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Experience with DC Polarization-Depolarization Measurements on Stator Winding Insulation

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***Abstract*— DC insulation resistance (IR) and polarization index (PI) testing is very widely used to assess the condition of the rotor and stator windings in motors and generators. The IR/PI tests are good at identifying contaminated windings; however, such issues as thermal deterioration or abrasion of the insulation due to coil vibration, are not detected by the IR/PI test in modern insulation. The polarization/depolarization current (PDC) test, where the charging current is measured for several minutes and then the test object is grounded and the discharging current is measured for several minutes, may provide more diagnostic information. This paper presents PDC data from a stator as well as individual stator coils and bars and compares it to results from other off-line tests including the low- and high-frequency PD, dissipation factor tip-up, and DC ramp tests. It seems that partial discharge tests are more sensitive to some insulation problems than PDC, however, more results are needed.**

Keywords—depolarization currents, polarization currents, stator winding insulation.

I. INTRODUCTION

The stator groundwall insulation in windings rated 3.3 kV and above can deteriorate and fail due to more than a dozen failure processes [1]. One of the most common deterioration processes is contamination of the winding by moisture or partly-conductive pollution. These issues are easily detected by the DC insulation resistance and polarization index tests performed with a megohmmeter, as described in IEEE 43 [2]. However, as discussed in [1, 2], the IR/PI test does not seem to be sensitive to many other stator winding insulation problems such as:

- Loose coils in the slot that lead to insulation abrasion,
- Delamination of the insulation due to operation at high temperature,
- Separation of the copper from the groundwall insulation due to load cycling,
- Deterioration of the stress relief coatings,
- Partial discharge (PD) between coils in different phases due to insufficient spacing in the endwindings.

Thus tests other than IR/PI are needed to detect these issues. The tests that tend to detect these additional problems are the off-line PD test and the off-line dissipation factor tip-up test [1, 3, 4]. These two tests are done with resonant or conventional 50/60 Hz AC high voltage. To test complete stator windings, the high voltage test supply must be rated in the 5 to 20 kVA range to energize the winding capacitance to rated line-to-ground or line-to-line voltage. This is a substantial, costly supply that is often difficult to obtain for on-site testing. As a result, these off-line AC tests are performed less frequently than perhaps they should be – and thus some stator winding insulation problems are not detected.

To overcome the requirement for a heavy AC supply, there are two possible alternatives:

- Use a very low frequency (VLF) test set to energize the winding with 0.1 Hz AC high voltage [5]
- Employ more sophisticated DC tests that some have proposed can detect more kinds of problems than the simple IR/PI test.

The VLF test has not been popular for rotating machine applications [9]. However, a more sophisticated DC test using the polarization/depolarization current method has recently been investigated by several researchers [6-8]. This paper describes PDC test results on some coils as well as a motor stator winding, and compares them to results from partial discharge, dissipation factor and DC ramp tests performed at the same time, to determine the effectiveness of the PDC method to detect problems other than moisture and contamination issues.

II. TEST OBJECTS

One motor stator rated 13.2 kV, 6000 HP was tested. The stator had an asphaltic mica insulation system and was several decades old. The insulation is known to be thermally aged, leading to groundwall insulation delamination. However the winding was clean and dry. The three phases in the stator could be isolated from each other to facilitate testing of each phase.

In addition, two similar (but not identical) 13.8 kV multiturn coils were tested. One coil had severe deterioration of the slot conductive (graphite) coating due to a voltage endurance test. The other was new. Both had epoxy-mica groundwall insulation systems. Also a new 13.8 kV stator bar with epoxy mica insulation was tested. All the bars/coils have silicon carbide stress relief coatings.

III. EXPERIMENTAL METHOD

The PDC test can be performed using a stable high voltage DC supply and an electrometer. Alternatively, a purpose built instrument can be employed. For these tests a PDTech DRA 3 was used. It applies a positive DC voltage to the test object at a selected voltage (usually 5 or 10 kV for these experiments) and for a selected time (usually 1000 s – about 16.7 minutes), while measuring the charging current. The DC supply is then removed from the test object and the test object is grounded. The discharge current-to-ground is then measured for the same amount of time. Software records these currents, inverts the discharge current and displays both the charge and discharge currents in the same plot against time, with the plot time origin starting from either the start of the charge cycle, or the start of the discharge cycle (Fig. 1). The difference in the charge and the (absolute value of) the discharge current can also be displayed. The instrument also calculates the IR and PI. All tests were done at 20°C.

The partial discharges were measured two ways. One method was using a conventional IEC 60270 PD detector working in the low frequency (<3 MHz), broadband range. A PDTech DeltaMaxx was used for this test. This instrument automatically converts the measured pulse magnitude in mV into pC, per the procedure in IEC 60270. The PD was also measured in the VHF range (30-300 MHz) range, more typically used for on-line PD monitoring. An Iris Power TGA-B was used for this. This device does not perform an automatic normalization, instead reports the PD magnitudes in mV. The PD tests were performed at rated line-to-ground voltage, and the data was recorded after stabilization at the test voltage for 10 minutes.

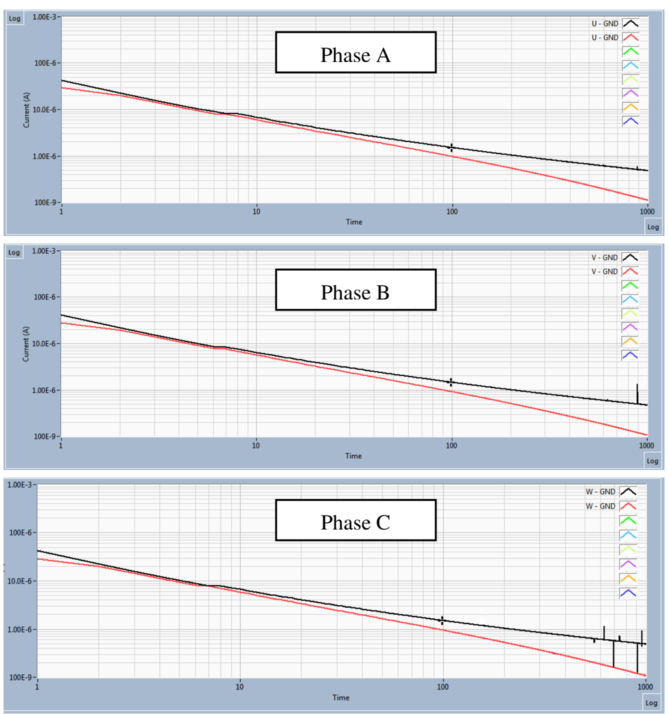


Fig. 1 PDC plot for each phase with a 10 kV charge cycle. The charge current is the upper line and the discharge current is the bottom line. The logarithmic vertical scale goes from 0.1 µA to 1000 µA and the horizontal axis ranges from 1 to 1000s.

The tip up tests were performed according to IEEE 286, with the tip-up calculated from the difference between 8 kV and 2 kV (i.e. 100% and 25% of the rated line-to-ground voltage). The DeltaMaxx instrument was also used to measure the tip-up. Of course, in the tip-up tests on the complete stator, the stress relief coatings were not guarded out.

The final test performed was a DC ramp test, as described in IEEE 95 [10]. An Iris Power DCR was used which ramped the DC voltage gradually from 0 to 25 kV, at the rate of 1 kV per minute, while monitoring the current.

IV. RESULTS

A. Motor

Table I shows a summary of the test results for each phase of the winding. PDC plots for each phase are shown in Fig. 1. When all three phases are super-imposed, all the charge currents and all the discharge currents overlap completely. The difference current (not plotted here for clarity) for all three phases is the same.

It is clear from Table I that A phase has the highest PD in both frequency ranges, although it is curious to see that the phase with the lowest PD is different between the LF and VHF PD tests. The low frequency (LF) and VHF phase-resolved PD plots for the worst phase (A phase) are shown in Fig. 2 and 3, respectively. Since the positive and negative PD is about the same (within +/- 25%), then based on normal PD interpretation rules (see IEEE 1434 or IEC 60034-27), one suspects the PD is due to groundwall delamination. In both cases, the PD pattern is also typical of delamination PD. Using published on-line PD interpretation rules for the magnitude of the PD using the VHF method [11], the A phase levels would be classified as very high (i.e. higher than 95% of similar stators).

The DC ramp result for A phase is shown in Fig. 4. The plots were the same for all three phases, to within a few percent. Note that no “snaking” or wiggles in the I-V curve are seen, although this has been reported by others on delaminated asphaltic mica windings [12].

The low voltage dissipation factor in Table I is high compared to modern insulation systems, but they are typical for asphaltic mica at 20°C. The stress relief coating cannot be guarded out in a complete winding, so the high tip-up levels probably reflect the contribution of the silicon carbide coatings, and masks the delamination discharge.

TABLE I. SUMMARY OF DIAGNOSTIC RESULTS FOR THE MOTOR STATOR WINDING

Test Configuration	IR	PI	VHF PD (mV)		LF PD (nC)	DF (@2 kV)	Tip-Up
	(GΩ)		Qm+	Qm-	Qm	(%)	(%)
A	5.1	3.4	1066	888	9.7	4.7	0.79
B	5.2	3.4	275	330	3.7	4.6	0.73
C	5.0	3.4	433	440	2.9	4.8	0.80

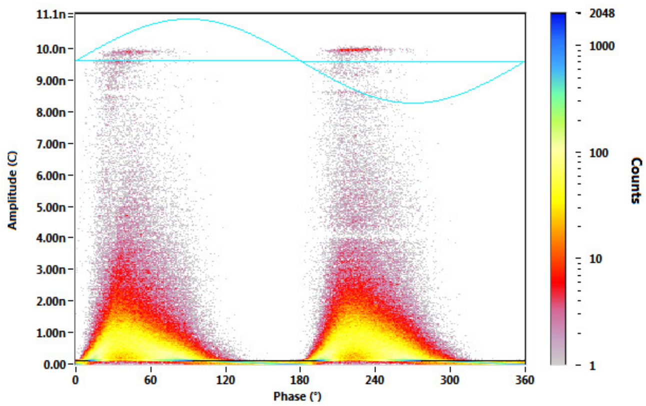


Fig. 2 LF PD plot for phase A, which had the highest PD at 8 kV. Note that the polarity of the PD plotted between 0 and 180 degrees has been inverted. The linear scale ranges from 0 to 11 nC.

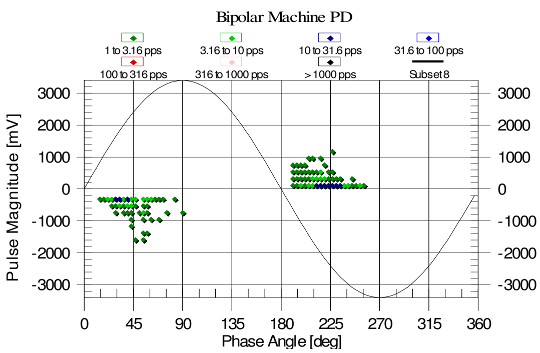


Fig. 3 VHF PD response from stator phase A, which had the highest PD at 8 kV.

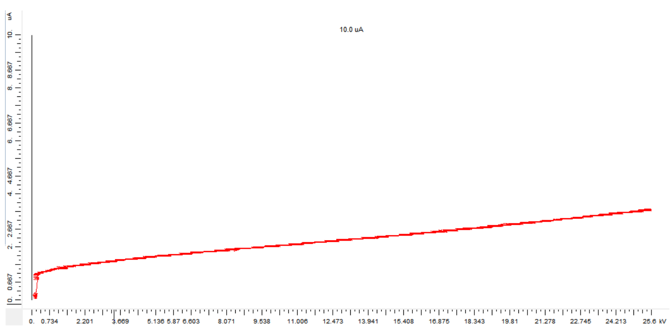


Fig. 4 DC ramp test for Phase A to 25 kV. The other two phases were the same. The linear horizontal scale ranges from 0 to 10 μA and the horizontal scale from 0 to 25 kV.

B. *Coils and Bars*

Table II is a summary of the results from the test on individual coils and bars. The aged coil has severe deterioration of the stress relief coatings. The one minute IR is exceptionally high for all coils/bars, which as suggested in IEEE 43:2000, makes the PI values suspect. Clearly the bars and coils are dry and not contaminated.

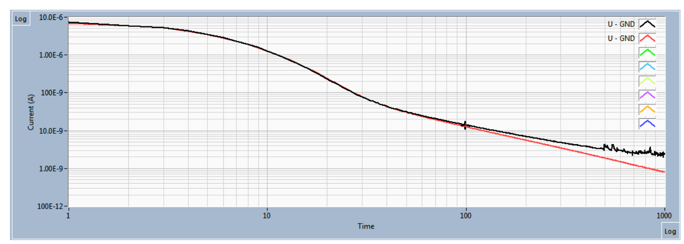
Figure 5 shows the PDC plots for the bars/coils. Since all these objects are of different sizes, it is not surprising that the PDC plots are different. However, it is clear that a larger difference occurs between the charge and discharge currents occurs in the aged coil compared to the new coil which is close in size, especially after about 1000 s.

Figures 6 and 7 show the PD patterns for the aged coil at 8 kV, using the LF and VHF PD detectors, respectively. As seen in Table II, the aged coil had more PD than the new coil. It is curious to see that the VHF PD patterns have a "negative predominance" which is suggestive of PD occurring in voids adjacent to the copper conductor. However, the primary source of the PD is the deteriorated stress relief coating (Fig. 8), which should yield a PD pattern with higher positive than negative PD. As discussed elsewhere, the expected PD patterns sometimes do not occur [13].

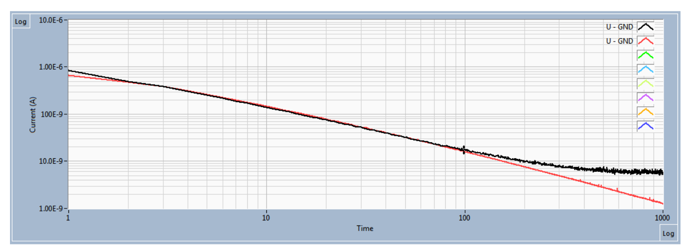
The DC ramp test was done on all the coils and bars. However, the leakage current was so small that there was not sufficient resolution to see any discernible difference between the I-V plots.

TABLE II. SUMMARY OF DIAGNOSTIC RESULTS FROM TESTS ON INDIVIDUAL COILS AND BARS

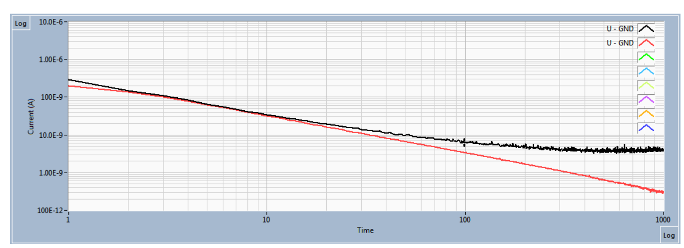
Test Configuration	IR	PI	VHF PD (mV)		LF PD (pC)	DF (@2 kV)	Tip-Up
	(GΩ)		Qm+	Qm-	Qm+	(%)	(%)
New Coil	405	8.4	17	18	120	0.68	0.05
New Bar	1170	2.18	12	15	590	0.71	0.03
Aged Coil	375	4.38	45	63	250	0.68	0.08



New Coil (vertical scale: 0.1 nA to 10 μA)



Aged Coil (vertical scale: 1 nA to 10 μA)



New Bar (vertical scale: 1 nA to 10 μA)

Fig. 5 PDC plots at 10 kV for 3 individual coils or bars. The logarithmic horizontal scale ranges from 1 to 1000 s.

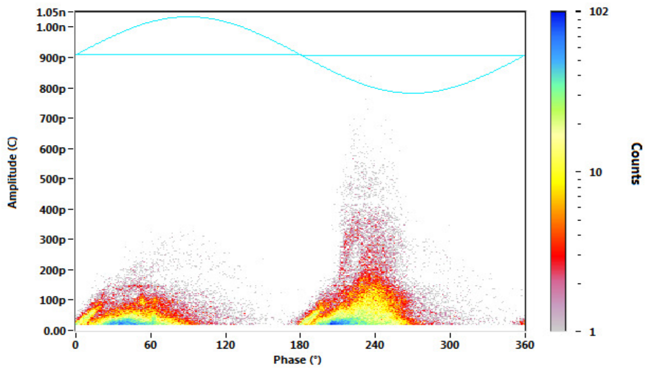


Fig. 6 LF PD Test on aged coil at 8 kV. The linear vertical scale ranges from 0 to 1000 pC.

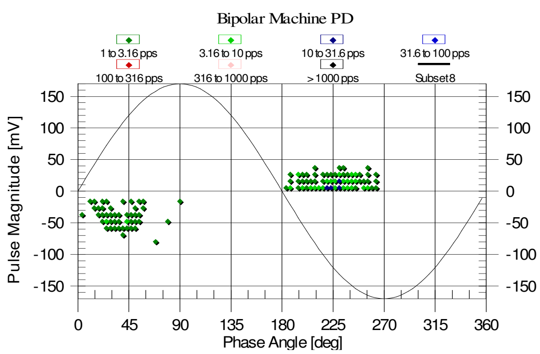


Fig. 7 VHF PD test on aged coil at 8 kV.

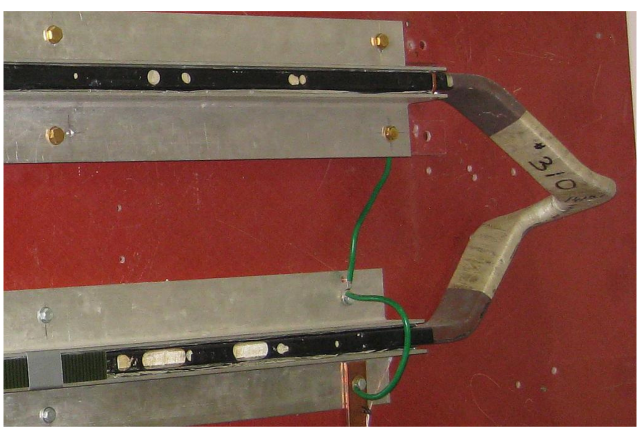


Fig. 8 Photo of aged coil with deteriorated stress relief coatings after a voltage endurance test.

V. DISCUSSION

The motor winding suffered from significant thermal aging. Phase A had about 3 times higher PD activity than the other two phases, and a pattern that is associated with thermal deterioration. Unfortunately, the PDC patterns (and DC ramp test I-V plots) do not show any difference between the phases. So at least for this test object, it seems that the PDC tests were not able to identify the phase with the greater aging (as determined by the PD tests). It is also interesting to note that the dissipation factor tip-up test results were the same for all phases. This is perhaps an expected result, since the tip-up is often dominated by the non-linear characteristics of the stress relief coatings, rather than by aging.

The aged coil sample had higher PD activity than the new coil. There also seems to be a greater difference between the charge and discharge currents for the aged coil compared to the similar (but slightly different shape) new coil. Also, the shape of the I vs. time plots differ between the new and aged coils, which some suggest may be an indicator of aging [7, 8].

VI. CONCLUSION

Owners of motors and generators would like an off-line test that can be used to confirm the diagnosis of insulation condition obtained from on-line PD testing, without having to use a large AC transformer to energize the winding in an off-line PD or tip-up test. PDC has been proposed as a tool that can detect issues besides contamination and moisture absorption. The comparison tests described here did not produce consistent results: it seems PDC was able to detect stress relief coating problems, but not thermal aging. Clearly more tests are required to determine its efficacy.

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