# CONDITION ASSESSMENT OF ROTATING MACHINES THROUGH OFF-LINE DIAGNOSTIC TESTING


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***Abstract*** - Many end users, manufacturers and service organizations now routinely employ some form of on-line monitoring technology, e.g., partial discharge (PD), as a significant component of a condition based maintenance program. The widespread and increasing use of such methods has led to some organizations questioning the value of performing off-line diagnostic testing to assess machine insulation condition. Traditionally, many end users would do one or more of these tests during major outages, however, due to economic pressures the interval between such outages has significantly increased, in many cases by a factor of two. Further, many plant managers are reluctant to permit electrical testing because of concerns that such testing may damage the machine even though the applied voltage used in the vast majority of tests is limited to the nominal line-to-ground operating voltage. In this contribution, we shall discuss the role that off-line tests have to play in the testing of rotor windings, stator windings and cores, the commonly used tests and their appropriate application. Only those tests that are covered by IEEE or IEC standards are discussed.

*Index Terms* — Stator, Rotor, Core, Off-line Diagnostic testing, Maintenance.

## I. INTRODUCTION

Many end users, manufacturers and service organizations now routinely employ some form of on-line monitoring technology, e.g., partial discharge (PD), as a significant component of a predictive or condition based maintenance program. The widespread and increasing use of such methods has led to some in the industry questioning the value of performing off-line diagnostic testing to assess stator winding insulation condition. However, several organizations still employ off-line diagnostic testing either as their sole means of assessing machine condition or to verify the results of data derived from on-line test methods. Consequently, off-line test techniques are still valid and worthy of consideration. This paper reviews the commonly used off-line diagnostic tests used in the industry. Only those tests that are covered by IEEE or IEC standards are discussed and ac and dc hipots are precluded because these are go/no-go tests with little diagnostic value.

## II. STATOR WINDING TESTS

### A. Insulation Resistance & Polarization Index

An insulation resistance measurement is one of the most basic and commonly employed tests used in the industry. The test involves applying prescribed dc voltage across the groundwall insulation and, on the basis largely of the leakage current, the resistance value after one minute of voltage application is derived. The polarization index is obtained by taking a further insulation resistance measurement at 10 minutes and dividing this value by that measured after 60 seconds. These tests are governed by IEEE 43 [1] that specifies, among many factors, the appropriate applied voltage (dependent on the rated voltage of the machine) as well as acceptance criteria for insulation resistance and polarization index. Until recently, there was no equivalent IEC standard for this type of testing, however, this situation did change in 2017 with the publication of IEC 60034-27-4 [2]. Typically, these tests are used either to determine that the stator winding is fit to undergo further diagnostic testing involving high voltages or to verify a ground fault in the event of an alarm or trip. While the diagnostic content of an insulation resistance test has been considered limited due to sensitivity to surface leakage currents, the latest version of IEEE 43 does include guidance on more sophisticated methods of interpretation that may provide insight into the bulk condition of the insulation. If the machine is shut down for maintenance, this test is strongly recommended.

### B. Capacitance & Dissipation Factor

Capacitance and dissipation factor measurements, see Fig. 1, have been routinely used by manufacturers and end users for decades as a means to assess the quality and uniformity of individual stator bars and coils. Dissipation factor testing belongs to the broad range of measurements of dielectric loss and is also commonly referred to as the tan delta or power factor test. Power factor is the cotangent of the loss angle (delta) whereas dissipation factor represents the tangent. At low values of loss angle the tangent and cotangent are virtually the same. The higher the dielectric loss in an insulating material the higher will be the dissipation factor. Defects in an insulation system, such as voids and delamination result in PD which is a loss mechanism. Thus, dissipation factor measurements may be used to determine the void content of an insulation system. Unlike a PD test, dissipation factor also incorporates information about the bulk insulation system. Thus, there may not be an exact correlation between the results obtained from PD and dissipation factor tests. Often the dissipation factor is obtained at two different voltages, e.g., at 25% and 100% of the nominal line-to-ground operating voltage, to derive the dissipation factor tip-up. At the lower voltage the insulation system is assumed to not be subject to PD. Thus, the tip-up is used as a means to differentiate between effects due to the bulk and defects such as voids. This testing is governed by IEEE 286 [3] and the recently published IEC 60034-27-3 [4]. Both documents provide guidance on performance of the test; however, the IEC standard also includes acceptance criteria, for individual stator bars and coils, which to some are controversial.

Measurement of dissipation factor and tip-up is complicated by the presence of silicon carbide stress control coatings on coils or bars rated at 6 kV or above. At low voltage, the silicon carbide is essentially a very high resistance coating, and no current flows through it. Thus, there is no power loss in the coating. However, when tested at rated voltage, by design the silicon carbide coating will have a relativity low resistance. Capacitive charging currents flow through the insulation and through this stress relief coating. The charging currents flowing through the resistance of the coating produce an $I^2R$ loss in the coating. The dissipation factor measuring device measures this loss. Since the loss is negligible at low voltage and nonzero at operating voltage, the coating yields its own contribution to tip-up. This coating tip-up creates a noise floor. Very significant PD must be occurring in most windings for the PD loss to be seen above the silicon carbide tip-up. Thus, with the widespread availability of either on-line or off-line PD testing, this test is becoming less popular as a maintenance test.

Fig.1: Capacitance and dissipation factor bridge (manual balancing method).

*C. Partial Discharge*

Off-line partial discharge measurements are employed to provide information on the void content of the insulation system. Unlike a dissipation factor measurement which spatially averages the test result, a PD test is sensitive to those voids with the largest dimensions (which are those of most concern). Where an off-line PD test indicates anomalously high PD magnitudes, corona (or TVA) probe testing may be deployed to aid in identifying sources of this activity. Partial discharge testing is also useful to uncover other defects such as surface contamination and inadequate clearances between phases. The identification of such issues which occur in the endwinding regions of machines are significantly aided by employing additional techniques such as corona cameras, radio frequency and ultrasonic probes. Extensive guidance on off-line PD test methods is given in IEEE 1434 [5] and IEC 60034-27-1 [6]. Comparing on-line PD testing to its' off-line counterpart there are many advantages to performing the test with the machine operating. Among these are; the voltage distribution is correct, the stator winding is at elevated temperature and the coil/bar forces are present. In short, there are a number of defect mechanisms, e.g., loose windings, that cannot be detected using an off-line PD test. Further, often the results from off-line measurements have to be treated with some caution because they may be pessimistic relative to the operating condition. For example, off-line PD testing of hydrogen-cooled machines is almost invariably done in air at atmospheric pressure. However, if one takes the view that these results would be worst case then the data thus obtained still have value. A significant advantage that off-line PD testing provides is that the test operator has control of the applied voltage. Consequently, despite the always present background electrical interference (which is a significant problem for on-line testing), the PD activity (if present) can normally be observed as the applied voltage is varied. Further, the discharge inception and extinction voltages can be measured which provide further insight on whether the PD activity is likely to be an issue during operation. Fig 2 shows the basic schematic for and off-line PD test and Fig 3 shows an example of the equipment employed in performing the test.

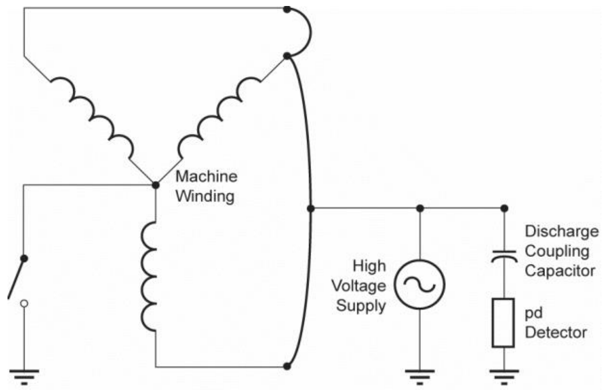


Fig. 2: Schematic of off-line PD test.

Fig. 3: Example of an off-line PD test in the field.

*D. Corona Probe Test*

The corona probe test, sometimes known as the TVA probe test, consists of scanning an electromagnetic probe along the length of each stator slot in the core. The output from the probe is connected to a tuned amplifier and quasi peak pulse meter. Typically, this test is performed when the results of PD testing (either off-line or on-line) have indicated anomalously high PD magnitudes and is used to locate sources of high PD in the winding. Details of the corona probe test may be found in IEEE Standard 1434 [5] which document also provides guidance on acceptable levels for asphaltic, polyester and epoxy-based insulation systems as well as CIGRE Technical Brochure 581 [7].

The corona probe test can only be performed on a turbine generator on an outage in which the rotor has been removed, and on salient pole machines with the rotor removed or with poles pulled. Performance of this test requires that the operator of the probe be in very close proximity to the energized stator winding. Consequently, this test should only be performed by those with significant experience and expertise in high voltage test methods and using appropriate personal protective equipment, e.g., adequately rated high voltage gloves, shock resistant footwear, etc.

The value of the corona probe test is enhanced when an off-line PD test has been performed and the PDIV and PDEV values have been recorded. On the basis that the PDEV value may be used as a measure of what proportion of the winding is likely to discharge in-service then consulting the winding diagram for the machine may provide insight into whether a coil or bar with a high corona probe reading would be at a high enough position from the line end to represent a risk to the winding. Fig. 4, demonstrates the performance of a corona probe test.

Fig. 4: Example of a corona probe test on a stator winding

*E. Corona Camera*

Corona cameras, Fig. 5, are optical devices with filters that render them preferentially sensitive to light wavelengths in the ultraviolet (UV) range. Consequently, they may be used to locate sources of surface PD activity such as those resulting from problems such as inadequate endwinding clearances, defective or degraded semicon / stress grading interfaces, etc. A relatively recent document, IEEE 1799 [8] provides guidance on the performance of such tests on rotating machines. The use of corona cameras had been hampered by their very high cost, however, more affordable devices are now available.

Fig. 5: Corona camera in use

*F. Ultrasonic Probe*

Another non-electrical discharge detection method is the ultrasonic probe, Fig. 6. Typically, these devices are responsive to surface discharge activity and may be used to locate similar issues to those identified above with the corona camera. However, the lack of an imaging capability as well as the high acoustic noise background in the average generating station environment renders these devices somewhat less useful.

Fig.6: Ultrasonic probe

## III. STATOR ENDWINDING TESTS

“Bump” (or impact) testing is the best way to ensure that damaging endwinding vibration does not occur on a new machine. Preferably, every 2- and 4-pole machine should be given a bump test after manufacture to find the global and local natural frequencies and mode shapes of the endwinding at both ends. As a minimum, each model/design of generator should be bump tested to find design related problems. However, such “type” tests will not find issues associated with workmanship – for example, misplaced blocking, poor impregnation with bonding resins, missed roving, etc.

The bump test, Fig. 7, involves striking the endwinding and measuring the response of the endwinding with piezoelectric accelerometers at several locations. The equipment required includes:

• A "calibrated hammer" with a mass of about 0.5 kg that can impact the endwinding and measure the magnitude of the impact force with a transducer mounted in the hammer.

• Detection accelerometers that are temporarily bonded to the coils/bars. At least two accelerometers or one dual-axis accelerometer are needed to measure the vibration in the circumferential and radial directions.

• A Fast Fourier Transform (FFT) type of spectrum analyzer that can respond to frequencies up to about 10 kHz to simultaneously capture the force input and the three accelerometer responses producing frequency response transfer functions for analysis.

• For advanced structural analysis, software to compute the vibration mode shape tables.

Such instrumentation and software is now widely available, and compared to bump tests performed in the 1980s, the current technology is relatively easy to use. Further information is contained in IEC 60034-32 [9].

Fig. 7: Performing a bump test

## IV. ROTOR WINDING TESTS

### *A. Voltage Drop Test*

Typically, this test is employed on salient pole rotors to detect and identify shorted turns in the field winding. Essentially, the test consists of applying a relatively low voltage (100 – 120 V, 50 or 60 Hz) to the entire winding and measuring the voltage drop across each pole. A pole with a lower voltage drop will likely have one or more shorted turns.

However, on high speed cylindrical (or round) rotors access to the individual rotor windings is often not possible and is very dependent on the design of the field. Thus, this method is not always applicable to these types of machines. A further drawback with this test, as with other off-line methods of detecting shorted turns in field windings, is that the defect may only be apparent with the rotor in operation. Consequently, there is a risk of obtaining a false negative result.

### *B. Recurrent Surge Oscillograph (RSO) Test*

The recurrent surge oscillograph (RSO) test involves injecting a fast rise time low voltage square wave pulse into each slip ring pair in turn and measuring its reflection for each half of the winding. By comparing (superimposing) the reflection traces from the two halves of the winding, it is possible to establish any divergences which would indicate an electrical differential between the two windings.

The test may indicate potential degradation of the winding interturn insulation (divergence of the traces) along with ground issues. Whilst this is a good test to determine the winding interturn condition, it should be noted that it does not indicate that any abnormalities observed are current carrying, but is good at identifying issues that either have the potential to be either now or in the future to permit further assessment.

### *C. Surge testing*

Whilst the RSO testing is performed on round rotors, salient pole machines have a major advantage - the terminals of the individual poles are usually accessible. That offers a more accurate diagnostic method: A charged high-voltage capacitor is switched in parallel to the pole windings, one after the other. The capacitor forms a resonant circuit with the winding whose natural frequency and damping increase if turn-shorts are present. The oscillations are measured using high voltage probes and oscilloscopes. Shorted poles are identified by comparison with healthy poles.

The test is usually carried out with high voltage, e.g. 1500 V on aged windings, so that even dynamic shorts, which sometimes only show up during operation, can often be detected at standstill.

## V. STATOR CORE FLUX TESTS

The objective of flux tests is to assess the integrity of the interlaminar insulation of the stator core. Failure of this insulation may lead to localized overheating due to eddy currents and, in extreme cases, burning or even melting of the stator core. There are three variants of flux testing that will be described briefly below.

### *A. Low Energy Flux Test*

This method, also commonly known as the EL CID test, involves exciting the core at a low energy, typically in the range of 4% of the rated flux in operation. Using such a low level of flux offers a number of advantages including being able to use standard 120 or 220 Vac, 15 A power outlets and that there is no risk of thermal runaway occurring on a core with a fault. In common with other core flux tests, an excitation winding is wound, as axisymmetric as possible, through the stator bore. The number of turns required to provide the required low flux density is obtained by calculation based on the parameters of the machine under test. A reference signal is derived by placing a current transformer around the excitation winding. A search coil, known as a Chattock potentiometer, Fig. 8, is moved along the entire length of each stator slot, the output of which is proportional to the magnetic potential difference between the two contact points on the stator core surface. The fault current signal derived is presented as a function of the axial position of the search coil as it is scanned along the core. Empirically, a fault current of at least 100 mA has been determined to be the minimum at which the core is considered to have sustained significant damage to the interlaminar insulation. Full details of the test are contained in [10, 11]. Fig 9, shows the instrumentation used to process the outputs from the search coil.

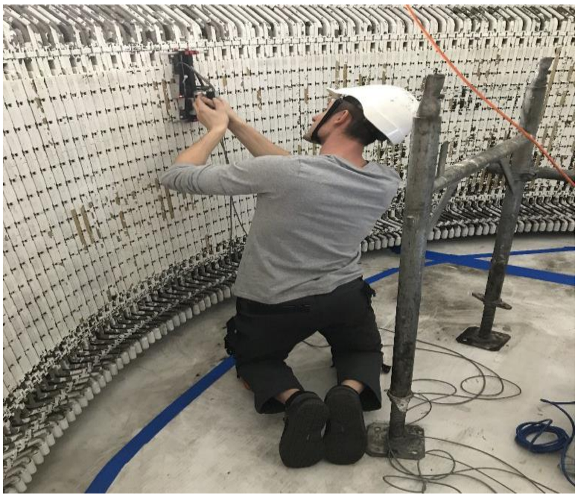

Fig. 8: Scanning of stator core with search coil

Fig. 9: Processing of search coil data

*B. Rated Flux Test – Power Frequency*

This method, also known as the ring flux test, involves inducing near-rated flux in the stator core. Consequently, in those areas where the core interlaminar insulation is damaged, the excess heating that results is detected using infrared imaging techniques. As in all core flux tests, the flux is produced by winding a number of turns of cable (determined by calculation) axisymmetrically through the stator bore. Unlike the low energy test described above, due to the higher flux requirement, the cables used are of higher voltage and current ratings. Procedures to calculate the required number of turns to produce the desired flux may be found in references [10] and [11]. Performance of the rated flux test should be approached with caution because of the possibility of causing serious core damage.

After establishing the required flux in the core, this value is maintained for a period of the order of 30 minutes to one hour to obtain core temperatures similar to those encountered in service. The core is then monitored using the infrared temperature monitoring devices to locate any hot spots that may require further investigation and/or maintenance action.

Fig. 10: Rated flux testing with power frequency

*C. Rated Flux Test – 500 Hz*

In the case of this variant of core flux testing, the principle of establishing near-rated flux in the core and observing any resulting hotspots by means of infrared imaging techniques is the same as for the traditional ring flux test. However, because the current required to induce the required flux is inversely proportional then performing the test at a frequency of 500 Hz provides advantages in terms of the power supply requirement. This method is discussed in more detail by Richter and Weidner [12].

## VI. CONCLUSIONS

While experience, to date, indicates that on-line condition monitoring methods such as PD are effective in providing information on stator winding insulation condition, off-line testing still has a significant role to play. In addition to verifying the results of on-line testing, off-line diagnostic tests, especially when more than one technique is used, provide additional information on which to base maintenance decisions.

## VII. REFERENCES


[1] IEEE 43, Recommended practice for Insulation resistance testing of rotating machines.

[2] IEC 60034-27-4:2017, Measurement of insulation resistance and polarization index on winding insulation of rotating electrical machines.

[3] IEEE 286, Recommended practice for measurement of power factor tip-up of electric machinery stator coil insulation.

[4] IEC 60034-27-3:2015, Dielectric dissipation factor measurement on stator winding insulation of rotating electrical machines.

[5] IEEE 1434, Guide for the Measurement of partial discharges in AC electric machinery.

[6] IEC 60034-27-1:2017, Off-line partial discharge measurements on the stator winding insulation of rotating electrical machines.

[7] CIGRE Technical Brochure 581, Guide – corona electromagnetic probe tests (TVA), 2014.

[8] IEEE 1799, Recommended practice for quality control testing of external discharges on stator coils, bars, and windings.
[9] IEC 60034-32:2016, Measurement of stator end-winding vibration at form-wound windings.
[10] IEEE 62.2, Guide for diagnostic field testing of electric power apparatus - electrical machinery.
[11] G. Klempner and I. Kerszenbaum, Operation and Maintenance of Large Turbogenerators, Wiley-Interscience, 2004.
[12] C-G. Richter and J. Weidner, “Testing stator cores of large turbogenerators using the ring flux method”, Proc. Power-Gen Europe, Vienna, Austria, 2013.

## VIII. VITA

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