COMPARATIVE STUDY OF IEC 60270 COMPLIANT INSTRUMENTS FOR PARTIAL DISCHARGE PATTERN ACQUISITION

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Abstract – The petrochemical industry considers offline partial discharge (PD) measurement an important quality assessment for new medium voltage motor and generator stator windings. A recent edition of API 541 requires an instrument compliant with IEC 60270 for the measurement of PD on sacrificial stator coils, and proposes 100 pC (pico-Coulombs) for guidance on acceptance criteria until more data becomes available. Given the industry's faith in PD as an acceptance test based on a representative sample, it warrants closer scrutiny.

The characteristic PD distribution pattern produced by each test instrument provides information on the origin of the discharges and therefore can be used to determine what type of defect has produced them. This paper shows how external factors such as instrument selection, testing environment, and time interval between tests can influence PD test results.

Three different IEC-compliant instruments were used to measure PD from sample coils of the same design, under identical conditions. Each sample coil was modified to create the same imposed defect, with the same technique used to interpret the PD magnitude and distribution pattern produced in each case. Each instrument recorded a different charge magnitude and characteristic PD pattern. The variation in charge magnitude measured by each instrument exceeds the proposed API 541 acceptance limit, and the observed PD patterns did not accurately reflect the imposed coil defect. Offline PD measurement therefore lacks sufficient repeatability, reproducibility and accuracy to support a standard acceptance limit.

Index Terms — rotating machine, partial discharge, winding, insulation, stator coil.

I. INTRODUCTION

API 541 [1] recommends offline PD testing of sacrificial stator coils as a means to determine the quality of a complete stator winding. PD amplitude is also widely used as a pass/fail criterion for stator bars used in hydro generator rewinds [2]. API requires test instruments to be compliant with the recommendations of IEC 60270 [3]. A previous paper compared PD tests performed on resin-rich, press-cured sacrificial coils, both in laboratory conditions controlled to minimize noise and the typical factory acceptance test (FAT) environment [4]. This paper examines how test environment, pre-test voltage conditioning, and imposed stator coil defects affect the charge magnitude and phase resolved partial discharge (PRPD) plots obtained using different IEC-compliant instruments.

As the PD test on sacrificial coils is considered a proxy for stator winding quality, it should be relatively straightforward to use, and the results obtained should be repeatable, reproducible and provide accurate information about the origin of discharges. Without this assurance, there is a significant risk of rejecting the complete stator winding or set of coils/bars or requiring significant effort to reduce the observed PD levels.

Accurate interpretation of PD results obtained using IEC instruments requires an expert technician to check amplifier linearity, saturation, and pulse-train response during the test. This level of expertise is not available in all facilities. This study simplified the interpretation by comparing the scalar value of the largest repeatedly occurring PD magnitude, Q_{IEC}, and by examining the characteristic PD patterns produced by each instrument [2]. According to IEC 60034-27-2, the PD patterns are not always indicative of the mechanism; therefore, visual inspection of the winding may then be warranted [5].

A stator coil or bar is small enough to be considered as a lumped capacitance within the acquisition frequency range of IEC 60270 compliant instruments. Following the technique of charge injection indicated by IEC should theoretically calibrate the instrument to allow the PD it detects in the sample to be compared to a known pulse magnitude. Controlling the experimental conditions and purposely imposing coil defects should ideally produce similar results for each instrument, addressing the question of repeatability and reproducibility. The study indicates that the PD test has generally unacceptably high variation, undermining its intended purpose.

II. EXPERIMENTAL DATA

The basis of the study is the use of three different commercially available IEC-compliant instruments to measure PD on two new, undamaged and un-aged sample coils. Each fully-processed, 13.8kV sample coil was prepared with grounded aluminum plates bolted to the straight (slot) sections to simulate the core-to-coil contact in a real stator. Each test was performed by the same technician in two different settings: (1) a manufacturing environment similar to that used for factory acceptance testing (FAT) and (2) in a Faraday cage designed to exclude interference from electromagnetic noise. The background noise contribution in each environment was confirmed to be below 5 pC. All tests were performed at V_{LG}, the voltage that is applied across the insulation while in operation. Ambient temperature and humidity were recorded for each test, and each coil received 20 minutes of exposure to the test voltage as conditioning before the PD measurements were acquired. Table I gives the broad-bandwidth ranges for each consecutively used instrument and the IEC-specified values.

TABLE I
PD INSTRUMENTS

Instrument	Type	Bandwidth (Δf)
A	Wide	40 – 250 kHz
B	Wide	100 - 400 kHz
C	Wide	100 – 400 kHz
IEC 60270	Narrow Wide	9 – 30 kHz 100 – 400 kHz

1) In-Factory Measurements with Three Instruments

Figure 1 shows the phase-resolved partial discharge (PRPD) of the PD measurement taken in the factory setting on resin rich Coils 1 & 2 [4]. Instrument A detected no PD in both coils.

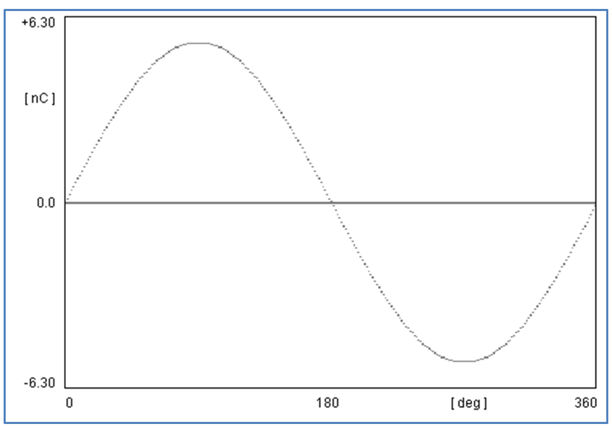


Fig 1a. PD measured on either coil, with Instrument A, in factory

When measured with Instrument B, Coil 1 showed a classical PD pattern at 45° in the AC wave, which is characteristic of discharges both internal to the insulation and external or on the coil's surface. The phase shift to the zero crossing of the signal for Coil 2 suggests that these discharges could possibly be associated with the slot exit locations.

When measured with Instrument C, the PRPD for Coil 1 showed a cloudy distribution above the main concentration of activity, indicating severe surface discharge. The PRPD for Coil 2 showed a smaller cloudy distribution with vertical streaks that suggest external noise interference.

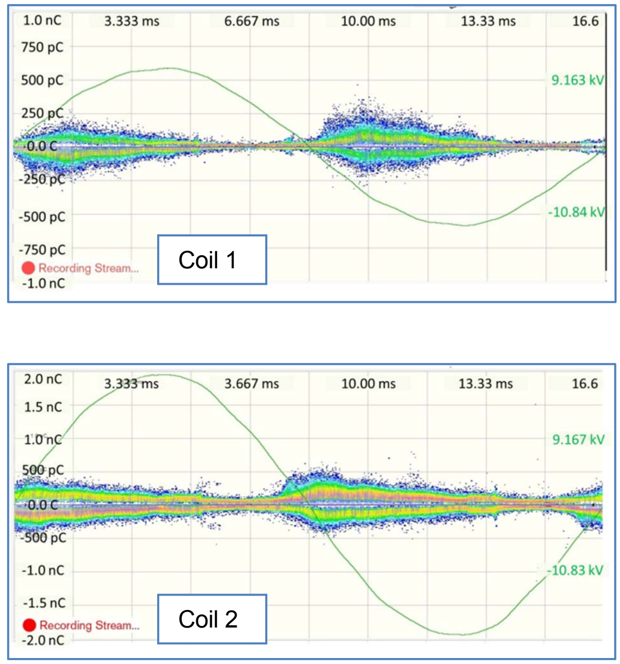


Fig 1b. PD measured with Instrument B, in factory

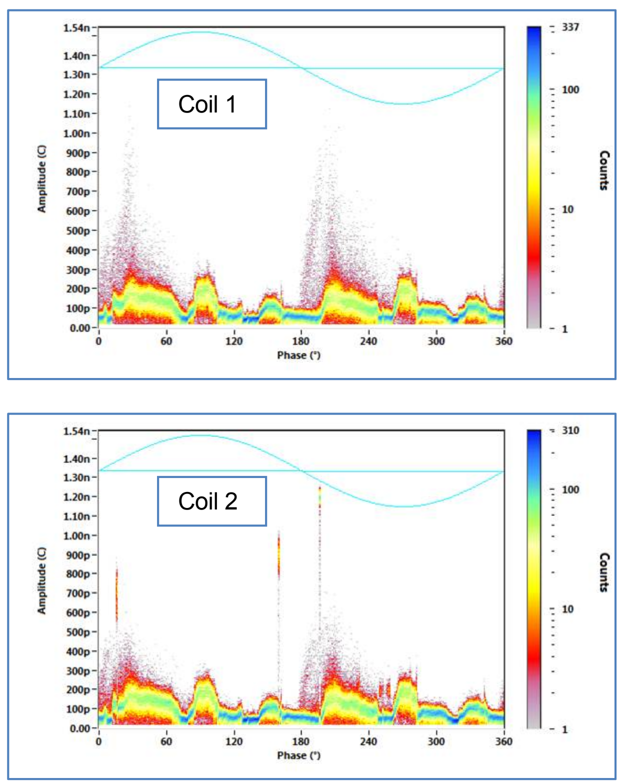


Fig 1c. PD measured with Instrument C, in factory

2) Faraday Cage Measurements with Three Instruments

Figure 2 shows the results of PD measurements taken in the Faraday cage on Coils 1 & 2. Instrument A showed a classical PRPD with moderate activity concentrated at the 90° point in the AC wave.

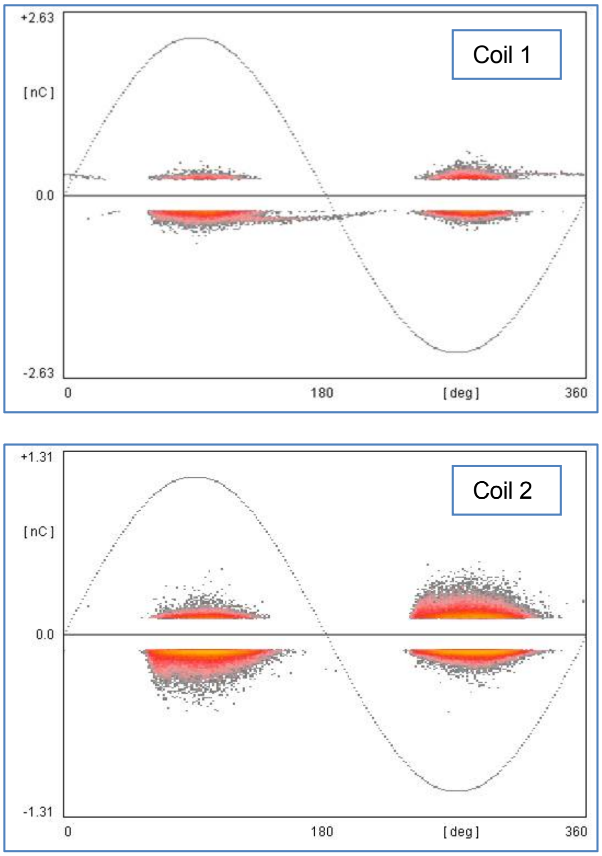
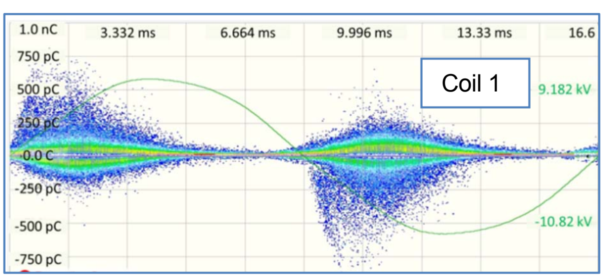


Fig 2a. PD measured with Instrument A, in Faraday cage

When the coils were measured with Instrument B, the Coil 1 PRPD indicated internal and surface discharges, while Coil 2 showed internal discharges only.



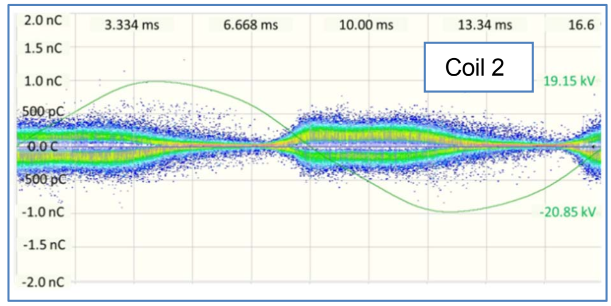


Fig 2b. PD measured with Instrument B, in Faraday cage

Instrument C measurements showed severe surface discharge in each sample coil, though the vertical streaks seen in Fig. 1c were gone.

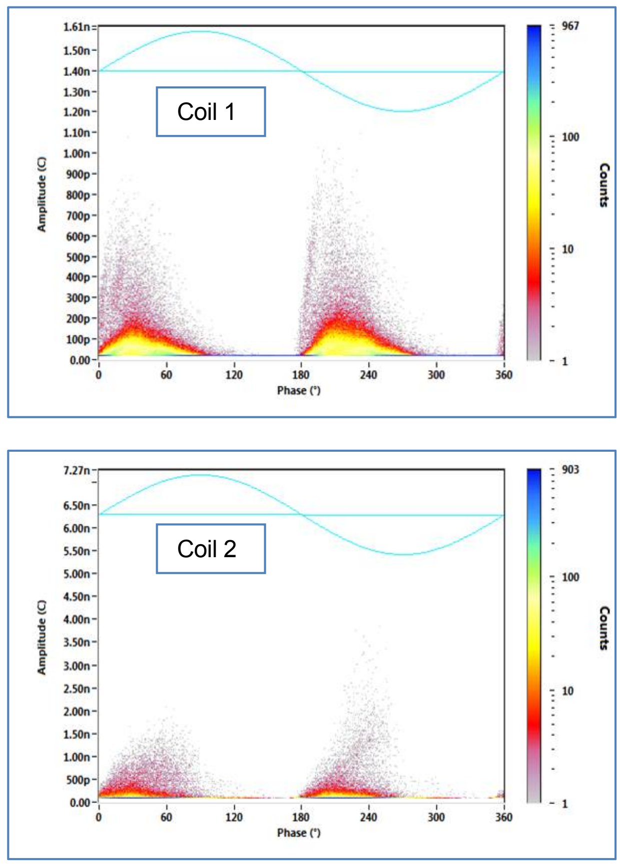


Fig 2c. PD measured with Instrument C, in Faraday cage

3) Variation in PD with Time, Using Instrument A

Instrument A was used to obtain an initial PD measurement on two globally VPI'd sample coils of identical design, rated 13.8 kV. The same measurement was performed roughly three weeks later, then again on the day after the second measurement. The coils and test setups were left undisturbed during this interval, and the same technician performed each test. As with the previous experiment, each sample received twenty minutes of voltage conditioning at V_{LG} = 8 kV before the measurements were obtained.

TABLE II
VARIATION IN PD WITH TIME, ON TWO COILS OF IDENTICAL DESIGN, USING INSTRUMENT A

Time	Coil	RH (%)	Temp (°C)	Q_{IEC} (pu)
Initial	55 59	33	21	1.0 (ref) 0.5
+ 23 d	55 59	18	20	0.6 0.6
+ 24 d	55 59	23	21	0.7 0.4

The PD of Coil 55 was initially measured at several times greater than the recommended API 541 upper acceptance limit; the PD then decreased significantly from its value in the second measurement. On the following day, the PD increased halfway back to its initial value. Similarly, the PD of Coil 59 was again much higher than the upper acceptance limit. After three weeks, the PD increased, then dropped to below its initial value when measured a third time. The PD measurements performed on these coils show no repeatability.

4) PD Variation in a Globally VPI'd Coil, With and Without an Imposed Defect, Using Instruments A and B

Damaged conducting slot armour is a common source of external PD in high voltage stator coils. This type of defect is useful for a study as it can easily be imposed on test coils in a location and manner that simulates realistic conditions. This defect was simulated on a VPI sample coil by using an electric tool to abrade a ring of conducting armour down to the outer layer of groundwall tape, just outside the grounded slot plate (Fig 3). Instruments A and B were used to measure the PD at V_{LG} = 8 kV on Coil 55 before and after the defect was created (Table III).

Fig 3. Damage simulation on conducting armour of a VPI'd coil rated 13.8 kV

TABLE III
VARIATION IN PD WITH DEFECT IN A VPI COIL, BY INSTRUMENT

		Q_{IEC} (pu) at V_{LG}				
		No Defect	With Defect			
Inst	Coil	5 min	1 min	5 min	RH (%)	Temp (°C)
A	55	1.00 (ref)	11.20	1.81	18	21
B	55	0.25	6.92	0.57	26	24

In both instruments, the results showed a remarkable change in observed PD level after voltage conditioning. Measurement variation due to instrument type and voltage exposure invalidates the significance of a 100 pC acceptance limit.

The various PRPD plots taken before and after the creation of the coil defect were then examined, as these plots convey the most information regarding the nature of the defect.

Figure 4 shows the PRPD plot taken by Instrument A on Coil 55 before the defect. The small "rabbit ears" on the rising side of the AC curve suggest PD activity in the coil endwinding. Figure 5 shows the PRPD plot from Instrument A on the same coil after the defect was imposed. The plot shows a similar distribution but much higher PD activity, which is expected as the defect is in the conducting armour just outside the slot. The PRPD plot shown in Fig. 6 was obtained by Instrument A after the corners of the coil were cleaned to remove tracking/carbonization. This plot shows much greater PD activity and cloudy clusters of data on the rising side of the AC wave, indicating that the coil has severe surface discharge activity.

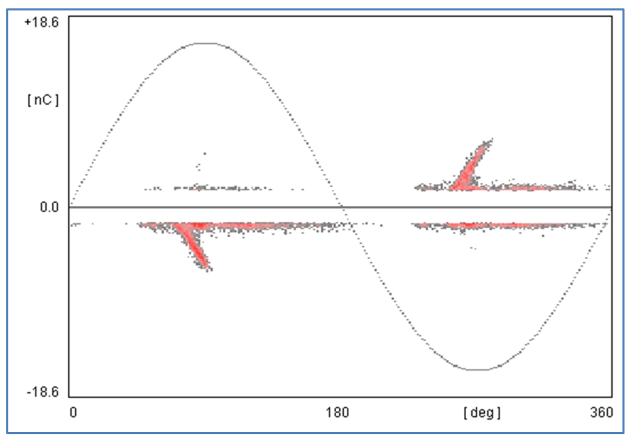


Fig 4. PRPD for Coil 55 without defect, measured with Instrument A

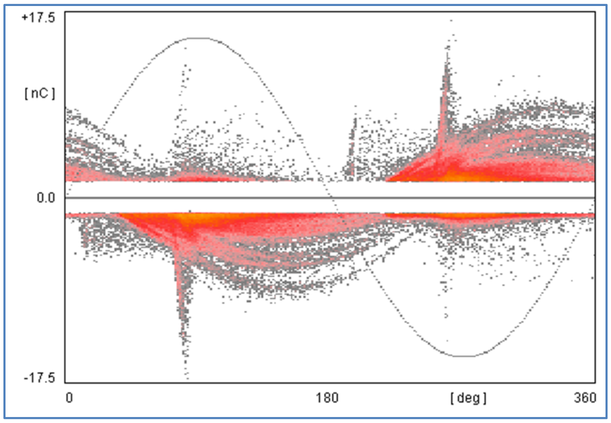


Fig 5. PRPD for Coil 55 with an imposed defect in the conducting armour, measured with Instrument A

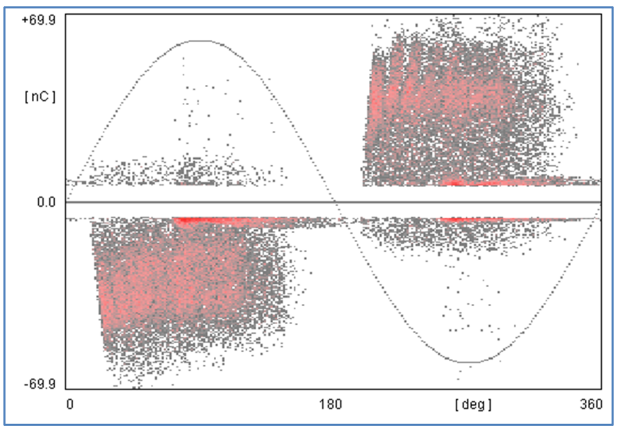


Fig 6. PRPD for Coil 55 with an imposed defect in the conducting armour, after cleaning, measured with Instrument A

Figure 7 shows the PRPD from Instrument B on Coil 55 before a defect. Its shape is characteristic of mild endwinding PD. Figure 8 shows the PRPD from Coil ID55 during the first minute of voltage application, while Figure 9 shows the PRPD after the voltage has been applied for 5 minutes. After 5 minutes, the PD returns to the original characteristic shape, albeit with higher magnitude than the initial value. This increased PD magnitude is expected, as the imposed defect is outside the slot simulator plates. As seen in Figure 8, there is a transition period where the PD signature assumes a new appearance.

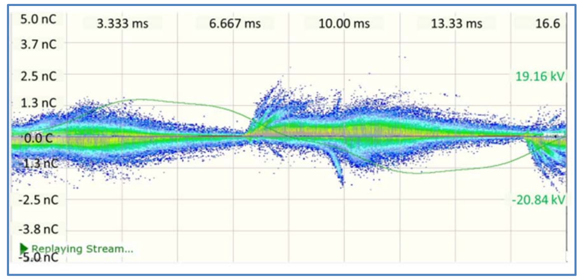


Fig 7. PRPD for Coil 55 without a defect, measured with Instrument B after 5 minutes of applied voltage at V_{LG} = 8 kV

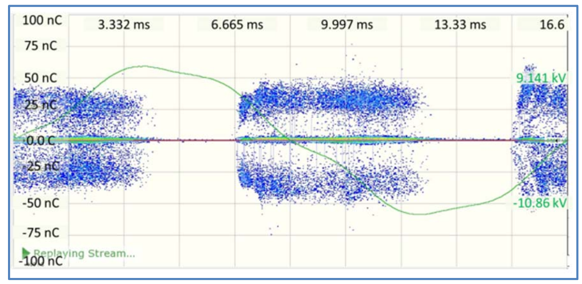


Fig 8. PRPD for Coil 55 with an imposed defect, measured with Instrument B, during the first minute of applied voltage at V_{LG} = 8 kV

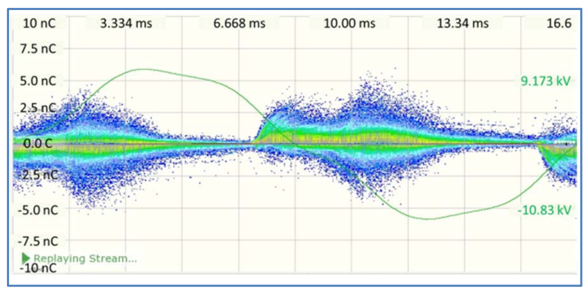


Fig 9. PRPD for Coil 55 with an imposed defect, measured with Instrument B, after 5 minutes of applied voltage at V_{LG} = 8 kV

5) PD Variation in a Resin-Rich Coil, With and Without an Imposed Defect, Using Instruments A and B

The same defect was simulated on the conducting armour of a resin-rich 11 kV sample coil, as shown in Figure 10. Instruments A and B were then used to measure the PD at V_{LG} = 6.4 kV on Coil 1021 before and after the defect was imposed (Table IV).

TABLE IV
VARIATION IN PD WITH DEFECT IN A RESIN RICH COIL, BY INSTRUMENT

		Q_{IEC} (pC) at V_{LG}				
		No Defect	With Defect			
Inst	Coil	5 min	1 min	5 min	RH (%)	Temp (°C)
A	1021	240	760	660	18	21
B	1021	95	1008	478	26	24

The initial PD differed between the two instruments. Instrument A gave charge magnitudes higher than Instrument B. Based on the initial measurements, Coil 1021 would have met the recommended API 541 limit if measured using Instrument B but would have failed if measured using Instrument A. Both instruments again showed an increase in observed PD level with the start of voltage conditioning, followed by an eventual decrease.

Fig 10. Damage simulation on conducting armour of a resin rich coil rated 11 kV

The PRPD produced by Instrument A for Coil 1021 before the defect was imposed recorded only a trace of PD (Figure 11). The plot for Coil 1021 after the defect (Figure 12) showed more activity typical of endwinding PD – as would be expected – after its corners were cleaned in a manner similar to that of the VPI coil in the previous study.

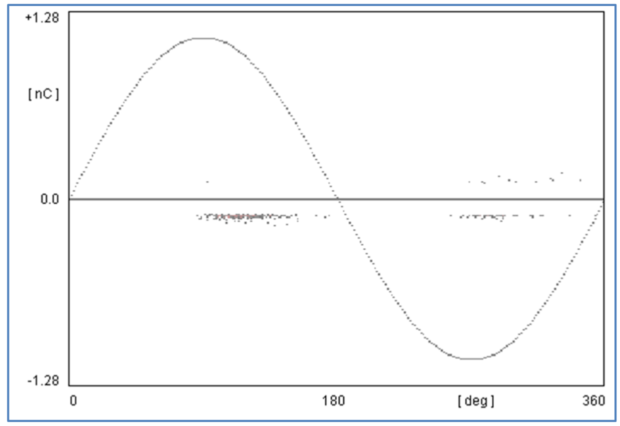


Fig 11. PRPD for resin-rich Coil 1021 without defect, measured with Instrument A

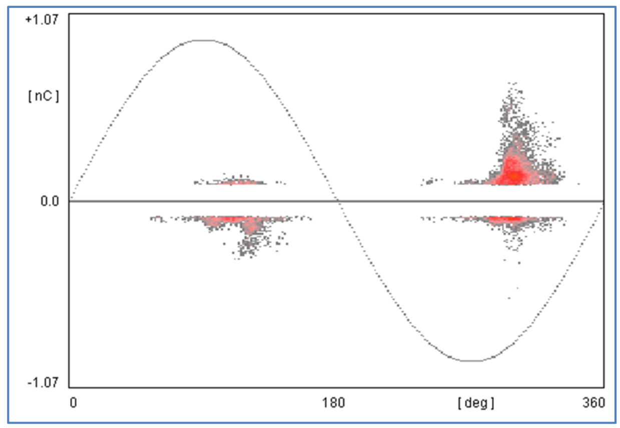


Fig 12. PRPD for resin-rich Coil 1021 with defect and following cleaning of its corners, measured with Instrument A.

Figure 13 shows the PRPD from Instrument B when no defect was present; at this time, Coil 1021 showed typical endwinding PD. After the defect was imposed, the PRPD changed to indicate severe surface discharge activity, as shown in Figure 14. The PD activity measured by Instrument B showed lower magnitudes than Instrument A.

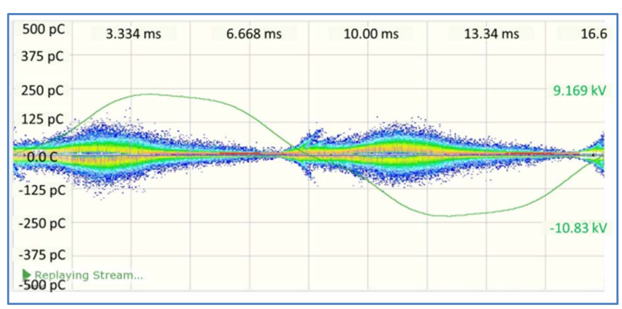


Fig 13. PRPD for resin-rich Coil 1021 without a defect, measured with Instrument B

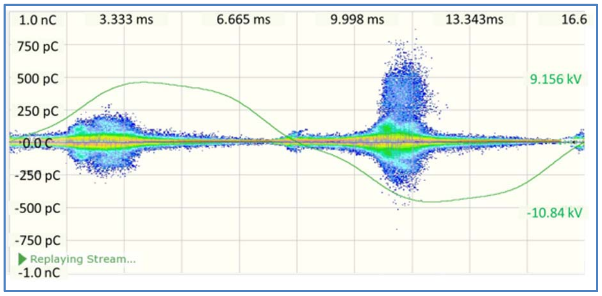


Fig 14. PRPD for resin-rich Coil 1021 with an imposed defect, after cleaning, and following 5 minutes of voltage conditioning, measured with Instrument B

III. CONCLUSIONS

When the same coils are measured using different instruments in two different test environments characterized by a low noise level, there is no consistency in the shape of the PRPD and therefore no agreement between instruments on the source of PD.

When the same instrument is used to measure PD on two coils of identical design with a time interval between the measurements, the PD shows significant variation.

When two different instruments are used to measure the same coil with an imposed defect, the measurement variation due to instrument type and length of voltage exposure (“conditioning time”) is larger than the acceptance level proposed by API 541. If insufficient time is allowed for voltage conditioning before a PD value is recorded, a non-equilibrium condition may lead to an erroneous conclusion about the origin of the PD. The outcome is true for both VPI and resin-rich coil designs.

The evidence presented by this study does not indicate that a specific PD magnitude limit can be recommended; furthermore, this study suggests that even a characteristic PRPD plot cannot be obtained with any degree of confidence. Based on the results of these investigations, it does not appear that PD measurements can be used reliably to assess the quality of sample coils with the present techniques.

It is also evident that setting a standard like 100 pC, will need clear understanding that how this magnitude is measured (calculated) and should be consistent for various PD instruments. Until a uniform definition of Q_m or Q_{IEC} is created, and the test conditions are narrowly defined, then it is not possible to set an absolute allowable pC level.

IV. ACKNOWLEDGEMENTS

The authors thank Jeffery Druif and Rick Glowacki for preparing the samples and performing the PD measurements.

V. REFERENCES

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VI. VITAE

Saeed Ul Haq (M’00) received his B.Sc. degree in Electrical Engineering from UET, Peshawar, Pakistan, in 1991, M.A.Sc. degree from the University of Windsor, Ontario, in 2001, and Ph.D. from the University of Waterloo, Ontario, in 2007. His main doctoral research interest was to the study of insulation behaviour in drive-fed medium-voltage motors. He joined GE in 2007 and in his current role as a Lead Insulation Engineer for GE Power Conversion is focused on the development of insulation systems for large rotating electric machines. Saeed has co-authored several papers for PCIC, PCIC Europe, and the IAS Transactions and magazine articles. He is a winner of the PCIC Best Paper award, and has performed extensive volunteer work for the IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP) and International Symposium on Electrical Insulation. Dr. Haq is a registered Professional Engineer in the Province of Ontario.

Meredith K. W. Stranges (M’00, SM’07) joined GE in 1997 with a B.Sc. (Chemistry) from Brock University in St Catharines, Ontario and B. Eng (Metallurgy) from McMaster University in Hamilton, Ontario. She has over 16 years’ experience on rotating machine insulation systems, and in her current role at GE Power Conversion is a senior project engineer. Meredith is an author of over twenty technical papers and tutorials for PCIC, PCIC Europe, the IEEE International Symposium on Electrical Insulation (ISEI), Insucon, and Industry Applications Society (IAS) Transactions and magazine articles. She is Chair of the PCIC Refining Subcommittee, a Best Paper co-author, and past recipient of the PCIC Outstanding Technical Contribution (OTC) award. Meredith is a member the IEEE Standards Association, Industry Applications Society, Dielectrics and Insulation Society, and the Power & Energy Society Materials Subcommittee. She is a member of the API 546 working group task force. She has been a Standards Council of Canada expert delegate to IEC Technical Committee 2 on Rotating Machines since 2002, and is a Professional Engineer in the province of Ontario.

Barry Wood (M’73 & M’79, SM’87, F’03) received the BSEE degree from Virginia Tech, Blacksburg, and the MSEE degree from the University of Pittsburgh in 1972 and 1978 respectively. He is a Fellow member of IEEE, a Professional Engineer in California and Pennsylvania, and past Chairman of the API 541, 546, and 547 Task Groups for induction and synchronous machines. He has authored or co-authored more than 15 PCIC papers, which include eight prize paper awards. Barry has been with Chevron since 1987 where he is a Chevron Fellow and Consulting Electrical Engineer with Chevron Energy Technology Company, Richmond CA. His primary responsibilities include consulting for company facilities worldwide in the areas of electrical power systems, adjustable speed drives, motors and generators.