Needed Changes in Medium Voltage Cable Testing

Were you in on it? Welcome to the World of VLF.

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Abstract **- Some technical developments come about by chance, some by adaption of existing applications, and some from necessity. Very Low Frequency technology was a deliberate engineering development effort to solve a problem: field testing high capacitance loads with AC voltage. Its introduction goes back to the early 60's, first used for testing motors and generators by GE, ASEA, and others. For that application use was and is seldom. Then, wishing to abandon the traditional DC voltage cable testing methods, the need came about for testing medium voltage cables with something else: that something else was VLF AC technology. Obviously there was widespread application for cable testing that drove VLF development and use to the mainstream technology that it is today. Let's take a brief look at a little history and how the VLF technology is used today.**

A Brief Explanation

In the late 80's early 90's, once DC testing was found to be deleterious to service aged solid dielectric insulation, and revealed to show little anyway in the way of diagnostic value based on leakage current readings, especially for accessories, an alternative was sought. The preferred method to test cable is of course with AC voltage. However, due to the limitations of size, weight, cost, and practicality, power frequency hipots and series resonant systems were found not suitable in most field applications. What to do?

Desirous of finding a replacement for DC voltage testing of cable and generators (mostly cable), work began on VLF. Applying basic physics, the lower the frequency of the voltage applied to a capacitor the lower the charging current required. Put another way, the lower the frequency, the higher the equivalent resistance of the cable, $X_c=1/2\pi fC$, requiring less current and power when a voltage is applied. Today, there are many VLF hipots to choose from. All output a frequency of 0.1Hz, resulting in a charging current 600x lower than 60 Hz. Some models reduce the frequency to 0.01Hz. We now have a means to hipot cable in the field with relatively portable and affordable AC hipots. A 100 lb VLF can take the place of a multi-ton Series Resonant or 60 Hz supply.

VLF was first used (still is extensively) to perform a withstand test: a simple go/no-go test. If your cable can't hold 2 – 3 times normal voltage, it is not healthy. Better to cause failure at the defect location, find the fault and fix it during a controlled outage. Now the use of VLF has grown to perform cable diagnostics, most notably Tan Delta and Partial Discharge, with the VLF providing the voltage source. AC Withstand testing, TD, & PD, all using VLF is here. Now utilities have the answer and solution to the oft-asked question, can't somebody invent something to AC test my cables in the field?

What is VLF?

VLF is Very Low Frequency. A VLF test set is an instrument that has a high voltage output with a frequency of 0.1Hz or lower. It is basically an AC hipot but with a frequency output much lower than the typical power frequencies used in standard hipots. Many commercially available models offer variable frequency from 0.1Hz – 0.01Hz. Different vendors produce this low frequency in different ways. There are presently 4 or 5 vendors of VLF.

The Early Days of VLF

VLF was first developed in the late '50s early '60s as a means to test large rotating machinery with equipment far smaller than the required 50/60Hz power supplies used at the time. ASEA and GE both constructed VLF generators for their own use, GE first in 1961 and soon after ASEA. Although these early VLF models were quite large, they still had a size, weight, price, and power requirement advantage over 50/60 Hz power supplies, and the yet to come series resonant systems. Today, VLF generators are used for testing large rotating machinery but the practice is not widespread. Many are tested with series resonant systems that were purchased in large numbers from the '60s to today and many motors/generators are not tested with an ac withstand test, hence there was/is little compelling reason to use VLF. Due to the small size and weight, VLF would be advantageous however for use in rewind shops. A 150 lb VLF can do the job of a multi ton SR. IEEE433-1974 details VLF testing of Large Rotating Machinery. The test voltage at 60Hz and 0.1Hz is not equivalent. The standard requires that the VLF test voltage be 15% higher than at 60 Hz. The VLF voltage is to be 1.63 times the rms AC voltage, which is 1.414 since VLF units are measured in peak output x1.15 more in voltage, for 1.63. The time duration is the same.

Today, probably 99% of the uses for VLF are to test medium voltage power cable. Higher voltage output VLF models are becoming available that will be used on HV cable. For this cable testing, there are several very good reasons to use VLF over anything else. VLF offers the user a means to AC test high capacitance loads, like long cable, with a relatively portable and affordable device. Its operation and 0.1 Hz output frequency have been researched extensively for cable testing and found to be similar enough in characteristics to take the place of 50/60 Hz machines. Most of the worlds engineering organizations have embraced VLF and several have written standards for its use, including the IEEE, VDE, IEC, etc. VLF is widely accepted and used by hundreds of utilities and others throughout the world in nearly 100 countries. It may not be a perfect solution, but between VLF, VLF TD, and VLF PD, nearly all the data capable of learning about a cable's health is available.

More Recent History

The first company to produce a commercially available VLF was Hagenuk in 1985, now part of Seba Dynatronic from Germany. They produced a model with a 54kV peak/rms output. Its peak & rms are the same since it is a rectangular bipolar waveform but with power frequency polarity transitions. It is commonly referred to as a cosine-rectangular waveform. It does not produce a sine wave so there are some limitations on using this device for tan delta and partial discharge testing.

Large Rotating Machinery Withstand for 1 min

	60 Hz rms	dc	0.1 Hz (crest)
Test voltage	V	1.7V	1.63V
End turn stress	Little of end turn stressed	Most of end turn stressed	Intermediate between 60 Hz and dc
Number of bursts of ionization	7200	Few	12

Table 1 from IEEE433-1974

The second company was Baur from Austria. Baur produces a 60 kV peak sine wave model, starting in 1988. Both of these waveforms worked well to perform withstand testing on MV cable. They were rather expensive, large, heavy (250lb/400kg Baur – 220lb/350kg Seba) and were best mounted in a van or truck. Both vendors have since produced smaller and more portable models. The first markets for these were European followed by other parts of the world with the US lagging behind, largely due to the lack of a standard and the high expense. It wasn't until the late '90s that people accepted the problems associated with DC testing solid dielectric cable and needed a replacement method. In 1998 High Voltage, Inc. from NY introduced the first line of truly portable and much more affordable VLF generators. With equipment now within the fiscal and practical reach of utilities, the trend took off and many more around the world took notice of VLF. The IEEE included VLF within IEEE400-2001, an omnibus cable-testing standard, and work began on a point document for VLF testing (IEEE400.2-2004). A VDE DIN standard already existed in Germany for some years. At this time, most vendors offer portable and affordable models.

VLF for Cable Testing

The original power cables were paper insulated, often oil soaked. These cables were tested with DC voltage, which seemed to work adequately. In the '60s and 70's solid dielectric cables were introduced, like High Molecular Weight (HMW), PVC, and others. With this new cable came the old test methods, namely DC voltage at 5 – 6 times normal-operating voltage. This cable was supposed to last for 40 years yet was failing after 15 – 20 years. Why? The original HMW cable was not double or triple extruded as it is now, guaranteeing the cleanest, and least contaminated method of constructing the cable. Not only was it subject to dirt contamination, but this method of manufacture also left many voids and impurities in the material. The insulation was primed for water tree contamination, trapping space charges, and other problems. Recognizing that the quality in manufacture had to improve, cable producers began multiple extrusion methods of manufacture. This better insured cable insulation purity and overall construction improvement. Also, new materials were soon used, like EPR and XLPE.

Testing Problems Continued

Even though cable quality improved, and new types of solid dielectric were used, there were still problems and apparently always would be, with thousands of miles of the questionable HMW cable was already installed and more and more of the XLPE and EPR was being installed, both solid dielectrics. The problem was that this cable was being tested with the same DC methods originally used on oil-insulated cable. There were no engineering studies that said this is the way to test solid dielectric cables. We just did what we always did. Years later we discovered the problems associated with testing this cable with DC voltage. The problems were two fold. The leakage current measured with DC on solid dielectric cables and the new types of splices and terminations used with this cable were not indicative of the cables quality. There were a high percentage of cables that failed in service following a DC test that supposedly passed. The second problem was that the use of a monopolar, negative output DC hipots caused space charges in the cable. Water tree regions and other defect locations would become polarized and create an area of high stress once AC was reapplied. Failure would occur. These regions of charge were called "trapped space charges" since following the DC test, they would remain in their localized areas since the solid dielectric material would not permit them to move and dissipate throughout the cable, like in oil filled cable. A non DC voltage method of testing had to be found.

Also, and as important, even if the insulation is perfect, workmanship has to be verified. With most failures due to poor workmanship during installation, improper splices during repairs, damage from over voltage thumping, etc., there is a definite need to VLF the cable. Worker safety is also an issue, with many utilities not satisfied with the minimal methods now used to verify a cables integrity.

Enter VLF

With cables failing due to DC voltage testing, and with the limitations of meaningful test results when using DC voltage, an alternate had to be found. That alternate was VLF. We would always have rather tested with AC voltage for obvious reasons but were limited in the field due to the size, weight, and cost of the equipment. The VLF units solved all that. The 0.1 Hz was considered similar enough in its instigation of partial discharge as 60Hz that it was accepted for use to hipot cables while offering a 600:1 advantage over 60 Hz in terms of the load it can test. Simple physics: drop the frequency and the current and power needed to charge the capacitance of the cable drops with it. There should be no doubt about the efficacy of using VLF.

What Voltage and Power Ratings are Available?

From various vendors there are models rated 0 – 20kV up to 0 – 200kV. VLF units are rated by the μF of load they can test. A typical specification might be 0-30kV peak, 0.1Hz @ .5μF. (An XLPE 15kV cable of .5 μF may be approximately 1 mile long.) Some models may or may not have variable frequency. If so, the load capability linearly increases with decreasing frequency. At 0.02 Hz the load rating would be 2.5μF, or 5 times the 0.1 Hz rating. Generally however, most testing is performed at 0.1Hz with the lower frequencies only used for very long cables. Also, diagnostic testing like Partial Discharge and Tan Delta are performed at 0.1Hz, so the set rating at that frequency is important. One important note is that IEEE433-1974 for rotating machinery requires 0.1Hz be used for testing motors and generators.

Some VLF models have μF ratings of 50 μF at 0.01Hz for testing extremely long cables. Most VLF units are voltage rated based on cable class. For instance, 44 kV and 62 kV sets are needed to conduct Acceptance tests on 25 kV and 35 kV cable, respectively. 28 kV – 30 kV sets are produced to test 15 kV cable and one vendor has a 120 kV and a 200 kV set for testing cables rated from 45 kV to 138 kV.

Defining the Test

In its simplest form, a VLF test is go/no-go withstand test. A voltage is applied for a length of time and the load either holds the voltage or fails. Table 2 & 3. In this case, if the cable holds the voltage, it is presumed, based on experience and research that the cable will not fail in the next 3 - 5 years. Think about it, if the cable can hold 2 – 3 times normal voltage for 30 – 60 minutes, it's a good cable. If the cable fails, then the fault must be repaired or the cable replaced, after which the test should be performed again. If the test is performed properly, the VLF does not aggravate defects only to cause an in-service failure later nor it does it harm good insulation.

IMPORTANT: If a defect is severe enough to be driven into partial discharge under the test voltage (the intention of the test), then enough test time must be allowed to cause that defect to grow to failure. Minor defects that are unaffected by the test voltage do nothing and good insulation is also unaffected. It is important to apply the proper test voltage for the proper time to allow the test to do its job. If a cable fails under test, it was not healthy and probably would have soon failed in service. Better to cause failures during controlled outages when a repair or replacement is on hand. The VLF is an excellent splice and termination checker as most failures are with accessories. It is also a great tool for post repair verification testing before reenergizing, far better than the megohmmeter, dc hipot, hot stick adaptors, or soak test methods presently used.

IEEE Std 400.2–2004
IEEE Guide for Field Testing of Shielded Power Cable Systems Using Very Low Frequency (VLF)

Table 5—VLF test voltage for sinusoidal waveform (see Note 1)

Cable rating phase to phase	Installation (see Note 2) phase to ground	Acceptance (see Note 2) phase to ground	Maintenance (see Note 3) phase to ground
rms voltage in kV	rms or (peak voltage)	rms or (peak voltage)	rms or (peak voltage)
5	9 (13)	10 (14)	7 (10)
8	11 (16)	13 (18)	10 (14)
15	18 (25)	20 (28)	16 (22)
25	27 (38)	31 (44)	23 (33)
35	39 (55)	44 (62)	33 (47)

Table 4—VLF test voltages for cosine-rectangular waveform (see Note 1)

Cable rating phase to phase	Installation (see Note 2) phase to ground	Acceptance (see Note 2) phase to ground	Maintenance (see Note 3) phase to ground
rms voltage in kV	rms voltage/peak voltage	rms voltage/peak voltage	rms voltage/peak voltage
5	12	14	10
8	16	18	14
15	25	28	22
25	38	44	33
35	55	62	47

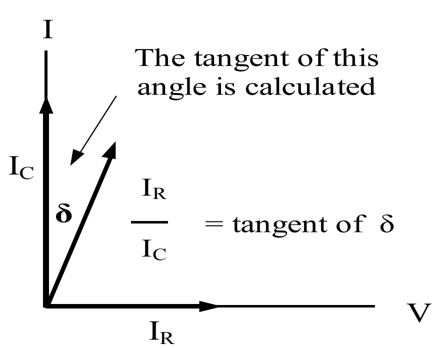
Tables 2 &3. Voltage test levels per IEEE400.2-2004.

Other Tests Using the VLF

So far we have described the VLF as a tool for withstand testing. What else can we do with it? A sine wave producing VLF can be used as the voltage source to supply cables with AC voltage for the purpose of performing diagnostic testing. Maybe you don't wish to risk failing your cable with a VLF test, you just want to learn something about its health, or test many cables for comparison and replace the worst first. There are two "diagnostic" methods available: Tangent Delta and Partial Discharge.

Tangent Delta Testing

Also called Loss Angle or Dissipation Factor testing, similar to power factor, is a means of generally identifying the water tree content in a cable and the presence of other defects in the insulation or splices/terminations. The general purpose and advantage of a TD test is to provide the data as to the quality of the cables insulation so that a comparative analysis can be made of many cables to help prioritize replacement or possible injection. Also, additional testing strategies can be determined by the results of this test.



The physics is this: if a cable's insulation is perfect, it is nearly a perfect capacitor. In a capacitor, there is a 90 phase shift between the applied voltage and the capacitive current Fig 1. The more degradation present in the cable, the less it's a perfect capacitor. There is a resistive element to it. We can measure the change in the angle between the two. The actual angle measured is the tangent between the resistive current Ir and the capacitive current Ic, or Ir/Ic. *See diagram*. By performing a TD test, the quality of cables insulation and accessories can be determined. One limitation of this test is that it gives and overall interpretation of the cable from start to finish. Another drawback is that it is best when used on only a single type of cable insulation, as different materials have different TD characteristics. Enough TD testing has been performed to have a good idea of the absolute numbers for different cables and how those numbers change with increasing voltage, a vital clue in the interpretation. The test may start at .5Uo with a reading taken. Raise the voltage to 1Uo, take a reading, then 1.25Uo, 1.5Uo, and depending how the cable looks, perhaps 1.75Uo and 2.0Uo. The intent is to get a curve of the increasing TD with increasing voltage, indicating contamination "Fig 2". To avoid possibly failing the cable during the test if the curve looks worrisome, the voltage does not exceed perhaps 1.2Uo or 1.3Uo. We've already learned that the cable is highly deteriorated. By performing the above, we are able to rate our cables as Highly Degraded, Moderately Degraded, and Acceptable, or as some use, Action Required, Further Study Required, of No Action Required. We can then decide where to put our replacement and/or injection money.

Partial Discharge

We just explained Tan Delta testing, where the overall health of the cable is determined. Now we will talk about Partial Discharge testing, where individual defects in the cable are located and measured in intensity. When done correctly, both offer good data, just different data. The choice of whether to use one or the other comes down to the expense, ease of performing the test, cable system design, and most importantly, what data are you looking for and what will you do with it. While there are others far more expert in PD than this author, a brief attempt will made to explain the different PD methods available.

There are four types of partial discharge detection for cables: on-line spot testing, on-line continuous monitoring, off-line using power frequency applied voltage, and off-line using VLF applied voltage.

On-line spot testing uses various types of sensors around the cable to monitor the PD activity in the cable while is operating. On a spot basis, it offers limited information as the voltage level measurements are made at operating voltage while there could be problems

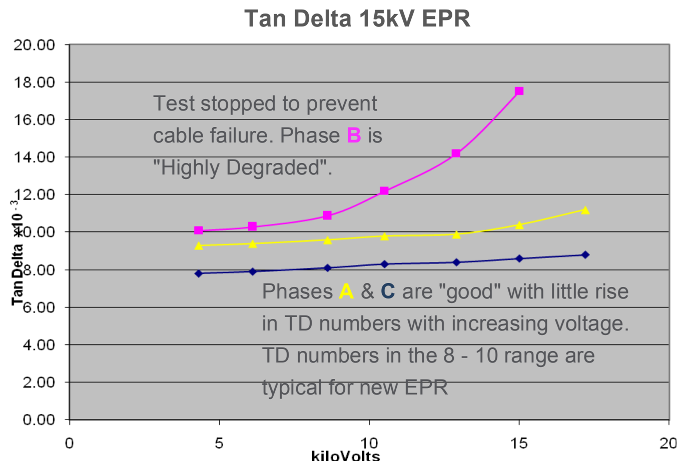


Fig. 2. Tan Delta curve for three phases, B indicating deterioration.

at levels slightly above that. It is more useful for detecting potential problems in accessories, where they can exhibit high levels of PD at operating voltage. There are many purveyors of this technology.

On-line continuous monitoring is what the name implies, continuous monitoring of a cable to watch for PD activity and catch any events that may occur to cause PD which can then be acted upon. This method is usually reserved for important feeders or transmission lines. There are many purveyors of this technology.

Off-line power frequency testing uses some form of 60Hz power to provide the voltage while PD is measured. This method best simulates factory testing as it uses 50/60 Hz and offers the ability to perform over voltage testing to measure Partial Discharge Inception Voltage, or PDIV, and the Partial Discharge Extinction Voltage, or PDEV. This way it can be seen exactly where PD begins relative to voltage and where it extinguishes when the voltage is lowered. However, it requires very large, heavy, and expensive series resonant power supplies truck mounted. At this time, it is mostly performed by service companies. There are few purveyors of this technology.

Off-Line VLF testing uses a VLF unit providing 0.1Hz output to supply the test voltage. While not exactly equivalent to the measurement at 60Hz, its close and works wells enough to indicate the same results, location and severity of PD. It too offers variable over voltage control to measure PDIV and PDEV. The obvious advantage here is that the VLF is 100 or 200 lbs rather than a couple of tons as is the 60 Hz approach. Several companies now produce PD detection equipment that mates to commonly available VLF products. This method is also far less expensive than the power frequency approach and the user generally owns the equipment and can use the VLF for withstand testing and TD testing. While TD testing is widespread using VLF, PD testing using VLF is just now coming to market. Now one system can perform VLF withstand and/or VLF TD and/or VLF PD testing. That's about all you learn about your cable. There are several purveyors of this technology trying to bring systems to market. Several PD companies are now able to integrate their PD detection equipment with presently available VLF units.

Conclusion

This was an overview on the subject of VLF. Of course there is much more detailed information on all subjects mentioned here. Hopefully this paper offered the uninitiated to VLF a brief explanation of the technology and its use. A few summary points:

- VLF has been successfully used worldwide for >15 years.
- VLF has been accepted by the IEEE and similar world organizations for >10 years.
- Standards exist in several countries for VLF testing.
- For field testing of solid dielectric cable, there is little alternative to VLF.
- There are many vendors of VLF.
- VLF Withstand, VLF TD, and VLF PD testing provide all the information needed about a cable.

02/2010

Note: This paper was written in 2010 based on the experience and knowledge of the industry and the author at that time. Some of the remarks may be dated. Since then, many advancements have been made in all areas of VLF testing, including the refinement of TD and PD diagnostic testing and computer controlled operation and data interpretation. Refer to newer materials from HVI and others for more up to date information. www.hvinc.com