# Charge relaxation on surfaces of polymeric insulating materials for outdoor applications

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The studies have been presented on spatial and temporal distributions of surface charge on samples of ethylene propylene diene monomer (EPDM) and silicon rubber (SIR). The charge was deposited from a positive impulse corona source located at 1 mm above the polymeric surfaces. During the experiments, the number of pulses and their voltage level were varied. It was observed that the spread of the charge over the surface of the samples as well as its magnitude were both increasing with increasing number of impulses applied. EPDM accumulated charge easier and had a longer relaxation time than SIR. A common feature frequently observed in both cases was that the resulting charge distributions had a saddle-like pattern. Performed computer simulations showed that this feature can be attributed to peculiarities of the corona charging in the considered system, which took place in a form of a burst corona, and the dynamics of the deposited charges could be related to burst corona pulses.

Key words: *outdoor insulation; composite insulators; surface charge; relaxation time*

## 1. Introduction

The use of polymeric materials in insulation systems of high voltage apparatuses increases steadily during the last decades [1]. It is believed that polymeric insulation will be dominant in ultra high voltage transmission systems, which are being developed presently for voltage levels up to 1000 kV ac and 800 kV dc for overhead lines and up to 500 kV ac and 300 kV dc for underground/submarine cables. Apparatuses and components, normally operating under system voltages, should also remain functional when exposed to overvoltages appearing in the network due to external causes, e.g., nearby or direct lightning strikes, or internal ones like switching operations, polarity reversal in HV dc systems, etc. Under these circumstances, the reliability and performance of the entire system and its components is influenced by the quality and proper design of HV electrical insulation.

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Two materials that have been extensively tested during the last decades and have been proved to be the most suitable for applications in outdoor insulation systems are ethylene propylene diene monomer (EPDM) and silicon rubber (SIR). At ultra high voltage levels insulation materials behave differently, giving rise to new phenomena that needs to be better understood if the design and construction of high voltage equipment is to be successful. This especially refers to accumulation and relaxation of electric charges at insulator surfaces and interfaces, which in turn may trigger unexpected flashovers during testing and operation [2].

In this paper, we focus on the analysis of experimental data on the dynamics of surface charges deposited on material samples (EPDM and SIR). The samples were exposed to positive corona produced from a needle electrode by applying lightning impulse voltages and resulting spatial distribution of the surface charges and their variations with time were detected. The charging process was analysed also by means of computer simulations of a positive corona in the electrode arrangement used in the experiments. The results indicated that the measured surface charge patterns can be attributed to burst corona mode in the considered system.

## 2. Experimental

*Experimental set-up.* The material samples examined were plane quadratic plates (147×147 mm$^2$) and 2 mm thick. The both types contained alumina trihydrate (ATH) as a filler. The samples were placed on a grounded copper sheet. Over the midpoint of the samples, a high voltage corona electrode was placed. It was a steel needle with a tip radius of 50 µm fixed vertically on another copper sheet of the same size as the grounded one. The high voltage set (needle and copper plate) was placed at a distance of 32 mm from the grounded plate and the resulting distance between the needle tip and the polymeric sample surface was 1 mm as shown in Fig. 1. Before voltage application, the surface of a sample was cleaned with a cloth soaked with isopropyl alcohol and then the sample was left to rest during approximately one hour.
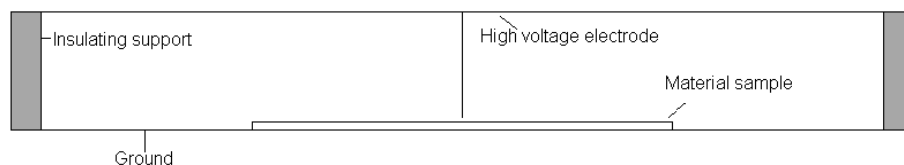


Fig. 1. Schematic view of the experimental set-up

A number (1, 3 or 5) of standard positive lightning impulses (1.2/50 µs) were applied to the corona electrode using an impulse tester HAEFELY PU12. The amplitude of the impulses was 6 or 11 kV. The time interval between the impulses was approximately 20 s. Thereafter, variations of the surface potential were measured with a vi-

brating capacitive probe (9 mm in diameter) connected to an electrostatic voltmeter, Trek 347, along the midlines of both perpendicular directions of the surface, as illustrated in Fig. 2. The probe was mounted onto a step motor driven robot that moved the probe along the lines. The distance between the aperture of the probe and of the scanned sample surface was 2 mm. The time lapsed from the last applied impulse until the measurements were commenced was equal to ca. 60 s.
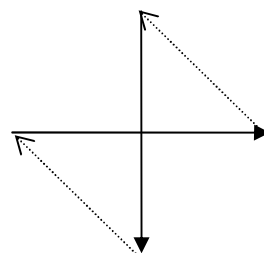


Fig. 2. Scanning procedure, the thick lines with arrows show
how the measurements were performed

The measurements were performed at constant ambient conditions in open air atmosphere at 18–20 °C and the relative humidity 21–24%.

*Characterisation of the material.* Both the volume and surface resistivities were measured for the investigated material samples using a three-electrode system. The voltage of 400 V was applied for 60 min during these measurements. The results are presented in Table 1.

Table 1. Results of resistivity measurements

| Material | Volume resistivity [$\Omega \cdot$cm] | Surface resistivity [$\Omega$ /sq] |
|---|---|---|
| EPDM | $2.50 \cdot 10^{16}$ | $5.0 \cdot 10^{15}$ |
| SIR | $2.12 \cdot 10^{15}$ | $6.9 \cdot 10^{14}$ |

One can see that EPDM samples exhibited much higher bulk and surface resistivities than SIR samples and, hence, one can expect different conditions for charge leakage through the volume of the materials as well as for its relaxation on the sample surfaces leading to different characteristic relaxation times for the studied materials.

## 3. Experimental results

### 3.1. Surface potential distribution

The surface potential distributions recorded on EPDM and SIR samples for the two different charging voltages are shown in Fig. 3. It is important to mention that the

distributions in both the scanned directions (Fig. 2) were similar to each other and, thus, they are shown below for one direction only. One can also notice from Fig. 3 that the measuring system was saturated at the initial stages after charging with the highest voltages and several impulses in series, meaning that the charge densities under these conditions were actually higher than the ones indicated on the graphs.
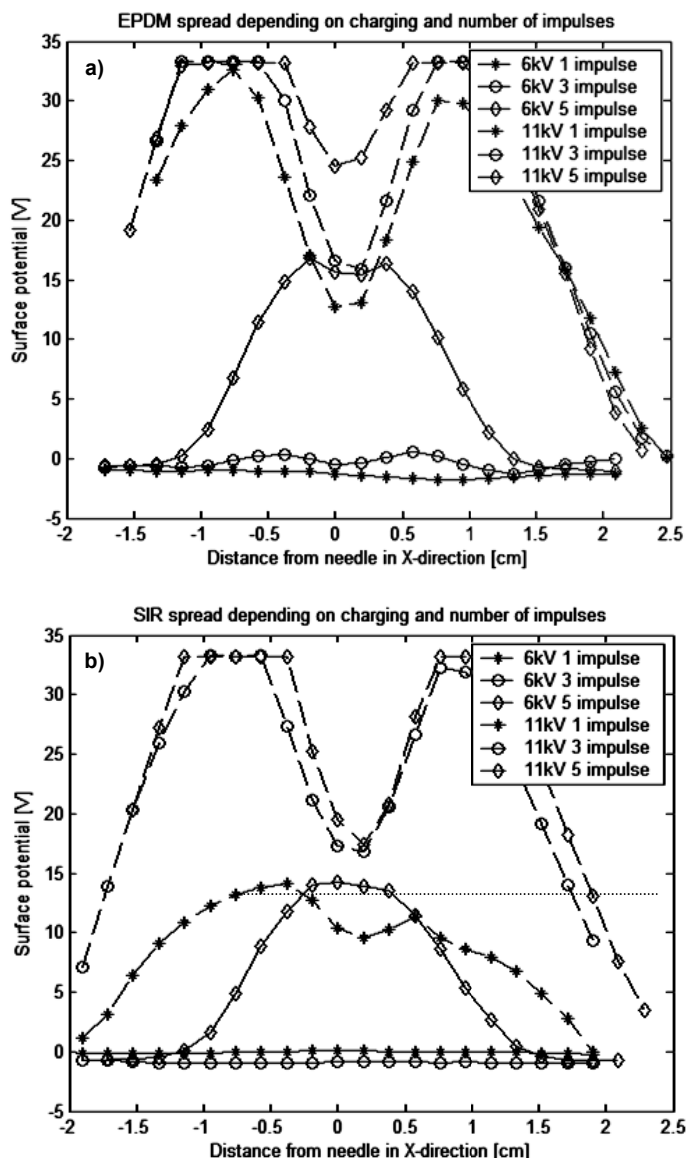


Fig. 3. Surface potential distributions along the midline of EPDM (a) and SIR (b) samples 60 s after charging with various numbers (1, 3 or 5) of corona pulses at 6 and 11 kV

The data in Fig. 3 shows that the surfaces of the samples were weakly charged when one and three impulses of low amplitude (6 kV) were applied and the sign of the measured surface potential was opposite as compared with the polarity of the applied impulses. The potential of the same sign (positive) was recorded on the surfaces when five impulses in series with the amplitude of 6 kV were applied as well as for any number of impulses with the amplitude of 11 kV. In the latter case, one can observe that the magnitudes of the measured surface potentials are higher for EPDM samples than for SIR, i.e. the charge accumulation process is more effective. This correlates with the measured volume resistivities of the materials: the higher resistivity of EPDM prevents leakage of deposited charges through the bulk of the material leading to their higher concentrations on the surface.

It can be also observed on Fig. 3 that the number of corona pulses as well as the magnitude of the charging voltage affected the expansion of the deposited charges over the surfaces of the samples. The distributions became broader at higher charging voltages and the difference between the spreads is about twice as large for the higher voltage. The same refers to the increasing number of corona pulses. This is in agreement with the observations reported in [3].

One may notice from Fig. 3 that for the same number of corona impulses and their magnitude, the spread of charges over the sample surfaces is stronger for SIR samples. This correlates with the fact that the measured magnitude of the surface resistivity of SIR is lower than that of EPDM (Table 1) and, hence, charge leakage along the surface of SIR samples is more intensive. It is also notable that the width of the charged regions is unexpectedly large (if compared with 1 mm gap between the corona needle and the sample surface). The explanation could be that the main expansion of deposited charges takes place very quickly during charging process, when the size of the charged region is very limited and the surface charge densities are extremely high. The process becomes slower with time due to reduction of the charge densities, and the results shown in Fig. 3 indicate the final stages of the process, when steady-state conditions are practically reached. Such a situation has been considered in [4], where fast expansion of charges over gas-solid interface (ca. 10 µs) was observed at streamer arrival to the insulator surface.

### 3.2. Surface potential decay

The time dependences of the surface potential measured at the point on the surface directly below the corona needle are presented in Fig. 4 separately for EPDM and SIR. The decay rates are dependent on the number of applied impulses (i.e., on the amount of the deposited charge). An exception is seen in Fig. 4b, where data for 3 and 5 impulses are practically on the top of each other. In general, the decay of the surface potential is faster for SIR material that can be attributed to its lower volume and surface resistivities leading to stronger charge leakage.

Table 2. Time constants in seconds for charging
at 11 kV with 1, 3 and 5 corona pulses

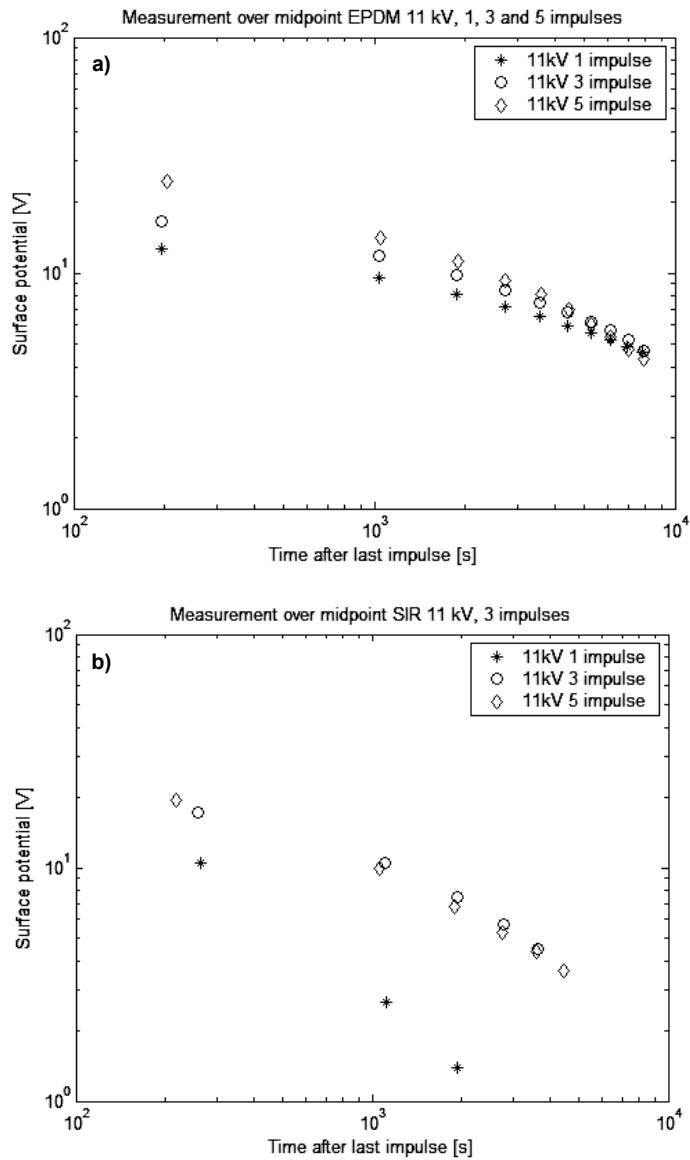| Material | EPDM | SIR |
|---|---|---|
| 1 impulse | 8928 | 662 |
| 3 impulses | 13 500 | 2440 |
| 5 impulses | 6142 | 4064 |



Fig. 4. Time variations of the surface potential on EPDM (a)
and SIR (b) samples for the different number of impulses

Fitting the data in Fig. 4 with exponential functions provided decay time constants shown in Table 2. At the same time, estimations of the time constants made based on the measured volume resistivities of the materials and their permittivities (the dielectric constants were found to be equal to 4) yielded values of ca.8850 s and ca. 750 s for EPDM and SIR, respectively, which are in agreement with the data in Table 2 for single impulse charging. An analysis of the data in the table leads to important observation that the ratio between the time constants for EPDM and SIR decreases with increasing number of applied impulses, indicating that material properties become less important for the potential decay at higher amount of deposited charges.

# 4. Discussion

The presented experimental results allow arguing that the dominating charge decay mechanism for the studied materials is mostly through the bulk of the samples, similarly as observed in [5]. An additional source of charge neutralization may be recombination with ionic species in the air. The fact that the spread of the surface charge distributions (Fig. 3) did not change with time may indicate that the driving force for the spreading originates from own electric field of the deposited charge. If this field appears too low, the width of the distribution remains fixed, as is shown in Fig. 5 for the low charging voltage. The own charge field, on the other hand, is most effective for the spreading during the short periods of corona pulse action, since the initial charge distribution is point-like and therefore has a strong own field.
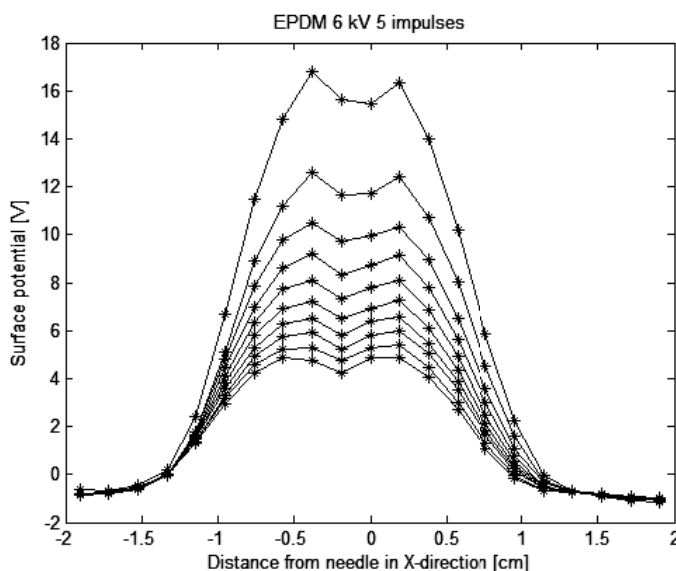


Fig. 5. Spatial- and temporal variations of the surface potential on EPDM sample
for 5 corona pulses at 6 kV; the time interval between the decaying potential curves is 15 min

An interesting feature observed was that the surface potential distributions had a saddle-like shape in the region close to the needle electrode. Vaious explanations may exist for this feature. A similar behaviour of the surface charge as reported here was observed by Baum et al. [6, 7] on thin polyethylene films when charging with negative corona pulses. The authors explained the faster decay in the central region in terms of photoinjection from the surface states into the material bulk which are induced by the corona radiation. At the same time the effects of positive corona pulses were also studied, but they did not yield the saddle-like shape of the surface charge distribution [7].

Numerical simulations showed that the positive impulse corona in the arrangement of Fig. 1 appeared in the form of burst pulses taking place even during one applied voltage impulse. Hence, several waves of positive charges were sent out from the needle. This led to accumulating each time more surface charge in the region close to the needle axis and producing a strong field component along the surface, which thereafter pushed the charge further away. The simulation resulted in the saddle-like surface potential distributions, similar to ones observed in the experiments. However, the magnitudes of the computed potentials were higher than those obtained experimentally and resulted from assuming infinite volume resistivity of the solid material. More experiments and simulations are required to clarify and to understand the observed phenomenon.

# 5. Conclusions

The behaviour of surface charge deposited by impulse positive corona on samples of two polymeric materials, EPDM and SIR, has been studied. It was found that the spatial spread of the surface charge was dependent on the amount of the deposited charges defined by the level of the charging voltage and the number of applied impulses. The higher charging voltage or more impulses applied, the wider spread of the surface charge was recorded. The temporal and spatial variations of the surface potentials were found to correlate with material surface and volume resistivities, however, the influence of these parameters on potential decay rates decreased with increasing amplitude of the voltage or number of the applied impulses.

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