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The effects of a series connected resistor on the positive SI breakdown voltage of large air gaps

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SUMMARY

Connecting a resistors in series to an air gap will influence the discharge characteristics of the air gap. This phenomenon is also referred as “inhibited discharges”. One of the effects of the resistor is the increase of the breakdown voltage of air gaps. This effect is useful for improving the insulation design for high-voltage systems. It is known that the streamer-to-spark process dominate the breakdown of shorter gaps up to 2 meters. For longer gaps, leader process becomes more important. To study such an effect, e.g., the increase in the breakdown voltage for longer gaps, experiments have been carried out on air gaps of 6 meters with and without the resistor.

Tests were performed with positive switching impulse voltage of the standard waveform. The gaps tested were a rod-plane gap and a sphere-protrusion-plane gap. For the sphere-protrusion-plane gap, the sphere used was of 1.6 meters in diameter. A metallic protrusion was installed on the sphere located at the underside of the sphere towards the ground plane. The resistor was in this case made of a water pipe. The value of this resistor was 1.2 MΩ. It was observed that with this resistor connected in series, a significant increase of the breakdown voltage could been obtained in both the rod-plane and the sphere-protrusion-plane gaps.

In this paper, the test results and observations are presented with discussions and conclusions on the effect of the resistors.

KEYWORDS

High Voltage, Electrical Insulation, Large Air Gaps, Switching Impulse, Inhibited Discharges

INTRODUCTION

It has been reported in literatures that by connecting a resistors in series with an air gap will influence the discharge characteristics of the air gap [1] - [5]. This phenomenon is also referred as "inhibited discharges" [6]. Such an effect has been used to facilitate the study of discharge processes. With this resistor, the propagation speed of the discharge may become slower and therefore allow a better observation of the discharges. In order to have a measurable effect, the value of this resistor should be in the range from a few kΩ to a few MΩ.

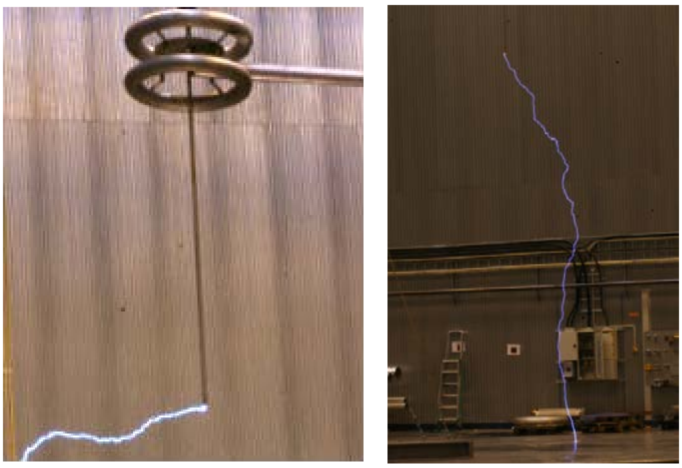
The other effect of the series connected resistor, also reported in literature [1], [6], is the increase of the breakdown voltage of the air gaps. This effect is useful for improving the insulation design for high-voltage systems. Under impulse voltages of both polarities such an effect has been observed on rod-plane gaps from a few millimeters to 1 meters. Study on this effect has led to the conclusion that the increasing of the breakdown voltage is caused by the increasing of the transition time between streamer discharges and the final jump; not by the reduction of the voltage across the gap. It has been interpreted that the capacitive energy in the gaps may support the streamer discharges while the resistive current will become necessary to support the final jump [6].

For air gaps of 1 meter, the streamer-to-spark process dominates the breakdown of the air gaps. For longer gaps, leader process becomes more important. Therefore, for this study, experiments have been carried out on air gaps of 6 meters. In this paper, the test results and observations are presented.

TEST SET-UP AND PROCEDURES

The test objects were rod-plane and sphere-protrusion-plane gaps with or without a series connected resistor. They were installed in the laboratory with a distance of 13.0 meters to the nearest wall or other grounded objects in the laboratory. The resistor was a water resistor in a plastic tube of 4 meters in length. The value of the resistor was 1.2 MΩ. The resistor was measure both before and after each test. No changed in the resistor value was observed.

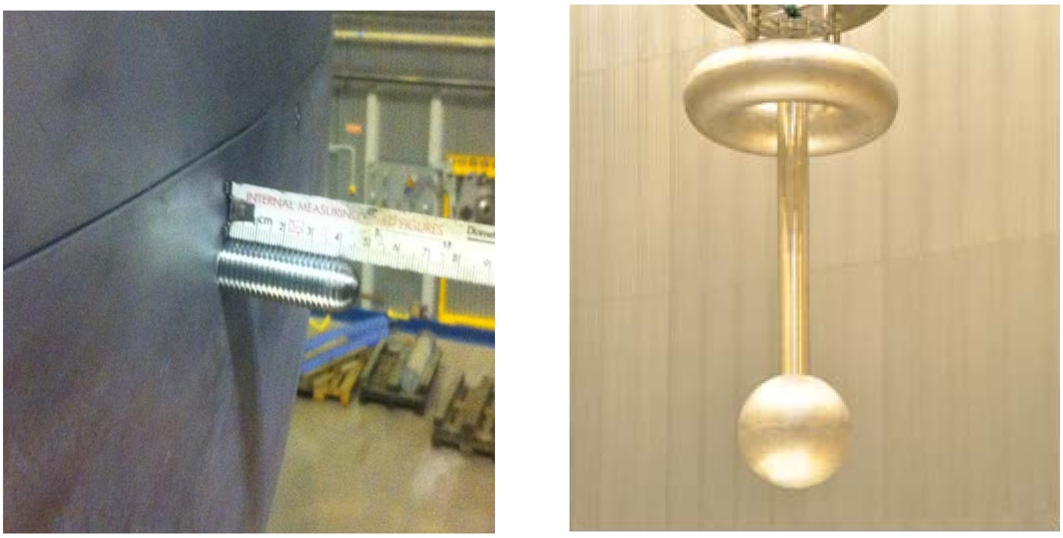
The rod used was an aluminum rod of 3 meters long and 30 mm in diameter. It was terminated by a hemisphere of the same diameter. The rod was vertically suspended from a double-toroid structure. The outer diameter of the double-toroid was 1 meter, as shown in figure 1. The gap distance tested was 6 meters.



(a) (b)

Figure 1, (a): the site-up of the rod in the rod-plane gap; (b): the whole gap under tests

For the sphere-protrusion-plane gap, the sphere was made of aluminum. The diameter of the sphere was 1.6 meter. The protrusion was made of a steel rod. The diameter was 16 mm with a hemisphere head of the same diameter. It was mounted so that it protruded vertically from the surface of the sphere by 50 mm, as shown in figure 2 (a). The sphere was suspended with an aluminum tube of 3 meters in length and 450 mm in diameter. Above the tube, a large double-toroid structure, with outer diameter of 2.5 meters, was used to terminate the tube, as shown in figure 2 (b). The protrusion was at the underside of the sphere pointing downwards to the grounded plane.



(a) (b)

Figure 2, (a): the protrusion of 50 mm mounted on the sphere of 1.6 meter; (b): the set-up of the sphere.

All the tests were performed with switching impulse of positive polarity. The waveform was 275/2500 μs. The voltage level of 50% breakdown probability, U_{50}, was obtained for each test set-up by the well-known up-and-down procedure with 30 valid voltage applications in each test. During the test, the applied voltage and the waveform of the voltage were recoded. Two digital cameras were used to record the trajectories of the discharges. All the test results presented have been corrected to the standard reference atmosphere.

TEST RESULTS

The test on rod-plane gap without resistor was performed also as a reference test for the whole test set-up. For testing with standard impulse waveform, 250/2500 μs, the U_{50} of a rod-plane gap can be evaluated by the well know Paris formula [7]:

$$U_{50} = 500\, d^{\,0.6} \quad \text{(kV)}$$

Where: d = gap distance in meter.

Tested with the waveform of 275/2500 μs (within the tolerance of the standard waveform), the U_{50} obtained from the test for this rod-plane gap of 6 m was 1480 kV and with a standard deviation of 3.9%. This value is only 1% higher than what can be evaluated by the Paris formula. In table 1 below, test results for the rod-plane gap both with and without series connected resistors are given.

Table 1: Test results with the rod-plane gap of 6 meters

Test conditions	U_{50} (kV)	Std. Dev. (%)
Without resistor	1480	3.9
With resistor	1952	4.5

In table 2 below, test results for the sphere-protrusion-plane gap with and without series connected resistors are given.

Table 2: Test results with the sphere-protrusion-plane gap of 6 meters

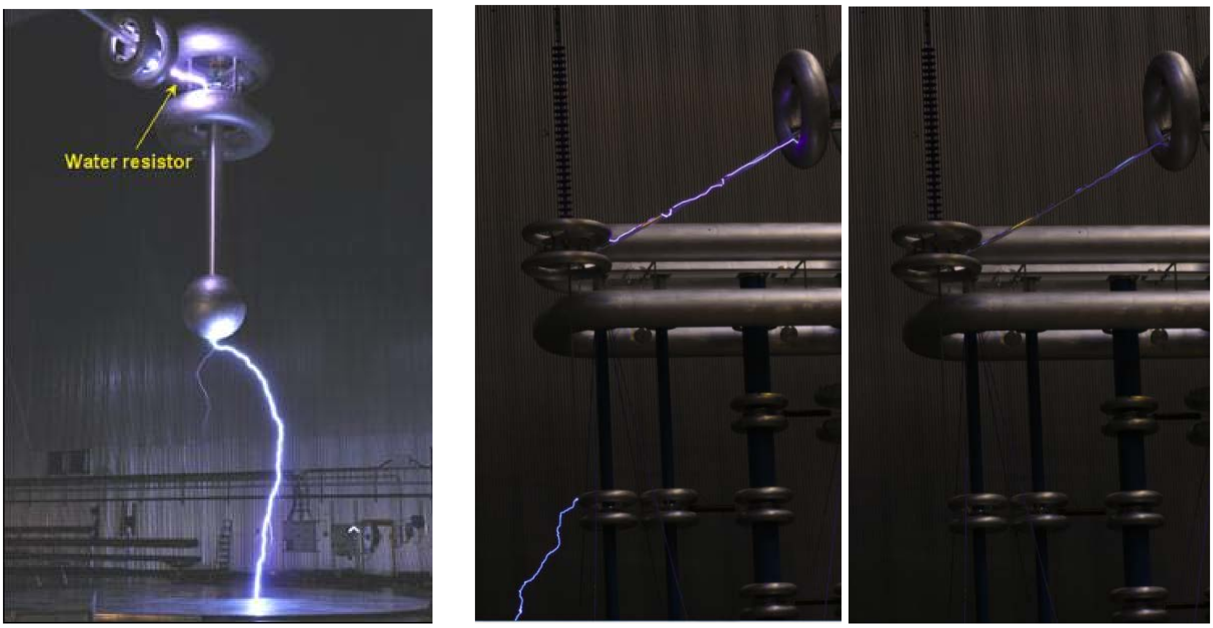
Test conditions	U_{50} (kV)	Std. Dev. (%)
Without resistor	1561	5.3
With resistor	2131	3.4

OBSERVATIONS AND DISCUSSIONS

With a gap length of 6 meters, significant increase in U_{50} has been obtained for the rod-plane gap by the introduction of the series connected resistor. The U_{50} is 32% higher with the resistor than that without the resistor. For rod plane gap at this length, leader process is expected to dominate the discharge process. The results confirmed that series connected resistor has the effect of increasing U_{50} even for long gaps.

It has been reported earlier [8] that by introduce a small protrusion, the U_{50} of the sphere-plane gaps with large spheres of 1.3, 1.6 and 2.0 meters in diameters, can be reduced to the level near rod-plane gaps. A sphere-protrusion-plane gap with a large sphere is expected to contain larger capacitive energy than a rod-plane gap. It is of interest to know if the discharge inhibiting effects of the resistor will still provide the same increase in U_{50} in this case. The test results in table 2 confirmed the effect with an increase of 37% in U_{50}. It is therefore confirmed that the discharge inhibiting effects of the resistor are applicable for electrode of various size. This is clearly a useful aspect for its application.

It was reported that the voltage drop in the air gap caused by the voltage across the resistor is not the reason for the increase of the U_{50}. However, it is inevitable that when the air gap collapsed into a total breakdown, i.e., disruptive discharge, flashover will also take place across the resistor. This was recorded with digital camera, as shown in figure 3, (a) for the sphere-protrusion-plane gap and (b) for the rod-plane gap. It is however of interesting to compare figure 3 (b) and (c) both for the rod-plane gap with the water resistor. As shown in the photos that, when breakdown took place in rod-plane gap, flashover appeared across the resistor, as in figure 3 (b). However, although no breakdown took place in the rod-plane gap, discharge across the resistor could still be observed, as in Figure 3 (c).



(a) (b) (c)

Figure 3, (a): the sphere-protrusion-plane gap with breakdown in the gap and flashover across the water resistor; (b): the rod-plane gap with breakdown in the gap and flashover across water resistor; (c): the rod-plane gap with no breakdown in the gap but discharge across the resistor.

It is evident that the discharge inhibiting effects took place a long time before the appearing of the final jump. As shown in table 1 and 2, the standard deviations of those tests with and without resistor were about the same. Those results indicate that the effects of resistor influence all voltage levels in the up-and-down procedure; not only the voltage application under which a breakdown took place but also the voltage application under which no breakdown took place.

CONCLUSIONS

Test results have confirmed that the U_{50} of the air gap can be increased significantly with the series connected resistor. Such an effect, the increase of U_{50}, applies to both shorter and long air gaps. It also applies to the air gap with large electrodes.

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