Laboratory Study of the Impact of Repeated VLF Withstand Test and Subsequent AC Operation on Service-Aged Cables

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ABSTRACT

VLF sources have proven effective for both withstand tests and diagnostic tests (partial discharge, dielectric loss) used to manage cable assets. Field studies confirm that overall VLF tests to the levels set out in IEEE 400.2 deliver practical improvements in reliability (fewer failures and longer times between failures) without initiating long-term problems. However, the field-based studies are not well-suited to investigating the impact of repeated testing, re-energization at power frequency and test parameters (voltage and time) outside the framework of IEEE 400.2. This study uniquely employed multiple long lengths (>70 m) of XLPE cables removed after more than 25 years of service to estimate the impact of a variety of VLF test parameters (1.8, 2.1 and 3.6 U_0, and 15, 60 and 120 minutes), plus multiple applications of VLF Simple Withstand testing.

KEYWORDS

Diagnostics, Reliability, Extruded Cable Systems, Endurance, Very Low Frequency

INTRODUCTION

Proof or withstand tests have been used for a very long time in the cable industry and find their origins in the well-known routine tests carried out in accessory and cable factories. [1][2][3][7] Recent studies show that withstand tests are the most commonly implemented of the diagnostic tests based on the Very Low Frequency (VLF) approach (Figure 1).

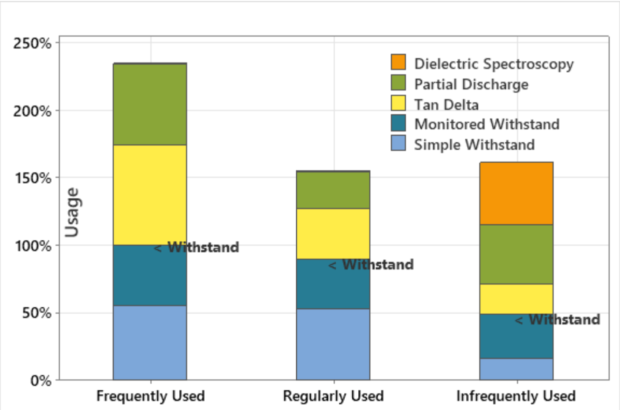

Figure 1. Usage of VLF-based diagnostic techniques

The majority (>90%) of VLF tests are conducted at a test frequency of 0.1 Hz. Laboratory and field studies [6] show that the VLF source frequency has a minimal impact on the breakdown strength of degraded cable insulations.

The withstand test has two parts: the initial ramp and the hold period. [7] The voltage exposure and hence the risk to which the cable system is exposed is determined by both the voltage level and the time of the application (Figure 2).

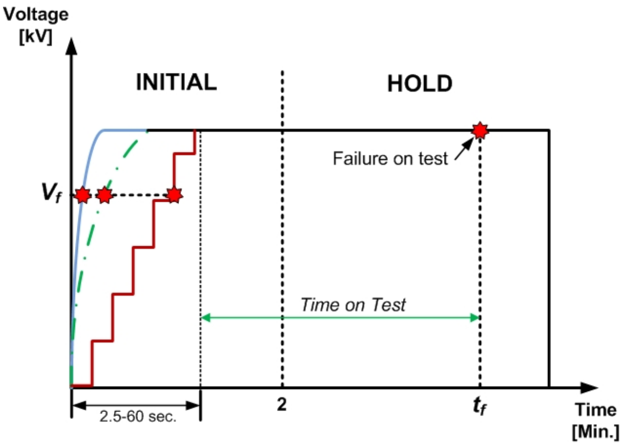

Figure 2.Withstand test "initial" and "hold" phases

The basic benefit of withstand tests is that they provide a practical way of providing the asset owner with assurance that the component can withstand a prescribed "over-stress." The results of these withstand tests are reported as either Pass or Not Pass. The unambiguous result alleviates the need to interpret a condition from the measurement data. This is a key benefit when it comes to implementing this approach in the field. Although the results are reported as either Pass or Not Pass, the outcomes can be used to categorise the cable system performance. As an example, failure at 2 minutes into a 2 U_0 test would be viewed as having poorer performance than a failure 10 minutes 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 systems. [8][9] This form of field withstand tests may conveniently be defined as a "simple" test in that no property is monitored during the voltage application and the exposure/risk is determined by the voltage and time recipe. In this work, this structure is known as a "Simple Withstand"

Although the "Simple Withstand" test continues to serve the industry well; making up over half the withstand tests conducted, when a Simple Withstand is implemented in the field, users continue to be concerned by three issues:

- Prior to the test, there is no way to estimate the health of the cable system — hence, the risk of failure prior to the application of the proof voltage.
- There is no way to adjust the length (time) of the test — hence, the risk of the test either decreasing or increasing in length according to the quality of the cable system.
- There is no way to judge the quality of the pass should the cable system support the proof voltage — i.e., was

the pass a good one or a marginal one.

To address these concerns, many tests now monitor a diagnostic parameter, such as dielectric loss or partial discharge, during a proof test to provide information to address the three issues noted above. [10] This approach is termed “Monitored Withstand” In such approaches; a property is monitored during the initial phase of the voltage ramp to get an appreciation of the asset health to establish whether the cable system would benefit from a withstand test. If the system proceeds to the hold phase, the condition is then monitored during the withstand. In the distribution arena, the monitoring is usually conducted using tan delta, though partial discharge (PD) is less commonly used. [3][8][10] On the other hand, the “Monitored Withstand approach using PD is commonly used for transmission applications. [10]

FIELD EXPERIENCE

VLF testing has been growing in popularity since the early 2000s as a practical alternative to DC hipot tests. [7] This transition has the dual advantage of avoiding the deleterious impact of DC hipot tests on aged, extruded insulation cables and ensuring the correct AC stress distribution within the devices (accessories, cables and interfaces) being tested. Two IEEE standards - IEEE 400.0 [2] and IEEE 400.2 [7] - support the growth in testing.

A great deal of data from the field has been collated and analysed as part of a multi-utility research project [8][9][10] This work has identified a number of practically important findings for testing on service-aged cables.

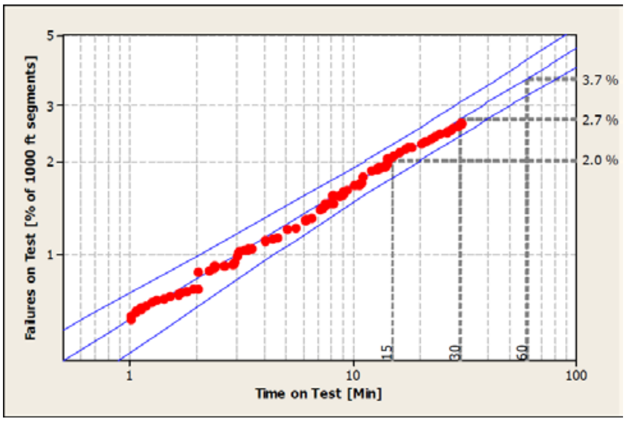

Figure 3. Meta analysis of failures on test for simple withstand testing (length adjusted to 300 m)

Failures on test

Analysis of the times at which VLF failures occur in the test cycle from testing more than 3,000 km of cable systems (cables and accessories) from five different utilities has been collated. This shows that the mechanism of failure, as represented by the Weibull Shape Parameter, is consistent between the utilities. It also shows that most, but not all, of the failures occur in accessories. To establish the likelihood of failure on test, it is important to analyse the field results based on a common length of cable. This is necessary, as longer lengths are more likely to contain weak areas; thus, outcomes based on test failures are inflated for long lengths compared to tests conducted on shorter lengths. This has been done for the multi-utility data in the form of a meta analysis; the results are provided in Figure 3. This work shows that a length-compensated failure rate of 2.7% (for 30-minute tests performed at IEEE 400.2 voltage levels and test times) might be expected for cable systems typically selected for diagnostic tests. [7] Clearly, even in aged cable systems that have already experienced service failures, the likelihood of failure on test is low.

VLF frequency

As noted earlier, the term VLF applies to a range of frequencies below 0.1 Hz, though 0.1 Hz is the most commonly used frequency (only 8% of tests use a frequency below 0.1 Hz). [5] However, comments have been raised over the impact of lower frequencies on the withstand outcomes (lower frequencies are used on very long lengths of cable systems when the power to energise at 0.1 Hz cannot be provided). Laboratory (Ashcraft Water Tree Tests) and field studies (350 km of cable system) [6] show that the breakdown strengths and survival rates (Figure 4) when using IEEE 400.2 recommendations are essentially the same for the two frequency groups. Thus, in terms of withstand, lower frequencies, down to 0.01 Hz, are equally effective.

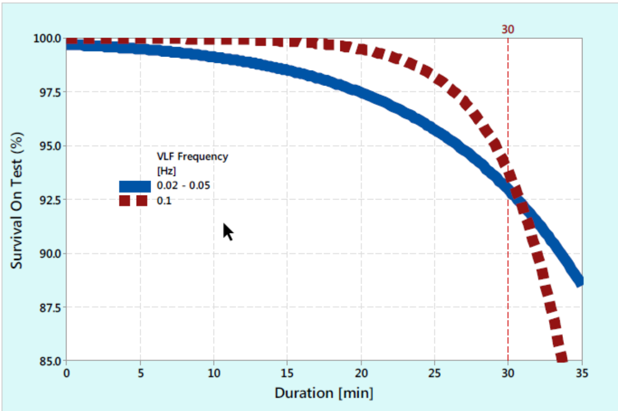

Figure 4. Survival plot for VLF tests at 0.1 Hz and 0.02-0.05 Hz as a function of time on test

System reliability after test

The goal of a withstand test, like the proof test applied to the barrel of a firearm, is to identify any weaknesses in the structure, leaving the survivor population with overall higher strength and reliability. In the case of an aged cable system, it is expected that an effective test procedure would cause more highly degraded components (accessories or cables) to fail under test, i.e., when they are not part of the customer supply grid and do not impact SAIDI or SAIFI. To test this hypothesis, one utility took a number of years of field test data using “Simple Withstand” and tracked both the failures on test and the subsequent failures in service for both the sections that failed and those that survived. If the withstand approach was effective, there would be proportionately fewer failures in the segment of the population that had been tested / repaired / re-tested than in the remaining segment that survived the test.

Figure 5 provides the results of this analysis. In looking at the data, it is important to recognise that all the cable systems that were tested had seen significant ageing, and may well have experienced failures. Thus, the health of these systems was in question. Traditionally, without any form of testing, the only recourse to address these cables would be replacement. The black curve in Figure 5 represents the cable systems that successfully survived the

VLF withstand (1.8 U_0 for 30 minutes [4]). These cable systems experienced a number of failures, with approximately 30% of the survivors failing again within 1,000 days after completing the test. The outcome for the cable systems that were tested / repaired / re-tested (red curve of Figure 5) is markedly different with proportionately far fewer failures: 3.5% of the repaired segments failing after 1000 days. It is also worth remarking that the gradients of the two curves are similar, indicating again that a similar mechanism of failure / ageing is at work. A separate analysis comparing an untested population of cable of similar design and vintage with the results in Figure 5 (black and red) showed that the overall failure rate was lower in the tested population.

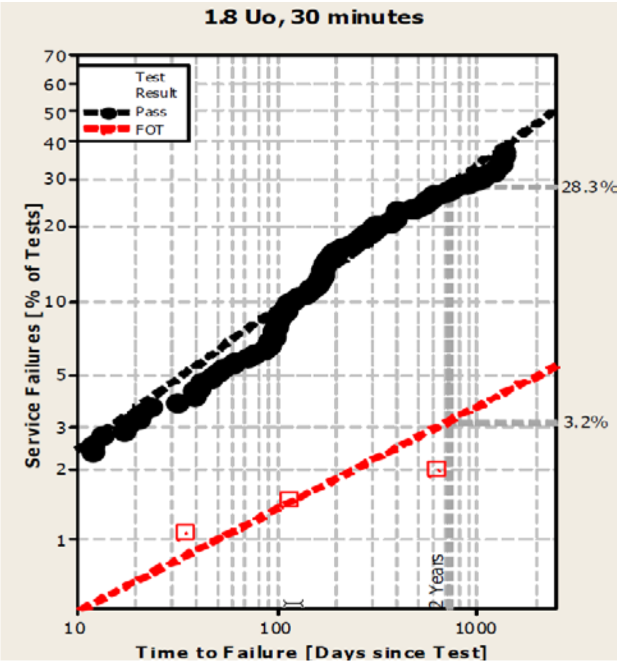

Figure 5. Time to in-service failure after VLF simple withstand tests

Field data analysis

The selected analyses in Figure 3 to Figure 5 show compelling evidence that the VLF procedures outlined in IEEE 400.2 [7] are effective at helping a utility assess the asset health and improve reliability. However, it is difficult to assess the impacts of the main test variables using the data mining methods described above. This is especially true when exploring the variables outside the time/voltage envelope of the recommendations in IEEE 400.2. The key topics that remain of interest are:

- Impact of elevated test voltage (IEEE 400.2 tabulates the voltages for different rated cable voltages and VLF waveforms (Figure 6))
- Impact of test time (IEEE 400.2 recommends 30 or 60 minutes for critical applications)
- Initiation of defects by the test conditions
- Test-induced degradation under operating conditions

EXPERIMENTAL DESIGN

To address the topics around "Simple Withstand" that are not amenable to study from field data, a large-scale laboratory test program was developed. Because it is well-established that laboratory qualification protocols do not replicate ageing in the field, it was determined to conduct the studies using cables removed from service. Luckily, more than 500 m of 1970-vintage unjacketed 15 kV (4.2-5.2 mm) XLPE cable had been extracted by a utility after it had experienced a number of failures in the field — i.e., it was known to have degraded performance. Long continuous lengths (85 m) of this cable were available for testing. These lengths are much longer than those used for typical qualification (AWTT) testing (approximately 6 m). It was decided to keep the cables in long lengths so that little was lost for terminations. Any failures would result in 6 m of cable being removed from the test, with the remaining lengths re-terminated and returned to test.

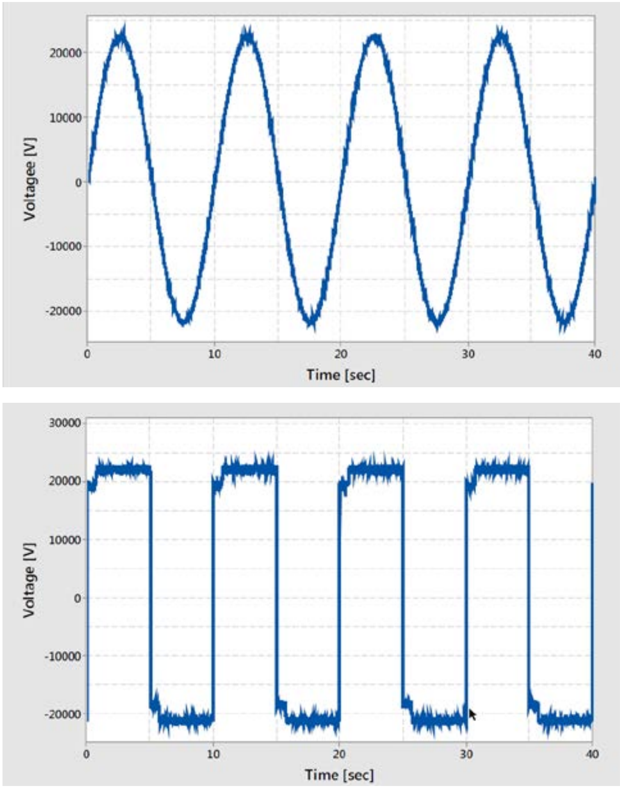

Figure 6. Measured VLF withstand waveforms – top = sinusoidal; bottom = cosine rectangular

Test components

The testing itself had four main components.

Conditioning – The cables used for this test were extracted from the utility system and transported to the test laboratory. To prepare for testing, a one-week conditioning period under 60 Hz AC in the test tanks was applied for all the conditions.

Pre-VLF / AC test – Prior to each VLF withstand and 60 Hz ageing, a partial discharge test (60 Hz at the ageing voltage) was conducted on the cable. The purpose was to establish whether either the withstand or the ageing had initiated any electrical treeing.

VLF research withstands – After the PD test, a VLF withstand was applied to the cable using a set of conditions (Table 1) designed in consultation with the project sponsors to explore outside of the 15 kV test envelope set out in IEEE 400.2. A power frequency (60 Hz) condition was included as a control.

As noted previously, sections (6 m in common with AWTT lengths) that did not survive the VLF withstand were removed. The cables in that condition (Table 1) were subjected to a repeat VLF withstand as recommended in IEEE 400.2 before proceeding to the next phase.

Two phases of VLF testing were employed. The first used a sinusoidal waveform and the second used a cosine rectangular (Figure 6).

Table 1. Test conditions for VLF withstand research

Voltage (U_0)	Time (min.)	Time (cycles)	Frequency (Hz)
3.0	0.25	900	60 "control"
3.0	120	720	0.1
1.8	120	720	
1.8	15	90	
2.1	60	360	

Power frequency ageing – This program applied multiple VLF withstands separated by long periods of power frequency ageing at 60 Hz with the cables in water-filled tanks (no water was introduced into the conductor). The goal of the ageing was to simulate, at a moderate level, the water tree ageing that was anticipated to occur for a cable in service. Two ageing protocols were eventually used for the different VLF test phases (Table 2).

Table 2. Test conditions for 60 Hz ageing in water

Phase	Voltage (U_0)	Water temperature (°C)	Time interval (weeks)
I	1	Ambient	12
II	2	45°C cycled	

Overall program

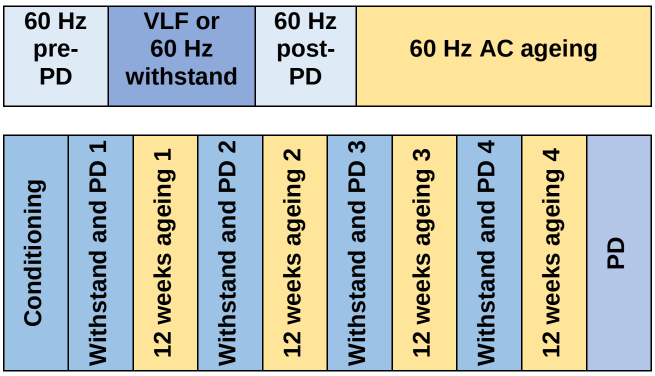

Figure 7. Schematics of testing (top) and ageing (bottom) portions of the program

The whole ageing program ran for 52 weeks, with eight PD assessments and four VLF applications in each phase (Figure 7 provides a schematic of how the elements of the testing were applied). Overall, this study was applied twice and ran for two years — Phase I followed by Phase II.

As this study looks to gain a better understanding of the variables that control the outcomes of the VLF withstand test, it was determined that the primary metrics would be the survival of the cables during both the 60 Hz ageing and the VLF withstand phases. Of secondary interest was the 60 Hz partial discharge measurements at the ageing voltages.

Survivor testing

When the test program was developed, there was an anticipation prevalent at the time that the VLF test conditions and / or the multiple applications of the VLF withstand testing would result in a high failure rate in the aged cable population (which had already seen failures in the field). Thus, it was not anticipated that a significant number of the samples (6 m sample lengths) would survive the testing. In fact, 63 of the 84 samples (75%) survived the VLF / Control testing and the AC ageing.

As these cables represented an important resource (25 years of service ageing and two years of laboratory ageing), it was decided to conduct *in situ* AC breakdown testing, up to the limit of the terminations used for the ageing.

TEST RESULTS

Overall, 21 of 84 samples failed during both phases of the test program (Figure 7). Two failures occurred during ageing Phase II, five during the VLF withstand of Phase I, two during the 60 Hz withstand of Phase I, and 12 during the VLF withstand of Phase II. The details of the failures are set out in Figure 8.

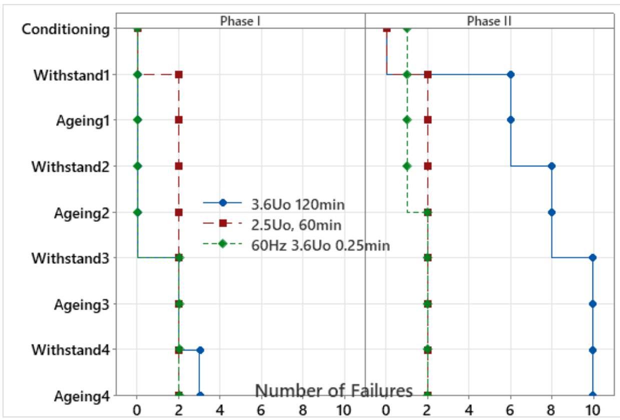

Figure 8. Withstand & ageing failures: see Figure 7

Failures on VLF test

In both Phase I (sinusoidal VLF; U_0 ambient) and Phase II (cosine rectangular; 2 U_0 45°C), no VLF test failures occurred at the 1.8 U_0 conditions (15 and 120 minutes). Failures occurred in both Phase I and Phase II at the 2.1 U_0 (four failures) and 3 U_0 (13 failures) VLF conditions (Figure 8). Moreover, the postulated increase in failures due to repeated application of VLF withstand was not observed (Figure 8).

The times on test that these failures occurred are provided in Figure 9. It is interesting to note that only two of the 17 VLF failures occurred at times before 15 minutes, and only three occurred after 60 minutes. Thus, the recommended test times in IEEE 400.2 seem reasonable, with a risk that defects would not be detected if the shorter time is chosen.

The 60 Hz, 3 U_0 control condition also resulted in two failures as the voltage was being raised in Phase I. Thus, it is not possible to determine the appropriate time at voltage for these defects.

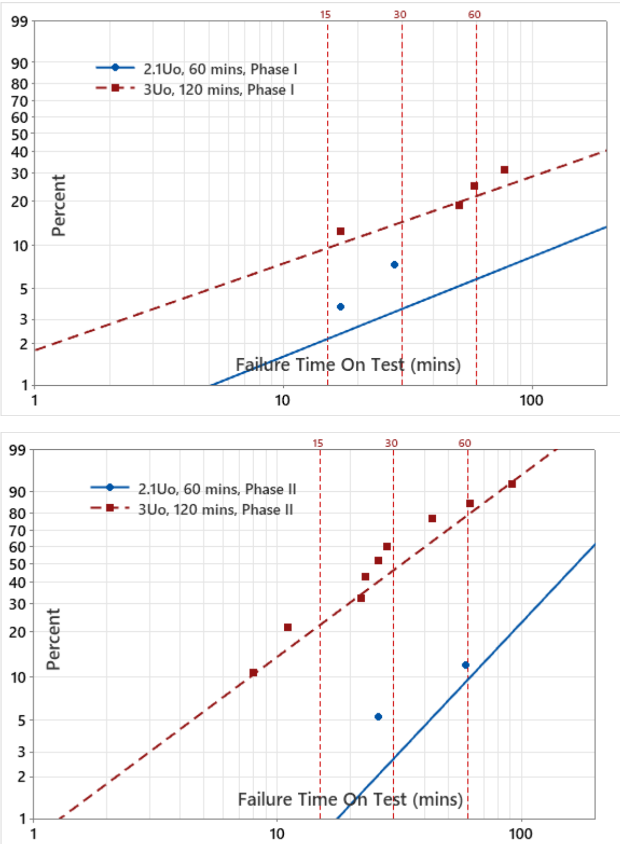

Figure 9. Times of failures on test (6 m sample lengths) for VLF withstand portions (Figure 7)

Failures under 60 Hz ageing

In the eight 12-week ageing periods of Phase I and Phase II, none of the VLF tested cables experienced failure.

The Phase II testing at 60 Hz, 3 U_0 experienced two ageing failures. One of these failures was in the conditioning period, and the other seven to eight weeks into an ageing period (green curve of Figure 8).

Pre- and post-withstand PD testing

Partial discharge tests were conducted on all the cables on 16 occasions during the course of this project. None of the tests (after withstand or after ageing) showed any measurable PD at 60 Hz (with 5 pC sensitivity).

Breakdown test of survivors

Step ramp breakdown tests were conducted on the surviving long lengths of cables (63 samples) using the standard protocol set out for AWTT Testing [2]. When a long length failed, testing was curtailed and there was no re-termination. The data were analysed based on a sample length of 6 m with the non-failed portions of that length treated as right censors / suspensions — i.e., the breakdown strength is not determined, but known to be above a condition. The outcome of this analysis, in Weibull format, appears as the red curve in Figure 10.

As the 60 Hz withstand performance of the whole population is known (Figure 8), it is possible to augment the breakdown data with this withstand information to develop an estimate of the strength of the pre-test population (84 samples). Working backwards, we know that there were 14 weaker samples in the population that ended the Phase I tests (these failed in Phase II) and 19 weaker samples that started the whole program. Inputting this information with suitable censoring refines the location of the failures on the y-axis, thereby providing the estimates in Figure 10 — grey curve for the data at the start.

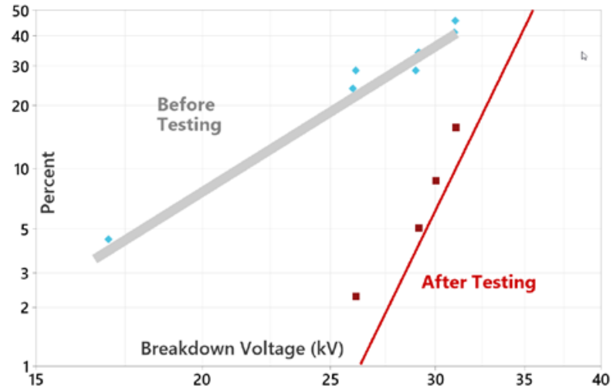

Figure 10. Breakdown strength (6 m lengths) of survivors (red) and estimations of pre-test case (grey)

DISCUSSION

Damage during testing

One of the concerns with simple withstand testing is that the testing may initiate an insulation defect, say an electrical tree, but not be under test long enough to allow that defect to grow through the insulation and fail within the time of the test. Such a defect could then fail under service conditions.

Even with the highest voltages (3 U_0), longest time (120 min) and repeated applications, the multiple PD tests indicated that no partial discharges appeared (within sensitivity level). This suggests that the VLF applications did not leave discharging defects in the cable. This is further supported by the absence of 60 Hz ageing failures. If defects were initiated, it is reasonable to expect that they would fail during the 12 weeks operating at 60 Hz, especially in Phase II where 2 U_0 was applied.

If the withstand testing was damaging the cables, it would be expected that the number of cables failing (either during the withstand or in the ageing period) would increase with the number of applications. Figure 8 shows that such an increase does not occur, and this supports the PD finding that the VLF Withstand is not causing cumulative damage to the cables.

Voltage level

As might be expected, the number of failures increases as test voltage increases (Figure 8 and Figure 9). However, as noted previously, this did not translate for the voltages studied here into more failures during the ageing period.

At first sight, it might seem that seeing more failures under test is beneficial, as these are defects that will no longer be capable of failing in service. However, it is not certain from this testing whether these excess failures were caused by defects that would actually have led to failure in service. Moreover, in practical situations, a failure stresses other components of the cable system. There is no doubt that the energy involved with a failure on test from a VLF unit is less than that from a 60 Hz service failure, yet every failure requires fault location (thumping is known to damage cables), excavation, then repair, often with two splices. Thus, it is not immediately clear that the cost and disruption would actually bring a reliability improvement for the excess fails.

Test times

The testing indicates that test times below the existing IEEE 400.2 recommendation of 30 minutes should be used very cautiously for simple withstands. This finding is drawn from the result that only approximately 10% of the cables failed during the first 15 minutes. In practice, there is often considerable pressure in the field to test for shorter times as there is the perception that time is being wasted during the hold phase. Generally, this is an incorrect perception, in that switching, connections and equipment setup account for more time than the test itself. In part, the adoption of monitored withstand procedures serves to address this wish, as a property is monitored, thereby providing a definitive assessment of the condition during the hold phase.

The results of this analysis suggest that there is a single distribution for the times to failure (similar gradients for each phase in Figure 9). Consequently, this study is unable to provide guidance on the maximum time to test. Certainly, out to 120 minutes, the longer the test, the more failures will occur. There is no clear change in mechanism, as postulated by some, that would appear as an upswing in the Weibull curve at long test times.

Reliability improvement

The cables used in this study were removed from service after experiencing in-service failures. Thus, the low breakdown strength (grey data in Figure 10) is consistent with their provenance. The breakdown strength assessment after completing the withstand and ageing tests (grey curve) shows that a number of the lower-strength sections have been eliminated. This leads to higher breakdown strengths and a change (steeper line and less scatter) in the mechanism of failure. At operating voltage and utility scale lengths, the analysis suggests that the VLF withstand testing causes an increase in the breakdown strength by a factor of approximately 20 (20% versus <1% at 25 kV).

There is a nonlinear [13] relationship between breakdown strength and endurance; thus, it is difficult to precisely determine the increase in endurance. However, laboratory and field studies show that improved endurance is correlated with increased breakdown strength — this being the basis of most qualification protocols. Moreover, the improvement seen here is due to a range of withstand tests, many of which would not be used in practice. Thus, this does not provide a way to estimate the efficacy of withstand tests following IEEE 400.2 guidance. Nevertheless, it does demonstrate clearly that the withstand procedure does remove weak locations without excessive damage to the strong locations, leaving the overall system with improved reliability. Recalling also that none of the VLF tested cables suffered failure in the AC ageing portions.

CONCLUSIONS

The studies described in this paper lead to a number of conclusions for the “Simple Withstand methodology:

- The VLF test conditions (voltage and time) set out in IEEE 400.2 [4] do cause life-limiting defects to fail under test, thus not impacting SAIDI / SAIFI.
- The VLF test conditions [4] do not initiate defects that degrade aged cables.
  - o No failures were seen in subsequent AC ageing.
  - o Failure rates did not increase with the repeated application of VLF.
- Great care and thought should be given when using parameters outside the IEEE 400.2 envelope (test time less than 15 minutes, voltages greater than 2.2 U_0).
- Reliability improvements seen from VLF withstand tests are significant and like those observed in the analyses of service experience. The test program delivers a >10 times increase in the breakdown strength, which correlates well with increased longevity.

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