Evaluation of Offline Partial Discharge in Vacuum Environments

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***Abstract*— An evaluation of several insulation types at various degrees of vacuum using repetitive discharge inception and extinction voltage offline testing will be presented. Insulation systems were evaluated in atmosphere and compared to values to 1mmHg using a commercial partial discharge surge tester. The insulation systems evaluated include unvarnished windings, dip and bake epoxy, epoxy trickle impregnation and vacuum encapsulated. The results provide the potential impact of partial discharge with repetitive surges for applications of electric machines in low atmosphere conditions with inverters.**

Keywords—vacuum insulation, encapsulation, epoxy, polyester, vacuum application, VFD, offline pd, partial discharge

I. Introduction

Vacuum encapsulated windings have been successfully applied in flywheel energy storage technologies which use vacuum to reduce friction and windage since 2012. A change to controls in 2018 resulted in multiple turn to turn winding faults in flywheels with less than 100 hours of operation. A root cause failure analysis was performed requiring research on the impact of the type of output from the variable frequency drive controls and the insulation systems which operate at 3 mmHg to 5 mmHg. Considerations during the analysis included partial discharge and turn insulation stress. A literature review was performed as part of research to determine the causes of failure and determine if improvements could be made to the design.

Limited literature is available on the impact of complete stators when applied in vacuum with variable frequency drives and the related fast rise time impulses. The authors performed initial research on partial discharge and inter-turn conditions using a commercial Partial Discharge (PD) surge comparison tester compatible with IEC/TS 61934[1] and a modified Vacuum Pressure Impregnation (VPI) tank. The experimental setup was as shown in Fig. 1 and Fig. 2. The stators windings were connected for their original 200 Volt design. The results are being applied to flywheel design improvements and can be applied to other low atmosphere applications.

Fig. 1. PD surge tester, VPI tank and two stators being tested in air

Fig. 2. Placement of stator in VPI tank with leads and connections

Four stators were selected with different materials including:

1. Stator 1: Original Manufacturer Material – spray-on varnish exposed conductors

2. Stator 2: Dip and Bake – epoxy-based dip and bake material
3. Stator 3: Trickle Impregnation – polyester-based material
4. Stator 4: Vacuum Encapsulation – 155C material applied in a vacuum to eliminate voids

The wire, slot materials and other winding construction were similar other than smaller conductors were used in Stators 2, 3 and 4. The conductors entering the VPI tank were shielded and connections were covered only with electrical tape. VPI soak times were an average of an hour to 5mmHg then approximately 20-30 minutes for each vacuum level to 1mmHg, then the stators were tested at each point. The stators were tested before and after in order to evaluate impact in vacuum and to determine if any significant damage occurred during testing.

II. Observations

With the setup one of the concerns was arcing between the connections to the stator as there would be virtually no resistance at the vacuum levels being tested. The stators were observed through a portal while video and images were taken as part of the record. It was also noted that no levels of RPDIV or RPDEV were found during testing in air. However, Stator 2 did have PD discharge voltage present.

During all the vacuum stages of testing, Stators 1, 2 and 3 showed as failed surge comparison tests at 2000 Volts with initial faults showing at the point of RPDEV and RPDIV values. Stator 4 had smaller imperfections in the surge waveform at all vacuum levels, but did show distortion. A review of the offline partial discharge waveforms, as shown in Fig. 3 and Fig. 4, help us define the causes of the faults within the surge waveforms. The distortions also correspond to video visible arcing, which showed as purple light, as remaining air was ionized.

The selected PD surge comparison tester was set up to continue to full test voltage, selected at 2000 Volts, in order to provide a full spectrum of conditions. During vacuum testing it was observed that in many cases, the RPDEV was higher than the RPDIV, which was unexpected. The values corresponded to visible arcing, which may have caused the anomaly. The partial discharge waveforms represented similar results as Fig. 3, which represents arcing, and Stator 4 had waveforms that were represented as in Fig. 4, which represents partial discharge in the windings when the stator was first applied to vacuum. This partial discharge discontinued after the stator was in vacuum for more than 90 minutes.

As noted in Fig. 5, the RPDIV values are highest, on average, with Stator 4, and one outlier with Stator 2. Stator 3, which was trickle impregnated, had the lowest RPDIV and RPDEV values. Fig. 6 identifies the RPDEV values, which were highest, on average, with Stator 4 with a close high average with Stator 2.

The discharge values are shown as mV in Fig. 7, which appear higher with Stator 4 at 5mmHg and 4mmHg, then drop to lower than average values during remaining testing. This is most likely due to air in any voids evacuating over time. The more intense discharges were found with Stator 1 and Stator 3 with Stator 2 having the lowest average discharge value.

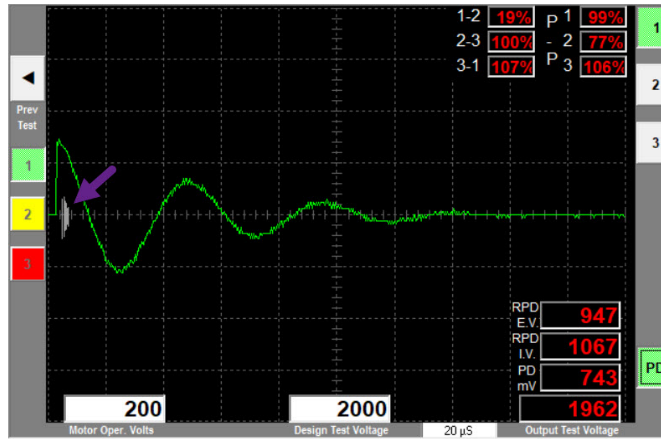

Fig. 3. Example of PD surge display related to arcing

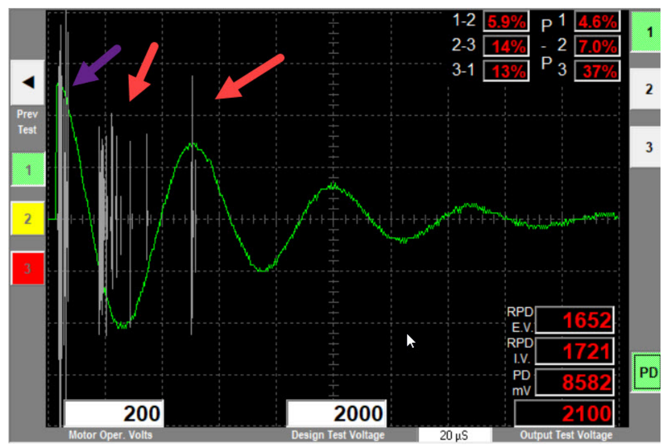

Fig. 4. Example of PD surge display related to partial discharge

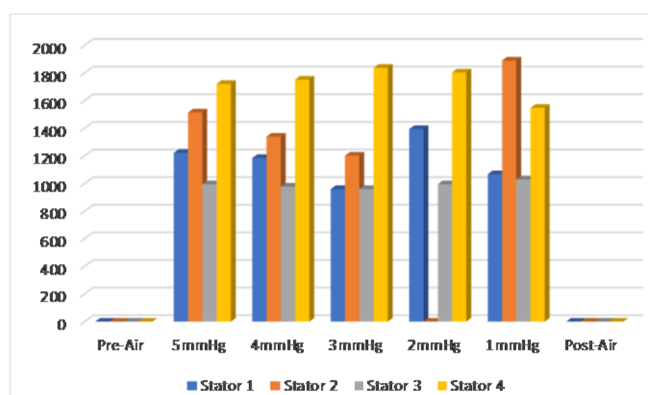

Fig. 5. RPDIV of stators in air and vacuum

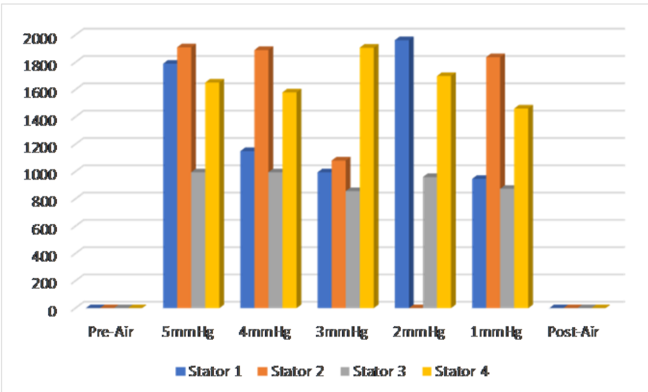

Fig. 6. RPDEV of stators in air and vacuum

Examples of the arcing are found in Fig. 8 and Fig. 9. Fig. 8 relates to arcing that occurs within the stator and back to the leads or to ground, as well as discharges between conductors. Fig. 9 is arcing directly between conductors at the connections to the stator.

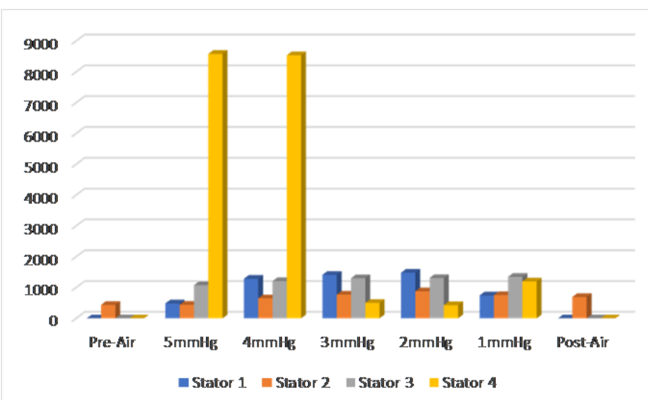

Fig. 7. mV discharge arc and PD of stators in air and vacuum

Stator 4 was the only stator that was identified with winding PD which corresponded to the excessive energy at 5mmHg and 4mmHg. This may represent that the PD that did occur within the windings was energetic due to trapped air around the stator leads. The arcing between connections had lower values with Fig. 9 representing the arcing that occurred between conductors on Stator 4 at 1mmHg.

III. Additional Tests and Observations

The PD surge tester provided the ability to test insulation to ground, high potential testing, surge testing, inductance, impedance, capacitive phase angle, and Q-factor. The low voltage tests of inductance, impedance, capacitive phase angle and Q-factor values did not change significantly in air or vacuum. The insulation resistance and high potential testing did change significantly between testing in air and vacuum at 1mmHg.

TABLE I. Insulation Resistance in Air and Vacuum

	IR Volts Air	IR in Air (MegOhms)	IR Volts 1mmHg	IR at 1mmHg (MegOhms)
Stator 1	1000	inf	130	2
Stator 2	1000	inf	190	1
Stator 3	1000	inf	345	3
Stator 4	1000	248	345	6

TABLE II. High Potential Test in Air and Vacuum

	HiPot Volts Air	HiPot in Air (uA)	HiPot Volts 1mmHg	HiPot at 1mmHg (uA)
Stator 1	2000	0	165	8.43
Stator 2	2000	0	225	11.37
Stator 3	2000	0	225	11.57
Stator 4	2000	2.34	455	17.89

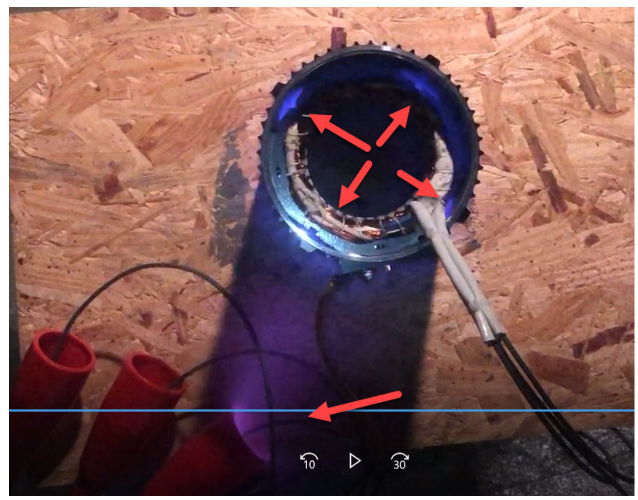

Fig. 8. Arcing in stator and to leads (purple) due to ionization of remaining gas

As noted in Table 1 the insulation resistance was performed at 1000 Volts DC with a maximum of 500 TerraOhms presented on Stators 1, 2 and 3 in air and 248 MegOhms with Stator 4 in air. At 1mmHg, the values drop significantly with the highest insulation to ground being Stator 4.

Table 2 shows the leakage during a 2000 Volt DC high potential test was 0 for Stators 1, 2 and 3, and 2.34 uA for Stator 4. At 1mmHg the highest applied voltage was Stator 4 while Stators 1, 2 and 3 had relatively low leakages and low voltages.

Once all of the stators approach 1mmHg the surge test results also fail. This is most likely due to both the exposed conductors, but also due to the lack of air between conductors and within the insulation systems. With Stator 4, the surge test results degraded as air appears to have bled from the insulation system under vacuum.

Fig. 9. Arcing at lead connections (purple) due to ionization of remaining gas

Fig. 10. Vacuum encapsulated stator with voids due to adding material after vacuum encapsulation. Voids progress through stator end with exits by leads.

IV. Discussion

Stators 1, 2 and 3 windings were directly exposed to vacuum while Stator 4 was sealed with the exception of where the leads enter into the encapsulant. Experience shows in larger stators that vacuum encapsulation can result in small voids on the connection end, which is at the top during the process, as shown in Fig. 10. This would result in air trapped in small voids that can result in high energy discharges between conductors until any remaining air is evacuated, if possible, usually past the leads. In areas where air cannot be bled off in the vacuum environment the electrical stresses will remain high.

Stator 4 appears to bleed off remaining air over time in vacuum with improvements to all test results. The insulation resistance decreases as the PD values decrease due to the vacuum environment. This indicates that air is both part of the insulation system and is required for partial discharge.

Open conductors and conductors with thin layers of insulation materials such as the wire enamel and epoxy or polyester varnishes allow for ionization between those points and either exposed connections, to ground, or both. With the single dip and bake with epoxy and vacuum encapsulation there is a greater global penetration of varnish through the stator including between conductive surfaces. Stator 1 has very limited varnish which results in higher losses in vacuum. The trickle impregnation only coats the conductors and does not penetrate the slot liner sufficiently.

V. Conclusion

A great deal more research is required in order to evaluate the conditions identified in this paper. Improvements to the study include evaluation of the conductors used that penetrate the VPI tank wall and sealing the connections. A greater range of vacuum points should also be selected to fully understand the processes and points where the stresses occur.

High voltage testing including insulation resistance, high potential testing, and surge comparison testing do not provide sufficient ability to test the condition of machines at vacuum levels approaching 5mmHg and less. Low voltage tests appear not to be effected so additional research related to the impact of insulation degradation is warranted. Offline partial discharge testing appears to be an effective quality assurance practice for these machines under vacuum.

Vacuum encapsulated windings appear to be effective for both partial discharge and to reduce the leakage currents and ionization. There is also a significant reduction in arcing between conductors and ground, although some surface ionization does appear visually, primarily from the stator core and frame. With thinner insulation systems, the arcing between conductors and ground, in addition to the frame, are visually more pronounced.

There were a number of conditions that were identified during the study. Future work would be required in order to further verify some of the findings from this study and to expand general insulation system understanding for vacuum applications. Some of these applications include flywheel technology and space exploration as proper application of insulation systems for vacuum would allow improved machine efficiency.

References

[1] IEC/TS 61934 Electrical Insulating Materials and Systems – Electrical Measurement of Partial Discharges (PD) Under Short Rise Time and Repetitive Voltage Impulses. Edition 2.0, 2011-04

[2] Penrose, H. W., and Wittmuss, Donald, "Evaluation of Vacuum Encapsulation Systems for Integral Motors," Proceedings of the 2011 Electrical Insulation Conference, pp. 180-183