Effect of Temperature and Humidity on Surface Discharge Activities under High Voltage Unipolar Pulses

Mohammad Saleh Moonesan
Shesha Jayaram
Edward Cherney
Dept. of Electrical and Computer Engineering
University of Waterloo
phone: (1) 519-888-4567 Ext. 35337
e-mail: msmoonesan@uwaterloo.ca

Abstract— **This paper presents the experimental results of surface discharge measurements in a point-plane electrode geometry having a 250 µm air gap and a Kapton® HN film barrier on the ground plane electrode. The test cell was placed in an environmental chamber while stressed using high voltage unipolar square waves. The humidity in the chamber was varied from 0.01 to 0.05 kg/m^3 at room temperature as well as at 50 °C. Unipolar square pulses of 6 kV peak with a repetition rate of 1 kHz was applied to the electrodes representing a single point source of partial discharges. A radio frequency antenna captured the discharge activities and a phase resolved method was used to analyze the data. Temperature did not show a noticeable effect on the partial discharge inception voltage of the air gap while increasing the humidity increased the amplitude and decreased the number of surface discharges on the film barrier.**

I. INTRODUCTION

Partial discharge (PD) is known as one of the main factors influencing the insulation degradation. Therefore understanding of the factors contributing to initiate or enhance PD has great importance in designing high voltage application related products. These factors could be the parameters of the applied voltage such as voltage and frequency, as described in our earlier publication [1], or could be related to the environmental parameters such as temperature and humidity which is the subject of the present research.

In the context of literature, there are numerous research works focusing on this subject. Nawawi et al. [2, 3] investigated the effect of humidity on PD using the CIGRE test cell. It was reported that the increase in humidity had no effect on partial discharge inception voltage (PDIV) while it decreased the surface resistivity and therefore the charge accumulation. Discharge time lag and PD amplitude were reported to decrease with increased relative humidity. On the contrary, Waldi et al. [4] reported increasing PD magnitude with increased relative humidity. Centurioni et al. [5] in another research showed that the accumulated charge on the surface is lower at higher humidity levels which is in agreement with [2, 3]. Fenger et al. [6] suggested that absolute humidity rather than relative humidity must be considered when evaluating the effect of humidity on PD. It was reported that PDIV increased with increased absolute humidity and also there would be an electric field enhancement due to condensation. Kikuchi et al. [7] showed a decrease in PDIV with increased absolute humidity at low temperatures on twisted wire stressed using 60 Hz sinusoidal voltage. However, at higher temperatures, PDIV showed an opposite trend and was observed to be increasing in higher absolute humidity levels. It was speculated that the water droplets absorb free electrons at higher temperatures which causes PDIV to rise. Soltani et al. [8, 9] investigated the effect of humidity on machine insulation using an asphalt coil and an epoxy bar. They reported that humidity amplifies internal discharges while it slightly decreases surface discharges. The PDIV was also reported to increase with increased humidity [9].

As it can be inferred, the test results are contradicting, depending on the test conditions and parameters. The aim of the present research is to address the effect of humidity on the degradation of turn insulation of electric machines stressed by converters. Although the IEC standard suggests a unique way of preparing samples [10], the presence of voids in the samples will affect the test results. Therefore, a special type of test cell was developed. In this test cell, the complexity of the system is reduced by using a point-plane electrode geometry having an air gap and an insulation film barrier on the ground plane electrode. It reduces the source of PD to a single point and discharges will develop on the surface of the insulating film. The test samples were stressed under square pulses with 6 kV peak and a frequency of 1 kHz while the humidity was varied from 0.01 to 0.05 kg/m^3. The tests were conducted at room temperature as well as at 50°C and the PD events were captured and analyzed.

II. MATERIALS AND METHODS

A. Test Setup

The experimental setup comprised of point-plane electrodes having an insulation barrier. Kapton film with a thickness of 0.1 mm was used as a barrier which was placed on the ground plane electrode and held in place using a cylindrical ceramic spacer. The point electrode with a tip diameter of 0.5 mm was fixed on top of the insulation film leaving an air gap of 0.25 mm between the tip of the point and the surface of electrode as shown in Fig. 1. Using this geometry provides the capability to generate single PD events in the air gap and on the surface of the insulator. The test setup placed in an environment chamber which had the ability to control both temperature and humidity level. A miniature RF antenna was fixed to the ceramic holder to capture partial discharge pulses.

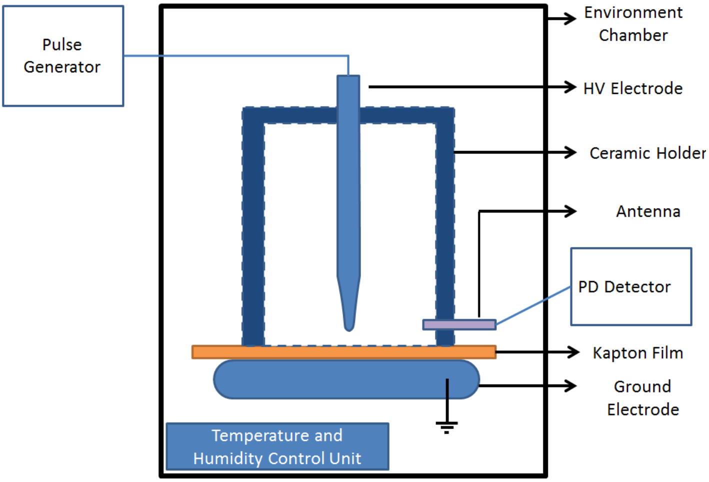

Fig. 1. Schematic of the test setup.

B. High Voltage Pulse Generator

A custom designed high voltage unipolar square wave generator based on IGBTs was used to conduct the research. Adjustable peak voltage, switching frequency, rise time and duty cycle provided the possibility of applying the desired waveform. Fig. 2 shows a sample output waveform of the generator. A fast protection system was implemented to disconnect the generator from the test setup in case of puncture or complete breakdown in the insulation barrier.

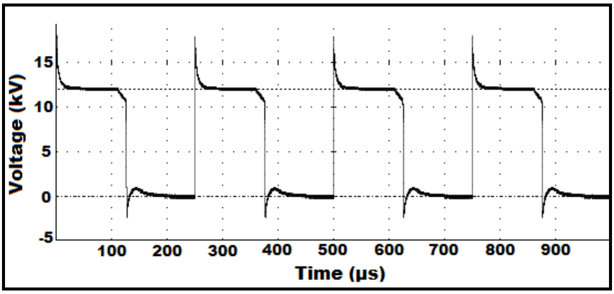

Fig. 2. Typical output voltage waveform of the generator.

C. PD Detection System Under Square Wave Pulses

PD was measured using an RF antenna, attached to the ceramic holder as shown in Fig. 1, and a 7-pole Chebyshev high pass filter was used to filter the voltage pulse from the generator allowing only the PD signal to pass. A Rohde & Schwarz RTO1024 oscilloscope with 2 GHz bandwidth and 10 Gsa/sec sampling rate was used to capture and record the PD. A MTLAB code was developed to analyze and classify the captured data.

III. RESULTS AND DISCUSSION

In order to have PD taking place in every test condition, the peak voltage level has to be selected slightly above the PDIV. Therefore, PDIV was measured equal to 4 kV peak when applying square waves with a switching frequency of 1 kHz. Hence, the peak voltage was fixed at 6 kV for all the considered test conditions in this paper. Table 1 shows the results on the effect of increasing humidity on PD features at room temperature. In each test point unipolar square waves with a peak voltage of 6 kV, switching frequency of 1 kHz and a rise time of 100ns were applied to the test cell for one minute and the PD events were captured with the antenna. Then the captured data were analyzed using MATLAB and PD features such as amplitude, and the number of occurrences in each part of the wave was extracted.

TABLE 1: DEPENDENCE OF PD FEATURES ON ABSOLUTE HUMIDITY AT ROOM TEMPERATURE (23 °C)

Humidity (kg/m^3)	Average Number on DC part of the wave	Time to Inception (ns)	Max Amplitude (V)
0.011	16	102	2.6
0.013	10	103	3.7
0.014	31	103	4.2
0.015	1	133	5.7
0.016	1	156	4.7
0.018	1	174	7.2
0.019	2	245	17.0

As it can be seen from Table 1, there is a threshold humidity at 0.015 kg/m^3 where the discharges on the DC part of the wave diminish in number. The time to inception represents the time measured from the point at which the voltage rises to the first PD. The time to inception increases with increased humidity so that PD occurs after the rise time.

In addition, higher humidity results in having higher magnitudes of PD as can be observed from Table 1.

These observations can be explained by considering the effect of humidity on charge accumulation and on the breakdown strength of air when pulsed voltage is applied.

The application of a positive pulse on the point electrode with respect to the ground plane enhances the electric field in the air gap. The field enhancement results in accumulation of charges with the same polarity as the applied field, according to the results presented by [11], on the surface of the insulation. Therefore, higher accumulation of these homo-charges reduces the electric field in the air gap. However, when the electric field in the air gap reaches the required level for developing a discharge, a PD occurs and neutralizes some of the accumulated charges. This discharge may appear anywhere along the DC portion of the wave. An increase in absolute humidity reduces the surface conductivity of the insulation, as reported in [3], which accelerates the rate of recombination of charges and decreases the space charge on the surface. In consequence, the electric field in the air gap increases with a decrease in the electric field arising from the space charge.

The outcome is an increased rate of occurrence of PD on the DC portion of the wave. This explains why the average PD number increases when the humidity level increases from 0.011 to 0.014 kg/m^3. Albeit, this is not the only consequence of increased humidity as inferred from Table 1 for humidity levels higher than 0.015 kg/m^3. As reported in [12] and [6], there is an increase in PDIV as well as the breakdown strength of air in the gap with increased humidity. Hence, the electric field is not high enough to form a discharge on the DC part of the wave, and the discharges appear only at the transients.

The occurrence of PD at polarity reversals of the waves is because of the combined effect of charge accumulation on the surface and rapid transient of the applied voltage. The electric field exceeds the required level to develop a discharge at the rise time of the waveform which generates a PD event. Then, as mentioned earlier, the application of electric field forms a space charge of homo-charges on the insulation surface which leads to electric field reduction in the air gap as long as the field is present. The reduction of electric field in the air gap decreases the chance of development of PD on the DC portion of the wave. Later on, when the applied voltage falls back to zero, the external field is removed while the space charge on the surface holds its high value considering the fact that the fall time is much faster than the rate of charge recombination. This sustained space charge imposes a reverse electric field in the air gap between the insulator’s surface and the point electrode, therefore, initiating another discharge right after falling edge of the wave. This scenario will be repeated in each polarity reversal. As a result, PD events take place at both rise and fall times of the wave even when the external electric field is zero at the fall times.

The PD amplitude at transients has higher magnitude because of increased PDIV as a result of increase in absolute humidity level. It also gives a rise to the time to inception of the discharges at rise times.

From Table 1, it can also be noted that at 0.019 kg/m^3 (94% relative humidity), the PD amplitude shows a large jump to 17 V which presents a very large discharge. This is due to very high humidity level, leading to the formation of water droplets in the air gap (at the interface). In some cases, the water droplets complete a path over the surface of the insulator which results in a complete breakdown over the surface.

The experiment was repeated at 50°C and the humidity was varied from 0.01 to 0.05 kg/m^3 under 6 kV square wave pulses and the PD events were recorded. Table 2 shows a summary of test results. For lower humidity levels the results follow the same pattern as at room temperature. However, and different from the results at room temperature, the peak PD decreased with increased absolute humidity. This may be due to the combined effect of humidity and temperature on forming the droplets; hence, reducing the charges while increasing the chance of complete breakdown on the surface of the insulation film.

Table 2: DEPENDENCE OF PD FEATURES ON ABSOLUTE HUMIDITY AT 50 °C

Humidity (kg/m^3)	Average Number on DC part of the wave	Time to Inception (ns)	Max Amplitude (V)
0.011	6	126	1.9
0.020	13	114	2.2
0.027	21	100	2.7
0.031	9	105	0.4
0.042	15	117	0.8
0.051	7	122	0.9
0.053	1	236	14.3

Fig. 3 A and B show the phase resolved representation of PD events with respect to the applied waveform at 23 °C and 50°C, respectively, while the absolute humidity level was fixed at 0.011 kg/m^3 and 6 kV peak voltage square waves having a switching frequency of 1 kHz was applied. PD events are classified with respect to their location of occurrence at rise time, DC part, fall time, and zero voltage level and marked with blue, black, yellow, and green circles, respectively.

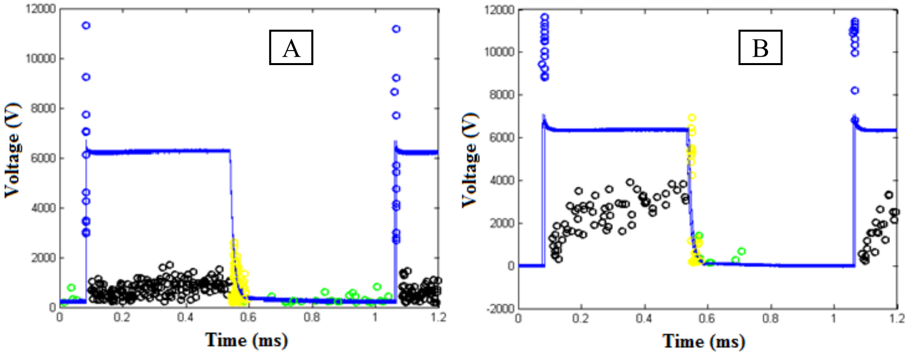

Fig. 3. Phase resolved PD pattern of point plane insulation barrier under 6 kV square waves with switching frequency of 1 kHz at absolute humidity of 0.011 kg/m^3 and at the temperature of 23 °C in (A) and 50 °C in (B). The circles represent the location and relative intensity of each PD event where blue, black, yellow and green circle represent PD at rise, fall, DC part, and zero part of the wave, respectively.

As evident from Fig. 3, increasing the temperature from 23°C to 50 °C resulted in a fewer number of discharges while their intensity increased on the DC part of the wave. Increasing temperature increases the rate of charge recombination on the surface thereby reducing the space charge and therefore reducing the number of discharges. In addition, the reduction in electric field, arising from the space charge, enhances the electric field in the air gap which results in the development of discharges with higher amplitudes on the DC portion of the wave. An increase in PD magnitude on the fall time of the wave, evident in Fig. 3, supports the mechanism presented earlier.

IV. CONCLUSION

The effect of humidity and temperature was investigated by stressing a point-plane electrode geometry using 6 kV unipolar square pulses and switching frequency of 1 kHz with a 250 µm air gap and a Kapton® film barrier on the ground plane electrode. The mechanism of PD development with humidity of the air gap has shown that increasing the absolute humidity enhances PD amplitude while the discharges appear mainly at the polarity reversals of the wave. It was also found that at lower absolute humidity an increase in temperature results in having a lower number of PD pulses with higher amplitudes on the DC portion of the wave.

REFERENCES

[1] M.S. Moonesan,S. Jayaram, E. Cherney,R. Omranipour, and S. Ul Haq, "Effect of voltage rise time on time-to-failure of form-wound stator coil enamelled turn insulation", *Electrical Insulation Conference (EIC)*, June 2014.

[2] Z. Nawawi, Y. Muramoto, N. Hozumi, and M. Nagao, "Effect of humidity on Partial Discharge characteristics", *Properties and Applications of Dielectric Materials 2003. Proceedings of the 7th International Conference on*, vol.1, pp.307-310, 2003.

[3] Z. Nawawi, Y. Murakami, N. Hozumi, and M. Nagao, "Effect of Humidity on Time Lag of Partial Discharge in Insulation-Gap-Insulation System", *Properties and applications of Dielectric Materials,8th International Conference on*, pp.199-203, June 2006.

[4] E.P. Waldi, Y. Murakami, and M. Nagao, "Effect of humidity on breakdown of low density polyethylene film due to partial discharge", *Condition Monitoring and Diagnosis International Conference on*, pp.655-658, 2008.

[5] L. Centurioni, F. Guastavino, and E.Torello, "An investigation about the PD degradation of thin polymer films and its correlation with surface charge decay measurements", *Electrical Insulation Conference Record of the 2002 IEEE International Symposium on* , pp.371-374, 2002.

[6] M. Fenger and G.C. Stone, "Investigation of the effect of humidity on partial discharge activity in stator windings", *Properties and Applications of Dielectric Materials, Proceedings of the 7th International Conference on*, vol.3, pp.1080-1083, 2003.

[7] Y. Kikuchi, T. Murata, Y. Uozumi, N. Fukumoto, M. Nagata, Y. Wakimoto, and T. Yoshimitsu, "Effects of ambient humidity and temperature on partial discharge characteristics of conventional and nanocomposite enameled magnet wires", *Dielectrics and Electrical Insulation, IEEE Transactions on*, vol.15, no.6, pp.1617-1625, 2008.

[8] R. Soltani, E. David, and L. Lamarre, "Study on the effect of humidity on dielectric response and partial discharges activity of machine insulation materials", *Electrical Insulation Conference,* pp.343-347, 2009.

[9] R. Soltani, E. David, and L. Lamarre, "The impact of humidity on partial discharge activity of large rotating machines", *Electrical Insulation (ISEI) Conference Record of the 2010 IEEE International Symposium on*, pp.1-6, 2010.

[10] Qualification and Acceptance Tests for Type II Electrical Insulation Systems used in Rotating Electrical Machines Fed from Voltage Converters, IEC/TC 60034-18-42, Ed. 1.0, 2008.

[11] D. Fabiani, G.C. Montanari, A. Cavallini, and G. Mazzanti, "Relation between space charge accumulation and partial discharge activity in enameled wires under PWM-like voltage waveforms", *Dielectrics and Electrical Insulation, IEEE Transactions on*, vol.11, no.3, pp.393-405, 2004.

[12] P. Ortega, R.T. Waters, A. Haddad, R. Hameed, and A.J. Davies, "Impulse breakdown voltages of air gaps: a new approach to atmospheric correction factors applicable to international standards", *Dielectrics and Electrical Insulation, IEEE Transactions on*, vol.14, no.6, pp.1498-1508, 2007.