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Experience of withstand testing of cable systems in the USA

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SUMMARY

High voltage withstand tests are used within manufacturing plants to ensure the quality of completed cable system components from MV to EHV. Thus, it is quite natural for utilities to also use withstand tests as commissioning and maintenance tests for cable systems in the field. The goal of these tests is the same as in the factory test, namely to have any weak components of the cable system fail in a controlled manner, such that the minimum number of customers are affected. In fact a recent study has shown that withstand tests are among the most routinely employed diagnostic tests in the USA; this study has also shown that the most preferred withstand tests use Very Low Frequency (VLF: 0.02 to 0.1 Hz) AC methods.

This paper describes the collation and analysis of data from a wide range of on going utility VLF withstand program conducted on medium voltage distribution systems. A significant feature of this study is that the data are not from research or pilot programs. As a result of the analysis described herein the authors conclude that:

- It is beneficial to collate and compare VLF test experiences across a range of utilities.
- VLF tests are very practical for a utility to perform and do not require specialized services.
- The Survivor rates are high for these tests with expected values, based on 1,000 ft (305 m) cable system segment lengths, in the range of 0.2 to 4 % for 30 min tests performed at the IEEE Std. 400.2 voltage levels.
- IEEE Std. 400.2 provides appropriate time and voltage test levels (determining optimal times and voltages was outside the scope of the work reported here).
- VLF tests at IEEE Std. 400.2 test levels do not significantly damage cable systems as would be manifested by cascading (or multiple) failures on test or shortened times to failure in service.
- Data have been collected using both of the commonly used VLF waveforms, there is little evidence of a significant difference in outcomes that can be ascribed to the voltage waveform.
- A number of areas for further technically useful work have been identified.

KEYWORDS

Cable System, Reliability, Very Low Frequency, Withstand

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I. INTRODUCTION

Utilities the world over, and especially in North America, are facing a significant future challenge to maintain and renew their assets. Utility assets (like most equipment) degrade over time and eventually reach the point at which their performance is lowered sufficiently that they can no longer perform their intended functions. Equipment populations with assets that are far enough into this process produce service failures. Unfortunately, immediate replacement is not practical either from the manufacturing or cost perspectives. Thus, asset management strategies are increasingly being used to help address the issue, such that the replacement of the ageing infrastructure is managed. Effective asset management strategies require the availability of appropriate information on the performance of the assets themselves. In essence, the extra information comes from an effective diagnostic program whose results enable the utility to undertake "smart maintenance" in that only those assets that will likely impact the reliability in the near future receive some form of remediation. This paper focuses on the management of underground cable systems (cable and accessories).

Presently (in North America) the most commonly employed diagnostic technique for assessing cable systems is the withstand test. These tests use a portable voltage source to apply elevated voltage to the cable system for predetermined time duration. The goal of these tests is the same as a factory test on new equipment, namely to have any weak components of the cable system fail while the circuit is not in service. The most obvious choice (in North America) of source is a 60 Hz AC waveform as it most closely replicates the routine tests applied to accessories and cables. Unfortunately, producing high voltage 60 Hz AC requires extremely large and expensive equipment that is not practical for many field testing applications since the source must supply a substantial capacitive charging current. Previously, DC voltage was used for this type of field test since the test units were compact and inexpensive. However, as utilities began to shift from laminar insulation (PILC) to extruded insulations (PE, HMWPE, XLPE, TRXLPE, and EPR) the use of DC testing has declined [1], [2]. This was due to the fact that DC has been shown to be damaging for aged PE-based insulations.

To address this need, voltage sources were developed that utilize AC frequencies in the range of 0.02-0.1 Hz. These sources provide an AC waveform from a unit that maintains the compact size of the DC test equipment. This frequency range minimizes the required capacitive charging current while avoiding the accumulation of significant charge within the insulation. These sources became known as Very Low Frequency (VLF) sources and are currently available with two waveforms, sinusoidal and cosine-rectangular [2]. A survey of North American utilities in 2006 shows that VLF sources are the most common sources now used in withstand tests. In response to this shift, IEEE Std. 400.2 was released in 2004. Data in North America did not exist at the time and so the standard was based primarily on testing experience developed in Germany [3] and Malaysia [4]. Since then, a substantial number of withstand tests have been carried out on upwards of 9,000 miles of cable in at least 13 utilities in North America.

The purpose of this paper is to address a number of issues that have been raised by users, such as:

- Do the test voltages and time provide the expected reliability benefits?
- What outcomes might be expected on test and in service after test?
- What does the collated experience tell utilities?

II. WITHSTAND TEST

Withstand tests are proof tests that use the application of voltage at levels above the normal operating voltage to stress the cable system in a prescribed manner for a set period of time (Figure 1). These tests are similar to those applied to new accessories or cables in the factory where they provide the purchaser with an assurance that the component can withstand a prescribed "over stress". The tests described here differ from factory tests in that the factory test often has multiple parts which are applied sequentially: High Voltage Withstand, Physical Inspection, and Partial Discharge. The field withstand tests may conveniently be defined as "simple" tests in that no property is monitored during the voltage application.

All withstand tests consist, in principle, of two phases (Figure 1):

(1) "Initial" Phase – portion of test required to go from no applied voltage to full test voltage.
(2) "Hold" Phase – Timed portion of test where the RMS voltage is maintained at a constant value.

The results of these withstand tests are reported as either Pass or Not Pass. This approach has been applied to all cable and accessory types. Although the results are often reported as either Pass or Not Pass the outcomes can be used to categorize the cable system performance. For example, failure at 2 min into a $2U_0$ test would be viewed as having poorer performance than a failure 10 min into a test at the same voltage level. Consequently, many practitioners and utilities record the details of the failures with the view that the withstand tests may be used to determine the "health" of their cable system.

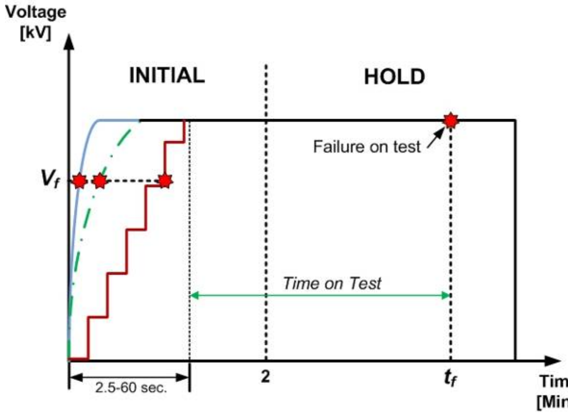

Figure 1: Withstand Test "Initial" and "Hold" Phases

III. SURVIVOR ANALYSIS

The results of withstand tests are often discussed in terms of the number or proportion of failures [2], [5], [6]. This approach focuses on the components that fail rather than on the majority of the tests that survive. However, the authors prefer to use survivor analysis to investigate the results of withstand tests. This technique looks at the entire population of components under test rather than just the subpopulation that fails and generates a survivor function that shows how the fraction of survivors declines (as a result of failures) during the test. The survivor function can be expressed either as a parametric distribution, such as log-normal or Weibull, or may be computed using non-parametric techniques such as the Kaplan-Meier estimator [6], [7]. The authors prefer to use a non-parametric survivor curve where the survivor percentage is computed from the times to failure, the tests that complete the test without failure are treated as censored results. An example of a non-parametric survivor curve for VLF withstand data is shown in Figure 2. It is instructive to reflect on the different and complimentary perspectives that the failure and survivor analyses bring to the same condition at 30 min in Figure 2; 93 % of the failures have occurred yet 89 % of the tests resulted in survival.

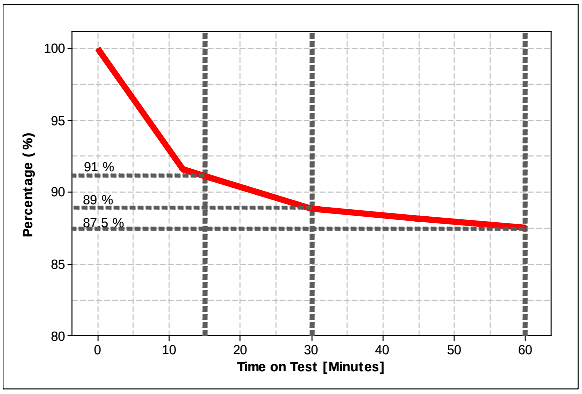

Figure 2: Example Survivor Curve Using VLF Withstand Data

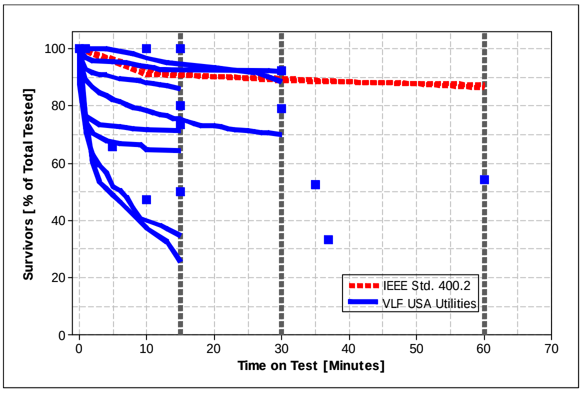

Figure 3: Survivor Curves for Both IEEE Std. 400.2 and North American Utility Data

The shape of the survivor function is determined by the test magnitude and test duration. Figure 3 shows the survivor curves for both data sets discussed in IEEE Std. 400.2 and North American utility data. Examination of the shapes of these curves indicates how successful the tests have been at finding all the weakest locations in the population: each segment that fails on test always does so at its weakest location. The gradients of these curves enable the utility to determine whether or not the test duration is long enough to fail all the failure-prone locations. In general, these gradients should reduce in magnitude with time and approach a zero gradient (asymptote) by the end of the test. This indicates that continuing to test the segments for more time will not yield any additional failures. On the other hand, a gradient that increases in magnitude would indicate that the testing time may be too long and was causing failures unnecessarily. The survivor function also allows a utility to assess the level of risk (missed failures) that would result by choosing a shorter test time.

Each survivor curve has been collected at a particular test time and test voltage pair. Thus, it is possible to understand the survivor rate for different test voltages (for any convenient time selected from the curve). Figure 4 shows the final survivor rate as a function of the applied test voltage. This analysis shows that the applied voltage has a significant impact on the survivability of segments on test. An increase of the test voltage from 2.3 U_0 to 4 U_0 decreases the "on test" survivor rate from 87 % to 46 %. This finding has a practical significance as it shows the risk of using voltages in excess of those detailed in IEEE Std. 400.2. Utilities often consider using elevated test voltages in an attempt to use shorter test times.

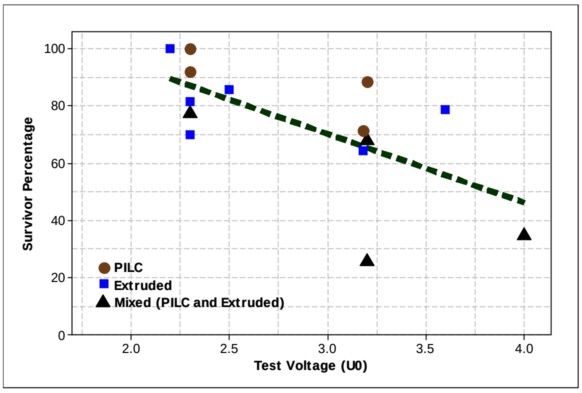

Figure 4: Percentage of Surviving Segments Versus Test Voltage (U_0)

A cursory examination of the curves in Figure 3 shows that the North American experience is, in general, quite different from that used to support the levels in IEEE Std. 400.2. Most utility programs have chosen, thus far, to employ 15 min tests while a few have also performed 30 min test programs. The North American experience as collated and presented here indicates:

- Most field tests experience the highest failure rate on test during the first minute of testing: the initial period in Figure 1.
- Only a few utility programs achieve a zero gradient at the end of the test.
- No utility currently tests for the same duration as was used to generate the values in the current IEEE standard.

A concern that has been voiced with VLF withstand testing [2] is that if the cable system has a high concentration of defects then a withstand approach may have limited effectiveness in that the elimination and repair of the weakest point will leave a similar but only marginally stronger point in the cable segment. Thus, this segment will likely fail in the subsequent retest after remediation or soon afterwards in service. In fact, there are reports of this phenomenon from utilities providing these datasets. Within this study there was sufficient information to examine this contention as the segment identification information was provided as part of the ancillary data. The results of this study are shown in Table 1, where the data suggests that for the 30 min IEEE Std. 400.2 conditions the risk of multiple failures is quite low. Further inspection of the conditions where multiple failures were regularly reported showed that, in these cases, voltage levels in excess of those detailed in IEEE Std. 400.2 had been used. Thus, this anecdotal evidence suggests that any possible advantage in time that might arise from shorter test times and higher voltages would be negated by the more regular occurrence of multiple failures on test. In principle this finding is consistent with the data shown in Figure 4.

Table 1 Occurrence of Failures for VLF Tests Using IEEE Std. 400.2 Test Conditions (30 Mins)

Number of failures on test	0 - No Failure	1	2	3
Tests with these failures (%)	94.2	5.7	0.1	0.1

VI. SEPARATION OF FAILURE MODES WITHIN SURVIVOR CURVES

Section II notes that the preferred form of the survivor curves is a smooth decline to an asymptotic survivor rate; however in many cases the decline is precipitous and the asymptote is not achieved. Thus, there is a practical need to understand the underlying mechanisms to ensure that the absence of the asymptote is due to overly aggressive test conditions. The authors prefer to examine the different mechanisms using a graphical approach that relies on the Weibull distribution [8], [9] with CDF defined in (1).

$$P(t) = 1 - e^{-\left(\frac{t}{\alpha}\right)^{\beta}} \qquad (1)$$

Where, α = Weibull scale parameter, β = Weibull shape parameter.

The probability of failure is estimated from the rank position of the times to failure after adjustment for the censored (successful – non failed tests) [8], [9]. When considering the failure mechanisms the most useful characteristic of the Weibull distribution is the shape parameter, β, which characterizes the mechanism(s) at work. If a single mechanism operates then the data will lie on a single straight line. Multiple lines, breaks, or cusps represent the transition from one mechanism to another. Examination of both DC and VLF withstand data show that it is quite common to see multiple mechanisms (Figure 5 and Figure 6). These mechanism can conveniently be split into those that operate at long times, we term this the "Hold" phase (Figure 1), and those that operate at short times ("Initial" phase). The "Initial" phase mechanisms are responsible for the precipitous drop in the survivor curves. Consequently these mechanisms must be considered separately when examining the evolution of the failures with test time.

A discussion of the failures in the "Initial" phase is very useful but is outside the scope of this paper. However, it is important to address them as they need to be separated to perform rigorous analyses of the "Hold" phase data [6], [8], [9]. The early failures cannot be simply omitted from the analyses as they are part of the data; however, they may be included by treating them as censored data. Once this process is accomplished the analysis shows that there is a single mechanism at work in the "Hold" phase (Figure 7). This is practically important as it shows that there is not an additional mechanism that becomes active at later test times.

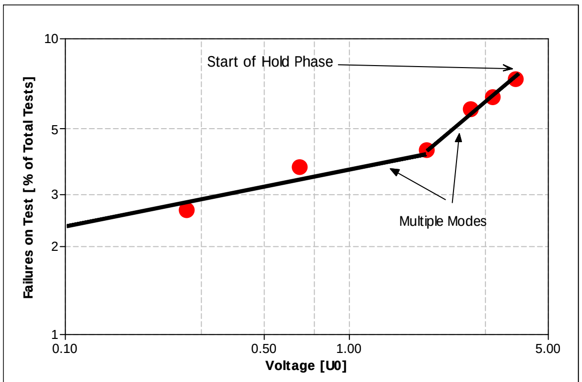

Figure 5: Weibull Plot of "Initial" Phase Failures on Test as a Function of the Applied RMS VLF Voltage

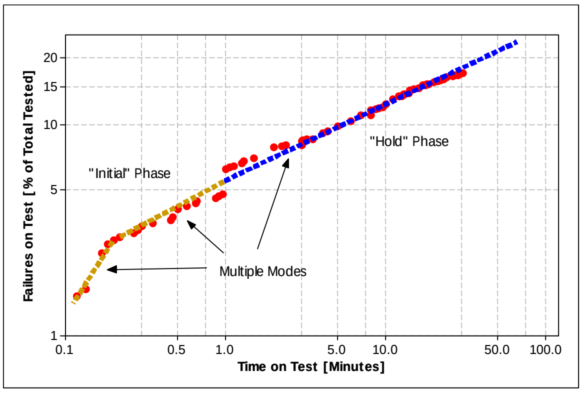

Figure 6: Weibull Plot of "Initial" and "Hold" Phase Failures on Test as a Function of Test Time

V. PERFORMANCE ON TEST

The collated survivor curves (Figure 3) represent a variety of utility sizes and within each utility there will be a range of cable system lengths that are tested. The test lengths involved can be quite long due to the low levels of current required when tests are carried out at VLF frequencies. Figure 8 shows the length distribution of tested circuits for North American utilities employing VLF sources. It is instructive to note that the median length is 3,500 ft (1,067 m) while lengths over 16,500 ft (5,000 m) have also been tested.

The variability in tested lengths means that it is not reasonable to directly compare the performance of, for example, a 1,000 ft (300 m) segment with that of a 10,000 ft (3,000 m) segment. It is, therefore, necessary to length adjust the data by normalizing all segments by a chosen base length, for example 500 ft (150 m) or 1,000 ft (300 m). This process yields several "pseudo" segments connected in series. In theory, any segment length may be used. However, it is important to select a meaningful and appropriate reference length – a 10,000 ft (3,000 m) test length could be subdivided into 100 ft (30 m), 5,000 ft (1,500 m) or 1,000 ft (300 m) lengths, yet how meaningful are 100 ft (30 m) and 5,000 ft (1,500 m) lengths in the context of a utility feeder! The authors prefer to use 1,000 ft (300 m) lengths for adjustments as this seems practically reasonable. The standard section length for a particular utility may also be used if appropriate. Once the number of "pseudo" segments is determined, the question is then how to treat them when examining the performance data. This becomes a significant issue in cases where the withstand test produces a failure during the test. Consider a failure that occurred 20 min into a 30 min test. Using a base length of 1,000 ft (300 m), the 4,000 ft segment originally tested is said to represent four "pseudo" segments (*A*, *B*, *C*, and *D*) of which *C* contains the failure site and *A*, *B*, and *D* have yet to fail. In the analysis, segment *C* will contribute a failure time of 20 min while the remaining segments will contribute censored times of 20 min [8]. It is important to note that those segments that have yet to fail are not assumed to be capable of passing the full 30 min test. The only assumption is that their failure times are longer than 20 min. This distinction proves vital for the analysis techniques described in the following sections. Figure 7 shows the effect of different pseudo segment lengths; the original failure & survival rates are 17.5 & 82.5 %, thus 82.5 % of the tests (irrespective of length) result in survival at 30 min. The failure rate decreases from 17.5 % to 2.4 % for 500 ft (150 m) pseudo segments.

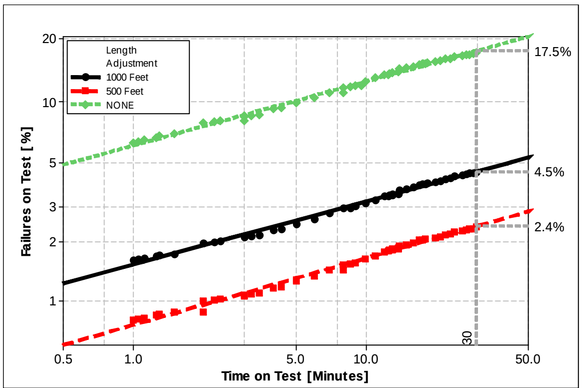

Figure 7: Length Adjustment of the Failures on Test for VLF Withstand Tests from One Utility

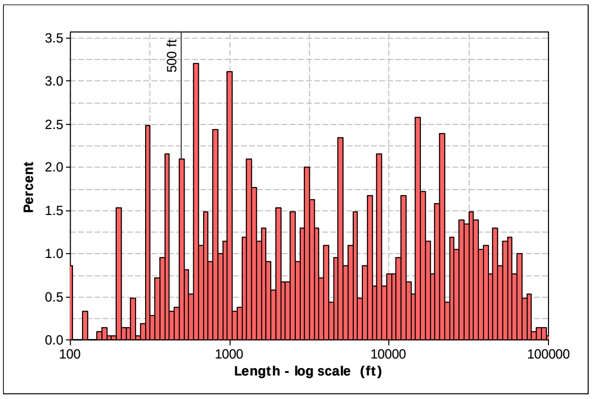

Figure 8: Length Distribution of VLF Withstand Tests Performed in North America

When test lengths are available or can be estimated with reasonable confidence, it is practical to adjust for length such that results from different locales may be compared in a consistent and rigorous way. Figure 9 and Figure 10 show two data comparisons that use the procedures described in Sections III and IV. The multiple failure mechanisms in the early phase of tests have been excluded and treated as censors – hence the absence of data at the shortest test times. In both of these examples, a length of 1,000 ft (300 m) was used to make the adjustment. Figure 9 shows a comparison of results from the same utility where two different test protocols were used; originally 2.5 U_0/15 min had been used but the protocol was changed to 1.8 U_0/30 min upon publication of IEEE Std. 400.2. The analysis shows:

- A single mechanism operates in both data sets during the "Hold" phase
- The mechanisms are different for the two protocols – note the difference in Weibull slopes (β)
- The estimated failure survival rates (independent of length) at 30 min are 69.3 % (100 – 30.7) and 83.1 % (100 – 16.7) for the 2.5 U_0/15 min and 1.8 U_0/30 min protocols, respectively

Table 2: Failures On Test (Length Adjusted) and Tested Lengths for the Analyses in Figure 10

Utility Dataset	A1	A2	D	H	I
Failures on Test @ 30 min [% of 1000 ft Segments]	3.5	3.2	0.2	35.5	4.3
Cable System Length [miles]	280	400	580	1	850

Figure 10 shows field data from five utilities where the cable system lengths are well established. Furthermore, these utilities represent the "apparent" extremes of the survivor curves shown in Figure 3. All the data have been adjusted to 1,000 ft (300 m) lengths as described previously. Examination of the data shows that there is significantly lower dispersion once the censoring and length adjustment has been completed. A comparison time of 30 min has been selected for the failure on tests. This shows the value of length adjusting since it allows the comparison at disparate test times (15 and 30 min) to be made in a consistent way. The analysis clearly shows that failure rates and failure mechanisms for datasets D and H are quite different from the bulk (1,500 miles (2,400 km)) of the data. Further inspection shows that dataset D is comprised of tests on a single insulation type whereas sets A1, A2, and I involve testing of hybrid (mixed insulation) systems. Dataset H displays a failure rate that is approximately 10 times larger than the others and on initial examination would caution against the use of VLF withstand. However, the more complete analysis of the collated data and an assessment of the cable system lengths, completed here, demonstrate the extreme care that needs to be taken about drawing conclusions from too small a utility system. This work shows that a length compensated failure rate of 2.7 % (for 30 min tests performed at IEEE Std. 400.2 voltage levels) might be expected for cable systems typically selected for diagnostic tests.

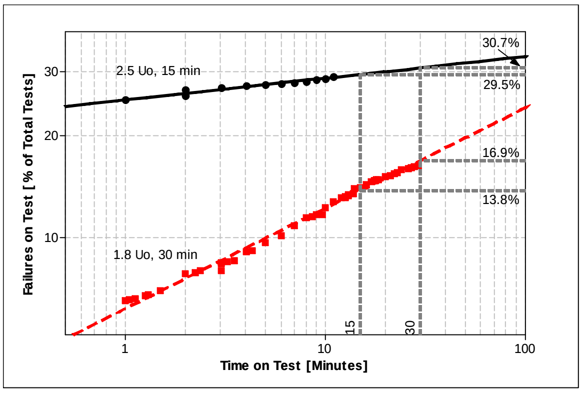

Figure 9: Weibull curves of time on test for two conditions on a utility system.

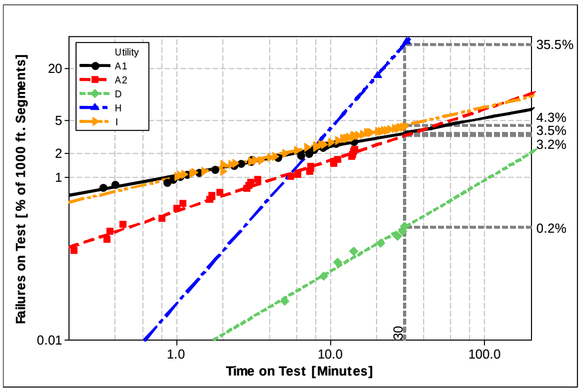

Figure 10: Weibull curves for data from 5 of the utility systems shown in Figure 3

VI. PERFORMANCE IN SERVICE AFTER TEST

The goal of VLF withstand testing is to improve cable system reliability by removing the portions (accessories or cables) that have a performance below the threshold defined by the IEEE Std. 400.2 criteria. As the tests are conducted with the cable segments disconnected from the utility grid, the remediation and the required retesting can be completed such that customers minimally impacted. The preceding sections have described the techniques used to address the disparate cable system lengths and to assess the failure mechanisms which operate during the tests. It is equally important to assess the performance of the cables systems after test. Figure 11 shows the performance after test for the two test protocols shown in Figure 9. The performance has been assessed in terms of the time between the VLF test and any subsequent service failures. The service data includes analysis of the segments that had not seen a failure within the assessment period, thus, the times to failure for 10 % of the tested segments are 1,200 and 2,200 days for the 2.5 U_0/15 min and 1.8 U_0/30 min protocols, respectively. The good fit made by a single Weibull distribution in this analysis shows that each of the protocols results in a single mode of failure for at least 2 to 3 years from the VLF testing. Another interesting feature is that there is no evidence of a threshold or grace period, where the system is immune from service failures. This absence of a threshold is common to all of the withstand data we have examined (AC 60 Hz, AC VLF, and DC).

The data used to construct Figure 11 has combined the circuits that survived the VLF test without failure with those that saw a failure and was then remediated. A subset of the data in Figure 11 had sufficient information to separate the service performance of the circuits that passed and failed the VLF tests. Figure 12 shows the data segregated for the 2.5 U_0/15 min and 1.8 U_0/30 min protocols. The analysis shows that the mechanisms are similar for both protocols for the circuits that passed the VLF tests. In these cases, the in service failure rates after two years are of the order of 33 % and 28 %

of tested segments (3-phase) for the 2.5 U_0/15 min and 1.8 U_0/30 min protocols, respectively. This finding is consistent with a common service response of the best performing circuits to the different protocols – if the segments are "good" then there is little sensitivity to the test method. The performance of the circuits that failed the VLF tests and were remediated (replaced or repaired with splices) is most revealing. The analysis shows that the failure rate is much lower for the failed and remediated circuits than for the circuits that survived the VLF tests. If the VLF tests were, in fact, damaging the remnant parts of the cable system then the "Not Pass" curves would lie either above the curve of the survivors or very near them. The fact that the curves are separated is a very strong indication that the VLF test does not cause systemic or unwarranted damage to the cable system. Of equal interest are the relative positions of the curves for the failures for the two protocols. It is clear that both protocols bring a benefit, but this benefit is much larger for the 1.8 U_0/30 min protocol. In this case, failure rate in service is approximately 80 % lower for the IEEE Std. 400.2 protocol: 17 % and 3 % for the 2.5 U_0/15 min and 1.8 U_0/30 min protocols, respectively.

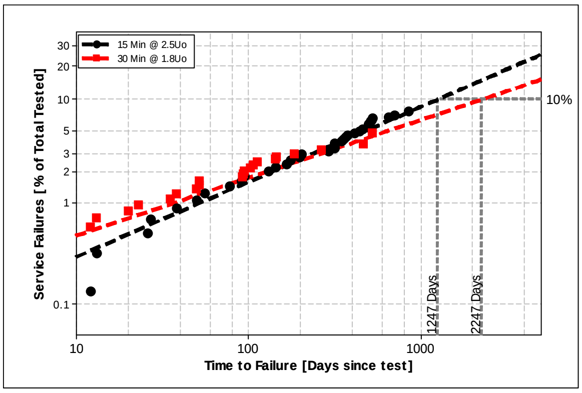

Figure 11: Proportion of Tests that Subsequently Result in Service Failure for Two VLF Test Protocols

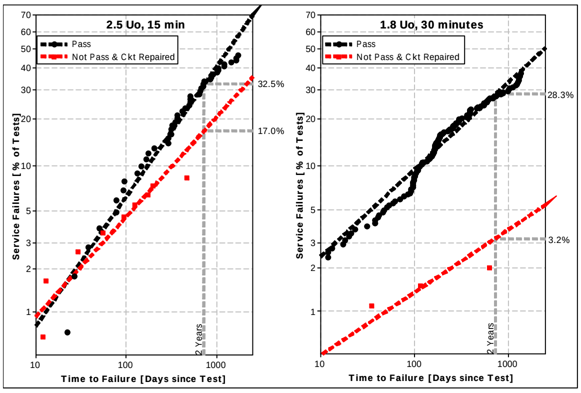

Figure 12: Proportion of Tests that Subsequently Result in Service Failure for Two VLF Test Results

VII. ISSUES WORTHY OF FURTHER STUDIES

One of the drawbacks of the simple withstand tests described in this paper is that there is no straightforward way to estimate the margin of "Pass" – once a 30 min test is completed it is not possible to differentiate cable systems that would have survived 120 min from those that would have survived 90 min. Thus, the authors believe that it would be profitable to explore the concept of a monitored withstand whereby a dielectric or discharge property would be monitored to provide additional data to perform a level assessment.

The utilities engaged in this study have generally recorded many ancillary details of the tested cable system beyond the results of the VLF test. These ancillary data have proved to be invaluable in this work. However, there is little guidance available to interested parties on the type and level of information reporting that should be undertaken. Work in this area would be of benefit to utilities.

The discussions in this paper have been limited to medium voltage cable systems. There is also growing interest in the diagnoses of high voltage systems. The authors believe that the approach and analytical techniques described herein would be useful to workers wishing to quantify the effects of simple or monitored withstand tests at elevated voltages on these types of systems.

Section II noted that there are a large number of failures early (either short times or during voltage steps) in VLF tests. These phenomena occur for all the VLF approaches and for all equipment classes. Therefore, utilities should be encouraged to rigorously collect failure on test data whereby deeper and more definitive studies might be conducted.

VIII. CONCLUSIONS

This paper has collated and examined data from a wide range of utility VLF withstand programs. These programs are not research or pilot programs and they are ongoing. As a result of the analyses that have been undertaken on these data the authors conclude that:

- It is beneficial to collate and compare VLF test experiences across a range of utilities.
- VLF tests are very practical for a utility to perform and do not require specialized services.
- The Survivor rates are high for these tests with expected values, based on 1,000 ft (305 m) cable system segment lengths, in the range of 0.2 to 4 % for 30 min tests performed at the IEEE Std. 400.2 voltage levels.
- IEEE Std. 400.2 provides appropriate time and voltage test levels (determining optimal times and voltages was outside the scope of the work reported here).
- VLF tests at IEEE Std. 400.2 test levels do not significantly damage cable systems as would be manifested by cascading (or multiple) failures on test or shortened times to failure in service.
- Data have been collected using both of the commonly used VLF waveforms. When analyzed there is little evidence that there is a significant difference in outcomes (either on test or in service) that can be ascribed to the voltage waveform.
- A number of areas for further technically useful work have been identified.

IX. ACKNOWLEDGEMENTS

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