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Review

# Effect of humidity on partial discharge in a metal-dielectric air gap on machine insulation at trapezoidal testing voltages

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ABSTRACT

The atmospheric relative humidity (RH) has a great impact on the partial discharge (PD) process which can damage the insulation in operating machines. This work investigates how the relative humidity would affect the PD activities in a metal-dielectric air gap on machine insulation, which consists of mica, epoxy resin and glass-fiber, with the application of periodic alternating trapezoidal voltage waveforms. The results show that the PD characteristics, such as discharge amplitude, the average number of discharge pulses, can be varied greatly with the increasing humidity. This is mainly due to the increased surface conductivity in humid air.

**Contents**

## 1. Introduction

Stator insulation is a critical part of high-voltage rotating machines with respect to the efficiency and reliability of operation, manufacturing costs and maintenance. The stator insulation system is exposed to electrical, thermal, mechanical and ambient stresses

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simultaneously during its operation, resulting in the gradual deterioration of insulation properties which can reduce the machine's lifetime. Many failures of power generators failure are caused by insulation damage; the two main reasons leading to these damages are aging and partial discharge [1]. In general, several common PD sources exist in stator insulation, such as internal discharge, end-winding discharge, surface tracking, delamination and slot discharge [2,3]. Even though modern machines based on epoxy-mica insulation system have been designed to be able to withstand an appreciable level of discharges, for instance, internal discharge in small volumes, some other PD activities are even more detrimental to the insulation system, such as slot discharge.

Slot discharge occurs in the air gap between the surface of the stator bar and the laminated magnetic core. It has been considered as the most severe damage to the stator winding groundwall insulation [4]. There are two main mechanisms that give rise to the slot discharge activity [5,6]. One is the mechanical slot discharge, which is developed from loose bars in the slot due to, for instance, the shrinking of insulation; this allows vibration of the bar in the slot leading to abrasion of the conductive coating of the bar. The other one is the electrical slot discharge, which is caused by poorly manufactured semiconductor coating with inappropriate surface conductivity or uniformity of the coating. If the surface conductivity is too low, a significant voltage could build up between the surface of the bar and the core in parts where the bar surface is not in direct contact with the core. The PD activity that follows may lead to the breakdown of the insulation between the bar and the core. The calculation in Ref. [7] gave a maximum acceptable surface resistivity of 25 kΩ per square for the surface coating. Besides, poor electrical connection of the conductive coating to ground also can initiate the slot discharge. It is well known that the typical phase resolved partial discharge (PRPD) pattern of slot discharge is characterized by a strongly asymmetric pattern, which is triangular with a sharp slope at the onset of the positive discharge appearing during the negative polarity of the applied voltage [2]. However, this pattern varies with other conditions, such as temperature and humidity in the air.

One typical and systematic investigation of slot partial discharge has been presented in Refs. [8–10], including the influence of gap size, temperature and humidity, as well as the surface degradation caused by different stresses, such as electrical, thermal and mechanical stress, on the slot discharge activity. Moreover, it is apparent that the air humidity has a great impact on the PD activity in operating machines; one of the clear evidences from Ref. [11] is that by monthly on-line monitoring on the generator up to 9 years, the PD activities on generators in winter were higher than that in summer with a changing rate higher than 100 because of the seasonal changes in humidity. There exist a large number of studies about the effect of relative humidity on the PD activity [12–18], most of them focusing on the variation of PD inception and extinction voltage, PD intensity, breakdown strength, surface conductivity of the insulating material, space charge accumulation on the material and the statistical time lag of discharge, and so on. From those studies, it has been recognized that humidity has a negative correlation with PD activities: the discharge activity decreases as the humidity increases. For instance, it was observed in Ref. [15] that the external PD activities such as slot discharge are strongly reduced and even disappeared if the ambient air humidity goes above 50%. A similar behavior was reported in Ref. [16] for surface discharges on an epoxy bar disappeared at the eighth day of exposure to humidity of 80%. It has been understood this is due to the electronegative nature of water molecules, which can capture electrons and reduce the availability of free electrons to generate electron avalanches. However, lower PD activities at high-humidity do not directly mean that humidity reduces damage to the insulation surface; on the contrary, it was reported in Ref. [18] that degradation of epoxy resin exposed to PDs was more severe in moist air than in dry air.

In this paper, the effect of relative humidity on partial discharges which take place in the air gap between a spherical metal electrode and the surface of epoxy-mica machine insulation is investigated. The PD analysis is performed with trapezoidal voltage waveforms as stimuli. The reason for this novel method is to investigate the character of the PD behavior with voltage stimuli that have two features, first a constant changing voltage d$U$/d$t$ during rising as well as falling voltage period and a second feature of including a short period of constant voltage between rising and falling voltage periods, rather than having continuously changing voltage that is the case with alternating sinusoidal voltages. The derivative of the applied voltage d$U$/d$t$ were varied from the maximum possible (approximately square-wave) to the minimum possible (triangle-wave) for a given amplitude and period of the voltage. The influence of those voltage waveforms on the PD activity under different humidity levels was investigated, focusing on PD characteristics, such as PD repetition, average number of PD pulses per cycle, PD amplitude and delay time of PD appearance.

## 2. Experimental

### 2.1. PD measurement system

The time-resolved PD measuring system consists of an Agilent 33120A function generator, a TREK 20/20 high-voltage amplifier, a detection resistance, an oscilloscope that was Yokogawa DL750 Scope Corder and a computer, as shown in Fig. 1.

The test voltage was generated by a function generator and then amplified by a high-voltage amplifier (with amplification factor 2000). The high voltage was applied to a steel spherical electrode with a diameter of 22 mm, in order to concentrate the discharges at one spot on the insulating surface. A short length of commercial stator bar was placed below the spherical electrode; the minimum electrode-surface distance was about 1 mm. The machine insulation consisted of mica, epoxy resin and glass-fiber and its approximate thickness was 1 mm. The detection resistance $R$ was 50 Ω, and the coupling capacitance $C_k$ was 500 pF. The discharge pulses were acquired with the oscilloscope, with 12-bit A/D resolution, a sampling rate of 10 MS/s, and a deep memory of 250 MS, which made long-time pulse sequence analysis possible.

The entire test cell was placed into a well-sealed plastic chamber where the relative humidity can be controlled by a saturated salt solution [19], and silica gel used as desiccant for the dry study. The relative humidity and the temperature inside the chamber were monitored by a Testo 625 thermo hygrometer.

### 2.2. Test voltages

The testing voltage waveforms used were of a trapezoidal shape with different time derivative of the applied voltage (d$U$/d$t$), as shown in Fig. 2 (b). The duration of the linearly increasing period from zero till peak voltage $U_{peak}$ is $T_1$; the peak voltage keeps constant during the period of $T_2$; then linearly falls back down to the zero with the duration of $T_3$, the negative half-cycle is a mirror of the positive half-cycle. So the period of the applied voltage is $T$, where $T = 2\,(T_1 + T_2 + T_3)$. In the entire work, the up and down d$U$/d$t$ are equal, i.e. $T_1 = T_3$. Moreover, there were two limit cases of this waveform. Fig. 2 (a) shows the triangular voltage at $T_2 = 0$ ms and the approximately square voltage could also be achieved in the case of $T_1 = T_3 \approx 0$ ms, shown in Fig. 2 (c). In the entire work, the testing voltages shown in all the plots were recorded from the function