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# Accumulation of surface charges on the particle contaminated spacer surface in compressed gas under impulse voltage stress

A. Moukengué Imano\*

*Institute of Power Transmission and High Voltage Technology, University of Stuttgart, Germany*

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## Abstract

In this paper, the influence of a conducting particle on the surface charging of a solid insulator during the stress with impulse voltages is investigated. The experimental study was carried out using a simplified spacer model with an adhering particle under homogeneous field conditions in SF<sub>6</sub> gas and also in different gas mixtures. A specially designed set-up was used to bring about the surface charge data through potential measurement by means of an electrostatic probe. The results show that the particle position, the type of impulse voltage, the type of gas and the gas pressure all combine to explain the accumulation of charges on the spacer surface.

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## 1. Introduction

For dielectric dimensioning of gas insulated power equipment (GIS and GIL) the support insulators (spacers) are of special importance. They can represent critical weak points for the entire insulation system and may reduce the reliability of the GIS/GIL installation.

To evaluate the breakdown strength of insulation systems, the conditions of the boundary surface solid insulation/gas are of special importance [1]. On the insulator

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\*Corresponding author. Present address: University Institute of Technology, University of Douala, B.P. 8698, Douala, Cameroon.

*E-mail address:* [moukengue@gmx.net](mailto:moukengue@gmx.net) (A. Moukengué Imano).

surface, for example, contamination can cause field distortions and consequently affects the dielectric strength of this insulator [2,3]. This contamination is, in practice, caused by both conducting particles and trapped surface charges on the insulator surfaces. It is well known that contamination of gas insulated equipment with conducting particles will occur during the assembly or operation [4]. Conducting particles placed on the insulator surfaces, or splinters at the conductor in the proximity of the insulator, can produce surface charges by partial discharge activities. These surface charges accumulate on the insulator surface and can be considered as another type of contamination.

Based upon a representative model arrangement, it was investigated how the surface charges on a supporting insulator (spacer) in insulating gases accumulate under impulse voltage stress. The influence of the duration of the impulse, the amplitude of the impulse, the number of applied impulses, the type of gas and the gas pressure on the accumulation of surface charges were also examined. In the preliminary section, the influence of surface contamination on the breakdown along the spacer surface is shown.

## 2. Experimental apparatus and procedure

### 2.1. Experimental setup

Fig. 1 shows the test vessel with installed experimental setup, which is made up of two large aluminium plate electrodes, a high voltage and a grounded electrode. The test vessel is a modified part of a commercial 420 kV GIS system.

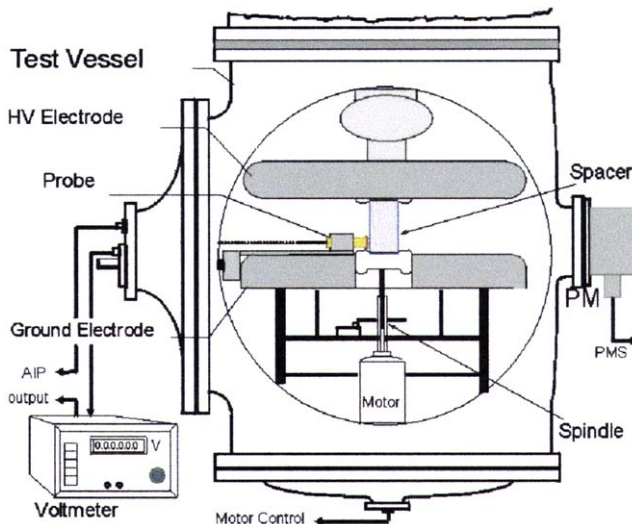


Fig. 1. Test vessel with inserted electrode/spacer set-up.

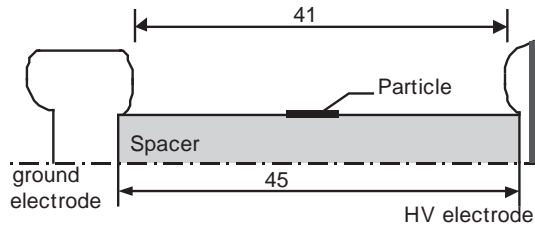


Fig. 2. Used electrode/spacer set-up.

The configuration of the electrode-spacer used is shown in Fig. 2. The triple junction at both ends of the spacer was shielded by two specially shaped electrodes which are made of stainless steel. A cylindrical solid insulator of 25 mm diameter and 45 mm height was used as spacer model. It is made from epoxy resin filled with  $\text{Al}_2\text{O}_3$ . Its relative permittivity was determined to be  $\epsilon_r = 5.2$ . A conducting particle of 0.20 mm diameter and 4 mm was cut from cylindrical NiCr-wire. No special tip geometry was used. The particle was fixed at the spacer surface with a small amount of silicon adhesive. Attention was paid to ensure that, no tip was covered with adhesive.

For evacuating and filling the test vessel, two compact gas handling assemblies were used (manufacturer: DILO). The filling of the test vessel up to the desired gas pressure was always performed after a preceding evacuation, to a pressure of less than 10 Pa.

Impulse voltages with an amplitude of up to 800 kV were generated using a Marx generator. They were measured with a peak voltmeter connected to a capacitive voltage divider. The nominal ratio of this voltage divider was 1:990. The voltage shape was recorded with a digital oscilloscope (Tektronix).

## 2.2. Surface charges measurement

To scan the potential distribution caused by accumulated charges on the entire spacer surface, the spacer was rotated using a spindle which was connected to a motor. This motor was electrically controlled from outside the test vessel. An additional indicator pulse was recorded after every turn during data acquisition. The measurement of the surface potential across the spacer surface was performed by means of an electrostatic voltmeter (OPTILAS TREK - Model 347) and an adapted probe which was constantly moved in axial direction by the rotating spindle. This was done under pressure after voltage applications. During the voltage application, the probe was moved into a “parking position” inside the test vessel with low electrical field, so that its presence would not disturb the global background field of the tested configuration. The shortest measuring cycle was 15 s.

The measurement of the surface potential took place non-reactively and without contact while placing the probe in a fixed distance  $d$  to the spacer surface. In order to achieve an optimal high local resolution or a distance-conditioned error within 1%

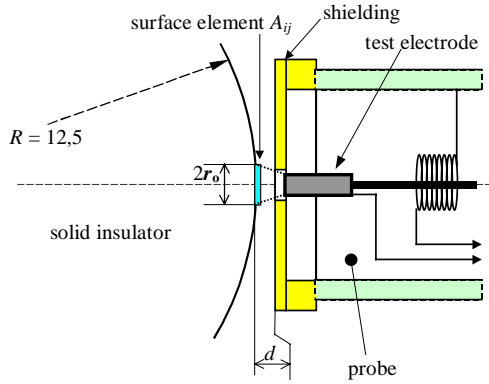


Fig. 3. Principle of potential measurement with an electrostatic probe.

with the measurement, this distance amounted to 1 mm [5]. The measurement principle is based on a potential measurement, which is characterized by a compensation of the electrical field between the test electrode of the probe and a surface element  $A_{ij}$  at the spacer. Fig. 3 shows the mode of operation of the probe.

Assuming a constant surface charge density over each scanned surface element  $A_{ij}$  by the probe, the output voltage of the electrostatic voltmeter was converted to surface charge values with the following equation:

$$\sigma_{ij}(d) = \varepsilon_0 \frac{U_{ij}(d)}{d} \quad (1)$$

with  $d = 1$  mm,  $\varepsilon_r \approx 1$  (for gases),

$$\sigma_{ij}(d) = k \cdot U_{ij}(d). \quad (2)$$

With the assumptions a conversion factor of  $k = 8.8 \mu\text{C}/\text{kV m}^2$  is found to convert the voltage readings. The potential distribution stored in a digital oscilloscope (Tektronix) and the position reference signal are transferred to a PC. The file stored in the computer can be further processed with the software package MATLAB. Suitable work windows in MATLAB were developed at the institute IEH for the analysis of the measurement resulting in different charge distribution patterns. Results of such measurement are available in different ways:

- in two dimensions in the form of ‘surfaces’,
- in two dimensions in the form of ‘profiles’ and
- in three dimensions in the form of ‘mountains’.

### 3. Results and discussion

#### 3.1. The effect of the conducting particle on the breakdown along the spacer surface

##### 3.1.1. Discharge propagation along the particle contaminated spacer surface

In this section, how the discharge propagates under the influence of the already attached surface charge is shown (Fig. 4). The recorded signals of the

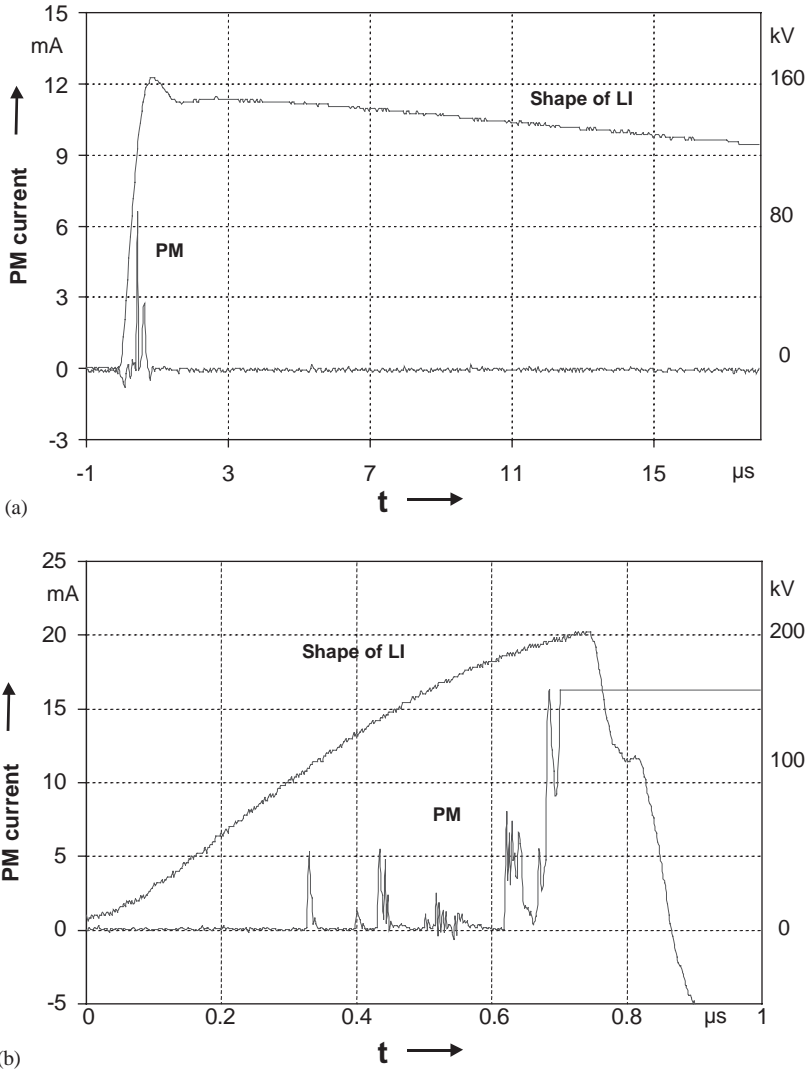


Fig. 4. Discharge development (a) without flashover for a particle contaminated spacer in 10% SF<sub>6</sub> + 90% N<sub>2</sub> mixture at 300 kPa. Particle length: 4 mm. (b) Discharge development until flashover for a particle contaminated spacer in 10% SF<sub>6</sub> + 90% N<sub>2</sub> mixture at 300 kPa. Particle length: 4 mm.

photomultiplier (PM in Fig. 4, with effective spectral ranges from 160 to 320 nm) show that the discharge activities occur only in wave-front of the impulse (Fig. 4a). The light emission up to  $0.8\mu\text{s}$  in Fig. 4b is due to the simultaneous streamer onset at the sharp edge of both particle tips. The generation of the charge carriers in the impulse front of the applied voltage can be explained by the processes of electron multiplication during the formation of the avalanche. As a result of the different developments of the discharge and the different electron- and ion-drift velocity the avalanche formation depend on the polarity of the very bent electrode and results, therefore, in a so-called polarity effect. According to the gradient of impulse front  $dV/dt$  and amplitude of the impulse a streamer corona can grow from avalanches [6]. The large value of  $dV/dt$  increases the density of the charge in the streamer channel [7]. For the charging of the particle-contaminated spacer surface under impulse voltage stress, the distribution of charge carriers in the gas gap (near the particle tips) or the distribution of charge density on the spacer surface can be expressed by the distribution of charge carriers in an avalanche.

The wave-front duration and the impulse amplitude also control the generation of the space charges and with it the pre-breakdown mechanism along the particle contaminated spacer surface. Therefore, nearly all flashovers get acquired at the wave-front of the impulse, as shown in Fig. 4b. A similar result was reported by Hama et al. [7]. Moreover, for AC voltage application and particle on spacer, it is reported by Wang [8] that pulsating discharge occurs only in the wave-front of the positive and negative half cycle. Contrary to that, it is well known for non-uniform field gap (needle in GIS) without an involved spacer that pulsating discharge occurs in wave-front as well as in wave-back of the voltage impulse (or in entire AC half cycle) [9]. It seems that the surface charge has a strong influence on particle initiated pre-breakdown events. It is also demonstrated in Ref. [10], that the surface charge can strongly influence the conditions for streamer corona inception along the particle contaminated spacer surface in 10%  $\text{SF}_6 + 90\% \text{N}_2$ . It is furthermore shown that the streamer inception voltage without surface charge was generally lower than the one with surface charge. It was assumed that a minimum deposited charge, in the vicinity of the particle on the spacer surface, is sufficient to reduce the inhomogeneity of the particle tips.

### 3.1.2. Reduction of the flashover voltage by conducting particle on spacer

Fig. 5a shows the influence of the particle length on the flashover field strength of  $\text{SF}_6$  and mixtures with the same intrinsic dielectric properties under LI voltage stress. There is a significant decrease in flashover field strength independent of the type of gas. The flashover field strength drops faster at the beginning and even out gradually with increasing particle length. A similar behaviour was also reported in pure  $\text{SF}_6$  without an involved spacer by Rong et al. [11] and Hauschild et al. [12]. This flashover behaviour of the particle-contaminated spacer surface is not only influenced by particle length or shape, but also by the accumulation of surface charges on the spacer surface. It was observed elsewhere [10] that the accumulation

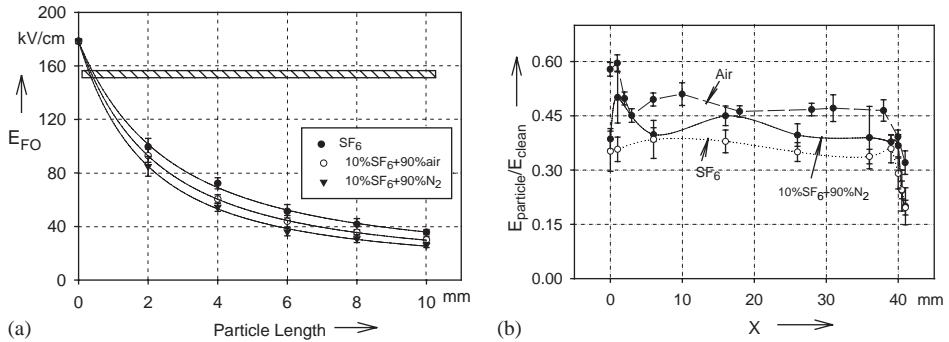


Fig. 5. LI flashover field strength for particle contaminated spacer in gases with equal intrinsic dielectric strength (a) and relative LI flashover field strength  $E_{particle}/E_{Clean}$  versus particle location  $x$  for a 4 mm particle at 400 kPa (b). Parameters: Type of gas. Interval of LI test field strength for 123 and 420 kV GIS.

of the surface charges involves two different effects on the particle-contaminated spacer surface:

- an inhomogeneity-reducing effect of the contamination, and
- a dielectric strength-reducing effect.

In the case of the dielectric strength-reducing effect of the surface charges, it is also shown by Farish et al. [13] that the charge deposited on the surface of solid insulators without particle contamination can locally enhance the electric field, and this may result in a reduction of the dielectric strength of the insulator. Furthermore, Tenbohlen et al. [14] show that the insulation strength of particle-contaminated spacer in pure  $SF_6$  is dependent on the magnitude of the surface charge on the spacer.

In addition, a corresponding interval of LI test field strength for 123 and 420 kV GIS is entered in Fig. 5a. For the model arrangement, used particles with a length starting from 0.5 mm lead theoretically to flashover in  $SF_6$  during the test with lightning impulse voltage. In 10%  $SF_6$ +90%  $N_2$  and 10%  $SF_6$ /90% air, the flashovers can already occur by shorter particles.

Fig. 5b shows the dependence of the particle location on the flashover voltage when the setup gets stressed with positive LI for a 4 mm particle on the spacer at a gas pressure of 400 kPa. The particle location on the spacer showed a significant influence on the flashover voltage. Independent of the particle properties, a polarity effect could be observed [15,16], similar to the one known for a gas gap [17]. The measurements for the determination of the flashover field strength have been evaluated according to the proposed method of IEC 60060/2. It is assumed that all experiments are normally distributed. The indicating bars show 95% confidence interval of the expected values. All flashovers occurred along the spacer surface, which could be seen from the flashover traces on the surface.

### 3.2. Influence of the voltage polarity on the charge distribution

The activity of partial discharges (PD) at both tips of the conducting particle determines the charge distribution along the spacer surface. Positive and/or negative surface charge, due to the partial discharge activities and field emission at the particle tips, was accumulated near the particle as the applied voltage exceeded a threshold value. According to Xie et al. [18], whether this voltage threshold value for surface charging occurs or not is dependent on whether or not the particle connects the electrodes. Thus the charge distribution along the spacer surface depends on the type of voltage and voltage polarity. The position of the conducting particle with respect to the grounded electrode or high voltage electrode (HV) likewise influences the field strength along the spacer surface. The spacer does not have large influence on this PD activity, which is linked with the discharge development along spacer surface and through the gas. Basically, the spacer influences distribution of the electrical field by its form and permittivity, as shown by Sudarshan et al. in Ref. [19].

Figs. 6 and 7 show typical charge distributions after voltage application with lightning impulses (LI) in pure nitrogen ( $N_2$ ) and 90%  $N_2$  + 10%  $SF_6$  gas mixture. In Fig. 6a, negative and positive charges accumulate simultaneously on the spacer surface in the vicinity of the conducting particle. Due to the short duration of the applied lightning impulses not all free charge carriers can move to the electrodes, where they are to be absorbed. When the impulse voltage dies out before the charge carriers reach the electrodes, they become attached to the spacer surface. For a conducting particle in the middle of the spacer surface in a 90%  $N_2$  + 10%  $SF_6$  gas mixture, the attached charge carriers are electrons,  $N_2^+$ ,  $SF_6^+$  and  $SF_6^-$  ions. They get attracted by the spacer and attach to the surface. Depending upon the peak value of the lightning impulse voltage, the electrons and  $SF_6^-$  ions accumulate in the area between the particle tip and the positive electrode (HV electrode). The  $N_2^+$  and/or  $SF_6^+$  ions remain in the particle surroundings. Because of their low mobility compared to the electrons, the  $SF_6^-$  ions remain predominantly near the particle tip. Therefore, the density of the negative surface charge is highest in front of the particle tip.

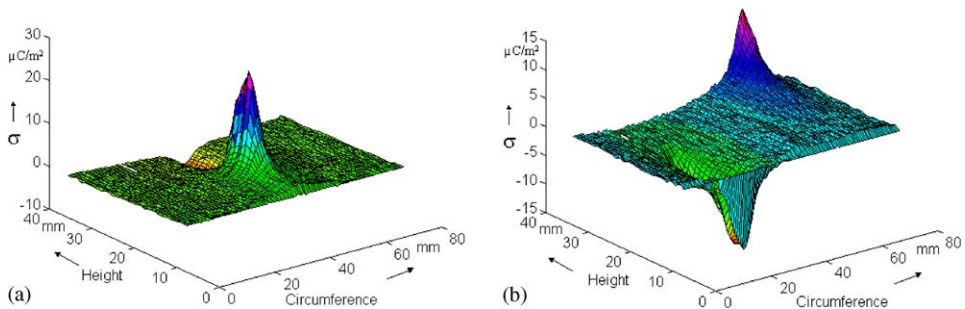


Fig. 6. Charge distribution after 10 positive impulses in 90%  $N_2$  + 10%  $SF_6$  gas mixture at 300 kPa: (a) for a particle in the middle of the spacer surface,  $U_p = 150$  kV; (b) for two particles in contact with one electrode each,  $U_p = 140$  kV.



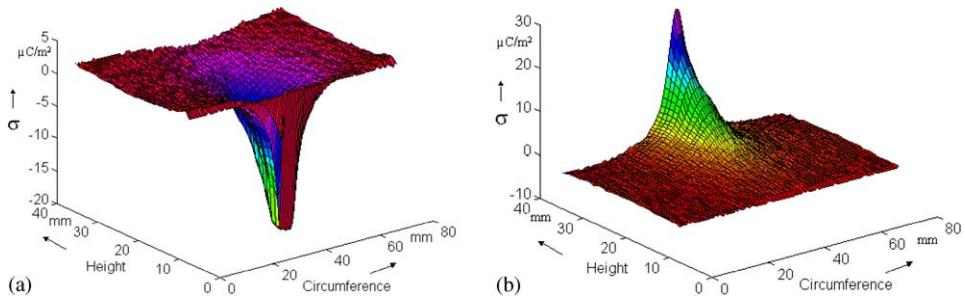


Fig. 7. Charge distribution on the spacer surface with a particle contacted to HV electrode in  $N_2$  gas at 300 kPa,  $U_p = 120$  kV: (a) after 5 negative impulses; (b) after five positive impulses.

The influence of the particle position or voltage polarity on the charge distribution on the spacer surface can be illustrated with Figs. 6b and 7. In Fig. 6b, two conducting particles were used, each in contact with one electrode. Because of the symmetry of the electrode arrangement, both conducting particles get opposite polarities during the stress with lightning impulse voltage. Accordingly, two different discharge channels develop during the voltage application. A separate accumulation of positive and negative surface charges can be observed in both particle areas on the spacer surface. At each of these conducting particles, the charge density is maximum. Further, this behaviour with only one particle in contact with the high-voltage electrode was verified with positive- and negative-voltage polarity in pure  $N_2$ . The results are summarized in Fig. 7. Contrary to Fig. 6b, the accumulation of either positive or negative surface charges can be observed, depending upon polarity of the impulse voltage. For a particle in contact with an electrode at a positive point, only a positive charge remains on the spacer surface, while a negative charge occurs for a particle at a negative point. For the charge distribution in Fig. 7 the purity of the used  $N_2$  amounted to only 99.8%. In the case of the lightning-impulse voltage, it is clearly visible that the type and the direction of motion of the charge carriers in the gas or on the spacer surface are determined by the voltage polarity.

### 3.3. Influence of the impulse duration on the charge accumulation

Due to partial discharges at the particle tips, the charge carriers are liberated during the impulse voltage application in the gas. Immediately after their release, these charge carriers move to the electrodes along the electrical field lines, by applications of the field force. When the impulse voltage dies out, the field force vanishes, and the charge carriers become attracted to the spacer. In some fixed distance from the particle tips, or to each electrode individual ions or electrons attached to the spacer surface, this distance depends on the impulse duration. In order to explain the influence of the voltage stress duration on the charge accumulation on the particle contaminated spacer surface, the so called time to half-value of the lightning impulse voltage was varied from 49 to 330  $\mu$ s. In order to get a

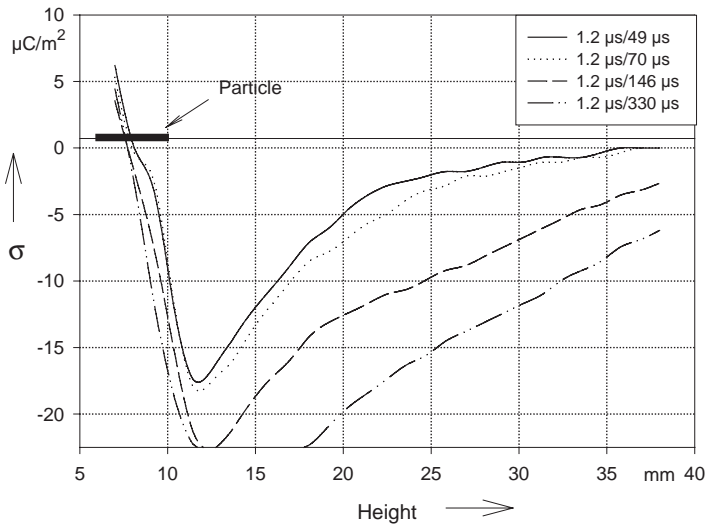


Fig. 8. Profile of the charge distribution on the particle contaminated spacer surface after 15 impulses in SF<sub>6</sub> gas at 200 kPa,  $U_p = 151$  kV. Parameter: impulse duration.

better outline of the influence of the impulse duration by using a unipolar charge distribution, the conducting particle was fixed on the spacer surface at a distance of 36 mm to the high voltage electrode. The SF<sub>6</sub> gas was used as a surrounding medium, with a pressure of 200 kPa.

In Fig. 8, is shown the profile representation of the charge distributions along the spacer surface for four various values of the time to half-value. This figure partially shows an accumulation of positive surface charges in the particle area. However, the negative surface charges which accumulated here between the particle tip and the high-voltage electrode is more relevant. It is therefore evident that the duration of the impulse voltage influences both the charge density and the spreading of the surface charges along the spacer surface. With an increasing time to half-value of the lightning impulse voltage, more charge carriers are liberated, and the total “flying time” of individual charge carriers along the electrical field lines becomes longer as well. The longer the impulse duration, the more surface charges accumulate on the particle contaminated spacer surface.

#### 3.4. Influence of the voltage amplitude on the charge accumulation

The height of the tangential field strength at the particle tips determines the discharges inception and development in the dielectric gas [20]. It depends mainly on the amplitude of the voltage applied at the high-voltage electrode. Partial discharge (PD) measurements performed elsewhere in a model setup with contaminated spacer showed that the PD activity in the gas or at the boundary surface gas/spacer increases with increasing voltage amplitude [21]. Fig. 9 shows that the same

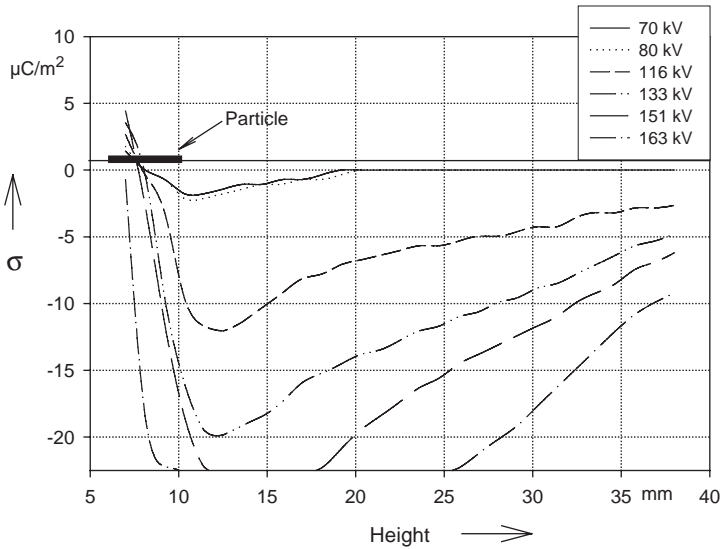


Fig. 9. Profile of the charge distribution on the particle contaminated spacer surface after 15 impulses 1.2/330  $\mu\text{s}$  in  $\text{SF}_6$  gas under 200 kPa,  $U_p = 151$  kV. Parameter: impulse peak value.

behaviour can be observed by means of a direct measurement of the surface charges on the particle contaminated spacer surface after voltage application with lightning impulse 1.2/330  $\mu\text{s}$ . The measurements were made for the same spacer/particle configuration and in the same dielectric gas, as in the previous paragraph. The voltage was increased gradually from PD inception up to flashover of the arrangement. The charge measurement was executed immediately after 15 impulses were applied for each voltage level. The particle initiated PD inception was controlled using a photomultiplier tube.

Fig. 9 shows that the accumulation of negative surface charges on the spacer surface increases with the increasing peak value of the impulse voltage in  $\text{SF}_6$  gas. The charge density in front of the particle tip increases, and the total “flying time” of the charge carriers which accumulate later as surface charges on the spacer surface becomes longer. Indeed, the increase of the charge density is a consequence of the increase of the charge carriers excess which is done via impact ionization processes in the gas during the voltage application. With the increasing impulse amplitude more charge carriers are thus liberated, because the kinetic energy of the individual electrons and concomitantly the number of ionizing electron collisions for each unit of length increase. Nevertheless this fact is not the only reason for the enormous spreading of the surface charges up to the HV electrode with increasing amplitude of the impulse voltage 1.2/330  $\mu\text{s}$ , as shown in Fig. 9 (see Fig. 10). In Fig. 11, it can be seen that the voltage amplitude or the height of the electrical field strength at the particle tips basically influences only the charge carriers excess, and, with it, the charge density in the vicinity of the particle tips. Concerning the influence of the total

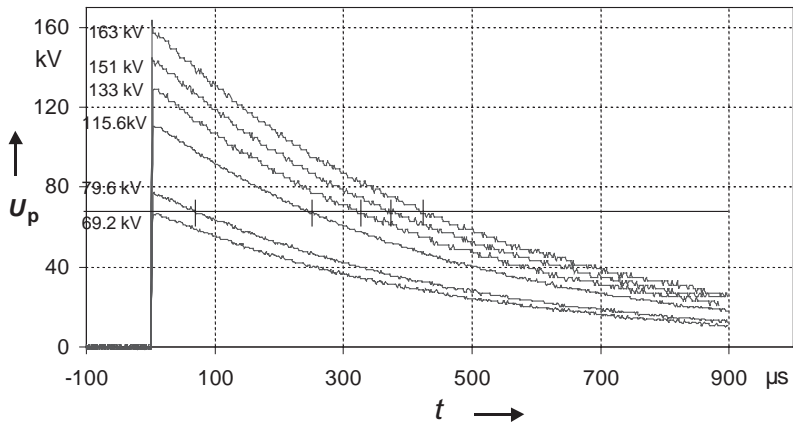


Fig. 10. shapes of impulse voltage 1.2/330  $\mu$ s. Parameter: impulse peak value.

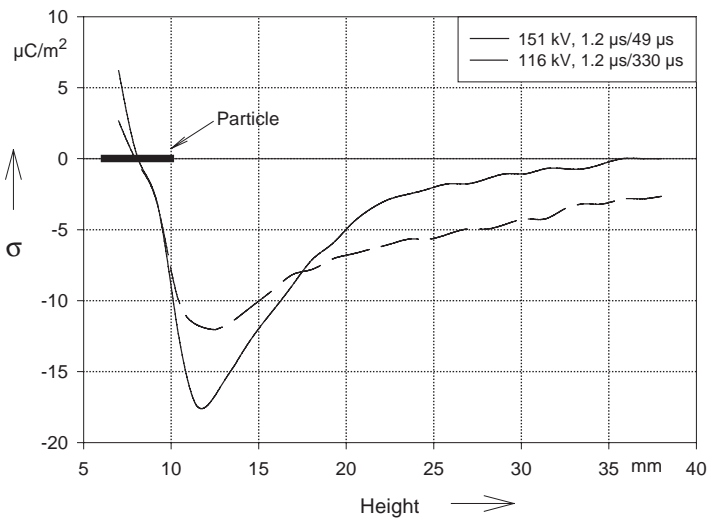


Fig. 11. Profile of the charge distribution on the particle contaminated spacer surface after 15 impulses in  $\text{SF}_6$  gas at 200 kPa. Parameter: impulse peak value and impulse duration.

“flying time” of the charge carriers and thus the spreading of the surface charges up to the HV electrode, this is guaranteed mainly by the impulse duration (impulse length).

Fig. 11 shows a profile representation of the charge distribution for the lightning impulse voltage 1.2/49  $\mu$ s with an amplitude of 151 kV and for the impulse voltage 1.2/330  $\mu$ s with an amplitude of 116 kV. The maximum charge density with the voltage amplitude of 151 kV (1.2/49  $\mu$ s) is almost 1.5 times higher than with 116 kV

Table 1

Difference time  $\Delta t$  of the impulse voltages with increased amplitude  $U_p$  in the reference to the inception voltage of the surface charges under LI 1.2/330  $\mu\text{s}$  stress

$U_p$ [kV]	69.2	79.6	115.6	133	151	163
$\Delta t$ [ $\mu\text{s}$ ]	0	70	254	334	388	432

(1.2/330  $\mu\text{s}$ ). Unlike the impulse voltage 1.2/49  $\mu\text{s}$  (151 kV), the surface charges reached the HV electrode during the stress with the impulse voltage 1.2/330  $\mu\text{s}$  (116 kV).

The variation of the peak value  $U_p$  of the impulse voltage does not only involve a variation of the impulse amplitude, but also the variation of a certain time  $\Delta t$ .  $\Delta t$  is a time during which the PD inception voltage or a fixed voltage reference value is exceeded, as illustrated in Fig. 10. The time  $\Delta t$  can also considerably influence the total “flying time” of the charge carriers along the electrical field lines during the voltage stress. In Fig. 10, a peak value of 69.2 kV is selected as voltage reference value. Its corresponding  $\Delta t$  amounts to 0  $\mu\text{s}$  for the impulse voltage 1.2/330  $\mu\text{s}$ , as indicated in Table 1.  $\Delta t$  increases monotonically with increasing peak value  $U_p$  of the impulse voltage. Therefore more negative surface charges can reach the HV electrode with increasing  $U_p$ .

### 3.5. Influence of the number of applied impulses on the charge accumulation

Depending upon gas pressure and type of gas the charge accumulation on the spacer surface is not influenced only by the peak value of the lightning impulse voltage, but also by the number of applied impulses. Figs. 12 and 13 show the variation of the charge distribution with the number of applied impulses along the particle contaminated spacer surface in 90%  $\text{N}_2$  + 10%  $\text{SF}_6$  gas mixture at 200 kPa and 400 kPa. During the first impulse, an important quantity of charges gets acquired already on the spacer surface. With further impulses of a constant amplitude, the available charge distribution changes constantly, depending upon gas pressure. In Fig. 12, the accumulated surface charges have already reached both electrodes by the end of the first impulse at a gas pressure of 200 kPa. Furthermore, the charge accumulation increases with the number of applied impulses. This means that after each impulse new charges overlay with already accumulated surface charges on the spacer surface. This process continues as long as the applied voltage remains higher than the PD inception voltage which is influenced again by the accumulated surface charges.

Compared to Fig. 12, the charge distributions in Fig. 13 exhibit a less variation with the number of applied impulses. The charge distributions according to the first and fifteenth impulse do not differ much from each other. More than 98% of the measurable surface charges after the fifteenth impulse will accumulate during the first impulse. Moreover, these surface charges have reached neither of the two electrodes. Both positive and negative charges remain in the particle area. As a

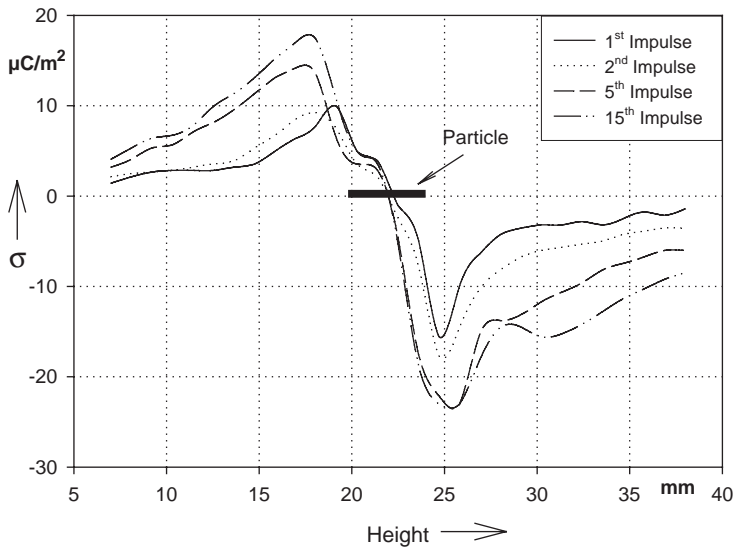


Fig. 12. Profile of the charge distribution on the particle contaminated spacer surface after LI 1.2/49  $\mu$ s stress in 90%  $N_2$  + 10%  $SF_6$  gas mixture at 200 kPa,  $U_p = 108$  kV. Parameter: number of applied impulses.

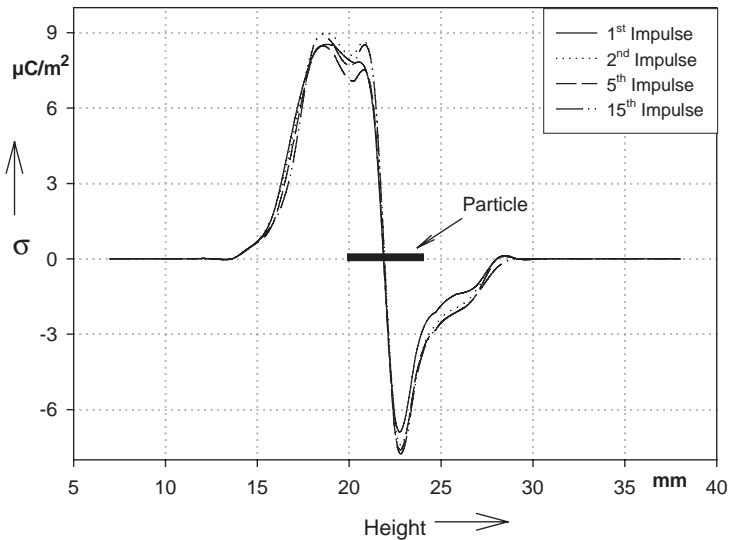


Fig. 13. Profile of the charge distribution on the particle contaminated spacer surface after LI 1.2/49  $\mu$ s stress in 90%  $N_2$  + 10%  $SF_6$  gas mixture at 400 kPa,  $U_p = 108$  kV. Parameter: number of applied impulses.

matter of fact, the accumulation of surface charges is influenced basically by the tangential component of the electrical field which determines the PD inception along the particle contaminated spacer surface. This component of the electrical field at the particle tips is relatively higher here during the stress

with the first impulse than with further impulses. Therefore, it accumulates very few charges with increasing number of applied impulses up to a possible saturation. This light saturation effect of the charge accumulation does not occur with impulse amplitudes in the proximity of the flashover voltage and with relatively low gas pressures.

### 3.6. Influence of the type of gas and the pressure on the charge accumulation

The physical and chemical characteristics of dielectric gases and gas mixtures belong also to the parameters which can influence the PD inception as well as the PD development along the particle contaminated spacer surface. Indeed, the charge accumulation on the spacer surface depends predominantly on the partial discharge (PD) processes in the gas. For example, electronegative dielectric gases (like  $\text{SF}_6$ ) behave differently from non-electronegative gases (like  $\text{N}_2$ ) in relation to the accumulation of charges on the particle contaminated spacer surface, as Figs. 14 and 15 show. In the two cases, the conducting particle was fixed in the middle of the spacer surface. Under equal gas pressure relatively more negative surface charges accumulate in the  $\text{SF}_6$  than in  $\text{N}_2$  gas. The profiles of the charge distributions in Figs. 14 and 15 exhibit an analogue spreading of the negative surface charges up to the HV electrode. However, the density of these negative surface charges in the vicinity of the corresponding particle tip in  $\text{SF}_6$  is relatively higher than in  $\text{N}_2$ . This fact can be explained by the fact that in the pure  $\text{N}_2$  gas only electrons are acquired as negative charge carriers, and an electron has a mobility approximately 833 times higher than that of a  $\text{SF}_6^-$ -ion. Also, in the  $\text{SF}_6$  gas the  $\text{SF}_6^-$ -ions remain almost motionlessly at

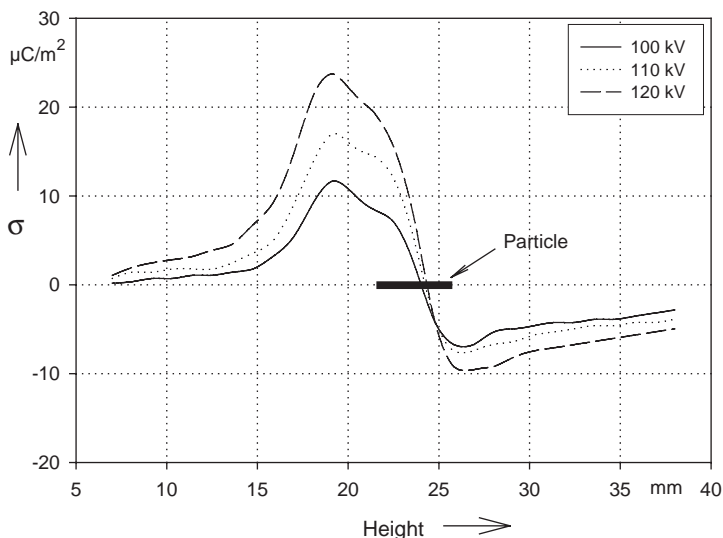


Fig. 14. Profile of the charge distribution on the particle contaminated spacer surface after 15 impulses  $1.2/49\mu\text{s}$  in  $\text{N}_2$  gas at 300 kPa. Parameter: impulse peak value.

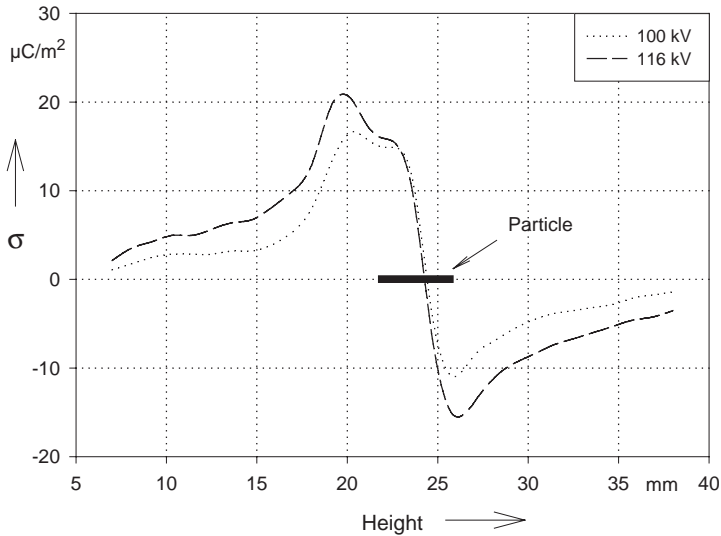


Fig. 15. Profile of the charge distribution on the particle contaminated spacer surface after 15 impulses  $1.2/49 \mu\text{s}$  in  $\text{SF}_6$  gas at 300 kPa. Parameter: impulse peak value.

the place of their emergence in the vicinity of the particle tip during the stress with lightning impulse voltage  $1.2/49 \mu\text{s}$ . Therefore, the distribution profile of the negative surface charges extends flatter in front of the corresponding particle tip in the  $\text{N}_2$  gas than in  $\text{SF}_6$ . Furthermore, it must be taken into consideration that the purity of the  $\text{N}_2$  gas used amounted to only 99.8% (commercial  $\text{N}_2$  gas). A part of the 0.2% gas pollution could be electronegative gases like  $\text{O}_2$  with which also a deposit of negative ions ( $\text{O}_2^-$  and  $\text{O}^-$ ) is possible.

In electronegative gas mixtures with different electronegativity degrees an equal quantity of negative surface charges can accumulate on the particle contaminated spacer surface, if these gas mixtures exhibit an equal dielectric strength. Fig. 16 shows a profile representation of the charge accumulation in pure  $\text{SF}_6$  and in some electronegative gas mixtures. The correspondence between these gases concerning their dielectric strength was determined for a clean spacer surface in Refs. [22,23]. Generally, the negative surface charges spread here on the spacer surface in the same way for all examined gases. In order to obtain approximately the same charge distribution as in  $\text{SF}_6$ , the pressure of pure dry air, 90%  $\text{N}_2$ +10%  $\text{SF}_6$ , and 70% air+30%  $\text{SF}_6$  gas mixture were increased accordingly. Since pure dry air is a weakly electronegative gas mixture with about 20%  $\text{O}_2$  and 80%  $\text{N}_2$ , the profile of the charge distribution extends here flatter than in  $\text{SF}_6$ . In addition,  $\text{O}_2^-$ -ions are 2.25 times more mobile than  $\text{SF}_6^-$ -Ions. This also means that at the same time more negative surface charges are acquired away from particle area in dry air than in strongly electronegative  $\text{SF}_6$ .



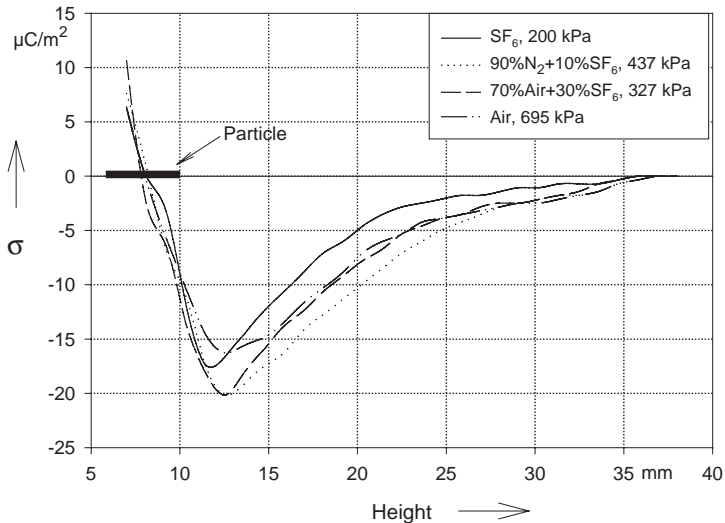


Fig. 16. Profile of the charge distribution on the particle contaminated spacer surface after 15 impulses  $1.2/49 \mu\text{s}$  in gases and gas mixtures with equal dielectric strength,  $U_p = 151 \text{ kV}$ . Parameter: type of gas and corresponding pressure.

#### 4. Conclusion

In this paper, It has been demonstrated that surface charges can be produced by impulse voltages in the surroundings of moving conducting particles. These conducting particles get stuck on spacer surface or jump in their proximity. For the investigated insulating gases, either bipolar or unipolar, charge distributions occur depending on the position of the conducting particle and the type of the test voltage.

During the stress with different impulse voltages the charge accumulation with increasing voltage amplitude and number of impulses increases independently of the type of gas. In addition, the movement of the charge carriers and, thus, the charge accumulation on the spacer surface depend on the impulse duration. Moreover, the electronegativity degree of the insulating gas has a considerable influence. Furthermore, the surface charge density on the spacer decreases with increasing gas pressure.

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