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Distinguishing Between Phase to Ground, Phase to Phase and Cross-Coupled PD Signals in Stator Windings

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***Abstract* - Partial discharge (PD) detection in stator windings is widely used to assess the condition of the electrical insulation. When the winding is excited by 3-phase AC voltage, PD current pulses can occur between each phase and ground (i.e. within the stator slot and just outside of the same slot). PD can also occur in the endwinding region, driven by the phase to phase voltage. In addition, PD occurring in one phase often induces a "cross-coupled" signal into another phase, presumably due to the capacitance between phases in the endwinding region. These three "sources" of pulses can complicate the phase-resolved PD (PRPD) plots from each phase. Although some methods to separate these three types of pulses from one another have been proposed using post-data acquisition processing – they still require considerable expertise to separate them reliably. In this paper, experiments are conducted on stator winding models to identify the characteristics of the phase to ground, phase to phase and cross-coupled PD signals, in order to separate the sources in real time. Such separation is important, since PD in the endwinding is often much easier to repair than PD occurring with stator slots.**

Keywords - partial discharge, stator winding, insulation, PRPD

I. Introduction

Partial discharge testing has long been used to assess the condition of rotating machine stator winding insulation. Phase resolved PD (PRPD) plots, where the PD pulse magnitude and PD pulse count rate data is displayed vs the 50/60 Hz phase position, have been used since the 1970s both to help separate stator PD from unwanted electrical interference, and to help identify the root cause of any PD [1-3]. Ideally the PRPD patterns are simple, with negative PD pulses between about 0 to 90 degrees of the AC cycle, and positive PD usually between 180 to 270 degrees of the AC cycle (Figure 1). Due to the phase position and the positive and negative PD having the same magnitude, the PD in Fig. 1 is due to voids within the groundwall insulation. However, in on-line rotating machine measurement, the PRPD patterns can appear to be quite complicated [2-6], even if the electrical interference has been suppressed using one or more of the methods in [2,3]. The reasons for the complicated PRPD patterns, even with no interference, include:

- multiple simultaneous failure processes,
- cross coupling of PD from one phase into another, and
- phase to phase PD that occurs between coils in different phases in the endwinding.

This paper discusses the causes of complicated patterns in detail. A 3-phase coil model was created to allow easy creation of both phase to ground and phase to phase PD, and to study cross-coupling. Results from the model tests are presented.

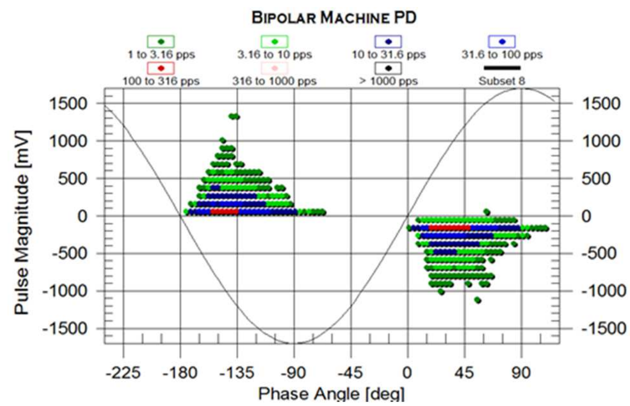

Fig. 1 Classic PRPD pattern caused by a single aging process driven by the phase to ground voltage. The horizontal scale is the phase angle of the 60 Hz AC cycle. The vertical scale is the magnitude of the pulses. The color of the dots represents the PD pulse count per second per magnitude window.

II. Causes of Complicated PRPD Patterns

A. Simultaneuos Failure Processes

The simultaneous occurrence of multiple failure processes is common in stator windings. Almost all stators rated >3 kV have PD in operation. That is, they are not expected to PD-free in operation, unlike most other apparatus. Also, PD is a cause or a symptom of a dozen insulation failure process in stators [7,8], and the PRPD patterns tend to be different between some of these failure processes [2,3]. When the PRPD pattern from one mechanism is combined with the PRPD pattern of one or more other patterns, the composite patterns are more complex. For example, Figure 2 shows a simulation of when PD due to voids within the stator slot are combined with endwinding PD in different ratios.

Separating which mechanisms are occurring is important. Some aging processes are slow (for example PD suppression coating deterioration) and others are relatively fast (loose coils in the stator slots). Maintenance personnel need to take quicker corrective action if the process itself can result in failure sooner. Also, most aging processes occurring in the stator endwindings, circuit rings or leads are relatively easy to repair. Whereas some processes that occur in the slot can only be repaired with a rewind (for example voids due to manufacturing defects or thermal aging).

Very experienced people can sometimes separate the different processes by observing the PRPD patterns directly. Obviously this is a subjective process. More objective methods for separation using statistical operators [9], neural networks/artificial intelligence [10], time-frequency maps [11] and simultaneous three-phase acquisition maps [12] have been employed to help automate separation. But there is still controversy on the effectiveness and the skill required to reliably separate the insulation aging mechanisms [4-6] with such methods, including a recent report that such methods have not yet facilitated unsupervised PD mechanism separation [13].

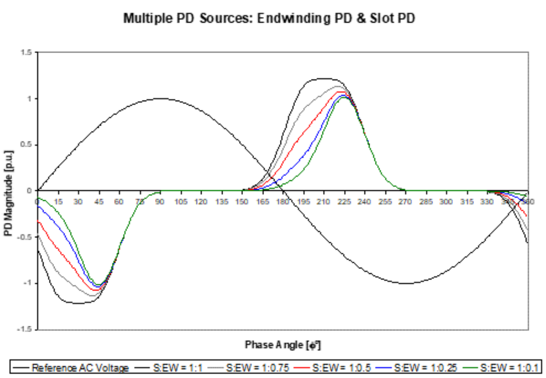

Fig. 2: Simulation of combining void PD with decreasing portions of endwinding PD, causing the PRPD pattern to change its overall shape and mode location. The Gaussian shape is due to voids in the slot alone. The flat top shape in each polarity occurs when void and endwinding PD occurs equally.

B. *Stator Winding Structure*

The unique layout of the motor and generator stator windings rated 3 kV and above can also lead to complicated PRPD patterns. In almost all cases there are two coils (or bars) in each stator core slot. Often these two coils are in different phases, and operate at different voltages (that is they are placed in different positions in the stator winding from line end to neutral). Since each coil in the slot usually has a partly-conductive, grounded coating (the "semicon" coating), any PD created in the slot and just outside of the slot is caused by the phase to ground voltage.

In almost all stators, a line-end coil in one phase is adjacent (between the top and bottom layer of coils, or circumferentially) to the line-end coil in another phase. Since there is no grounded shielding between the phases in the endwinding, this can create phase to phase (interphasal) PD if the spacing between coils in the endwinding is too small. Such interphasal PD is not possible in most transformers or GIS, since the elements of each phase never get close to another phase. As shown in Figure 3 from an operating turbine generator, interphasal PD produces PD that is phase shifted from the normal phase to ground PD by +/- 30 degrees, since the phase to phase voltage is phase shifted from the phase to ground voltage by +/- 30 degrees [6,14]. PD in the endwinding between phases also produces patterns that, at the same instant of time (as determined by a vertical line drawn between the three phases in Figure 3), have a reverse polarity and are approximately the same magnitude. Thus interphasal PD in the endwinding area or between the circuit rings has the following characteristics:

- for the two phases, one cluster of pulse is shifted closer to the AC voltage zero crossing, whereas the other phase in the pair has the cluster shifted closer to the peak of the AC cycle.
- The pulses have reverse polarity in one phase as compared to the other phase [6, 14]
- They occur at the same instants of time
- At the same instant of time, the **absolute** magnitude of the PD in the pair are about the same.

The stator endwinding structure also creates cross-coupling of PD signals from one phase to another. That is, PD occurring in phase A can be detected as pulses in Phases B or C or both [6]. Again this is a feature of PRPD patterns that are less likely to be noticed in other types of apparatus due to, for the most part, the large physical distance between components of different phases.

The mechanism for the cross-coupling seems to be the capacitance between adjacent coils in the endwinding. The coil to coil capacitance depends on the distance between adjacent coils, as well as the length of the coil (bar) endarms. Thus anecdotally, stators rated at lower voltages and higher speeds tend to have the greatest cross-coupling between phases. Review of many on-line PRPD patterns indicates the cross-coupling can be as high as 50%, that is a 1 V PD pulse on Phase A may show up as a 0.5 V on B phase, at the same instant of time. Interestingly, the pulse polarity is sometimes reversed from that in the original phase [6]. Figure 3 shows PD in A and B phases that is about 25% cross-coupled into C phase.

III. EXPERIMENTAL VERIFICATION ON THREE PHASE COIL MODEL

To demonstrate the interphasal and cross-coupling effects in a controlled manner, a three phase coil model was constructed. Three new coils rated 2.4 kV were prepared. The groundwall insulation was mica paper tapes impregnated with epoxy using the VPI process. Although unusual for a 2.4 kV coil, a partly-conductive (semicon) tape was applied to one leg in each coil for most of the straight portions of the coils, as well as 4 cm of a silicon carbide PD suppression coating at the ends of the straight portions (Fig. 4). The slot semicon coating could be directly connected to ground or floated (depending on the experiment). The three coils were approximately aligned axially, and insulating boards could be adjusted to create different spacings between the coils in the endwinding - to allow the creation of phase to ground PD, interphasal PD or simultaneously both types of PD (Fig. 4).

The coils were energized by a three phase high voltage transformer, with each coil connected to one phase. Usually the PD tests were performed at about 6.9 kV rms, phase to phase (or 4.1 kV line to ground). A commercial PD instrument (Iris Power TGA-B) was used that measures PD in the VHF range. The PD sensors are 80 pF capacitors.

IV. PRPD PATTERNS FROM MODEL

Fig. 5 shows the PRPD pattern on all three phases from pure phase to ground PD occurring in each phase (i.e. the slot section was grounded on one coil leg in each phase). In this case, the three coils were spaced normally in the endwinding (about 1 cm between adjacent coils), so no phase to phase PD was possible. The PRPD pattern (Fig. 5) is a classic example of void type PD in the slot, with both the positive and negative PD having about the same magnitude, and centered on 45 and 225 degrees of the AC cycle. Phase A had the highest activity. The cross-coupling of B phase PD into C Phase (adjacent but about 1 cm apart) is about 30%, and occurs at the same instants of time.

An experiment was also done with pure interphasal PD occurring between the endwindings of A and C phase coils, operating at 6.9 kV phase to phase. In this case the endwindings of the A and C coils were shifted together so that they were almost touching. The slot sections were not grounded, preventing any phase to ground PD in the slots. B phase was spaced at least 1 cm from phases A and C. Figure 6 shows the resulting PRPD patterns, with substantial A to C phase PD. This interphasal PD between A and C phases was confirmed with an acoustic imaging camera. Note that the positive predominance on C phase shows as negative predominance on A phase. The cross-coupling from A and C phases into B phase was <10%.

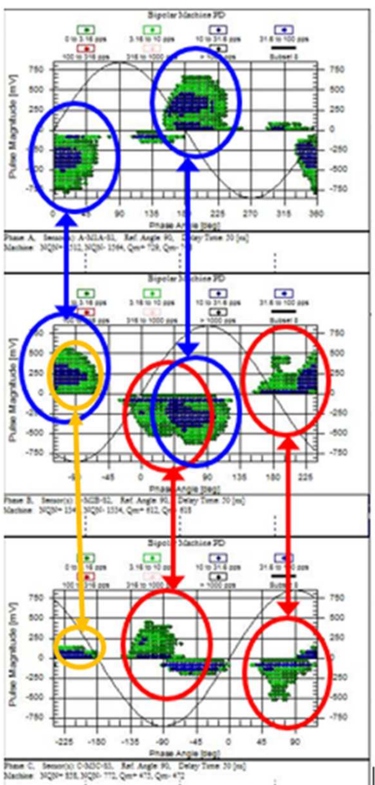

Fig. 3 PRPD examples of interphasal PD occurring between A and B phases (blue circles) and between Phase B and C phases (red circles) on an **operating** turbine generator, which were confirmed visually on this 80 MVA, 13.2 kV TG. The yellow circle shows signals cross-coupled from A and B phases into C phase. Note the 120-degree phase shift between the start of the AC cycles for each phase, thus the plots are aligned in time.

The composite PRPD plots when both phase to ground and A to C interphasal PD were occurring at the same time at 6.9 kV phase to phase is shown in Figure 7. Since the groundwall phase to ground PD was higher in magnitude than the interphasal PD, only an experienced person can see that both mechanisms are occurring in Fig. 7

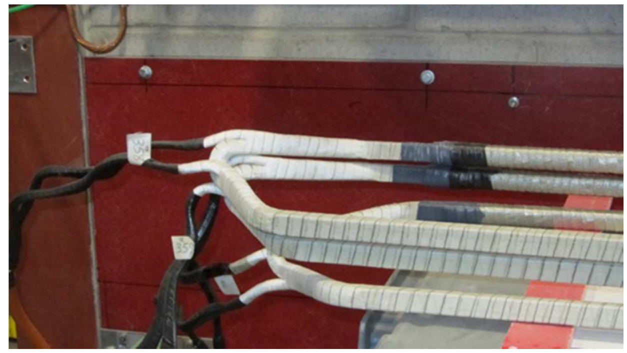

Fig. 4: Photo of three coil model that is connected to a 3 phase voltage supply. The top coil (Phase A) is just a few mm from the middle coil (Phase C)-producing A to C phase PD. B phase is well separated from the other two phases.

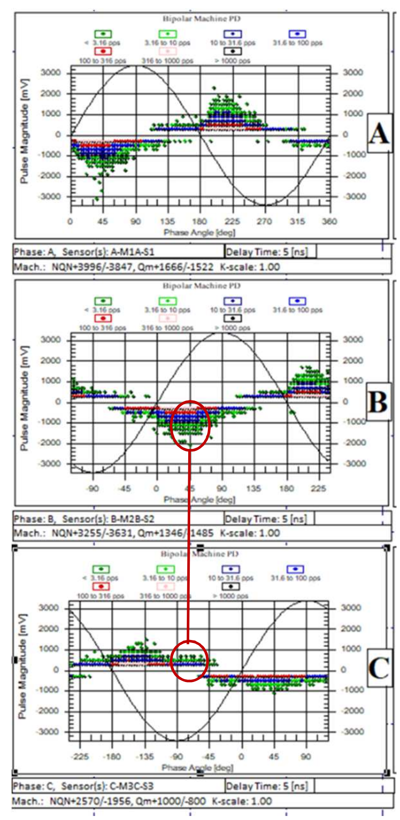

Fig. 5 Cross-coupling into other phases from phase to ground PD only on all three phases. The PD in Phase B is cross-coupled into Phase C – see red circles. There is no interphasal PD due to the wide spacing.

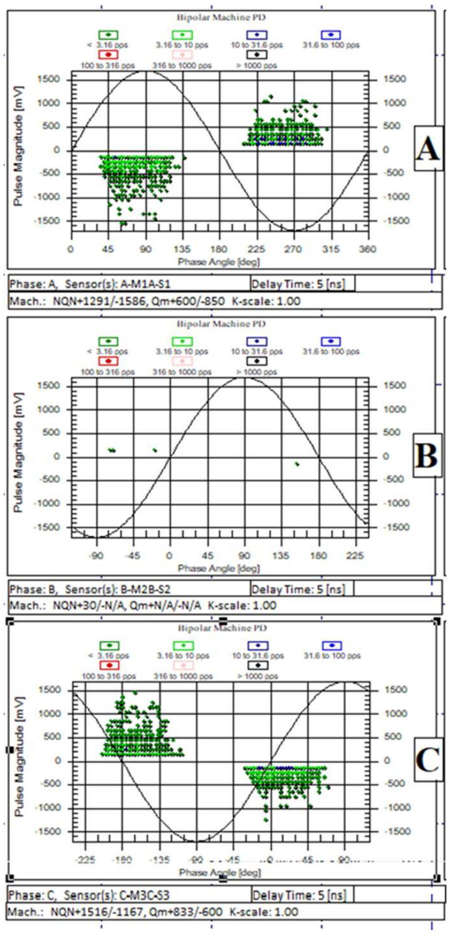

Fig. 6: Pure phase to phase PD between A and C phases. All three phases are energized to 6.9 kV phase to phase.

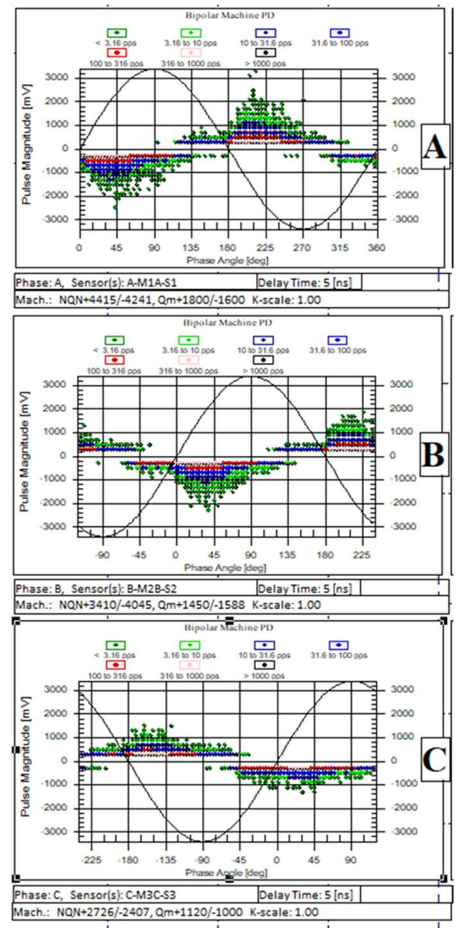

Fig. 7 Void PD in the slot and A to C interphasal PD occurring at the same time.

V. CONCLUSION

Although examples of phase to ground and phase to phase PD, together with cross-coupling, have been anecdotally reported for many years, a simple laboratory model was constructed which was able to isolate these three types of signals. Based on these results, better methods of digitally separating different stator winding aging mechanisms may be possible. Specifically, phase to ground, interphasal PD and cross-coupled PD signals can be identified by simultaneously noting the phase position, polarity, magnitude and co-incidence in time.

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REFERENCES

[1] A. Kelen, "The functional testing of HV generator stator insulation", Proc. CIGRE Conf, Sept 1976.

[2] IEEE 1434:2014, "IEEE Guide for the Measurement of Partial Discharges in AC Electrical Machinery"

[3] IEC TS 60034-27-2 "On-line partial discharge measurements on the stator winding insulation of rotating electrical machines", 2012.

[4] G.C. Stone, "A perspective on on-line PD monitoring for assessment of the condition of rotating machine stator winding insulation", IEEE Electrical Insulation Magazine, Sept 2012.

[5] G.C. Stone, et al, "Relevance of phase resolved PD analysis to insulation diagnosis in industrial equipment", IEEE ICSD, July 2010.

[6] G.C. Stone et al," Characteristics of Noise and Interphasal PD in operating stator windings", IEEE EIC, June 2011.

[7] IEEE 56-2016, "IEEE Guide for the insulation maintenance of electrical machines".

[8] G.C Stone, et al, "Electrical insulation for rotating machines", Wiley-IEEE Press, 2014

[9] A. Contin, M. Cacciari, G.C. Montanari, 'Use of a Mixed Weibull Distribution for the Identification of PD Phenomena', IEEE Trans DEI, December 1995, pp1166-1178

[10] E. Gulski, A. Krivda, "Neural Networks as a Tool for Recognition of PD", IEEE Trans EI, October 1993, p984-990

[11] A. Cavallini, M. Conti, A. Contin, G.C. Montanari, F. Puletti, "A new algorithm for the identification of defects generating partial discharges in rotating machines", IEEE ISEI, Sept 2004, pp 204-207.

[12] W. Kalkner, et al, "Synchronous 3 phase PD detection on rotating machines", International Symposium on High Voltage Engineering, Aug 2005.

[13] R. Ghosh, P. Seri, G.C. Montanari, "A track towards unsupervised PD inference in electrical insulation systems", IEEE EIC, 2020.

[14] V. Warren et al, "Advancements in PD analysis to diagnose stator winding problems", IEEE ISEI, 2000.