1) VLF Withstand Voltages (IEEE Std. 400.2 Clause 5.1)

Table 1: VLF Maintenance[1] Test Voltages for Cosine-Rectangular and Sinusoidal Waveforms (IEEE Std. 400.2- 2013, Clause 5.1)

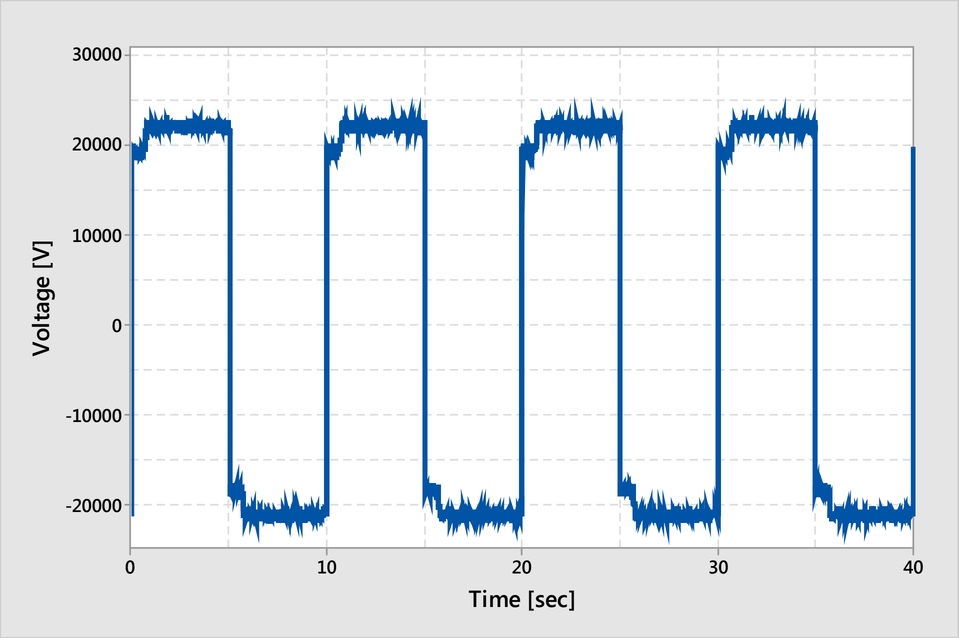
Cable Rating phase to phase rms voltage (kV)	Sinusoidal				Cosine Rectangular			
	rms		peak		rms		peak	
	kV	U_0 (rms)	kV	U_0 (rms)	kV	U_0 (rms)	kV	U_0 (rms)
5	7	2.4	10	3.5	10	3.5	10	3.5
8	10	2.2	14	3.0	14	3.0	14	3.0
15	16	1.8	22	2.5	22	2.5	22	2.5
25	23	1.6	33	2.3	33	2.3	33	2.3
35	33	1.6	47	2.3	47	2.3	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 2.



Sinusoidal Waveform



Cosine Rectangular Waveform

Figure 2: Withstand Voltages Waveforms (Top – Sinusoidal, Bottom – Cosine-Rectangular)

The advantages and disadvantages of Simple Withstand testing are summarized in Table 2 and Table 3.

Table 2: Advantages and Disadvantages of Simple Withstand Tests for Different Voltage Sources used on MV Cable Systems

Source Type	Advantages	Disadvantages
60 Hz System Voltage (Online)	• No extra equipment needed. • Serves as an easy-to-deploy commissioning test or post maintenance 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.
10 - 300 Hz Resonant ac Offline	• 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.
Very Low Frequency (VLF 0.1 Hz) ac Offline 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.
Very Low Frequency (VLF 0.01 – 1 Hz) ac Offline 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 3: Overall Advantages and Disadvantages of Simple Withstand Techniques on MV Cable Systems

Advantages	• Easy to employ. • Clear recommendations for test voltages and times in IEEE Std. 400.2 - 2013. • 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 for frequencies higher than 0.1 Hz. • Retest procedure after failure and repair are well specified in standards but inconsistently applied by utilities. • Impact of resonant ac and VLF on cable system has not been determined.
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 cable system defects.

9.3.2 HV and EHV Cable Systems

Simple Withstand tests on HV and EHV cable systems are typically performed as commissioning tests on new systems using Resonant ac. These tests are often augmented with partial discharge measurements. Significant work was undertaken in recent years by the CIGRE B1.28 study committee [26] on on-site tests for HV and EHV cable systems using partial discharge. Table 4 shows the recommended test voltage for commissioning tests.

Table 4: CIGRE / IEC Recommended Test Voltages for Commissioning Tests (Generally undertaken in concert with PD measurements)

Voltage Class [kV]	Test Level [U_0]	Frequency Range [Hz]	Duration [min]
40/47	2.0	10-300	60
60/69	1.9		
110/115			
132/138	1.7		
150/160			
220/230			
275/285			
345/400			
500			

CIGRE B1.28 also generated recommended test voltages for aged systems that are 5-15 years old and greater than 15 years. Table 5 shows the recommendations. Note that the CIGRE working group intended these withstand tests to be conducted in conjunction with partial discharge measurements. However, such tests also carry a withstand element and thus are included here for reference.

Table 5: CIGRE Recommended Test Voltages for Maintenance Tests
(Generally undertaken in concert with PD measurements)

Voltage Class [kV]	**Frequency Range [Hz]**	**Duration [min]**	**Test Voltage**	
			5 Years* to 15 Years [U_0]	**> 15 Years [U_0]**
60-69	10-300	60	1.5	1.1
110/115			1.5	1.1
132/138			1.4	1.1
150/160			1.4	1.1
220/230			1.4	1.1
275/285			1.4	1.1
345/400			1.4	1.1
500			1.4	1.1

9.4 Success Criteria

Simple Withstand test results fall into two basic classes: Pass – no action required; Not Pass – action required. Table 6 shows the requirements for Pass and Not Pass indications for Simple Withstand.

Table 6: 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 & resonant ac	HMWPE	No Failure.	System will not withstand the applied voltage (circuit fails).
	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.

9.5 Estimated Accuracy

For the pass and not pass test result scenarios, 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 considered for a two-year horizon. Simple Withstand accuracy must be treated a bit differently than other diagnostics since the required action is integrated with the test for those circuits that fail as they cannot be operated again until repaired. The result of such a test is a failure, not a condition assessment and 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 Withstand diagnostics. The only information that can be reported relates to failures in service after a test was performed.

Table 7 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 7: 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	

9.6 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; and
- 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 simple withstand technique but is merely a consequence of the amount of information contained in this large volume of data.

9.6.1 DC Withstand Usage

The use of dc voltage to assess the condition of extruded cables has been the source of much discussion and significant work. According to this work [10], [21], [22], it is clear that the application of dc withstand voltage 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 can cause 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. 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 often 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 extruded cables.

9.6.2 Damped AC Withstand Usage

Damped ac has been discussed in the industry as being useful as a Simple Withstand test. However, it does not fit the definition of Simple Withstand as defined in this document. As indicated in Section 9.3, DAC does not meet the “proven stress enhancement” requirement as no failures on test have been reported. Indeed, an examination of a typical DAC waveform output appears to produce a voltage stress that marginally exceeds the normal operating voltage. Figure 3 shows both sinusoidal VLF (2.2 U_0 for a 7.2 kV phase to ground operating voltage) and DAC (1.7 U_0) including both the DAC portion (last few milliseconds) and the charging period (approx. 4 s for this load).

Utilizing the periodicity of the repeat DAC applications (shots of 15 s each) and sinusoidal VLF (10 s) waveforms, it is straightforward to calculate the corresponding RMS voltages. While not a perfect indicator of the effect of each waveform on the cable system, it is still a useful comparison. The RMS voltage of the sinusoidal VLF waveform is 16 kV while the DAC RMS voltage is 8.9 kV. In the case of a system operating voltage of 7.2 kV, these test voltages translate to 2.2 U_0 and 1.2 U_0.

A thorough review of the literature for DAC testing was conducted to find data the supports the use of DAC as a withstand test. From the documents referenced in the current draft of IEEE 400.4 (Damped ac testing), all indications suggest that DAC breakdown voltages are far higher than those required for 60 Hz ac, 0.1 Hz VLF, or even dc [see technical references in IEEE 400.4]. This implies that the suggested 1.7 U_0 and 50 shot protocol is likely not sufficient to produce stress enhancement that can cause significant insulation system defects to grow and fail during the test.

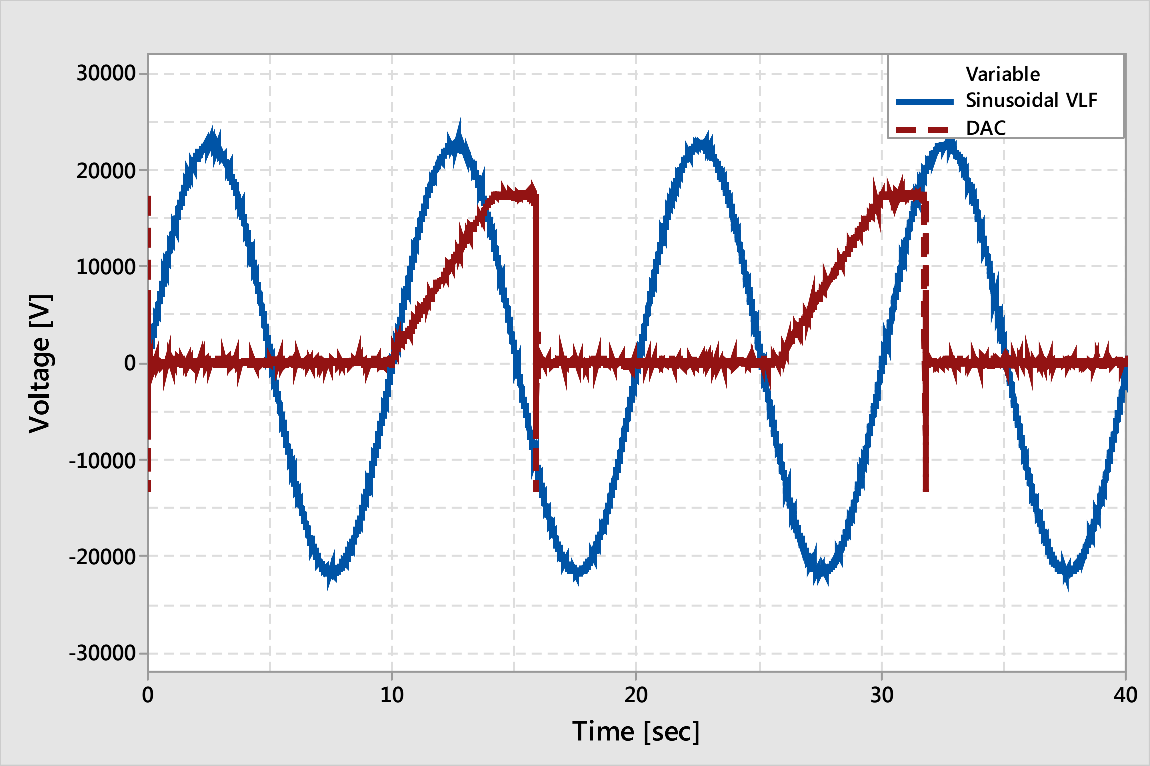


Figure 3: Sinusoidal VLF (0.1 Hz) and DAC Waveforms for 15 kV Cable Systems

The preceding discussion emphasizes the lack of information to support the use of DAC for Simple Withstand purposes. An additional factor to consider is the fact that no DAC unit currently available is designed to be used in a pure withstand mode. None of the systems used within the *CDFI* could be easily configured as Simple Withstand units as the partial discharge portion of the device is always active. Given this information, DAC is not considered in the *CDFI* to be a Simple Withstand test option.

9.6.3 Different Approaches

The underlying principles of withstand tests are common to all Simple Withstand test approaches. However, there are many ways that the required voltage stress may be applied to the system. The variety of approaches (resonant ac, dc, VLF ac – sinusoidal, and 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.

It is also useful to understand the current usage of these voltage sources for withstand tests on MV and HV/EHV cable systems. Figure 4 shows the current estimated usage of resonant ac, dc, DAC, and VLF for MV cable systems. (DAC is included because at the time the usage survey was conducted, it was thought that it could be used as a Simple Withstand test). As the figure shows, VLF is the most widely deployed source type for Simple Withstand for medium voltage cable systems.

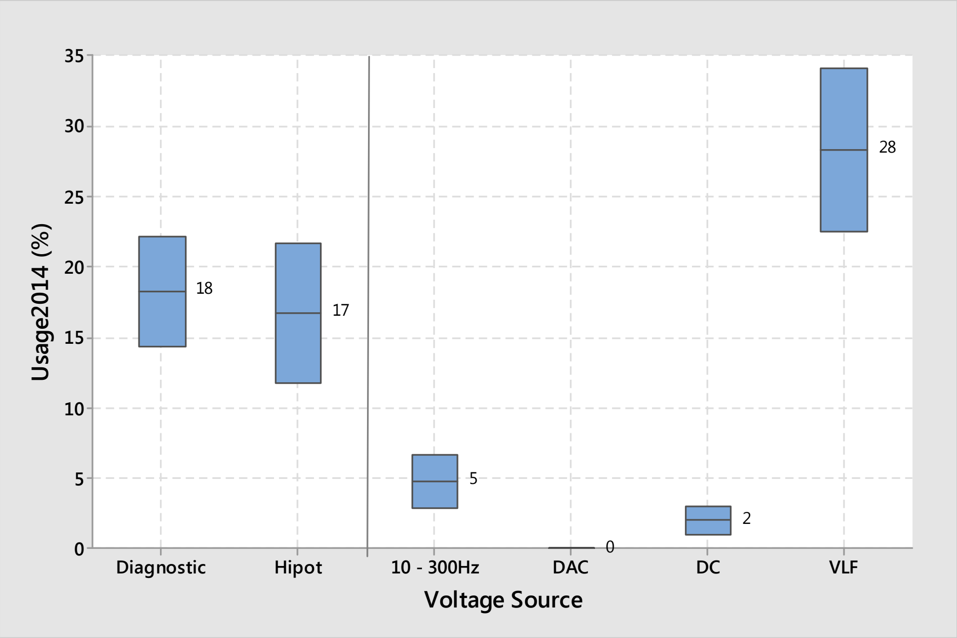


Figure 4: Voltage Source Usage for Utilities Deploying Diagnostics

Resonant ac has been increasingly used as the voltage source for HV and EHV cable systems as evidenced by tests performed since 2000 in Figure 5. At these voltage levels, the test is often conducted as a Monitored Withstand test with Partial Discharge as the monitored property (see Chapter 10).

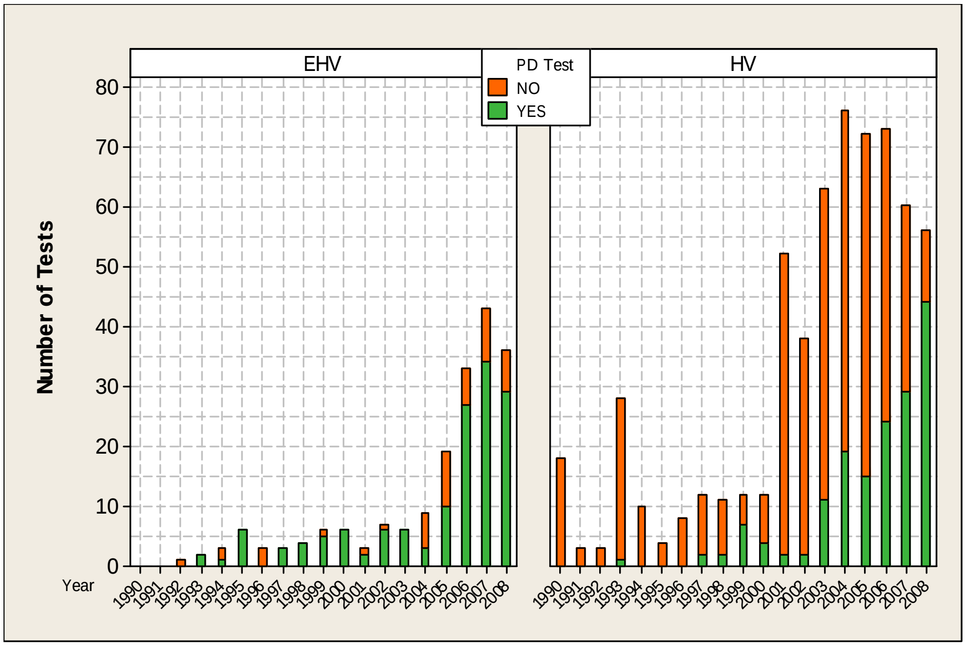


Figure 5: Resonant ac Tests on HV and EHV Cable Systems – Both Simple and Monitored Withstand Approaches Increasing in Usage [26]

As the use of Simple Withstand on HV and EHV systems is declining, the focus for the remainder of this chapter is Simple Withstand testing on MV cable systems.

9.6.4 Reporting and Interpretation

Although all variations of withstand tests report the outcome of the test as either Pass or Not Pass, many other data are often recorded about the tested circuit. Table 8 is an extract from a typical Simple Withstand test data sheet received from a utility.

Table 8: Sample Test Log (VLF ac – Sinusoidal)

Date	Feeder	Cable Type	Ckt Voltage [kV]	Phases Tested [#]	Conductor Length [ft]	Test Voltage & Duration	Failure During Test [Yes / No]	What failed?	Time to Fail	Comments
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			
5/3/2005	Y1932	PL	12	3			Yes		11:00 & 6:00	AØ fail @ 18.1kV CØ fail @ 20.2kV
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
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
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			
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

The notes and other observations from Table 8 are provided below:

- 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. (Note A – failures on first test and Note 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 (Note 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 (Note C) at times greater than 15 minutes (the lower limit presently allowed in IEEE Std. 400.2).

Regarding the last bullet above, Figure 6 shows the collated results of VLF tests from two utilities for a one-year period.

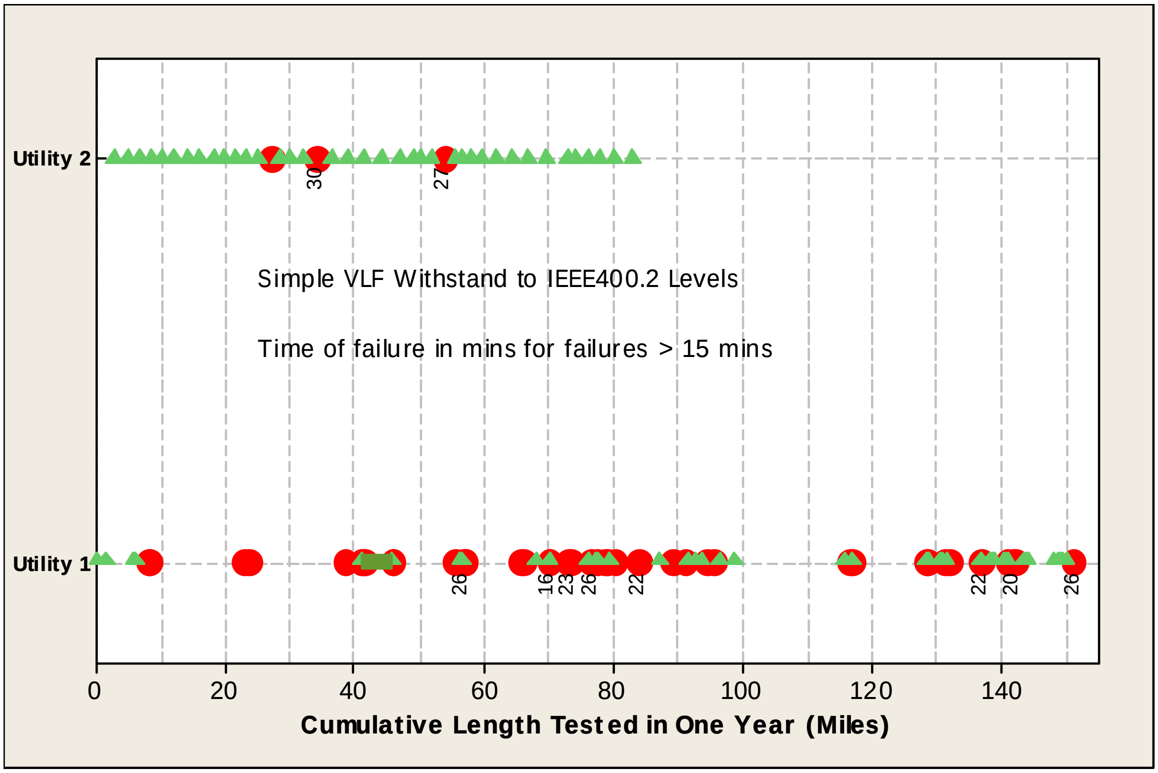


Figure 6: Collated VLF Test Results from Two Utilities over a One-year Period (IEEE Std. 400.2 recommended 30-minute tests)

The test results shown in Figure 6 were completed using the times and voltages recommended in IEEE Std. 400.2 (30 min tests). The X-axis is the cumulative circuit length tested. The red symbols identify 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 min or less). The test results in Figure 6 come from data of the type recorded in Table 8.

Although it is not readily apparent from the figure, the majority of circuits tested resulted in a Pass. Additionally, most of the failures are associated with longer test circuit lengths. While IEEE Std. 400.2 recommends a test time of 30 min, the 15 min test time allowed in IEEE Std. 400.2 has found favor with some utilities. Inspection of the failure times shown above for these two utilities indicates ten failures representing more than 230 conductor miles would have gone undetected if the test had been terminated at 15 min.

9.6.5 Collated Performance on Test (MV)

A critical issue for withstand testing is the voltage-time combination used for the test. All withstand tests are performed at voltages higher than normal operating voltage (with the exception of so-called online “soak” tests) with a goal of causing defects to grow to failure at a faster rate than would occur in service. If the voltage is too high, every defect including those that never would have impacted system performance will initiate and grow towards failure. Equally important is the time the defect has to grow during the test. If the time is too short, then degraded cables may be put back into service without failing under test. As a result, the voltage-time combination used for withstand tests must be carefully chosen to balance the need to identify critical defects with the time to grow them to failure during the 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 typically successfully complete the test. *CDFI* pioneered a way to address this deficiency by performing 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, though the rate of decline drops off significantly after 15 min. Such an analysis can be conducted empirically without any assumptions or using a distribution approach such as Weibull Analysis. Figure 7 shows the empirical data for cable circuits tested for as long as 60 min for two utilities. It is based on data from two non-US utility studies [9, 12, 15].

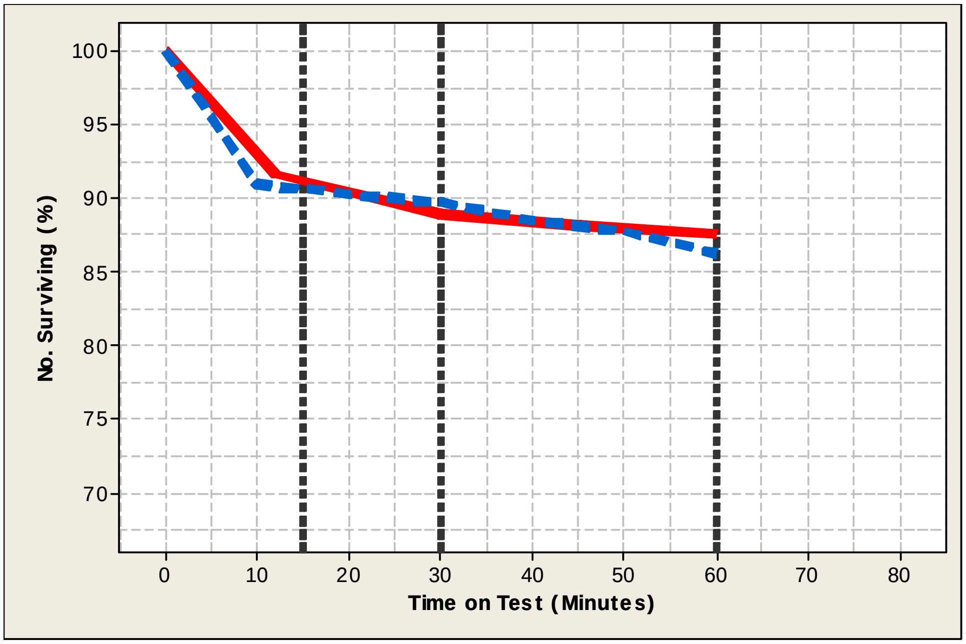


Figure 7: Percentage of Cable Survival for Selected ac VLF Voltage Application Times

Figure 7 shows that the survival curves are similar for these two datasets. However, they are not asymptotic (i.e. flat with respect to test time) at 15, 30, or even 60 minutes. This implies:

- The test time of 15 min 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 min 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 min.
- The absence of data for test times longer than 60 min makes it impossible to quantify the degree of risk (missed failures) in using test times of 60 min or less.

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 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 8. It is important to note that the data contained in this figure are for segments of widely varying lengths (300 – 20,000 ft). The process of length adjusting these data is discussed in Section 9.6.6.

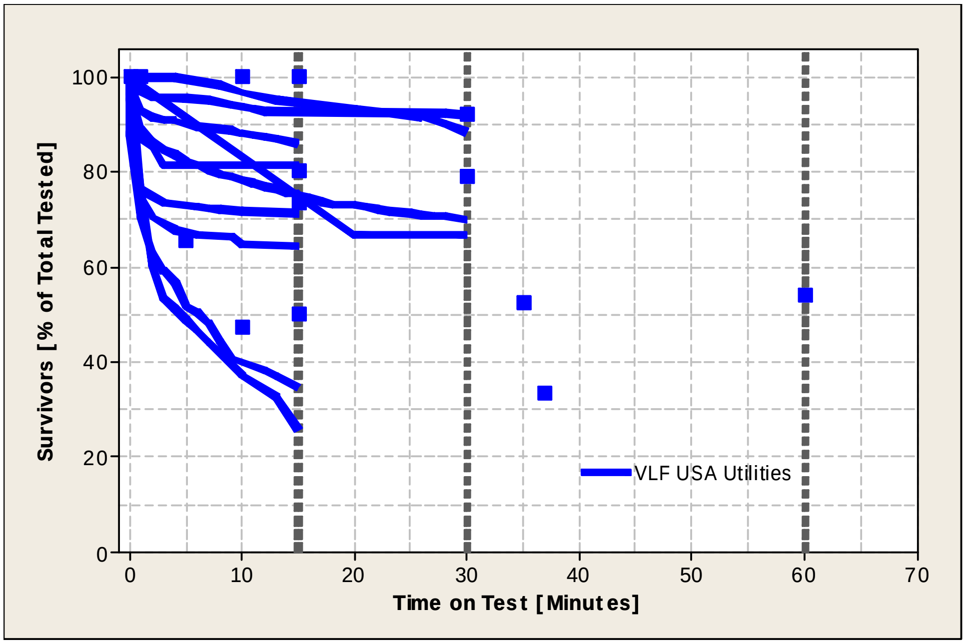


Figure 8: Survivor Curves for Collated US Experience with VLF Withstand Tests [14]

Figure 8 came from data of the type recorded in Table 8 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 level.

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 6). A number of particularly noteworthy observations include:

- The median survival rate at the end of a 15 min test is 77% of the circuits tested. However, there was no allowance for the high variability of circuit lengths included in each dataset.
- Ideally, at the end of a Simple Withstand test, the survivor curve should have decayed to a stable value with a slope of zero. This would indicate there were no additional failures to find. However, it is clear that in 50% of the cases shown in Figure 8, at both 15 and 30 min test times, this is not the case.

9.6.6 Length Adjustments to Performance Data

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 9 [14]. 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 8, 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.

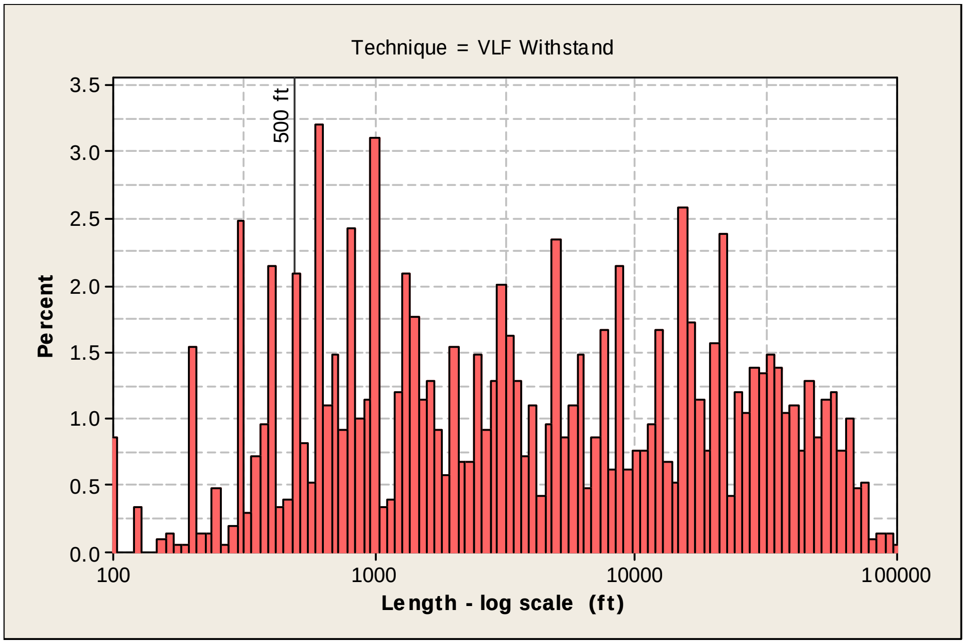


Figure 9: Distribution of Test Lengths for the VLF Withstand Technique [14]

In cases where the segments lengths 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 is insufficient for meaningful quantitative analysis. Instead, five steps are necessary:

1. Selection of a meaningful and appropriate reference length – A 10,000 ft test length could be subdivided into 100 ft, 5,000 ft, or 1,000 ft lengths, but how meaningful (Figure 9) 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 min test would provide 50 censors (5×10) at 30 min.
   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 min into a 30 min test would provide one failure at 20 min and nine censors at 20 min (all we know is that these nine have survived 20 min, we do not know nor can assume that they would have survived 30 min).
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 "inspections" 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 10 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 apparent that too short a reference length provides unrealistically optimistic estimates.

An analysis of the data shown in Figure 10 also demonstrates that the data can be well fitted 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 in the hold phase do not exhibit this sort of behavior.

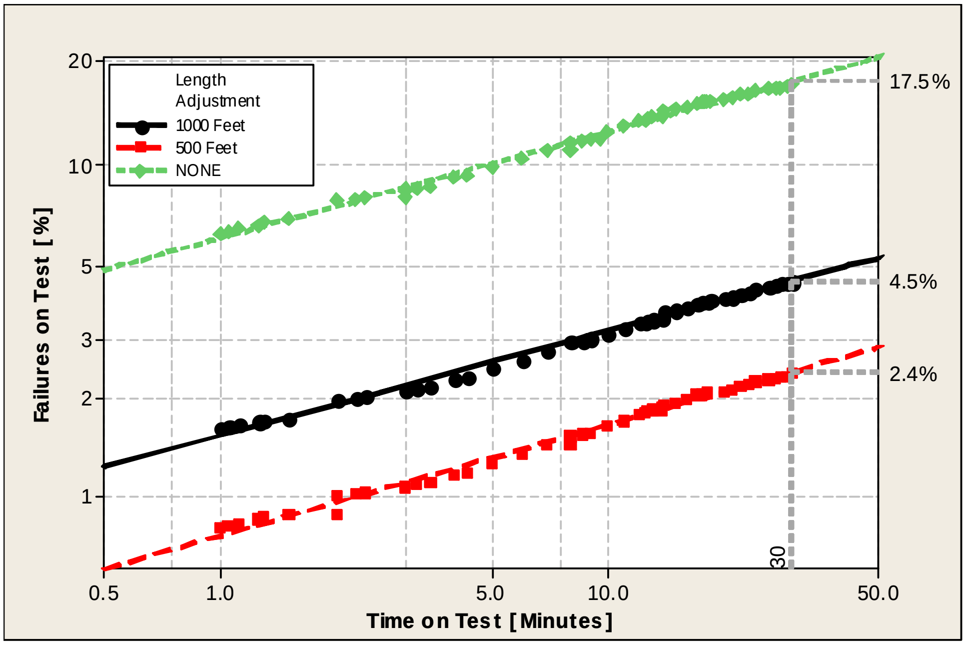


Figure 10: Impact of Reference Circuit Length on Probability of Failure for Hold Phase of VLF Test

Figure 11 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 performance is nearly identical between the systems.

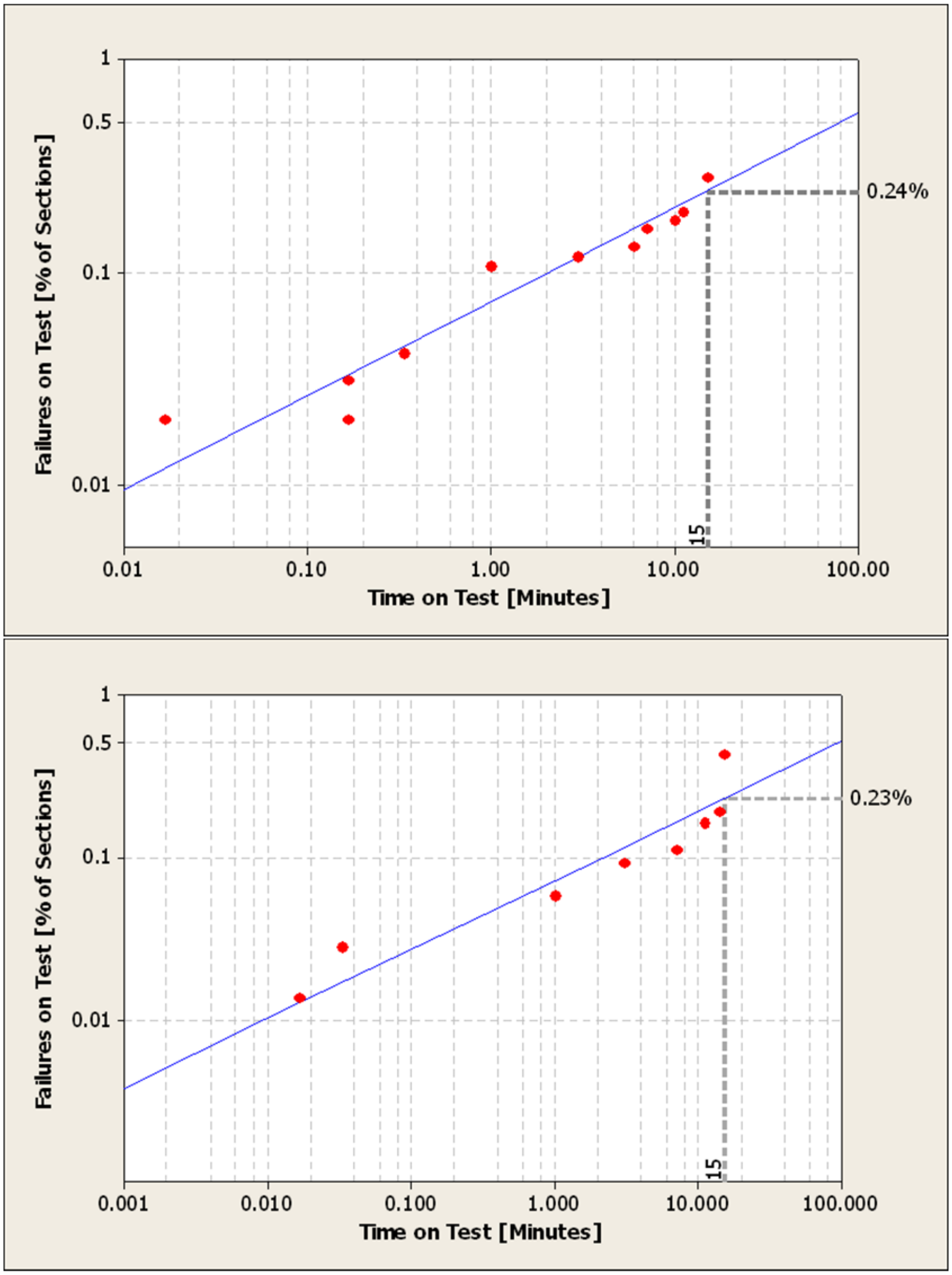


Figure 11: Distributions of Length Adjusted Failures on Test by Time for VLF Tests Length Adjustment Based on Number of Feeder Sections 13 kV System (Top) and 27 kV System (Bottom)

The results shown in Figure 10 and Figure 11 apply to other utilities as well. Figure 12 shows five of the survivor curves shown originally in Figure 8. These curves appear substantially different from one another in terms of shape and Failure on Test rate.

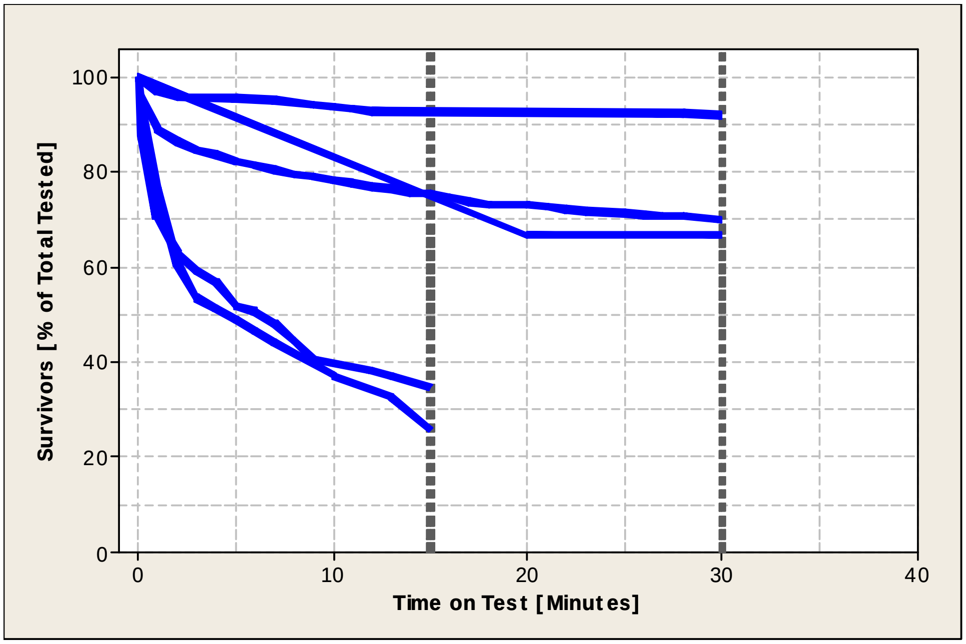


Figure 12: Survivor Curves for Five Datasets

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 12 may be transformed into the Weibull curves shown in Figure 13.

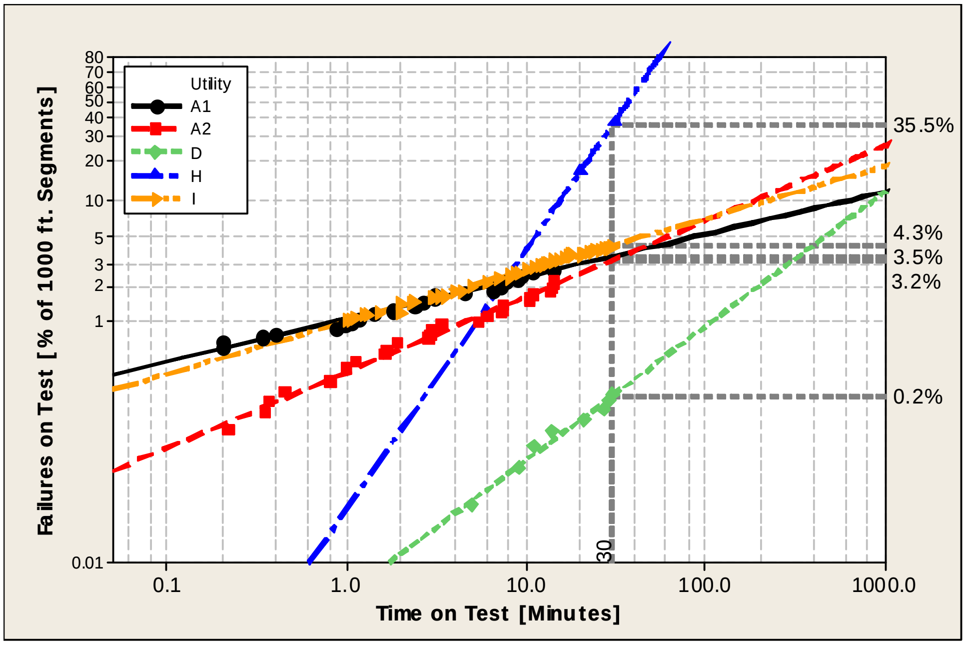


Figure 13: VLF Withstand Test Data Sets Referenced to 1,000 ft Circuit Length [14]

As Figure 13 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 14 where the replotted survivor curves use the length-adjusted data. As these figures show, four out of the five datasets have failure-on-test rates of 4.5% or less for 1,000 ft segments.

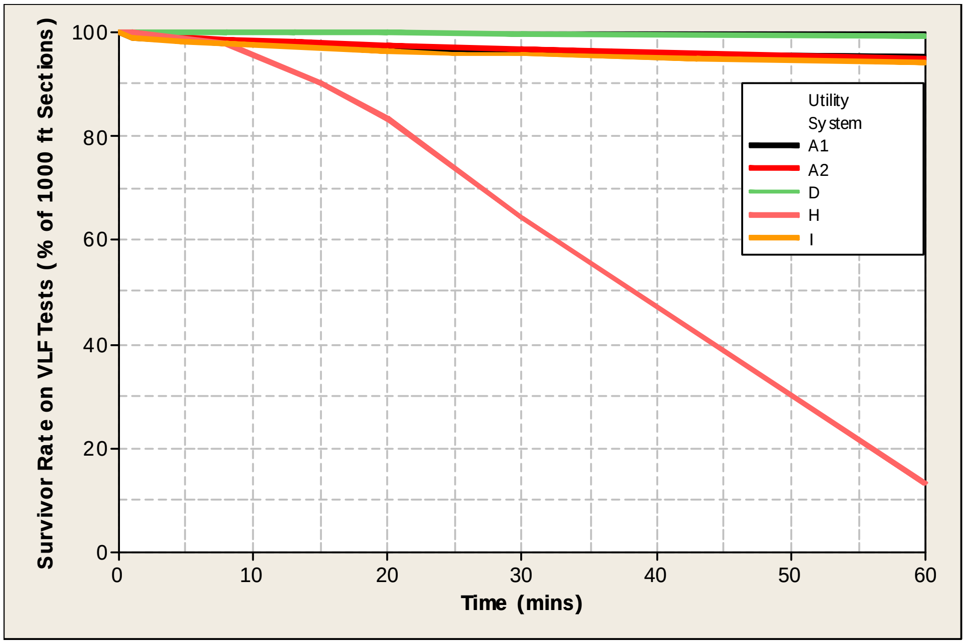


Figure 14: Length Adjusted Survivor Curves

Figure 15 shows a high failure-on-test rate for the one outlier dataset represented as ■ in Figure 14 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.

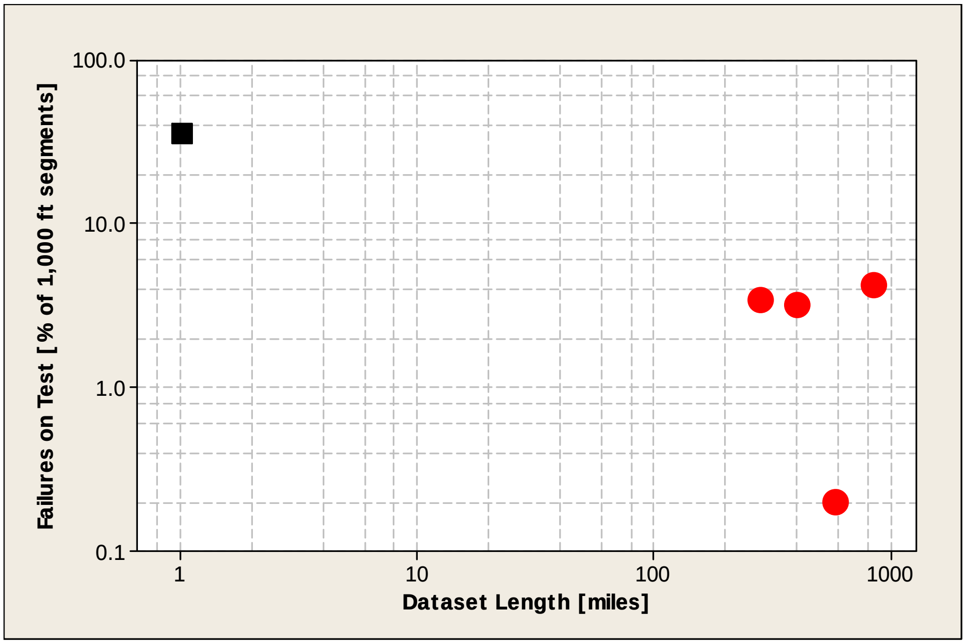


Figure 15: FOT Rates and Total Lengths of Datasets in Figure 12.

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 min tests.
- It is possible to extrapolate the curves to estimate the failures on test at times longer than 30 min. Estimates out to 120 min may be possible. This is useful if a utility wishes to perform non-standard Simple Withstand tests (i.e. longer than 30 min).
- The overall likelihood of failure, as evidenced by the likelihood of failure of 1,000 ft sections tested for 30 min, is approximately 2.7% 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 ft 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 16 shows that the failure-on-test rate for 30 min test protocols is 2.7% (based on 1,000 ft segments).

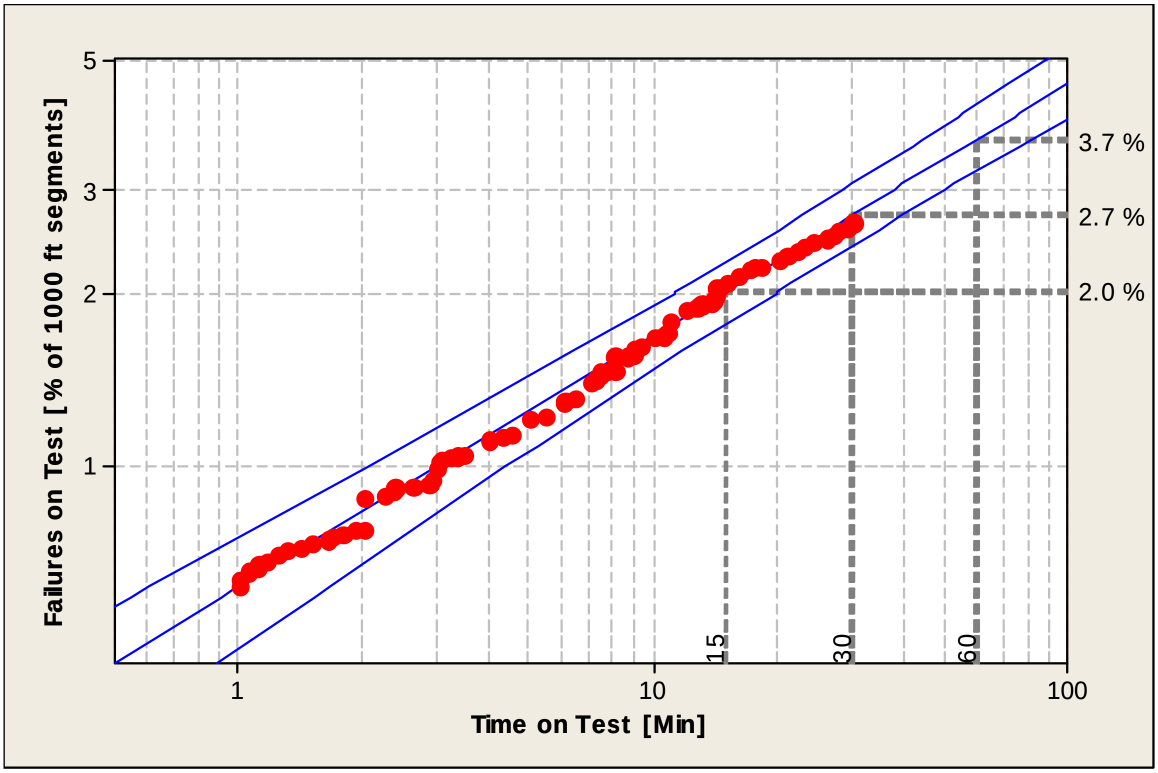


Figure 16: Combined Weibull Curve for all VLF Data in Figure 13

9.6.7 Separation of Failure Modes – Early and Hold Phases

In the previous section, the early phase failures were censored so that they could be included in the analysis of the hold phase but would not affect the failure gradient calculations. The early phase does make an important contribution to the performance on test for Simple Withstand tests. It is, therefore, worth taking a closer look as these data. A close inspection of the survivor curves in Figure 8 (see previous section) reveals three important observations:

1. The number of survivors decreases rapidly during few first minutes of voltage application for all datasets. This rate decreases as the test time increases.
2. Only a few of the curves show the flattening that would indicate they were approaching an asymptote.
3. None of the survivor curves display a sharp decrease in survivors near the end of the test.

Initially, 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 17) 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 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 17). This finding is only apparent once the failure modes are separated and length adjustments made.

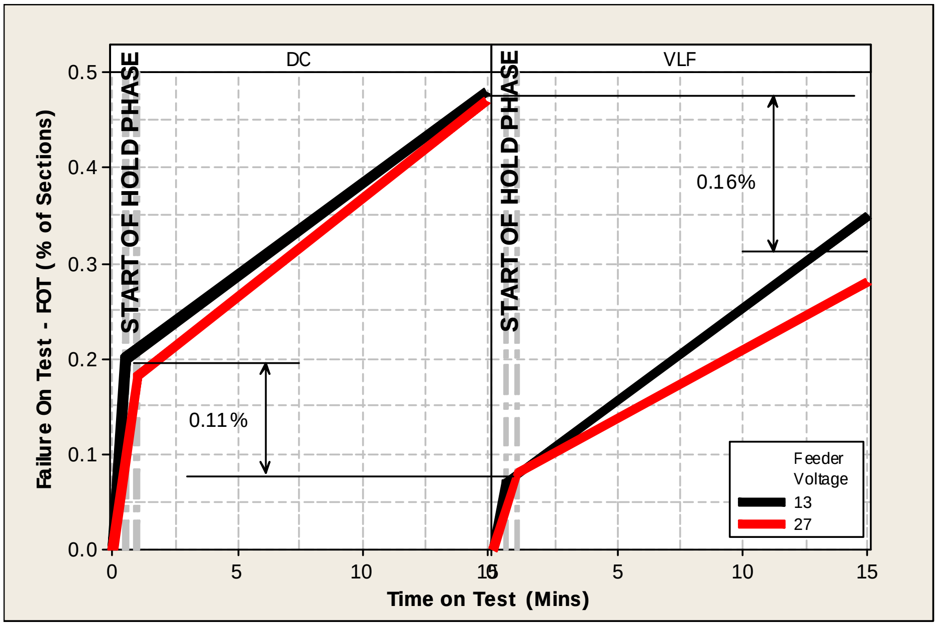


Figure 17: Distribution of Failures on Test as a Function of Test Time for DC and VLF Tests at One Utility [13 = 13 kV & 27 = 27 kV]

In analyzing the datasets available to the CDFI, it turns out to be common (Figure 18) 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 min into the test) and a different mode for failures during the constant voltage (hold) portion of the test.

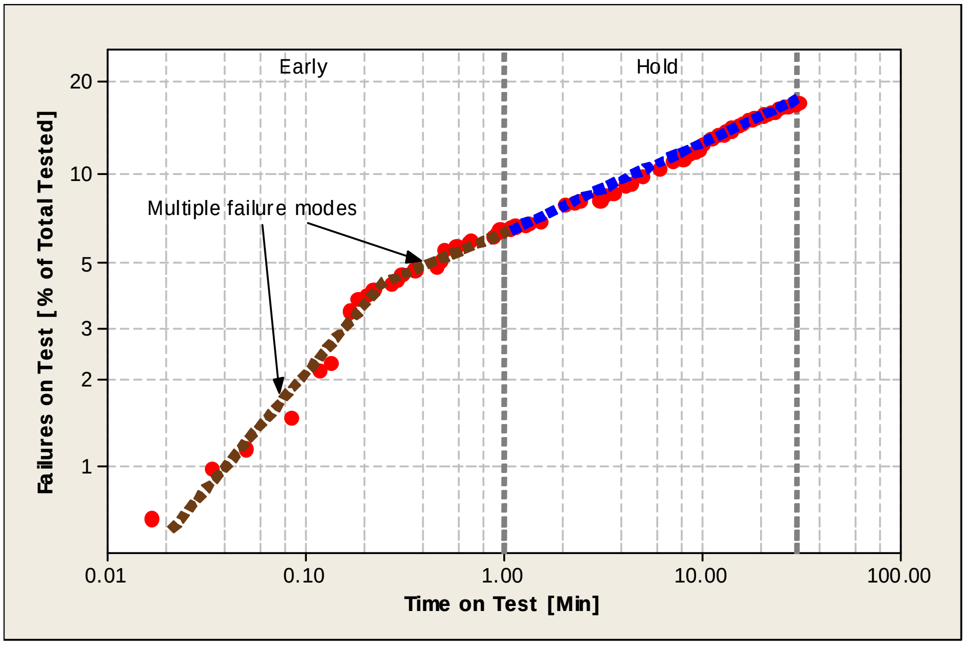


Figure 18: Distribution of Failures on Test as a Function of VLF Test Time (Direct application of test voltage without ramp phase)

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 19). The differences in the early failure modes likely arise from the two subclasses that exist for this phase of the test. This behavior results 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 19 shows the data on dc and VLF tests where, in both cases, the voltage was 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.

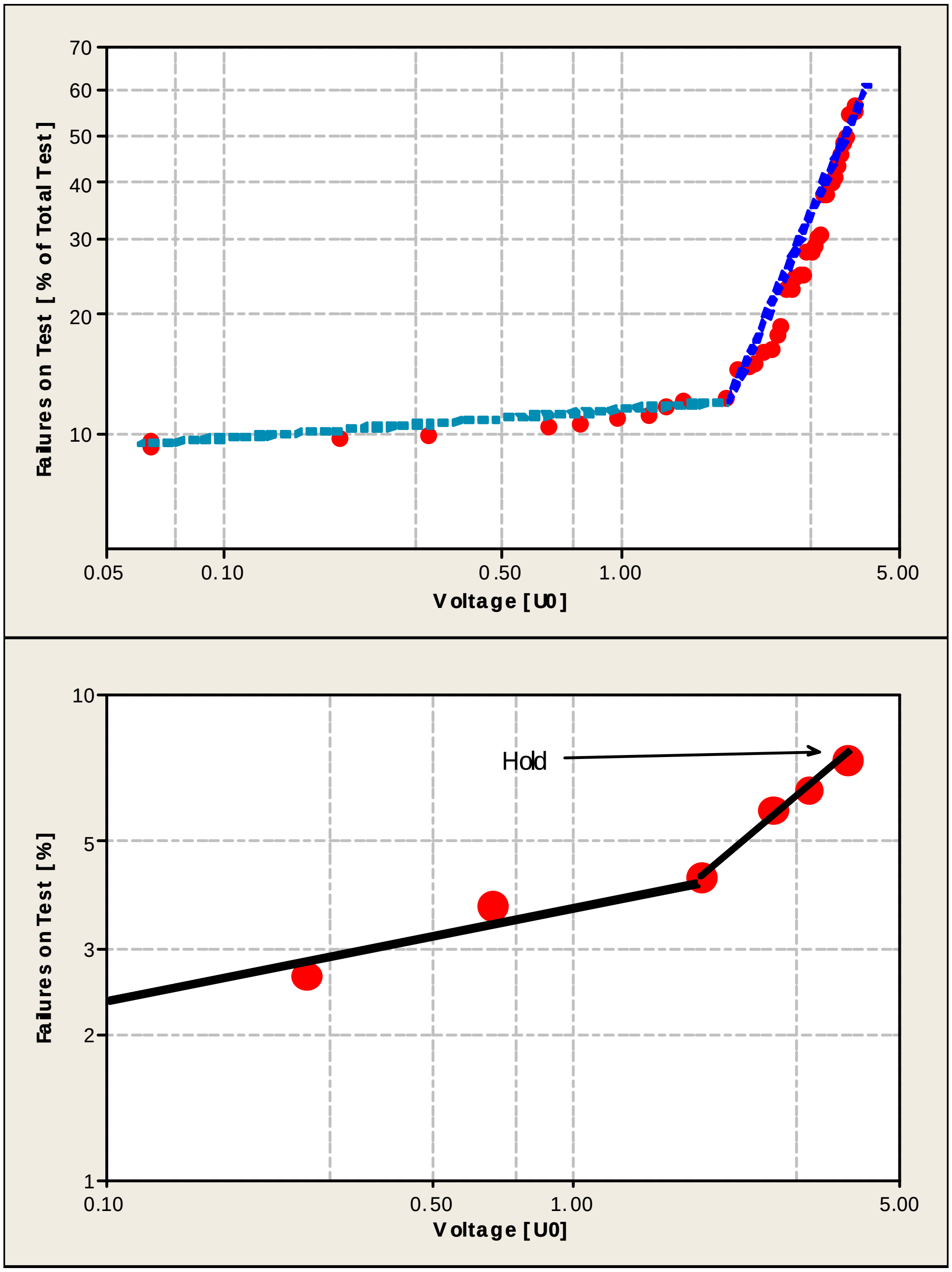


Figure 19: Dispersion of Failures on Test as a Function of Test Voltage during Ramp Phase for DC (Top) and VLF (Bottom)
(Highest VLF Test Voltages Used Exceed IEEE Std. 400.2 Recommendations)

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 and VLF), voltage class, insulation (EPR, Paper, XLPE), or component (cable and accessory). In Figure 20, where voltage class is used to separate the data, these data show the different modes between the early and hold portions of the test as well as the two voltage related modes within the early portion.

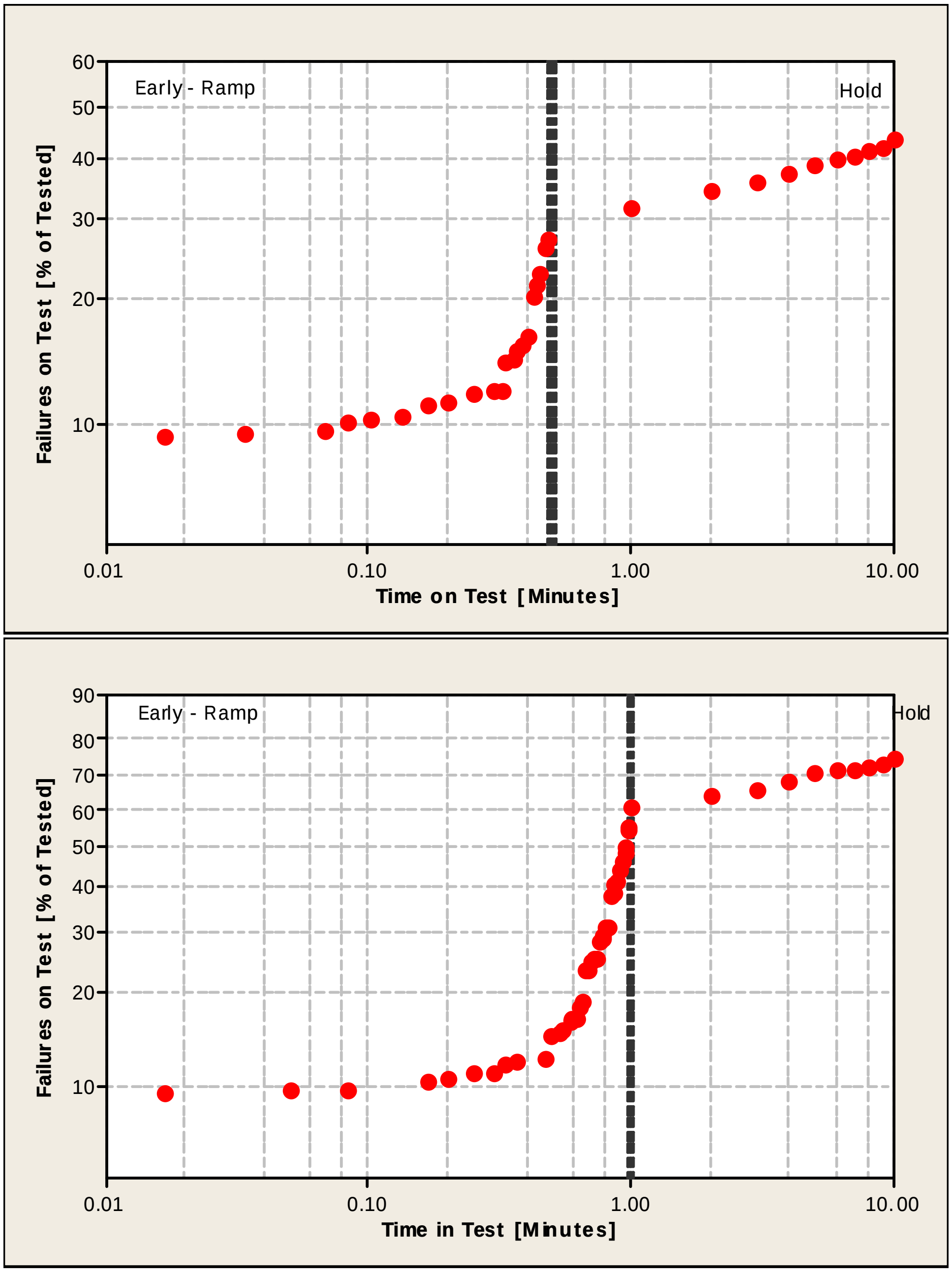


Figure 20: Dispersion of Failures on Test as a Function of DC Test Time
13 kV System (Top) and 27 kV System (Bottom)
(After a Linear Increase in Voltage to the Hold Phase)

With these modes identified, it would then be possible to select a test voltage that eliminates a second early mode as this appears to cause an unnecessarily high numbers of failures.

9.6.8 VLF Frequency Studies

The effect of reduced VLF frequency (0.01 Hz versus 0.1 Hz) on the performance on test for Simple Withstand tests was examined as part of *CDFI* in both laboratory and field studies (the latter was carried out using data supplied by *CDFI* participants). The most commonly used VLF frequency is 0.1 Hz; however, it is also often the case that the VLF source must reduce the frequency to as low as 0.01 Hz in order to energize longer cable system lengths. One question left unanswered has been the effect of frequency on the breakdown strength of aged cable systems. IEEE Std. 400.2 specifies the test time and test voltage but not the test frequency. As the test frequency decreases so does the number of cycles that can be completed within the time period specified in IEEE Std. 400.2.

The work in this area is limited, though the most extensive field work is that completed by Shew Chong Moh of TNB in Malaysia. Moh extracted data from VLF cable system tests in the field and a small part of this data was examined in terms of the VLF frequency employed. The reductions in test frequency were the result of increasing length and cable system voltage (both of these increase the power demand on the VLF source and so will cause the frequency to drop). The data suggest that the fraction of failures-on-test (FOT) decrease and the fraction of failures-in-service (FIS) increase as a result of the reduced VLF frequency. On the face of it this would suggest that the lower VLF frequencies are less effective. This implies a potential need to either increase the test voltage or increase the test time to restore the perceived balance between FOT's and FIS's to that seen with the 0.1 Hz tests. The assumption is that an FOT is a future FIS that was forced to occur at a time of the utility's choosing thereby enabling a swifter and lower cost repair and avoiding customer interruptions.

There are other factors are at work in addition to those that may be derived from the VLF frequency. These factors include:

- Longer lengths are likely to experience more failures due to the increased probability of weak links; and
- Higher voltage cables are tested at higher stresses, thereby increasing the number of failures.

Both of the above factors are also correlated with a reduced VFL test frequency as they increase the power required from the voltage source. Hence, the impact on FOT and FIS may be due to a correlation rather than causation with respect to test frequency.

Assessing the impact of length and stress is reasonably straightforward using the Weibull equation. However, the relevant length and stress parameters are not known in these tests; though it may be possible to determine these from other datasets that include more specific data. Another issue to be considered is the relatively small number of test samples in the TNB field tests that were made at test frequencies other than 0.1 Hz tests (5% and 3% of total tests for 0.05 Hz and 0.02 Hz, respectively). Furthermore, the number of FIS are small (64 and 36) compared to the population size thereby increasing any impacts from variations in counting / data collection. It is quite possible, for example, for failures on higher voltage cable systems (33kV in this case) to be more carefully reported than those occurring on more common lower voltage systems (11 kV). These potential differences in reporting could make the lower voltage systems appear disproportionately more reliable. Although there is no evidence that such reporting issues occurred in the TNB data, much of the results could be explained in this manner.

Furthermore, if the VLF test frequency did impact the effectiveness of the testing then it is expected that there would be differences in the number of FOTs and FITs between 0.1 and 0.05 Hz as well as between 0.05 Hz and 0.02 Hz. Inspection of the results suggests that there is only a difference between 0.1 Hz and 0.02 / 0.05 Hz and no difference between 0.02 Hz and 0.05 Hz. One would expect a similar difference in these two cases if the performance difference was due only to the different frequencies used.

Thus, upon inspection of the data it is not clear whether the VLF frequency has an effect or not given the multitude of issues occurring simultaneously. Clearly, an experimental program would help to:

a) Establish if lower test voltage frequencies are less effective at finding circuit problems or
b) Estimate by how much the test times or voltages might need to be increased to achieve the same effectiveness as the standard 0.1 Hz frequency.

The work by Moh is very useful as it identifies the important elements of an experimental program to address this issue. Such a program needs to address/include the following:

- Test objects that are in a degraded state (i.e. aged in a controlled manner),
- The degradation is achieved using aging mechanisms that are reasonable when compared to true field aging,
- The achieved degradation should be consistent between test samples as multiple test samples are needed,
- The achieved degradation should be quantifiable such that it is possible to compare the degradation on different test samples, and
- The test objects should be sized so that the test frequency may be selected by the test set operator rather than because of a test device limitation (i.e. the voltage source should be capable of energizing the test sample at any frequency between 0.01 – 0.1 Hz without overloading).

The following section describes a laboratory program that was undertaken as a part of the *CDFI* to investigate the effect of frequency on VLF breakdown.

9.6.8.1 Laboratory Study of VLF Frequency Effects

The laboratory program used the Ashcraft Water Tree Growth Method to age plaques of XLPE and EPR insulation compounds. The breakdown strength of these samples was determined for sinusoidal VLF voltage frequencies of 0.1 Hz and 0.05 Hz. The major drawback in field tests is that field aged cables are not homogeneous from segment to segment so establishing the impact of test voltage frequency is difficult. By employing the Ashcraft Method to age cable insulation plaques, a relatively homogeneous population of degraded test samples could be constructed.

The samples were prepared in accordance with the Ashcraft method (ASTM Test Method D6097-97) as shown in Figure 21.

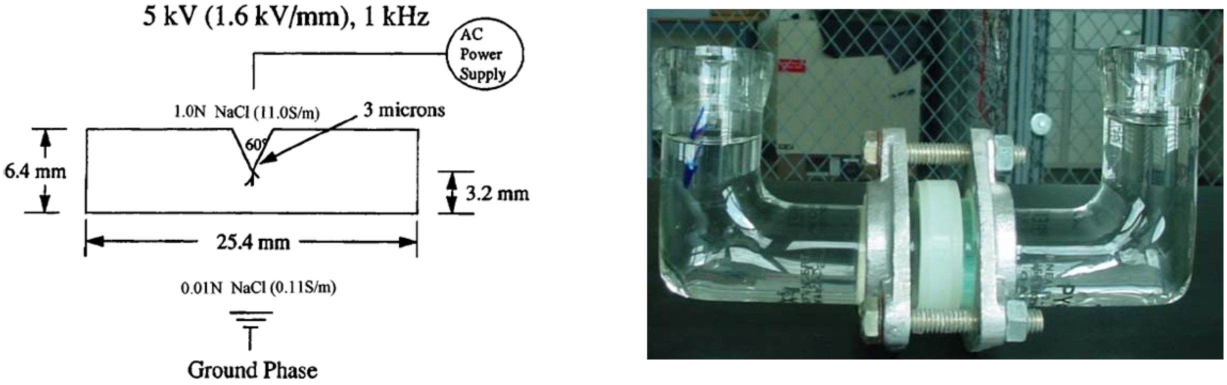


Figure 21: Insulation Plaque Geometry (left) and Aging Cell for Ashcraft Method (right)

These samples were aged at 1.6 kV/mm ac voltage stress for 30 days at ambient temperature prior to performing the ac breakdown tests. A total of 87 samples were tested in groups of three using a sudden death approach (i.e. one sample tested to failure and two samples left intact as censored samples for water tree length and point-to-plane distance measurements).

A ramp protocol was used for the breakdown measurement as shown in Figure 22. Each step voltage was held for 1 min regardless of VLF frequency.

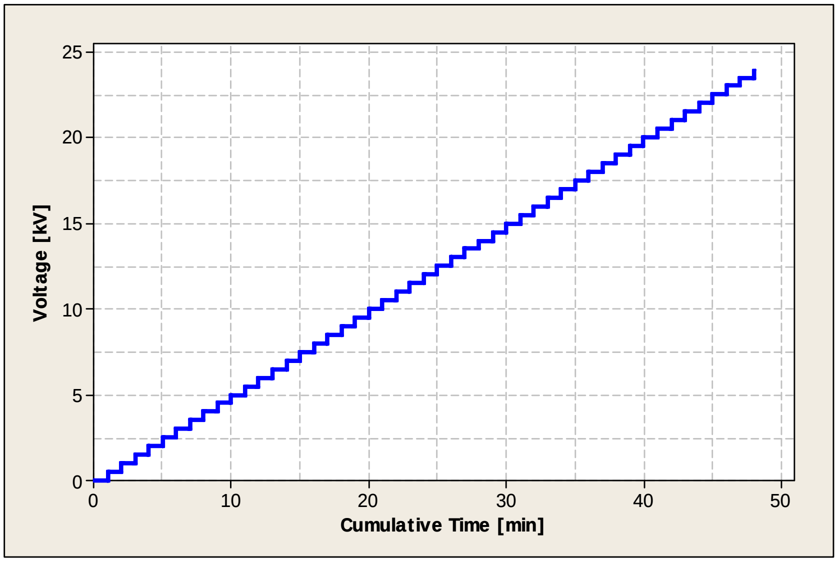


Figure 22: Test Voltage Protocol (Ramp – 1 min hold, 0.5 kV/step)

Test Program Results

The water tree lengths for all materials are shown in Figure 23. Random samples of each insulation type were chosen for 0.05 and 0.1 Hz breakdown tests. As these histograms show, the tree length distributions for each randomly chosen group were quite similar.

The resulting VLF breakdown stresses for MV insulation materials are shown in Figure 24. The estimated breakdown strengths are based on the results from the group of three samples tested where all three were subjected to the test voltage. When one broke down, the breakdown value was recorded and the other two samples were treated as censored values.

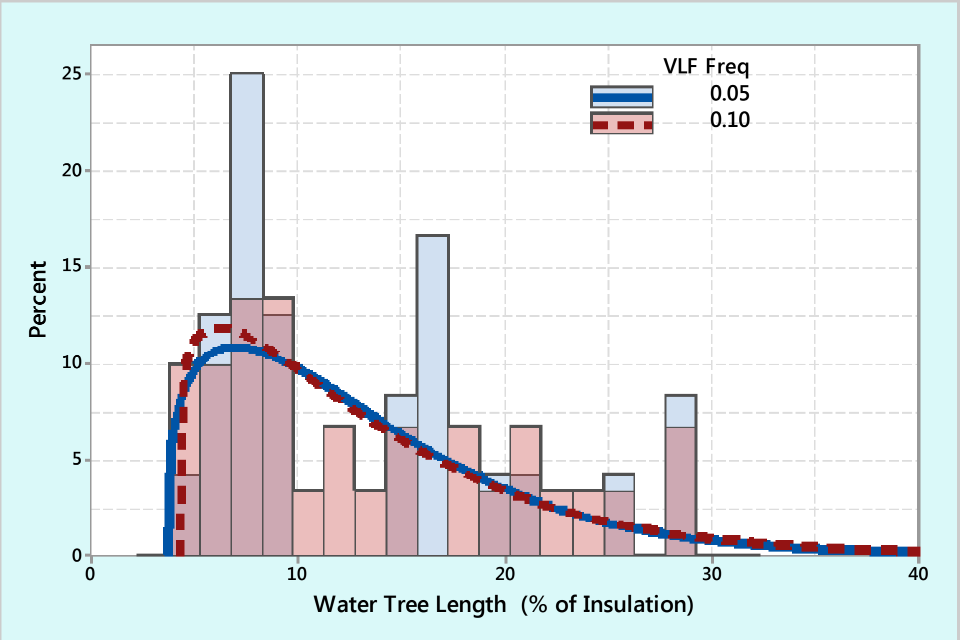


Figure 23: Water Tree Lengths Observed in Ashcraft Tests

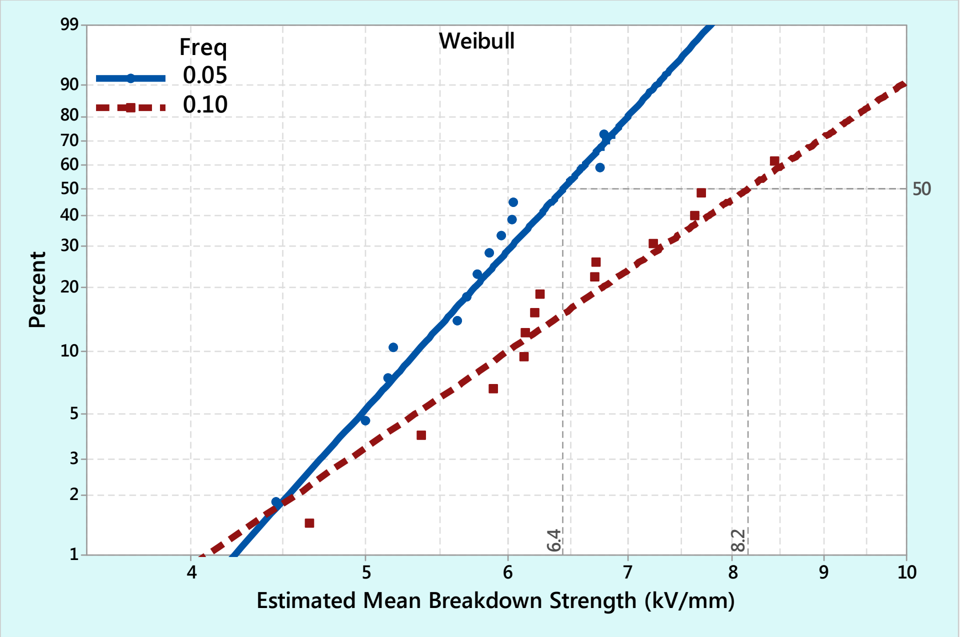


Figure 24: VLF Breakdown Voltages of Aged MV (EPR & PE-Based) Insulations After Accelerated Wet Aging (Separated by VLF Test Frequency)

As Figure 24 shows, the median ac breakdown strength (ACBDS) based on the mean breakdown stress using point to plane distance for this group of insulations was 6.4 kV/mm and 8.2 kV/mm for

0.05 and 0.1 Hz, respectively. The current IEEE Std. 400.2 test voltages for "maintenance" tests are 3.5 kV/mm and this work suggests that it would require a well treed cable system (i.e. tree growth through > 10% of the insulation) to fail purely as a result of water tree degradation. Figure 25 shows the ranges of breakdown strength as functions of water tree length.

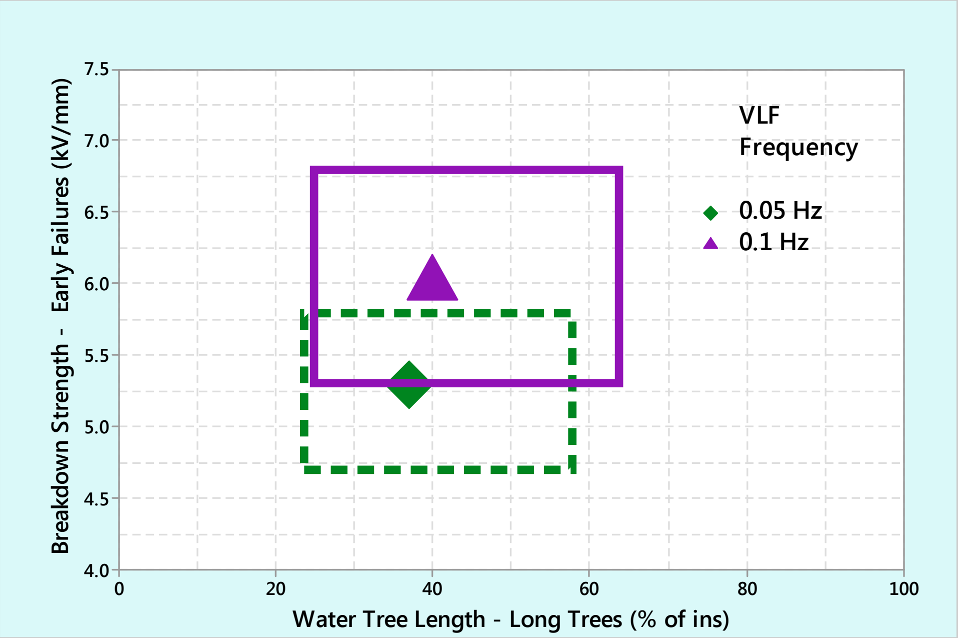


Figure 25: 95% Confidence Intervals of Breakdown Strength and Water Tree

It is also useful to examine the differences in breakdown stress between each of the insulation types: EPR, WTRXLPE, and XLPE. Figure 26 shows Weibull plots of the mean breakdown strengths for each insulation type and VLF frequency. Is it important to note that in all cases, the 0.05 Hz curve is the same or to the left of the 0.1 Hz curve. For reference, the mean stress of 3.53 kV/mm applied during a 15 kV class VLF Maintenance test (as defined in IEEE Std. 400.2) is shown.

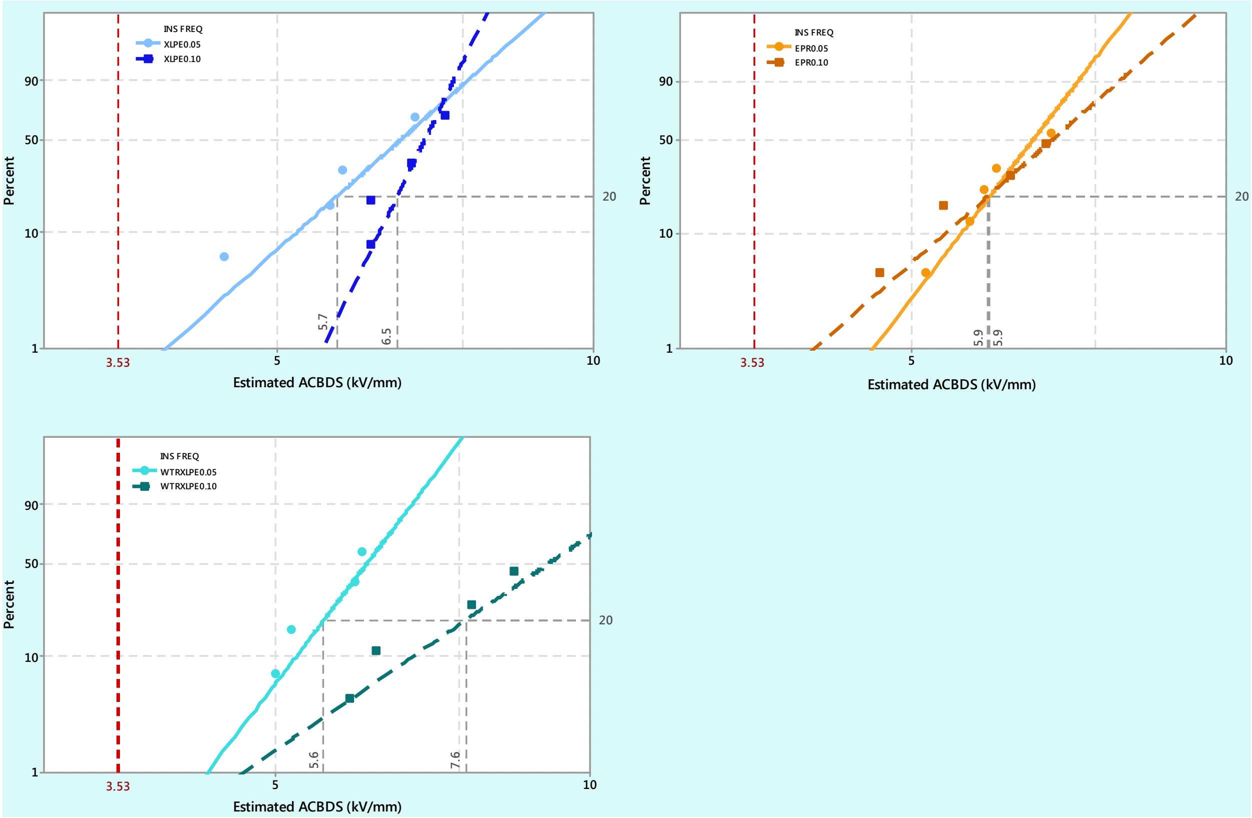


Figure 26: Weibull Mean Breakdown Stresses by Insulation Type

The breakdown data may be further examined using a boxplot as shown in Figure 27. As this figure demonstrates, the distributions for EPR and XLPE at the two frequencies overlap somewhat indicating there is not a significant difference between the different frequencies. On the other hand, there appears to be a much larger difference for the WTRXLPE breakdown data.

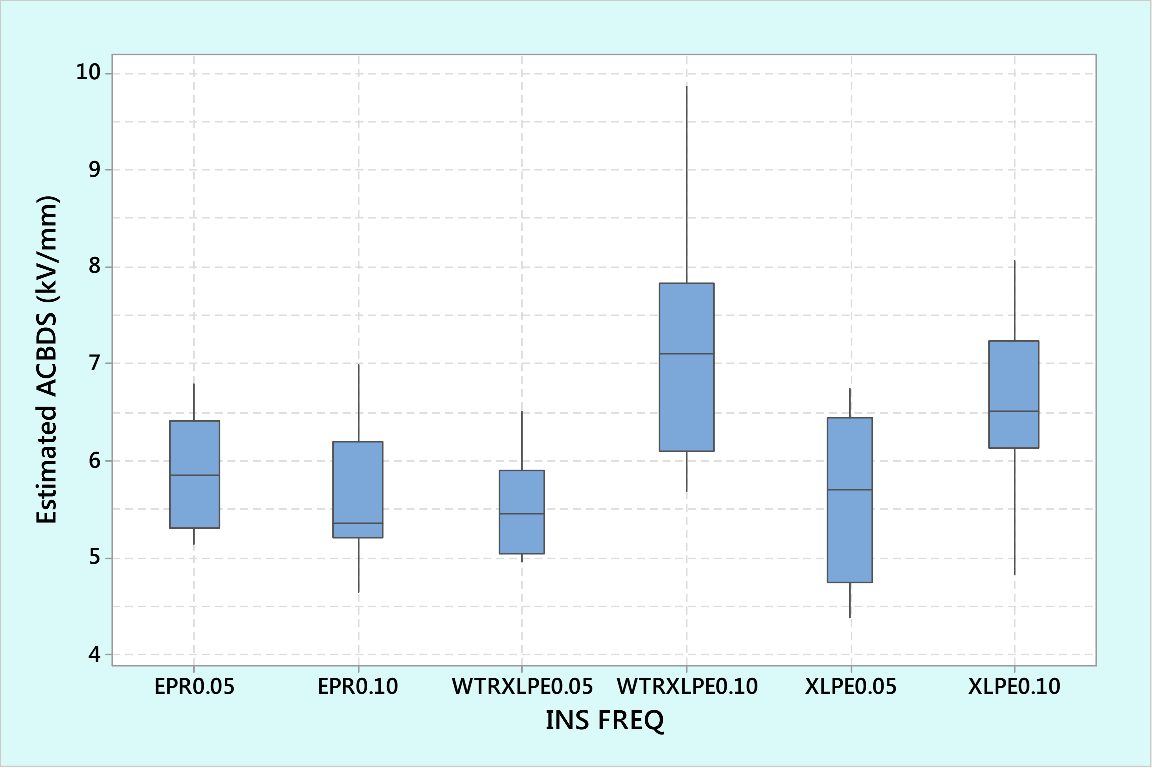


Figure 27: Estimated VLF Breakdown Stress Distributions for Insulation Materials and Frequencies (0.05 & 0.1 Hz)

Figure 24 through Figure 27 imply:

- The 0.05 Hz breakdown strength is likely lower (by 10 – 15%) than the breakdown strength at 0.1 Hz value.
- The notion of higher breakdown strength at lower frequencies (< 0.1 Hz) does not hold and so an increase in the test time is not supported for these lower frequencies.
- Testing at lower frequencies (often required for testing longer lengths) is no less effective and may be marginally more effective than at the more common 0.1Hz frequency.

9.6.8.2 Field Study of VLF Frequency Effects

Analysis was also undertaken on field data derived from tests on aged PILC cables in the field. The data set encompasses Simple VLF Withstand Tests made from 2004 to 2009 using a sinusoidal waveform voltage source. This covers 220 miles of PILC cable systems with a median length of 2 miles per test. Most interesting is that approximately 50% of the tests were undertaken with frequencies below the typical 0.1 Hz. All of the tests were conducted for 30 min at the IEEE Std. 400.2 recommended voltages for the cable systems. The test frequencies and cable system lengths are shown in Figure 28.

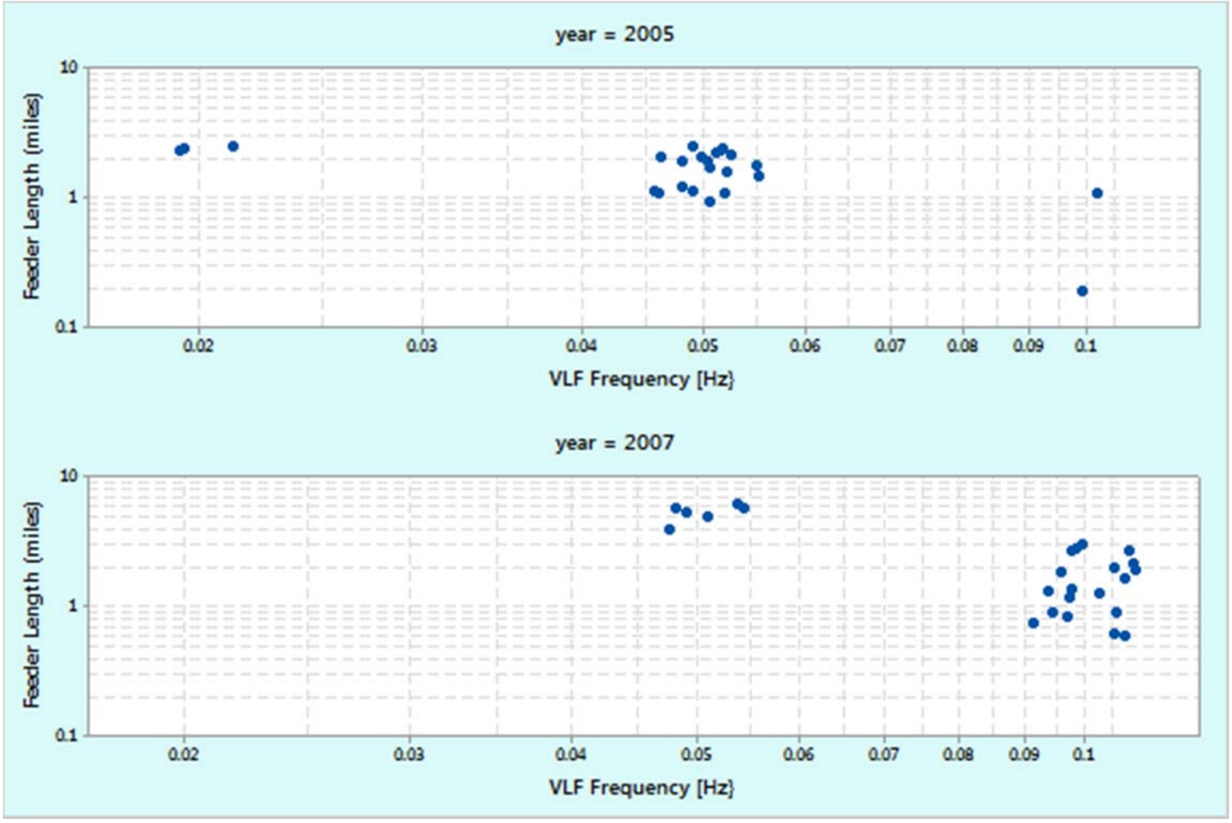


Figure 28: VLF Test Frequencies and Cable System Lengths

The records for these tests are very thorough with the lengths, frequencies, and outcomes all recorded making it possible to conduct a detailed analysis. Inspection of the records enables the ranges of the failure rates to be estimated (Table 9). The failure rates are low overall at 6%. However, the uncertainty in the estimate of the failure rate is large due to the small number of tests and the low number of failures. Although this is not optimal from an analytical point of view, it reflects the reality of trying to derive an understanding of data collected from the field. Nevertheless, using the number of tests as the basis the analysis indicates that there is no difference in failure rate resulting from the application of different test frequencies. The situation is the same if the analysis is extended to include circuit lengths.

Table 9: VLF Simple Withstand Failure Rates segregated by VLF Frequency based on both Tests Conducted and Lengths Tested

		VLF Frequency [Hz]	
		0.02 - 0.05	0.1
Length Based	**Length Failing [Miles]**	3	5
	Length Passing [Miles]	87	77
	Failure Rate (95% Confidence Limit)	1% – 9%	2% – 14%
Circuit Based	**Number Failing [Tests]**	3	3
	Number Passing [Tests]	46	45
	Failure Rate (95% Confidence Limit)	1.3% - 18%	1.3% - 18%

Included in the data are the times at which the failures occurred during testing as well as the number circuits that passed. Thus, it was possible to construct a Survival Curve (length adjusted) for the frequency segregated data as shown in Figure 29. This figure shows that, in addition to the ultimate percentages being the same, the survival curves are also the same at 30 min. Furthermore, this analysis again confirms the importance of keeping the Simple VLF Withstand tests as no less than 30 min tests. Reductions to shorter times should only be considered when using a Monitored Withstand test (see Chapter 10).

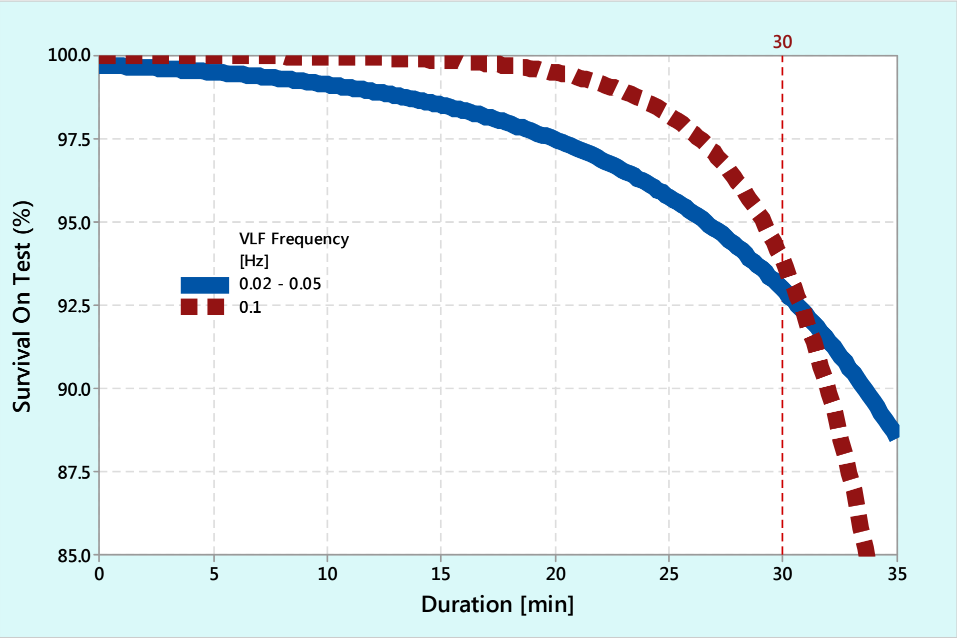


Figure 29: Survival Plot for VLF Tests at 0.1 and 0.02 - 0.05 Hz as Function of Time on Test

This analysis on PILC cable systems shows that data from the field does not display a frequency effect when similar cable systems are tested in the same manner.

The performance of all of these tested cable systems in service after VLF Simple Withstand testing was followed. Up until 2014 there were no dielectric failures recorded for any of the cable systems that were tested at the two voltage frequency groups outlined above. This time period represents considerable service experience: >450 mile-years for 0.02 -0.05 Hz and >200 mile-years for 0.1 Hz. It is likely that any deficiencies in the low frequency tests would have manifested themselves given this experience. Thus, there is no data to suggest that there is any different in the efficacy between the two VLF test frequencies.

9.6.9 VLF Voltage, Time, and Waveform Studies

9.6.9.1 Laboratory Study – Aged Cable

Although simple VLF withstand tests are routinely employed in the field, few if any 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 [16] 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; and
- Sequential application of VLF test and 60 Hz aging voltages. Figure 30 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 30 schematically illustrates the test program schedule.

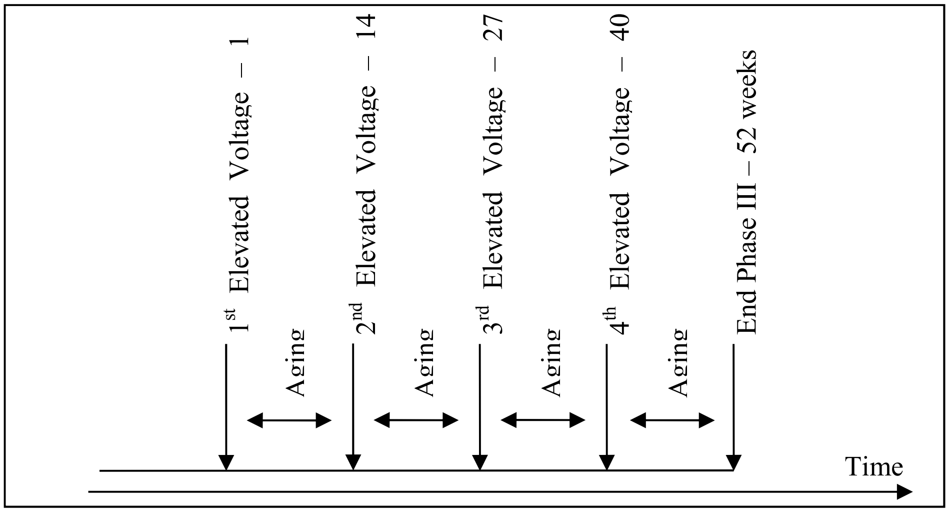


Figure 30: Laboratory Test Schedule for Impact of VLF Withstand Tests

The VLF Simple 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 10 and Table 11.

Table 10: 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)			Test Freq. [Hz]	Test Duration [min, *cycles]*	Failures			
		Multiple of		Actual RMS [kV]			During Aging [#]	Time to Failure During Aging [days]	Total Failures (During Aging and During VLF) [#]	Time on Test [min]
		Rated Voltage	Op Voltage							
1	280	None	None	--	--	--	0	N/A	N/A	N/A
2	280	1.8	2.2	16	0.1	15, 90	0	N/A	0	N/A
3	280	3.0	3.6	26	0.1	120, 720	0	N/A	3	51, 59, 78
4	280	2.1	2.5	18	0.1	60, 360	0	N/A	2	17, 28
5	280	1.8	2.2	16	0.1	120, 720	0	N/A	0	NA
6	280	3.0	3.6	26	60	0.25, 900	0	N/A	2	On Ramp

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

Table 11: 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)			Test Freq. [Hz]	Test Duration [min, *cycles*]	Failures			
		Multiple of		Actual RMS [kV]			During Aging [#]	Time to Failure During Aging [days]	Total Failures (During Aging and During VLF) [#]	Time on Test [min]
		Rated Voltage	Op Voltage							
1	280	None	None	--	--	--	0	N/A	N/A	N/A
2	280	1.8	2.2	16	0.1	15, 90	0	N/A	0	NA
3	220	3.0	3.6	26	0.1	120, 720	0	N/A	10	8, 11, 22, 23, 26, 28, 43, 43, 61, 91
4	240	2.1	2.5	18	0.1	60, 360	0	N/A	2	26, 59
5	280	1.8	2.2	16	0.1	120, 720	0	N/A	0	N/A
6	240	3.0	3.6	26	60	0.25, 900	2	0, 54	0	N/A

A number of useful results are noted from these tables:

- 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 2.2 U_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 (all at 2.5 or 3.6 U_0), only two failures occurred within the first 15 min of testing. Three failures occurred after 60 min on test.
- The absence of failures in the aging phase indicates that the VLF test conditions used do not appear to have allowed defects to remain that subsequently degraded "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 min test time and 3.6 U_0 test voltage). None of these conditions caused incipient defects that led to failure during the "service" aging 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 31 using a Weibull Analysis for the different VLF test voltages. As a 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 min.
- Only three of the 17 failures occurred at times in the range 60 to 120 min.
- More failures occurred using the cosine-rectangular waveform and 2 U_0 aging (Table 11) than occurred with the sinusoidal waveform and U_0 aging (Table 10).

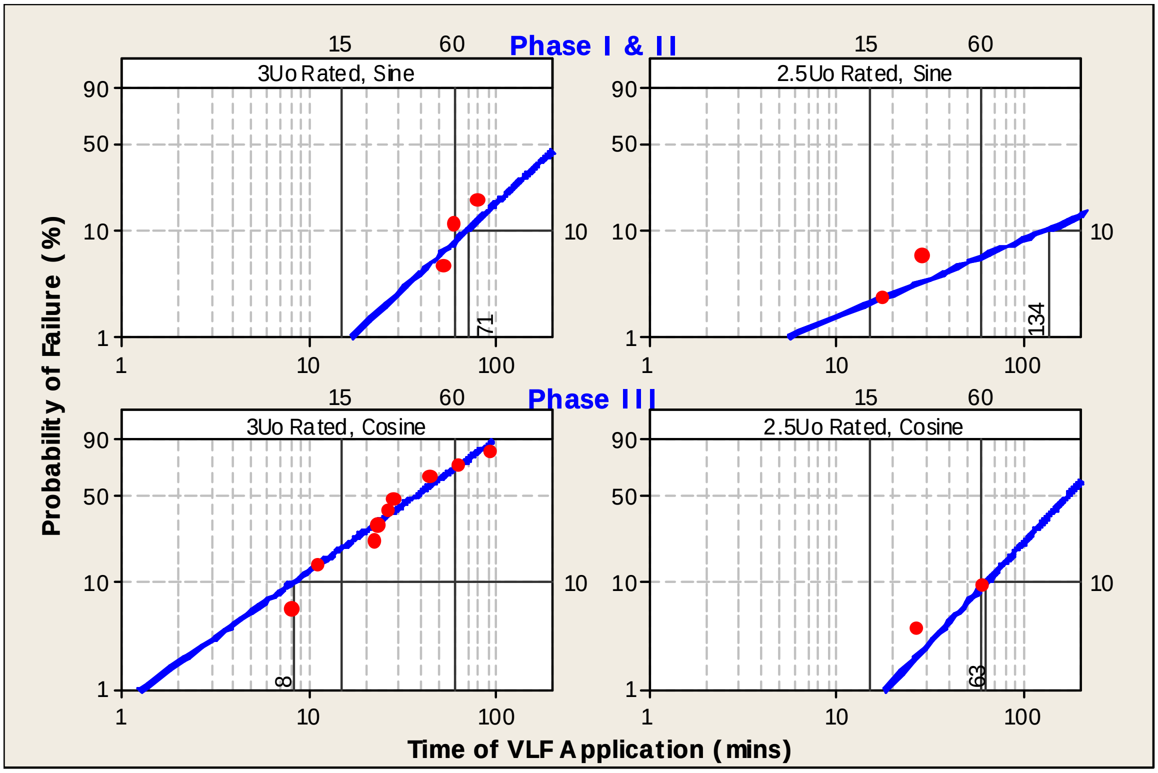


Figure 31: Weibull Analysis of Failures on Test for Phases I, II, and III [16]

Since no failures have occurred on samples tested at 2.2 U_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 31. 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 32. 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.

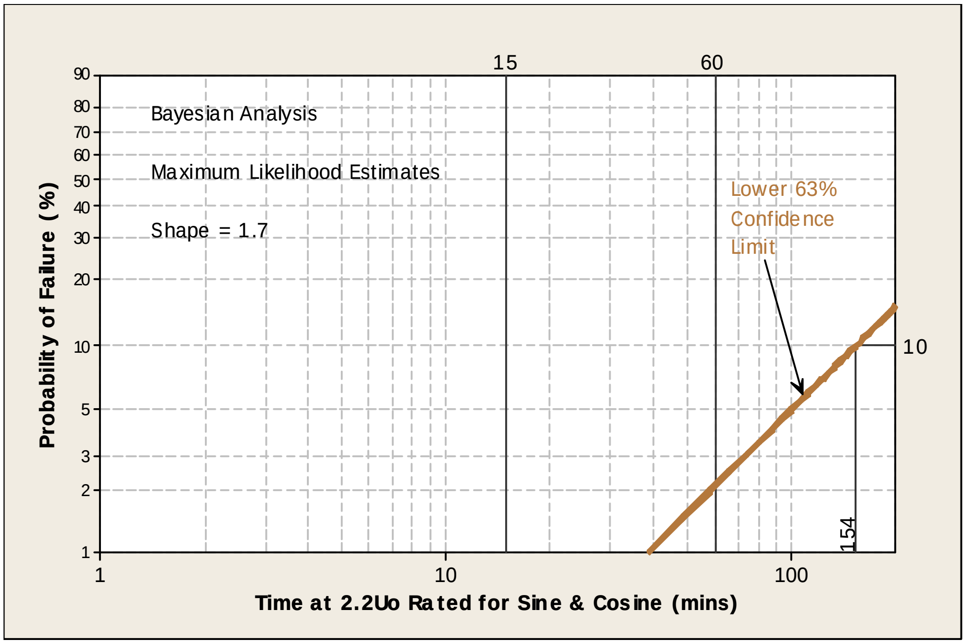


Figure 32: Bayesian Estimate of Weibull Curve for VLF Samples Tested at 2.2 U_0

Using the times on test for the 10% failure rate from Figure 31 and Figure 32, it is possible to plot time on test as a function of the test voltage for all three test phases. Figure 33 shows the results of this analysis. For all test phases, the increasing test voltage clearly translates into a shorter time on test (i.e. higher failure rate). It is important to 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.

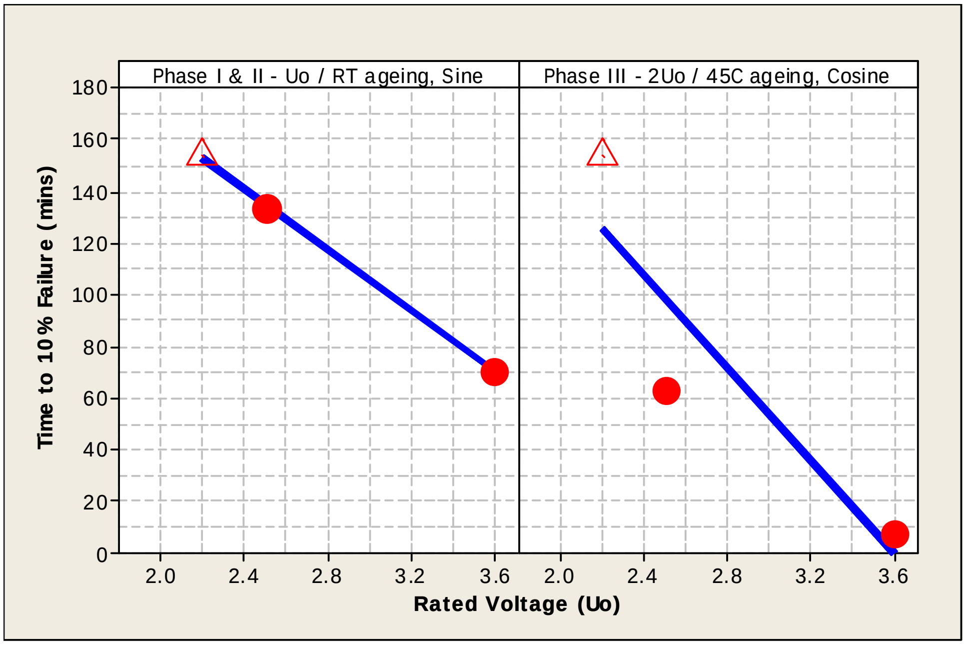


Figure 33: Failures on Test as a Function of Test Voltage [16]
(The Open Upward Arrow Shows that the True Estimate Lies Somewhere Above this Estimate)

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.

9.6.9.2 Field Study – Utility Cable Systems

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 34 shows an analysis of simple DC withstand tests for two types of tests, a regular withstand of 15 min 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 feeders within this single utility appear on this graph as different curves (symbol shapes indicate a specific region, open symbols are for proactive 15 min dc hipot tests while the closed symbols are for 5 min return to service dc hipot tests).

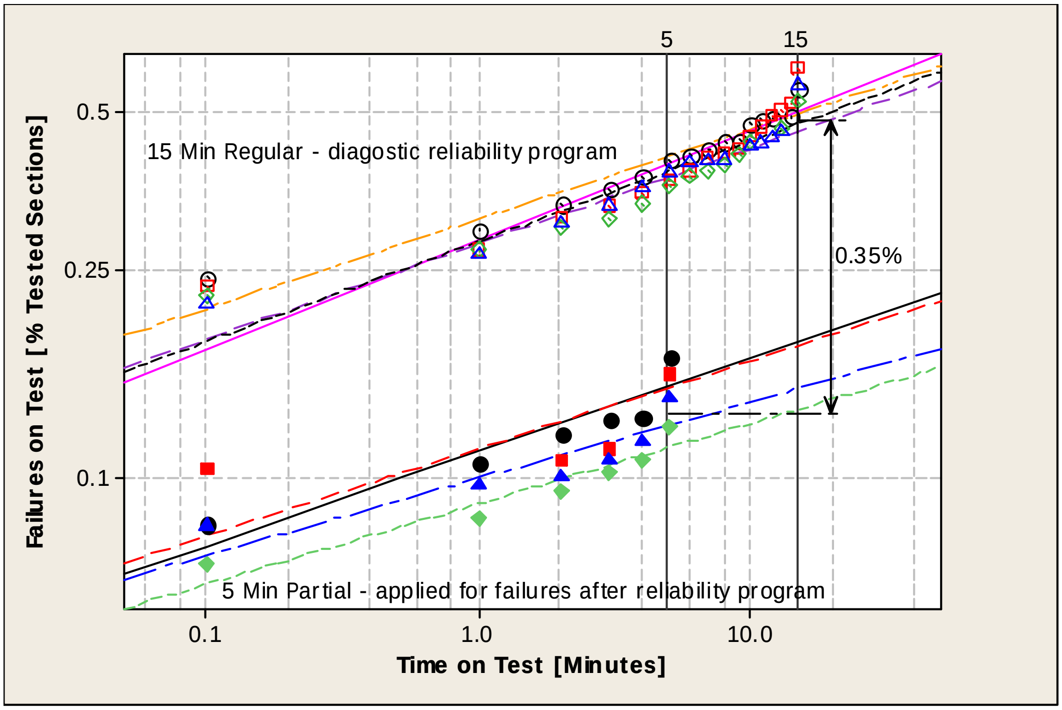


Figure 34: Failures on Test for Proactive (15 min) and Return to Service (5 min) DC Field Tests (Data are Size-Adjusted by the Number of Feeder Sections)

The analysis shown in Figure 34 provides an estimate of the effectiveness of each diagnostic test program. A number of points emerge in this analysis:

- The average likelihood of failure is much lower (0.12% for 5 min tests vs. 0.47% for the 15 min tests) after the cable section failed in a controlled manner and was then repaired. This implies that a weak location was removed.
- 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 min retest data has the same gradient and lower failure rate than the 15 min 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 35 shows the results of a service performance audit for one utility system with a hybrid cable system that utilized two different VLF Simple Withstand protocols. Both protocols were performed using sinusoidal VLF but with different voltage-time combinations. 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 min at 2.5 U_0 and 30 min at 1.8 U_0. The analysis uses censoring for the tests that have not resulted in service failures.

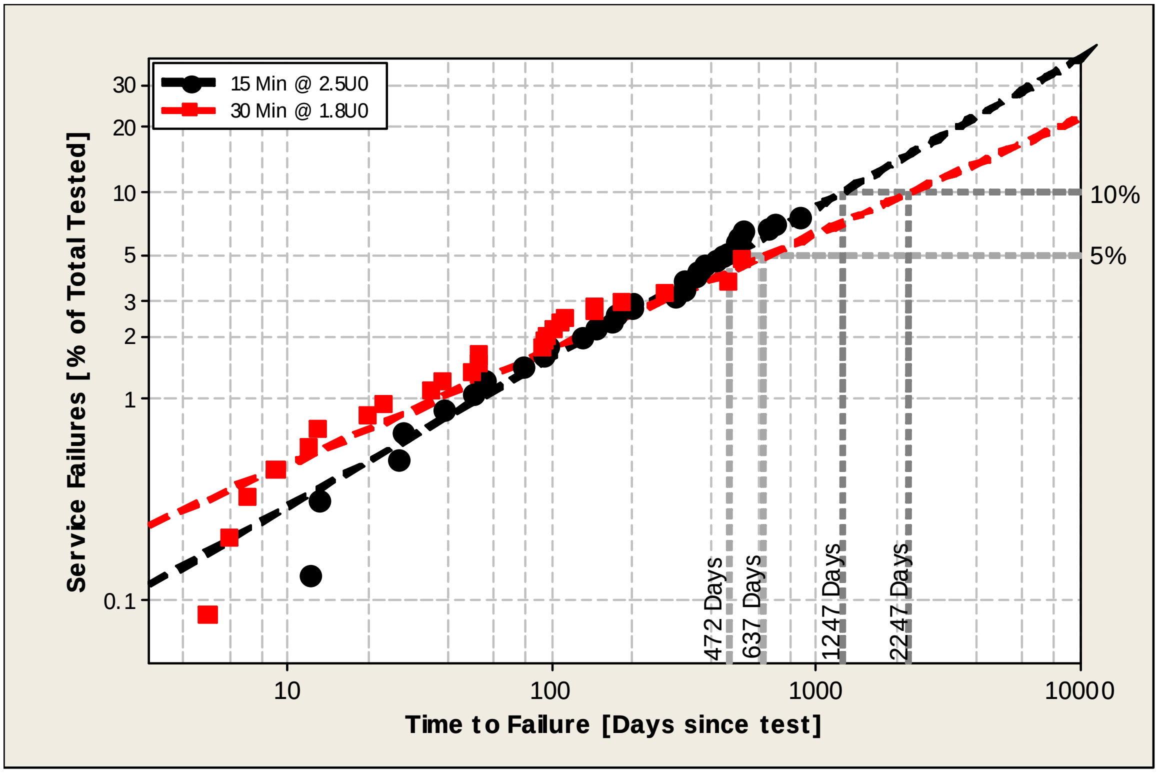


Figure 35: Distribution of Times to In-service Failure after a Simple VLF Withstand Test [14]

The results in Figure 35 show the percentage of tests that are likely to result in service failures. Inspection shows that for relatively short times, less than 200 days after test, the cable systems tested at the lower voltage (1.8 U_0) longer duration withstand test experienced more early service failures, but the failure rate itself is lower than for those cable systems tested at 2.5 U_0. 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 min 1.8 U_0 test program results in fewer service failures than the 15 min, 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 12.

Table 12: 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 Min @ 2.5 U_0	472	1247
30 Min @ 1.8 U_0	637	2247

The analysis in Figure 35 shows that in the long term the highest reliability results from a test of 1.8 U_0 for 30 min (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 36. The data shown in Figure 35 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 36:

a) 15 min test, no failures on test (left);
b) 30 minute test, no failures on test (right);
c) 15 min test, failure on test and repair (left);
d) 30 min test, failure on test and repair (right).

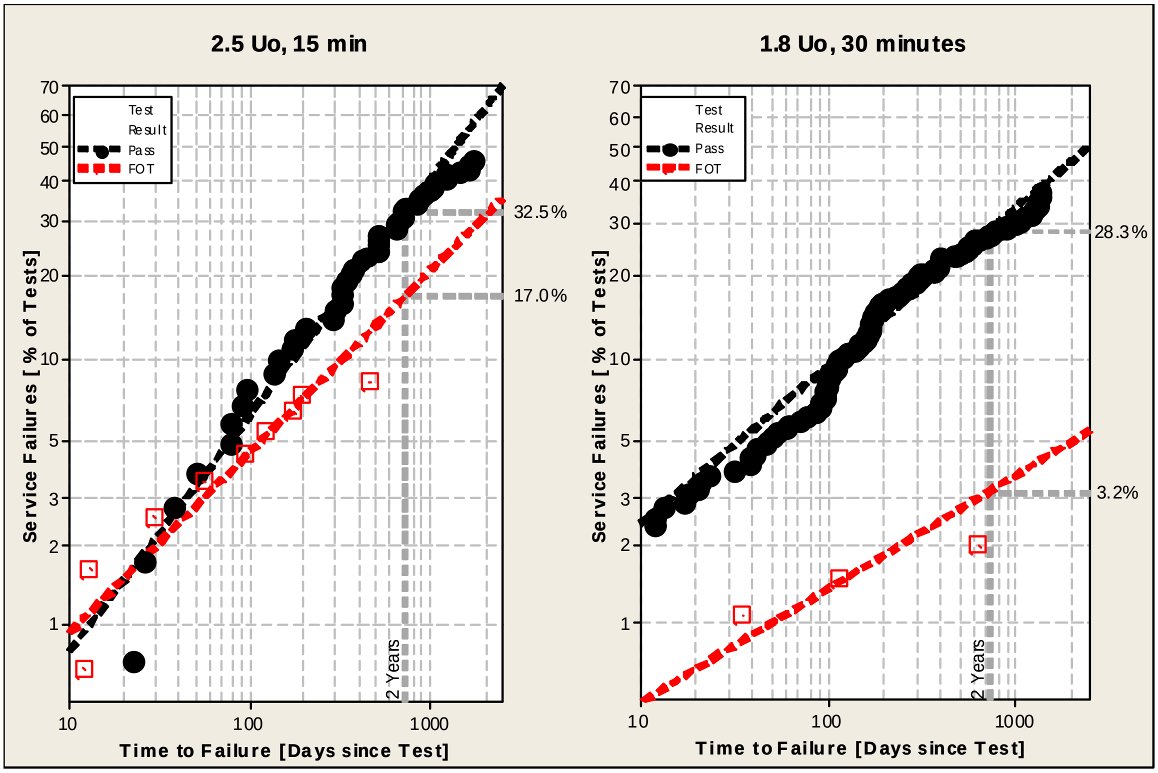


Figure 36: Time to In-Service Failure After Simple VLF Withstand Tests (3-Phase Sections) [14]

The in-service performance of cable segments after 15 and 30 min tests that did not result in failure on test (solid symbols) are quite similar. The research shows that 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 36 represent the tests that failed and were subsequently remediated. A number of points emerge:

- The likelihood of failure is notably 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.

Similar analyses were undertaken looking at traditional dc hipot testing and VLF Withstand. The following section discusses a case study in which the performance differences both on test and in service were examined for different testing protocol.

9.6.10 Case Study – Voltage and Time Formulations

Withstand tests using dc voltage were commonly employed on paper insulated cable systems. As extruded insulations became the standard cable system design used by utilities, a great deal of work was invested in explaining the observed negative effects of dc on these newer systems. As things now stand, dc is no longer recommended for general use on aged PE-based cable systems. However, some utility systems have evolved from their originally pure fluid impregnated paper insulated systems to hybrid systems containing both paper and extruded insulations (PE and EPR). As part of the CDFI, an extensive analysis of withstand test data and service performance data was undertaken to quantify the differences in performance between the traditional dc withstand test and VLF (0.1 Hz) withstand tests.

Two different cable systems voltages were analyzed. Each system was tested with two different test protocols (Table 13) as part of a proactive diagnostic program. The VLF protocols were implemented in October 2010. The dc protocols were implemented prior to 2001. It is important to recognize that the voltage-time formulations used in Simple Withstand tests cannot be treated independently. Equally important is the fact that manipulating one parameter has a non-linear effect on the other. As an example, doubling the voltage does not allow the test time to be halved. The time serves one function (growing defects to failure) while the voltage serves another (initiating defects to grow).

Table 13: Withstand Test Protocols

System Voltage [kV]	Source Type	Test Voltage [kV]	Test Duration [min]
13	dc	30	15
	VLF	15	30
27	dc	60	15
	VLF	25	30

As mentioned above, the analysis is split between performance on test and Service Performance resulting from the use of the different withstand protocols. The performance on test is discussed first.

9.6.10.1 Performance on Test

This section focuses on the Pass/Fail rates of the circuits tested using the withstand protocols in Table 13. Figure 37 provides an overall comparison of the dc protocols (top) with the VLF protocols (bottom) and separates the test results into Pass, Fail (Ramp & Hold) and Unknown. These correspond to the following interpretation:

- Pass – No failure (dielectric puncture) during the withstand test.
- Fail – Failure (dielectric puncture occurs) during the withstand test. Ramp and Hold describe which phase of the test the failure occurred in.
    - Ramp – Beginning of the test when the voltage is raised at a rate of 1 kV/s to the final test voltage. This phase lasts 15 – 60 s depending on the intended test voltage.
    - Hold – Test voltage is held at the target voltage. This phase lasts 15 – 30 min depending on the protocol.
- Unknown – Data do not clearly indicate the result of the test.

As Figure 37 shows, the Pass rates for the two VLF protocols (88% and 82%) are significantly higher than those for the dc protocols (45% and 22%). This figure also demonstrates that many of the failures on test in these cable systems occur during the voltage ramp before the final test voltage is reached.

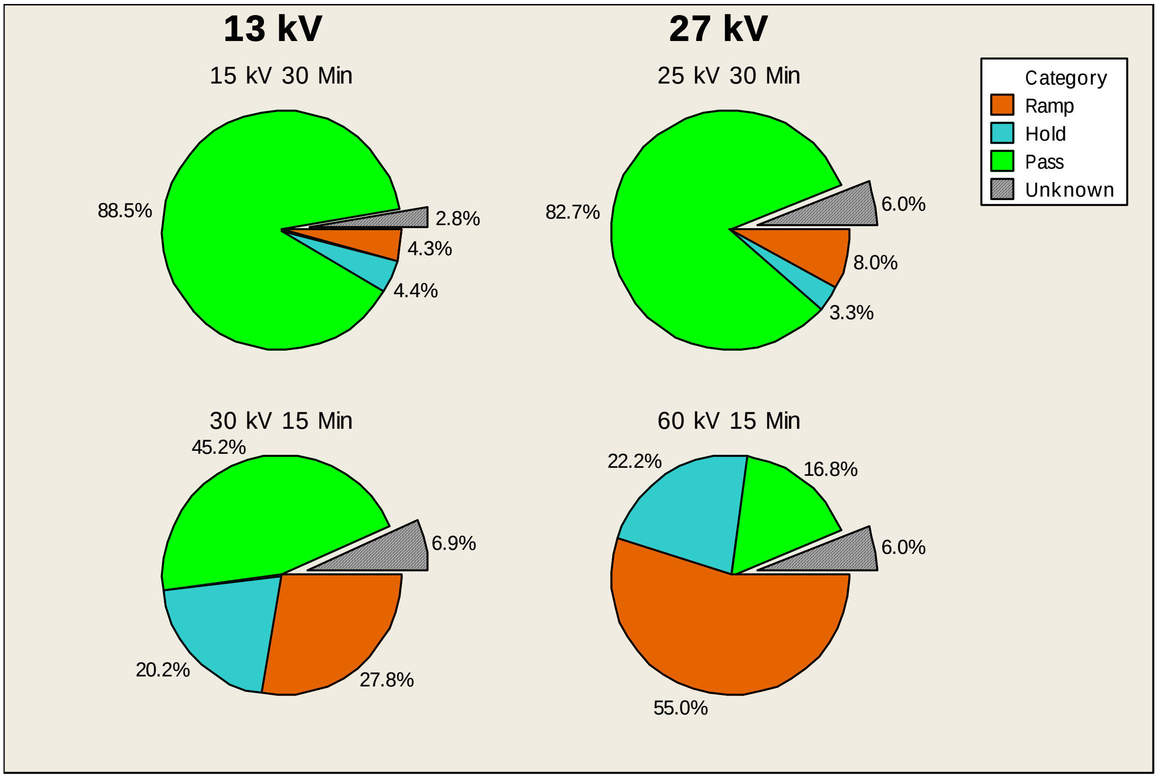


Figure 37: Comparison of VLF (Top) and DC (Bottom) Protocols for 13 kV (left) and 27 kV (Right) Cable Systems

The above data can be resolved into four different Survivor Curves. Figure 38 shows the historical Survivor Curves with the addition of the dc and VLF curves for the data discussed above.

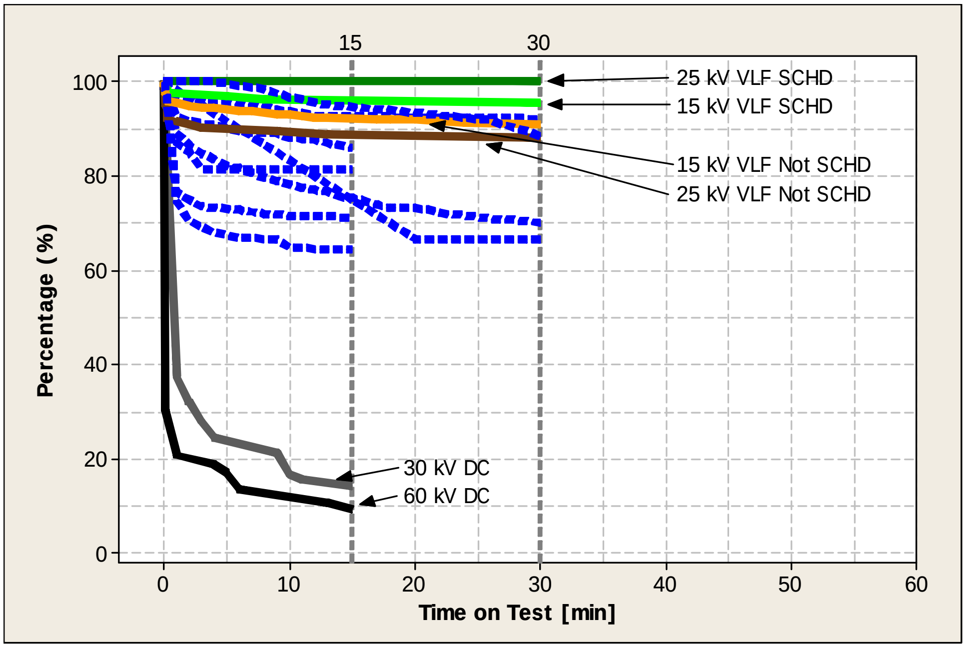


Figure 38: Survivor Curves with New VLF Protocols (US Utilities are represented by dashed lines)

As Figure 38 illustrates, there are significant differences between the dc protocols at this utility and the VLF protocols currently in use in the North America. The data available for the 13 and 27 kV systems under investigation here allow the VLF tests to be split into “scheduled” (proactive) and “unscheduled” (after work or repair). In both scheduled and unscheduled cases, the survival rates on test are well above 85% while the dc protocols are both less than 20%.

It is worthwhile to examine the cable systems one system at a time as the protocols were implemented at different times.

13 kV System

The Weibull curves for the dc and VLF protocols employed on the 13 kV system are shown in Figure 39. As these curves illustrate, the performance during the Ramp phase is quite different from that of the Hold phase. As the 30 kV 15 min dc curve shows, once the time exceeds 20 sec (20 kV according to the established ramp rate) the slope increases dramatically within the Ramp phase. Once the 30 kV test voltage for these tests is reached (Hold phase), the slope decreases and, in fact, looks remarkably like the slope for the 15 kV 30 min VLF curve. It can be argued that a reduction of test voltage in the dc test would have eliminated the steep portion of the dc Ramp phase curve. This would have the effect of avoiding a large number of failures from the Ramp phase. Unfortunately, this modification could not be verified with field tests.

Since the Hold phase portions of both curves appear to have similar slopes, it is reasonable to assume that the lower VLF test voltage has not led to a higher failure rate during the Hold phase. Overall, this suggests that the high voltage (> 20 kV) was causing unnecessary failures to occur in the dc protocol.

Overall, the performance on test for the 13 kV system improves significantly from a failure rate of 48% under dc to only 8% with VLF with the voltage modification.

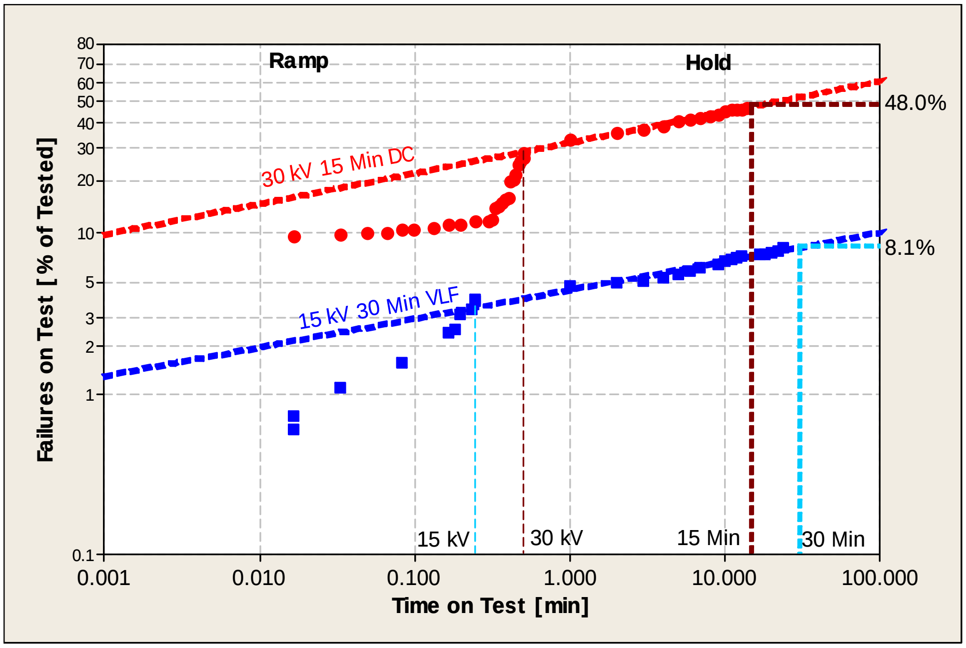


Figure 39: Weibull Analysis of DC (Red) and VLF (Blue) Protocols (not Length-Adjusted)

The performance improvement can be further investigated using Weibull Analysis such that the relative contributions of the different protocol changes can be estimated. Figure 40 shows the performance change caused by each protocol modification. The red text below each bar shows what test parameter was changed from the adjacent bar. The left most bar represents the 30 kV, 15 Min dc protocol while the far right bar represents the final VLF test protocol.

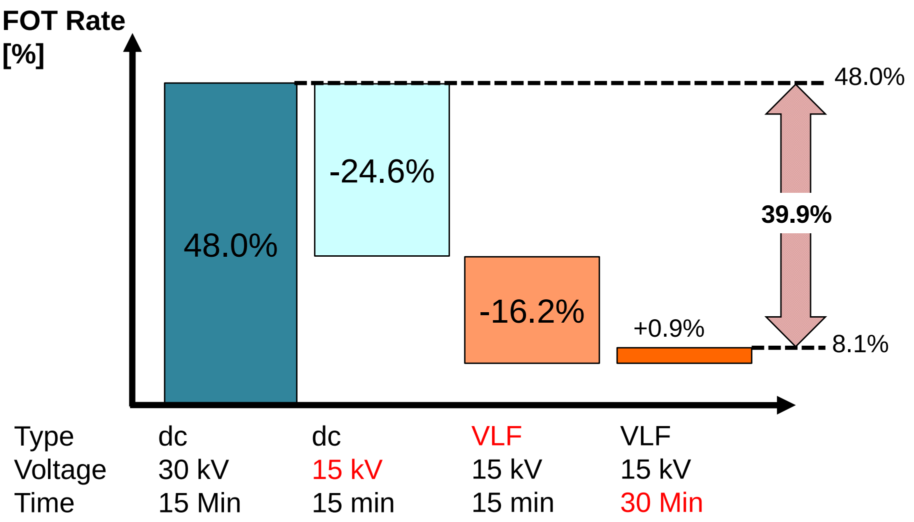


Figure 40: Performance Changes by Protocol Parameter (Red Indicates the Test Parameter that Changed from Column to Immediate Left)

Figure 40 shows that if the test voltage were reduced from 30 kV to 15 kV, the failures on test would be reduced by over 50% (reduced from 48% to 23.4%). A further reduction of 33% occurs by switching the voltage from dc to VLF (reduces failures on test from 23.4% to 7.2%). The final component, the time increase from 15 to 30 minutes produces a small increase in the failure rate of 0.9% thus yielding the final failure on test rate of 8.1%.

27 kV System

A similar analysis to the one discussed above can be applied to the data from the 27 kV system. The Weibull curves for the dc and VLF protocols are shown in Figure 41. Again, the performance improvement in going from dc to VLF is significant (81.2% for dc and 12.1% for VLF). The key difference appears to be the voltage level.

The primary difference is again in the voltage reduction. Thus, far fewer failures occur during the Ramp phase of the VLF protocol than had occurred with the dc protocol.

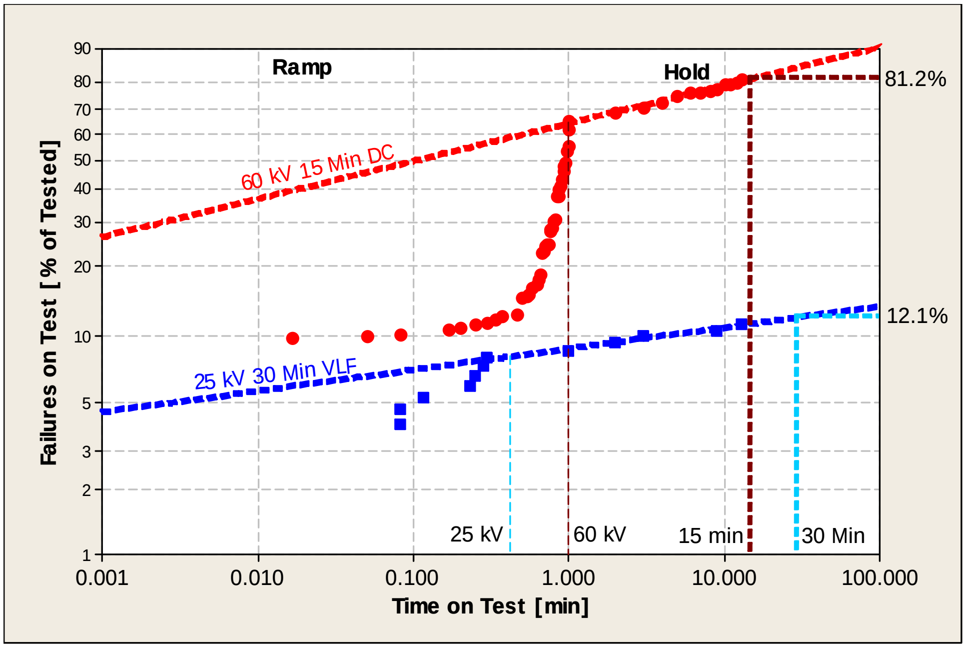


Figure 41: Weibull Analysis of DC (Red) and VLF (Blue) Protocols (not Length-Adjusted)

Estimates of the effects of the different protocol parameters can also be made as shown in Figure 42. The red text below each bar shows what test parameter was changed from the adjacent bar. The left most bar represents the 60 kV, 15 Min dc protocol while the far right bar represents the final VLF test protocol.

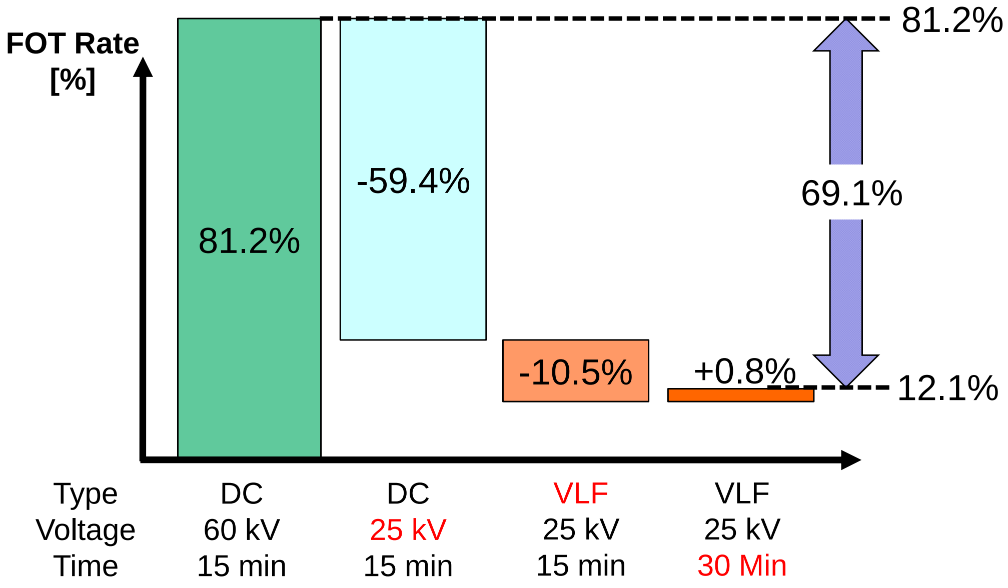


Figure 42: Performance Changes by Protocol Parameter
(Red Indicates the Test Parameter that Changed from Column to Immediate Left)

Figure 42 shows that the reduced test voltage contributes to a reduction in failures on test of over 72% (failures on test reduced from 81.2% to 21.8%). A further reduction of 13% occurs by switching the voltage from dc to VLF (reduces failures on test from 21.8% to 11.3%). The final component, the time increase from 15 to 30 min again produces a small increase in the failure rate of 0.8% thus yielding the final failure on test rate of 12.1%.

Clearly, both 13 and 27 kV systems experience far fewer failures on test using the VLF protocols than they had using the dc protocols. The question that remains is how this affects the service performance of these systems. The concern being that fewer failures on test could lead to more failures in service. Section 9.6.10.2 examines this question in detail.

9.6.10.2 Service Performance

Service performance data may be analyzed a number of different ways. In this research, the Crow-AMSAA technique was used as this method is very useful for identifying performance changes. In its most basic form, Crow-AMSAA plots cumulative failures versus cumulative time or experience on log-log scales. The idea is to then use linear regression fits to identify regions with similar slopes. The slopes are proportional to the failure rate and so changes in slope correspond to changes in failure rates (i.e. increase in slope = increase in failure rate). Figure 43 illustrates this graphically using artificial data.

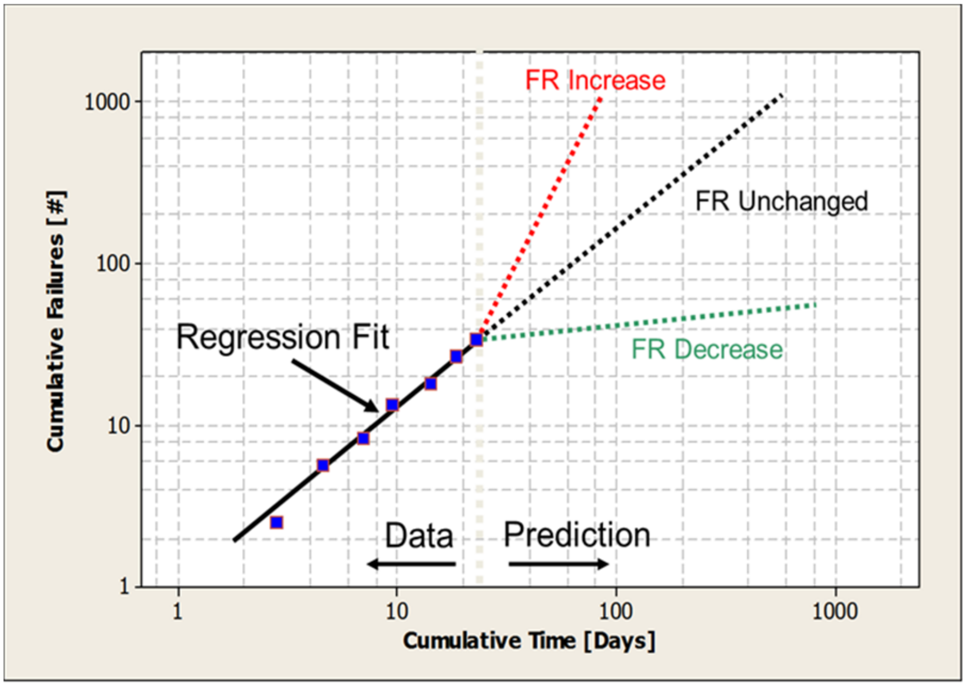


Figure 43: Basic Interpretation of Crow-AMSAA Technique

The linear regression fits may also be used to make predictions about performance in the future assuming the failure rate remains constant.

The service data for the 13 and 27 kV systems are plotted in Figure 44 in Crow-AMSAA format going back to 2004. Figure 45 shows an expanded view of Figure 44 and focuses on service data after 2007.

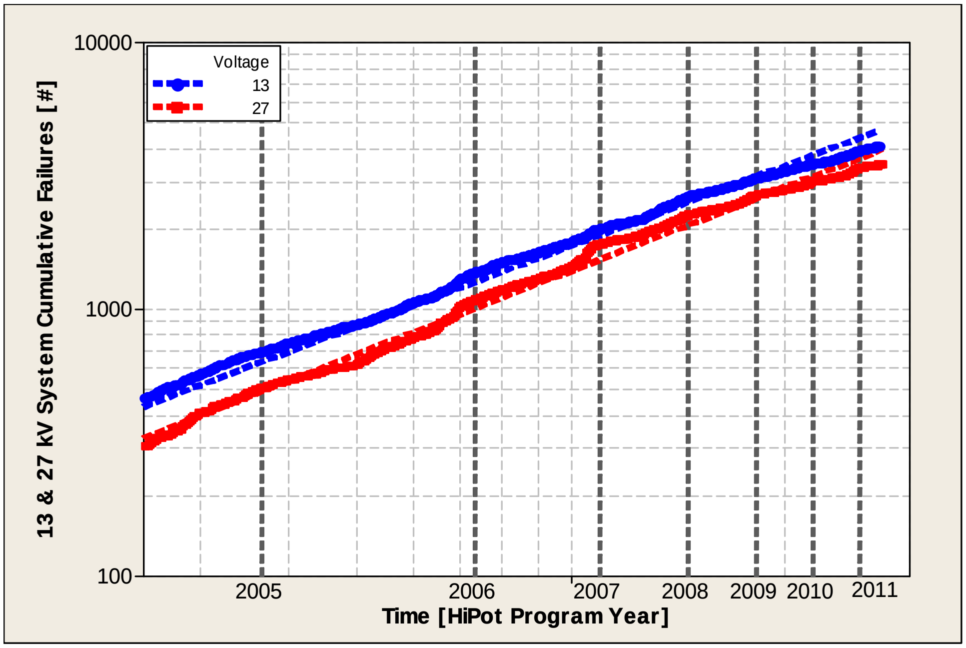


Figure 44: Crow-AMSAA Plot for 13 kV (Blue) and 27 kV (Red) Systems Since 2003

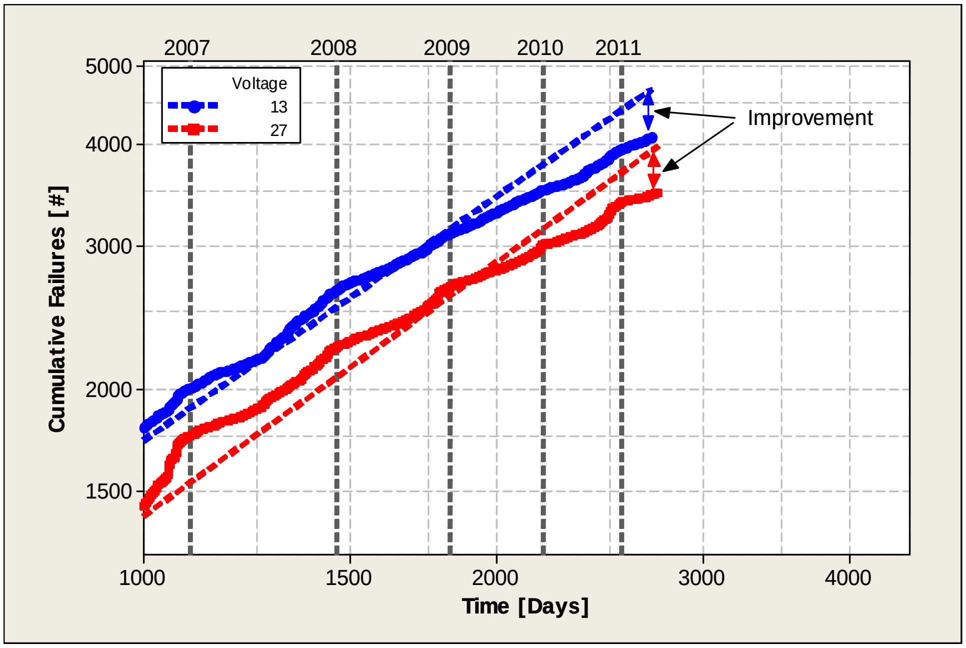


Figure 45: Expanded View of Figure 44 Showing Failure Rate Reductions on Both Systems

Figure 44 shows the failure rate on both systems was relatively constant up to 2008. The ups and downs are indicative of seasonal conditions. This particular utility is a summer utility and so the "ups" correspond to the summer periods. Note that the year designations correspond to September of the previous year through August of the named years. In other words, “2006” as shown on these graphs corresponds to September 1, 2005.

Figure 45 shows both the cable system data points as well as the regression fit that uses all the data back to 2004. Clearly, the slope indicated by the data after 2009 is shallower than the slope of the regression line. This indicates the failure rate at present is actually lower than would have been expected based on the past failure data. This reduced failure rate began prior to the implementation of the VLF protocols and was likely due to a number of other system enhancements. The important point to note is that the failure rate has not increased since the switch to VLF. As discussed above, the concern was that the reduction in failures on test would lead to more failures in service. This is clearly not the case. The VLF protocols do not appear to have reduced the reliability of either cable systems.

In order to provide a more quantitative comparison of the system performance, failure estimates for one year were made using the 2009 – 2011 service data. These estimates consider system service performance with the dc protocol (2009 – 2010) and the VLF protocol (2010 – 2011). Figure 46 shows four Crow-AMSAA curves in order to complete the estimates for both types of protocols on each of the cable systems.

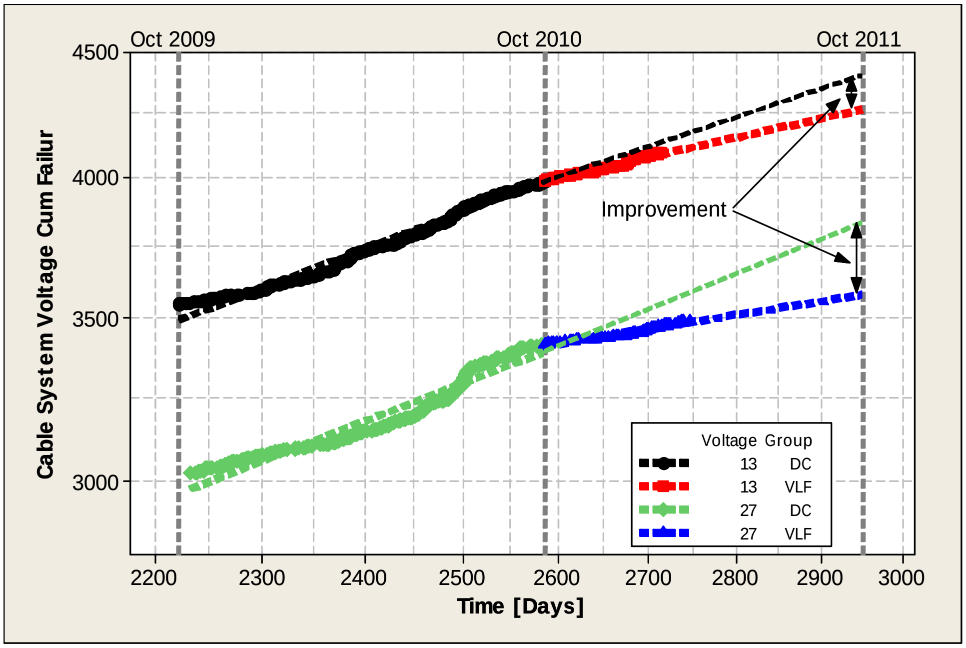
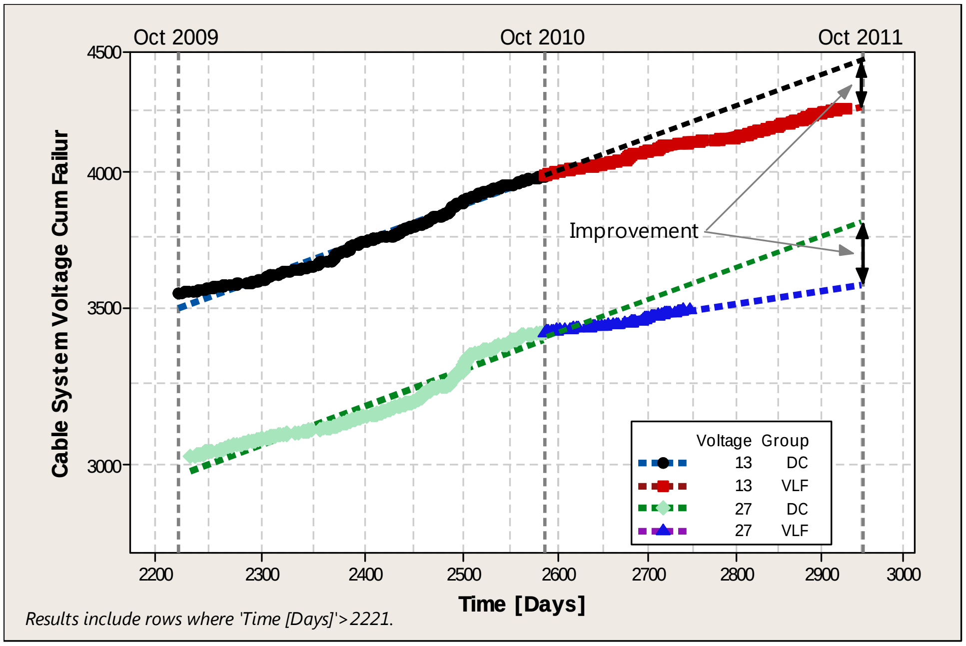


Figure 46: Annual Forward and Reverse Failure Projections (at time of analysis)

A close examination of Figure 46 shows that the slopes after October 2010 are slightly lower than those before 2010. Figure 47 shows the actual performance as monitored by the utility.



Results include rows where 'Time [Days]'>2221.

Figure 47: Actual Performance 13 kV System

As Figure 47 shows, the service performance for the 13 kV system continued with the same gradient as shown in Figure 46. Using this information, the differences in the two programs can be estimated. Table 14 shows the resulting estimates and indicates the total failures for 2010-2011 are 40.4% and 60.1% lower than the 2009-2010 levels for the 13 and 27 kV systems, respectively.

Table 14: One Year Failure Performance Estimates

System Voltage [kV]	Type	Total Service Failures (1 Year Prediction) [#]
13	dc	492
	VLF	276
27	dc	427
	VLF	167[1]

[1] – Projections based on available data

This information is useful for comparison purposes; however another way to utilize these data is in a techno-economic capacity. This is discussed in the following section.

9.6.10.3 Techno-Economic Analysis

Avoiding failures both on test and in service carries a certain technical benefit for the utility. On the other hand, it is useful to try and quantifying an economic benefit for the utility. One way of approaching this is to examine the time the utility was spend implementing and repairing the system. After all, one of the issues that is often raised is the fact that 30 min is twice as long as 15 min.

Within this utility, a repair is reported to require on average 53 h to complete. In addition, a Simple Withstand test is also performed after any repair either on test or in service.

As a result of the differences both on test and in service, the VLF Simple Withstand program yields a net savings of over 55,000 crew hours over the course of the one year program. This includes 140 avoided failures on test and 801 service failures.

Table 15: Summary of Techno-Economic Case for dc and VLF Simple Withstand Programs

Component	**DC** **30 kV for 15 Min**	**VLF** **15 kV for 30 Min**
Set Up Time [1 hour / test]	**600 h**	**600 h**
Test Time	**150 hrs**	**300 h**
Time to Repair FOT [est 53 hours / failure]	**15,264 h** (288 FOT's)	**2,544 h** (48 FOT's)
Modified HiPot (After Repair)	**24 h** (5 Min HiPot)	**24 h** (30 Min HiPot)
Out of Service Time	**16,038 h**	**3,468 h**
Service Failures	**111,459 h** (2,103 OA's)	**69,006 h** (1,302 OA's)
Overall Program Difference	**55,023 h** (140 Avoided FOT's & 801 Avoided OA's)	

9.6.11 Diagnostic Aspects of Simple Withstand Tests

Withstand tests are sometimes 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 48 through Figure 50 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 20 and Figure 10). Figure 48 shows the situation for a combination of four regions from within a single utility system (the early failures are not shown in Figure 48 but are accounted for using censoring). The combined Failure on Test rate for these four areas is different from those mentioned above. Figure 50 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.

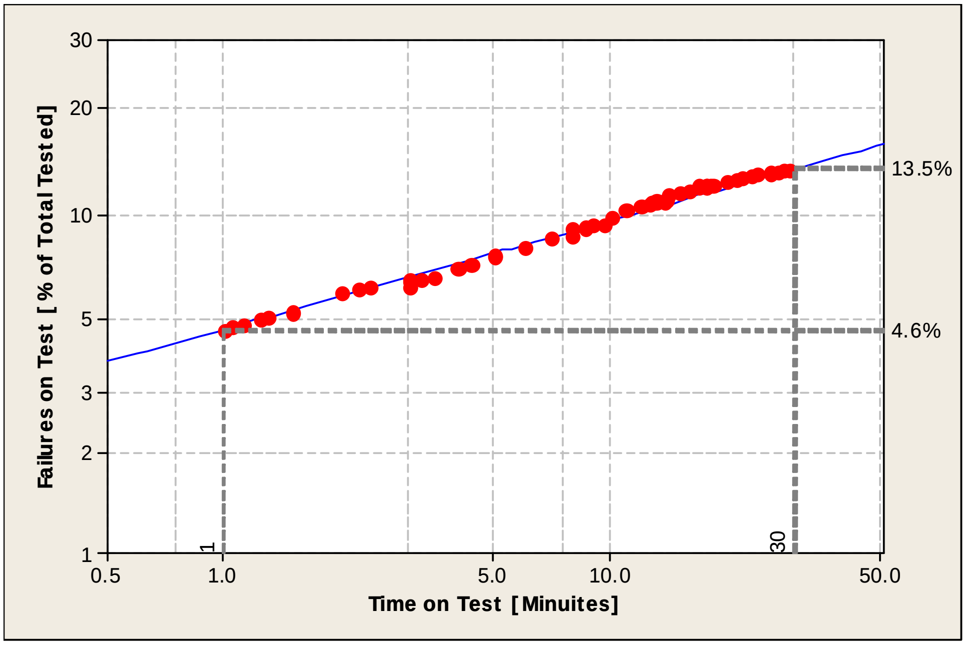


Figure 48: Failures on Test for Four Regions (Combined) within a Utility System (Data Adjusted for a Length of 1,000 feet)

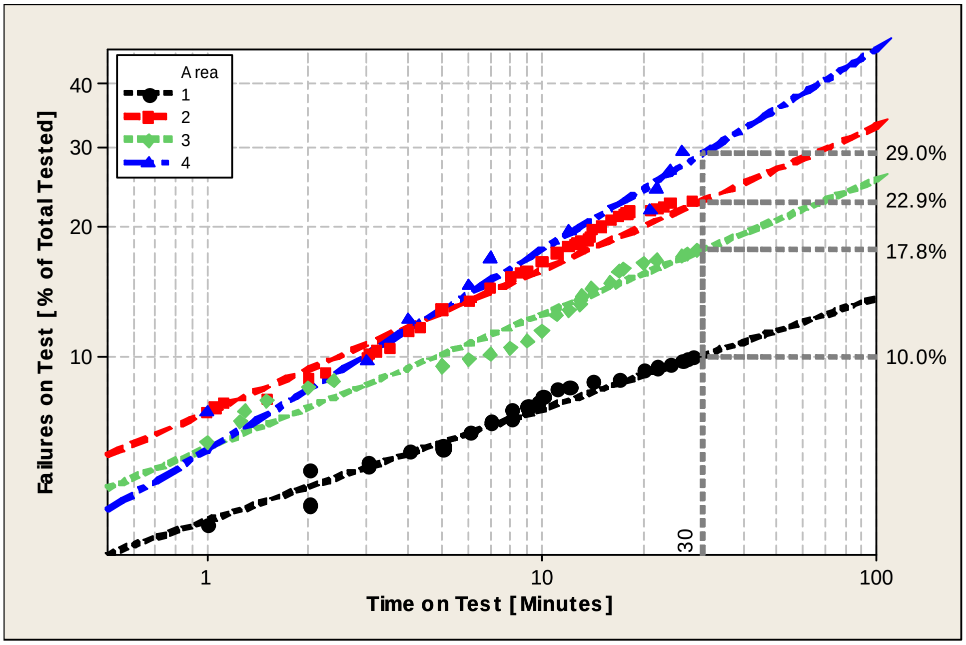


Figure 49: Failures on Test for Four Regions (Segregated) within a Utility System (Data Adjusted for a Length of 1,000 feet)

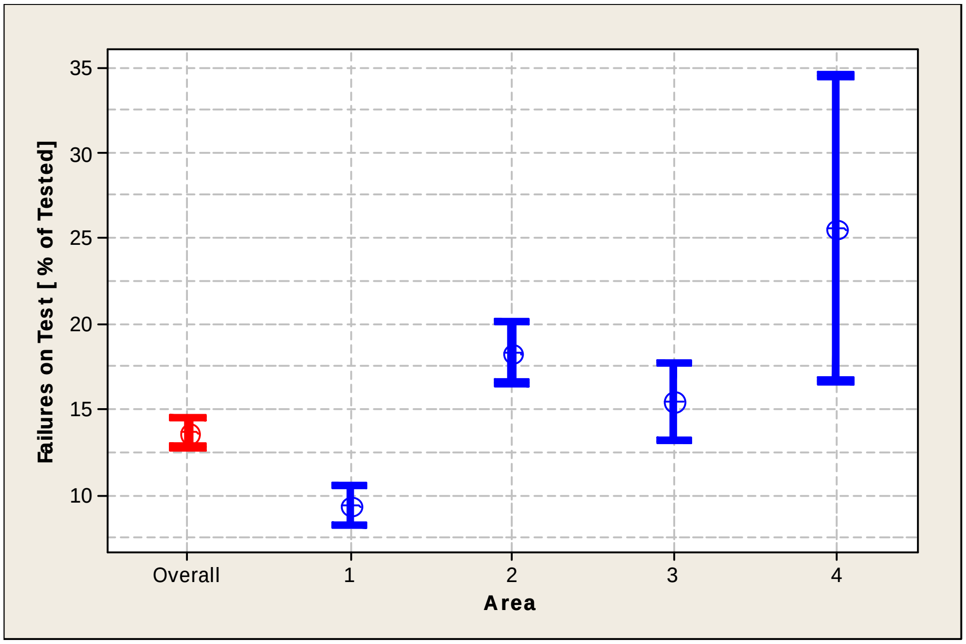


Figure 50: FOT Estimate at 30 minutes for Four Regions (Segregated) within a Utility System (Data Adjusted for a Length of 1,000 feet, 95% Confidence Limits Shown)

Simple Withstand is a widely deployed diagnostic technique that is applicable to all cable systems. Unlike all other diagnostic techniques, Simple Withstand can be applied to hybrid systems regardless of the combination of insulation materials and accessories.

9.7 Outstanding Issues

There only outstanding issue remaining for Simple Withstand is the comparison of VLF frequencies to performance under 60 Hz ac. A similar experiment to that discussed in Section 9.6.8.1 could be conducted for VLF and 60 Hz.

9.8 References

1. L.A. Dissado, and J.C. Fothergill, "Electrical degradation and breakdown in polymers," IEE Materials and devices series 9, Peter Peregrinus Ltd., London, 1992
2. J. Densley, "Aging Mechanisms and Diagnostics for Power Cables-An Overview," IEEE Electrical Insulation Magazine, vol. 17, no. 1, pp. 14-22, Jan. /Feb. 2001.
3. IEEE Standard 400.2-2004, *IEEE Guide for Field Testing of Shielded Power Cable Systems Using Very Low Frequency (VLF),* 2005.
4. ICEA S-94-649-2004, *Standard for Concentric Neutral Cables Rated 5 through 46 kV,* 2004.
5. P. Mohaupt, M. Baur, and T. Schlick, "VLF Testing and Diagnosis on Medium Voltage Power Cables," IEEE 10th Inter. Conf. on Transmission and Distribution Construction, Operation, and Live Line Maintenance, pp.202-209, Apr. 2003 IEEE ESMO.
6. C. Goodwin, "Practical Smart Withstand Programs for MV Cable Systems," IEEE Insulated Conductors Committee, Subcommittee F Spring 2010.
7. IEEE Standard 400-2001, *IEEE Guide for Field Testing and Evaluation of the Insulation of Shielded Power Cable Systems,*. 2002.
8. IEEE Standard 400.2/D8, *Guide for Field Testing of Shielded Power Cable Systems Using Very Low Frequency (VLF),* 2003.
9. M. Kuschel, R. Plath, I. Stepputat, and W. Kalkner, "Diagnostic techniques for service aged XLPE insulated medium voltage cables," *International Conference on Insulated Power Cables, JICABLE95*, pp. 504 – 508.
10. G. S. Eager, C. Katz, B. Fryszczyn, J. Densley, and B. S. Bernstein, "High Voltage VLF Testing of Power Cables," IEEE Transactions on Power Delivery, vol. 12 no. 2, pp. 565–670, 1997.
11. H. R. Gnerlich, "Field Testing of HV Power Cables: Understanding VLF Testing," IEEE Electrical Insulation Magazine, vol. 11, no. 5, pp. 13–16, Sep./Oct. 1995.
12. S. C. Moh, "Very low frequency testing—Its effectiveness in detecting hidden defects in cables," 2003 CIRED (17th International Conference on Electricity Distribution), Barcelona, Paper 84, May 12–15, 2003.
13. R. N. Hampton, J. Altamirano, J. Perkel, and J. C. Hernandez, "VLF Tests Conducted by NEETRAC as Part of the CDFI," IEEE Insulated Conductors Committee, Fall 2007 Meeting, Scottsdale AZ, 2007.
14. R. N. Hampton, J. Perkel, J. C. Hernandez,, M. Begovic, J. Hans, R. Riley, P. Tyschenko, F. Doherty, G. Murray, L. Hong, M. G. Pearman, C. L. Fletcher, and G. C. Linte, "Experience of Withstand Testing of Cable Systems in the USA," CIGRE 2010, Paper No. B1-303.
15. C. Goodwin, H. Oetjen, and M. Peschel, "Use of VLF Methods in Utility Reliability Programs - Basic Concepts," IEEE Insulated Conductors Committee, Subcommittee F, Fall 2009 Meeting, Scottsdale AZ, 2009.
16. J. Perkel, J. Altamirano, and N. Hampton, "Investigation of VLF Test Parameters," IEEE Insulated Conductors Committee, Subcommittee F, Spring 2010 Meeting, Nashville, TN, 2010.
17. Draft: IEEE Guide for Field-Testing of Laminated Dielectric, Shielded Power Cable Systems Rated 5kV and above with High Direct Current Voltage, IEEE Std. 400.1, Draft 5 D5, Oct. 2004.

18. M. Begovic, R. N. Hampton, R. Hartlein, J. C. Hernandez-Mejia, and J. Perkel, Validation of the accuracy of practical diagnostic tests for power equipment," *CIGRE 2008,* Paris, France, Study Committee D1 Paper 205.
19. M. Begovic, R. N. Hampton, R. Hartlein, and J. Perkel, Validating Cable "Diagnostic Tests", *International Conference on Insulated Power Cables, JICABLE07*, Versailles France, June 2007.
20. G. E. P. Box, W. G. Hunter, and J. S. Hunter, *Statistics for Experimenters*, John Wiley & Sons, Inc., New York, NY, USA, 1978.
21. N. H. Srinivas and B. S. Bernstein, "Effect of D.C. Testing on Aged XLPE Insulated Cables with Splices," *International Conference on Insulated Power Cables, JICABLE91*, Paris, France, Paper B.3.1, June 1991.
22. N. H. Srinivas, B. S. Bernstein, and R. Decker, "Effects of DC Testing on AC Breakdown Strength of XLPE Insulated Cables Subjected to Laboratory Accelerated Aging," IEEE Trans. on Power Delivery. Vol. 5. No. 4. Oct. 1990, pp. 1643-1657.
23. L. M. Leemis, *Reliability – Probabilistic Models and Statistical Methods*, Prentice Hall, Inc., Upper Saddle River, NJ, 1995.
24. M. G. Kendall, *Rank Correlation Methods*, C. Griffin, London, 3rd Edition, 1962.
25. International Electrotechnical Commission (IEC) 61164, *Reliability Growth – Statistical Test and Estimation Methods*, Second Edition 2004-03.
26. CIGRE B1.28 Technical Brochure, "On Site PD Measurements", 2014
27. Hampton, N. and Perkel, J., "VLF Diagnostics," IEEE PES Insulated Conductors Committee Meeting (ICC) - C18D. Spring 2007. Dr. Perkel provided support for the data analysis.
28. Hampton, R.N., Hernandez, J.C., Perkel, J., Tomer, V., and Kunetzov, M., "Estimating the impact of VLF Frequency on Effectiveness of VLF Withstand Diagnostics", International Conference on Insulated Power Cables JICABLE15, Versailles France, June 2015. Awarded Best Paper JICABLE15
29. Hampton, R.N., Hernandez, J.C., Perkel, J., Tomer, V., and Kunetzov, M., "Estimating the impact of VLF Frequency on Effectiveness of VLF Withstand Diagnostics", IEEE Insulated Conductors Committee – Subcommittee F (ICC), Fall 2014, Colorado Springs, CO
30. Hampton, N. and Perkel, J., "Withstand Tests – More than Meets the Eye," IEEE Insulated Conductors Committee (ICC) Meeting - Subcommittee F, Fall Meeting 2008, October 2008

9.9 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*
- 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 – 2013: *IEEE Guide for Field Testing of Shielded Power Cable Systems Using Very Low Frequency (VLF)*
- IEEE Std. 404 – 2006: *IEEE Standard for Extruded and Laminated Dielectric Shielded Cable Joints Rated 2500 V to 500 000 V*