Investigations into the Effect of Humidity on Stator Winding Partial Discharges

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ABSTRACT

On-line partial discharge (PD) testing has become a powerful tool to plan the maintenance of stator windings of high voltage motors and generators. Interpretation of PD data is best done by monitoring the trend in PD over time. Unfortunately the trend in PD is sometimes difficult to ascertain, especially if the humidity within the stator is variable over time. This paper shows several examples of how PD is affected by humidity in operating machines. Laboratory experiments were also performed to duplicate this phenomenon. In most practical situations, it appears that the PD activity decreases as the humidity increases.

1 INTRODUCTION

ON-LINE partial discharge (PD) testing has been used for decades to help maintenance personnel detect stator winding insulation problems in motors and generators [1, 2]. Specifically, the test can find loose, overheated, and contaminated windings, sometimes years before these conditions lead to failure. As a result, on-line PD testing has become an important tool for planning machine maintenance. The test has also found use in determining the effectiveness of any repair work. With the advent of electrical noise separation technology developed in the 1970s and 1980s, reliable on-line PD testing and basic interpretation was made possible by plant engineering staff with moderate training [3, 4]. The result has been the widespread application of the so-called PDA and TGA tests on machines throughout the world, with over 50% of utility generators > 20 MW in the USA and Canada employing on-line PD monitoring.

One of the most important ways of interpreting PD data is to monitor the trend in PD magnitudes over time. If the PD magnitude more than doubles in 6 months, then experience has shown that the rate of insulation deterioration is significant, and winding maintenance would be prudent. Unfortunately, it has become clear over the years that the PD activity is not solely determined by insulation condition. Specifically, machine operating voltage, stator winding temperature, machine load, and hydrogen pressure can affect the PD levels [3]. Thus to ensure sensitive detection of any increasing trend in PD activity as a result of insulation deterioration, temperature, voltage, load and pressure must be essentially the same.

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As will be shown below, it has become apparent that atmospheric humidity also may have an effect on the PD activity in operating motors and generators. This effect can make trending of the PD over time as a means of maintenance planning less certain, since one cannot usually control the atmospheric humidity. This has also been noted by others [5, 6]. This paper presents data from operating machines as well as data obtained via simple laboratory experiments to verify the existence of this phenomenon. The implications for on-line PD testing of machines are also discussed.

2 PD IN OPERATING MACHINES

In the past 10 years, a large number of monitors that can continuously measure the PD in machines were deployed in generating stations [7]. Most of these monitors have the ability to also track the voltage, load, winding temperature, etc. at the time of each PD measurement, to ensure that PD magnitude can be trended over time with data collected under the same operating conditions. The following case studies show that in fact in some machines, the PD activity was still very variable, in spite of these controls. The root cause of the unexplained variation was eventually determined to be humidity, moisture content, dew point or related phenomena associated with the atmosphere in which the machine operates.

2.1 CASE STUDY 1

Figure 1 shows the effect of dew point measurement in the plant environment on the peak PD magnitude (Qm). Qm is defined as the largest magnitude of pulses having a repetition rate of 10 pulses per second. The data was collected with a PDA-IV instrument, connected to 80 pF

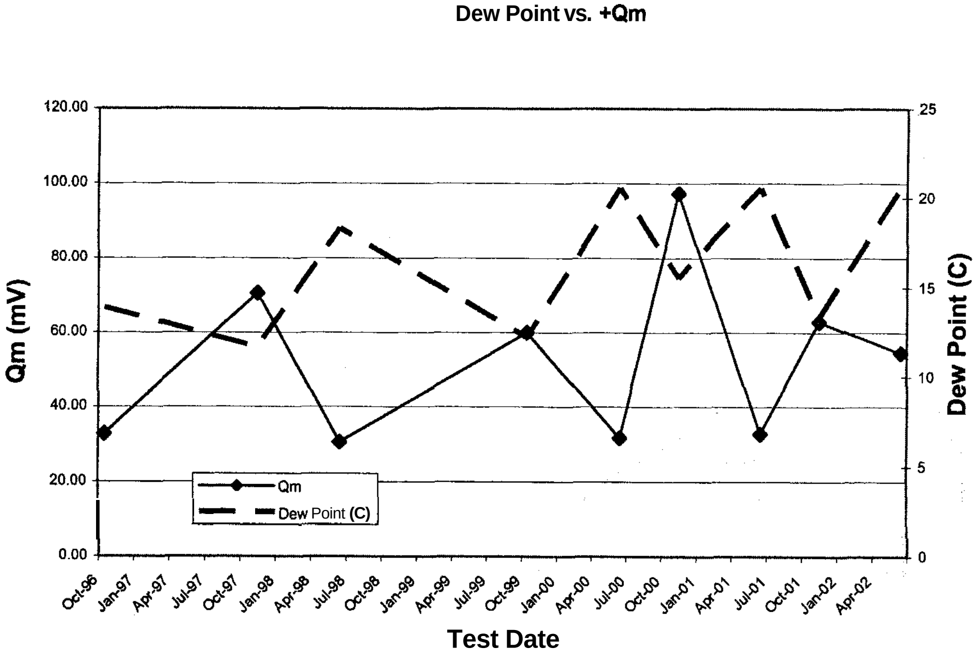

Figure 1. PD activity vs. dew point in an operating pump-storage generator over a 6-year period. The data was collected using portable instrumcntation.

capacitive sensors. The machine was a 20 kV, 450 MVA pump storage generator. It is clear from the figure that as the dew point decreases, the PD magnitude increases. That is, the PD activity increases in drier (less humid) air. Visual inspections of the stator winding showed deterioration of the semiconductive slot coating/stress control coating interface, where PD was occurring between the semiconductive and stress control coatings. Silicon carbide is commonly used in the stress control coating.

2.2 CASE STUDY 2

A 4.1 kV cooling water motor in a nuclear power plant was equipped with a continuous PD monitor employing 80 pF capacitive sensors. At the same time, a portable relative humidity indicator monitored the humidity of the air in the motor environment. Figure 2 shows that over a 48 h period there is an excellent inverse correlation between the PD activity, expressed by Qm and NQN (IEEE Std 1434–2000), and relative humidity. That is as the relative humidity increases from 32% to 54%, the peak PD magnitude (Qm) drops from 200 mV to 100 mV, over a 5 h period. In subsequent testing using a portable turbine generator analyzer (TGA) instrument, it was apparent that the PD was occurring in the end-winding area between phase A and B, since the PD was phase shifted +30° in A phase and −30" in B phase from the normal phase position in the ac voltage cycle for PD occurring in the stator slot [4]. Such pulse phase analysis patterns are indicative of PD occurring outside of the stator slot, in the end-winding area, where the PD is driven by phase-to-phase

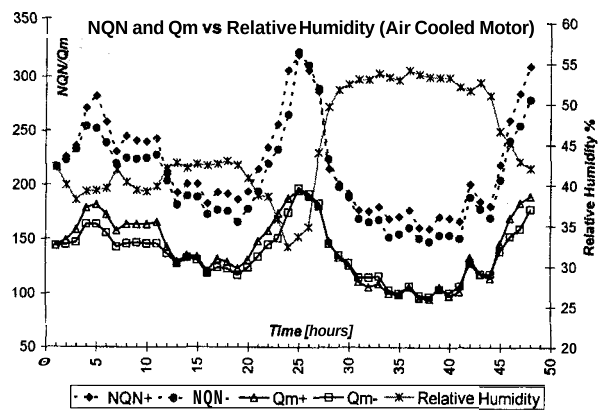

Figure 2. PD activity vs. relative humidity in an operating 4.1 kV motor over a 48-hour period.

(rather than phase to ground) voltage. In a later visual inspection of the winding by plant staff, the end-windings of this vertical motor were found to be soaked in oil from an upper bearing oil leak. In addition, a heavy layer of dead insects covered the end-winding. Such contamination is known to produce electrical tracking in the end-windings of coils connected to the phase terminals. Thus for this motor it appears that lower humidity causes the end-winding electrical tracking to accelerate.

2.3 CASE STUDY 3

Figure 3 shows the relationship between PD and humidity in a different 4.1 kV motor on the Gulf coast of the USA. No continuous humidity sensor was available near

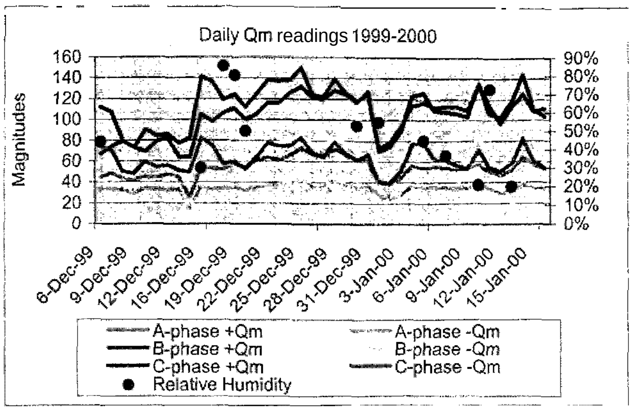

Figure 3. PD activity vs. relative humidity for a 4.1 kV motor.

the motor. Instead the humidity was taken from the database of a nearby US weather service monitor. Only discrete humidity data was available. This example is much less clear than those discussed above, but it seems that as the humidity increases the PD also increases. This is opposite to the effect in Case Studies 1 and 2. However, the results may be confounded with changes in load and temperature. A visual inspection has not been possible yet, so the root cause of the PD has yet to be confirmed, but the PD patterns indicate the root cause is slot discharge within the slot.

The implication from these case studies is that humidity may either increase or decrease the PD. The first two case studies show that PD occurring in the end-winding area, and on the surface of the insulation, is inversely affected by humidity. The humidity influence is large enough that it makes it difficult to trend the PD over time (and thus determine maintenance priorities) if the humidity is varying. To date, we have seen no evidence that humidity affects the PD activity in machines where the PD is occurring within (as opposed to the surface of) the stator winding insulation.

3 EXPERIMENTAL TEST SETUP

There are limitations in the collection of PD and humidity data in operating machines, since often the exact source of the PD is not known, and other operating conditions (load, voltage, etc) may also be changing. To study the influence of humidity on PD more precisely, laboratory experiments were conducted.

The purpose of these tests is to examine the influence of ambient humidity and ambient temperature on the discharge inception voltage (DIV) occurring in atmospheric air on insulation surfaces. Experiments at different values of relative humidity and temperature were done to determine the effect of relative humidity and absolute humidity on the measured values of DIV. A climate chamber with dimensions 120 $\times$ 60 $\times$ 60 cm was constructed. The sidewalls were made out of 3mm thick polycarbonate material, allowing for a visual inspection of the test setup within the climate chamber. The top and bottom sides were made out of thermally and electrically insulating materials and the chamber was equipped with humidifiers and heaters. To ensure a constant temperature and humidity distribution throughout the chamber air-circulation fans were installed. The chamber was equipped with one high voltage bushing (Figure 4).

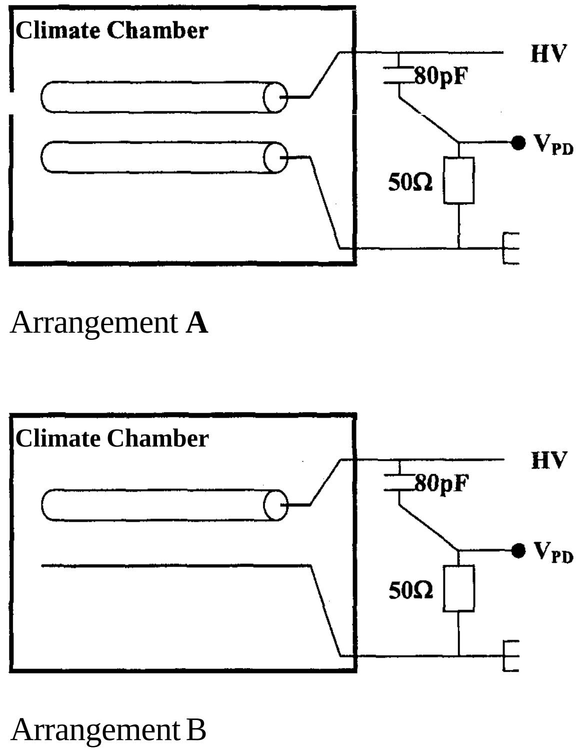

Figure 4. Experimental arrangements.

A 320 pF capacitive PD coupler was connected to the HV lead outside the climate chamber. This allowed for measurement of PD activity, and consequently, DIV as well as the discharge extinction voltage (DEV), via an oscilloscope or a PD monitor. A 30 kHz to 1 MHz filter was placed in series between the capacitive coupler and the scope.

Frequent measurement of the DIV of the electrical connections of the chamber was found to be consistently above 42 kV_{rms} for the range of humidity used in the experiments, which is well above the voltages applied to the insulation samples placed in the chamber.

A commercial ultrasonic type humidifier and resistive electrical heaters enabled the humidity and chamber temperature to be independently controlled. The relative humidity and the ambient temperature were measured with thermocouples and a hygrometer. The resistive heaters and the humidifier were controlled so that there was less than 5% fluctuation in the measured temperature and relative humidity.

3.1 SPECIMEN CONFIGURATIONS

As illustrated in Figure 4, two categories of tests were carried out. Arrangement A was used to study the impact of humidity and temperature on DIV for PD occurring between two insulating surfaces. Arrangement B was used to investigate the impact of humidity and temperature on DIV for PD occurring between an insulating surface and a ground plane.

Unshielded, 35 kV ethylene propylene rubber (EPR) insulated cable samples, with a length of 30 cm each, were used to simulate stator coils in these experiments. The insulation surface was cleaned with isopropyl alcohol and left to dry in a clean environment.

Two 35 kV cable samples were placed in the chamber in Arrangement A. The bottom cable was put on an insulating spacer and the cable conductor was connected to ground. The top cable was then suspended over the bottom cable. The top cable was connected to a high voltage ac supply. The cables were not straight, but had a bend to ensure PD occurred between the cables at the point where the cables were closest. The spacing between the cables at the closest point was 4 mm, 2 mm or 0 mm (touching).

For Arrangement B, the top cable was suspended over a grounded metal plate. The top cable was then connected to a high voltage ac supply. The distance between the mid point of the cable and the grounded plate was 4 mm, 2 mm or 0 mm (touching).

3.2 TEST PROCEDURE

Each experiment was performed at a constant temperature and the relative humidity was varied, increasing from about 20% to 90% in approximately 10% steps. The maximum variance in the measured humidity was 1.7% at any given experimental condition. The maximum discrepancy in ambient temperature was 1.2 K.

Once experimental conditions were achieved, i.e. a given combination of humidity and temperature is reached; the DIV was measured by slowly increasing the voltage until the first discharges were observed on the oscilloscope (Tektronix 644 B, 2.5 GS/s). The PD magnitudes at DIV were somewhat fluctuating and, consequently, a correlation between PD magnitude at DIV and humidity could not be reliably established. The DIV was measured seven times and the mean and standard deviation calculated. The DIV presented in this publication is the midpoint of seven observations.

4 EXPERIMENTAL RESULTS

The results obtained for Arrangement A, i.e. for PD occurring between dielectric surfaces in atmospheric air, are presented in Figures 5 and 6. The figures illustrate the relationship between DIV and humidity at 298 K (25 °C) and 323 K (50 °C), respectively and for insulation samples spaced 4 mm, 2 mm and 0 mm apart. Figure 5 displays the relationship between DIV and humidity with reference to relative humidity whereas Figure 6 displays the relationship between DIV and humidity with reference to absolute humidity measured in g/m^3. A comparison between the two representations shows that similar trends are displayed.

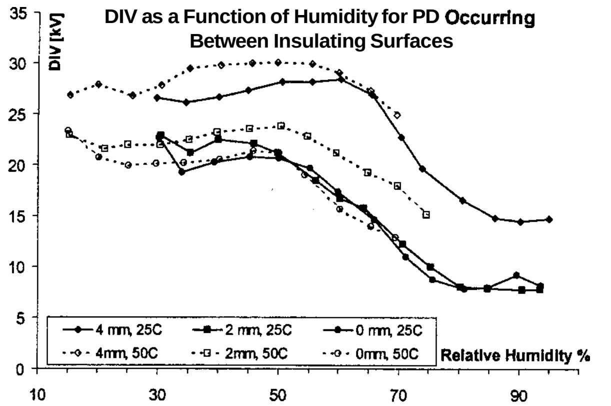

Figure 5. DIV as a function of relative humidity between insulating surfaces.

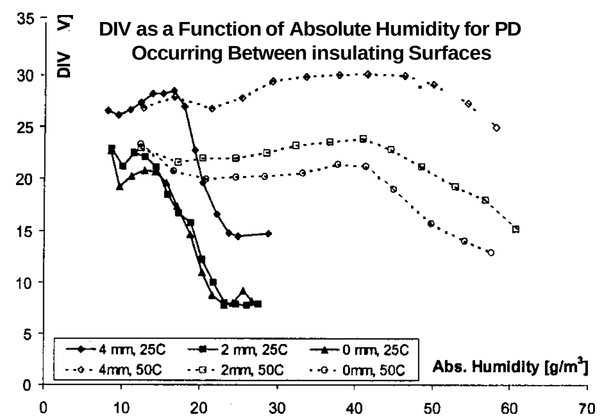

Figure 6. DIV as a function of absolute humidity for PD between dielectric surfaces.

In general, when examining the relationship between DIV and humidity, three regions may be identified. As shown in Figure 6, at 25 °C, below approximately 10 g/m^3, the DIV decreases with humidity. Between 10 g/m^3 and 15 g/m^3, the DIV increases with increasing humidity, then reaches a peak around 10–15 g/m^3 after which the DIV decreases. At 50 °C, only two regions may be observed. Initially, the DIV increases with increasing humidity reaching a peak at approximately 40 g/m^3 after which the DIV decreases. The shape of the DIV curves, obtained at 25 °C and 50 °C, are similar but the slopes at 50 °C are less than measured at 25 °C. For the data obtained at 25 °C, only two data points were collected, and they may not be repeatable. Given the limitation of the test setup, it was not possible to go below 10 g/m^3 humidity and, as such, this effect could not be investigated further, i.e. the

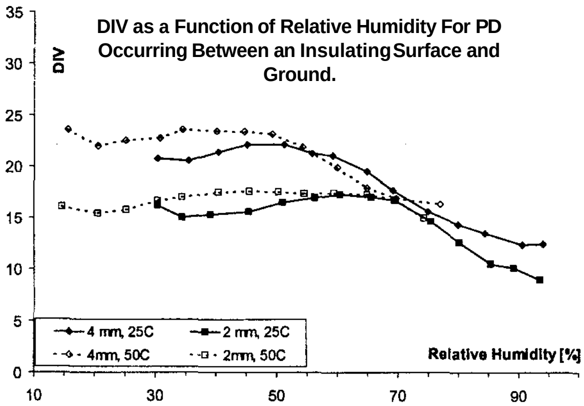

Figure 7. DIV as a function of relative humidity for Arrangement B.

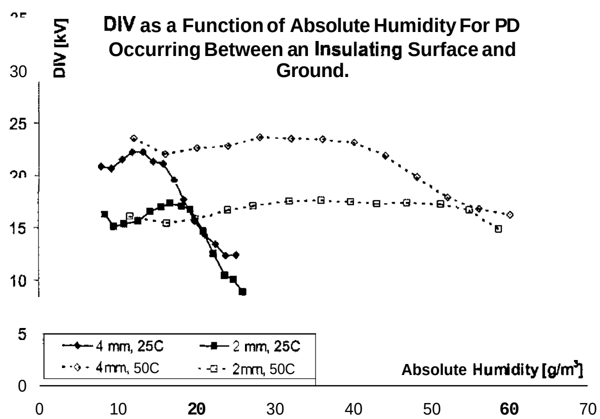

Figure 8. DIV vs. absolute humidity for Arrangement B

validity of the relationship between DIV and humidity at humidities below 10g/m^3 could not be validated. Thus we will disregard the data collected below 10 g/m^3.

Arrangement B tests produced similar results. Figure 7 displays the relationship between DIV and relative humidity whereas Figure 8 displays the relationship between DIV and absolute humidity measured in g/m^3. As shown in Figure 8, at 25°C, the DIV initially increases with the humidity reaching a peak around 12–18 g/m^3 then the DIV decreases noticeably. At 50 °C, the DIV increase with increasing humidity reaching a peak at approximately 40 g/m^3 where after the DIV decrease. The DIV measured between an insulating surface and a metallic ground plane is less than that measured between two insulating surfaces. Lastly, when comparing the DIV curves obtained at 0 mm, 2 mm and 4 mm, a simple scaling effect can be seen: Not surprisingly, the larger the spacing, the higher the DIV.

5 DISCUSSION

The DIV curves obtained for PD in atmospheric air occurring between two insulating surfaces and an insulating surface and a grounded metal conductor show the DIV to increase with increasing humidity until a peak value is reach after which the DIV decreases with increasing humidity. In other words, the results show both an inverse and a proportional relationship between DIV and humidity respectively.

Considering data with absolute humidity of 10 g/m^3 and above, the repeatable occurrence of a peak in DIV would suggest the presence of two mechanisms that affect the DIV. The first mechanism deals with a proportional relationship between DIV and humidity, the first region of the DIV versus humidity curve. The impact of the moisture content on the gas discharge process itself is a factor in the initial increase in DIV with increasing humidity. Water vapor acts like an electro-negative gas and increases the electrical breakdown strength of the atmospheric air [8]. As the electrical breakdown strength increases, for a given fixed electrode geometry, so does the voltage at which a discharge will occur. Therefore, this may be the cause of a DIV increase at low humidity.

The second mechanism deals with the inverse relationship between DIV and humidity, the second region of the DIV versus humidity curve. It is understood that condensation of water on insulating surfaces can change the electrical field distribution on the insulation surface. The electrical field will be enhanced around areas of local condensation, perhaps causing the DIV to decrease, if this is occurring. The decrease in DIV at higher values of humidity thus may be caused by droplet formation due to condensation of water on the insulation surface(s).

As can be seen from Figures 5 and 6, since the breakdown strength of atmospheric gas increases with increasing moisture content, the absolute humidity rather than the relative humidity is most likely the parameter of interest when determining the influence of ambient humidity on partial discharge behavior at low humidity values. However, the data indicate that, at higher humidity values, the relative humidity may be a better measure since the decline in DIV seems to correlate to increasing values in relative humidity regardless of the ambient temperature.

For an insulation-system such as a stator winding in a rotating machine, the geometry of the insulation system can be considered fixed and, consequently,. the resulting electrical field distribution is primarily defined by the Laplace equation and the applied voltage, disregarding insulation surface contamination which would give rise to a surface charge distribution (a Poisson field component). Thus, when extrapolating the results of the experiments obtained here to on-line PD measurements on stators, the inverse relationship between DIV and humidity suggests that, on aggregate, the PD activity would increase with decreasing humidity

Extrapolating this argument to case studies 1 and 2 of this publication where it is observed that PD activity as evaluated by Q_m and NQN decreased with increasing humidity, i.e. an inverse relationship between PD activity and humidity and consequently and proportional relationship between DIV and humidity. As described earlier, the predominate discharge source in both cases is located in the end-winding area. Given the type of discharge source and the observed inverse relationship between PD activity and humidity, we may thus infer that these tests are in the region where water condensation affects the electric field (i.e. we are in the second region of the DIV curve after the peak in Figures 5-8). Had the conditions under which these on-line tests were obtained been similar to those of the first region of the DIV versus humidity curve, a proportional relationship between PD activity and humidity would have been observed.

In case study 3, perhaps we are before the peak, and thus the breakdown strength of air is still being modified by the moisture and resulting in an increase in breakdown strength (yielding an increase in PD magnitude and presumably an increase in DIV) as the moisture content increases.

6 CONCLUSION

HUMIDITY has been found to either increase or decrease the PD activity in operating high voltage stator windings suffering from surface insulation deterioration. Experiments investigating the relationship between DIV and ambient humidity were performed. The results indicate that both the absolute and relative humidity need be considered when evaluating the influence of humidity on PD activity. At lower humidity values, good correlation exists between DIV and absolute humidity whereas at higher humidity values, good correlation exists between DIV and the relative humidity.

Furthermore, the results indicate that the two mechanisms may be dominating the influence of humidity and temperature on DIV. One mechanism relates to the increase in DIV observed at lower humidity. We speculate that the increase in DIV is caused by an increase in the electric breakdown strength of the air as a result of increase in absolute humidity. The other mechanism may relate to field enhancement effects occurring on the insulation surface as a result of moisture condensation. The humidity at which the peak in DIV occurs would therefore relate to the point where the increase in DIV, due to effect of moisture on the breakdown strength of atmospheric air, is neutralized by the decrease in DIV. This is due to surface field enhancement effects caused by condensation.

The practical importance of this work is that the humidity of the environment should always be measured when PD measurements are made. Detection of deteriorated insulation based on the trend in PD activity over time will only have meaning if results are obtained under the same humidity conditions.

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