# Motion of Free Conducting Particles in $SF_6$ Insulated Systems under dc Switching Voltages

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## ABSTRACT

**The dynamic behavior of free conducting particles in $SF_6$ insulated systems under switching impulse (SI) superimposed on a dc voltage is investigated. This study includes the influence of the most important design parameters on the particle motion, such as value of dc/switching voltage ratio, particle parameters, shape of switching voltage and system configuration; parallel plane and coaxial cylinders. The computations have concluded that the behavior of contaminating conducting particles in GIS when subjected to a dc bias voltage and SI wave is more dangerous than its behavior under pure switching impulse voltage.**

## 1. INTRODUCTION

THE development and design improvement of gas-insulated substations (GIS) and transmission lines have made possible a rapid increase in their use during the last few years. Equipment of 550 kV maximum system voltage are in service, and 1200 kV development programs are in progress [1]. It is a fact that free conducting particles in GIS could reduce the insulation strength drastically. In practical systems, it is very difficult to avoid conducting particle contamination. Such contamination may be caused by mechanical abrasions, incorrect assembly procedures and movement of conductors under load cycling [2]. The particles may either be insulating or conducting. Insulating particles proved relatively innocuous [3]. Some investigations have involved the calculation and measurement of particle lift-off forces, flashover voltages and the motion of the particle under the influence of direct, alternating and impulse voltages [4–13]. ac voltage equipment is stressed by dc voltages. This stress occurs after interruption of capacitive currents, when a dc voltage is left on the load side. This phenomenon is known in the case of capacitive switching with circuit breakers, but is also known during disconnector switching, where a trapped charge is left on the load side. Depending on the discharge time constant, this charge may exist for hours or even for days. When closing the switching device, a fast transient superimposed on a dc prestress does appear on the load side. The strength under this composite stress may be important factor for GIS design [14]. The analysis of the dynamic behavior of free charged particles under this practical condition is of a great importance to design engineers. As a first step, interest is devoted here for analyzing and computing the dynamic behavior of contaminating conducting particles in compressed $SF_6$ insulated systems under switching impulse voltage, SI, superimposed on dc voltage (DC/SI). The performance of these contaminating particles under SI voltage superimposed on ac voltage will be the subject of a following paper.

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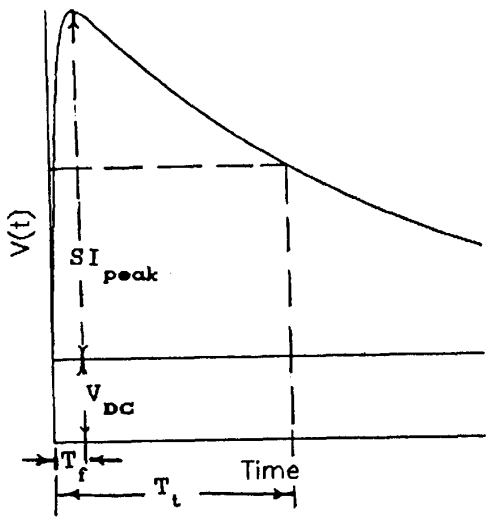


Figure 1.

SI superimposed on dc voltage $T_t$ = tail time, $T_f$ = front time.

## 2. PARTICLE MOTION UNDER DC/SI VOLTAGE

THE equation of motion of a conducting particle carrying a charge $q_o$ is

$$m\dot{X} = F_e - F_d \pm F_g \tag{1}$$

where $F_e = q_o E(t)$ is the electrostatic force [8], $E(t)$ being the ambient field, $F_d = B_1 \dot{X}$ is the drag force, $B_1$ is in general a function of the particle velocity $\dot{X}$, $F_g = mg$ is the gravity force, $m$ is the particle mass and $g$ is the gravitational acceleration.

Figure 1 shows the applied DC/SI voltage waveform, where a switching impulse 250/2500 $\mu$s is superimposed on a dc voltage having a maximum value equal to the particle lifting voltage. It must be noticed that all computations are carried out during a time period ranging from 15 to 25× the SI tail time. During this period of time it is sure that the SI wave had completely died.

According to the DC/SI voltage wave shown in Figure 1, the voltage equation is

$$V(t) = k_p(\exp[-\alpha t] - \exp[-\beta t]) + V_{dc} \tag{2}$$

where $k_p$, $\alpha$ and $\beta$ are constants relating to the SI waveshape and magnitude and $V_{dc}$ is a ratio from the lifting voltage. Therefore, the ambient field $E(t)$ may be written as

$$E(t) = \frac{k_p}{G}\{\exp[-\alpha(t+T)] - \exp[-\beta(t+T)]\} + \frac{V_{dc}}{G} \tag{3}$$

where $G$ is the gap spacing and $T$ is the time to lift off, obtained by solving Equation (2) after replacing $V(t)$ by the lifting voltage $V_1$

Equation (1) now reduces to

$$\ddot{X} = A\{\exp[-\alpha(t+T)] - \exp[-\beta(t+T)]\} - B\dot{X} - C$$
$$A = \frac{q_o k_p}{mG} \quad , \quad B = \frac{B_1}{m} \quad , \quad C = \left[g - \frac{q_o V_{dc}}{mG}\right] \tag{4}$$

Integrating Equation (4) gives the particle velocity

$$\dot{X} = A\left[\frac{[\exp[-\alpha(t+T)]}{-\alpha} - \frac{\exp[-\beta(t+T)]}{-\beta}\right] - BX - Ct + C_1 \tag{5}$$

where

$$C_1 = A\left[\frac{\exp[-\alpha T]}{\alpha} - \frac{\exp[-\beta T]}{\beta}\right] \tag{6}$$
$$\dot{X}(t=0) = 0$$

Finally, the distance traveled by the particle at any instant $t$ can be obtained from the following equation

$$X(t) = \frac{-A}{\alpha(B-\alpha)}\exp[-\alpha(t+T)] + \frac{A}{\beta(B-\beta)}\exp[-\beta(t+T)] - C\left[\frac{t}{B} - \frac{1}{B^2}\right] + \frac{C_1}{B} + C_2\exp[-Bt] \tag{7}$$

where

$$C_2 = \frac{A\exp[-\alpha T]}{\alpha(B-\alpha)} - \frac{A\exp[-\beta T]}{\beta(B-\beta)} - \frac{C}{B^2} - \frac{C_1}{B} \tag{8}$$
$$X(t=0) = 0$$

## 3. RESULTS AND DISCUSSION

FIGURES 2 and 3 illustrate respectively, the distance traveled by a spherical aluminum particle with radius 0.75 mm and a wire aluminum particle with a radius of 0.5 mm and a length of 3 mm, in a coaxial cylinder gap ($r_i$ = 10 mm, $r_o$ = 35 mm) as a function of time for different values of the dc bias voltage. It is clear that as the dc voltage value increases (FA increases) the distance traveled by the particle increases. The value FA represents the ratio between the applied dc bias voltage and particle lifting voltage.

It is also clear from Figures 2 and 3 that the distance traveled by the particle is larger in the case of

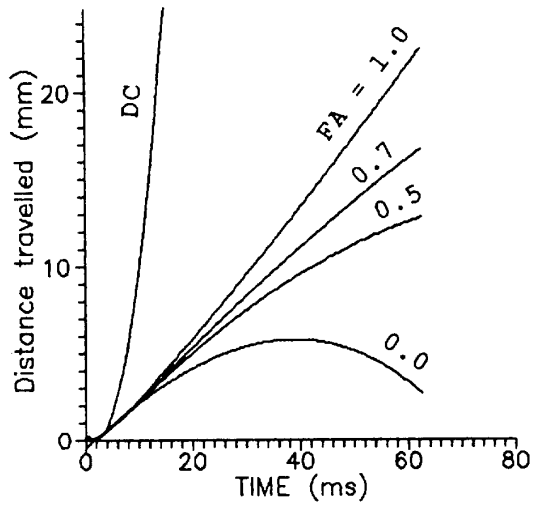


Figure 2.

Distance traveled by a spherical aluminum particle as a function of time, for different values of dc bias voltage in a coaxial electrode gap.

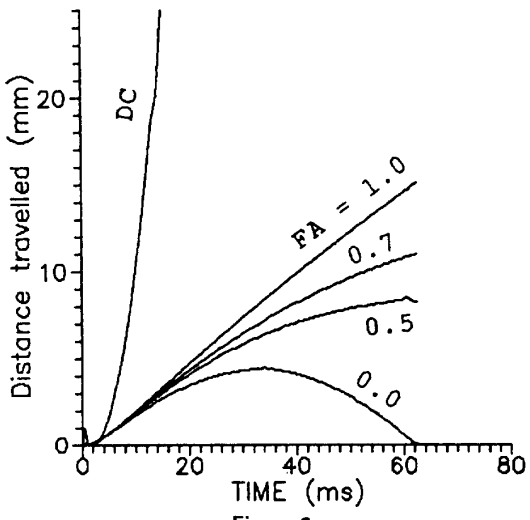


Figure 3.

Distance traveled by an aluminum wire particle as a function of time, for different values of dc bias voltage in a coaxial electrode gap.

DC/SI than that in the case of applying switching impulse (250/2500 $\mu$s) only. This means that DC/SI is more dangerous than a pure impulse. The Figures show also the distance traveled as a function of time when only a dc voltage of 300 kV is applied. It is clear that the particle crosses the gap in a shorter time than that for DC/SI (total peak = 300 kV) and for pure switching impulse (250/2500 $\mu$s) with 300 kV peak.

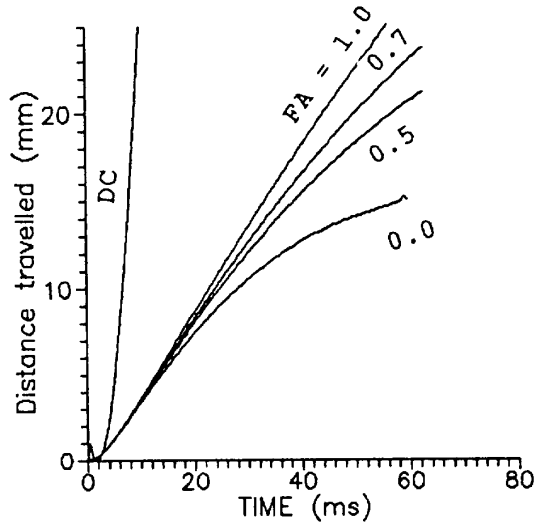


Figure 4.

Distance traveled by an aluminum wire particle as a function of time, for different values of dc bias voltage in a parallel plane gap.

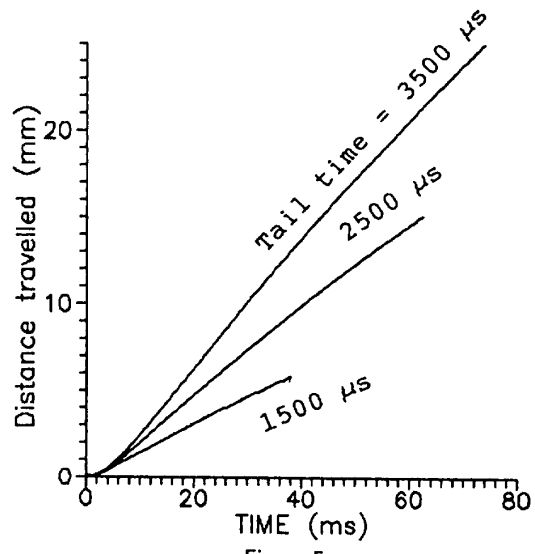


Figure 5.

Distance traveled by an aluminum wire particle in a coaxial electrode gap as a function of time, for different switching impulse tail time.

Figure 4 shows the same results but for an aluminum wire particle of radius 0.5 mm and of length 3 mm in a parallel plane gap of spacing 25 mm.

Figure 5 shows the distance traveled by an aluminum wire particle (0.5/3 mm) in a coaxial gap (10/35 mm) as a function of time, for different values of the switching

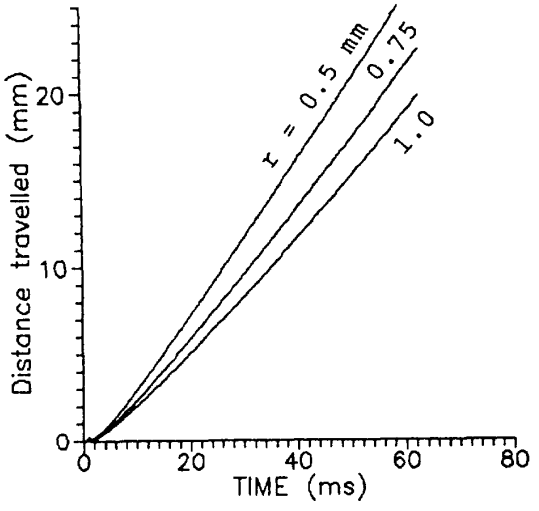


Figure 6.

Distance traveled by a spherical aluminum particle as a function of time, for different values of particle radius.

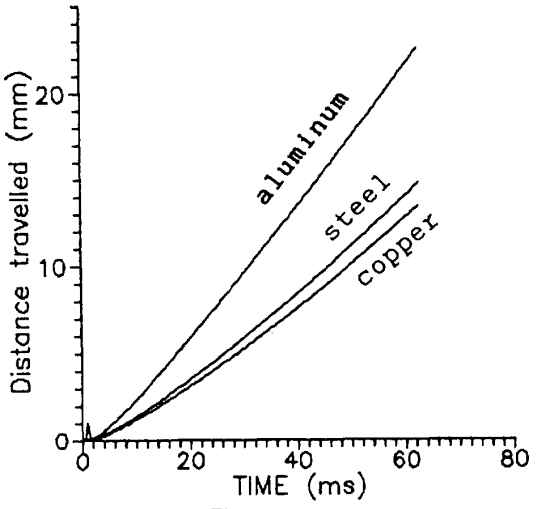


Figure 7.

Distance traveled by spherical particles as a function of time, for different particle materials.

impulse tail time. It is seen from this Figure that, as the impulse wave tail time increases (from 1500 to 3500 $\mu$s, with constant impulse wave front time of 250 $\mu$s and a dc bias voltage equal the lifting voltage of 28.63 kV), the particle crosses the gap more rapidly, this is because of the fact that most of the particle motion develops under the decaying part of the impulse tail time.

Figure 6 illustrates the distance traveled by a spherical aluminum particle in a coaxial cylinder gap (10/35 mm) as a function of time. The total applied DC/SI voltage stress is 300 kV and the gas pressure is 300 kPa. for three spherical particles having different values of radii, namely, 0.5, 0.75 and 1.0 mm. It is clear from the Figure that the lighter particle ($r = 0.5$ mm) reaches the upper electrode in a shorter time than the heavier ones.

Figure 7 shows the motion of three spherical particles having the same radius of 0.75 mm but with different materials, namely, aluminum, steel and brass, in a coaxial cylinder gap (10/35 mm) as a function of time. It can be noted from the Figure that, the lighter aluminum particle reaches a maximum distance which is larger than that of the steel and the brass particles, due to the smaller mass of the aluminum particle.

Figure 8 shows the distance traveled by different aluminum wire particles having the same weight, for different length to radius ratios as a function of time. It is seen from the Figure that as the length to radius ratio of the wire particle increases, the particle crosses the gap faster. This can be explained as follows. As the length to radius ratio increases, the enhancement field factor will increase due to increasing the wire particle height.

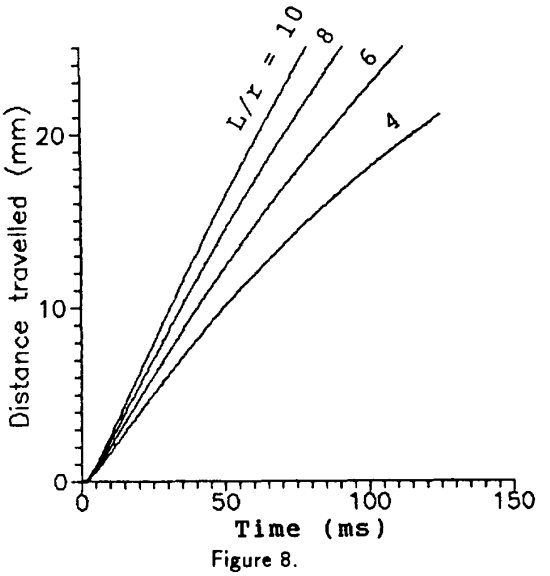


Figure 8.

Distance traveled as a function of time, by different aluminum wire particles of the same weight with different length to radius ratios.

Figure 9 shows the velocity as a function of time for different aluminum wire particles having the same weight, for different length to radius ratios. It is seen that the velocity increases as this ratio increases.

Figures 10 and 11 show the relationship between the

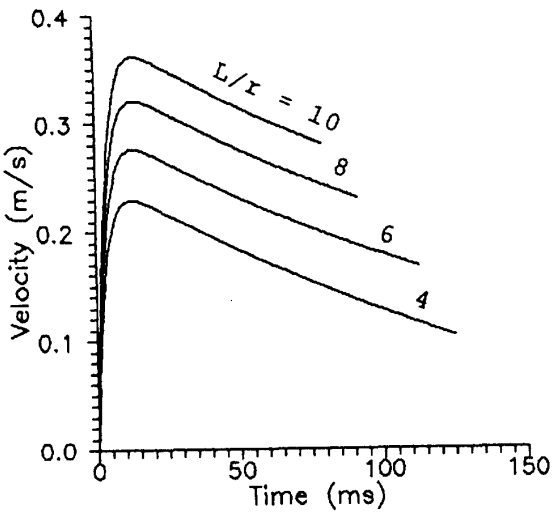


Figure 9.

Velocity of aluminum wire particles of the same mass having different length to radius ratios as a function of time.

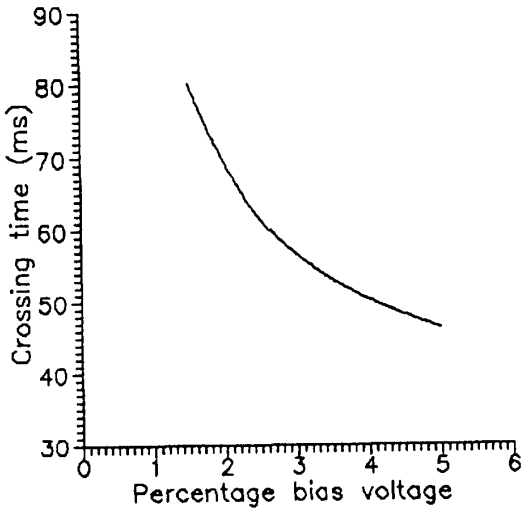


Figure 10.

Crossing time of an aluminum wire particle as a function of the percentage bias voltage.

crossing time in ms and the percentage bias voltage for wire and spherical aluminum particles in a parallel plane gap ($d = 25$ mm) respectively. It is seen from the Figures that as the percentage bias voltage $[V_{dc}/(V_{dc} + SI_{peak})]$ increases, the crossing time decreases. This may be explained as follows. When the bias voltage increases, the particle takes a minimum time to lift off, and consequently crosses the gap faster.

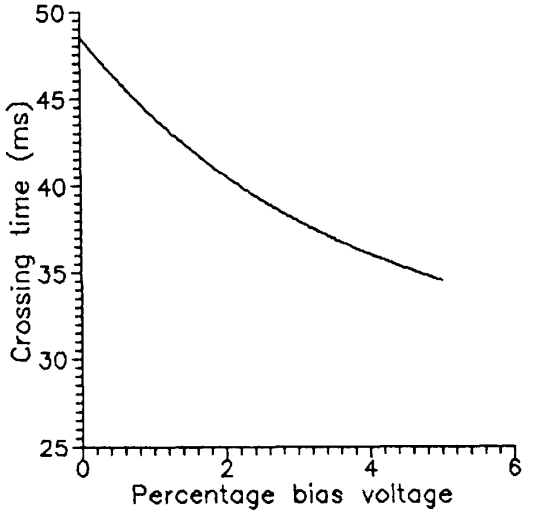


Figure 11.

Crossing time of a spherical aluminum particle as a function of the percentage bias voltage.

## 4. CONCLUSIONS

1. The performance of conducting particles under DC/SI voltage is more dangerous than with a pure impulse voltage for both spherical and wire particles in GIS parallel plane or coaxial systems.

2. The particle crosses the gap in a much shorter time under dc voltage than under pure switching impulse or switching impulse superimposed on dc bias voltage, having the same total amplitude for any electrode configuration.

3. The particles cross the gap in a shorter time when increasing the tail time of the switching impulse voltage and the length to radius ratio of wire particles.

4. The particle crossing time decreases as the percentage of dc bias voltage increases.

## REFERENCES

[1] A. H. Cookson, P. C. Boln, H. C. Doepken, R. E. Wootton, C. M. Cooke and J. G. Trump, "Recent Research in the United States on the Effect of Particle Contamination Reducing the Breakdown Voltage in Compressed Gas-insulated Systems", CIGRE, Paper no. 15–09, pp. 1–10, August 1976.

[2] H. Parekh, K. D. Srivastava and R. G. Heeswijk, "Lifting Field of Free Conducting Particles in Compressed $SF_6$ with Dielectric Coated Electrodes", paper no. F78 734-6, presented at the IEEE PES Summer Meeting, Los Angeles, Ca., July 16-21, 1978.

[3] A. Diessner and J. G. Trump, "Free Conducting Particles in a Coaxial Compressed-gas Insulated System", IEEE Trans. on PAS, Vol. 80, pp. 1970-1978, Nov/Dec 1970.

[4] R. M. Radwan, Fathi M. H. Youssef, S. S. El-Dessouky and Samir M. El-Makkawy, "An Approach to Dynamic Behavior Simulation for Particle Contaminants in Compressed $SF_6$ Gas Insulated Systems", 5-ISH, Braunschweig, paper no. 12-11, August 1987.

[5] R. M. Radwan, S. S. El-Dessouky, Fathi M. H. Youssef and Samir M. El-Makkawy, "Dynamic Behavior Simulation of Metallic Particles in Compressed $SF_6$ and GIS Reliability Improvement", 11. Wissenschaftliche Konferenz der Sektion Elektrotechnik mit Internationaler Beteiligung, Germany (DDR 1987), Paper No. H1-04, pp. 17-19, November 1987.

[6] R. M. Radwan, Fathi M. H. Youssef, S. S. El-Dessouky and Samir M. El-Makkawy, "Design Factors Affecting the Dynamic Motion of Free Conducting Particles in Compressed Gases", 6-ISH, New Orleans, LA, USA, Paper No. 32-10, August 1989.

[7] A. H. Cookson, O. Farish and G. M. L. Sommerman, "Effect of Conducting Particles on ac Corona and Breakdown in Compressed $SF_6$", IEEE Trans. on PAS, Vol. 91, pp. 1329-1338, 1972.

[8] H. Kuwahara, S. Inamura and T. Watanabe, "Effect of Solid Impurities on Breakdown in Compressed $SF_6$, IEEE Trans. on PAS, Vol. 93, pp. 1546-1555, 1974.

[9] F. Rizk, C. Manetti and R. Comsa, "Particle-initiated Breakdown in $SF_6$ Insulated Systems under High Direct Voltage", IEEE Trans. on PAS, Vol. 98, pp. 825-835, May/June 1979.

[10] C. M. Cooke, R. E, Wootton and A. H. Cookson, "Influence of Particle on ac and dc Electrical Performance of Gas Insulated Systems at Extra-High Voltage", IEEE Trans. on PAS, Vol. 96, pp. 768-777, 1977.

[11] H. Anis and K. D. Srivastava, "Movement of Charged Conducting Particles under Impulse Voltages in Compressed Gases", Conf. Record of the 1980 IEEE Industry Application Society Annual Meeting in Cincinatti, IEEE Publ. 80CH1575-0, pp. 1048-1055, Sept. 1980.

[12] W. Mosch, W. Houschild, J. Speck and S. Schierig, "Phenomena in $SF_6$ Insulations with Particles and their Technical Valuation", 3-ISH (Third International Symposium on HV Engineering), Paper 32. 01, Milan 28-31 August 1979.

[13] H. Anis and K. D. Srivastava, "Particle Initiated Breakdown in Compressed Gas Insulation under Time-varying Voltages", IEEE Trans., on PAS, Vol. 100, pp. 3694-3702, August 1981.

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