Particle-initiated Breakdown Characteristics around Spacer under Lightning Impulse Voltage Superimposed on Pre-stressed DC

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This paper deals with the effect of the magnitude and polarity on the particle initiated breakdown characteristics around a simple shaped spacer in quasi-uniform field gap under lightning impulse voltage superimposed on pre-stressed DC voltage. The results are discussed on the dust figure technique and also on the breakdown voltage / delay time characteristics, while keeping in view the magnitude of the pre-stressed DC applied voltage. Consequently, it was found that the surface charges accumulated on the spacer in the vicinity of the particle tip under the pre-stressed DC voltage play an important role in the particle initiated breakdown phenomenon.

Keywords: metallic particle, spacer, particle motion, lightning impulse, corona, breakdown

1. Introduction

The use of compressed Gas Insulated System (GIS) has enabled compact design of gas insulated switchgears and substations. However, the conducting particle contaminations in gas insulated equipments can significantly impair the integrity of the insulation⁽¹⁾. To further improve the reliability of GIS, many experimental results have been published involving the particle motion behavior and particle triggered breakdown characteristics in different field gaps with and without spacers under various applied voltage waveshapes^{(2)~(8)}.

The impulse breakdown characteristics are of fundamental importance in the insulation coordination in GIS. The critical voltage waveshapes for the insulation is the lightning impulse (LI) voltage⁽⁴⁾. In practical, surge overvoltages appear on the electrical equipment while it is stressed under DC or AC working voltages. Hence, for a short period of time the equipment is subjected to surge voltages superimposed upon the operating DC or AC voltages.

It is well known that, from the insulation point of view the insulators supporting the conductors in GIS are generally the weakest part of the equipment. Furthermore, the dielectric strength of the insulators is affected by local field distortions in the presence of metallic particles. Therefore, in the present study, we report the effect of the magnitude and polarity of the

pre-stressed DC voltage on the particle initiated breakdown characteristics around simple shaped spacer under standard LI (1.2/50 μ sec) superimposed on the pre-stressed DC voltage in the quasi-uniform field gap. Consequently, it is found that the surface charges accumulated on the spacer in the vicinity of the particle tip under the pre-stressed DC voltage play an important role in the breakdown phenomenon. The results are discussed on the basis of the dust figure technique and also on the breakdown voltage / delay time characteristics.

2. Experimental Setup and Method

Although the basic configuration of electrode system in GIS is commonly coaxial, non-uniform electric field distribution along the electrode surface is also found at the ends of the electrodes, joints, particle traps, around spacers and so on. Therefore, in order to simulate the gap configuration commonly found in GIS which has non-uniform field distribution along the electrode surface, the electrodes arrangement as shown in Fig.1 was used. This electrode system consists of a pair of circular stainless steel

Fig. 1. Electrode and coordinate system

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Fig. 2. Schematic diagram of experimental setup

Fig. 3. Applied voltage waveforms (before breakdown)

electrodes. The high voltage electrode (H.V.E.) designed such that the angle between the edge and the centre of the circular H.V.E. was 3.5° ⁽⁸⁾⁽⁹⁾ to the horizontal grounded plane electrode (G.E.) and a PTFE (Polytetrafluoro ethylene) cylindrical shaped spacer of height 10 mm and diameter 20 mm was mounted in the centre between the two electrodes as shown in Fig.1. The electrode arrangement (Fig.1) is mounted in the circuit diagram as shown in Fig.2. This circuit is used to superimpose the LI on the pre-stressed DC applied voltage.

By using the circuit shown in Fig.2, different unipolar and bipolar superimposed impulse stresses can be generated as shown in Fig.3 i.e. positive LI was superimposed on $(\pm)$ DC voltages. Moreover, negative LI can also be superimposed on $(\pm)$ DC voltages.

Contaminating particles commonly found in GIS are non-spherical, rather elongated or needle-shaped. Therefore, in order to simulate the particles commonly found in GIS, every experiment was conducted with an aluminum wire particle (length $L=3\text{mm}$ and dia. $D=0.25\text{mm}$). The ends of these wire particles were not rounded to make it similar to particles commonly found in actual GIS. Distance between the conducting particle's centre and the G.E. along the spacer surface is denoted by h [mm], as shown in Fig.1.

The superimposed impulse voltage breakdown characteristics were determined for pre-stressed DC voltage of 0, ± 4 , ± 6 and $\pm 8\text{kV}$, respectively. Before, the application of LI, positive or negative DC voltage was gradually increased at a rate of 0.5kV/s till the required level for about 5 minutes and then LI voltage of desired polarity and level was applied. The flashover voltage was measured with special compact voltage divider with a response time of about 7ns and was recorded by digital oscilloscope. The critical flashover voltage was determined as follows. The composite voltage was applied and the flashover voltage V_{BD} was determined by "Up and Down" method by increasing or decreasing the magnitude of superimposed impulse voltage by a step of $\sim 3\text{kV}$. The total number of shots were limited and varied in

Fig. 4. Applied voltage waveforms (after breakdown)

the range of 20-25 applications. The 50% V_{BD} was calculated and plotted alongwith the 1σ of the upper and lower limit of 50% breakdown voltage. After each breakdown test, the V_{BD} (kV) and delay time t_d (μsec) as shown in Fig.4, were noted.

After each experimental run at a given particle location, the spacer surface was cleaned with soft tissue saturated with ethanol to remove surface and bulk charges and then dried. To make the experiment easy, every experiment was conducted in the laboratory air controlled at 1 atm., around 50% of relative humidity and 20°C .

3. Experimental Results and Discussion

3.1 Particle Motion and Breakdown Characteristics around Spacer under DC Voltage

The forces acting on the wire particle in the non-uniform field around the spacer are, (i) Coulomb force, (ii) gravitational force, (iii) electrical gradient force towards the high field region, (iv) viscous force, (v) repulsive force at the instant of impact with an electrode and (vi) image force that acts on the particle when the particle is close to the spacer ⁽³⁾⁽¹⁰⁾.

Keeping in view the above mentioned forces acting on the particle, the authors already reported the wire particle motion behavior and breakdown characteristics around different shaped spacers in non-uniform field gap ⁽¹⁰⁾. The free wire particle motion behavior and breakdown characteristics under DC voltage is briefly explained below.

(1) Motion behavior It was found that under DC voltage, the particle around the spacer tends to move towards the spacer, oscillate along the spacer surface and finally adhere to the spacer. When the voltage was off, the particle remains adhered to the spacer and can hardly escape. This particle's firm adhesion with the spacer is due to the increased image force between the particle and the spacer surface. A schematic diagram of particle motion behavior around simple shaped spacer is as shown in Fig.5.

The reason why the wire particle under DC voltage can firmly adheres to the spacer, can be explained as follows. When a charged particle is in the vicinity of a spacer, despite various forces acting on the free conducting particle as explained above, an additional force known as "image force or the induced electrostatic force" also acts on the particle in the direction perpendicular to the spacer surface. The image force (F_i) acting on a wire particle around a spacer is given by equation, as stated below ⁽¹⁰⁾,

Fig. 5. Free wire particle motion behavior around spacer

Fig. 6. Simulation results of image force acting on particle around T-SP

$$F_i = \left[\frac{\lambda^2}{4\pi\epsilon_0 d^2} \right] \left[\frac{\epsilon_2 - \epsilon_1}{\epsilon_2 + \epsilon_1} \right] \times L^2$$

where, $\lambda = q/L$ i.e. charge per unit length on the wire particle and d (mm) is the distance of particle from the spacer.

If we numerically calculate the various forces acting on the particle i.e. $F_q (= qE_r)$, $F_g (= \pi r_p^2 L g(\rho_p - \rho_0))$ and F_i , etc., the results can be seen from Fig.6, which indicates that in the vicinity of the spacer, the only effective force on the particle is F_i due to which the particle remains adhered to the spacer surface.

It was experimentally confirmed that under DC voltage, the free wire particle without steady corona discharge can easily adhere to the spacer. Whereas, a wire particle with steady corona discharge can hardly adhere to the spacer⁽⁸⁾.

(2) Breakdown Characteristics under DC Voltage It was found that under the DC applied voltage, the breakdown characteristics for initially free but adhered to spacer after levitation and for artificially fixed particle were almost in the same range. Whereas, the corona inception voltage (V_c) for the adhered particle dispersed widely around the V_c for artificially fixed particle⁽¹¹⁾. This can be briefly explained as follows.

The field strength at the tip of an adhered particle is stronger than that of an artificially fixed particle due to charge magnitude carried by particle. So, the minimum value of V_c for a free conducting particle would be lower than that of an artificially fixed particle. However, when a charged particle adheres to a spacer, corona discharge may also occur between the particle and spacer. Here, the corona discharge from the particle adhered to the spacer is called as partial discharge (PD). In this case, the charge on the particle is reduced and at the same time the field distribution will also be changed by the presence of surface

charges produced by PD. In this case, the subsequent corona can hardly occur until the applied voltage is significantly increased. Since V_c is measured after the particle adhesion with the spacer, the above mechanism might effect the relation between magnitude of V_c 's for artificially fixed and electrostatically adhered particles.

3.2 Breakdown Characteristics around Spacer under Impulse Voltage Superimposed on Pre-stressed DC As explained in section 3.1(2) above, that negligible effect on the breakdown characteristics was observed in case of adhered or artificially fixed particle. Therefore, in case of composite overvoltage, in order to make the experiments easy, the particle is artificially fixed at $h=1.5$ mm (attached to G.E.), 4.5mm and 8.5mm (attached to H.V.E.), respectively. The 1σ breakdown voltage characteristics under (1) unipolar and (2) bipolar superimposed impulse voltages, were investigated while changing the magnitude of pre-stressed DC voltage.

(1) Unipolar Superposition In this case the pre-stressed DC and the superimposed impulse voltages are of the same polarity. The experimental results of 50% V_{BD} were calculated and plotted alongwith 1σ upper and lower limit of the 50% breakdown voltages for positive LI superimposed on positive DC and negative LI superimposed on negative DC are as shown in Fig.7(a) and (b), respectively.

The presence of spacers in clean conditions does not alter appreciably the breakdown strength under the DC voltage as well as under composite overvoltages. It was observed that breakdown voltage in both cases (i.e. under the DC voltage only and under superimposed impulse) was in the range about ~ 24 kV. Whereas, the particle initiated breakdown voltage shows strong polarity as well as particle adhesion position dependence along the spacer surface under DC as well as under the superimposed impulse voltages, as shown in Fig.7. In case of $\pm$ DC applied voltage only, the breakdown voltage data is represented by " ", whereas the LI is indicated by " ". Furthermore, the breakdown under the composite overvoltage with prestressed DC applied voltage of ± 4 kV is indicated by " ", ± 6 kV as " " whereas ± 8 kV is represented by " ". It was observed, that the flashover voltage in case of superimposed impulse voltage depends on the magnitude of the pre-stressed DC applied voltage. For example, $V_{BD}(\text{Impulse}) > V_{BD}(4\text{kV}) > V_{BD}(8\text{kV}) > V_{BD}(6\text{kV}) > V_{BD}(\text{DC only})$. These results can be explained as follow.

In case of LI voltage only, as the formation time for the space charges that are responsible to trigger breakdown, is very short. Therefore, for flashover, higher magnitude of LI voltage is needed as compared to DC voltage only. However, in case of composite overvoltage ($V_{LI} + V_{DC}$), the breakdown characteristics depends on the magnitude of the pre-stressed DC voltage. This is because of the space charges accumulated near the tips of the particle due to streamer corona discharge. For example, under $V_{DC}=4$ kV, no corona current pulses were observed, therefore negligible effect of pre-stressed DC ($= 4$ kV) as compared to $V_{BD}(\text{Impulse})$ only, was experienced. Whereas, under $V_{DC}= 6$ kV, corona current pulses were observed, therefore the space charges due to this streamer corona discharge reinforces to reduce the magnitude of V_{BD} . Furthermore, in case of $V_{DC}=8$ kV, fine luminous discharge at the tip of the particle due to corona stabilization, was observed. Hence slightly higher impulse voltage was needed under $V_{DC}= 8$ kV as compared to $V_{DC}= 6$ kV due to "Hermstein Sheath" effect. Therefore, the characteristics under the various magnitudes of the

(a) $[(+V_{DC} + (+)V_{LI})]$

(b) $[(-V_{DC} + (-)V_{LI})]$

Fig. 7. Breakdown characteristics under unipolar superimposed voltages

Fig. 8. Breakdown characteristics under bipolar superimposed voltages $[(-)V_{DC} + (+)V_{LI}]$

Fig. 9. Characteristics of superimposed impulse V_{BD} on the magnitude and position of the pre-stressed DC

pre-stressed DC voltages were obtained as $V_{BD}(4kV) > V_{BD}(8kV) > V_{BD}(6kV)$.

(2) **Bipolar superposition** In case of bipolar superposition, the pre-stressed DC voltage and the superimposed impulse are of opposite polarity. The breakdown voltage characteristics in case of bipolar superposition i.e. positive LI superimposed on negative pre-stressed DC voltage, are as shown in Fig.8. It was observed that the particle initiated breakdown characteristics along the spacer depends on the net polarity of the composite overvoltage. In this case too, the net composite overvoltages show strong position as well as polarity dependency. However, no specific sequence in the V_{BD} characteristics was noticed as observed and already explained above in section 3.2(1) above in case of unipolar superposition. Moreover, in this case, slight decrease in the magnitude of V_{BD} was observed as compared to unipolar.

3.3 Influence of the Magnitude and Polarity of the Pre-stressed DC Voltage The effect of magnitude and polarity of the pre-stressed DC applied voltage is also shown in Fig.9. In case of unipolar superposition (Quadrant I & III of Fig.9), it is noteworthy, that if no corona discharge occurs under pre-stressed $V_{DC}(=4kV)$, negligible effect of the pre-stressed DC was observed

compared to $V_{BD}(LI)$ only). Whereas, if streamer corona discharge occurs ($V_{DC}=6kV$), the magnitude of V_{BD} tends to decrease. Further, due to corona stabilization effect by "glow corona discharge" under pre-stressed $V_{DC}=8kV$, the V_{BD} characteristics showed an increasing tendency. This tendency can be explained by the Hermstein sheath effect phenomena. Similar phenomenon was also observed when the negative lightning impulse was superimposed on negative DC, as shown in Fig.7(b) as well as shown in quadrant-III of Fig.9.

Furthermore, in case of bipolar superposition (Quadrant II & IV of Fig.9), a slow decrease in the flashover voltage under the superimposed impulse voltage with the increase in pre-stressed DC voltage can be noticed even in pre-stressed DC voltage regions below corona inception.

3.4 Dust Figure Results The distribution of the surface charges accumulated around the metallic particle tips on the tested spacer surface due to pre-stressed DC applied voltage were obtained using the dust figure results. The dust used in this method is the negatively charged fine powder used as a toner is the ordinary copier machine. The technique works on the principle that the negatively charged particle (toner) cling to the spots of the spacer surface where the positive residual charges

Fig. 10. Dust figures results after the application of pre-stressed DC voltage

Fig. 11. Dependence of delay time on the LI voltage superimposed on pre-stressed DC

accumulate, i.e., the technique relies on the existence of residual charges. Fig.10(a)~(c) are the examples of the observed dust patterns appeared just after the pre-stressed DC voltage application of various voltage levels. These dust figures can easily explain the results described in sections 3.2 and 3.3, above.

Similarly, the surface charges around the needle tip enhance the field strength in the vicinity of the needle tip when the impulse voltage has the opposite polarity to the surface charge. Therefore, continuous slow decrease in the flashover voltage was observed in case of bipolar composite overvoltages, as stated in section 3.3 above.

3.5 Delay Time (t_d) Characteristics The delay time (t_d) characteristics in case of composite overvoltages for various magnitudes of pre-stressed DC applied voltages, are as shown in Fig.11. These characteristics can be briefly explained as follows.

For example, at composite overvoltage of $V=15.8\text{kV}$ (shown in Fig.11), the delay time characteristics of flashover voltage under the various magnitudes of pre-stressed DC voltages are t_3 (6kV) < t_2 (8kV) < t_1 (4kV) were noticed. Again this can be easily explained based on corona stabilization (Hermstein sheath effect) as well as on the dust figure results, as described in previous sections.

4. Concluding Remarks

In this study, the effect of the magnitude and polarity on the particle initiated breakdown characteristics around a simple

shaped spacer in quasi-uniform field gap under lightning impulse voltage superimposed on pre-stressed DC voltage is investigated experimentally. The results are discussed on the basis of dust figure results as well as on the delay time characteristics and are summarized as below:

The particle initiated breakdown voltage shows strong polarity as well as particle adhesion position dependence along the spacer surface under DC as well as under the superimposed impulse voltages. The magnitude of pre-stressed DC applied voltage plays an important role in the composite over-voltage breakdown characteristics. It was found that the space charges around the wire particle tips changes the local electric field, which consequently effects the breakdown voltage magnitude. This phenomena should be taken into account while considering the design of actual GIS.

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