TWO DIMENSIONAL PARTICLE-IN-CELL SIMULATION OF PREDISCHARGE PHENOMENA ALONG AN INSULATOR

W. Pfeiffer, L. Z. Tong, D. Schoen*

1. ABSTRACT

A two-dimensional model for simulation of gas discharges along a resin insulator in SF_6/N_2 gas mixtures is developed by means of the Particle-in-cell and Monte Carlo (PIC-MCC) approach. The electron swarm and the following streamer developments are fully simulated, in which the elastic, exciting, ionising and attaching collisions between electrons and neutral gas molecules are considered, and the gas photoionisation and the photoelectric emission from cathode surface are realised by using a probabilistic scheme. Considering the effects of the space charges, Poisson fields are solved for each time step. The attached charges at the insulator surface are calculated according to the electric field distribution and taken into account for the solution of Poisson fields. The dynamic behaviour of electron swarms and streamer formation during the discharge are presented and analysed.

2. INTRODUCTION

An accurate description of the discharge phenomena requires the solution of a coupled equation system, composed of Poisson's- and transport equations together with suitable relations. Moreover, the surface discharges along an insulator additionally requires the analysis of attached surface charges. However, the current models for simulating the surface discharges are generally "Electrostatic Models" based on fractal theory[1, 2] and "Fluid Models" based on the solution of the continuity equations[3, 4]. The former is simplified as the iterative solution of the Laplace's equation in the considered region with changing boundary conditions; whereas the latter requests that all the transport and rate coefficients have to be well known prior to the analysis. As a result, some approximations have to be chosen with caution in these models, being difficult to apply for different conditions. This paper uses a combined particle-in-cell and Monte

---

* Laboratory for Electrical Measuring Techniques at Darmstadt University of Technology, Germany

Carlo approach (PIC-MCC)[5], fully realising a two-dimensional simulation at a needle-plane configuration inserted by a resin insulator with cut plane shown in Figure 1.

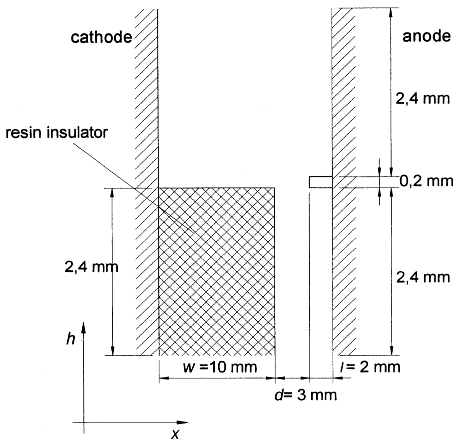


Figure 1. Needle-plane configuration inserted by a resin insulator with cut plane

3. SIMULATION MODEL

In the present research it is considered that the electrons in SF_6/N_2 mixtures have 9 types of collisions with the neutral-particles.

Momentum Transfer :	$e + N_2 \rightarrow e + N_2$
Excitation:	$e + N_2 \rightarrow e + N_2^*$
Ionisation:	$e + N_2 \rightarrow N_2^+ + 2e$
Momentum Transfer:	$e + SF_6 \rightarrow e + SF_6$
Attachment:	$e + SF_6 \rightarrow SF_6^-$
Dissociative Attachment:	$e + SF_6 \rightarrow SF_5^- + F$
Dissociative Attachment:	$e + SF_6 \rightarrow SF_5 + F^-$
Excitation:	$e + SF_6 \rightarrow e + SF_6^*$
Ionisation:	$e + SF_6 \rightarrow SF_6^+ + 2e$

In general, the PIC-MCC method needs fine grids because at high electron densities, the Debye length becomes very small. By plasma theory, the cell size Δx will have to be satisfied with the following condition:

$$\Delta x \approx \lambda_D \tag{1}$$

where, λ_D is the electron Debye length.

Considering the request of CPU time and computer memory, we choose the cell size $\Delta x = 10^{-4}\,\text{m}$, and the gas number density $N = 1.768 \times 10^{23}\,\text{m}^{-3}$. The goal of this paper is to develop a numerical model used for discharge simulation and certify its efficiency. Its application for specific discharge phenomena is to be carried out in the further research.

The surface charge accumulation plays a significant role in the insulation characteristics of GIS, and the mechanism of „charge transport via the gas space“ is dominant during the surface charge accumulation in GIS[6]. In the present research we focus on discharge phenomena over the gas/solid interface.

The surface charge density at the dielectric interface can be deduced by the boundary conditions. The boundary conditions at the interface can be described as

$$\varepsilon_0 E_{\mathrm{n,0}} - \varepsilon_{\mathrm{d}} E_{\mathrm{n,d}} = \sigma_{\mathrm{s}} \tag{2}$$

$$\sigma_0 E_{\mathrm{n,0}} - \sigma_{\mathrm{d}} E_{\mathrm{n,d}} = -\frac{\partial \sigma_{\mathrm{s}}}{\partial t} \tag{3}$$

where E is the electric field, ε is the dielectric constant, σ is the conductivity, while the subscripts 0 and d separately indicate the gas side and insulator side, and the subscript n indicates the field component normal to the interface. σ_{s} is the surface charge density. Both solid insulator and the insulating gas are considered non-conductive, i.e. $\sigma_0 = 0$ and $\sigma_{\mathrm{d}} = 0$. An adequately long charging time is considered in our research. Under this condition the charge accumulation reaches a stable condition such that an electron departing from the electrode never touches a solid insulator, which relevant boundary condition is given[7]

$$E_{\mathrm{n,0}} = 0 \tag{4}$$

Elimination of $E_{\mathrm{n,0}}$ in (2) gives

$$\sigma_{\mathrm{s}} = -\varepsilon_{\mathrm{d}} E_{\mathrm{n,d}} \tag{5}$$

It is well known that gas photoionisation is the main mechanism leading from a single electron avalanche to streamer formation and electrical breakdown in positive streamer discharges. Unfortunately, little literature is available concerning the photo-ionisation data. For this, we took access on the experimental results of Penney and Hummert[8] in which the photoionisation rate with ionisation rate is related by a coefficient ψ, shown as follows:

$$\psi = \frac{N_{\mathrm{p}}}{N_{\mathrm{D}} \theta p d} \tag{6}$$

N_{D}: the number of ion pairs per second formed by collisions; θ: the fraction of emitted radiation that is intercepted by the ion collector; *pd*: pressure times depth of the ion collecting surface; N_{p}: the number of photoion pairs generated per second.

Since no information is available on photoionisation in SF_6/N_2 mixtures, in the present research a threshold of photoionisation, 15,8 eV for SF_6 and 15,6 eV for N_2, the same as those[9-11] of the electron impact ionisation, are assumed. The photoionisation probability is considered directly proportional to excitation collisions since photo-electrons are generated when excited molecules return to lower energy levels. Because of the use of superparticles produced by scaling technique, a simple probability of $P = 5 \times 10^{-3}$ is used for each excitation collision. If P is above the R, a uniformly distributed random number between 0 and 1, one ion-electron pair will be produced.

In order to assure enough collision ionisations to occur during the movement of the photoelectron to the anode, a sub-mesh technique is developed in the present simulation to determine the photoionisation position. A probability P' is introduced to decide the photoionisation position, that is

$$P' \approx 1 - \frac{D_{ij}}{\sqrt{RD^2 + D_{ij}^2}} \tag{7}$$

where D_{ij} is the distance between excitation point i and photoionisation point j. *RD* is the assumed discharge radius[12], deciding the extent of radial expansion of the discharge.

It is known that the number of secondary electrons released at the cathode by the impact of photons is proportional to the number of photons hitting the surface of the cathode and an efficiency factor γ_p has been proposed and applied[13]. Considering the use of superparticles, a probability of $P'' = 5 \times 10^{-3}$ is applied in the present research.

The details with regard to numerical simulation techniques such as „*leap-frog*" finite difference scheme, weighing scheme, null collision technique, scattering scheme, and scaling technique, refer to our previous work[9-11].

4. SIMULATION RESULTS

Considering the electron attachment behaviour of SF_6, in the present research 2000 electrons are emitted from the cathode as „seed" particles for the start of the PIC self-consistent simulations. The simulations are performed within several tens of nano-seconds, so that ions, including the attached surface charges, are considered as fixed. Figure 2 shows the calculated electric field distribution along the insulator surface in consideration of the effect of the surface attached charges. It is clearly shown that the surface attached charges enhance the electric field near to the cathode and decrease the electric field near to the anode. Due to this reason the first avalanche from the cathode is easier to be produced, which leads a possibility that the discharges occur easier than that without the attached charges. Due to the existence of radial dielectric boundary of the insulator at x = 0.01 m, the dielectric constant changes over the boundary so that the electric field has an abrupt change at the position.

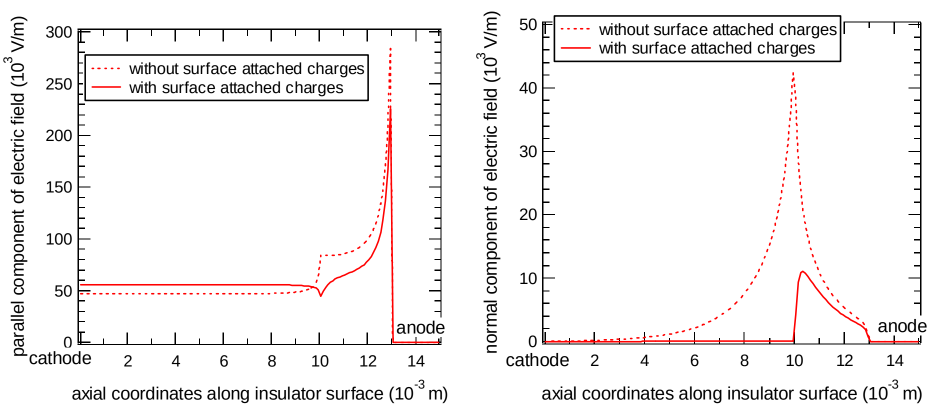
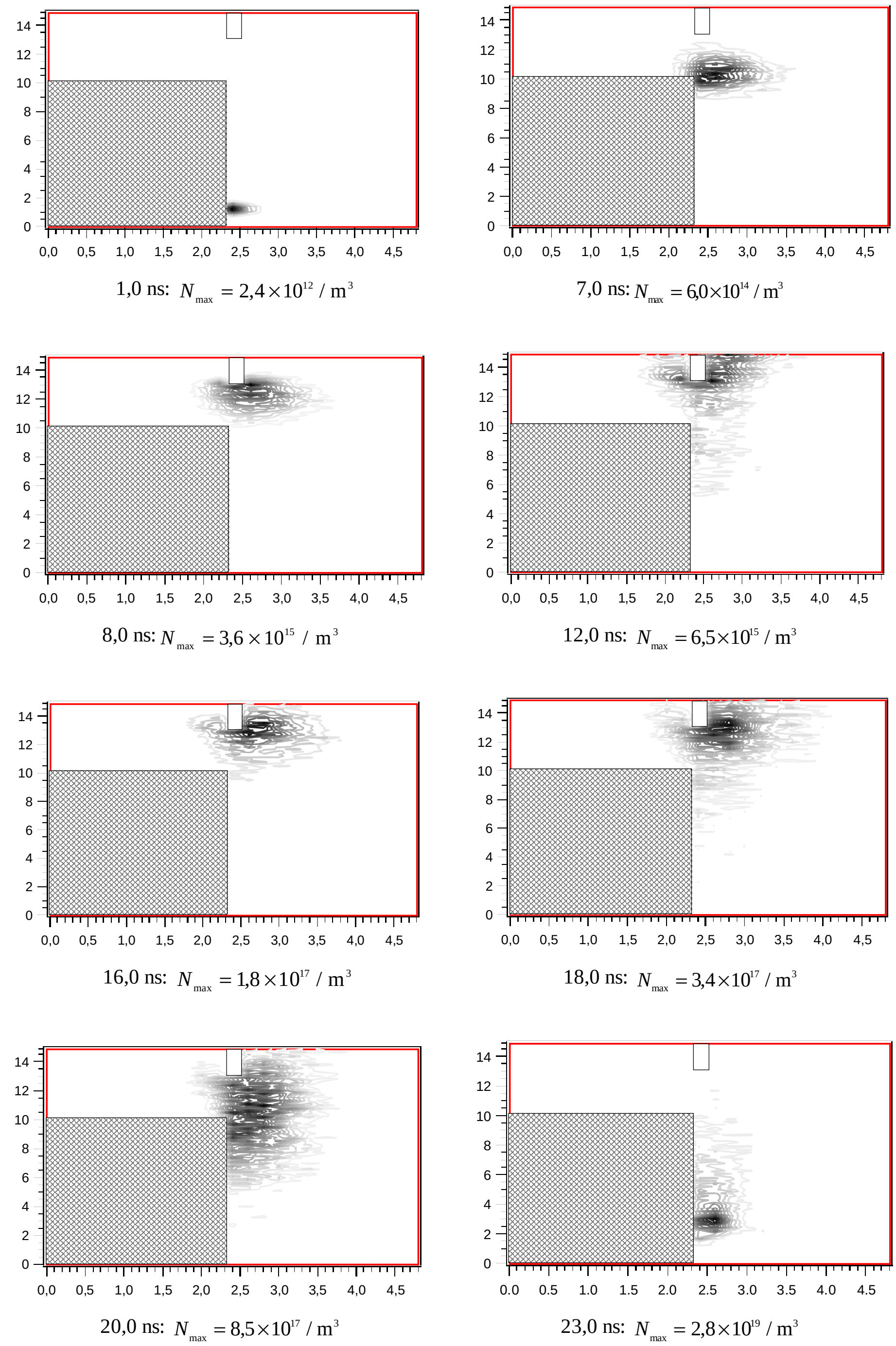


Figure 2. Electric field along the insulator surface



1,0 ns: $N_{max} = 2{,}4 \times 10^{12}$ / m^3

7,0 ns: $N_{max} = 6{,}0 \times 10^{14}$ / m^3

8,0 ns: $N_{max} = 3{,}6 \times 10^{15}$ / m^3

12,0 ns: $N_{max} = 6{,}5 \times 10^{15}$ / m^3

16,0 ns: $N_{max} = 1{,}8 \times 10^{17}$ / m^3

18,0 ns: $N_{max} = 3{,}4 \times 10^{17}$ / m^3

20,0 ns: $N_{max} = 8{,}5 \times 10^{17}$ / m^3

23,0 ns: $N_{max} = 2{,}8 \times 10^{19}$ / m^3

Figure 3. Electron avalanche and streamer development

Based on the calculated surface charges, we simulate the electron avalanche and streamer development, which results are given in Figure 3. At t = 0 the initial electrons start to drift from the cathode towards the anode and the first avalanche appears and grows over the insulator. At t = 7,0 ns the avalanche starts to leave from the insulator surface, and at t = 8,0 ns the avalanche arrives at the anode with a peak of electron density of $N_{max} = 3{,}6\times10^{15}\,\mathrm{m}^{-3}$. In the meantime, the electrons start to be absorbed by the anode. A second avalanche is started at t = 12,0 ns by photoionisation, which grows and combines with the first one to a peak of electron density $N_{max} = 1{,}8\times10^{17}\,\mathrm{m}^{-3}$ at t = 16,0 ns. A third avalanche appears at t = 18,0~19,0 ns, which quickly combines with the previous avalanches and forms a quite strong avalanche at t = 20,0 ns. The following new avalanches produced by photoionisation continue to combine with the previous avalanches and the electron cloud with a large electron density starts to move towards to the cathode, i.e. the streamer is formed. At t = 23,0 ns the streamer arrives at the cathode with a peak of electron density $N_{max} = 2{,}8\times10^{19}\,\mathrm{m}^{-3}$. It should be noted that a new avalanche always starts at the cathode side of the previous avalanche in the present simulation. After the occurrence of the third avalanche, the streamer starts to form and quickly develops towards to the cathode.

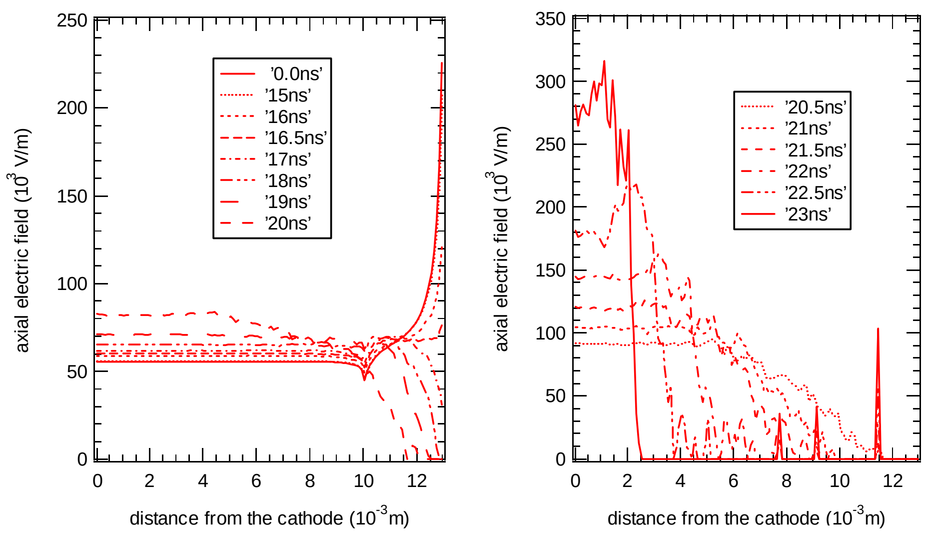


Figure 4. Electric field distribution along the axis

Figure 4 shows the electric field distribution along the axis during the discharge. The results demonstrate that the space charge field distortion starts to become important at 15,0 ns with a decrease of electric field at the anode down to below $2{,}0\times10^{5}$ V / m. With increasing time, the accumulation of positive ions decreases the electric field near the anode and enhances the electric field in the region far away from the anode. At t = 18,0 ns, the electric field at the anode reduces to zero, indicating that the reversed space charge field balances the applied field at the anode. It is noted that some fluctuations appear after t = 20,0 ns. This is possibly due to the fact that with the development of the electron swarm towards to the cathode, the electrons continuously drift towards to the anode before they are absorbed by the anode or attached by SF_6 molecules so that at that time the electric field between the electrons and the anode is enhanced.

5. CONCLUSIONS

A two-dimensional model of gas discharge over an insulator surface has been developed in this paper. The conclusions are given as follows:

(1) The PIC-MCC method can fully simulate the electron swarm and streamer development, and MCC module can simulate the collisions between electrons and neutral gas particles. Moreover, the use of null collision technique can greatly reduce the CPU time.
(2) The combination of the mesh for the PIC with the sub-mesh for photoionisation is first proposed and developed to simulate electron swarm development on the basis of photoionisations.
(3) The surface attached charges can effectively enhance the electric field near to the cathode and decrease the electric field near to the anode.
(4) Under given condition, a new avalanche always starts at cathode side of the previous avalanche and combines with the previous avalanche.
(5) Due to the request of CPU time and computer memory, in the present research the considered gas number density is limited up to $N = 1.768 \times 10^{23}\,\mathrm{m}^{-3}$. The application for real discharge phenomena in GIS is to be considered in the further research.

5.1 Acknowledgments

We acknowledge that this work is financially supported by the federal German research institution DFG.

6. REFERENCES

1. N. Femia, et al , Characterization of the active zone for leader propagation in SF_6, *Gaseous Dielectrics* VII, edited by L. G. Christophorou and D. R. James (Plenum Press, New York, 1994), pp.105-112.
2. Takehisa Hara, et al, Fractal characteristics of the random patterns of the surface streamer corona, 10th Int. Conf. on Gas Discharges and Their Appl., UK, pp. 306-309 (1992).
3. M. Tanaka and Y. Murooka, Study on nanosecond surface discharge using modeling and simulating method, 10th Int. Conf. on Gas Discharges and Their Appl., UK, pp. 860-863 (1992).
4. V. Gibalov and G. Pietsch, Surface discharge phenomena in barrier discharges with dielectric anode, 10th Int. Conf. on Gas Discharges and Their Appl., UK, pp. 552-555 (1992).
5. V. Vahedi and M. Surendra, A Monte Carlo collision model for the particle-in-cell method: applications to argon and oxygen discharges, Comput. Phys. Commun., **87**, pp. 179-198 (1995).
6. T. Jing, Surface charge accumulation: An inevitable phenomena in dc GIS, IEEE Trans. Diele. Elect. Insul., **5**(2), pp. 771-778 (1995).
7. S. Sato, W. S. Zaengl, A. Knecht, A numerical analysis of accumulated surface charge on dc epoxy resin spacer, IEEE Trans. Elect. Insul. **22**(3), pp. 333-340 (1987).
8. G. W. Penney and G. T. Hummert, Photoionization measurements in air, oxygen, and nitrogen, J. Appl. Phys., **41**, pp. 572-577 (1970).
9. W. Pfeiffer, D. Schoen, and L. Z. Tong, Simulation of predischarge processes in SF_6/N_2 mixtures stressed by very fast transient voltage stress, IEEE Conf. on Elect. Insul. and Diele. Phenomena, Texas, pp. 391-394 (1999).
10. W. Pfeiffer, D. Schoen, and L. Z. Tong, Simulation of prebreakdown phenomena at a gas/solid interface in a SF_6/N_2 mixtures stressed by very fast transient voltage stress, IEEE Int. Symposium on Elect. Insul., CA, pp. 408-411 (2000).
11. W. Pfeiffer, D. Schoen, and L. Z. Tong, An improved method for simulation of prebreakdown phenomena in SF_6/N_2 mixtures, 13th Int. Conf. on Gas Discharges and Their Appl., UK, Volume **1**, pp. 389-392 (2000).
12. J. Liu and G.R. Govinda Raju, Streamer formation and Monte Carlo space-charge field calculation in SF_6, IEEE Trans. Elect. Insul., **28**(2), pp. 261-270 (1993).
13. R. Morrow, Theory of negative corona in oxygen, Phys. Rev. A, **32**(3), pp. 1799-1089 (1985).