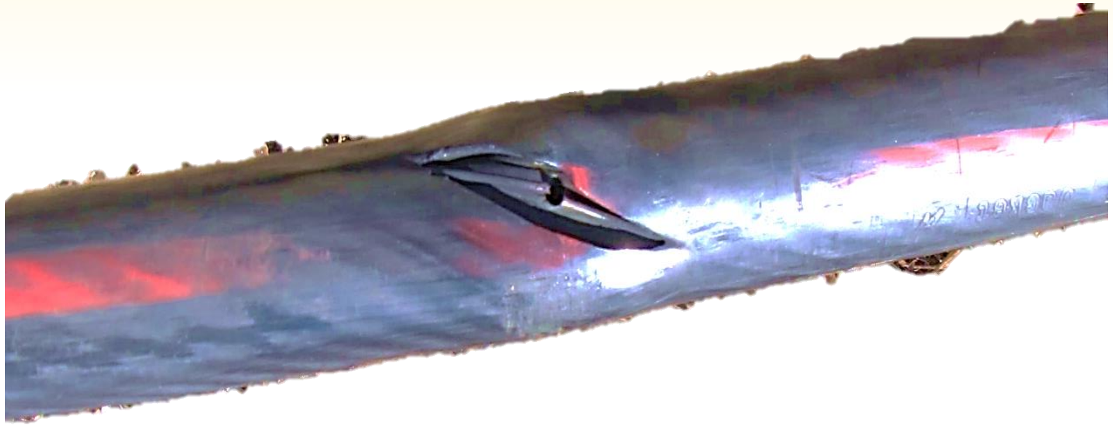
MEDIUM & HIGH VOLTAGE CABLE TESTING
NEW TECHNOLOGIES BRING NEW METHODS

VERY LOW FREQUENCY AC TEST SETS
0.1 Hz. – 0.01 Hz. with Sinusoidal Output Voltage

WHY MUST WE CABLE TEST?

BECAUSE THIS CAN BE PREVENTED!



In-service failures cause great damage beyond just the faulted cable. Do something to prevent many of them.

CABLE TESTING SUBJECTS COVERED

Cables Need To Be Tested

Why DC Is Not Preferred

What Is VLF

History of VLF

VLF Withstand Testing

VLF Applications

IEEE, IEC, & Others Standards

Model Sizes & Vendors Designs

How To Perform VLF Test

VLF for Diagnostic Testing

VLF Tan Delta Testing

VLF Partial Discharge Testing

Selecting A Cable Test Method

Selecting a VLF Model

Waveform Issues

Who Uses VLF

Summary & Conclusion

Field Testing Photos

ALL CABLE SYSTEMS DETERIORATE

New or Old Cable Can Fail

Old: All insulation deteriorates with age. Causes of degradation are changes due to thermal, mechanical, chemical, and atmospheric conditions, corrosion, physical damage, movement, moisture ingress, over voltage transient stresses, etc.

New: Commission testing new cable. Even if no insulation or component defects exist, what about faulty workmanship on splices, terminations, or joints during installation, or over pulling & bending?

New Cable ≠ Good Cable

MOST DON’T ADEQUATELY TEST CABLES?

Our cable infrastructure is the most extensive, fragile, and oldest part of the Distribution system, yet so many fail to use the testing tools now available to keep it healthy. Why?

Would you perform no tests on your new or old transformers? Never test a relay or switchgear? Ignore bucket truck HV dielectric testing?

Of course not, we perform many tests on apparatus to learn all we can: Hipot, IR, TTR, Oil Analysis, FRA, PD, TD, PF and more.

Why don’t cables get the same respect? At least the critical ones and those just installed or repaired?

Possibly because there was no good way to test cables for meaningful results prior to the development of VLF AC technology. Now there is no excuse to not test cable assets and other high uF loads, like motors.

DO SOMETHING! THERE ARE NOW SEVERAL MEANINGFUL TESTS AVAILABLE

DC Voltage Testing is not an option - No testing is even worse

There are several suitable field tests to perform on newly installed or service aged solid dielectric insulated cable. Some are inexpensive and easy, some are expensive and complicated. Different data is gained from different tests. You decide what data you need, what remedial action you're prepared to take, and then select the test equipment and other resources needed.

DC VOLTAGE OR AC VOLTAGE TESTING? Edison or Westinghouse?

DC voltage testing of solid dielectric cable is no longer used in most cases due to several known problems associated with it, most notably, insulation degradation from negative DC voltage and its limited effectiveness to provide reliable and meaningful results. Oil insulated cable can still use DC.

AC voltage has always been the standard used for factory testing and some field testing, but only since the late 90's can AC now be economically and conveniently used in the field to perform **Overvoltage Withstand** testing and **Tan Delta** and **Partial Discharge** diagnostics, all common to factory testing. The development of VLF technology made this happen.

George Westinghouse & Nicolas Tesla won the AC vs. DC battle against Thomas Edison. In 1892, AC current was selected as the mode of electricity generation, distribution, and usage.

DC USED FOR DECADES TO TEST PILC CABLE

THEN CAME SOLID DIELECTRICS LIKE EPR, XLPE, ….

DC WORKS WELL FOR PILC, IT SHOULD WORK FOR SOLIDS?

WRONG: PILC – YES. SOLIDS – NO

Issue: 10 – 15 years after solid dielectric cable was installed, it started to fail prematurely. Testing, research, and field experience has shown that solid dielectric cable is prone to develop water trees and DC testing at high voltages creates **"trapped space charges"** within these trees that leads to failure. Also, DC leakage currents measured have been shown to be unreliable, unrepeatable, and too affected by many factors to accurately predict a cables or terminations insulation integrity, especially under AC voltage conditions. Also, no "standards" exist to define their levels for all the field situations possible.

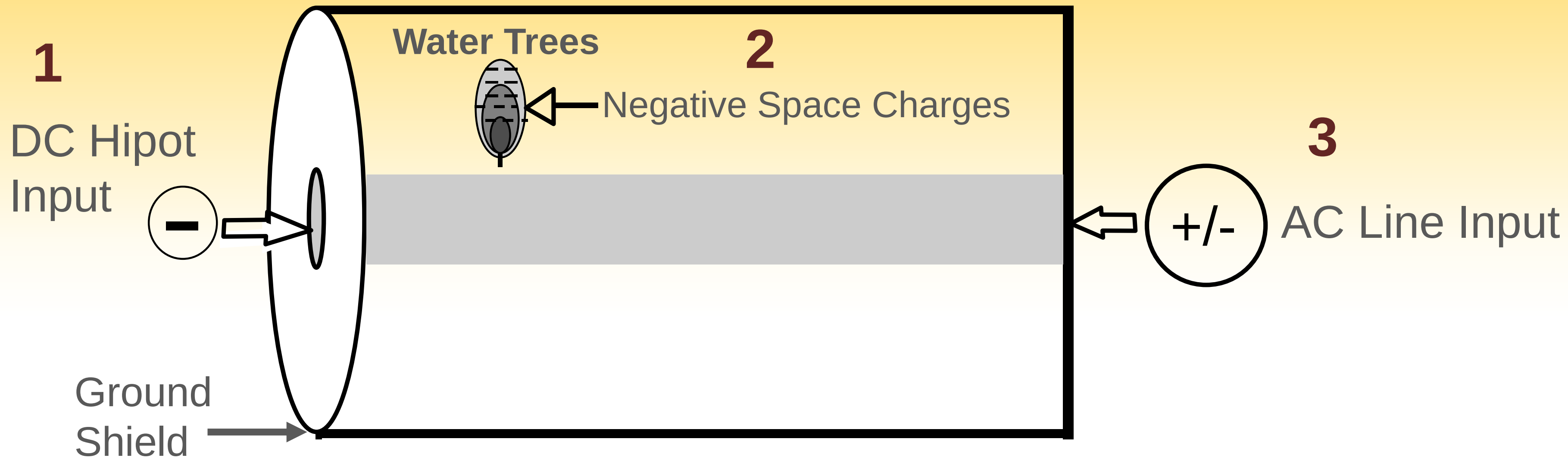
Q: Can't there be an economical and practical AC method for field hipoting cables, like in the factory?

A: Yes - enter VLF. Traditional 50/60 Hz AC power supplies are too big, too heavy, too expensive, and not portable enough to field test cable. To solve the problem, work began on commercially viable VLF in the 90's and the use of VLF is now widespread and available from many vendors. Standards exist worldwide.

WHY IS DC UNNACEPTABLE FOR SOLIDS?
ANSWER: WATER TREES ARE CHARGED BY DC

- **Tree shaped channels** are found within the insulation of operating cables resulting from the presence of defects & voids.
- **Prevalent in solid dielectric** cables.
- **Monopolar DC** aligns molecules in voids
- Eventually **leading to PD** thru the creation of electrical trees.
- **Leads to insulation failure**.
- **DC testing hastens** failures.

TRAPPED SPACE CHARGES IN WATER TREES



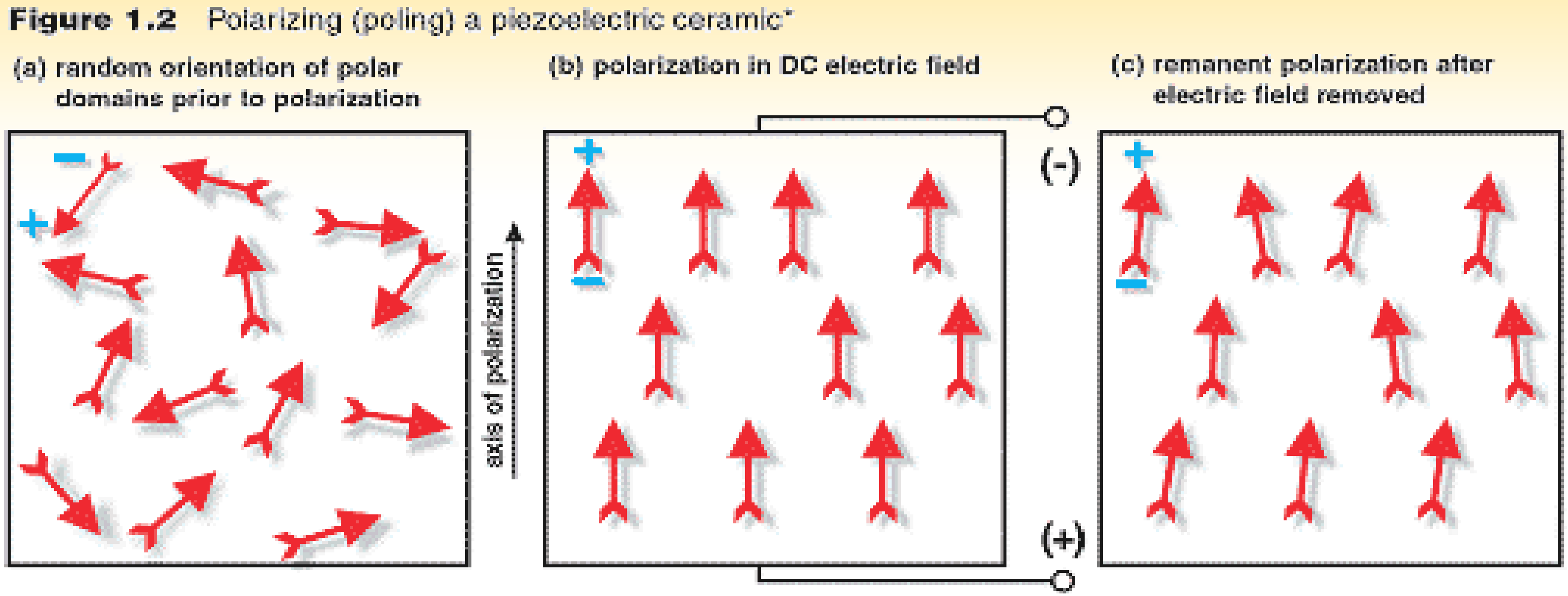
1 The 4 – 5 U_o negative output of a DC hipot polarizes water tree areas, aligning molecular charges in a di-pole fashion.

2 Unlike ***"fluid"*** oil insulated cable, in ***"solid"*** dielectric insulation like XLPE, EPR, PVC, etc. these "trapped space charges" remain in place after the test.

3 When AC is reapplied, a high difference of potential exists across the remaining insulation. Leads to electrical trees, PD, & cable failure.

ATOMIC POLARIZATION of MOLECULES

Before & After DC Voltage Applied



Prior to DC Voltage	DC Voltage Applied	DC Removed
Random Orientation	***Polar Orientation***	***Di-polar effect leaves neg/pos orientation***

WHAT WE KNOW ABOUT DC

- **PILC & <u>new</u> EPR, XLPE, PVC, etc.   DC OK - no space charges created**
- **"Service Aged" Solid Dielectrics   No DC - all develop space charges**

Again, **"Space Charges"** trapped in isolated areas of solid dielectric cable insulation cause high stress points during normal operation and more severely during over voltage tests. When over voltage AC stress is too high, partial discharge initiates, starts electrical tree growth, and cable fails. IEEE, IEC, utilities, cable manufactures, cable research labs, and most world engineering associations agree on issue. **A change was needed**

VLF Withstand, VLF Tan Delta, and VLF Partial Discharge are all mainstream tests performed worldwide for over thirty years.

WE SHOULD TEST CABLES WITH AC ANYWAY

Why Wouldn't We if Possible?

- Cables are designed to carry AC voltage.
- They are factory tested with AC voltage.
- Cables operate under AC voltage stress.
- Why wouldn't cables be tested with AC voltage?
- Overvoltage Withstand and Diagnostic methods exist.

DECIDED - WE NEED AC VOLTAGE, NOT DC

The Big Question? Is there a way to test long cables in the field with AC voltage, not DC, without needing a multi-ton, million dollar HV resonant transformer and a few hundred kVA to power it?

Yes! Reduce the frequency of the test voltage to reduce the AC charging current needed, using a Very Low Frequency (VLF) AC hipot.

Of course, it's basic physics. For a capacitor: $A = 2\pi fCV$

- Lower frequency = lower charging current.
- If 100 V @ 60 Hz = 1 Aac charging current
- Then 100 V @ 0.1 Hz = 1.7 mAac charging current. 60 Hz. vs. 0.1 Hz = 600:1
- Work began to produce VLF high voltage generators in the 1990's.
- (Actually, in the late '60s, GE built their own 0.1 Hz VLF to test generator coils.)

MEDIUM & HIGH VOLTAGE CABLE TESTING

VLF TECHNOLOGIES BRING NEW METHODS & FACTORY TYPE TESTS TO THE FIELD

Three Common Field Tests Using VLF

- ❑ *VLF Overvoltage Withstand*
- ❑ *VLF Tan Delta (TAN δ) or TD* **
- ❑ *VLF Partial Discharge or PD*

** **Dissipation Factor** and **Loss Angle** are two other names for Tan Delta testing. **Power Factor** testing will reveal the same values as TD due to the very small angles measured: <1

VERY LOW FREQUENCY (VLF) AC HIPOT

A VLF hipot is simply an AC high voltage instrument but with a frequency output of 0.1 Hz. and lower. Most VLF models produce from **0.10 Hz. – 0.01 Hz.**

The **lower the frequency, the lower the current** and power required to test high capacitance loads like cables and rotating machinery.

DON'T OVERCOMPLICATE IT. IT'S A SIMPLE AC WITHSTAND TEST.

VLF is among the easiest, least expensive, most certain way of testing the AC integrity of MV/HV cable or rotating machinery.

Note: A sinusoidal output VLF supply is required by the IEEE and others to perform tan delta and partial discharge testing, and for motor and generator testing

DROP THE FREQUENCY - DROP THE POWER

The Practical Benefit of VLF?

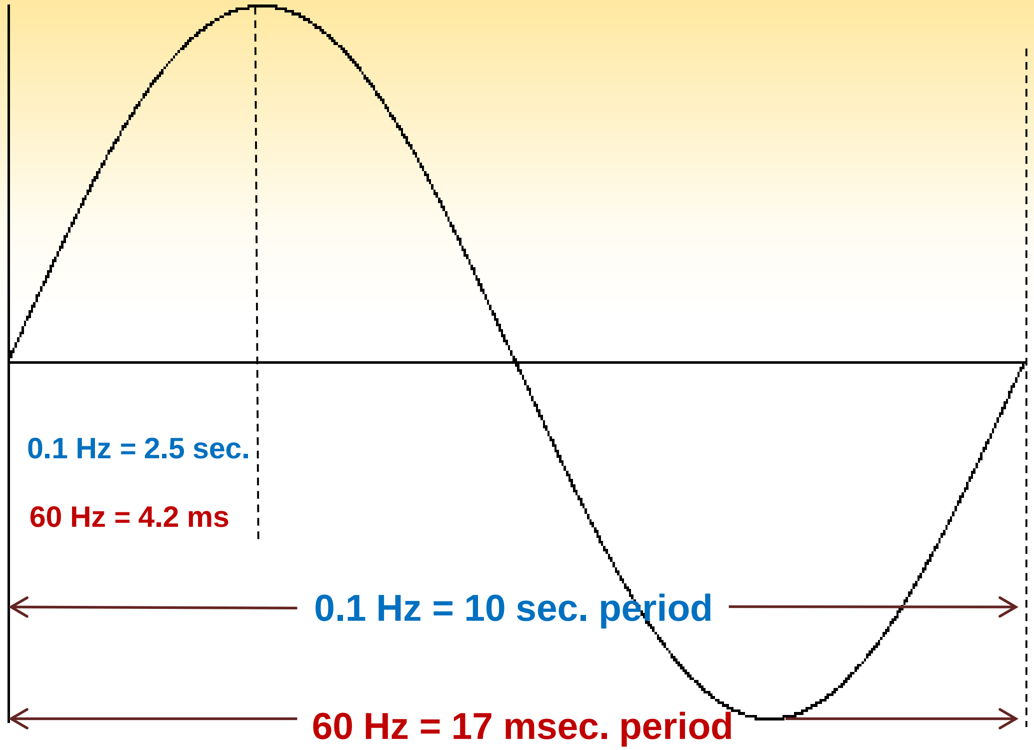
By decreasing the frequency, it is possible to test miles of cable with a small and affordable hipot.

Output frequencies range from 0.1 – 0.01 Hz.

IEEE 400.2 recognizes frequencies as low as 0.01Hz.

At 0.1 Hz, it takes ~**600 times less power** than at 60 Hz. to test a cable or any other high capacitance load. At 0.01 Hz, 6000 times higher capacitive loads can be tested than at 60 Hz with the same power consumption. ***Basic physics, nothing mysterious.***

0.10 Hz. vs. 60 Hz. WAVEFORM



AC Charging Characteristics of Capacitance

At 60 Hz., only 4.2 mS are required to charge a cable to the peak voltage (from 0° – 90°).

At 0.10 Hz., since it takes 2.5 seconds to reach peak voltage, **600x less current** is required than at 60 Hz.

Analogy: to accelerate to 60 mph in 2 seconds, a car needs a far more powerful engine than if 10 minutes were allowed from 0 - 60 mph.

At 0.1 Hz the charging time to max. voltage is 2.50 seconds

At 60 Hz the charging time to max. voltage is .0042 seconds

Capacitive Charging Current Equation

A = 2πfCV A = Amps, C = Farads, V = Voltage

VLF EXPLAINED CALCULATING Xc

(the equivalent resistance, or capacitive reactance, of a cable)

$$X_c = \frac{1}{2 \times pi \times f \times C}$$

f = frequency
C = capacitance in Farads

The lower the frequency, the higher the capacitive reactance, or X_c. The higher X_c , or resistance across the AC voltage applied, the lower the current and power needed to charge to full voltage.

Remember Ohm's Law: I = V/R

Lower frequency = higher resistance = less current

WHAT A DIFFERENCE THE FREQ. MAKES

A 1 µF cable tested at 60 Hz. versus 0.1 Hz.

At **60 Hz,** the cable's **X_c =** **2.65 kOhms**.
A **30 kVac** test voltage will need **11.7 amps** of current
The voltage source (hipot) power rating must **> 351 kVA**

At **0.1 Hz** the **cable's X_c =** **1.6 megohms.**
A **30 kVac** test voltage will need **0.019 amps** of current
The voltage source (hipot) power rating must be **> .570 kVA**

A 1.0 µF, 15 kV 500 mcm xlpe cable is ~ 1.6 miles long
A 1.0 µF, 35 kV 500 mcm xlpe cable is ~ 2.7 miles long

HIPOT COMPARISON OF 60 Hz. vs. 0.1 Hz.

50/60 Hz.
Hipot

72 lbs.

0.10 Hz.
VLF

75 lbs.

0 - 50 kVac @ 3 kVA

Can test ***~ 50’ of 15 kV cable***

Great for switchgear - not good for cables

0 - 30 kVac peak, .4 uF load @ 0.1 Hz

Can test ***~ 4000’ of 15 kV cable***

Ideal for cables per IEEE 400.2 and motors/generators per IEEE 433.

VLF FOR CABLE TESTING HISTORY REVIEW

- Original cables were PILC - many oil filled - DC worked well, still does
- Solid Dielectrics introduced in '60's. DC use continued, assumed good
- Later, forty year insulation failing after 10 – 20 years. Why?
- Unlike oil insulated cable, solids developed water trees. Water trees charged up by DC test, programming cable for future failure & DC leakage currents not very meaningful
- We factory test with AC – we want to test cables in the field with AC
- VLF permits us to AC field test cables with ease for the first time. Also makes AC diagnostic testing possible: Tan Delta & Partial Discharge
- 0.1 Hz - 0.01 Hz. permits testing miles of cable with portable equipment and lower kVA input
- Reliability of Distribution systems worldwide is improving with VLF use.
- Motor & Generator testing also benefits greatly

THE EARLY & PRESENT DAYS OF VLF

- **GE first developed VLF in the late 50's early 60's**. ASEA also around that time.
- VLF first used to test large rotating machinery: generators and motors per **IEEE 433-1974**.
- VLF work faded after development of 50/60 Hz. **Series & Parallel Resonant Technology,** designed to **test high capacitance loads at power frequency** with far less power than normal hipots.
- Factory testing still uses 50/60 Hz, but field maintenance testing is where VLF is used.
- Following premature solid dielectric insulation failures in the **70's & 80's**, development of AC field testing methods was accelerated, particularly VLF technology.
- Late **90's and into >2000** several companies introduced VLF products.
- **IEEE 433-2009** permits VLF testing of generators and motors. The spec calls for 15% more VLF voltage than 60 Hz. It is ideal for rewind shops and field testing.
- **IEEE 400.2-2013** defines VLF Withstand & Tan Delta testing for Medium Voltage cable and some High Voltage cable. Other 400.X standards describe PD and other VLF testing.

DIN VDE 0276-620, and PVC cable, DIN VDE 0276-621

MEDIUM & HIGH VOLTAGE CABLE TESTING

VLF TECHNOLOGY BRINGS FACTORY TYPE TESTS TO THE FIELD

65 kVac Tan Delta

200 kVac VLF Withstand

200 kVac VLF Withstand

35 kVac VLF TD Test

70 kVac Tan Delta
& Partial Discharge

62 kVac VLF Withstand

62 kVac VLF

200 kVac VLF Withstand, TD & PD

MEDIUM & HIGH VOLTAGE CABLE TESTING

VLF TECHNOLOGY BRINGS FACTORY TYPE TESTS TO THE FIELD

More VLF Field Test Photos

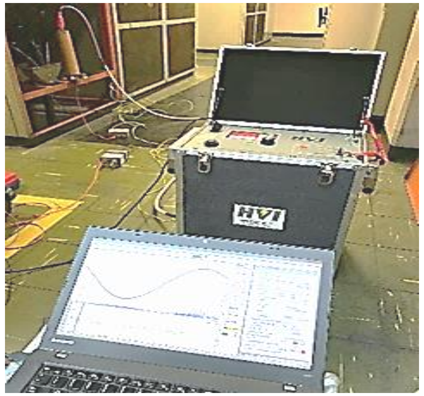
VLF-34E Testing Mining Cable

200 kVac Withstand of 138 kV

200 kVac Withstand of 138 kV

62 kVac Withstand

VLF-65E in Subst.



HISTORY OF VLF DEVELOPMENT

In the mid 1990s, High Voltage, Inc. from NY developed its line of VLF products, the first being a 40 kV peak model rated for 1.1uF @ 40kV @ 0.1Hz, released in 1998. This model was two pieces with one weighing 72 lbs and the other 50 lbs: the first truly portable system. It was also relatively inexpensive. With this development, and the models that followed, users had a portable and affordable VLF. Shortly after, the IEEE took up writing a standard for VLF testing: IEEE 400.2-2004. A revised edition was released in 2013. Several European companies created their own version of the VLF technology several years earlier, but those models were no portable enough nor economical enough to be considered for use by most.

Several more vendors now exist offering VLF models mostly made in Europe. Most offer modern solid state designs with the automation, data reporting, and computer control needed. They tend to be sophisticated in design and control and expensive.

Since the late 1990s, thousands of VLF units and many Tan Delta accessories have been shipped worldwide to over 130 countries.

WHERE IS VLF USED TODAY?

Medium and high voltage cable testing is probably 90% of the application for VLF, followed by ***motor/generator testing***. Long cables with high capacitance need VLF to test them. It is used by thousands of **utilities, testing contractors, & large industrials.** VLF satisfies the need for proof testing **newly installed, newly repaired, & any critical application cables**. VLF hipoting is an excellent method of checking the integrity of splices and terminations.

Small, light & economical 30 kVac models are available to check the integrity of 15 kVac cables, models up to 200 kVac to test HV cables are now routine, and dozens of different voltage and µf ratings in between are available. VLF generators are also used to provide the variable voltage needed for **off-line diagnostic testing**, like **Tan Delta and Partial Discharge**, for both power cables and motors/generators.

Users have many choices from nearly 10 vendors worldwide and all the major rental houses carry many models. The TD and PD measurement accessories are also readily available. There is no reason to not use VLF technology.

Withstand & Diagnostic Testing Possible

MEDIUM & HIGH VOLTAGE CABLE TESTING

VERY LOW FREQUENCY AC TECHNOLOGY

THREE METHODS OF VLF CABLE TESTING NOW ROUTINE

VLF WITHSTAND – VLF TAN DELTA – VLF PARTIAL DISCHARGE

DC voltage testing of newly installed and service aged solid dielectric cable insulation is now rare worldwide. VLF AC testing is the preferred method. Let’s take a look at VLF and the present methods used for testing medium & high voltage cable.

VLF AC CABLE TESTING TECHNOLOGY
WITHSTAND & DIAGNOSTIC APPLICATIONS

Three commonly used methods for VLF field testing medium and high voltage cable. Use one, two, or all three.

- **VLF Withstand** — **Proof/hipot testing**
- **VLF – TD** — Tan Delta Diagnostic testing
- **VLF – PD** — Partial Discharge Diagnostic testing

All tests are off-line using elevated voltage up to 3Uo.

DEFINING THE WITHSTAND TEST

Apply the Overvoltage – Pass or Fail

We have used AC withstand testing for decades to test most types of substation apparatus. Is the item ***good or bad,*** does it hold the necessary AC voltage or not? DC is not used, shouldn't be used, to "interpret" whether the load is good or bad? The vacuum bottle, rubber glove, hot stick, bus work, insulator, etc. either holds voltage or doesn't, there is no in-between. ***Now do the same with cable.***

The most basic ***VLF test is a withstand, or proof, test.*** Apply the voltage for some length of time. ***The cable either holds the voltage or fails.*** If there are severe defects that initiate partial discharge, the test forces their growth to failure. If it fails, repair or replace and retest. ***Minor defects unaffected by the test voltage*** remain as is. If it passes, the cable is assumed to be good for at least another ~5 years. If it fails again, further thought must be given to decide future steps.

PREMISE BEHIND VLF TESTING

The VLF voltage is applied to the cable. ***Defects severe enough to be triggered into partial discharge, creating an electrical tree, are allowed to grow to failure.*** (VLF rapidly grows electrical trees to failure.) Defects small enough to not be triggered into PD are not affected, or aggravated. Good insulation is not affected. (It's factory tested at voltages far higher.) **If a VLF test is performed properly – at the correct voltage level and time duration - the user can be >95% assured of no in-service failure for >5 years.**

If a cable can hold 2 – 3x operating voltage, it's healthy.

CABLE APPLICATONS FOR VLF

There are several obvious and common sense reasons to use VLF.

1. **Test after installation.** The cable is already de-energized. Guarantee no damage occurred during installation and prove the workmanship on accessories is good. Most faults are in terminations, splices, etc.
2. **Test after repair.** Initial fault may have damaged other cables. Over voltage thumping may have created more faults. Avoid the need for another repair in two months. Often rapid repairs are not done properly. VLF after repair to perform a quick check of cable to verify safe to re-energize. Not a full VLF test but a better check than other methods.
3. **Test critical cables** on a regular basis. Cause failure when convenient and not during service. <u>VLF failure causes very little damage to cable</u>.
4. **Diagnostic Testing:** VLF is also used to provide the voltage for health assessment testing, like **Tan Delta** and **Partial Discharge.** (More on that later.)

OTHER METHODS DON'T GET IT DONE

CABLE NOT AC STRESSED ABOVE OPERATING VOLTAGE

DC Hipot
5 kVdc "Megger"
DC Hot stick adaptor
24 hour soak

VLF It! **An overvoltage AC withstand test is the most certain method of testing a cable's AC voltage integrity.**

STANDARDS DEFINING VLF TESTING

Medium Voltage Cable & Rotating Machinery

Standards for using VLF AC output high voltage sources for testing various loads have been developed by numerous Standards writing bodies, most notably the IEEE for the North American market and the IEC for the European and other countries' market. There also exist numerous standards written by various countries for their own domestic use.

WORLDWIDE VLF STANDARDS

IEEE 400-2001	Cable testing standard approving VLF for use
IEEE 400.2-2013	Standard specific for VLF & Tan Delta methods testing
IEEE 400.3-2006	Partial discharge testing of shielded power cable systems in a field environment. Permits VLF
IEEE 433-2009	Defines VLF testing for rotating machinery.
VDE 0267-620/621	German standards for VLF cable testing
IEC 60060-3	Standard for field testing power cable, including VLF
Cenelec H620	Harmonized European Standard
	Other world standards being written in several countries

STANDARDS FOR VLF CABLE TESTING

IEEE 400.2 - 2013

IEEE Guide for Field Testing of Shielded Power Cable Systems Using Very Low Frequency (VLF) (less than 1 Hz)

Sponsor

Insulated Conductors Committee
of the
IEEE Power and Energy Society

Approved 6 March 2013

IEEE-SA Standards Board

Original standard was released in 2004.

IEEE 400.2 - 2013

THE SECOND GENERATION VLF STANDARD

IEEE 400.2 defines the required test voltages and time

The Voltage level = ~ 1.5 – 3 Uo and measured in peak V **

Time Duration = 30 - 60 minutes, depending on several factors

* * The actual test voltages are determined by the kV/mm of voltage stress needed, based on the insulation thickness and nominal voltage rating.

Note: Perform the test properly or do not test at all. Suggested testing times and voltages are necessary to *allow electrical trees initiated by the test voltage to grow to failure*. A test too short in time and/or too low in voltage may only aggravate, not clear, existing defects and lead to future in-service failures. Let the technology, the established procedures and test values, and the physics of AC testing work.

STANDARD for MOTORS & GENERATORS
IEEE 433 – 2009

IEEE

IEEE Recommended Practice for Insulation Testing of AC Electric Machinery with High Voltage at Very Low Frequency

IEEE Std 433™-2009
(Revision of
IEEE Std 433-1974)

IEEE 400.2 - 2013 FIELD TEST VOLTAGES

For Shielded Power Cable Systems Using Sine Wave Output VLF

System Voltage phase to phase kV rms	0.10 Hz. Test Voltage Installation phase to ground kV rms/kV peak	Acceptance phase to ground kV rms/kV peak	Maintenance phase to ground kV rms/kV peak
5	9/13	10/14	7/10
15	19/27	21/30	16/22
25	29/41	32/45	24/34
35	39/55	44/62	33/47
46	51/72	57/81	43/61
69	75/106	85/119	63/89

Test voltages are generally 1.5 – 2.5 times the line-to-ground system voltage.

IEEE 400.2-2013 FIELD TEST VOLTAGES

For Shielded Power Cable Systems Using Sine Wave Output VLF

Waveform	Cable system rating (phase to phase) [kV]	Installation (phase to ground)		Acceptance (phase to ground)		Maintenance[2] (phase to ground) (see Note 2)	
		[kV rms]	[kV peak]	[kV rms]	[kV peak]	[kV rms]	[kV peak]
Sinusoidal	5	9	13	10	14	7	10
	8	11	16	13	18	10	14
	15	19	27	21	30	16	22
	20	24 (Note 3)	34 (Note 3)	26	37	20	28
	25	29 (Note 3)	41 (Note 3)	32	45	24 (Note 3)	34 (Note 3)
	28	32	45	36 (Note 3)	51 (Note 3)	27	38
	30	34	48	38	54	29 (Note 3)	41 (Note 3)
	35	39	55	44	62	33	47
	46	51	72	57	81	43	61
	69	75	106	84	119	63	89

ELECTRICAL TREE GROWTH RATE UNDER DIFFERENT VOLTAGE STRESSES

Test voltage factor (V/V_0)	Growth rate at 50-Hz test voltage (mm/h)	Growth rate at 0.1-Hz sinusoidal test voltage (mm/h)	Growth rate at 0.1-Hz VLF Cos-Rectangular voltage (mm/h)
2	1.7–2.4	2.3	1.4
3	2.2 –5.9	10.9–12.6	3.4–7.8
4	175–611	58.3–64.2	22.2–30.3
5		336	125

Channel tree growth rate on field aged samples of XLPE at different test voltage levels and waveforms where V is test voltage and V_0 is operating voltage to ground.

VLF WITHSTAND TEST PROCEDURE

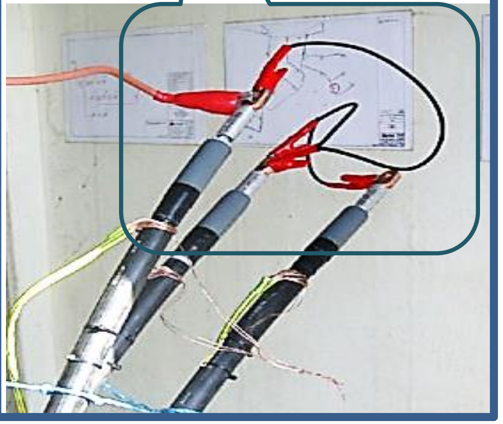
VLF testing is easier than DC testing. No leakage current measurements taken. Only current is charging current each half cycle. Just apply voltage for set time.

- Remove all arrestors, capacitors, transformers, etc.
- Isolate cable ends like with DC testing, although less cleaning, bagging, installing corona rings, etc. is necessary.
- Connect VLF HV lead to conductor & ground to shield.
- Select test frequency depending on length. Maybe test all 3 phases at once.
- Apply voltage. Test is go/no-go, there are no leakage currents to read.
- If cable holds, test is over. Cable is presumed good .
- If cable fails, make repairs and repeat test, or replace.
- If second insulation failure occurs, further consideration necessary.

WIND & SOLAR 35kV CABLES - IDEAL FOR VLF

VLF Acceptance Test
per IEEE 400.2

VLF Hipot testing
3 phases at once
62 kVac peak for
30 - 60 mins.



Cable system is new but needs **VLF Withstand** test to find faulty workmanship on splices, terminations, and possible cable installation damage. Tan Delta and Partial Discharge testing are optional. VLF It!

BUT I DON'T WANT TO FAIL MY CABLE!

Use Diagnostic Testing Methods - not Withstand

Use a non-destructive method to learn the quality of the overall insulation, and/or the locations and severity of partial discharges that may need immediate remedy, and/or to determine the expected life of the cable to help prioritize repair, replacement, injection, or additional testing.

Two tests are commonly performed using a VLF voltage source

VLF-TD: Tan Delta Testing – Global Assessment

How good is my insulation from end to end?

VLF-PD: Partial Discharge Testing - Defect Location

How many, where, and how bad are any defects?

DIAGNOSTIC TESTING CABLES WITH VLF

We have introduced Very Low Frequency AC Technology and have described its origin, its design, why and how it works well to test high capacitance loads like power cables, the standards defining its use, and the basic application of the VLF, which is to provide AC over voltage stress to check the **AC Withstand integrity** of a cables insulation and its accessories.

To sum it all up: a high voltage output VLF instrument is a low frequency sinusoidal output AC hipot that is close enough and measurably predictable enough in its affect on insulation to use in place of power frequency AC hipots. Not exactly the same but close enough and predictably enough to be useful and very advantageous for testing cable and motor/generator loads in the field where portability, economy, and ease of the test is required.

Even though is provides 0.10 Hz. – 0.01 Hz. output instead of 50/60 Hz., it is similar enough and predictable enough to used in the same way as a power frequency AC hipot is to provide the voltage to test various loads for either simple over-voltage Withstand/Proof testing and as a voltage source for diagnostic testing using Tan Delta, Power Factor, and Partial Discharge methods. used to provide variable voltage too

VLF AC CABLE TESTING TECHNOLOGY

OFF-LINE ELEVATED VOLTAGE TESTING

Three commonly used methods for field testing medium and high voltage cable using VLF technology.

➢ VLF Withstand	Proof or Hipot testing – Pass/Fail
➢ VLF – TD	Tan Delta Diagnostic testing
➢ VLF – PD	Partial Discharge Diagnostic testing

DIAGNOSTIC TESTING WITH THE VLF

Tan Delta (TD) & Partial Discharge (PD)

Performed off-line with elevated voltages up to ~2U_0 using a VLF sinusoidal output voltage source, usually with an output frequency of 0.10 Hz. or 0.05 Hz.

Tan Delta (δ), also called Dissipation Factor or Loss Angle Testing

Tests the overall quality of the insulation: the degree of deterioration of the total cable length. Done to comparatively grade cables to help prioritize replacement or rejuvenation/injection or to determine other tests that may be useful. Relatively inexpensive, easily performed, and common.

Partial Discharge - Overall PD and Locations and Severity of PD Events

Testing locates specific sites of PD, or electrical and acoustical discharges from defects, and their severity. Measures inception voltage (PDIV) and extinction voltage (PDEV) to better determine the nature of the defect. Good way to inspect accessories. Very useful but more expensive and complicated than TD testing and interpretive analysis can be problematic.

VLF TANGENT DELTA (TAN δ) MEASUREMENT

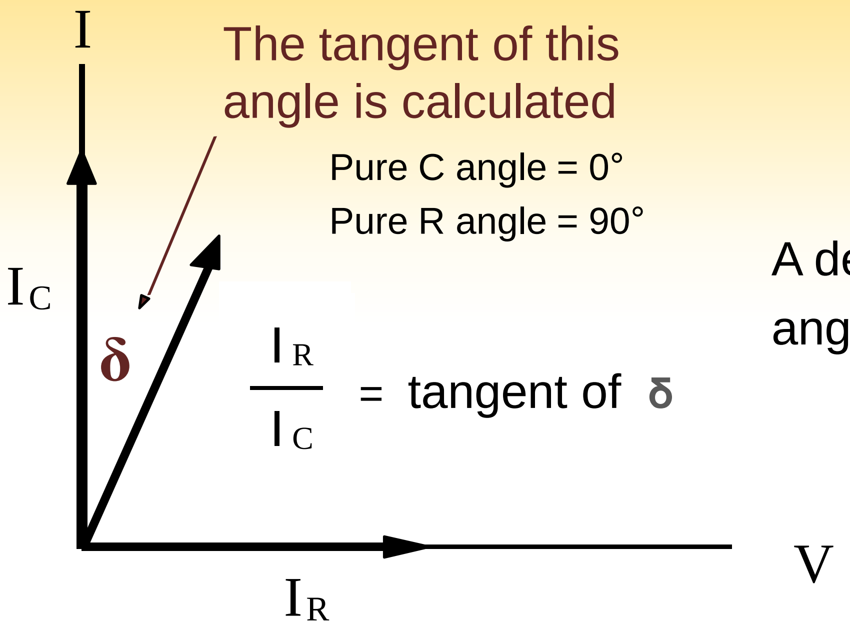
Also called Dissipation Factor or Loss Angle

Over time, cable insulation degrades due to thermal, chemical, mechanical, and atmospheric conditions, water ingress, vibration, as well as physical damage during installation. Accessories degrade for the same reasons and often from improper workmanship. ***TD testing is a non-destructive method to determine the extent of insulation and accessory degradation over the entire cable length measured*.**

Find out which of your cables are

Highly Degraded, ***Slightly Degraded***, or ***Good***?

Tan Delta (δ) = I_R/I_C = $1/(2\pi fCR)$



A deteriorated cable may show an angle of 0.5° or 0.0175 radians

In a perfect cable, characteristics are similar to a capacitor. Current Ic is 90° phase shifted from voltage V, making the angle δ = 0°. The more deteriorated the insulation is, the more the angle δ grows, to maybe 0.5°. The greater the angle, the more resistive the cable appears, or the more deteriorated the cable's insulation and accessories are. Test many cables, rate them, and compare to prioritize maintenance or replacement work.

TAN DELTA (δ) MEASUREMENT BENEFITS

Using VLF @ 0.1 Hz – 0.05 Hz.

- Excellent predictive tool for determining the integrity of cable
- Absolute values, variations vs. applied voltage, and trending of values are useful for predicting insulation and accessory integrity
- Evaluates over all condition of cable (rather than local as with PD measurement)
- Tan Delta is more easily measured at 0.1 Hz. vs. 50/60 Hz. (magnitude increases)
- Requires VLF sinusoidal applied test voltage
- Excellent method to evaluate Water Trees
- Easy to use and interpret measurements
- **Evaluates entire cable system. Best as a comparative test to prioritize cable replacement, injection, or to determine what other tests may be useful.**

WATER TREES ADD RESISTIVE ELEMENT

Cable No Longer 100% Capacitive δ increases >0°

- TD can measure the extent of water tree damage
- Tree shaped channels are found within the insulation of operating cables resulting from the presence of moisture in voids within an electrical field
- Most prevalent in aged XLPE and PE cables
- Water trees grow to become electrical trees and emit partial discharge
- PD activity leads to in-service failures

CHARACTERISTICS OF WATER TREES

Typical Water Tree in XLPE Insulation

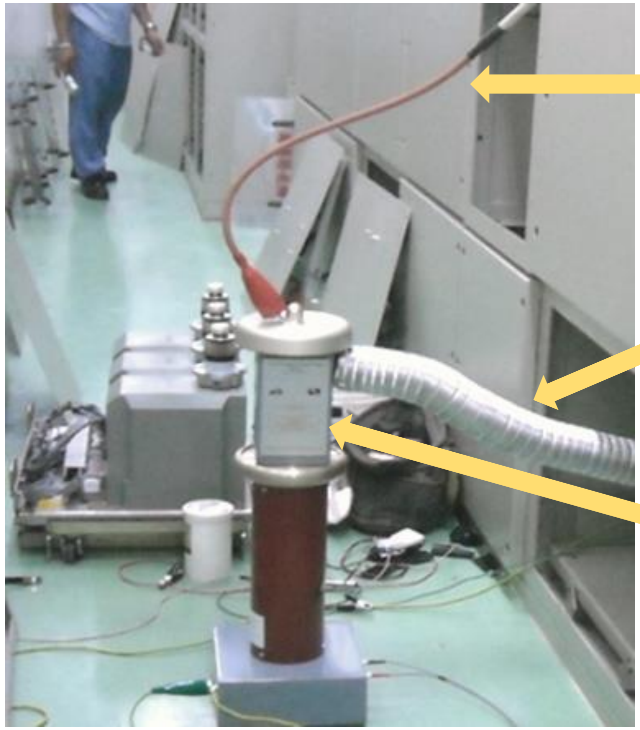
Water Trees Effects on Insulation

- ❑ Addition of a new parallel R - C component
- ❑ The R component makes TD numbers voltage dependent
- ❑ TD numbers trend upward “Tip-Up” with increasing voltage
- ❑ Other data collected useful in interpreting insulation integrity

TAN DELTA HOOKUP USING HVI VLF

Hook up is easy. Just insert the Tan Delta module in series with the VLF high voltage output to the cable. The TD module captures the voltage and current waveforms and sends the data wirelessly to the VLF for data storage and computation of the TD values. The data is also sent to and stored in a USB drive on the VLF and to the laptop.

VLF-65E & TD-65E

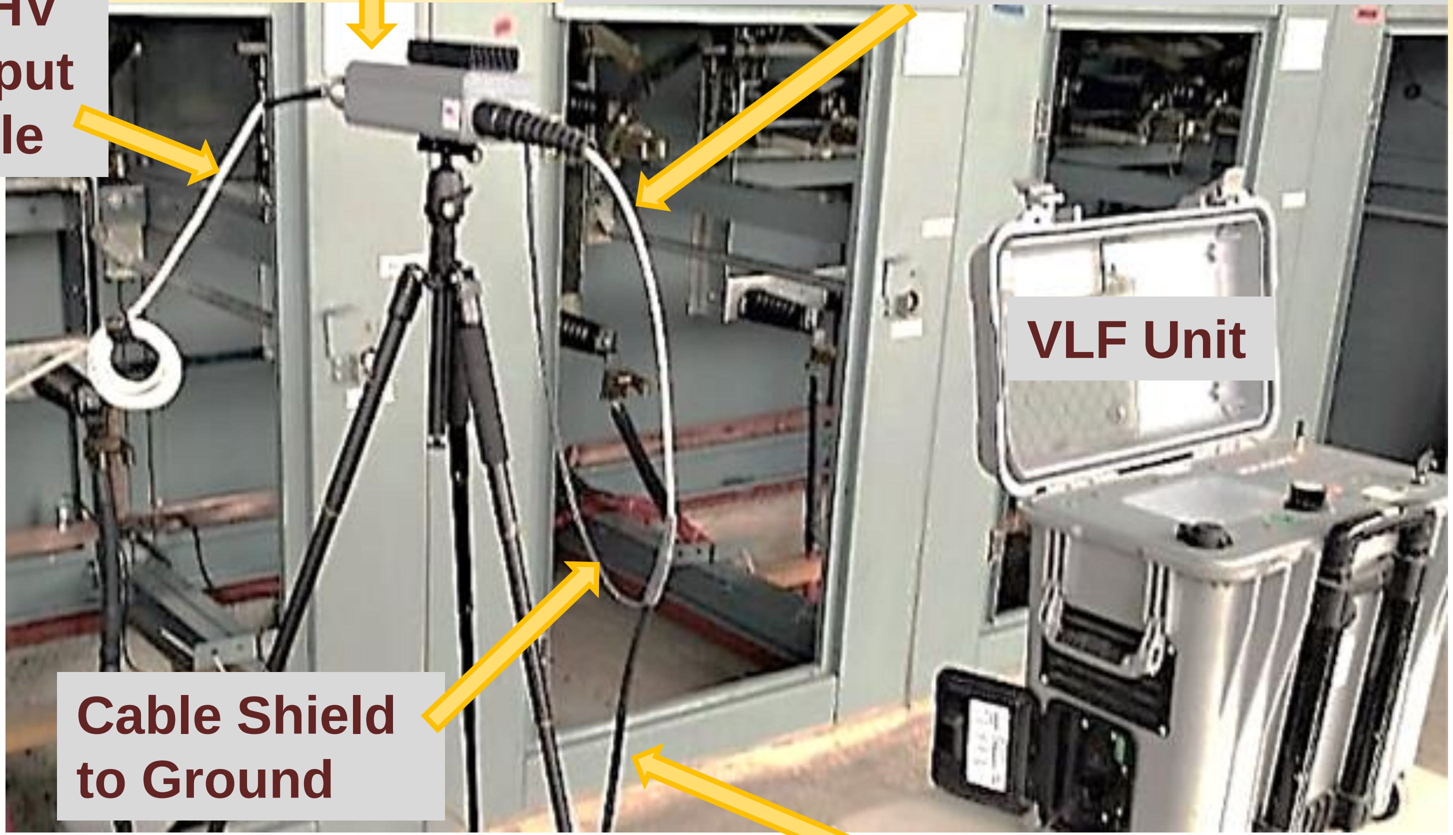


HV Output cable from VLF

HV Output to cable tested.
Aluminum dryer duct used

Tan Delta HV Divider
with data collection

VLF HIPOT - TD MODULE TEST HOOKUP



TD HV Output Cable

Tan δ Module

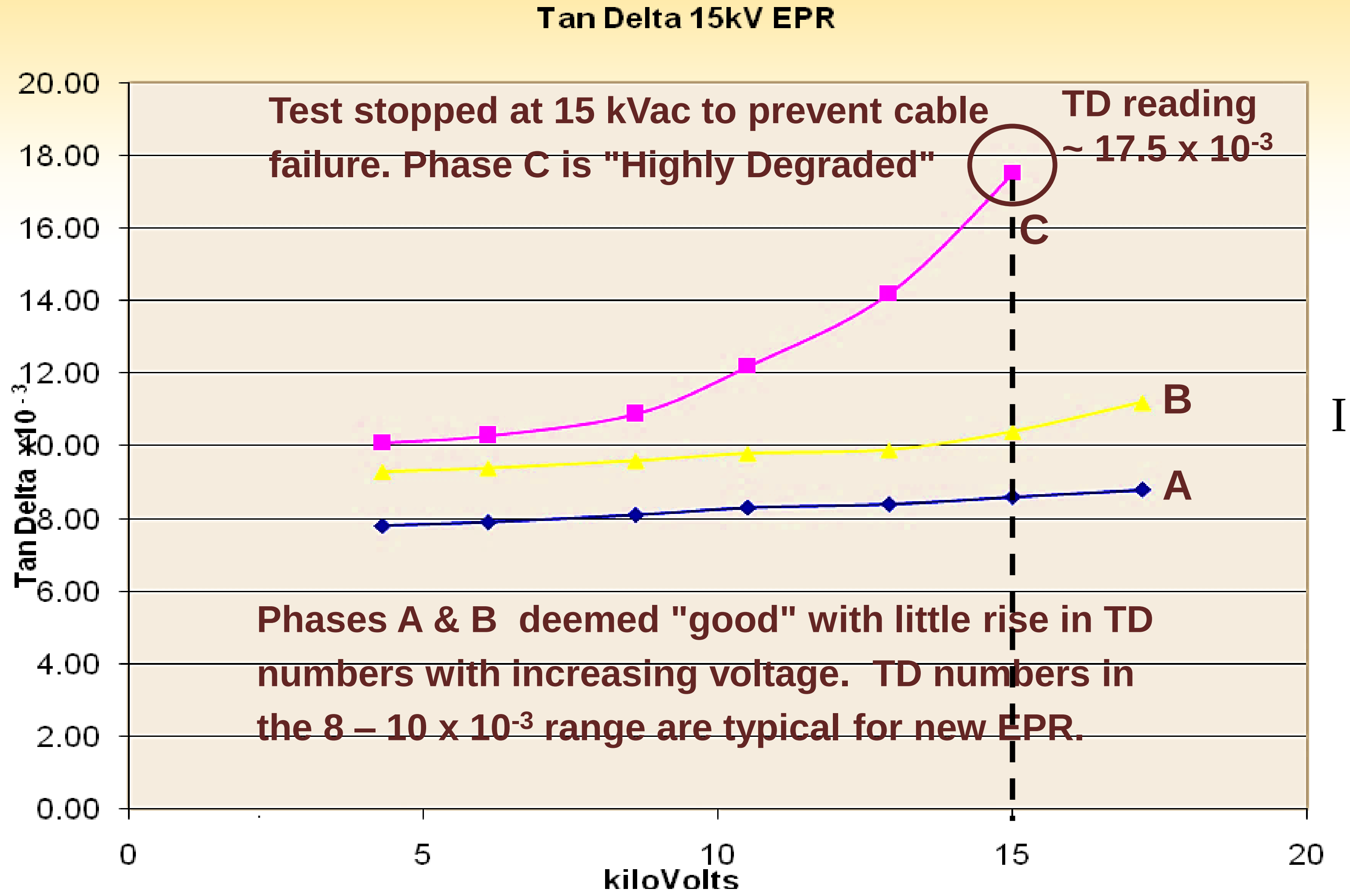
VLF HV Output Cable - Stripped

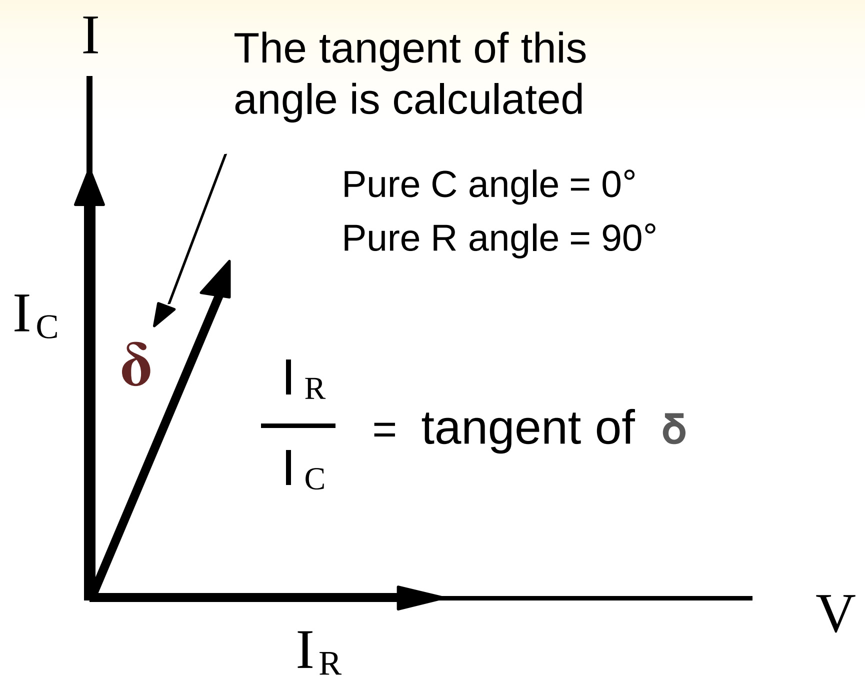
VLF Unit

Cable Shield to Ground

VLF HV Output Cable - Shielded

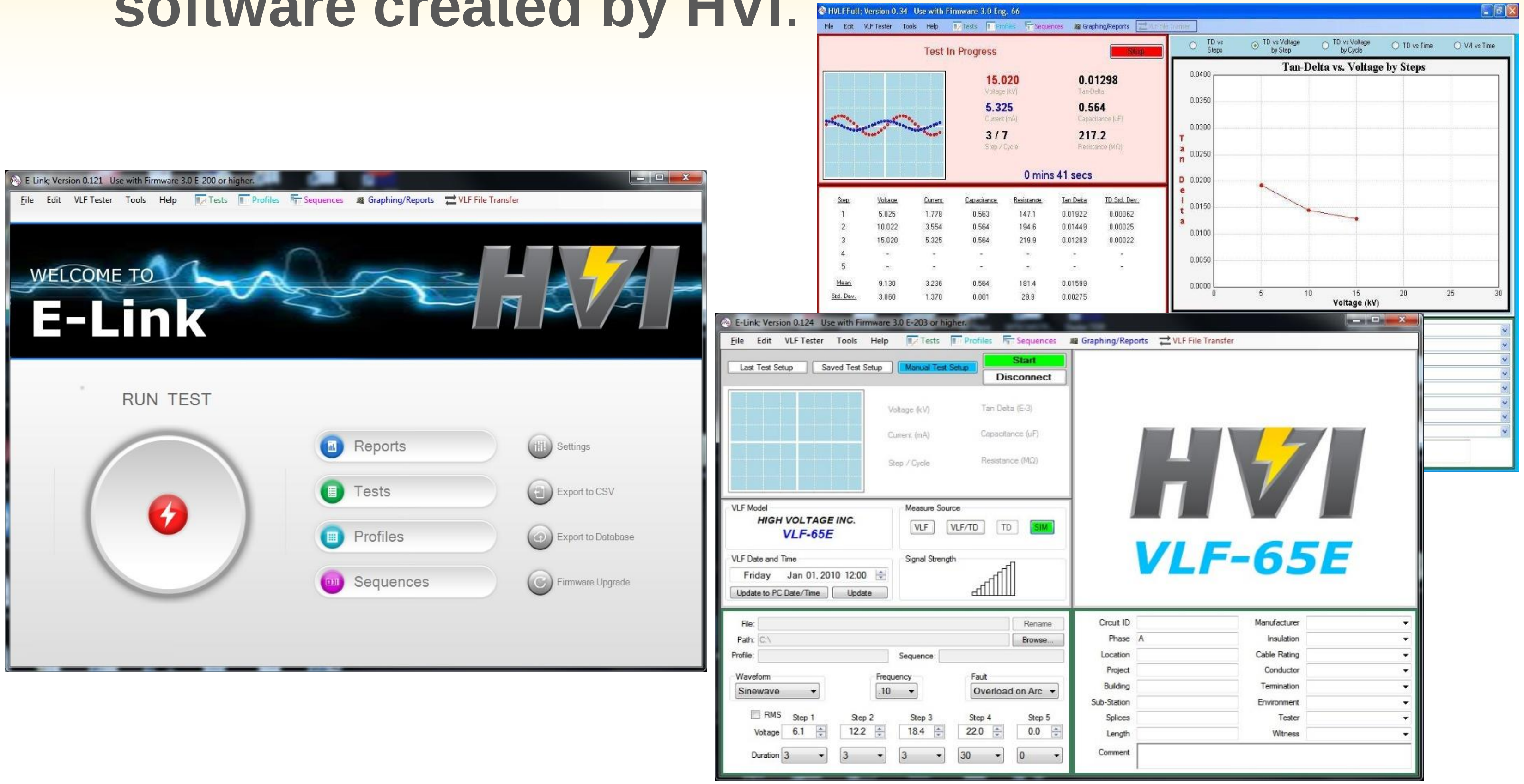
Typical TD Graph of Three Phases
TD #'s Rising vs. Test Voltage

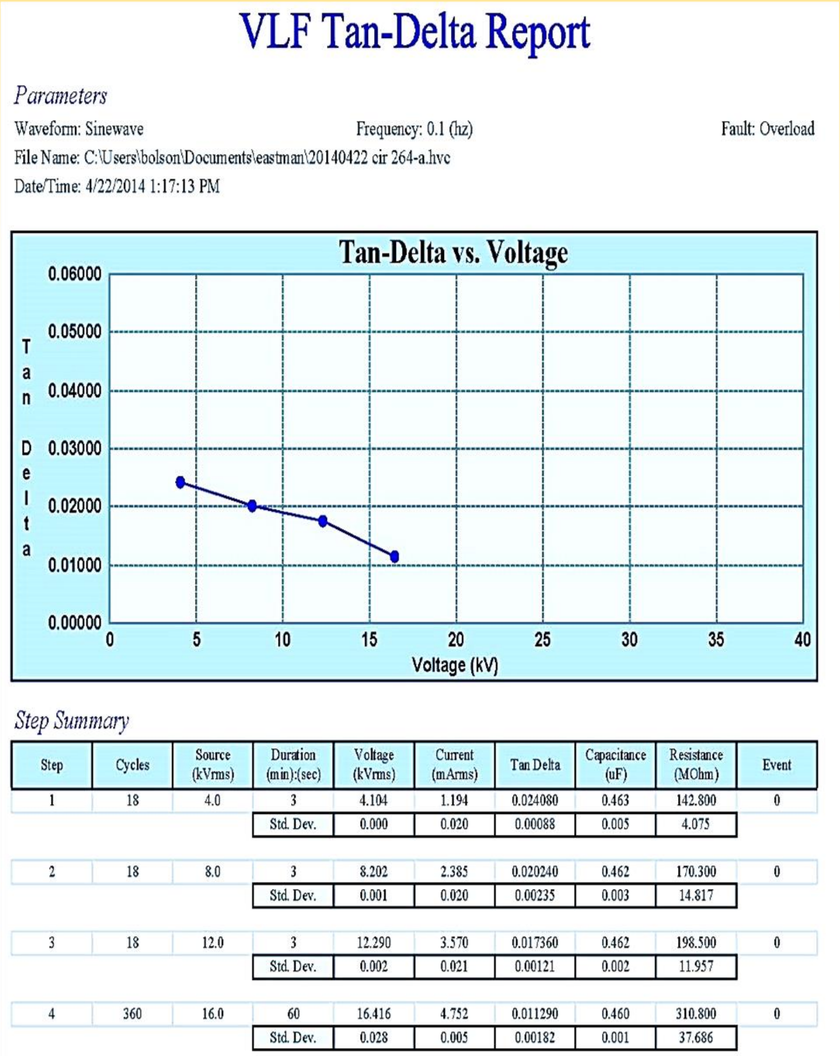




VLF/TD SOFTWARE SCREEN SHOTS

Many vendors models are software driven for ease in operation, data collection, and data reporting. Below are screen shots of the **E-Link VLF/TD software created by HVI**.





VLF Tan-Delta Report

Parameters

Waveform: Sinewave Frequency: 0.1 (hz) Fault: Overload

File Name: C:\Users\bolson\Documents\eastman\20140422 cir 264-a.hvc

Date/Time: 4/22/2014 1:17:13 PM

Step Summary

Step	Cycles	Source (kVrms)	Duration (min):(sec)	Voltage (kVrms)	Current (mArms)	Tan Delta	Capacitance (uF)	Resistance (MOhm)	Event
1	18	4.0	3	4.104	1.194	0.024080	0.463	142.800	0
			Std. Dev.	0.000	0.020	0.00088	0.005	4.075	
2	18	8.0	3	8.202	2.385	0.020240	0.462	170.300	0
			Std. Dev.	0.001	0.020	0.00235	0.003	14.817	
3	18	12.0	3	12.290	3.570	0.017360	0.462	198.500	0
			Std. Dev.	0.002	0.021	0.00121	0.002	11.957	
4	360	16.0	60	16.416	4.752	0.011290	0.460	310.800	0
			Std. Dev.	0.028	0.005	0.00182	0.001	37.686	

TAN DELTA TESTING SUMMARY

Advantages

- Less destructive than VLF or 60 Hz withstand
- Measures overall condition of cable system
- Collects comparison data from many cables
- Aids in prioritization of cable replacement/repair
- Tests easily performed and interpreted
- Can be performed along with other tests

Disadvantages

- Can be destructive if test voltage too high
- Gives overall condition of cable, not individual singularities
- Not best for mixed type cable runs
- More useful with historical comparison data
- Accuracy depends on neutral integrity

Conclusion

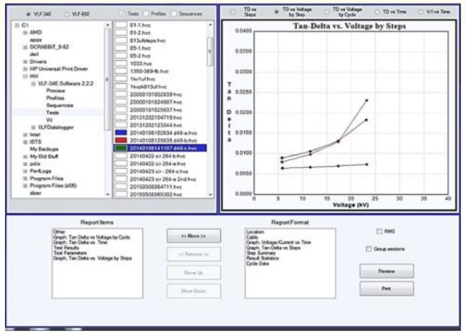
- TD testing is an easy method to evaluate many cables for comparison
- Helps determine where replacement or injection efforts are best spent
- Helps to determine what other tests may be useful

VLF TAN DELTA MEASUREMENT DEVICES

Models available up to 200 kVac peak

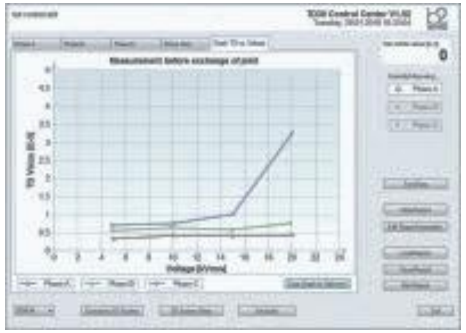
VLF output is run through TD transducer to the load. Voltage and current waveforms are captured and the phase separation is calculated to determine level of deterioration. All vendors offer some form of TD system, including custom software for analysis and data reporting. Some VLF vendors also offer TD capability integral to the VLF supply itself.

High Voltage, Inc.
TD-65E 65 kVac peak



Seba/Megger

B2/Omicron



Megger/Power Diagnostix
Tan Delta & Partial Discharge

VISIT *NEETRAC* FOR MORE VLF INFO

An excellent source for more information on VLF cable testing, including Tan Delta testing and other methods. NEETRAC conducted a multi year study of this subject and have presented dozens of articles and technical papers and have issued their report on the subject. The web site for the report can be downloaded at:

www.cdfi.gatech.edu/

Their main web site address for information on many other issues is:

www.neetrac.gatech.edu

VLF AC CABLE TESTING TECHNOLOGY
WITHSTAND & DIAGNOSTIC APPLICATIONS

There are three commonly used methods of field testing medium and high voltage cable using VLF technology.

- **VLF Withstand** — Proof/hipot testing
- **VLF – TD** — Tan Delta Diagnostic testing
- **VLF – PD** — **Partial Discharge Diagnostic testing**

VLF PARTIAL DISCHARGE TESTING

Off-Line PD testing is a method of evaluating a cable's insulation and accessories to **locate and measure the severity of defects**. If performed properly, it is a **non-destructive test**. ***Where are the bad spots and how bad are they?***

Cable insulation degrades due to thermal, chemical, mechanical, and atmospheric conditions, physical damage during installation, and for many other reasons. Accessories degrade for the same reasons and often from improper workmanship during installation.

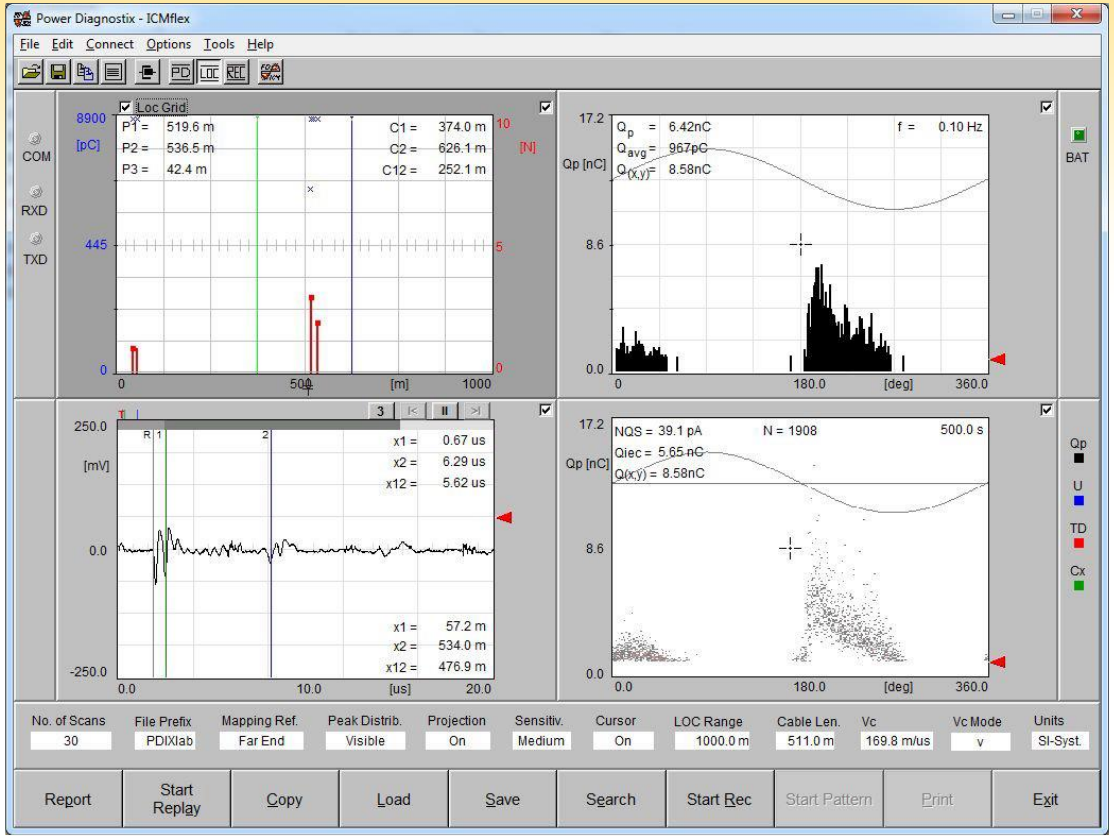
PD testing is a critical test performed in the factory using power frequency equipment. Now, portable and readily available **VLF products bring PD testing to the field** in a more practical way than using Series or Parallel Resonant technology or power frequency AC test sets.

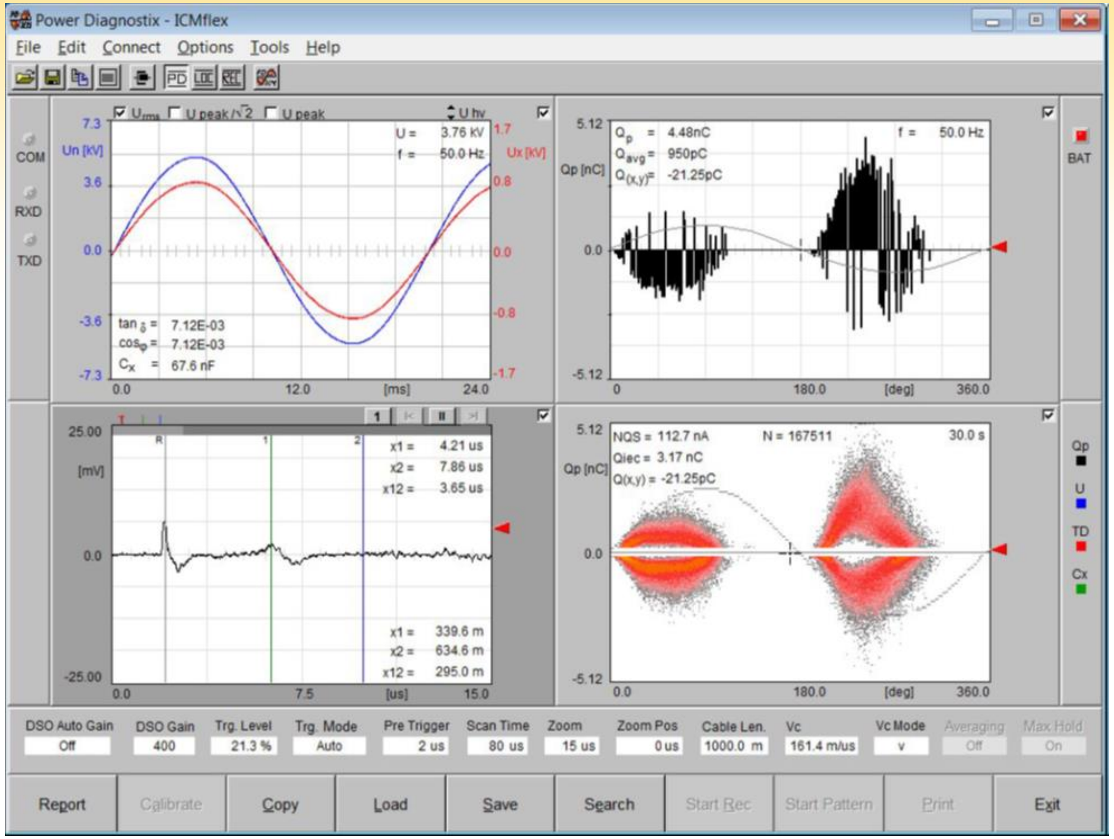
OFF-LINE PARTIAL DISCHARGE TESTING

PD testing locates areas of discharge and their magnitude. We measure the **PD Inception Voltage**, the **PDIV** (at what voltage does PD begin) and the **PD Extinction Voltage**, the **PDEV** (at what voltage does it extinguish). Some levels of PD are acceptable while others are not. Generally, any PD in the insulation is not acceptable, however, splices and terminations can live for years with high PD. For example, a discharge that initiates in the insulation at 1.7 – 2.0 U_o may be acceptable, for a while. But, if it starts at only 1.2 – 1.3 U_o, it is too close to operating voltage and some action may be required.

Performed properly with the right equipment and interpretation, locations of PD can be accurately measured and evaluated.

ICM*flex* Partial Discharge & Tan Delta Measurement





Two screens showing results from TD & PD testing a cable. The eight windows display the background PD, PD locations along the cable, phase resolved PD, TD loss factor, capacitance, and other details.

(Shots taken of Power Diagnostix ICMflex displays.)

VLF AC CABLE TESTING TECHNOLOGY
WITHSTAND & DIAGNOSTIC APPLICATIONS

We have described three commonly used methods for field testing cable using VLF technology. Which ones are right for your application depend on many variables. Not all will be practical or even prudent for every situation. Know the differences in results, availability, ease of use, and cost.

- **VLF Withstand** Proof/hipot testing
- **VLF – TD** Tan Delta testing
- **VLF – PD** Partial Discharge testing

SELECTING A CABLE TEST METHOD

Common Methods Include:

- ❑ AC Power Frequency - Withstand & Diagnostics
- ❑ AC Series & Parallel Resonant - Withstand & Diagnostics
- ❑ DC Hipot Dielectric Test - IR and Leakage Current/Hipot
- ❑ Very Low Frequency (VLF) AC Hipot - Withstand & Diagnostics
- ❑ Other methods of analyzing cable behavior vs. pure capacitance

Selection often depends on the information desired and the options available for repair and/or replacement based on situation

SEVERAL METHODS – WHAT TO USE?

VLF Withstand - VLF Tan Delta - VLF Partial Discharge

Ideally, all should be used to gain all the data possible.
However, there are real world factors affecting the decision.

- ❑ The remedial repair or replacement actions possible
- ❑ Type of test results desired, based on actions possible
- ❑ Ease of use and interpretation of test equipment
- ❑ Cost & availability of test equipment

There is no single method that does it all. A variety of approaches are needed to learn as much as possible about the cable. What test data can best serve what you want and are able to take action on?

DEFINE THE GOALS OF YOUR TESTING

Which tests are best & what will you do with the data?

- ❑ Verify new installation: fail, find, and fix
- ❑ Verify repaired and adjacent cables before re-energizing
- ❑ Verify critical cables during downtime
- ❑ Compare many cables to prioritize replacement or injection and/or to determine if other tests are needed
- ❑ Is cable direct buried requiring exact fault location, or is it in conduit and easily replaceable
- ❑ Cost of equipment, availability, ease in use, ease in analysis, etc.. all must be weighed against the usefulness of the data gathered

Match the test methods to your situation

WHAT'S THE INSTALLATION SITUATION?

- ❑ Direct buried – must pinpoint problem to repair
- ❑ Cable in conduit or trench - replaceable
- ❑ Cable in raceways – visible and easily replaceable
- ❑ How old is cable
- ❑ What is the failure history
- ❑ How easy is it to repair
- ❑ Is there alternate feed should failure occur during test
- ❑ Is fault location and repair available
- ❑ How much downtime can be tolerated

EXAMPLES OF SITUATION vs. METHOD

New Install: Diagnostic test not needed, the insulation is good. VLF it to make sure there is no installation damage, bad splice work, etc.

Old cable: There may be many defects, don't VLF. Use TD to see how degraded cables are to prioritize replacement. If modest degradation, then VLF or maybe PD test the better ones.

Critical cable in conduit: VLF it. If it fails, replace it. No need for TD or PD.

Direct buried: TD test to evaluate condition to prioritize injection or replacement. Could PD and then use VLF & Thumper to find defects if just a few.

Prioritization for replacement or injection: If a comparative assessment test is desired, Tan Delta is the most effective and easiest method.

Post repair test: VLF repaired and adjacent cables to make sure it holds and there is no further damage caused by over voltage thumping.

SO, WHAT TO DO? NO EASY ANSWER

Look at the Big Picture - The Test Specs Should Match What Tests Are Possible, Practical, with Results Actionable.

Depends on money, time, ability to interpret diagnostic data, access to the site, time allowed for testing, available people, action possible for repair or replacement, and other factors.

A combination of methods is needed: some easy and economical (VLF) and some more complicated and more expensive (TD & PD), and each yielding different but important data about your cable.

IT ALL STARTS WITH A VLF HIPOT

VLF Withstand testing and **VLF Tan Delta** testing have been widely accepted and **used for over 20 years**. **VLF Partial Discharge** testing has been common for over ten years. VLF testing of some type is in your present and future.

In addition to performing VLF AC stress tests, a VLF hipot is the voltage source for other tests, like Partial Discharge and Tan Delta.

At the very least, a VLF should be available to verify new installation work, repairs, and/or critical cables that cannot fail in service.

Whether the frequency is 50 Hz, 60 Hz, 0.1 Hz, 0.05 Hz, or 0.02 Hz. all are effective to perform AC withstand testing and as a voltage source for TD & PD testing. VLF technology makes it affordable and portable.

SELECTING A VLF MODEL

Specs to know before model selection

- ❑ Must know the cable voltage and test specs to select VLF voltage rating.
- ❑ Must know the cable load capacitance, the µF rating, to size the VLF.
- ❑ Must know the required frequency of test: 0.1 - 0.01 Hz. Withstand or 0.1or 0.05 Hz. for TD/PD.
- ❑ Will it be used for TD and PD testing? Test voltages are lower and 0.1 – 0.05 Hz. required.

VLF ratings and selection

- ❑ VLFs are sized from 20 kV – 200 kV, peak and rms specs.
- ❑ Rated by the uF of load they can test. Ratings from 0.4 – 50 uF.
- ❑ Most are variable frequency of 0.1 – 0.01 Hz: does spec allow frequencies below 0.1 Hz for withstand testing? For TD & PD testing, 0.1 Hz is typically used, sometimes 0.05 Hz.
- ❑ Should select a VLF rated for the uF rating needed at 0.1 Hz.
- ❑ Lower frequencies permit higher uF testing. 0.05 Hz can test twice the cable length than 0.1 Hz.

Typical VLF Output Specification

Output Volt: 0 - 65 kVac Peak
Sinusoidal Waveform

Output Load: 0.10 Hz @ 1.1 µF
0.05 Hz @ 2.2 µF
0.02 Hz @ 5.5 µF
0.01 Hz @ 11.0 µF

VLF MODEL SIZES AVAILABLE

There are many models from the 5 or 6 major vendors.

Models are designed for a voltage output and a capacitance (µF) load rating at several specific frequencies from 0.1 Hz – 0.01 Hz.

Voltage ratings range from 20 kVac – 200 kVac with capacitive load ratings from 0.4 µF – 50 µF.

Most vendors design their models based on voltage testing specs for standard size cables. Typical model ratings in kVac include:

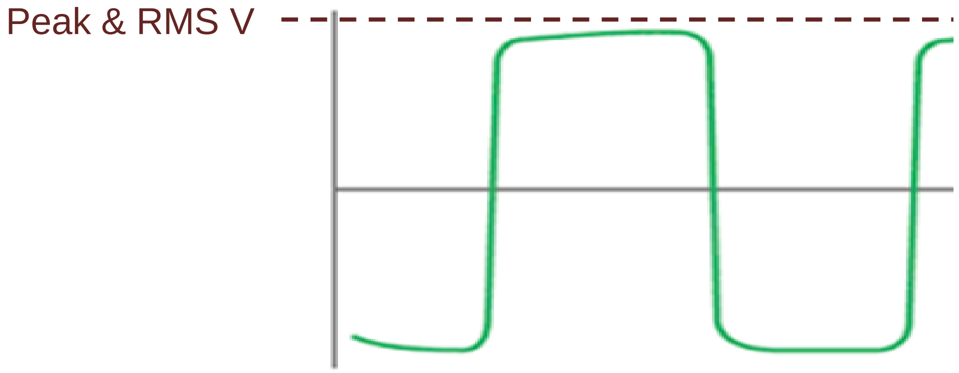
0 – 28, 34, 42, 45, 50, 62, 65, 90, 120,140, 200 kVac peak voltage

SINUSOIDAL vs. COSINE-RECTANGULAR WAVES

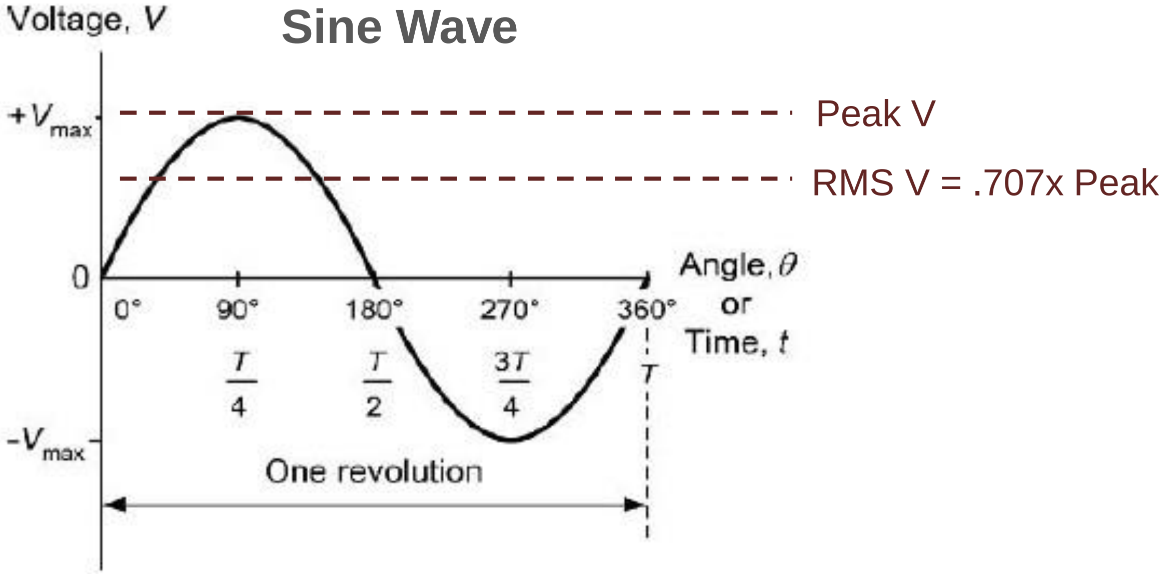
Sine Wave & Cosine-Rectangular (CR). Of the major VLF vendors, two output waveforms are offered. Both work well to **VLF Withstand** test cable.

However, a **Sine Wave** is best suited for use as a voltage source for **Tan Delta** and **Partial Discharge** testing, both desirable add-ons to VLF testing. Also, a sine wave is the required waveform for **motor/generator testing per IEEE 433.**

Cosine-Rectangular



Sine Wave

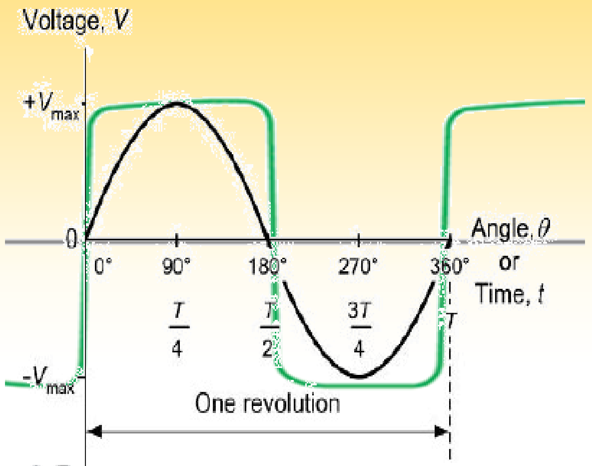


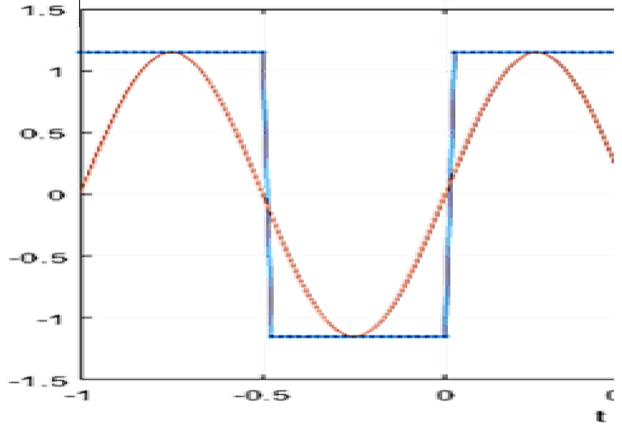
SINUSOIDAL vs. COSINE-RECTANGULAR WAVES

Differences You Should Know. Both waveforms work well for AC Withstand testing cables, although the electrical tree growth rate in cable insulation differs. It has been shown that once PD occurs during a test, the tree growth rate under the sine wave stress is faster than under the CR waveform stress, thus the testing times and/or test voltages applied must be altered and different. Refer to IEEE 400.2-2013.

The CR waveform (trapezoidal) is produced in Germany and conforms to the IEC Standards from decades ago and still today. These standards state the VLF CR Withstand test voltage must be **3Uo rms for 60 minutes**. Since the CR waveform is a rectangular shape, the **rms and the peak voltages are nearly equal**, so the standard is stating that 3Uo rms = 3Uo peak. True for CR waveform only.

CR Test levels are ≠ to the sine wave VLF. With a sine wave, the peak voltage is 1.414 ($\sqrt{2}$) times the rms voltage. If rms were used for both waveforms, the sine wave VLF test would apply 1.414x higher peak voltage than the CR. **Testing voltages must be specified in Peak, not RMS.**





Note, since the CD waveform is essentially a rectangular wave, the rms and peak voltage values are nearly identical. (The leading and lagging edge of each period simulates the rise and fall time of a 50 Hz. frequency sinewave, believed to instigate partial discharge similarly to a sine wave, even if the remainder is a flat DC voltage.)

VLF WAVEFORM OUTPUTS BY VENDOR

High Voltage, Inc. - USA	Sine Wave
Baur - Austria	Sine Wave
Seba – Germany	Cosine-Rectangular & Sine Wave
Megger/Seba - USA	Cosine-Rectangular & Sine Wave
Omicron/B2 - Switzerland	Sine Wave
Others from China, India, Russia, Europe, et al.	Sine Wave
For PD/TD diagnostics & motor/generator testing	Sine Wave

VLF OUTPUT VOLTAGE – PEAK vs. RMS

WHY DO WE READ PEAK VOLTAGE

In all discussions and written standards pertaining to AC voltage, it is the rms value of the waveform that is used as the standard measure of voltage. This is not so with VLF AC waveforms, where the maximum voltage stress applied is most important and significant in initiating partial discharge. The rms measure of energy under the waveform is less important for the purpose of VLF withstand and VLF diagnostic testing.

Originally and still, VLF units were metered in peak voltage output for two reasons. The original VLF products produced (from only one vendor then and now) offered a nearly rectangular waveform output (called a cosine-rectangular waveform), so the peak and rms were the same. Now, all but one VLF vendor produce sine wave output models, which are measured by their peak voltage. **So peak vs. rms is an issue and must be noted when specifying test voltages.**

Secondly, using peak recognizes that it is the peak of the waveform, not the rms, that initiates partial discharge, the central element in causing defects to grow to failure or be measured under the test voltage. The maximum, or peak, voltage is what is important in this case.

WHO USES VLF?

UTILITIES **TESTING SERVICES** **INDUSTRIALS**

LARGE COMMERCIAL **ELECTRICAL CONTRACTORS**

Other methods of cable testing have their place, but VLF is embraced worldwide as the easiest, most effective, most economical method of field cable testing.

VLF AC Hipots enable the world to employ various withstand and diagnostic test methods to cables, motors, generators, and other loads to gain as much knowledge as possible about these assets to make the best possible decisions as to future action to improve system reliability.

SUMMARY OF VLF TESTING

- **No one test method can do it all.** Use one or all three discussed to learn the most about your cables, recognizing that not all may be appropriate for the application.
- Before selecting the testing approach and product, **know what cable data you need, what action can be taken from the data gathered, and what method is most economical and practical for your application.**
- **Match the test technology with the desired results**, weighed against cost, availability, ease of test, etc.
- **Years of experience**, standards, and results verify VLF, now used worldwide.
- After decades of **VLF Withstand** testing, **VLF-TD** and **VLF-PD** testing became natural and technically proven off-shoots for diagnostic testing long cables in the field.

SUMMARY OF VLF TESTING

- VLF Withstand testing is the most effective method of exposing cable and accessory defects. **With the Tan Delta and Partial Discharge options, both hipot and diagnostic tests are possible.**
- Suitable for use on **cables and rotating machinery**.
- Worldwide **standards exist** for both.
- **Thousands of users worldwide** have embraced VLF with more joining the ranks continuously.
- **VLF It!** It's fast, easy, and sure.

VLF MODELS FROM VARIOUS VENDORS

HVI (High Voltage, Inc). NY	Baur/Austria	Seba/Germany Megger/Seba USA	Omicron/b2 Switzerland

Voltages shown are in peak


HVI
The World's Source for
High Voltage Test Equipment
Tan Delta
for VLF
VLF 0.1 Hz. Hipots
Oil Insulated
& Solid State
Designs
AC Dielectric Test Sets
& Aerial Lift Testers
HV AC/DC Precision Dividers
Oil Dielectric Testers
200 kVac VLF
Parallel Resonant AC Test System
DC Hipot/Megohmmeters
Ω-Check® Concentric
Neutral Tester
Thumpers & VLF/Thumper
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