Estimating the Impact of VLF Frequency on Effectiveness of VLF Withstand Diagnostics

Nigel **Hampton** (1)**,** Jean Carlos **Hernandez-Mejia** (2), Marina **Kuntsevich** (3), Joshua **Perkel** (1), Vivek **Tomer** (3)
1 - NEETRAC, Atlanta, USA, nigel.hampton@neetrac.gatech.edu, josh.perkel@neetrac.gatech.edu
2 - Universidad de Los Andes, Mérida, Venezuela, hmjeanc@ula.ve
3 – Dow Chemical, Spring House, USA, kuntsem@dow.com, VTomer@dow.com

ABSTRACT

Hipot or voltage proof tests have long been used to assure the health of cable systems in the factory and when commissioning. A recent concern with this approach is that there is no way to judge if the effect of dropping VLF frequency (required to test long lengths) has a significant and deleterious impact on the effectiveness of a Simple Withstand Test. This paper shows how this problem has been practically addressed with both Laboratory and Utility based studies. Both of these approaches conclude that there is no deleterious impact on the effectiveness of VLF testing at the lower end of the frequency band.

KEYWORDS

Diagnostic Techniques, Very Low Frequency (VLF), Water Treeing, Electrical Treeing, Withstand.

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. Experience shows that the most common voltage source used in service is the Very Low Frequency (VLF) approach (Figure 1). Although this test continues to serve the industry well and is described in detail in IEEE 400.2. However, when a Simple Withstand is implemented in the field users continue to raise concerns about the VLF frequencies: IEEE 400.2 discusses frequencies within the range 0.01 to 0.1 Hz. In most cases the need to move to lower frequencies is a result of needing to test longer (higher capacitance) system lengths.

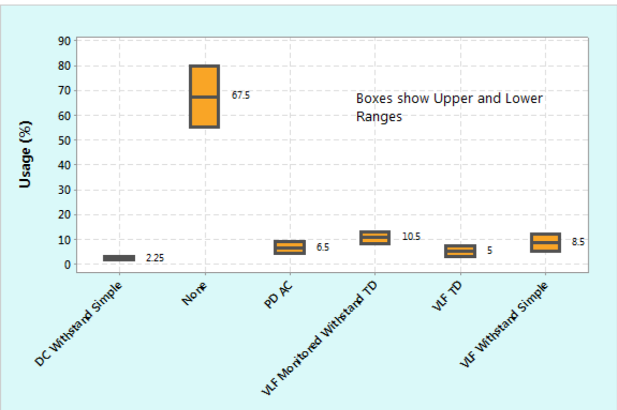

Figure 1. Results of a 2014 Study on the Use of Diagnostics on MV Cable Systems in North America

One of the useful studies [3] has suggested that lower frequencies are correlated (Table 1) with a reduced survival probability (Failure On Test {FOT} plus Failure In Service {FIS}): 87% and 75% for 0.1 Hz and 0.05 / 0.02 Hz, respectively. It may be hypothesized that this was because the defects in the cable systems inherently had higher breakdown strengths when tested at the lower VLF frequencies. However, it has been conjectured that this finding may not be due to the frequency of test, but to the reduced strength of longer lines where there is a higher likelihood of weakened links (joints, terminations, and/or degraded portions of cable) being present: the longer the chain the more weak links. Furthermore, the rates do not change between 0.05 to 0.02 Hz. The practical importance of any such difference in test frequency is that, if correct, there may be a need to extend the test time to compensate for the lower frequencies, i.e. the concept of a minimum number of cycles. To provide further information on this topic studies are needed where the test frequency is varied independently of the system characteristic. Besides, it would be advantageous to conduct such tests on test objects with a consistent level of degradation; this is the main focus of this paper.

Table 1 Reported effect of VLF Frequency on Outcome of Simple Withstand Tests in Malaysia on 11 & 33kV System, Moh, CIRED 2003 [3

Test Frequency (Hz)	0.1	0.05	0.02
Performance (%)			
Survival	87	75	74
Fail On Test (FOT)	10	19	20
Fail In Service (FIS)	3	6	6

The study discussed in this paper takes two directions. The first makes use of the well-known Ashcraft Water Tree object to grow a series of Water Trees to a consistent range of lengths. These objects act as models for a degraded extruded cable insulation. Subsequently, these objects are then subjected to VLF Withstand Tests at selected VLF frequencies of 0.1 Hz and 0.05 Hz. The electric stress at failure of these objects provides an indication of the effectiveness of the selected frequency. The second direction is an analysis of a well-defined long term Utility program where many of the VLF and cable system parameters (primarily length) are known; furthermore, the main elements of the program (time of voltage application and voltage level have remained constant).

SIMPLE WITHSTAND TESTS

Simple Withstand tests are proof tests that apply voltage above the normal operating voltage to stress the cable system in a prescribed manner for a set time [1 - 5]. These tests are similar to those applied to new accessories or cables in the factory where they provide the purchaser with assurance that the component can withstand a defined voltage. An alternative and more sophisticated implementation of the Simple Withstand approach requires that, in addition to its surviving the voltage stress, a property of the system be measured and monitored. This implementation of a withstand test, called Monitored Withstand, is related to the work described in this paper.

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

LABORATORY TESTS

The work by Moh [3] 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).

These requirements were addressed through the use of the well-known Ashcraft Water Tree object to grow a series of Water Trees to a consistent range of lengths Single water trees are grown from a water needle in a plaque

Test Objects

The schematic of the Ashcraft Method is shown in Figure 2. The prepared plaque containing the water needle is clamped in glass ware to contain the ionic solutions and provide the requisite electrical insulation (Figure 3). The water tree inception & growth are accelerated by:

- Field enhancement at the water needle
- Ionic solution
- High AC frequency

After 30 days a well-made group of cells will deliver a set of consistently treed cells that can be tested using the VLF Simple Withstand approach at selected conditions.

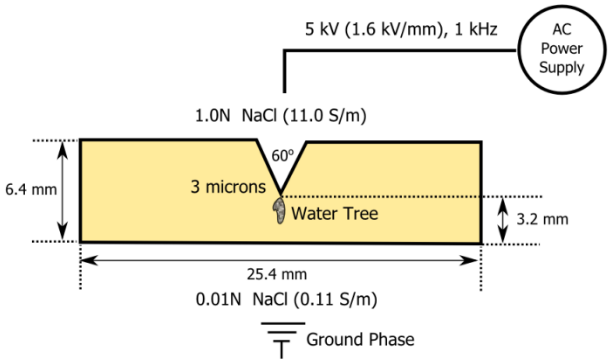

Figure 2. Schematic of the Ashcraft Approach

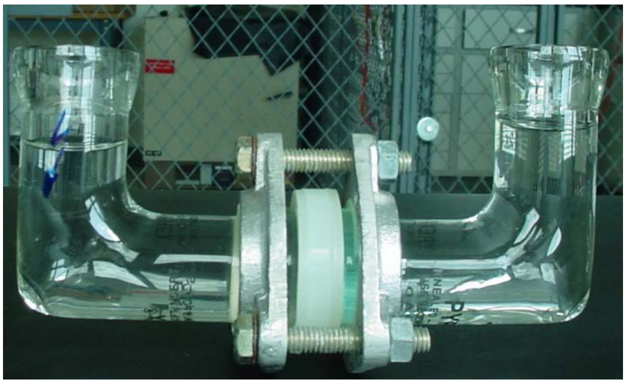

Figure 3. Ashcraft Cell installed and ready for test

In this work it was decided to mould the test samples from the three main insulation types encountered whilst conducting Simple VLF Withstand Tests: EPR, WTRXLPE, and XLPE.

Test Protocol

Approximately 100 samples were manufactured using the three insulation materials. 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 15 were dissected to confirm correct and consistent moulding of the defects and that water trees were present i.e. the samples were degraded. The remainder 85 samples were subjected to a VLF step ramp test to failure at a rate of 0.5 kV/min. The voltage wave form used was sinusoidal; this being by far the most commonly used in North America. Two VLF frequencies were selected for this study: 0.1Hz & 0.05Hz. It is important to note that in this work, unlike work in the field, the frequencies were selected rather than the result of the capacitance / voltage required. The samples were connected in parallel and tested in groups of three (selected at random) 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). Thus it was possible to determine both the AC VLF breakdown strength and estimate the water tree length.

Results

The first analysis was of the water tree length. The reason for this was twofold, a) to confirm that the samples contained trees and b) to confirm that the selection of samples for the 0.1 Hz and 0.05Hz tests were indeed random. Inspection of Figure 4 shows that both of these criteria were met.

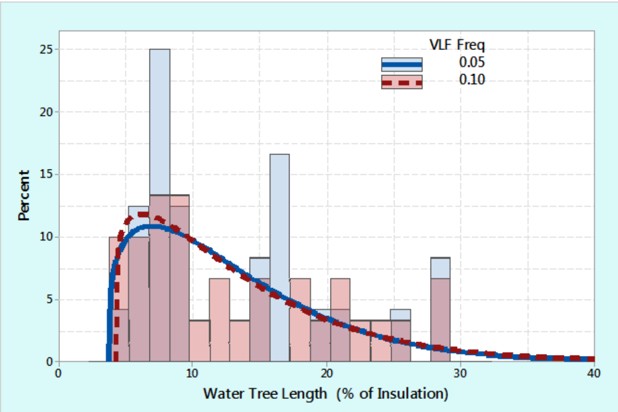

Figure 4. Distribution of Water Tree Lengths randomly selected for use with each frequency of VLF Voltage

The resulting VLF breakdown stresses for MV insulation materials are shown in Figure 5. 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 in the analysis (i.e. the breakdown stress was not determined but it was known to be higher than that of the failed sample).

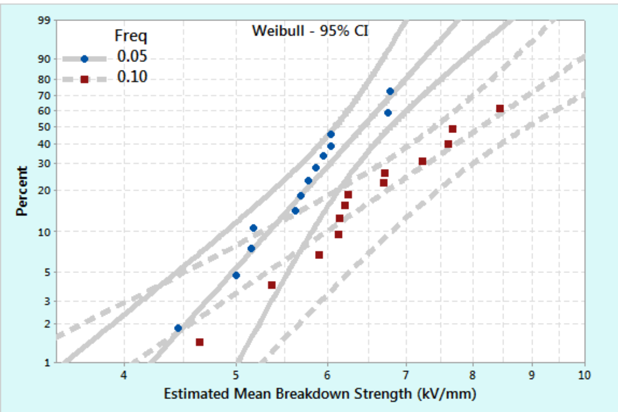

Figure 5. Weibull Analysis of the VLF Breakdown Strengths of Aged MV (EPR & PE-Based) Insulations After Accelerated Wet Aging segregated by the VLF Frequency

As Figure 5 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 [1] 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. > 10% of the insulation) to fail purely as a result of water tree degradation. Figure 6 shows the ranges of breakdown strength as functions of water tree length

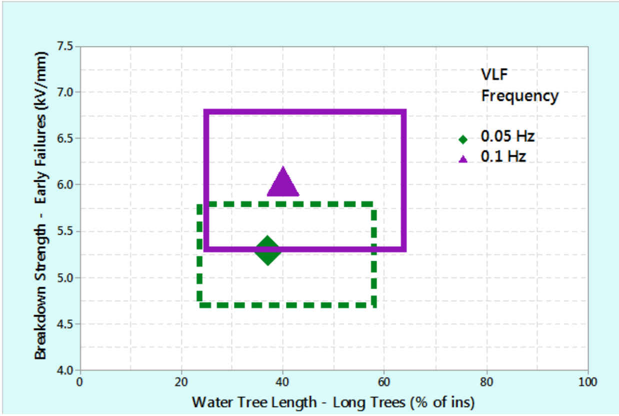

Figure 6. 95% Confidence Intervals of Breakdown Strength and Water Tree Lengths for 0.05 and 0.1 Hz Sample Groups

One of the possible inferences from the work by Moh [3] is that the lower VLF frequencies are less effective at finding defects. If this hypothesis were correct then in this work we would expect to find that the VLF breakdown strength would be higher for 0.05 Hz than 0.01Hz. In this work (Figure 5 & Figure 6) we find that the VLF Breakdown Strength on consistently degraded samples is certainly not higher at 0.05Hz than 0.1Hz. In fact the reverse of the Moh [3] hypothesis is plausible; namely that frequencies down to 0.05Hz maybe a little more effective. Clearly this trend cannot continue through the frequency spectrum as it has been established in many diverse studies that using DC tests are in effective and overly degrading – thus there has to be a limit, but it seems to be below the frequencies commonly used for VLF Simple Withstand Tests.

SERVICE PERFORMANCE

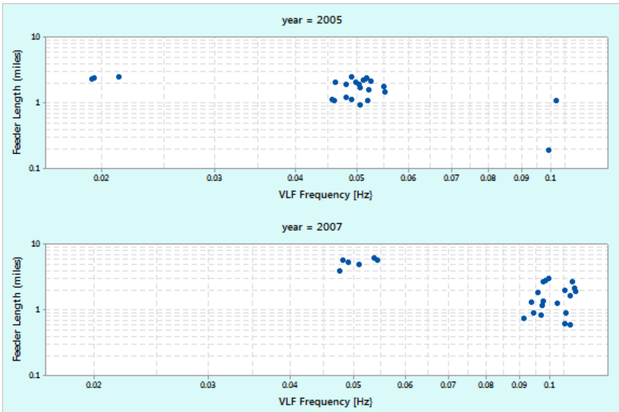

Figure 7. VLF Test Frequencies and Cable System Lengths

To complement the laboratory analysis described previously on EPR, WTRXLPE and XLPE insulations; analyses have been undertaken on field data derived from tests on aged PILC cables in the field. The data set encompasses Simple VLF Withstand Tests using a sinusoidal waveform tests from 2004 to 2009. This covers 220 miles of PILC cables 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 minutes at the IEEE400.2 [1] recommended voltages for the cable systems. The test frequencies and cable system lengths are shown in Figure 7.

The records for these tests are excellent with the lengths, frequencies and outcomes all recorded. Thus it is possible to conduct some detailed analyses. Inspection of the records enables the ranges of the failure rates to be estimated (Table 2). The failure rates are low overall: 6%. However the uncertainty in the estimates of the rates is large due to the small numbers tested and failing. Although this is not optimal from an analytical point of view this reflects the reality of trying to derive an understanding of data collected in the field. Nevertheless, using the same basis as the original Moh [3] study, namely the number of tests, it is not possible to assert that there is a difference due to the test frequency. The situation is the same if the analysis is extended to include the lengths – recall that Moh [3] noted that the lower frequency tests were carried out on longer higher voltage cables.

Table 2. VLF Simple Withstand Failure Rates segregated by VLF Frequency based on both Lengths Tested (top) and Tests Conducted (bottom)

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

Although slightly outside the scope of this paper; the data provided the times for all of the failures and those passing. Thus it has been possible to construct a Survival Curve (length adjusted) for these frequency segregated data (Figure 8). Figure 8 shows that in addition to the ultimate percentages being the same so are the survival curves.

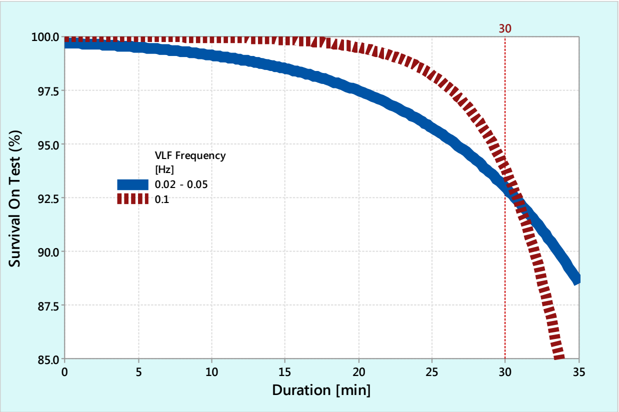

Figure 8. Survival Plot for VLF Tests at 0.1 and 0.02 to 0.05 Hz as a function of the time on test

Thus the data from the field does not display any 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 2010 there were no dielectric failures recorded for any of the cable systems that were tested using either of the voltage frequencies. 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 efficiency of testing between the two VLF frequencies.

FUTURE CHALLENGES

This paper has clearly shown that there is no distinguishable difference between failure rates on test for the common VLF test frequencies of 0.05 Hz and 0.1 Hz, from data obtained through laboratory and field tests, and all insulation types. Nevertheless there may be future challenges that would need to be addressed, such as:

- Evaluation of a wider frequency range.
- Separate analysis by insulation type.
- Increase the size of data from laboratory and field tests for even more significant results.
- Correlation between laboratory and field results.
- Updates to International; Standards.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the useful discussions with many of the engineers involved within the Cable Diagnostic Focused Initiative and the financial support of a large number of utilities in North America and the US Department of Energy under award number DE-FC02-04CH11237. They are especially endebted to the utilities who took the time to contribute data from the field.

CONCLUSIONS

This paper has reports two studies that were conducted to better understand the hypothesised effect of VLF frequency upon the outcome of the Simple Withstand Test procedure.

The laboratory studies have shown that when used on a set of samples degraded to a consistent degree (initial defect size and water tree length) the original hypothesis is not supported. In these tests the VLF Breakdown Strength is not lower at 0.05 Hz than at 0.1Hz. Furthermore there is some indication that the lower breakdown strength achieved with lower frequencies makes this more effective.

The utility study confirms that there is no distinguishable difference between the failure rates on test for those conducted lower VLF frequencies (0.02 to 0.05 Hz) than the more usual 0.1 Hz. The good performance in service after test indicates that both frequencies are equally good at detecting and eliminating defects that impact the cable system reliability.

These studies indicate that there is no benefit in modifying either the test time of the test voltage to compensate for any hypothesised in efficiency of a lower VLF frequency.

REFERENCES

1. IEEE Standard 400.2-2004™, *IEEE Guide for Field Testing of Shielded Power Cable Systems Using Very Low Frequency (VLF),* 2005.

2. IEEE Standard 400-2001™, *IEEE Guide for Field Testing and Evaluation of the Insulation of Shielded Power Cable Systems*, 2002.

3. S. Moh, “Very low frequency testing – its effectiveness in detecting hidden defects in cables”, Cogrès International des Réseaux Electriques de Distribution (CIRED), 2003, Session 1, paper No. 84.

4. RN Hampton et al, “Experience of Withstand Testing of Cable Systems in the USA”, CIGRE 2010 B1- 203.

5. J. Densley, “Aging Mechanisms and Diagnostics for Power Cables - An Overview,” IEEE Electrical Ins. Mag, vol 17, no 1, pp 14-22, Jan/Feb 2001.

6. Diagnostic Testing of Underground Cable Systems (Cable Diagnostic Focused Initiative), DOE Award No. DE-FC02-04CH11237, December 2010.

7. J Perkel et al, “Challenges associated with the interpretation of dielectric loss data from power cable system measurements”, *JICABLE11*, Versailles France, June 2011.

8. J Perkel et al, “Challenges associated with the interpretation of dielectric loss data from power cable system measurements”, *JICABLE11*, Versailles France, June 2011.