Inception Voltage of Corona Discharge from Suspended, Grounded and Stressed Particles in Uniform-Field Gas-Insulated-Gaps at Varying Pressures

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Abstract—In this paper, a criterion is developed for computing the inception voltage of negative corona from a particle irrespective of its position in a uniform field gap between two parallel plates. The gap is positioned in air or SF\textsubscript{6} at varying pressure. The particle takes different positions in the gap; in touch with the stressed plate, suspended in the gap, and near to the ground plate. The criterion is a formulation of the condition necessary for the recurrence of electron avalanches growing in the vicinity of the particle. This calls for a method to be proposed based on the charge simulation technique for evaluating the electric field in the vicinity of spherical and wire particles where avalanches grow. An experimental step-up has been built up to measure corona inception voltage in air. The computed inception voltage values agreed reasonably with those measured experimentally in air and SF\textsubscript{6} for spherical and wire particles, irrespective of their positions in the gap. The increase of the computed inception voltage with the increase of gas pressure agreed reasonably with that obtained experimentally.

Keywords—Corona discharge, inception voltage, electron avalanche, gas-insulated gaps, gas pressure, spherical particles, wire particles

I. INTRODUCTION

The development of gas-insulated systems (GIS) has made rapid progress in the last few years. Practically, GIS is normally operated at pressures above 1atm and the breakdown phenomenon depends on gas pressure. Free conducting particles could reduce drastically the insulation strength in such systems. Intensive experimental studies have been made to determine the effects of particle size, shape and position in the gap on the breakdown voltage [1]. A criterion was developed for computing the discharge inception voltage in three-electrode systems, i.e. inception voltage from free particles existing in a uniform field gap [2]. The particles pick up a potential depending on its position within the electrode spacing.

A conducting particle situated on an electrode in a uniform field gap acquires a charge which is a function of the applied electric field and the size, shape and orientation of the particle. When the electrostatic force on the particle exceeds the gravitational force, the particle will lift [3]. Once the particle is lifted, the attraction force on the particle due to the image charge further promotes the lifting effect.

It is well known that free conducting particles in gas insulated power apparatus can cause a serious reduction of the insulations strength. In practical systems, it is very difficult to avoid metallic particle contamination due to imperfections in fabrication and maintenance, mechanical abrasions, deterioration of spacers, movement of conductors under load cycling and vibrations during shipment. Such particles are known to reduce drastically the corona inception and breakdown voltages as a result of their movement in the electric field [4]. In a uniform field gap, an infinite mathematical series was proposed [4] to express the ratio of the electric field value at the particle surface to that of the uniform field.

Experiments under particle conditions in SF\textsubscript{6} revealed that the breakdown voltage was decreased due to mutual interference of corona discharges from both particle tips. However, the reduction in breakdown voltage by the particle was small compared with that one in the air gap [5]. Particle-triggered corona phenomena in SF\textsubscript{6} gas due to its electro negativity are complicated and the influence of mutual interference of corona from both tips of particle on the corona activity is small as compared to those in air gap.

This paper presents a mathematical modeling of the inception voltage of corona discharge from a particle in uniform field gaps between two parallel plates. The inception voltage in air and SF\textsubscript{6} is obtained by formulating the conditions necessary for the discharge to be self sustained. The model takes into account all the individual processes and events, e.g. gas ionization, attachment, photo-ionization, etc, thought to be effective in the discharge process. As these events are field dependent, the accurate charge simulation technique [6] and the method of images are used for field calculation. The inception voltage is computed and measured in air in the laboratory. The computed inception voltages agreed well with those measured experimentally by the authors in air and by others [5] in SF\textsubscript{6} for spherical and wire particles whose major axis extends along the gap axis.

First, the method of computing the applied field between the two parallel plates and its distortion by the particle is explained. Then, the mathematical modeling of the discharge inception is presented. Finally, the results obtained are discussed and compared with the corresponding measured values.

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II. ELECTRIC FIELD CALCULATION

Fig. 1 shows a two parallel plate electrode system with free spherical and wire conducting particles located in the gap between the plates. The gap spacing is $H$. The spherical particle has radius $r$ and spaced $S$ from the ground plate. Therefore, the particle height $h_p$ above the ground plate is equal to $S + r$, Fig. 1-a. The wire particle has radius $r$ and length $L$ and spaced $S$ from the ground plate, Fig. 1-b. The particle picks up a potential $V_P$ depending on the applied voltage $V$ and the particle position with respect to the stressed plate.

A. Charge Simulation Technique

The charge simulation method [6] is used to compute the potential and the electric field in the space surrounding the particle between the two parallel plates. The simulation charges are rings for the stressed plate and the particle. Image charges with respect to the ground plate are considered. This ensures that the ground plate is kept at zero potential.

The stressed plate is simulated by a set of $N_1$ ring charges. Each ring has a coordinate $z(j)$ related to its radius $r(j)$ as expressed by equation (1):

$$z(j) = H + r(j) \quad j = 1, 2, \ldots, N_1$$

The value of the $r(j)$ extends along the radial direction at gradually increasing displacements as shown in Fig. 1.

Either the spherical or wire particle is simulated by a set of $N_2$ ring charges inside the particle. The radius $r(j)$ of the ring charges is chosen equal to a fraction $\beta$ from the particle radius at the same $z$ level. The rings are uniformly distributed along the particle height as shown in Fig 1.

A.1 Electric Potential

The potential at any point $G(r, z)$ is the algebraic sum of the potential due to the unknown simulation charges and their images;

$$V_o(r, z) = \sum_{j=1}^{N_1+N_2} Q(j) \cdot P(j)$$

where,

$$P_j = \frac{1}{4 \pi \varepsilon} \cdot \frac{2}{\pi} \left[ \frac{K(k_1)}{\alpha_1} - \frac{K(k_2)}{\alpha_2} \right]$$

where,

$$\alpha_1 = \sqrt{(r + r_j)^2 + (z - z_j)^2}$$
$$\alpha_2 = \sqrt{(r + r_j)^2 + (z + z_j)^2}$$
$$k_1 = 2 \cdot \frac{r_j \cdot \alpha_1}{\alpha_2}$$
$$k_2 = 2 \cdot \frac{r_j \cdot \alpha_2}{\alpha_1}$$

and $K(k)$ is the complete elliptic integral of the first kind.

A.2 Boundary conditions

The first boundary condition is that the potential at any boundary point $(r_p, z_p)$ on the stressed plate electrode –being of equipotential surface- must be equal to the known applied negative voltage $V_a$, i.e.

$$V(r_p, z_p) = V_a$$

The second boundary condition is that the potential at any boundary point $(r_p, z_p)$ on the particle -being of equipotential surface- is equal to the unknown potential $V_p$ picked up by the particle, i.e.

$$V(r_p, z_p) = V_p$$
The potential at any point on the ground plate electrode is zero and is automatically satisfied by considering the image charges which are symmetrical located with respect to that plate.

For floating particles between the gap plates, the sum of the charges simulating the particle must be equal to zero, i.e.

\[ \sum_{j=N_1+1}^{N_2} Q_j = 0 \]  

(5)

**A.3 Boundary points**

(1) To satisfy the boundary conditions (3) and (4), boundary points are chosen on both the stressed plate and the particle. Corresponding to each simulation charge of stressed plate, a boundary point is chosen at the same r-coordinate of the ring as shown in Fig. 1. The z-coordinate of the boundary points \( z_j \), \( j = 1, 2, 3, \ldots, N_1 \) is equal to the gap spacing \( H \).

(2) On the spherical particle surface, the angle \( \theta \) (j), Fig. 1, defines the coordinates \( r_p(j) \) and \( z_p(j) \) of the jth boundary point, \( j = N_1+1, N_1+2, \ldots, N_1+N_2 \) as given by

\[ \theta(j) = (j - N_1) \pi / (N_2+1) \]

Subsequently, the coordinates of the boundary points are expressed as:

\[ \begin{align*}
  r_p(j) &= r \sin \theta(j) \\
  z_p(j) &= (S + r) - r \cos \theta(j)
\end{align*} \]

(6)

On the wire particle surface, the coordinates \( r_p(j) \) and \( z_0(j) \) of the jth boundary points, \( j = N_1+1, N_1+2, \ldots, N_1+N_2 \) are expressed as:

\[ \begin{align*}
  r_p(j) &= r \\
  z_0(j) &= S + [L/(N_2+1)] \cdot (j - N_1)
\end{align*} \]

(7)

The number of boundary points is equal to the number of the unknown ring charges (i.e. \( N_1+N_2 \)). However, the total number of unknown is \( (N_1+N_2+1) \), as the potential \( V_p \) picked up by the particle is also an unknown. If the particle is not floating, the number of the unknowns is \( (N_1+N_2) \).

**A.4 Determination of the unknowns**

Equation (2) for the potential written at each boundary point defined above using the conditions (3) and (4) plus the supplementary condition (5) (for floating particle) form a set of linear algebraic equations whose number equals \( N_1+N_2+1 \), i.e. the number of unknowns. The values of these unknowns are determined by solving simultaneously these equations using the Gauss eliminations method [7].

**A.5 Accuracy of solution and check points**

To check the accuracy of the obtained simulation charges, check points have been chosen of the surface of the stressed plate. The check points were located mid way between the boundary points. The deviation of the computed potential at these check points from the applied voltage is a measure of the accuracy of proposed simulation method. The rms value of the potential deviation \( \Delta V \) averaged over the stressed plate should not exceed a prescribed value; \( \pm 0.01 \% \) in the present work.

**B. Electric field**

With the knowledge of the unknowns, the potential \( V_p \) picked up by the particle - being an unknown - is now defined and the components \( E_x \) and \( E_z \) of the electric field in the vicinity of the particle are computed using the following expressions [5].

\[ E_z = \sum_{j=1}^{N_1+2} \frac{Q_j}{4 \pi \varepsilon_0 x} \left\{ \left( \frac{r_{-z_j}^2}{a_1 x_j} \right)^2 + \left( \frac{r_{+z_j}^2}{a_2 x_j} \right)^2 \right\} \]

(8)

\[ \beta_1 = \sqrt{(r-r_j)^2 + z_j^2}, \quad \beta_2 = \sqrt{(r-r_j)^2 + (z+z_j)^2} \]

(9)

**III. Calculation of Corona Inception Voltage**

**A. Criterion**

When the electric field strength at the particle surface reaches the threshold value for ionization by electron collision, an electron avalanche starts to develop along the direction away from the particle as shown in Fig. 2. With the growth of the avalanche within the ionization zone of thickness \( r_i \), more electrons are developed at its head, more photons are emitted in all directions and more positive ions are left in the avalanche wake.

The number of electrons \( N_e(z) \) at a distance \( z \) from the starting point \( z = 0 \) is given by:

\[ N_e(z) = \exp \left( \int z (\alpha(z) - \eta(z)) \, dz \right) \]

(10)

The ionization and attachment coefficients depend on the electric field [8]. The electric field \( E \) is the resultant of the space-charge-free field due to the applied voltage \( V \) and the space charge field of the avalanche itself.

For a successor avalanche to be started, the preceding avalanche should somehow provide an initiating electron at the particle surface, possibly by photoemission, positive-ion impact, metastable action, or field emission, Fig. 2. Field emission is possible only at field strengths exceeding \( 5 \times 10^7 \) V/m [9]. Electron emission by positive-ion impact is more than two orders of magnitude less probable than photoemission [9]. Metastables have been reported to have an effect approximately equal to that of positive-ion impact [8].
Therefore, only the first mechanism (electron emission by photons) was considered in determining the inception voltage \( V_0 \) [10].

The number of electrons photo-emitted from the particle surface is

\[
Ne(\phi h) = \gamma_{\phi h} \int_0^\infty \alpha(z) N_e(z) g(z) \exp(-\mu z) d\zeta 
\]

(11)

where \( r_i \), the ionization-zone thickness, is the limiting value of \( z \) at which \( \alpha = \eta \), \( \gamma_{\phi h} \) is Townsend’s second coefficient due to the action of photons. \( g(z) \) is a geometry factor to account for the fact that some photons are not received by the particle [11].

The condition for a new (successor) avalanche to develop is

\[
Ne(\phi h) \geq 1 \quad (12)
\]

The inception voltage does not appear explicitly in the relation (12). However, the applied voltage affects the values of \( \alpha(z) \), \( \eta(z) \), \( \mu \) and hence, \( Ne(z) \). The inception voltage \( V_0 \) is the critical value which fulfills the equality (12).

**B. Numerical Data**

The inception voltage of corona in air and SF\(_6\) from the spherical and wire particles positioned between the two parallel plates is computed wherever the particle is close to the ground plate, suspended or in touch with the stressed plate. This calls for accurate determination of the different discharge parameters in air and SF\(_6\) in terms of the electric field [12, 13]. Appendix I reports the equations defining the discharge parameters in air and SF\(_6\).

**IV. EXPERIMNTAL SETUP AND TECHNIQUE**

**A. Setup**

Two brass disc electrodes of 50 mm diameter and 18 mm thickness forming a parallel-plate electrode system were installed inside a pressure vessel to vary the gap spacing over the range 10-20 mm. The edges of the electrodes were rounded to avoid edge flashover, Fig. 3. The vessel is designed to withstand air pressures up to 5 atmospheres.

Two shapes of particles, spherical and wire particles, were tested in the pressure vessel. The spherical particles were made of silver with radii 1.175 and 1.825 mm. The wire particles were cut from a copper wire of radius (0.125 mm) with length 4 and 6 mm. The particles were positioned between the two brass electrodes by a thin plastic rope (radius = 0.05 mm) extending parallel to electrodes as shown in Fig. 3.

A negative high D.C voltage, obtained from a half-wave rectifier circuit, was applied to the upper electrode through a limiting resistance to prevent any damage of
the instruments when flashover occurs between the electrodes. The lower electrode was grounded through a sensitive micro ammeter for measuring the corona inception voltage in air at varying pressure.

**B. Electric field**

The inception voltage is the applied voltage when the micro ammeter starts to record a reading. The inception voltage in air was measured for spherical and wire particles with different dimensions when they were near to the ground plate, suspended in the gap and in touch with the stressed plate.

**V. RESULTS AND DISCUSSION**

**A. Accuracy of proposed charge simulation technique**

For a unit applied voltage, Fig. 4 shows the computed potential with respect to the applied value along the surface of the stressed plate —being an equipotential- for spherical \((r = 0.5 \text{ mm}, S = 10^{-3} \text{ mm}, H = 15 \text{ mm})\) and wire \((r = 0.125 \text{ mm}, L = 4 \text{ mm}, S = 10^{-3} \text{ mm}, H = 15 \text{ mm})\) particles positioned in the gap. The simulation charges of the stressed plate \(N_1\) and the particle \(N_2\) were 115, 90 for spherical particle and 201, 150 for wire particle. The potential-deviation of the computed potential from the applied voltage value along the stressed plate did not exceed 0.4 %, which confirms the accuracy of the proposed simulation of surface charges on the stressed plate and the particle.

The integral of the computed electric field along the gap axis excluding the space occupied by the particle \((= \text{diameter } 2r\text{ for spherical particle and length } L\text{ for wire particle})\) is equal to the applied voltage with a deviation less than 2 %. This is another measure of the accuracy of the proposed charge simulation technique.

**B. Normalized particle-surface electric field \(E_{\text{max}}/E_0\)**

In the absence of the particle, the electric field between the plates is uniform and equal to \(E_0\). With the presence of the particle, the field is distorted in the vicinity of the particle with a value \(E_{\text{max}}\) at the particle surface. It is worthy to mention that the field pattern around the particle depends on the particle position in the gap; in touch with the stressed plate or suspended in the gap or near to the ground plate.

The present computed values of the normalized surface electric field \(E_{\text{max}}/E_0\) for a spherical particle at variable spacing \(S\) from the ground plate, agreed reasonably with those reported before [4, 14] with a deviation not exceeding 0.001 %, Fig. 5. The normalized field \(E_{\text{max}}/E_0\) decreases with the increase of the ratio \(S/r\), Fig. 5.

Fig. 6 shows that the normalized surface electric field \(E_{\text{max}}/E_0\) for a spherical particle depends only on the ratio of \(S/r\) irrespective of the value of particle radius \(r\) in
conformity to previous findings [4].

Fig. 7 shows the normalized surface electric field $E_{\text{max}}/E_0$ for a spherical particle of radius $r = 0.5$ mm positioned in a gap with spacing $H = 15$ mm. The surface electric field $E_{\text{max}}$ is more than four times that of the uniform-field value $E_0$ when the particle is very near to the ground plate, three times $E_0$ for suspended particle close to the middle of the gap and 3.4 times $E_0$ when the particle touches the stressed plate. All these values are close to those obtained before [2, 4].

Fig. 8 shows the normalized surface electric field $E_{\text{max}}/E_0$ for a wire particle of length $L = 4$ mm, radius 0.125 mm positioned vertically in a gap with spacing $H = 15$ mm. The electric field value is more than 7.2 times that of the uniform-field value $E_0$ when the particle is very near to the ground plate, 6.3 times $E_0$ value for suspended particle close to the middle of the gap and 6.8 times $E_0$ value when the particle touches the stressed plate.

C. Normalized electric field $E/E_0$ in particle vicinity

Fig. 9 shows the normalized electric field $E/E_0$ along the gap axis for a spherical particle of radius $r = 0.5$ mm, positioned in a gap with spacing $H = 15$ mm. When the
particle is positioned near the ground plate, the surface electric field value is more than 3 and 5.5 times that of the uniform field value. The normalized field $E/E_0$ decreases from its surface value and approaches the uniform-field value toward the negatively stressed plate.

Fig. 10 shows the normalized electric field $E/E_0$ along the gap axis in the vicinity of a wire particle (length $L = 4$ mm, radius $r = 0.125$ mm) positioned in a gap with spacing $H = 15$ mm. When the particle is positioned near the ground plate, the surface electric field value is more than 6 and 9.3 times that of the uniform field value. The normalized field $E/E_0$ decreases from its surface value and approaches the uniform-field value, the same as the case for spherical particle, Fig. 9.

D. Particle pick-up voltage

Fig. 11 shows the calculated space potential $V_p$ picked-up by a spherical particle of radius 0.5 mm positioned in a gap of spacing $H = 15$ mm and unit applied voltage. When the particle moves along the gap axis, the space potential picked-up by the particle increases almost linearly as the particle approaches the stressed plate.

Fig. 12 shows the calculated space potential $V_p$ picked-up by a wire particle (length $L = 4$ mm, radius $r = 0.125$ mm) positioned in a gap of spacing $H = 15$ mm and unit applied voltage. When the particle moves along the gap axis, the space potential picked-up by the particle increases almost linearly as the particle approaches the stressed plate, the same as the case for spherical particle, Fig. 11.

E. Experimental validation of results

E.1 Inception voltage for spherical particles at atmospheric pressure

Tables I and II give the computed and measured
corona inception voltages $V_0$ for spherical particles of radii 1.175 and 1.825 mm positioned in atmospheric air between the two parallel plate electrodes with spacing $H = 10$ mm. It is satisfactory that the computed inception voltages agreed reasonably with those measured experimentally with a deviation not exceeding 8.5%.

Tables I and II show that the inception voltage of corona from suspended particles is the highest where the electric field at particle surface is the lowest as depicted in Fig. 9. Not only the surface field but also the field in
the vicinity of the suspended particle is also the lowest when compared with the other positions of the particle in the gap.

On the other hand, the inception voltage for the particle in touch with the stressed plate is higher than that of the particle near to the ground plate, Tables I and II. This is because the electric field is not symmetrical along the gap axis, i.e., the field values near the stressed plate are different from those near the ground plate. Therefore, the electric field at particle surface and in its vicinity is lower for the particle in touch with the stressed plate as compared with that for the particle near the ground electrode, Fig. 9-b.

For the tested spherical particles, the inception voltage was close to the pre-breakdown voltage in agreement with previous findings [15].

Tables I and II for air. On the other hand, the inception voltage for the particle in touch with the stressed plate is higher than that of the particle near to the ground plate, Table III, the same as in air as depicted in Tables I and II. Of course, all the inception voltages values in SF6 (Table III) are higher than those in air (Tables I and II) because of the high electron affinity of SF6 compared to air. The inception voltage values in air and SF6 for the spherical particle with radius \( r = 1.825 \) mm are smaller than those for the particle with radius \( r = 1.175 \) mm irrespective of the position of the particle in the gap with spacing \( H \). This is simply attributed to smaller net gap spacing \( (H - 2r) \) between the gap plates and subsequently higher electric field values for the particle with \( r = 1.825 \) mm when compared with the other particle. It is quite clear that the larger the radius of the sphere, the lower is the electric field at sphere surface at constant gap spacing for the same applied voltage. In Fig. 13, the net gap spacing \( (H - 2r) \) is different as \( r \) is changing from 1.175 to 1.825 mm. It worthy to mention that the field values in the spacing between particle and ground plate for \( r = 1.825 \) mm are higher than for \( r = 

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### Table IV

<table>
<thead>
<tr>
<th>Position of particle</th>
<th>Computed ( V_0 ) [kV] at ( L = 4 ) mm</th>
<th>Measured ( V_0 ) [kV]</th>
<th>Deviation (%)</th>
<th>Computed ( V_0 ) [kV] at ( L = 6 ) mm</th>
<th>Measured ( V_0 ) [kV]</th>
<th>Deviation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Near to ground plate (( S = 10^{-3} ) mm spacing)</td>
<td>12.810</td>
<td>13.400</td>
<td>4.6</td>
<td>15.00</td>
<td>15.50</td>
<td>8.8</td>
</tr>
<tr>
<td>suspended (at the middle of gap)</td>
<td>15.10</td>
<td>14.500</td>
<td>3.9</td>
<td>20.225</td>
<td>20.00</td>
<td>1.1</td>
</tr>
<tr>
<td>In touch with stressed plate</td>
<td>13.210</td>
<td>14.00</td>
<td>5</td>
<td>17.810</td>
<td>16.20</td>
<td>9</td>
</tr>
</tbody>
</table>

### Table V

<table>
<thead>
<tr>
<th>Position of particle</th>
<th>Computed ( V_0 ) [kV] at ( L = 4 ) mm</th>
<th>Measured ( V_0 ) [kV]</th>
<th>Deviation (%)</th>
<th>Computed ( V_0 ) [kV] at ( L = 6 ) mm</th>
<th>Measured ( V_0 ) [kV]</th>
<th>Deviation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Near to ground plate (( S = 10^{-3} ) mm spacing)</td>
<td>12.81</td>
<td>13.4</td>
<td>4.6</td>
<td>17</td>
<td>17.00</td>
<td>8.8</td>
</tr>
<tr>
<td>suspended (at the middle of gap)</td>
<td>15.1</td>
<td>14.5</td>
<td>3.9</td>
<td>20.225</td>
<td>20.00</td>
<td>1.1</td>
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<tr>
<td>In touch with stressed plate</td>
<td>13.21</td>
<td>14</td>
<td>5</td>
<td>17.81</td>
<td>16.2</td>
<td>9</td>
</tr>
</tbody>
</table>

### Table VI

<table>
<thead>
<tr>
<th>Position of particle</th>
<th>( V_0 ) [kV] at ( L = 4 ) mm</th>
<th>( V_0 ) [kV] at ( L = 6 ) mm</th>
<th>( V_0 ) [kV] at ( L = 6 ) mm</th>
<th>( V_0 ) [kV] at ( L = 6 ) mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Near to ground plate (( S = 10^{-3} ) mm spacing)</td>
<td>12.81</td>
<td>13.4</td>
<td>4.6</td>
<td>17</td>
</tr>
<tr>
<td>Suspended (at the middle of gap)</td>
<td>15.1</td>
<td>14.5</td>
<td>3.9</td>
<td>20.225</td>
</tr>
<tr>
<td>In touch with stressed plate</td>
<td>13.21</td>
<td>14</td>
<td>5</td>
<td>17.81</td>
</tr>
</tbody>
</table>
1.175 mm. This is true in order to achieve that the integral of the electric field along the net gap spacing is constant and equal to the unit applied voltage. A smaller gas spacing corresponds to a lower pre-breakdown voltage or inception voltage.

E.2 Inception voltage for wire particles at atmospheric pressure

Tables IV and V give the computed and measured corona inception voltages $V_0$ for wire particles ($r = 0.125$ mm, $L = 4$ mm and 6 mm) positioned in atmospheric air between the two parallel plate electrodes with spacing $H = 15$ and 20 mm. It is satisfactory that the computed inception voltages agreed reasonably with those measured experimentally, with a deviation not exceeding 11.7%.

Tables IV and V indicate that the inception voltage of corona from suspended particles is the highest where the electric field at particle surface is the lowest as depicted in Fig. 10. Also, the inception voltage when the particle in touch with the stressed plate is higher than that of the particle near the ground plate, Tables III and IV. This is because the electric field at particle surface and in its vicinity is lower for the particle in touch with the stressed plate as compared with that for the particle near to the ground plate, Fig. 10-b, the same as for spherical particles, Tables I and II.

Table VI gives the computed corona inception voltages $V_0$ for wire particles ($r = 0.125$ mm, $L = 4$ mm and 6 mm) positioned in SF$_6$ gas between the two parallel electrodes with spacing $H = 15$ and 20 mm. The table gives that the inception voltage of corona from suspended particles is the highest in agreement with tables IV and V for air. On the other hand, the inception voltage for the particle in touch with the stressed plate is higher than that of the particle near to the ground plate, Table VI, the same as in air as depicted in tables IV and V. A gain, the inception voltage values in SF$_6$ (table VI) are higher than those in air (Tables IV and V).

The inception voltage values in air and SF$_6$ for wire particle with length $L = 6$ mm are smaller than those for the particle with length $L = 4$ mm irrespective of the position of the particle in the gap with spacing $H$. This is simply attributed to smaller gas spacing $(H - L)$ between the gap plates, and subsequently higher electric field values for the particle with $L = 6$ mm when compared with the other particle.

The inception voltage values in air and SF$_6$ for the same wire particle at gap spacing $H = 20$ mm are higher than those for gap spacing $H = 15$ mm irrespective of the position of the particle in the gap. This is simply attributed to the increase the gas spacing $(H - L)$ between the gap plates with a subsequent decrease of electric field in the vicinity of the particle.

E.3 Inception voltage as influenced by air pressure

The effect of pressure on the corona inception voltage from a wire particle ($r = 0.125$ mm and $L = 6$ mm) is studied by increasing the air pressure inside the vessel using a compressor.

Fig. 14 shows the increase of the computed and measured inception voltages with the increase the pressure when the particle is in touch with the stressed plate, suspended at the middle of the gap and near to the ground plate. It is satisfactory that the computed values agreed reasonably with those measured experimentally with a deviation less than 11.7%.

E.4 Inception voltage as influenced by SF$_6$ pressure

The corona inception voltage in SF$_6$ from a wire particle ($r = 0.5$ mm and $L = 10$ mm) is also computed at varying gas pressure.

Fig. 15 shows the increase of the computed inception voltages with the increase the SF$_6$ pressure when the particle is near to the ground plate. It is satisfactory that the computed values agreed reasonably with those measured experimentally [5] with a deviation less than 9.33%. 

![Fig. 14.](image-url)
E.5 Inception voltage as influenced by length of a particle positioned in SF6 at varying pressure

The effect of particle length on the corona inception voltage from a wire particle (radius \( r = 0.5 \) mm) is computed at varying SF6 pressure. Fig. 16 shows the decrease of the computed inception voltages with the increase of particle length \( L \) positioned in SF6 at varying pressure when the particle near to the ground plate. This is simply attributed to the increase of the electric field in the vicinity of the particle because of the decrease of gas spacing \( (H - L) \), where \( H \) is the gap spacing.

E.6 Inception voltage as influenced by radius of a particle positioned in SF6 at varying pressure

The effect of particle radius on the corona inception voltage from a wire particle (length \( L = 10 \) mm) is computed at varying SF6 pressure.

Fig. 17 shows the increase of the computed inception voltages with the increase of particle radius \( r \) positioned in SF6 at varying pressure when the particle near to the ground plate. This is simply attributed to the decrease of the electric field in the vicinity of the particle with the increase of its radius.

VI. CONCLUSION

From the present analysis one can conclude the following.

1. A method is proposed based on the charge simulation technique for evaluating the electric field in the vicinity of spherical and wire particles positioned in a uniform field gap (i) in touch with the stressed plate, (ii) suspended in the gap, and (iii) near to the ground plate.

2. A method is described for computing the inception voltage of negative corona from the particle irrespective of its position in the gap. The method is based on a criterion for the recurrence of electric avalanches growing in the vicinity of the particle. The electron emission by photons was considered the effective mechanism for triggering the successor avalanches.

3. Surface electric field changes from 6.3 to 7.2 times of uniform field for wire particles (of radius 0.125 mm with length 4 and 6mm) and changes from 3 to 4.2 times of uniform field for spherical particles (of radius 1.175 and 1.825 mm) in gaps with spacing in the range 10-20 mm.

4. The corona inception voltage was very close to pre-breakdown voltage in agreement with previous findings for spherical particles.

5. The corona inception voltage is the highest for suspended spherical and wire particles when compared with their positions in touch with stressed plate and near to the ground plate.

6. The voltage picked-up by the suspended spherical and wire particles increases almost linearly with the distance of the particle from the ground plate.

7. The computed inception voltage values agreed reasonably (within 10 %) with those measured experimentally for spherical and wire particles, irrespective of their positions in the gap.
(8) The computed and measured inception voltage values increase with the increase of gas pressure in the vessel where the test gap is positioned either in air and SF$_6$.

APPENDIX: THE DISCHARGE PARAMETER IN AIR AND SF$_6$

The ionization coefficient $\alpha$ in air [12].

$$\alpha/P = 4.7786 \exp (-221 P/E) \left[ \frac{V}{cm \ torr} \right] \quad 25 \leq E/P \leq 60$$

$$\alpha/P = 9.682 \exp (-2642 P/E) \left[ \frac{V}{cm \ torr} \right] \quad 60 \leq E/P \leq 240$$

And the attachment coefficient $\eta$ in air is

$$\eta P/cm^3 \ torr = 0.01298 - 0.541 x 10^{-3} (E/P) + 0.87 x 10^{-6} (E/P)^2$$

The ionization coefficient $\alpha$ in SF$_6$ [16].

$$\alpha P/(m^{-3} \ kPa^{-1}) = 0.0242 \times E/P - 1323.31.$$ 

And the attachment coefficient $\eta$ in SF$_6$ is

$$\eta P/(m^{-3} \ kPa^{-1}) = 9.7594 - 0.541 x 10^{-3} \times E/P + 0.1157 x 10^{-6} (E/P)^2$$

The photon absorption coefficient in air and SF$_6$:

$\mu = \mu_0 P$ at $P \leq 1$ atm

$\mu = \mu_0$ at $P > 1$ atm ($1$ atm = 101.3 kPa)

Where $\mu_0$ is the absorption coefficient at atmospheric pressure, $\mu_0 = 500$ m$^{-1}$ for air and $\mu_0 = 600$ m$^{-1}$ for SF$_6$.

The Townsend's second coefficient $\gamma_{ph}$ due to the action of photons is constant at its value, $3 \times 10^{-4}$ for air [17] and $8 \times 10^{-6}$ for SF$_6$ [18].

REFERENCES


