Motor and Generator High Voltage AC Testing

Over Voltage Coil Testing: Withstand & Qualitative Diagnostics Explained

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Abstract: **There are many tests made to a motor or generator at various steps along its production and upon completion, when *Acceptance* tests are conducted. For medium voltage input coils like 2.4 kV, 4.16 kV, 13.8 kV, etc., testing during and after winding or repair with high voltage is one of many recommended, really essential, tests to verify the integrity of the coils. Off-line, elevated over voltage testing (>Uo) should be part of any testing program. Many use AC voltage, many use DC voltage, and many do not perform any over voltage testing. Who's right, who's wrong, and what are the considerations?**

This paper provides a brief overview of the commonly performed over voltage tests, explains why AC voltage should be used and not DC, and describes the test equipment options with a guide to selecting the proper high voltage equipment.

Time to Test, but with AC Voltage

Periodically, testing procedures should be reviewed for their properness, effectiveness, and currency. Proper testing procedures should not be neglected for expediency, cost savings, to avoid the expense of buying the required test equipment, or from lack of knowledge of the newer technologies. In a perfect world, test decisions made would be based purely on technical analyses, but that is rarely the case. For motor/gen testing, many use DC voltage for tests that require AC or perform no high voltage testing at all. DC voltage testing may be convenient, inexpensive, easily performed, and used "because that's the way we always did it", but those reasons do not make it the technically correct method to use. Your coils, cables, bushings, etc. are designed for and operate under AC voltage stress. A proper AC over voltage test will prove the AC integrity of the test specimen better than any other method, as it most mimics real world operating conditions. Over voltage DC testing may be very common, even suitable, for some applications, but often lacks the meaningful results gained from testing with AC voltage and cannot be used to perform several crucial diagnostic tests. AC voltage testing offers great benefit and more vital test data over using DC voltage.

So, what have I been missing? This is 2013. Lose the old misconceptions about AC voltage testing, like AC is destructive and DC is not. Tests once not practical are now commonly performed. Over **voltage AC Withstand, Tangent Delta**, and **Partial Discharge** testing are commonplace, available, and should be considered. You owe it to yourself and your customers to take a fresh look at the new technologies, the tests they offer, and the benefit of elevating your test procedures to the newer ways.

Three Tests using Elevated AC Voltage

AC Withstand: Pass/Fail? Can the coil hold voltage?

Tangent Delta: Assesses the overall integrity of the coil.

Partial Discharge: Locates electrical discharges.

The first is a simple go/no-go hipot or proof test to see if the coil can hold the over voltage without breakdown and the two others are diagnostic tests, performed at slightly lower voltages to minimize the risk of an insulation failure during the test. One of these tests measures the overall insulation integrity of the load, or the extent of insulation degradation over time, and the other measures the location and severity of unwanted electrical noise indicating a possible defect. All three tests require elevated AC voltages supplied from a conventional 50/60 Hz AC test set, a Series Resonant system, or a Very Low Frequency AC tester.

1. AC Withstand or Hipot Test: Good/Bad, Pass/Fail: The simplest of these tests is the AC Overvoltage hipot test. Question: can the test specimen withstand the necessary overvoltage conditions expected during its life? If not, find out through testing, locate the problem, fix it, and avoid an in-service failure. For Acceptance or Certification testing, an AC overvoltage of 2Uo + 1kV, or twice the operating line-line voltage plus 1000 volts is commonly used. For service aged test objects, the test voltage may be 75% - 80% of the Acceptance test value. If the windings hold the test voltage and are deemed good, the coil is accepted. If there are weaknesses that cannot hold the test voltage, an arc or overcurrent between windings, turns, coil to core, etc. will occur. The winding is not good and fails, requiring the location of the failure to be found and repaired. Inconvenient yes, but far better than permitting that coil to be shipped, only to fail during service and cause a possibly catastrophic, always expensive, avoidable outage. AC voltage will “blow” the defect, which has to be fixed or replaced anyway, while not harming any of the “good” insulation. If using DC, the fault location probably/hopefully won’t arc and one is left to interpret the leakage current readings. (How does that find the fault?)

To perform AC withstand testing, a power frequency AC Dielectric Test Set, a Series Resonant System, or a Very Low Frequency (VLF) AC hipot is needed. The test voltage ratings are set by the standards’ for testing, but the power, or kVA rating of the device depends on the maximum capacitance of the loads to be tested and to what voltage.

2. Tangent Delta Measurement to Assess the Overall Quality of the Insulation

Tan δ, also known as Dissipation Factor or Loss Angle testing, and similar to Power Factor testing, of a coil, cable, winding, etc. is a long used and well proven method for measuring the extent of total insulation degradation. A motor or cable with perfect insulation is nearly all capacitive, yielding a phase shift between the applied voltage and the subsequent capacitive current. If the insulation is perfect, this phase shift is nearly 90°. The more deteriorated the insulation is with added resistive elements (water trees in polymeric cables, moisture, voids, cracks, etc.), the more this phase shifts lessens from 90° as our load becomes a CR circuit, no longer purely Capacitive. Figure 1 shows the test apparatus, a TD phasor diagram and sample TD curves. We measure this change in the angle and make a determination as to the health of the insulation, usually on a comparative basis against other similar coils, historical records, known benchmarks, etc.

The test is simple to perform. Apply a sine wave AC voltage, up to perhaps 1.7 Uo – 2.0 Uo, or 1.7 – 2.0 times the normal operating voltage, to the motor and monitor and record with the TD equipment the absolute TD or PF numbers and how they change relative to increasing voltage. The recorded numbers are then compared to the known numbers for that type of coil and insulation, or compared to other similar coils, or to the other phases of the same coil, and/or to any test results available from previous testing during the life of the motor. An analysis can then be made to determine the extent of insulation degradation to help you select possible preventive actions that should be taken.

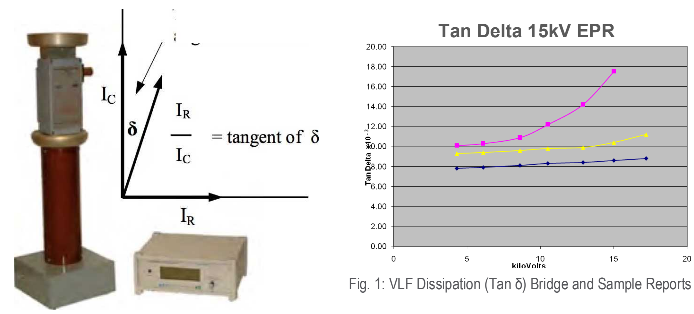


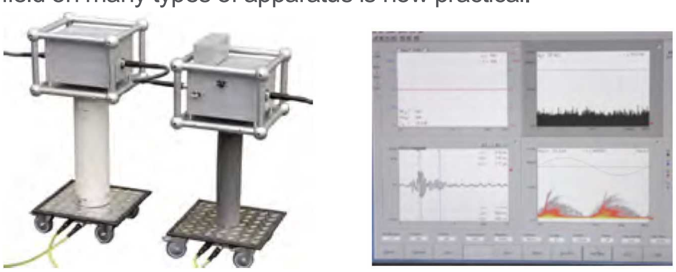
Fig. 1: VLF Dissipation (Tan δ) Bridge & Sample Reports

This is a diagnostic test designed to reveal important data about the health of the coil without risking a failure during the test. It take less than a minute to capture each data point and the test results can be observed while the voltage is increased, allowing the test to be stopped if the data shows a highly contaminated coil that may fail. The hardware needed is a 50/60 Hz or VLF AC voltage source and a Tan Delta Bridge. Several companies offer TD measurement products at 50/60 Hz and/or VLF.

3. Partial Discharge Detection – Locates unwanted electrical discharges. Where are the bad spots?

PD – partial discharge – an electrical discharge within an insulating material that is contained in a localized area that does not breach the entire insulation, becoming a full discharge and causing breakdown/failure. PD testing attempts to locate the source and magnitude of unwanted electrical noise within a coil, cable, switchgear, etc. There should be little or no PD occurring within the coil at normal operating voltages or even at voltages of perhaps 1.5 times the normal operating voltage. To PD test, an AC sinusoidal voltage is applied to the coil, usually starting at maybe ½ normal voltage, or .5 Uo, and raised in steps up to maybe 1.7 Uo – 2 Uo, or sometimes higher. While the voltage is increased, the PD activity is observed and recorded. If all looks good, the voltage rise is continued until the maximum level is reached. It is then lowered back down to zero, still recording the PD activity. The data provided will show the Partial Discharge Inception Voltage (PDIV - where it starts), the Partial Discharge Extinction Voltage (PDEV – where it stops), and the magnitude, or severity of the electrical discharges. From this data, conclusions can be made as to the health of a coil and whether it needs immediate attention or can operate safely for some time. If there is insulation nearing breakdown or a defective termination about to blow, we can react and avoid an in-service failure. Figure 2 shows the test apparatus and a sample PD measurement screen shot.

This test is somewhat complicated, interpretive, and the equipment can be expensive, but it does provide valuable data, and like Tan Delta testing, it is a diagnostic test where the method of testing minimizes the possibility of coil insulation breakdown during the test. The hardware needed is either a 50/60 Hz AC power supply, a power frequency Series Resonant system, or a sinusoidal output VLF AC hipot to supply the overvoltage, and a Partial Discharge measurement system. There are several well qualified vendors of PD detection and measurement equipment designed for off-line, elevated voltage operation under power frequency and several have adapted their products to work well with the unique 0.1 Hz output frequency of the VLF technology. Whether using 60 Hz or 0.1 Hz AC voltage, PD testing in the field on many types of apparatus is now practical.



PD & TD HV Dividers
50/60 Hz & VLF

Sample PD Screen
TD Display also possible

Fig. 2: VLF Partial Discharge Measurement and Sample Graph.

AC Dielectric test Set Technologies: Three Alternative Designs

There are three different design technologies for high voltage AC power supplies, or test sets, used for this application. The most common is a simply a 50/60 Hz AC hipot consisting of a two winding step-up transformer designed to supply the necessary test voltage, the second is a Series or Parallel Resonant System where the HV transformer, or a separate HV reactor, has a variably gapped core intentionally altered to tune the system's inductive reactance to match the load's capacitive reactance, thus minimizing the input power needed. There are also Variable Frequency supplies used in a similar manner. The third uses Very Low Frequency (VLF) AC technology. A VLF system provides an output frequency of 0.1 Hz – 0.01 Hz rather than 60 Hz. The lower the frequency the lower the current and power needed to charge the capacitance of a winding. All three technologies have advantages and disadvantages that will be discussed.

1. Power Frequency Test Set – Typical 50/60 Hz Hipot
The first and most common is a simple power frequency, 50/60 Hz, transformer design based supply to step-up the input voltage to the desired HV output voltage. This method is the simplest in design and construction, as it is a conventional type of two winding transformer, with some means to vary the input voltage to vary the output voltage, usually a variable auto-transformer, like a variac. Figure 3 shows two lower kVA AC test set models. The benefit of these supplies is that they are of a conventional, well known design, and are readily available, at least in the lower kVA ratings of perhaps 1 – 3 kVA. Since they provide a normal power frequency output, they mimic precisely the nature of the voltage stresses on a load as if under operating conditions. They are very well suited for performing AC Withstand testing and for providing a voltage source for Partial Discharge testing. The downside of these supplies is that they operate at power frequency.

Most loads tested under AC conditions appear capacitive in nature, especially coils and cables. When AC testing, the load must be charged and discharged every half cycle of the waveform. At 60 Hz the period of the sine wave is 16.7 ms from 0 – 360 degrees. Thus, the capacitance of the load must reach full voltage charge in just 4.2 ms, or from 0 to 90 degrees of the sine wave. This must happen twice every cycle. To charge a high capacitance that fast can require a very high level of current, or mA/amps. This results in a very large, heavy, expensive, and high power consuming supply to test a load of only .2 µF or .3 µF of capacitance but at a high voltage. A small, portable, and relatively economical 30 kVac @ 3 kVA AC Hipot, like the one pictured in the opposite column can test only ~0.002 µF of load, which may be only a dozen stator coils of a medium size motor. To test even a medium size winding, say 0.2 µF or 0.3µF, would require a supply rated more than 100 kVA (depending on the test voltage). This is not practical and is when other technologies are considered. Figure 4 shows several higher power testers.

60 Hz AC Hipot <10 pc
0-60 kVac @ 5 kVA

50/60 Hz AC Hipot
0-30 kVac @3kVA

Fig. 3: Two AC Dielectric Test Sets

Fig. 4: Various AC Dielectric Test Sets

2. Very Low Frequency (VLF) AC Technology

A VLF tester is a high voltage AC hipot that produces a frequency output of 0.1 Hz and lower rather than the 50/60 Hz of conventional test sets. In this case, it must produce a sinusoidal wave shape output per IEEE 433-2009 standards for testing motors and generators. Again, to apply an AC voltage to a capacitive load can require a high charging current every half cycle to bring the load up to the test voltage: every 4.2 ms @ 60 Hz but a far longer 2.5 seconds @ 0.1 Hz. At 60 Hz input, this charging current must be 600 times higher than at 0.1 Hz. The use of VLF technology for testing rotating machinery of any size is defined by the standard IEEE 433-2009 (originally 1974). Figure 5 compares 0.1 Hz to 60 Hz. Don't over complicate it. A VLF instrument is simply an AC hipot but with a frequency output much lower than the typical 50/60 Hz hipot. It is basic physics: the lower the frequency of the applied voltage to a capacitive load, the lower the charging current required. Using VLF technology, large motors & generators and long cables can be economically and conveniently factory and field tested with AC high voltage.

There is nothing unknown or magical about VLF technology. VLF got its start for motor and generator testing in the late 60's, early 70's at General Electric for its own use in testing the very large generators they

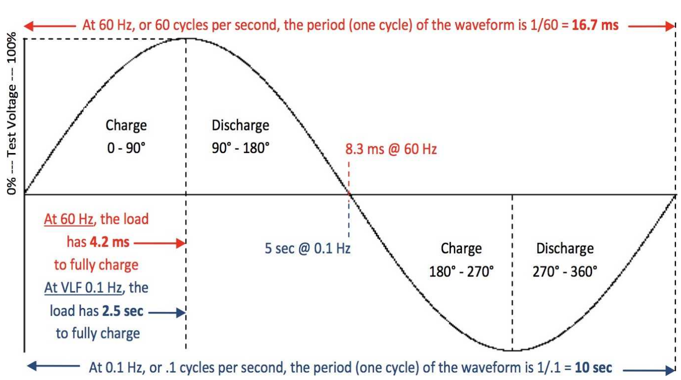


Fig. 5: VLF 0.1 Hz vs. 60 Hz. Sine Wave Period – Charging Rate

produced, the reason for IEEE Standard 433 for testing large rotating machinery was first written in 1974, since upgraded in 2009. Over the last 20 years, VLF testing, including VLF TD and VLF PD, has been embraced widely for cable testing and is in widespread use worldwide. IEEE 400, IEEE 400.2, IEC, VDE, and other countries' Standards define its use for cable. Figure 6 below shows several VLF models.

Fig. 6: Three VLF AC Hipot kVA Ratings vs. 60 Hz.

3. Series/Parallel Resonant and Variable Frequency

As stated previously, when testing very high capacitance loads with AC voltage, like cables, GIS, motor/generator coils, etc. often a tremendous amount of power is needed to charge the high load capacitance at the line frequency rate. To overcome this problem, the "Series Resonant" system of high voltage testing was developed in the 1960's. Using a high voltage transformer designed to supply the test voltage, along with a HV reactor with a manually or automatically variable gapped steel core, the internal "inductance - L" of the power supply is "tuned" by adjusting the core's air gap to match the load "capacitance – C". Once this match is achieved, the reactive power requirement from the test set is minimized and the output voltage is raised with far less real power pulled from the input line. This method is mostly for very high uF loads tested at high voltages, principally long MV & HV cables & Gas Insulated Switchgear. The development of tuned resonance test sets permitted the world to test high capacitance loads at high voltages with far lower power requirements and smaller, lighter equipment than ever before. Parallel Resonance systems are also produced that achieve similar goals and Variable Frequency systems, where the frequency is altered to decrease the power requirements, are also used. Figure 7 shows two models. Unless you are testing motors and generators in the megawatt range, the resonant sets will not be used. Instead, use power frequency and VLF supplies SR's & PR's are presently used extensively worldwide for factory testing and often field commissioning new MV & HV cable systems and generators.

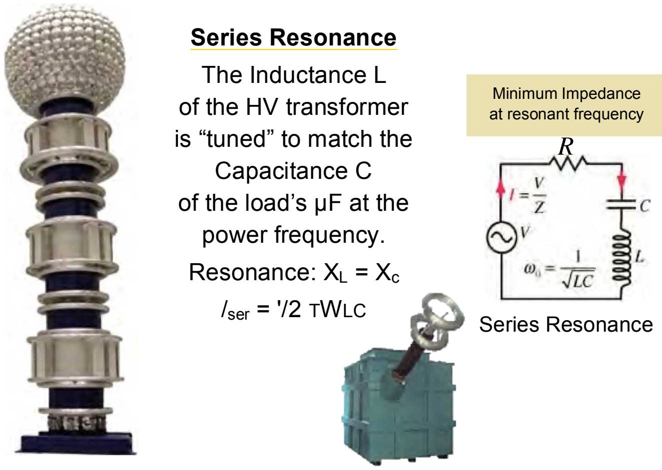


Fig. 7: Series & Parallel Resonant Systems: "tank type" design for lower voltage loads and "modular type" for higher voltage and higher μF loads like long cables.

No More DC Over-Voltage Testing But Isn't AC Destructive to My Windings?

The above notion is an issue that persists and is misunderstood by many. It depends on how you define destructive and what the purpose of your test is. The belief is that applying DC voltage to perform an over voltage dielectric or Hipot test to measure the leakage current does not harm the insulation of the wire. Advocates say that if there is a severe problem during the test that spikes the current upward, the operator of the hipot can quickly turn down the voltage to prevent any breakdown of the coil. This of course assumes the current readings are being watched closely and the operator's reaction time is swift. Also, DC voltage does not incite partial discharge, so there is little risk of the over voltage initiating PD at a defect site that can then quickly grow to failure. Taking only the above, one could think that DC is harmless to the insulation and is an effective test, ignoring for the moment the argument that DC leakage currents are not very meaningful as a diagnostic tool with the many variability's involved in the test and the lack of any benchmarks for acceptable leakage currents. Is 2 mAs good or 4 mAs? What about 20 mAs? Is the DC hipot a half wave rectified design or a full wave? Are the HV terminations shielded against generating corona and are the atmospheric and temperature conditions the same as when last tested? All affect the results.

DC voltage is harmful in the long term to solid dielectric insulation like the tapes, papers, pressboards, epoxies, etc. used for insulation in the construction of a motor or transformer. It is known that some materials are adversely affected by the negative output polarity of DC hipots, causing harm to the insulation during the test that shortens its life and/or programs the materials for future failure. Briefly, when a mono-polar high voltage is applied, like the negative output of a DC Hipot, the molecules in the insulation are polarized and become oriented in a dipolar fashion, essentially lining up along magnetic lines of force. This lineup within the insulation creates a greater localized stress in many areas, lessening the dielectric strength, since the charges are no longer randomly aligned. This makes the insulation more prone to failure during transient activity and reduces its overall life.

OK, the DC test is usually "non-destructive" to the insulation during the test but can be "destructive" to the long term health of the materials tested and hasten failure and/or shorten life, not to mention that many false positive "pass" tests result in in-service failures later.

When testing with AC, the voltage divides across the load by the relative differences in the impedance, or capacitive reactance, across the turns of the coil, which is usually rather uniform, thus spreading the voltage similarly across the coil: not true with DC voltage. AC testing is very effective at equally stressing the turns to provide a meaningful stress test of each turn-turn, or coil-coil, coil-core, etc. If there is a defect in the insulation from a material flaw or workmanship error, a breakdown will occur at that spot. The fault must be found and fixed. Yes, AC over voltage testing is destructive but only to an existing defect that can't hold the voltage, not to the remaining good insulation. Wire and cable producers' hipot their products before shipment at levels over 5 times normal AC voltage. Some don't like that a failure and the resulting arc during an AC voltage test will cause damage in the area of the fault, requiring a portion of the coil, or all, to be rewound. Although an uncomfortable truth, you just saved that coil from a certain in-service failure had it been shipped without performing the test. Potential troubles are not averted if you don't test, or go easy with DC voltage; they are still there and will surface later. It comes down to when you want the defects to fail, now when still in your shop or after the item is installed.

Your product is designed for and operates under AC voltage stress. DC ≠ AC. Test it with AC voltage to perform a simple and conclusive Withstand test or the more diagnostic "health check-up tests" of Tan Delta and Partial Discharge.

Sizing the AC Test Set. The Test Voltage is Known – What Current Rating is Needed?

When testing with AC voltage, the capacitance of the windings tested will determine the current needed, and the subsequent kVA when the voltage is considered. Somehow you must figure the current draw of the worst case load and at what voltage that current is needed to select the test set. Maybe you can get away with testing only a section of stator windings as they're installed, thus requiring a less powerful hipot. If you must test each phase individually after winding, the current required from the tester will then be higher. If test specs require a full system test after completion, hipoting all windings/phases at once, you will need far more power to get it done. To properly size the AC hipots current output, you must know your load characteristics and your intended tests. Figure 8 in the next column is an example of how to size an AC hipot based on the windings capacitance.

Here are a few tips to help to determine the AC current:

1. Do you know or can you measure the capacitance of your load and then calculate the AC current needed? To calculate the AC current needed to test a capacitive load, use the following equation: ***Amps = 2πfCV***

   ***f** = frequency in Hz* ***C** = load capacitance in farads*

   ***V** = test voltage in volts*

2. If you don't know the windings' capacitance, find out what AC hipot model may have worked before, or came close? We can find out its rating to know what is needed.

3. Are there old test reports showing the AC charging current at the test voltage, or at any voltage? If you have a small AC hipot, even with a lower voltage output, use it to apply a few kV and measure the current. The charging current of the load will be fairly linear with increasing voltage. If it draws 20 mA at 5 kVac, it will be draw approximately 200 mA at 50 kVac.

To test a medium to large winding, needing to buy a 50 - 100 kVA AC test set is not appealing. Consider the VLF alternative? A VLF tester might work better for you than a power frequency model. A small and relatively inexpensive power frequency 30 kVac @ 20 mA (a 600 VA hipot) can handle a small motor; while a more powerful 30 kVac @ 1 A (a 30 kVA test set) may be needed for a medium sized 13.8 kV motor. If you handle larger sizes, and due to the high capacitances, it may take a power supply rated 50, 100, even 500 kVA to perform overvoltage testing. For this reason, a power frequency test set, or even an SR system is often prohibitive. Follow IEEE 433-2009 and use a VLF hipot.

Conclusion

This paper is intended to serve as an introduction to the options for AC over voltage testing coils. With knowledge of the tests commonly performed and the test equipment available, you should be able to make an educated decision as to which approach is best for your situation. Much time, energy, and money are spent on producing, installing, and using generators and motors. Much time, energy, and money are spent rebuilding failed generators and motors. Don't short change yourself and the reliability of your system by skimping on the very tests that can best verify the AC integrity of your apparatus and identify potential problems early to allow for corrective action before it's too late.

Fig. 8: Example Coil Size with AC & DC Hipots needed

REFERENCES

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[2] IEEE Std 286, IEEE Recommend Practices for Measurement of Power Factor Tip-Up of Electric machinery Stator Coil Insulation.

[3] IEEE Std 1434, IEEE Guide to the Measurement of Partial Discharges in Rotating Machinery

[4] IEEE Std 56-1977, IEEE Guide for Insulation maintenance of Electric Machines

[5] IEEE 400-2001, IEEE guide for Field Electrical Testing and Evaluation of the Insulation of Shielded Power Cable Systems

[6] IEEE 400.2-2004, IEEE guide for Field Testing of Shielded Power Cable Systems using Very Low Frequency (VLF)

[7] IEC 60034-1, Rotating Electric machines – Part 1: Rating and Performance Section 17: Dielectric Tests for Rotating Electrical Machines.

PHOTOGRAPHS USED

Figure 1: Tan Delta instrument from M & B Systems from Manchester England

Figure 2: Noise and separation filter hardware data collection circuitry and screen shot of PD and TD software courtesy of Power Diagnostics Systems GMBH.

Figures 3, 4, 6 & 8: High voltage instruments courtesy of High Voltage, Inc., NY, and USA.

Figure 7: Series resonant photos courtesy of KVTEK of India & Samgor of China.