CONDITION ASSESSMENT OF STATOR WINDINGS IN MEDIUM VOLTAGE GVPI MACHINES

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ABSTRACT

Traditional tests of insulation resistance, polarization index (IEEE 43) and the controlled DC high voltage test (IEEE 95) have been effective in evaluating certain aspects of global vacuum pressure impregnation (GVPI) stator windings; however, they have not proven adequate for determining whether or not the insulation system is well-consolidated. Recently there has been the development of an IEC standard (IEC 60034-27) that defines the test procedures for performing off-line partial discharge testing as part of quality assurance testing. In addition, globally there has been a move towards using a dielectrics characteristic test, either power factor or dissipation factor, as part of the QA testing for GVPI systems. Partial discharge tests have proven to be effective in locating isolated problems that could lead to failure; whereas, the dielectrics characteristic tests provide a more general condition assessment. Based on experience to date, both are needed to fully evaluate how well the winding is consolidated.

This paper describes research done by EASA service shops on the effectiveness and practicality of using offline partial discharge combined with a dielectrics characteristic test to evaluate the consolidation of stator windings in medium voltage machines manufactured by GVPI. Advantages and disadvantages of each test and industrial standards will be described as appropriate.

INTRODUCTION

If manufactured properly, large squirrel cage medium voltage global VPI stator windings in induction motors (greater than a few hundred horsepower) and synchronous motors typically enjoy 20 years or more of operation. However, if the during the motor manufacturing process, the resin did not properly penetrate the tapes, failure may occur in just a few years due to premature aging. Premature failure can also occur as a result of installation errors, such as insufficient spacing or misapplication of surface coatings. [see Table 1]

Over the past decades, a number of new offline tests have become widely available, but are rarely used as quality assurance testing for new global VPI windings or for assessment of existing windings. By using these tests in combination with tried and true tests such as insulation resistance testing, unexpected in-service winding failures can be minimized, thus increasing process reliability.

Please see the Reference section at the end of this paper for industry standards and recommendations regarding the use of the tests mentioned in this paper.

Table 1: Stator Winding Failure Mechanisms [1]

Failure Mechanism	Symptoms	Detection Tests
Inadequate bonding	Partial discharge	Capacitance, tan δ, power factor, tip-up, partial discharge
Electrical slot discharge	Partial discharges, slot discharge, ozone	
Semi-con/stress interface	Partial discharge, white powder, ozone	

STATOR WINDING OFF-LINE TESTS

Off-line tests are used to locate and determine the severity or risk of failure, and whether repairs are possible. Off-line tests have the advantages of accessibility, noise-free environments, ease of repair, and variety. The disadvantages are no mechanical or thermal stresses, abnormal voltage stresses, they require a machine outage, and they can be time-consuming.

For the best test results, the motor should be isolated from the power supply cables. If possible, the winding phases should be tested individually. There are four tests that are recommended by various standards for GVPI insulation systems: capacitance, dissipation factor, power factor, and offline partial discharge.

CAPACITANCE TESTING

(EPRI LEMUG)

If some of the organic resin is displaced with a void that fills with air this changes the dielectric constant of the insulation system. Caution - the variability in capacitance of newer insulation systems is usually so subtle that unless the winding is severely deteriorated it is difficult to observe any changes.

The capacitance can be measured at a low voltage and best done with a bridge that will eliminate the effect of the stray capacitance of the test supply. As the winding cures there will likely be a notable decrease in the capacitance as the polarizing and conductive currents decrease. This decrease will be observable independent of changes in voltage, that is, across all voltage steps the capacitance should be lower. [11]

A variation on the capacitance test is the capacitance tip-up test, which is performed on complete windings or preferably individual winding phases, and measures the void content in the groundwall of the stator coils. Measurements shall be taken at 20% of the motor rated line-to-ground voltage (0.2E) and at the motor rated line-to ground voltage (1E). [7]

The tip-up is based on the fact that phase-to-ground voltage, if there are voids in the groundwall insulation, the gas in the void ionizes to produce sufficiently high conductivity to short the void out. This reduces the effective thickness of the insulation producing an increase in capacitance between low and high line-to-ground voltage. One void would have no impact, but if there are excessive voids due to the inadequate resin impregnation or problems with the tape or bonding material in the insulation system, the change in capacitance would be noticeable. [11]

Normally this test is performed on each phase of a winding with an accurate capacitance bridge. The capacitance C_{lv} is measured at 0.2E where E is the rated phase-to-phase voltage and also C_{hv} is measured at line to ground voltage which is about 1E. The capacitance at low voltage is the capacitance of the insulation with the voids; whereas, as the higher voltage the voids have been shorted, so it is the capacitance of the insulation alone. *Therefore, increase in capacitance with voltage is an indication of internal voids.* In the absence of void, the capacitance will not change as the test voltage is increased. The capacitance tip-up is:

$$\Delta C = (C_{hv} - C_{lv})/C_{lv}$$

Uncured/moisture contamination ⇒ C is high
Delamination ⇒ ΔC increases with voltage

The higher ΔC is, the more voids there are in the winding groundwall. Note that as shown in Figure 1, as the void volume increases so does the ΔC percentage. For well bonded modern epoxy mica groundwall insulation, typically the ΔC is less than about 1%. [7]

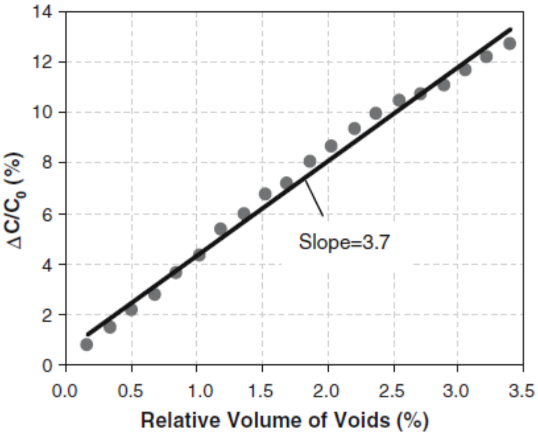


Figure 1. Change of ΔC as a function of the relative volume of voids within the epoxy resin specimen [11]

It should be noted that if the coils have semi-conducting and grading voltage stress control layers, these influence the results of this test. At the higher voltage, the grading layers of silicon carbide material conduct to increase the effective surface area and thus the capacitance of the sections of winding being tested, and so may give a false indication of high void content. However if the results are trended against time, an increase in ΔC may give a true indication of increased void content in the groundwall insulation. [11]

DISSIPATION FACTOR (TAN δ)

(NEMA MG-1, IEEE 286, EPRI LEMUG, IEEE 56 and IEEE 432)

Like the capacitance test, the dissipation factor (tan δ) test also looks for any changes in the insulation system of the winding. When a 60-hertz voltage is impressed across the stator insulation, the total current that flows is similar to that of any capacitor. The total current has two components: a relatively large capacitive current (i_c), which leads the voltage by 90°, and a smaller resistive current (i_r) which is in phase with the voltage. In a perfect insulation system, there would be no resistive current (i_r) as all of the current would be capacitive (i_c). However, as with the capacitance test, if there are voids, then the dielectric characteristics of the insulation system will change.

The dielectric of this simulated capacitor is the insulation system which is embedded between two electrodes: the high-voltage copper conductors and the stator iron core. The dissipation factor is the tangent of δ, the angle between the i_r and i_c, or the angle between the capacitive current and the total current (Figure 2). [2]

This test is normally done at voltage steps that increase from 0.2E (DF_{low}) to normal line-to-ground voltage, 1E (DF_{high}), preferably on individual phases. The intention of the test is to observe the increase in real power loss due to the presence of voids in a delaminated insulation ($\Delta \tan \delta = DF_{high} - DF_{low}$). As with the capacitance test, increases as a function of voltage are due to partial discharge and the ionization of the gas in the voids of the insulation system. [11]

As the applied test voltage increases so will the partial discharge activity in the voids and thus an increase in resistive current (i_r) or real power loss. The absolute value of the dissipation factor is also useful in determining the extent of curing in a new insulation system since uncured components have different dielectric characteristics from cured components.

$$DF = \tan \delta = I_R / I_C$$

Uncured/moisture contamination ⇒ tan δ is high
Delamination ⇒ Δ tan δ increases with voltage

Typically the DF for epoxy mica windings is about 1-2% and the Δ tan δ is less than 1%. Trending the results against time makes the best use of this test. As with the Δ capacitance test, voltage stress coatings can lead to ambiguous results obtained at high voltage. [7]

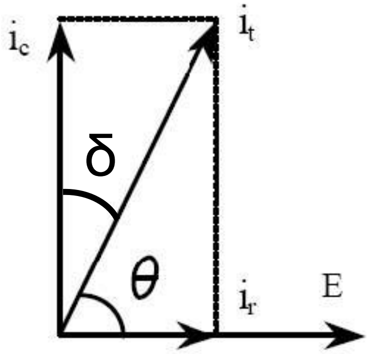


Figure 2. Dielectric of a winding

POWER FACTOR (COS θ)

(NEMA MG-1, IEEE 56, EPRI LEMUG and IEEE 432)

Similar to the dissipation factor (tan δ) the power factor test is looking for any changes in the insulation system of the winding. The power factor is the cosine of θ, the angle between the applied voltage and the total current (Figure 2). The test is normally done at a specific applied voltage that makes it possible for comparing the results to other machines, 0.2E. This is a valuable test for determining the extent of curing in new coils or winding. Because the presence of the voltage stress control in a complete winding greatly affects the results, tests on complete windings can be ambiguous. [2]

The tip-up test (Δ cos θ) is done at two voltages, one below the inception of partial discharge activity (PDIV), 25% of line-to-ground voltage, 0.25E (PF_{low}), and one at 100% line-to-ground voltage, 1E (PF_{high}), preferably on individual phases. As with the Δ tan δ test, the difference in the power factors at these two voltages can be attributed to the energy loss due to partial discharges.

$$PF = \cos \theta = mW / mVA$$

moisture contamination ⇒ cos θ increases
delamination ⇒ Δ cos θ increases with voltage

Typically, the PF for epoxy mica windings is about 0.5% and the Δ cos θ is 0.5%.

However, as with the capacitance tip-up test, the results of this test are influenced by the presence of voltage stress coatings on the coils, since at high line-to-ground voltage currents flow through it to produce additional power losses. Because this test method measures total energy it is only sensitive to how widespread the PD is and not how close the winding is to failure (worst spot).

OFF-LINE PARTIAL DISCHARGE TEST

(IEEE 1434-2000, *IEEE 56-2012, IEC 60034-27-2 and EPRI LEMUG)*

Partial discharges (PD) are small electrical sparks which occur in stator windings rated 3.3 kV or higher. PD is non-existent or negligible in well-made stator windings that are in good condition. However, if the stator winding insulation system was poorly made, then PD will occur. A PD test directly measures the pulse currents resulting from PD within a winding.

Each PD produces a current pulse that has high frequency components to the hundreds of megahertz. Any device sensitive to high frequencies can detect the PD pulse currents. In a PD test on complete windings, the most common means of detecting the PD currents is to use a high voltage capacitor connected to the stator terminal. Typical capacitances are 80 pF to 1000 pF. The capacitor is high impedance to the high AC current in the stator, while being very low impedance to the high frequency PD pulse currents. The output of the high voltage capacitor drives a resistive load. The PD pulse current that passes through the capacitor will create a voltage pulse across the resistor, which can be displayed on an oscilloscope, frequency spectrum analyzer, or other display device. The lower band of the detector is the frequency range of the high voltage detection capacitor in combination with the resistive or inductive-capacitor network load. Early detectors were sensitive to the 10 kHz, 100 kHz or 1 MHz ranges. Modern detectors can be sensitive up to the several hundred megahertz range. In addition, high frequency current transformers are sometimes installed on surge capacitor grounds to detect the PD.

The key measurement in a PD test is the peak PD magnitude Qm, i.e. the magnitude of the highest PD pulse, since this is proportional to the largest defect in the stator insulation.

Tests are usually taken at increasing voltage steps starting at 0.2E to line-to-ground voltage (1E), preferably on individual phases. Measurements include: [6][10]

1. the voltage at which partial discharge starts, or the inception voltage (PDIV),
2. the voltage at which partial discharge stops, or the extinction voltage (PDEV), and
3. the largest repeatedly occurring PD magnitude at rated voltage

Both the PDIV and the PDEV should be above 50% of line-to-ground voltage. [7] [9]

CASE STUDIES

Using these tests and acceptance values, several motors were tested at various stages. Tests were done using two different sets of test instruments:

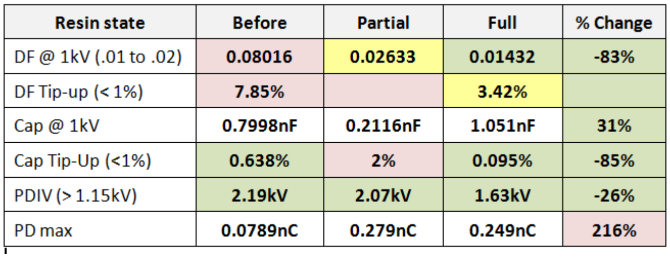
1. Using a PDTech DeltaMaxx to measure capacitance, dissipation factor and partial discharge

2. Using a Biddle power factor/capacitance test instrument along with an Iris Power HF/LF partial discharge test

Please be advised that when testing partial discharge, the measuring bandwidth of the test configuration influences results, so standard acceptance values for PD magnitudes are not possible. However, comparison among results using a similar test configuration is possible.

CASE STUDY 1: COIL RESIN IMPREGNATION

A single coil 4kV was tested at various stages of the resin impregnation process from before (green) to partial to full impregnation.



Resin state	Before	Partial	Full	% Change
DF @ 1kV (.01 to .02)	0.08016	0.02633	0.01432	-83%
DF Tip-up (< 1%)	7.85%		3.42%	
Cap @ 1kV	0.7998nF	0.2116nF	1.051nF	31%
Cap Tip-Up (<1%)	0.638%	2%	0.095%	-85%
PDIV (> 1.15kV)	2.19kV	2.07kV	1.63kV	-26%
PD max	0.0789nC	0.279nC	0.249nC	216%

Discussion:

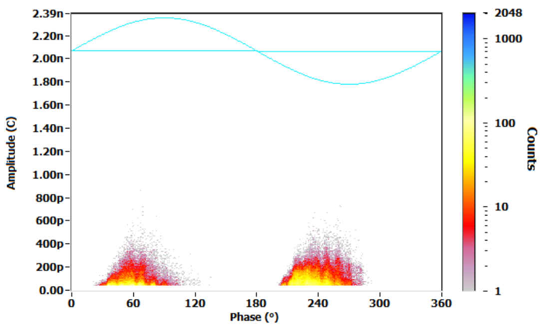
Dissipation Factor (DF): decreases to between 0.01 and 0.02 as the quantity of resin is increased. The slightly elevated tip-up may be an issue.

Capacitance Tip-Up: since this is primarily testing for curing, then it makes sense that the partial (wet) state would have the highest activity along with the elevated DF values. Note that after full impregnation and curing, the values were significantly less than 1%. The increase in capacitance at 0.2E is unusual (see PD Max below).

PDIV: in all cases the PDIV was higher than standard recommendation of 0.5E

PD max: this was puzzling in that the magnitude of the measurable PD increased with impregnation. It is hypothesized that before resin impregnation the voids were too large to have detectable PD.

Void shape and pattern are typical for small internal voids with the clusters within the first and third quadrants of the AC cycle as shown.



CASE STUDY 2: NEW WINDING

A reconditioned 4kV motor was tested.

PF @ 1kV (.01 to .02)	0.0073
PF Tip-up (< 0.5%)	1.54%
Cap @ 1kV	0.73nF
Cap Tip-Up (<1%)	0.55%
PDIV (> 1.15kV)	1.6kV
PD max (2.3kV)	290mV

Discussion:

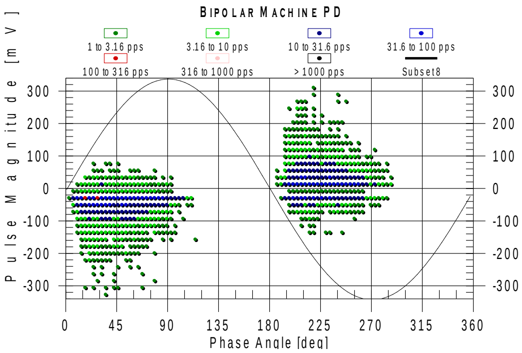
Power Factor (PF): was within range

Power Factor Tip-up: was outside of standard recommendation of 0.5% which suggests moderate internal voids

Capacitance tip-up was within range

PDIV: the PDIV was higher than standard recommendation of 0.5E

PD max: there is no standard; however, the patterns were typical of internal voids and elevated when compared to the PD instrument manufacturers database.



CASE STUDY 3: RECONDITIONED WINDING

A 4kV winding was tested before and after reconditioning.

Resin state (C phase)	Before	After	% Change
DF @ 1kV (<.01 to .02)	.03744	.02152	-43%
DF Tip-up (< 1%)	0.105%	-0.321%	
Cap @ 1kV	64.77nF	58.7nF	-9%
Cap Tip-Up (<1%)	.0618%	.0341%	-45%
PDIV (> 1.15kV)	2.4kV	2.19kV	-9%
PD max (2.42kV)	0.326nC	0.169nC	-48%

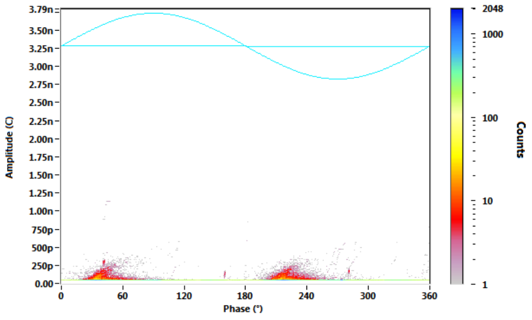
Discussion:

Dissipation Factor (DF): decreases after reconditioning to levels between 0.01 and 0.02; while the tip-up decreases as well.

Capacitance: high capacitance is an indication of contamination, so the decrease may be normal and not an indication of delamination. The tip-up values were acceptable and improved following the refurbishment.

PDIV: in all cases the PDIV was higher than standard recommendation of 0.5E

PD max: the decrease in PD activity is likely due to the cleaning and re-varnishing that reduced any surface PD activity. The PD patterns are classic and typical.



CASE STUDY 4: REWOUND WINDING

A 4kV winding tested "as-Is" state before a rewind and after.

Condition (C phase)	Before	After Rewind	% Change
DF @ 1kV (<.01 to .02)	.0596	.02327	-61%
DF Tip-up (< 1%)	8.81%	1.20%	
Cap @ 1kV	89.63nF	33.08nF	-63%
Cap Tip-Up (<1%)	0.212%	0.151%	-29%
PDIV (> 1.15kV)	2.2kV	2.17kV	-1%
PD max (2.42kV)	0.537nC	0.0791nC	-85%

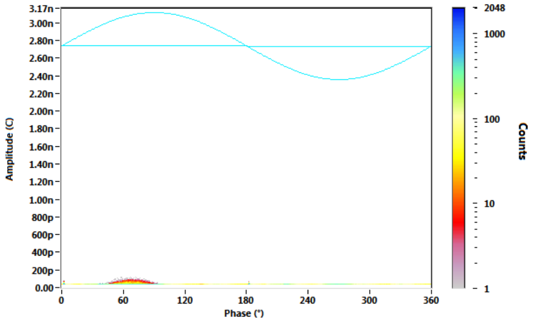
Discussion:

Dissipation Factor (DF): decreases after reconditioning to levels almost between 0.01 and 0.02; while the tip-up decreases as well though is still slightly higher than the standard recommendation of less than 1%..

Capacitance Behaved as expected with the lower capacitance in the rewound motor

PDIV: in all cases the PDIV was higher than standard recommendation of 0.5E

PD max: the decrease in PD activity is expected in a new winding with minimal PD activity.



CASE STUDY 5: RECONDITIONED WINDING

A 12.5kV winding was tested before and after reconditioning.

Refurbishment	Before	After	% Change
DF @ 1.5kV (<.01-.02)	.01945	.01254	-36%
DF Tip-up (< 1%)	140%	254%	
Cap @ 1.5kV	82.93nF	81.27nF	-2%
Cap Tip-Up (<1%)	3.29%	3.65%	17%
PDIV (> 3.65kV)	3.09lV	3.65kV	18%
PDEV (> 3.65kV)	2.56kV	3.07kV	20%
PD max (7.3kV)	7.38nC	2.43nC	-67%

Discussion:

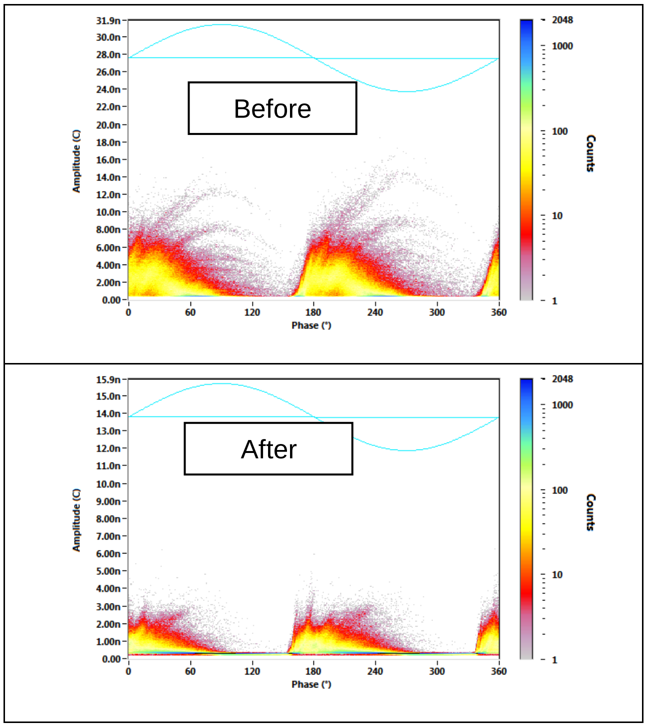
Dissipation Factor (DF): decreases after reconditioning to levels between 0.01 to 0.02.

DF Tip-up: both before and after the DF tip-up were well above the standard recommendation which suggests noticeable internal voids supported by the low PDEV.

Capacitance Behaved as expected with minimal change in the values, but still elevated tip-up values suggesting internal voids.

PDIV/PDEV: after reconditioning the PDIV was higher than standard recommendation of 0.5E; however, the PDEV though better was still lower that acceptable by standard

PD max: the decrease in PD activity is likely due to the cleaning and re-varnishing that reduced any surface PD activity. The PD patterns are classic and considered moderate from the PD instrument manufacturer.



SUMMARY

Though it is premature to establish acceptance criteria for the capacitance results at 0.2E or the PD Max values at 1E, it is obvious based on these case studies that these five (5) tests in combination provide valuable information about the quality of a GVPI insulation system before and after refurbishment or rewind. Each test evaluates a different aspect of the insulation, so it requires all five for a full evaluation:

1. DF or PF at 0.2E – curing state
2. DF or PF tip-up – widespread internal voids
3. Capacitance at 0.2E – curing state
4. Capacitance tip-up – widespread internal voids
5. PD (PDIV/PDEV) – isolated problems

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