Effect of various excitations on the performance of gas insulated substations with metallic particle contamination

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Abstract. Compressed Gas Insulated Substations (GIS) consist basically of a conductor supported on insulators inside an enclosure, which is filled with sulfur hexafluoride gas $SF_6$. The voltage withstand capability of $SF_6$ bus duct is strongly dependent on field perturbations such as those caused by conductor surface imperfections and by conducting particle contaminants. The particles can be lifted by the electric field and migrate to the conductor or insulators where they initiate breakdown at voltages significantly below the insulation characteristics of the $SF_6$ gas. In this paper for optimized design of GIS by changing the inner and outer diameter to 40mm and 137mm is considered for analysis and compared with a single phase enclosure with outer diameter as 152mm and inner conductor diameter of 55mm with aluminum, copper and silver particles of size 10mm in length and 0.25 as radius present on the enclosure. Very often, the operation of electrical equipment may seem normal, but under a certain combination of conditions, the impact of harmonics is enhanced, with damaging results. To study the behavior of Metallic Particles in the presence of harmonics different types of input voltage waveforms like square, triangular and Asymmetric sine wave are applied to single-phase gas insulated busduct. The maximum movement of Aluminum, Copper and Silver particles for applied voltages of 75 kV, 100 kV, 132 kV, 145 kV, and 200 kV for Triangular, Square and Asymmetric Sine wave are determined. The results have been presented and analyzed.

Keywords: electric field, gas insulated substations, metallic particles, particle contamination

1 Introduction

Sulphur hexafluoride is the electric power industry’s preferred gas for electrical insulation and, especially, for arc quenching current interruption equipment used in the transmission and distribution of electrical energy. Compressed Gas Insulated Substations (GIS) and Transmission Lines (CGIT) consist basically of a conductor supported on insulator inside an enclosure, which is filled with $SF_6$ gas. As one is aware of the attractive features of a Gas Insulated Substation (GIS), they also suffer from certain drawbacks. One of them is the outage due to seemingly innocuous conducting particles, which accounts for nearly 50% of the GIS failures. The contaminants can be produced by abrasion between components during assembly or operations. Flash over in a GIS is, in general, associated with longer outage times and greater costs than in a conventional air insulated substation. A conducting particle can short-circuit a part of the insulation distance, and thereby initiate a breakdown, especially if electrostatic forces cause the particle to bounce into the high field region near the high voltage conductor.

A study of CIGRE group suggests that 20% of failure in GIS is due to the existence of various metallic contaminations in the form of loose particles. These particles may exist on the surface of support insulator,
enclosure or high voltage conductor. Under the influence of high voltage, they can acquire sufficient charge and randomly move in the gap due to the variable electric field. Several authors have reported the movement of particles with reference to a few parameters. The presence of contamination can therefore be a problem with gas-insulated substations operating at high fields [2, 4].

The purpose of this work is to develop techniques, which will formulate the basic equations that will govern the movement of metallic particles like aluminum, copper and silver particles. The specific work reported deals with the charge acquired by the particle due to macroscopic field at the tip of the particle, the force exerted by the field i.e., electric field on the particle, drag due to viscosity of the gas and random behavior during the movement. In this paper an optimized design of GIS by changing the inner and outer diameter to 40mm and 137mm is considered for analysis and compared with a single phase enclosure with outer diameter as 152mm and inner conductor diameter of 55mm with aluminum, copper and silver particles of size 10mm in length and 0.25 as radius present on the enclosure. It is required to be done because competitive prices of several manufactures of GIS and cost of gas are increasing. The results will have a bearing on the extent of reduction of inner diameter of the HV electrode and the overall volume. This will provide information on the extent of particle movement for the same condition of the gas and particle geometry. Power systems designed to function at the fundamental frequency are prone to unsatisfactory operation and, at times, failure when subjected to voltages and currents that contain substantial harmonic frequency elements. The movement pattern for higher voltages class has been also obtained.

2 Modelling of gas insulated busduct

Fig. 1 shows a typical horizontal busduct comprising of an inner conductor and an outer enclosure, filled with $SF_6$ gas is considered for the study. A particle is assumed to be at rest at the enclosure surface, until a voltage sufficient enough to lift the particle and move in the field is applied. After acquiring an appropriate charge in the field, the particle lifts and begins to move in the direction of the field after overcoming the forces due to its own weight and drag. For particles on bare electrodes, several authors have suggested expressions for the estimation of charge on both vertical/horizontal wires and spherical particles. The equations are primarily based on the work of Felici[2]. The lift-off field for a particle on the surface of an electrode can be estimated by solving the following equations.

### 2.1 Electrostatic force

The charge acquired by a vertical wire particle in contact with a naked enclosure can be expressed as:

$$Q_{net} = \pi \varepsilon_0 \frac{1^2 E(t_0)}{\ln\left(\frac{2l}{r}\right) - 1}$$

where $Q_{net}$ is the charge on the particle until the next impact with the enclosure, $l$ is the particle length, $r$ is the particle radius, $E(t_0)$ is the ambient electrical field at $t = t_0$.

The charge carried by the particle between two impacts has been considered constant in the simulations. This is a reasonable assumption when the applied voltage is low or when the gas pressure is high. Disregarding the effect of charges on the particle, the electric field in a coaxial electrode system at position of the particle can be written as:

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\[ E(t) = \frac{\hat{V} \sin \omega t}{[r_0 - y(t)] \ln\left[\frac{r_0}{r_i}\right]} \]  

where \( \hat{V} \sin \omega t \) is the supply voltage on the inner electrode, \( r_0 \) is the enclosure radius, \( r_i \) is the inner conductor radius, \( y(t) \) is the position of the particle which is the vertical distance from the surface of the enclosure towards the inner electrode. The electrostatic force is

\[ F_e = K Q_{net} E(t) \]  

Where \( K \) is a corrector and is a factor less than unity.

However, for length-to-radius ratios greater than 20 the correction factor, \( K \), is close to unity. In the simulations performed in this work, the smallest ratios are \( 20(1 = 5 \text{mm and } r = 0.25 \text{mm}) \); hence the correction factor was neglected in the simulations.

### 2.2 Gravitational force

The gravitational force is given by:

\[ mg = \pi r^2 1pg \]  

### 2.3 Drag force

\[ F_d = y\pi r (6\mu K_d(y) + 2.656[\mu \rho_g 1y]^{0.5}) \]  

where \( y \) is the velocity of the particle, \( \mu \) is the viscosity of the fluid \((SF_6: 15.5 \times 10^{-6} \text{kg/m/s at } 20^\circ \text{C})\), \( r \) is the particle radius, \( \rho_g \) is the gas density, \( l \) is the particle length, \( K_d(y) \) is a drag coefficient.

Using the above forces, the particle motion equation can be expressed as

\[ m \frac{d^2y}{dt^2} = F_e - mg - F_d \]  

The influence of gas pressure on the drag force is given by empirical formula.

\[ \rho_g = 7.118 + 6.332p + 0.2032p \]  

where \( \rho_g = \text{density of gas, } p = \text{Pressure of gas} \) and \( 0.1 < p < 1 \text{MPa} \), So, two initial conditions are necessary for solving

\[ m \dot{y}(t = 0_) = -Rm \dot{y}(t = 0) \]  

and \( y(t = 0_) = 0 \)  

where \( R \) is the restitution coefficient given by the ratio of incoming-to-outgoing impulses.

The restitution coefficient for copper and aluminum particles seem to be in the range of 0.7 to 0.95: \( R = 0.8 \) implies that 80% of the incoming impulse of the particle is preserved when it leaves the enclosure.

The motion equation using all forces can therefore be expressed as [4].

\[ m\ddot{y}(t) = \left[ \pi \geq 0 \frac{1^2 E(t_0)}{\ln\left(\frac{r_0}{r_i}\right)} - 1 \right] \times \frac{V \sin \omega t}{[r_0 - y(t)] \ln\left(\frac{r_0}{r_i}\right)} - mg - \dot{y}(t)\pi r (6\mu K_d(y) + 2.656[\mu \rho_g 1y(t)]^{0.5}) \]  

The motion equation is a second order non-linear differential equation and in this paper, the equation is solved by using Runge-Kutta 4\textsuperscript{th} Order Method.
3 Results and discussions

Tab. 1 shows the radial movement of Aluminum, Copper and Silver particles in a 1-Phase Gas Insulated Bus duct with 152/55 mm enclosure for applied voltages of 75 KV, 100 KV, 132 KV, 145 KV, and 200 KV for Triangular, Square and Asymmetric Sine waves. The input voltage waveforms applied to single-phase gas insulated busduct have been given in Fig. 2 to Fig. 4. Fig. 2 shows triangular waveform with magnitude 200 kV. Fig. 3 shows square waveform with magnitude 200 kV. Fig. 4 shows asymmetric waveform with magnitude 200 kV. The movement of Aluminum, Copper and Silver particles for applied voltages of 75 KV, 100 KV, 132 KV, 145 KV, and 200 KV in a 137/40 enclosure for Triangular, Square and Asymmetric Sine wave are given in Tab. 2. Fig. 5 to Fig. 22 shows the movement patterns of Copper, Aluminum and Silver particles with the application of Triangular, Square and Asymmetric Sine wave for both the busducts.

As the applied voltage increases the maximum radial movement also increases as given in Tab. 1 and Tab. 2. Further calculations may reveal the limiting voltage to enable the particle to reach the high voltage conductor. It is also observed that the movements are significantly higher in case of a 152/55 mm electrode system compared to 137/40 mm electrode systems. The main reason for the lower movement is the lower electric field inside the busduct. For both particles (Al and Cu) the nature of movement is similar. However the maximum movement for aluminum particle is higher than that of the copper particle. This is expected since aluminum particle is lighter.

![Fig. 2. Triangular /200 kV](image1)

![Fig. 3. Square /200 kV](image2)

![Fig. 4. Asymmetric /200 kV](image3)

Table 1. Variation of axial and radial movement of aluminum, copper and silver particles in single phase GIB with application of triangular, square and asymmetric sine waves

<table>
<thead>
<tr>
<th>Type</th>
<th>Max. Radial Movement (mm) 152/55 Enclosure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Triangular Input</td>
</tr>
<tr>
<td>75</td>
<td></td>
</tr>
<tr>
<td>Al</td>
<td>41.12</td>
</tr>
<tr>
<td>Cu</td>
<td>15.48</td>
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<tr>
<td>Ag</td>
<td>12.36</td>
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<td>100</td>
<td></td>
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<tr>
<td>Al</td>
<td>59.37</td>
</tr>
<tr>
<td>Cu</td>
<td>29.90</td>
</tr>
<tr>
<td>Ag</td>
<td>26.03</td>
</tr>
<tr>
<td>132</td>
<td></td>
</tr>
<tr>
<td>Al</td>
<td>C.G</td>
</tr>
<tr>
<td>Cu</td>
<td>42.4</td>
</tr>
<tr>
<td>Ag</td>
<td>22.49</td>
</tr>
</tbody>
</table>

4 Conclusion

It has been observed that metallic particle contamination is often present in GIS and such contamination adversely affects the insulation integrity. In this paper for optimized design of GIS by changing the inner and
Table 2. Variation of axial and radial movement of aluminum, copper and silver particles in single phase GIB with application of triangular, square and asymmertric sine waves

<table>
<thead>
<tr>
<th>Voltage (kV)</th>
<th>Type</th>
<th>Max. Radial Movement (mm) 137/40 Enclosure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Triangular Input</td>
</tr>
<tr>
<td>75</td>
<td>Al</td>
<td>16.34169</td>
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<tr>
<td></td>
<td>Cu</td>
<td>2.327303</td>
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<td>100</td>
<td>Al</td>
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<td></td>
<td>Cu</td>
<td>6.10086</td>
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<tr>
<td></td>
<td>Ag</td>
<td>3.612827</td>
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<tr>
<td>132</td>
<td>Al</td>
<td>33.82981</td>
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<td></td>
<td>Cu</td>
<td>13.74521</td>
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<tr>
<td></td>
<td>Ag</td>
<td>11.04546</td>
</tr>
</tbody>
</table>

Fig. 5. Movement pattern for triangular wave Al/75kV/10 mm/0.5 mm radius

Fig. 6. Movement pattern for triangular wave Cu/75kV/10 mm/0.5 mm radius

Fig. 7. Movement pattern for triangular wave Ag/75kV/10 mm/0.5 mm radius

Fig. 8. Movement pattern for square wave Al/75kV/10 mm/0.25 mm radius

Fig. 9. Movement pattern for square wave Cu/75kV/10 mm/0.25 mm radius

Fig. 10. Movement pattern for square wave Ag/75kV/10 mm/0.25 mm radius

Fig. 11. Movement pattern for Asymmetric wave Al/75kV/10 mm/0.25 mm radius

Fig. 12. Movement pattern for Asymmetric wave Cu/75kV/10 mm/0.25 mm radius

Fig. 13. Movement pattern for Asymmetric wave Ag/75kV/10 mm/0.25 mm radius

Fig. 14. Movement pattern for triangular wave Al/75kV/10 mm/0.25 mm radius/137 mm-40 mm enclosure
outer diameter is considered for analysis. It is required to be done because competitive prices of several manufacturers of GIS and cost of gas are increasing. The results will have a bearing on the extent of reduction of inner diameter of the HV electrode and the overall volume. This will provide information on the extent of particle movement for the same condition of the gas and particle geometry. Power systems designed to function at the fundamental frequency are prone to unsatisfactory operation and, at times, failure when subjected to voltages and currents that contain substantial harmonic frequency elements. Very often, the operation of electrical equipment may seem normal, but under a certain combination of conditions, the impact of harmonics is enhanced, with damaging results. To study the behavior of Metallic Particles in the presence of harmonics different types of input voltage waveforms like square, triangular and Asymmetric Sine wave are applied to single-phase gas insulated busduct. The maximum movement of Aluminum, Copper and Silver particles for applied voltages of 75 kV, 100 kV, 132 kV, 145 kV, and 200 kV for Triangular, Square and Asymmetric Sine wave are determined. The results show that the maximum movement is decreased in 137mm/40mm bus duct than with 152mm/55mm bus duct as the electric field of the bus duct conductor is decreased.

References


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