Surface Charge Accumulation in SF$_6$
SURFACE CHARGE ACCUMULATION IN SF$_6$
Mechanisms and Effects

PROEFSCHRIFT

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To Chien
To my parents
Preface

Spacers are widely used in gas insulated switchgear (GIS) to support the conductors. One of the essential phenomena at the spacer surface is the charge accumulation under stress, which changes the electric field and therefore affects the GIS performance. Research on this aspect was carried out during 1988 ~ 1992 in the High Voltage Laboratory of Delft University of Technology. The results are presented in this thesis.

Summary of this thesis

Studies were performed on detection techniques, accumulation phenomena, mechanisms of accumulation and decay, and effects of surface charge.

Chapter 1 gives a general introduction in which the topics are specified and the object of this thesis is defined.

Chapter 2 describes the detection techniques of surface charges, especially the application of a capacitive probe. In order to improve the calibration of the probe, a two-step calibration method is proposed in §2.4 which makes it possible to take the bulk capacitance of the dielectric into account. In §2.5 this method is used to calibrate a probe whose sensing area is not parallel to the dielectric surface, so that charges at the curved surfaces of actual spacers can be determined
experimentally.

Chapter 3 deals with the design and the facilities of the experiments. The electrodes and the samples are designed by field computing (§3.2). The measuring program and the programs processing test data are also developed in this chapter. The experiments were mainly arranged to reveal the accumulation mechanisms.

Chapter 4 presents the experimental results. The fundamental phenomena of charge accumulation at various conditions are given and the factors influencing charge accumulation are reviewed. The results show that arrangements with inserts result in a slight charge accumulation, while the accumulations with toroids are much stronger. In this chapter, the decay behaviour of surface charge is also determined.

Chapter 5 studies the mechanisms of surface charge accumulation and decay. It is concluded that micro ionization at electrodes is the main charge origin and that the charge transport in the gas space is the dominant mechanism of the charge accumulation in GIS. The charge density is determined by both the normal field at the spacer surface and the emission at the electrodes. A field study shows that surface charge will be accumulated at spacer surfaces because of the variations in the material properties at the gas-spacer interfaces.

Chapter 6 discusses the effects of surface charge. This chapter can be divided into two parts: effects on the fields and effects on spacer design.

In the first part it is shown that charge accumulation reduces the magnitude of the normal field, but it can never change the polarity of the field. Inserts improve the initial field distribution and toroids deteriorate the field strongly. In this part, it is also shown that a DC field can easily be calculated at electrostatic conditions (as under AC) but taking into account the accumulated charge at the interfaces.

In the second part, the spacer design criteria are discussed and examples are given. It is suggested that spacers for DC GIS can be designed with acute field angle (the angle between the interface and an equipotential line close to a triple junction is less than 90°). A design suppressing charge accumulation might be achieved by designing the
normal component of the initial field as small as possible.

Chapter 7 summarizes the conclusions of this thesis and gives some suggestions for future work.

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Chapter 1
Introduction

1.1 Gases and Gas Insulated Switchgear (GIS)

The introduction of electro-negative gases in switchgear as insulation media in the 1960s can be attributed to their excellent insulating properties [1,2,3]. In an electro-negative gas electrons can readily attach to the gas molecules. This attachment forms heavy ions which are much slower than electrons and prevents the forming of avalanches, leading to higher breakdown stress [4]. Therefore, more compact and compatible Gas Insulated Switchgear (GIS\(^1\)) can be built. From an environmental standpoint, the GIS technique is expected to be put into use in power systems at all voltage levels [3].

The electrical properties of electro-negative gases, such as sulphur hexafluoride (SF\(_6\)), freon (CCl\(_2\)F\(_4\)) and their mixtures including those with carbon dioxide (CO\(_2\)) and air have been studied [5,6,7,8].

\(^{1}\)The abbreviation GIS also represents Gas Insulated Substations or Systems in the literature. However it really means compressed gas insulated units.
1.1.1 Sulphur hexafluoride ($SF_6$)

$SF_6$ is the most widely used gas due to the following properties: it has no colour and no odour, it is not poisonous, not aggressive\(^2\) and it is not combustible. Besides the attachment of electrons to ions, the advantage of this gas is also achieved by the larger diameter and the heavier weight of its molecules than those in air. The former reduces the free path ($\lambda$) of the electrons in a field and resists them from getting enough energy to ionize other molecules by colliding. The latter makes the mobility of the ions lower. Hence the possibility for the ions to recombine is increased and the formation of charged particles in the space is decreased [11].

These three processes, which are unfavourable to the growth of a discharge channel, can be described as

\[
SF_6 + e \xrightarrow{\text{attachment}} SF_6^- \\
SF_6 + e \xrightarrow{\text{collision}} SF_6 + e \\
SF_6^+ + SF_6^- \xrightarrow{\text{recombination}} 2SF_6 \\
SF_6^+ + e \xrightarrow{\text{recombination}} SF_6
\]

Hence, $SF_6$ can withstand higher electrical stress. Under homogeneous field conditions, the electrical strength of $SF_6$ is $2.3 \sim 3.0$ times that of air at the same pressure [4,12].

1.1.2 Study aspects

The growth of ionization in electron avalanches is described by the effective coefficient of ionization $\bar{\alpha}$ [5,13]:

\[
dN(x) = \bar{\alpha}(x) N(x) \, dx, \quad \bar{\alpha} = \alpha - \eta, \quad (1.1)
\]

\(^2\)High temperature ($>4000^\circ$K) caused by electrical discharge in the gas, however, causes aggressive and poisonous by-products. See [9,10].
1.1 GASES AND GAS INSULATED SWITCHGEAR (GIS)

with \(x\) being the coordinate along the field direction. \(N(x)\) is the total number of electrons in an avalanche. \(\alpha\) represents the effective coefficient; \(\alpha\) is the ionization coefficient and \(\eta\) is the attachment coefficient. Because GIS works at quite high stress and \(\alpha\) increases quickly with increasing field strength \(E\), the electric strength of GIS depends strongly on any distortion of the field. Therefore, besides the physical study of the gas properties [11,12,14,15,16,17,18], intensive studies have also been performed on the influences of surface conditions and the contamination within GIS [5,6,19,20,21,22].

Electrode surface roughness was found to cause, under the strong operating field in GIS, a pronounced reduction in the electrical strength [23]. By microscopic treatment, it was found that a protrusion with a height of \(h'\) at electrodes has an effect if [6]

\[
P h' \geq 4 \text{ kPa} \cdot \text{mm},
\]

with \(P\) being the pressure. Macroscopically, the distortion caused by the surface roughness can be described by a field enhancement factor \(m\) (the maximum field strength \(E_{\text{max}}\) of a rough surface divided by the maximum field strength \(E_{\text{a}}\) of the idealized macroscopic geometry), where \(m\) can be determined experimentally [24].

The electrode area effect has also been studied because a larger area provides more probability of breakdown. The cumulative breakdown probability \(F(S', E)\) increases with increasing area \(S'\) [21]:

\[
F(S', E_{\text{bd}}) = 1 - e^{-\zeta S' \left( \frac{E_{\text{bd}}}{E_{\text{i}}} - E_{\text{m}} \right)^m}
\]

where \(\zeta\) is a constant dependent on the gas, surface roughness and pressure; \(E_{\text{bd}}\) is the breakdown field for the area \(S'\), and \(E_{\text{i}}\) the theoretical one; \(E_{\text{m}}\) represents the minimum breakdown field for a very large area in a certain gas at a particular pressure; \(m\) is constant for \(SF_6\) (= 7.4).

The electrode effect has also been studied with respect to the electrode materials and its geometries, as well as dielectric coatings (with epoxy, teflon, polyester etc.) on the electrode surfaces [5,6,19,25].
More attention has been paid to the effect of the insulator surface, which will be reviewed in the next section.

*Foreign particles* form the main contamination in GIS. Under a certain AC stress, conductive particles will bounce in the interelectrode gap [20,26]. They may cause an intensive space charge density to deform the field, or form distortions themselves and shorten flashover distances [9,26]. A particle at a place where the field is strong has more effect [26]. Also, more effect results from particles attached to the spacer surface [27], especially at the location where the tangential component of the field is the largest [6,21,28]. Small conductive particles, say < 200\(\mu\)m, as well as dielectric ones, have little effect [9,26,29,30].

Other factors which result in the contamination in GIS are moisture in the gases and their decomposition by-products [10,29,31,32,33].

It is expected that GIS will become more compact in order to reduce its size and cost [3,6]. There is also a need to obtain a better understanding of the breakdown mechanism in the gases and to evaluate the relationship between theoretical model studies and those of full scale GIS [22]. Therefore further studies should be performed to determine the origin of the initiatory electrons, the ionization and the attachment coefficients and the collision cross-sections at higher pressure and in non-uniform fields [6] with the knowledge of actual spatial charge distributions in the vicinity of an avalanche.

### 1.2 Surface Phenomena in GIS

Spacers are used in GIS to support the conductor and to isolate it from the enclosure. Normally GIS are constructed coaxially. The inner conductor is at a high voltage to transfer the power. The outer conductor is earthed as a shielding and used as the enclosure of the gases. An understanding of the flashover characteristics along the gas-solid interfaces is of importance when trying to improve the per-
formance of GIS because such an interface constitutes the weakest electric location in GIS.

The introduction of a surface results in distortions of the original field owing to the variation of the permittivity. The insulation condition can also be deteriorated by the contaminations, or conductive particles, on the surface, therefore the onset voltage of a discharge is decreased. On the other hand, as soon as a discharge is ignited, the discharge channel grows more easily due to the photo-ionization and/or thermal ionization in the vicinity of the surface [35, 36].

### 1.2.1 Surface flashover models

Most of the existing flashover models have paid little attention to the processes at the surface itself, or have paid attention only to one of the factors which influence the flashover behaviour [30].

One model for the study of leader behaviour is set up by sticking a conductive tape on the reverse side of a plane insulator to control the leader direction [37]. With this model, it was found that the gas pressure does not influence the propagation velocity, the average field and the onset voltage of a leader. The discharge was described in terms of input energy to the channel. In this model, the geometry of the channel (lengths, diameters etc) was also determined. Nevertheless, this model does not explain the role that a surface plays in the ionization dynamics.

When a flashover is initiated by a cylindrical metal particle, with hemispheric tips, at the surface, the field distribution in the vicinity of the particle can be calculated [28]. Substituting the critical criterion (10⁸ electrons) of a streamer resulted in a threshold for a surface flashover:

\[
E_{bd} = \frac{0.68 + 0.09 P (X_c - \frac{D}{2})}{(X_c - \frac{D}{2}) \left(1 + \left(\frac{L}{D} - 1\right) \frac{D}{2X_c} + \frac{D}{2} \frac{(D + X_c)}{X_c^2}\right)}
\]  \quad (1.2)

where \(E_{bd}\) is the applied discharge field in kV/mm; \(L, D\), the length
and the diameter of the particle in \( mm \) \((L \gg D)\); \( P \) the pressure in \( kPa \). \( X_c \) defines the ionization zone, from the tips of the particle, in \( mm \). Obviously, this model is only related to a specially formed particle, not to the surface.

Both of the above models are essentially based on the conceptions of discharges in a free space.

The photo-emission coefficient\(^3\) \( \delta \) has been introduced as a secondary ionization coefficient to describe the electron emission from the surface by photons [35]. Hence, (1.1) can be rewritten as

\[
dN(x) = \bar{\alpha}(x) N(x) \, dx \quad , \quad \bar{\alpha} = \alpha + \delta - \eta
\]

This \( \delta \) can, in some degree, represent the contribution of the dielectric surface to the discharge process. The spatial charge before discharging is taken into account in this model by field-dependent coefficients \( \alpha(E) \) and \( \eta(E) \). \( \delta \) is obtained by comparing the experimental results and those predicted only by \( \alpha(E) \) and \( \eta(E) \).

However, the real process on the surface may again be masked by that in the gas. In a full-scale GIS where the flashover distance is large, the physics in the flashover channel cannot be described by a photon process only.

One of the fundamentals relevant to surface flashover is the surface charge accumulation [30]. The charges accumulated on the surface can influence the flashover dynamics in various ways. More work is necessary to accurately correlate the surface charge distribution with the flashover dynamics [38].

### 1.2.2 Practical aspects

Besides the studies into flashover physics, much has been performed with respect to the design of spacers. By a proper design, a spacer

\(^3\)Mean number of electrons emitted from the surface by the photons originating from molecules that were exited by one electron travelling 10mm in the direction of E-field.
1.2 SURFACE PHENOMENA IN GIS

Efficiency\(^4\) \(\xi\) of \(~100\%\) can be achieved [39,40]. But in practice, as mentioned in §1.1, the dielectric strength is strongly influenced by any distortions of the field. By the introduction of spacers, these distortions can be distinguished as [26,28,29]:

- Triple junction;
- Conductive particles;
- Irregular dielectric surface;
- Static charges.

Triple junction indicates the conductor-spacer-gas junctions where any poor contact, i.e. a gas layer, between the spacer and the conductor results in a field intensification due to the difference of the permittivities\(^5\). Such a defect on the cathodes has more influence on the flashover voltage due to the supply of initial electrons for an avalanche [41]. However a gap of < 80\(\mu m\) shows little effect on the insulation [9]. This may result from the charge accumulations around the gap which shield the defect [41]. In actual practice, this problem is overcome by optimization designs of spacers [42,43,44], and also by designing the profile of conductors, including the application of inserts, toroids and recessed electrodes [9,27].

Conductive particles are more deterioration as they are attached to the spacer surface. As indicated in §1.1.2, the effect also depends on the position where such a particle attaches. Gross defects, as well as particles, can make the surface irregular. The analysis of the influence is the same as that for triple junctions.

As indicated in §1.1, distortions of the field by defects become stronger with increasing dielectric strength, therefore the effect is greater at a higher designed stress. This is also valid for the analyses of \(\xi\). With spacers being present, the intensifications at the triple junctions and at the surface irregularity also depend on the

\(^4\)Flashover voltage at the presence of a spacer divided by that without spacer.

\(^5\)Exactly, a field intensification takes place at the interface between the spacer and the conductor, not at a junction, though the term triple junction is usually used.
permittivity $\varepsilon$ of the spacer material — they become stronger with increasing $\varepsilon$. By introducing $K_c$, the spacer contact constant, and $K_s$, the spacer roughness constant, to represent other influences from the triple junctions and the spacer surfaces respectively, the spacer efficiency can then be described by an empirical expression [45]:

$$\xi = \frac{K}{\ln(U_{bd})} \cdot \frac{K_s}{K_c} \cdot \frac{\ln(\varepsilon_r)}{\varepsilon_r}, \quad K_c > 1.0, \quad K_s < 1.0 \quad (1.3)$$

where $K$ is a constant depending on the experimental conditions. $K_c$ decreases with increasing gap length of the crack at triple junctions. It approaches 1.0 when the gap length approaches zero. $K_s$ increases with a smoother spacer surface. It approaches 1.0 when the spacer surface is “smooth”.

The influences of the surface charges have not been taken into account in this model.

### 1.2.3 Study prospects

The decrease of the breakdown voltage $U_{bd}$ by placing spacers in GIS must arise from some variations of parameters which describe the electron growth [30]. These variations would be those of the pre-breakdown conditions, and those involving the flashover dynamics [9].

Pre-breakdown conditions are changed due to a spacer. Locations of intensive field may occur midway at the interface. This can arise from its profile, from the defects on it, and also from the surface charges accumulated on it [6].

The decrease of $U_{bd}$ means also the variation of the parameters describing the flashover dynamics. Little has been published to incorporate the intrinsic properties of a surface with the flashover dynamics. Besides the possible pre-energy on a surface, the existence of a surface may also increase the electron gain coefficient ($\bar{a}$). On the other hand, the velocity for the electrons to diffuse may be hindered by the surface. Furthermore, a normal field along the surface may press the discharge channel onto the surface, to gain more collision,
resulting in a higher temperature to promote a precursory leader in the channel.

Special consideration should be given to surface charge accumulation, which influences not only the pre-breakdown conditions, but also the flashover dynamics. At atmospheric conditions, the accumulated charges play such an important role, as they supply enough energy for a flashover along a surface before it is initiated [46]. This phenomenon was also emphasized for GIS [28]. The spatial charges can result from the micro-discharges at the electrode surface, but also from those on the spacer surface at voids or particles. The distribution varies significantly under different conditions.

Only after these data are collected from the pre-variation, initial processes, secondary processes and charge diffusions, etc., can a comprehensive analytical model for surface flashover be developed. T.S. Sudarshan and R.A. Dougal [30] indicated that this is, in fact, virtually the only way to tackle the complex problem. Hence, the comprehensive model is a function of various independent processes, each of which depends upon several system parameters. For example, streamer is one of the processes. It is related to the parameters as in (1.2). Hence the flashover voltage $U_{bd}$ can be described as:

$$U_{bd} = \mathcal{F}(\text{process}_1, \text{process}_2, \ldots, \text{process}_n)$$

$$= \mathcal{F}(f(L, D, p, \ldots), \ldots, ) \quad (1.4)$$

In practice, a test can be arranged especially to make one process significant, but others negligible, hence the relation with the former can be determined.

### 1.3 Specification of the Problem

As reviewed in §1.2, surface charge accumulation plays an important role in flashover. It changes not only the pre-breakdown conditions, but also influences the flashover dynamics; therefore it plays a part in the GIS behaviour. However, in present-day AC GIS, the accumulation is not so significant to cause concern, because GIS works under
impermanent (alternating) stresses with quite large tolerations [22]. When one tries to develop HVDC GIS where the accumulation is heavy, or to make GIS more compact, this phenomenon has to be well understood. From the theoretical aspect, such a study is, of course, necessary in order to gain a better interpretation of the surface flashover.

Since the early eighties [47], the study has been performed with GIS under different conditions. The aspects that are being considered are:

- How to determine its distribution;
- Where it comes from;
- What effects it has on the flashover behaviour;
- How to avoid it.

Up to now, though much work has been done, a comprehensive understanding of the charge accumulation has not yet been achieved [48]. A number of conflicting results have appeared. More details regarding these aspects will be reviewed in the following chapters together with the contributions of this thesis.

1.4 Object of the Present Work

The present work has been aimed both at the improvement of the detection techniques and the study of the accumulation behaviour of large-scale spacers in GIS.

The former is specified as:

- The improvement of the calibration procedure of surface charge measurements;
- Charge detection on actual spacers with a curved surface.

The latter is specified as the study of:

- Spatial distribution of the charges;
1.4 **OBJECT OF THE PRESENT WORK**

- Factors influencing the accumulation behaviour on large-scale spacers.
  - Protrusions on electrodes;
  - Roughnesses on spacer surfaces;

- Influence of the geometrical design to reveal the significances of both the tangential and the normal component of the field;

- Decay behaviour.

After these have been investigated, the accumulation mechanism is also studied. With respect to field distortion by the accumulated charges, the criteria for spacer design are then discussed.
Chapter 2
Charge Detection

In this chapter, the techniques for the surface charge measurement are reviewed first. The emphasis is placed on those which will be employed in the following chapters. Thereafter, the arrangements and the experiments which determine the parameters for the data calibration are described. Finally, the calibration is improved experimentally and the probe method is further developed for the application to actual spacers used in GIS. The calibrations for samples which will be studied later in this thesis are also defined in this chapter.

2.1 Lichtenberg Figures

Since the beginning of this century, when the investigation of surface flashover phenomena began, Lichtenberg figures have been employed to demonstrate surface charge distributions after a discharge [49,50]. This method has the advantage that the charge distribution of both polarities can be visibly demonstrated using differently coloured powders.
The applied powders are: red-coloured lead oxide ($\text{Pb}_3\text{O}_4$) powder, which can be charged positively; yellow-white sulphur ($S$) powder, which can be charged negatively. In practice, some other alternatives, such as various coloured powders for copying machines, have also been used [51,52,53]. The mixture of these powders can be sprinkled before or after the voltage application to a dielectric surface. The track and the strength of the discharge, or pre-discharge, are clearly shown.

With the development of the probe method for investigation with GIS, Lichtenberg figures are also frequently employed to verify the patterns of surface charge [51,52,54,55] or, contrarily, to show the limits of the probe method [54,56]. Unfortunately, no quantitative measurement can be performed using this method and the enclosure of GIS has to be opened to sprinkle the powders, which can destroy the original charge distribution [56]. Therefore the application of a capacitive probe is preferred to the use of Lichtenberg figures, although Lichtenberg figures have been used in a few cases.

### 2.2 Capacitive Probe

The quantitative measurement may be performed by means of a field-mill (rotating vane) or a capacitive (electrostatic) probe. As the stability of electronic circuits has been improved, the latter has become more popular for surface charge measurement, while the former has fallen into disfavour [57]. In the present thesis, the principles of the latter will be reviewed; those of the former, as well as its applications, can be found in [54],[58] and [59].

The probe method was introduced in [60]. What is measured is the induced voltage (or charge) on the probe. Fig. 2.1 shows a diagram [61] and its equivalent circuit. Such a probe can be operated by vibrating it above the surface (or by any other motions), which makes $C_1$ vary periodically. At a certain charge density, the induced charge on the probe changes the same way as $C_1$. Therefore a corresponding current output can be obtained from the probe [62]. In
2.2 CAPACITIVE PROBE

Figure 2.1: Capacitive probe: a. diagram, b. equivalent circuit. A→sensing area, A'→effective area, h→separation, d→dielectric thickness, C₁→capacitance in h, C₂→input capacitance of probe, C₃→bulk capacitance in d, Q→surface charge, u₂→measured voltage

principle, this operation is the same as that of a field-mill in changing C₁. To ensure an identical C₂ during a measurement, the probe has to be fixed on the meter, measuring the output, rigidly (see §3.1.1). Hence the meter has to be vibrated as well. This results in some difficulties in practice.

As stable meters with high input impedance are now available, it is possible and more popular to operate a probe when it approaches the charged surface to a certain separation (h) with its sensing area parallel to the surface [60]. The induced voltage at the probe is then measured. Because the input impedance parallel to the capacitance C₂ is very high, the leakage of the induced charge on the probe can be ignored, and the surface charge density can be determined by the measured voltage. For the application to GIS, this method has been developed on the following assumptions [55,56,63,64]:

- The charged surface in the effective area is of one polarity only;
- The charge density in the effective area is homogeneous;
- The effective area is dependent on the geometry of the separation (i.e. C₁) only, but independent of the thickness and the
permittivity of the dielectric (i.e. $C_3$);

- There is no spatial charge nor polarization effect inside the dielectric.

The principles are described below.

### 2.2.1 Principles of the probe

As a probe approaches the charged surface from far away, the total charge $Q$ present under the probe will be divided over the capacitances $C_3$, and $C_1$ in series with $C_2$, so that the induced voltage $u_2$ on the probe is

$$u_2 = \frac{C_1}{C_1 + C_2} \cdot \frac{Q}{C_3 + \frac{C_1 C_2}{C_1 + C_2}}$$

$$= \frac{C_1}{C_1 C_2 + C_1 C_3 + C_2 C_3} Q$$

(2.1)

where the charge $Q$ corresponds to that in a certain area under the probe. On the assumption that the charge distribution is homogeneous in this area, the field in the separation is considered to be uniform if the probe is placed close to the surface with the sensing area $A$ parallel to it [55], see Fig. 2.1. Then

$$Q = \sigma_S A$$

with $\sigma_S$ being the density of the surface charge. To take any deformation of the field into account, the sensing area $A$ should be replaced by an effective area $A'$:

$$Q = \sigma_S A'$$

(2.2)

Then (2.1) can be rewritten as

$$u_2 = \frac{C_1 A'}{C_1 C_2 + C_1 C_3 + C_2 C_3} \sigma_S$$

(2.3)
2.2 CAPACITIVE PROBE

Equation (2.3) correlates the induced voltage at the probe $u_2$ to the surface charge density $\sigma_S$, therefore the latter can be determined by measuring the former:

$$\sigma_S = \frac{C_1 C_2 + C_1 C_3 + C_2 C_3}{C_1 A'} u_2$$

$$= M u_2 \quad (2.4)$$

where

$$M = \frac{C_2}{A'} \cdot \frac{C_1 C_2 + C_1 C_3 + C_2 C_3}{C_1 C_2} \quad (2.5)$$

is defined as the calibration coefficient, which has to be determined for the data calibration as discussed below.

2.2.2 Probe calibration

In practice, $C_2$ is the capacitance of the probe plus the input capacitance of the meter. It is normally thousands of times higher than $C_1$, therefore (2.5) changes into

$$M = \frac{C_2}{A'} \left(1 + \frac{C_2}{C_1}\right) \quad \text{as} \quad C_1 \ll C_2 \quad (2.6)$$

In some actual cases, $C_3 \ll C_1$ and

$$M = \frac{C_2}{A'} \quad (2.7)$$

The term $\frac{C_2}{A'}$, being the input capacitance divided by the effective area, is an important factor for each case of (2.5), (2.6) and (2.7). $\frac{C_2}{A'}$ is determined by means of a metal plate at potential $V_s$ [56,59,64,65], instead of a dielectric (Fig. 2.2), provided that the effective area $A'$ is the same as in Fig. 2.1. Then

$$\frac{V_s}{u_2} = \frac{C_2 + C_1}{C_1} \quad (2.8)$$
Figure 2.2: Calibration of the probe with a metal plate at potential $V_s$

or

$$\frac{V_s}{u_2} = \frac{C_2 + \frac{\varepsilon_o A'}{h}}{\frac{\varepsilon_o A'}{h}} = \frac{C_2}{A'} \frac{h}{\varepsilon_o} + 1 \quad (2.9)$$

due to the uniform field existing in the separation. So, $\frac{C_2}{A'}$ is obtained by

$$\frac{C_2}{A'} = \frac{\varepsilon_o}{h} \left( \frac{V_s}{u_2} - 1 \right)$$

$$= \frac{\varepsilon_o}{h} \left( K_1 - 1 \right) \quad \text{if} \quad K_1 = \frac{V_s}{u_2} \quad (2.10)$$

where $K_1$ is the measured value of the dividing ratio. Because $C_2$ can be measured directly, $A'$ is determined by (2.10). However, an error might be introduced because the charge mobility on the metal surface is different from that on the dielectric surface.

Other capacitive parameters for the calibration by (2.5) or (2.6) can be calculated by ($C_2$ can be measured directly)

$$C_1 = \frac{\varepsilon_o A'}{h} \quad (2.11)$$
and

\[ C_3 = \frac{\varepsilon_r \varepsilon_0 A'}{d} \]  \hspace{1cm} (2.12)

at the conditions that the field in the separation is uniform and that the dielectric is a plane plate, with a relative permittivity of \( \varepsilon_r \).

Hence, (2.6) changes into

\[ M = \frac{C_2}{A'} \left( 1 + \varepsilon_r \frac{h}{d} \right) \quad C_1 \ll C_2 \]  \hspace{1cm} (2.13)

In §2.4 and §2.5, a general technique to determine the calibration coefficient \( M \) which is valid for various situations will be introduced.

### 2.2.3 Possible use of the multi-point method

As discussed above, the application of a metal plate in the calibration procedure may originally introduce some error due to the different charge mobilities on both surfaces. Even in the case where the charge distribution on the dielectric surface is homogeneous, the field distribution within the separation between probe and charged surface also differs from that by a metal plate [63]. Hence the response of the probe at one position also relates to the charges in other locations other than those in the effective area [68,69]. A better calibration is achieved if all the charges are taken into account. One of the possibilities is to perform the calibrations for all the area elements in a system simultaneously by means of the solution of a set of linear equations, as described below.

As the whole system (including the charged surface, the electrodes and the probe) is considered to be a self-contained electrostatic system, the induced charge and therefore the induced potential \( u_2 \) at the probe is related to the total charges in the whole system [70]:

\[ ^1 \text{With } \Lambda \text{ being a probe response function, the response can also refer to other quantities, e.g. the induced charge, instead of } u_2. \]
CHAPTER 2  CHARGE DETECTION

\[ u_2 = \iint_{s_o} \Lambda \sigma_s \, ds + \iiint_{\Omega_o} \Lambda \rho \, d\Omega \quad (2.14) \]

where \( \Lambda \) is a position function which is only dependent on the position of \( ds \) and \( d\Omega \) if the system is linear. \( \sigma_s, \rho \) are the charge densities on the surfaces in the system and inside the dielectric respectively. If there is no charge on the surface of electrodes and the charge inside the dielectrics can be negligible (\( \rho = 0 \)), by digitizing (2.14) appears as:

\[ u_2 = \sum_{i=1}^{n} \Lambda_i \sigma_{s_i} \Delta s = \sum_{i=1}^{n} d_i \sigma_{s_i}, \quad d_i = \Lambda_i \Delta s \quad (2.15) \]

if there are \( n \) area elements \( \Delta s \). \( \Lambda_i \) represents the response function of the area element \( i \) to the probe. \( d_i \) is the response coefficient. For the charge being detected \( n \) times in different positions, we obtain \( n \) equations as

\[ u_{2j} = \sum_{i=1}^{n} d_{ij} \sigma_{s_i}, \quad j = 1, \ldots, n \quad (2.16) \]

with \( d_{ij} \) being the response coefficient of element \( i \) to the probe when it is at position \( j \). Let

\[ \bar{U} = \left( u_{21} \quad u_{22} \quad \cdots \quad u_{2n} \right)^T \quad (2.17) \]

\[ \bar{D} = \begin{pmatrix} d_{11} & d_{12} & \cdots & d_{1n} \\ d_{21} & d_{22} & \cdots & d_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ d_{n1} & d_{n2} & \cdots & d_{nn} \end{pmatrix} \quad (2.18) \]

and

\[ \bar{\sigma}_S = \left( \sigma_{s_1} \quad \sigma_{s_2} \quad \cdots \quad \sigma_{s_n} \right)^T \quad (2.19) \]

then

\[ \bar{U} = \bar{D} \cdot \bar{\sigma}_S \quad (2.20) \]
or
\[ \overline{\sigma_g} = \overline{M} \cdot \overline{U}, \quad \overline{M} = \overline{D}^{-1} \] (2.21)

Hence, for the determination of the charge distribution on a surface, one can first divide the surface into \( n \) elements and assume that the density in each element is homogeneous, then perform the measurements at \( n \) positions above the surface to get \( n \) responses. The charge densities on all elements form the solution of (2.21). This was introduced as the multi-point method [63,55,71]. The elements of \( \overline{M} \) can be determined by computation. In fact, they are the mutual capacitances of the area elements and the probe at certain positions in an independent electrostatic system [72].

The multi-point method means that all the charges on the surface (in the system) are taken into account. The finer the area elements, the better the solution. The difficulty here is the necessity to employ a three-dimensional program for field calculation. For a fine resolution, the order of matrix \( \overline{M} \) (\( n \times n \)) might also be quite large. This method was therefore not employed in the present work.

2.3 Basic Experiments for Calibration

For the studies in the following sections some basic experiments have to be performed beforehand, such as the measurements of the dielectric permittivities of the materials and the determination of \( \frac{C}{A} \). They are conducted in this section.

All through this thesis, a probe of \( \phi 2.3 \) diameter with a shield of \( \phi 5 \) inner diameter and \( \phi 12.5 \) outer diameter, was used to conduct the tests. Several parts can be plugged together to obtain a length suitable for each test. The whole probe is then mounted on an electrometer whose input impedance is \( > 10^{14}\Omega \), shunted by \( 20pF \) of the capacitance. The value of the capacitance \( C_2 \), including that of the meter, is fixed at values between \( 25.0pF \) and \( 76.5pF \), depending on the length of the probe. Appendix A gives the geometry of the probe and the field distributions in front of it at the separation \( h = 5mm \).
2.3.1 Permittivity measurement

To evaluate the influence of the spacer materials on the calibration coefficient $M$, the permittivities have to be measured. For this purpose, a specimen of each material to be used later was made, and was measured using a standard sample holder\(^2\) at 1000 Hz. Table 2.1 gives the results of the specimens. The first PVC (polyvinyl chloride)

<table>
<thead>
<tr>
<th>Nr.</th>
<th>Material</th>
<th>Dimension</th>
<th>$\varepsilon_r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>PVC</td>
<td>$\phi 50.00 \times h 2.55$</td>
<td>4.6</td>
</tr>
<tr>
<td>2</td>
<td>PVC</td>
<td>$\phi 49.05 \times h 1.95$</td>
<td>3.3</td>
</tr>
<tr>
<td>3</td>
<td>Epoxy resin</td>
<td>$\phi 39.70 \times h 2.75$</td>
<td>4.2</td>
</tr>
</tbody>
</table>

material is to be used to study the influence of the bulk capacitance on the probe calibration (see §2.4); the second is for the development of the two-step method (§2.5). Epoxy resin is the material from which the GIS spacer (§2.5.4) and the cylindrical spacers (§2.4.4) are made.

It is assumed that the permittivities in the charging fields in the following tests do not drift much from that measured at 1000 Hz.

2.3.2 Determination of $\frac{C_2}{A}$

To perform the probe calibration, it is essential to determine the value of $\frac{C_2}{A}$, as discussed in §2.2.2. This is achieved by means of a metal plate (see Fig. 2.2). For this purpose, an aluminum plate was mounted before the probe with high voltages ($V_s$) of 0.5 kV, 1 kV, 1.5 kV or 2 kV. The distance between the probe and the aluminum plate was varied to determine the calibrations at different separations. Fig. 2.3 shows the results when $C_2 = 36.5 pF$.

Because of the special geometry of the probe (Appendix A), more field lines from the metal plate will end at the sensing area of the

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\(^2\)1690-A Dielectric Sample Holder, General Radio, USA.
probe when the separation is very small. However, field homogeneity exists in a certain range of the separation where \( A' \) remains identical. This is reflected in the range of \( 3 \sim 8 \text{ mm} \) of the separation. Further increase of the separation will result in an increased inhomogeneity of the field, which seems to cause \( A' \) to increase a little. Nevertheless, \( C_2/A' \) varies only between \( 7.5 \sim 8.0 \mu \text{C/m}^2/\text{V} \) when the separation is \( 3 \sim 12 \text{ mm} \).

### 2.4 Determination of Capacitances

After \( \frac{C_2}{A'} \) has been determined using a metal plate, (2.5) or (2.6) should be employed to perform the calibration. However, for the lack of a proper approach to determine all the capacitances when the dielectric is not plane, the data have often been calibrated just with (2.7) ignoring \( C_3 \), even when \( C_3 \) is of the same order as \( C_1 \) \([48,64,65,66]\). In fact, a frequently used cylindrical spacer as small as \( \phi 40 \times h 40 \) even without any insert may make \( C_3 > C_1 \), due to the larger permittivity of the spacer material, resulting in large errors when the data is transformed.
Other instances where the charge distribution is presented with this kind of error are those cases where the charge is presented by a "residual potential" instead of a charge density \[51,74,75\] and where the measurement is performed by a field-mill calibrated using a metal plate \[59\].

A proper calibration requires that all the values of the parameters of the capacitances \(C_1, C_2, C_3\) and of the effective area \(A'\) are known. In this section, cylindrical samples are employed to develop an experimental approach determining the bulk capacitance in spacer samples, i.e. to first calibrate using a metal plate, and then to perform another measurement using the actual arrangement. The results show that the value of the calibration coefficient would be wrong by half if the bulk capacitance \(C_3\) is ignored.

### 2.4.1 Principle

Fortunately, the input capacitance \(C_2\) of the probe (and the meter) can be measured separately; then \(C_1\) can be determined by calibration using a metal plate. From (2.8) follows

\[
C_1 = \frac{C_2}{K_1 - 1} = \frac{C_2}{K_1} \quad \text{if} \quad K_1 \gg 1 \tag{2.22}
\]

where

\[
K_1 = \frac{V_{s,1}}{u_{2,1}}
\]

is the dividing ratio measured with the metal plate. Because the probe is operated perpendicularly to the surface, the field between the probe and the surface is approximately homogeneous and \(A'\) is obtained by the application of (2.11)

\[
A' = \frac{h C_1}{\varepsilon_0} \tag{2.23}
\]
2.4 DETERMINATION OF CAPACITANCES

For the calibration using (2.5) or (2.6), one has to know the value of $C_3$. The simplest case is that when the dielectric is a plane plate with a thickness of $d$.

In practice, the dielectric samples may have various profiles. Fig. 2.4 gives an example of a cylindrical spacer. Though the configuration of $C_3$ varies, a knowledge of its effective value is enough for the calibration with (2.5) or (2.6). As defining $C_1$ via a dividing ratio, an attempt can be made at defining $C_3$ via a dividing ratio by applying a certain voltage at nodes other than $b$ in Fig. 2.4.b. A similar condition should be assumed as that determining $C_1$, i.e. the charged surface is considered to be conducting at the effective area. With the knowledge of $C_1$, there are two possibilities to apply the voltage: first, it can be applied at $a$ in Fig. 2.4.b, i.e. through the probe, the low arm voltage can then be detected at $c$ (when the earthing is broken); second, it can also be applied at $c$ and detected at $a$. For convenience sake, the latter is conducted in this section.

To begin with, a voltage $V_{s,1}$ has to be applied at the node $b$ to determine the ratio $K_1$, and therefore $C_1 ((2.22))$. Then a second calibration has to be performed by applying another voltage $V_{s,2}$ at
the node $c$. Therefore,

$$K_2 = \frac{C_1 C_3 + C_1 C_2 + C_2 C_3}{C_1 C_3}, \quad (2.24)$$

where

$$K_2 = \frac{V_{s,2}}{u_{2,2}}$$

is the dividing ratio by the second voltage application. From (2.24) and (2.22)

$$C_3 = \frac{C_2}{(K_2 - 1) - \frac{C_2}{C_1}} = \frac{C_2}{K_2 - K_1} \quad (2.25)$$

Substitute (2.22), (2.23), (2.25) into (2.5), then

$$M = \frac{\varepsilon_0}{h} \cdot \frac{(K_1 - 1) K_2}{K_2 - K_1} \quad (2.26)$$

or

$$M = \frac{\varepsilon_0}{h} \cdot \frac{K_1 K_2}{K_2 - K_1} \quad K_1 \gg 1 \quad (2.27)$$

Equation (2.27) represents the calibration coefficient. If $C_3$ is very small, $K_2$ becomes larger and (2.27) tends to be the same as (2.7) (see also (2.10)).

So, the calibration is performed by two steps (two-step method):

**Step 1** Application of potential $V_{s,1}$ at the node $b$ to determine the ratio $K_1$;

**Step 2** Application of another potential $V_{s,2}$ at the node $c$ to obtain $K_2$.

Then (2.27) can be employed to perform the calibration. In the following, the difference between the calibration coefficients with and without $C_3$ is shown with cylindrical spacers.
2.4 DETERMINATION OF CAPACITANCES

2.4.2 Experiments and results

Three cylinders of PVC, whose relative permittivity is 4.6, were made to perform the two-step calibration. They are shown in Fig. 2.5. All three are 16cm high and 15.3cm in diameter. One is solid without any insert. The other two have an insert at each end: they are 5cm in depth, 5.5cm and 6.5cm in radius respectively. The diagram of the electrodes can be found in Fig. 3.7.

This arrangement was placed in a tank (see §3.1 for details). Fig. 2.6 shows the diagram of the set-up. During a measurement, the probe was placed 5mm away from the surface. Its output was recorded by an X-Y recorder.

**STEP 1**

The dividing ratio $K_1$ was obtained by applying a DC voltage of 1.5$kV$ to an aluminum plate (three times to have get a mean value).

**STEP 2**

A voltage of $+4kV$ was applied to obtain $K_2$. In order to reduce any effect of the stress from outside the sample, the voltage was applied to a conductive layer stuck to the sample surface as shown in the zoom in Fig. 2.6. The data at two circumferential positions along each sample were recorded.

The variation of $K_2$ with the axial (vertical) position along the
spacer surfaces is shown in Fig. 2.7 together with the mean value of $K_1$. It can be seen that the dividing ratio $K_2$ decreases to approximately half the value without inserts; $K_2$ is only $0.5 \sim 1.5$ times higher than $K_1$. Therefore a large error is expected by assuming the former is much higher than the latter. $K_2$ can thus not be neglected in the formula (2.27).

2.4.3 Discussion

The bulk capacitance $C_3$ for the present arrangement varies with the radius of the inserts, due to the distance from the effective area to the
inserts (the back electrode). Fig. 2.8 gives the capacitances for different insert radii versus the vertical position along the samples. The capacitances become larger at the sample ends when the effective area approaches the electrodes. At the vertical position of $z = 3 \sim 4 \text{ cm}$, the capacitances are mainly determined by the distance to the inserts, so they change a little in this region. As the inserts are 6.5 cm in radius, the bulk capacitance $C_3$ is about twice the value of $C_1 \left(5.48 \times 10^{-15} \text{ F}\right)$. With the aid of $A'$ determined by the $K_1$ measurement, it is estimated to be $12.6 \times 10^{-15} \text{ F}$ in the insert region. The relative error of the measured value is $< 5\%$. Further increase of vertical coordinate $z$ will lead to a sharp decrease of the capacitance, e.g. from $\sim 12 \times 10^{-15} \text{ F}$ to $\sim 6 \times 10^{-15} \text{ F}$ as $r = 6.5 \text{ cm}$, because there is no insert at that point; but $C_3$ is still higher than $C_1$. Also the bulk capacitance $C_3$ without an insert remains large, especially at the end of the sample. It

![Figure 2.7: Dividing ratio $K_2$ of Step 2 along the PVC spacers at different vertical positions $Z$ ($K_1$, the ratio of Step 1)](image-url)
Figure 2.8: Bulk capacitance $C_3$ of the PVC spacers versus the vertical coordinate $Z$

changes more than 100% over the entire height. Near the end of a sample ($z < 1 cm$), the bulk capacitance is mainly determined by the distance to the end section. Hence the capacitances are still higher than those shown in Fig. 2.8.

The calibration coefficient $M$ is strongly influenced by $C_3$ (see (2.6)). As $C_3$ is half of $C_1$, the calibration coefficient changes 50% from that when $C_3$ is neglected. If $C_3$ equals $C_1$, $M$ increases 100%. Hence at the value of $C_1$ at the present separation, the calibration coefficient will change more than 100% when the spacers are provided with inserts. The coefficients for all the samples are shown in Fig. 2.9. For the purpose of comparison, the coefficient neglecting $C_3$ is also given in this figure. Obviously, it would lead to quite large errors if the probe is calibrated using a metal plate only. Moreover, the calibration coefficients are not identical over the entire height of the sample. As the insert has a radius of 6.5 cm, the coefficient increases
2.4 DETERMINATION OF CAPACITANCES

Figure 2.9: Calibration coefficient $M$ for the PVC spacers as a function of the vertical coordinate $Z$

by $\sim 50\%$ at the insert region. When the insert radius is $5.5\text{cm}$, it increases by $\sim 10\%$ at the insert region and by $\sim 40\%$ close to the end; even for a solid sample it increases by $\sim 40\%$ close to the end.

For the quantitative measurement of the surface charge on various samples, a calibration relation other than a constant coefficient versus the probe trace should be established. For the small cylindrical samples widely used in other experiments found in literature, the distances from the effective area to the inserts (i.e. $\sim 5\text{mm}$) and to the electrodes are even shorter than those shown in Fig. 2.8; the calibration error is then much larger when neglecting the bulk capacitance.
2.4.4 Calibration for epoxy cylinders

To study the accumulation mechanism, some cylinders of epoxy resin were designed as shown in Fig. 2.10. The design and the field distributions are described in §3.2. Here, as an example of the application of the newly developed method, their calibrations are presented in Fig. 2.11, when $C_2 = 76.5$\,pF.

**Figure 2.10:** Cylindrical spacers of epoxy resin: a. insert A ($r=27\,mm$), b. insert B ($r=16\,mm$), c. no insert

2.4.5 Conclusions

- The bulk capacitance inside a dielectric sample can be determined experimentally by applying voltages to a metal plate at the position of the charged surface, and to the electrode(s) of the set-up respectively, so that the calibration coefficient is improved.

- The bulk capacitance $C_3$ changes greatly along the entire height of a cylindrical sample with inserts. If the inserts are 6.5\,cm in radius, the capacitance close to the end is twice as large as that at the middle. On the other hand, $C_3$ is of the same, or higher, order as the capacitance $C_1$ within the separation. A large error would result from employing a constant calibration coefficient for all the surface measured. Even for a solid sample, it increases
by \sim 40\% at the end. With respect to the bulk capacitance, the calibration coefficient is modified by more than 100\% when inserts are used.

2.5 Measuring at a Curved Surface

As described in §2.2, the calibration method requires the probe to be operated perpendicularly to the surface. This makes it difficult to employ the probe to measure the charges on a curved surface, like that of an actual spacer in GIS (Fig 2.16). For the study of an actual spacer, a rotatable [55] or a bent-tip probe could be used, but this is accompanied by other problems. It would be more convenient if the
probe could be operated at various angles to the charged surface. The difficulty here is to calibrate it this way. This section develops a calibration method which makes it possible to perform measurements on a curved surface.

2.5.1 Determination of $A'$ via $C_3$

Fig. 2.12 shows the diagram of the probe arrangement with an deviation angle $\beta$ to the surface. As described in §2.2.1, the surface charge will be divided by the capacitances, therefore (2.6) applies. If the dielectric is so thick that $C_3 \ll C_1$, relation (2.7) exists. Again it is essential to determine $A'$, as well as $C_1$ and $C_3$. $C_1$ and $C_3$ can be defined by the approaches in §2.4 (two-step method). Because of the geometric variation of $C_1$, $A'$ has to be defined in another way than (2.23).

Upon the assumptions given in §2.2, the effective area remains identical, independent of the shape of the dielectric. Therefore, a dielectric plate can be employed to achieve a homogeneous field inside the plate under $A'$, so $C_3$ can be described by a plain parallel capacitor. This provides a possibility to determine the effective area $A'$ via $C_3$ (by means of (2.28) in the succeeding subsection). Nevertheless,

Figure 2.12: Probe arrangement, not perpendicular to the surface: $\beta$—deviation angle, other symbols are the same as in Fig. 2.1
an error is also introduced here and becomes larger when the probe is used at an angle because the distance from $A'$ to the probe is not constant.

### 2.5.2 Calibration

The calibration follows a two-step procedure as introduced in the preceding section.

**STEP 1**

Though $C_1$ is not a plane-parallel capacitor here, it can still be measured by applying a certain voltage $V_{s,1}$ to a metal plate at the position of the charged surface to obtain a dividing ratio $K_1$, see Fig. 2.13. The expression (2.22) is valid:

$$C_1 = \frac{C_2}{K_1 - 1}$$

**STEP 2**

Now the capacitance $C_3$ inside the dielectric can be measured as described in the preceding section: a voltage $V_{s,2}$ is applied to a metal plate backing the dielectric, as shown in Fig. 2.14, to get a new dividing ratio $K_2$. $C_3$ is then obtained by (2.25):

![Diagram](image)

**Figure 2.13:** Determination of $C_1$ at an angle $\beta$ with a metal plate at potential $V_{s,1}$
Figure 2.14: Determination of $C_3$ with a dielectric plate backed by a metal plate at potential $V_{s,2}$

$$C_3 = \frac{C_2}{K_2 - K_1}$$

Because $C_3$ here is a plane-parallel capacitor,

$$A' = \frac{d C_3}{\epsilon} \quad (2.28)$$

and $d$, $\epsilon$ are the thickness and the permittivity of the dielectric.

Hence the calibration coefficient can be defined at a deviation angle $\beta$. This was introduced together with the two-step method by the present author in [61].

### 2.5.3 Experiments and results

For calibration, a PVC plate of 21mm in thickness was used. Its relative permittivity is 3.3. For practical application later to an actual GIS spacer, the distance from the charged surface perpendicularly to the centre of the probe remained unchanged at $h = 12\, mm$. For the first calibration (to obtain $K_1$), a metal plate was used. Metal foil was stuck carefully to the other side of the dielectric to perform the second calibration (to determine $K_2$).
2.5 MEASURING AT A CURVED SURFACE

Figure 2.15 gives the results of $C_1$, $C_3$ and $A'$ versus the angle $\beta$ between the probe and the normal line of the charged surface. As is seen, the capacitances $C_1$, $C_3$ and the effective area $A'$ change little, certainly if the probe deviates up to 30°.

![Diagram showing parameter variations with the deviation angle $\beta$ of the probe: $A'$→effective area, $C_1$→capacitance within the separation, $C_3$→capacitance inside the dielectric.]

Figure 2.15: Parameter variations with the deviation angle $\beta$ of the probe: $A'$→effective area, $C_1$→capacitance within the separation, $C_3$→capacitance inside the dielectric

The knowledge gained here, regarding both $C_1$ and $A'$, can be employed in practice with the probe in any position. A better calibration is obtained if $C_3$ is also determined in the specific practical case.

2.5.4 Application to a spacer

To study the accumulation behaviour in GIS, an actual spacer for 380kV GIS and its enclosure, as well as a conductor of the same diameter as that in service, are used here. Fig. 2.16 shows the geometry and the measures of the experimental arrangement [73]. The spacer is made of epoxy resin. Its relative permittivity is 4.2. The
Figure 2.16: Diagram of a GIS spacer

Figure 2.17: Calibration coefficient $M$ along the GIS spacer at the separation $h=12\text{mm}$
probe is to be moved vertically and horizontally. Under this condition, the angles of the probe to the normal of the spacer surface $\beta$ are first calculated along the entire surface. The values of $C_1$ and $A'$ presented in Fig. 2.15 are then used to establish the calibration of the spacer. Owing to the thickness of the actual spacer, the measurement of $C_3$ was not performed. Fig. 2.17 gives the calibration determined as $C_2 = 62\mu F$.

### 2.5.5 Conclusion

By using the proper geometry of the dielectric sample, the effective area $A'$ can be defined by the bulk capacitance $C_3$ of the sample (see (2.28)) as a function of the deviation angle of the probe when measuring surface charges. The obtained values of the capacitance $C_1$ and the effective area $A'$ can then be employed in practice.
Chapter 3
Experimental Facilities

The experimental facilities for the present work are described in this chapter. First, the main setup is introduced, consisting of a gas tank with its accessories. Second, the design of the electrodes and the spacers is described. Third, the development of programs for charge detection and the presentation of the results is given, and the techniques to vary the surface roughnesses are described thereafter. The last section gives the experimental procedure.

3.1 Tank Arrangement

Figure 3.1 shows the experimental arrangement of studies with $SF_6$. Each spacer was placed in a gas tank made of steel. This tank has a net volume of $1.4m^3$ with an inner diameter of $1m$. A DC motor at the bottom of the tank is used to move the objects tested. Being operated from outside, an object can be moved $15cm$ vertically, and rotated $360^\circ$ horizontally.

A pressure flange on the wall of the tank supplies six individual
coaxial sockets for the transmission of signals; they are employed to transmit the position coordinates at a spacer surface to a personal computer.

Charge measurements were performed using the capacitive probe described in the preceding chapter and in Appendix A. The input capacitance ($C_2$) of the probe is $76.5pF$. Together with the meter, the probe is mounted on the tank and can be moved forward through a rubber gasket towards an object placed in the centre of the tank, to perform a measurement (see Fig. 3.1). The output of the probe is measured by the electrometer and stored in the personal computer, together with the relevant position coordinates. This setup is described in more detail in the following subsections.
3.1 TANK ARRANGEMENT

3.1.1 Probe shutter

Because of the high input impedance of the meter and its low capacitance (§2.3), a small variation of the capacitance \(C_2\) of the probe, or of the charge at the probe, can introduce quite large meter deflections. A deformation of the probe can make \(C_2\) vary, and a change of the mechanical stress on the probe could cause some charge due to a piezoelectric effect. Therefore, the probe itself has to be rigid, and the mechanical stress has to be constant throughout a measurement procedure. A displacement of the probe through the gasket may vary the mechanical stress on the probe, owing to the inevitable relative displacement of the probe in a direction perpendicular to the motion forwards.

Under the present experimental conditions, the probe has to be moved by 272\,mm toward the spacer before a measurement is made. The variation of the mechanical stress on the probe then results in some meter deflection. This deflection varies while the probe is being moved because of the different mechanical stresses in different positions. Fig. 3.2 shows a result where the deflection is presented versus the separation of the probe from the spacer surface \((h\text{ in Fig. }2.1)\), when there is no charge on the spacer surface. For this measurement, the meter was earthed (locked) at its input before moving the probe, so that any residual charge in the meter circuitry was released. Then the meter was unlocked at the extreme outer position and moved directly to a position where the reading is taken. (In this way, the meter has been unlocked for the shortest time before a reading is taken and, therefore, the influence of the offset current in the meter circuitry is the smallest, see §3.3.) Fig. 3.2 shows that the displacement over the full distance produces a potential of 10\,mV at the meter input. The deflection differs from one time to another owing to the non-identical mechanical stresses. This would introduce unexpected errors when performing a surface charge measurement. A proper procedure should move the probe toward the spacer while the input of the meter is earthed. The meter could then be unlocked at the measuring position \((h = 5\,mm)\).

However, in §2.2, it was seen that the probe has to be operated
from far away. To meet this, an earthed metal shutter, which can be operated manually from outside the tank, is built at the front of the probe. The probe is thus moved to the surface in an earthed state and is unearthed at the measuring position. Thereafter, the shutter is turned aside and charges are induced at the probe according to the capacitive parameters. The charge density at the surface is determined using (2.4).

Obviously, this shutter ensures a constant mechanical stress on the probe during measurement, but also obviates the need to move the probe from far away. The measuring precision is thus improved.

### 3.1.2 Position determination

Every time a charge density is detected, the geometrical coordinates (vertical and circumferential) of that location are also recorded. The determination of each coordinate is performed by a potentiometer linked to the driving system within the tank by means of a set of gears. After a spacer is put in the tank, position calibrations have to
be performed between the electrical outputs (the voltages) and the actual geometrical positions of the spacer. Thus can the position of a spacer and the location on its surface where the probe is present be determined horizontally and vertically.

Two of the six sockets within the pressure flange are used for the output of the vertical and the circumferential coordinates. Two others are used to give the computer a signal when a spacer has been turned 360° both clockwise and counterclockwise (horizontal ends). The rest are for the voltage input to the potentiometers. The signals for horizontal ends are taken from two end-contactors.

### 3.1.3 Earthing

A breakdown between electrodes may result in a large current in the circuit. This current can introduce a high voltage surge along the earthing bus due to the earthing resistance and the impedance along the bus. Instruments employing the same earthing bus may then be damaged by this surge. Measures need to be taken to isolate a possible high voltage surge during a high voltage application. This can be achieved by proper interfaces between the tank setup, where breakdowns may take place, and other parts, i.e. the operating circuitry, the signal circuitry, the power supply for the meters mounted on the tank and the probe.

First, three plug-in mechanisms were built on the tank in order to be able to cut off all the circuit links to the tank under high voltage. One, which is multi-core, is for the operating circuitry. The second is for the position output (§3.1.2). The third is for the power supply to all the instruments inside and on the tank. All three mechanisms were disconnected during high voltage applications.

Second, during a voltage application, the probe, as well as the sensitive meter, was moved to the extreme position and was shielded by the probe shutter. The shutter, which is earthed to the tank, protects the probe from any direct breakdown and reduces any induced surge. The probe and the meter were well isolated from any part of the tank. Their protective earthing was connected to a separate point.
The power was supplied to the meter via a $1:1$ isolation transformer.

Finally, other instruments which are mounted inside or on the tank, such as the DC motor, the position potentiometers and the DC supplies, were well grounded at the tank wall and were connected together to the same earthing point as that for the high voltage source. Thus the potentials of these instruments float with the potential at the tank during a possible breakdown, but the instruments endure no potential difference. The breakdown current returns to the voltage source inside its own loop with little interference with the earthing system of the laboratory.

### 3.2 Shaping of the Fields

The electric field is responsible for charge accumulation. The amplitude of the electric field, as well as its distribution in the vicinity of a surface, play important roles. Therefore, the field has to be designed beforehand in order to study the role it plays under certain conditions. In this section the fields are shaped by the designs of electrodes, including toroids and inserts.

The cylindrical epoxy spacers used in this thesis are $100\,mm$ high and $80\,mm$ in diameter, as introduced in Fig. 2.10. For the application of an electrode arrangement with inserts, recesses are machined at both ends of the spacer according to the insert geometry. The epoxy used here is araldite filled with silica possessing $90\%$ silicon dioxide ($SiO_2$).

The geometry of the electrodes was designed to fulfil various requirements:

- They can be assembled with two alternative field effecting techniques: toroids and inserts;
- Various field distributions can be achieved by changing the positions of the toroids or the profile of the inserts;
- The roughness of the electrode surfaces should be as low as possible to suppress micro-discharges at the electrodes.
In the following, electrodes are designed by field calculations with an axial symmetric computer program using the finite-element method.

It has to be indicated that the field designed here is only the initial condition of charge accumulation, which is determined by the configuration of the permittivity $\varepsilon$. At a DC voltage, this field will slowly change into a configuration that follows the conductivity $\nu$, accompanied by the charge accumulation. This transit and the determination of the field at the steady state of DC stress will be studied in more detail in §6.1. As initial conditions all the fields are calculated here according to the configuration of $\varepsilon$.

### 3.2.1 Design of toroids

First a pair of plane electrodes were chosen which are 220mm in diameter, 40mm in thickness and round-edged. Toroids were then designed which will be employed together with these plane electrodes. The toroids have an inner radius of 55mm and an outer radius of 80mm. The vertical section is rounded off with a diameter of 25mm. These toroids can be moved up and down to vary the field distribution along the spacer surface. The geometry of the electrodes, as well as that of the solid spacer (Fig. 2.10.c), is shown in Fig. 3.3. The electrodes and the toroids are made of brass and were well polished with fine sandpaper and with copper-polishing liquid. The roughness of the surface is $\approx 0.5\mu\text{m}$.

By varying the separation $s$ between the toroids and the plane electrodes (see Fig. 3.3), the field is varied. Fig. 3.4 gives the field strength calculated at a voltage of $+100kV$ when distance $s$ is 0mm, 5mm, 10mm respectively. Fig. 3.4.a shows the tangential fields along the solid spacer and Fig. 3.4.b shows the normal ones. These toroids designs will be used for the study of charge accumulation in chapter 4.

### 3.2.2 Design of inserts

The plane electrodes can also be employed in combination with inserts at the ends of the spacers (when these electrodes are turned over
due to the grooves for the toroids). The inserts were achieved by machining recesses in a spacer and by painting the surface of the recesses with conductive paint.

The insert designs will be used for the study of charge accumulation mechanisms. In chapter 5 it will be seen that quite different conclusions have been drawn in the accumulation mechanism. Charge accumulation is explained by charge transport in the gas in [59] and [76], whereas it is explained by the variation of surface conductivities in [52]. The former implies the dominant effect of the normal component of the field; the latter emphasizes the tangential component.

To reveal which of the field components dominates, opposite normal fields are designed in the following as insert A, and identical tangential fields are designed as insert B, both as compared to the toroid induced fields shown in Fig. 3.4. If the normal field would play the dominant role, the accumulation should change its polarity when the normal field changes its direction; whereas if the tangential field were dominant, the accumulation should not change significantly when the tangential field remains identical (refer to §5.2 and §5.3 for details).
Figure 3.4: Field variations at +100kV by varying the separation $s$ between toroids and plane electrodes: a. tangential fields $E_t$, b. normal fields $E_n$.
CHAPTER 3 EXPERIMENTAL FACILITIES

INSERT A VERSUS TOROID: FIELDS WITH OPPOSITE NORMAL COMPONENTS

Two normal fields are said to be opposite when they possess the same amplitude but reversed directions along the spacer surface. They can be produced by electrodes with toroids and those with inserts. Toroids at separation $s=5\text{mm}$ are employed for this purpose. By contrast to their field distribution (shown in Fig. 3.4), the inserts are designed: the radius of the cross section of the inserts, the height of the inserts and their top curvity have been optimized to make the strength of the normal field, the positions where its maxima occur and their profile identical with, but opposite to those with toroids.

During the calculations, each of these parameters was first given an initial value. Then the height of the inserts was determined according to the maximum positions. Thereafter the insert radius was optimized to get the proper field strength. The top curvity of the inserts was finally changed to obtain the right field profile. After many calculations, it was found that an optimal design is achieved when the height, the radius and the top curvity radius of the inserts are $30\text{mm}$, $27\text{mm}$ and $12.5\text{mm}$ respectively (Fig. 2.10.a). Under these conditions, the maximal strength of the normal field differs only 0.2% from that with the toroids, the tangential field differs 25.0% (see Fig. 3.5). The test results with the two arrangements can be found in §4.3, and conclusions are drawn in §5.3.

INSERT B VERSUS TOROID: FIELDS WITH IDENTICAL TANGENTIAL COMPONENTS

Two fields are said to be identical when they are equal in amplitude and identical in direction along the spacer surface. Inserts are designed here which make the tangential field along the spacer surface identical to that with toroids at a separation $s$ (the normal field has the opposite direction).

The design presented here is also used for the evaluation of techniques to improve the field at a triple junction under DC voltage.
Figure 3.5: Distributions of tangential field $E_t$ and normal field $E_n$ with insert $A (r = 27\,mm)$ at $+100\,kV$, as compared to those with toroids when the separation $s = 5\,mm$: the normal fields are equal in amplitude but opposite in direction.

This evaluation is made in §6.4.3.

Using the same optimization procedure as above, the height, the radius of the inserts, as well as their top curvature radius, have been determined as $27\,mm$, $16\,mm$ and $16\,mm$ respectively (see Fig. 2.10.b). With this geometry, the tangential field along the spacer surface is close to that of the toroid arrangement with $s = 0$. Their relative difference is $< 1.0\%$. The normal field with toroids is 2.3 times that of the inserts with an opposite polarity. Fig. 3.6 gives the comparison of the fields produced by those two techniques. The test results using these arrangements can be found in §4.4 and are discussed in §5.3 and §6.4.

3.2.3 Plane electrodes for PVC spacers

A pair of aluminum electrodes were designed to assemble PVC spacers as shown in Fig. 2.5. This arrangement is used to study the influence of the bulk capacitance on the calibration (§2.4) and the influence
of protrusions at electrode surfaces on the accumulation (§4.5). The surface roughness of the electrodes is 4.2 μm. The geometry of this arrangement is given in Fig. 3.7 and, as an example, the field distribution along the spacer surface (the radius of the inserts is 5.5 cm) is presented in Fig. 3.8. This spacer (shown in Fig. 2.5.b) is stressed in §4.5 after protrusions have been placed at the cathode surface.

### 3.3 Measuring Program

The programs developed in this thesis are all written in Quickbasic. One is used for the measurements; the rest are for the post processing of the data and for the graphic presentations. The measuring program is introduced in this section; the others are described in the next section.

Charge measurements are performed by moving a spacer in front of the probe, while a computer records the output of the probe at each location on the spacer surface simultaneously with the relevant
coordinates. Hence the distribution of the accumulated charges over a surface can be defined. With this distribution, other statistical data can also be determined and analyzed to interpret the accumulation.

Five sampling channels are used by the computer: one is for the input of the charge measurements from the probe; two are for the coordinate readings from the potentiometers (§3.1.2), and the remaining two are to detect whether a spacer has been turned for 360°. The last
two channels are also necessary for the computer to calibrate the horizontal coordinate while the program is being run.

### 3.3.1 Performance of the program

For the charge measurement in the present work, a program needs to be written which incorporates with the following functions:

- Recording of the geometrical coordinates on the surface corresponding to the surface charge recordings;
- A matrix of the recordings for data manipulation;
- Graphic presentation of the results after a measurement;
- Calibration (suppression) of the inevitable offset of the meter.

In the program, a $m \times n \times 3$ array is set up to store the measured data, where $m \times n$ is the total number of the samples of a measurement. $m$ represents the total number in the axial direction, and $n$ that in the circumferential direction. They are defined as 20 and 125 in the program respectively. However, these values can also be changed via the keyboard after the program has been run. For each sampling, three data (in volts) are taken: the vertical coordinate ($Z$), the horizontal coordinate ($X$) and the potential caused by surface charges ($u_2$).

The horizontal end-contactors allow the program to perform the horizontal calibration (from volts into millimeters) at any time. The vertical calibration is performed in the program according to the data taken each time a new spacer is replaced. These data can then be fixed in the program, or can be keyed in after it is run. The third calibration transfers the surface residual potentials into charge densities (probe calibration). This is carried out differently for each spacer because of the different calibrations, see §2.4.4.

After the calibrations, the array is saved in a file and the result is shown on the monitor graphically in terms of mean charge densities. This is discussed in detail in the next section. The following describes the offset of the meter and how to depress it automatically in this program.
3.3 MEASURING PROGRAM

3.3.2 Suppression of the Offset

Offset is defined as the meter deviation without any signal at its input. This deviation comes from leakage (offset current) of the meter circuitry. In the meter used in the present work, two matched transistors are used at the input to function as a differential amplifier. Any imbalance of the working of these two transistors can result in an offset current which, unfortunately, carries charges continuously to the input after the meter has been unlocked. Depending on the working order of the circuitry in the meter, the offset current varies and therefore different deviations can result. Fig. 3.9 gives an exam-

![Graph showing deviation versus time](image)

Figure 3.9: Meter deviation caused by its offset versus time \( t \) after unlocking: dashed line→at another balance level

ple of the meter deflection cause by this offset, where the dashed line indicates the deviation when the balance level of the meter circuit was changed. Typically, the offset contributes 0.012\( V \) per minute. If a charge measurement takes 5 minutes this will add 0.06\( V \) to the last sampling. The resultant errors are not the same for all samples.

However the offset current is constant within several minutes so that the resultant deflection on the meter is linear versus time. This deflection can then be calibrated (suppressed) in the program as described below.
Before taking samples, when the meter is unlocked and the probe is shielded by the probe shutter, the program reads the time \( t_a \) and the deflection of the meter \( v_a \), then the shutter is turned aside to carry out a measurement. Meanwhile, instead of reading the time for each sample, the time \( t_{i,1} \) of the first sampling and that of the last \( t_{i,n} \) at each circumference at an altitude \( i \) are recorded to improve the sampling speed. After the whole measurement, as the probe is shut down and the meter is still unlocked, the time \( t_b \) and the deflection \( v_b \) are read in again. Then the error \( \Delta v_{i,j} \) of the \( j \)th sampling at the \( i \)th altitude introduced by the offset is:

\[
\Delta v_{i,j} = \frac{v_b - v_a}{t_b - t_a} \left( t_{i,1} + j \frac{t_{i,n} - t_{i,1}}{n} - t_a \right) + v_a \tag{3.1}
\]

where \( n \) is the total samples at that circumference. This amount is subtracted before data is calibrated into a charge density.

During a measurement, samples are taken horizontally at an identical altitude (see §3.3.4). The computer stops sampling while the altitude is being changed. Therefore, the reading of the times \( t_{i,1} \) and \( t_{i,n} \) during the program run has little influence on the sampling speed; the measuring of other values mentioned above has little influence as well.

### 3.3.3 The flow chart

The construction of the program is described by the flow chart shown in Fig. 3.10. The variables used are:

- \( n \) — Total number of samples along one circumference;
- \( x \) — Horizontal coordinate,
- \( x_{i,j} \) — Horizontal coordinate of a point,
- \( x_o \) — Beginning value of \( x \),
- \( x_m \) — End value of \( x \);
- \( u_h \) — Variable of the channel for \( x \),
- \( v_o \) — \( u_h \) at \( x_o \),
- \( v_m \) — \( u_h \) at \( x_m \);
- \( z \) — Vertical coordinate,
3.3 MEASURING PROGRAM

\[ z_{i,j} \] — Vertical coordinate of a point,

\[ z_o \] — Beginning value of \( z \),

\[ z_m \] — End value of \( z \);

\[ u_z \] — Variable of the channel for \( z \),

\[ u_o \] — \( u_z \) at \( z_o \),

\[ u_m \] — \( u_z \) at \( z_m \);

\[ s_h \] — Horizontal sampling step;

\[ v_{s1} \] — Variable of the channel for the end-contactor at \( x_o \);

(If \( x=x_o, v_{s1}=1; \) else \( v_{s1}=0. \))

\[ v_{s2} \] — Variable of the channel for the end-contactor at \( x_m \);

(If \( x=x_m, v_{s2}=1; \) else \( v_{s2}=0. \))

\[ \sigma_S \] — Charge density,

\[ \sigma_{Si,j} \] — Charge density at a point;

\[ u_{\sigma_S} \] — Variable of the channel for \( \sigma_S \);

\[ M_{i,j} \] — Charge calibration coefficient at a point.

The following variables were introduced in §3.3.2:

\[ t \] — Variable of the time channel,

\[ t_a \] — \( t \) at the start of the sampling,

\[ t_b \] — \( t \) at the end of the sampling;

\[ v_a \] — \( u_{\sigma_S} \) at \( t_a \) (when probe is closed),

\[ v_b \] — \( u_{\sigma_S} \) at \( t_b \) (when probe is closed);

\[ i \] — Sequential counter in vertical direction,

\[ j \] — Sequential counter in horizontal direction;

\[ t_{i,1} \] — \( t \) when the first sample of \( i \)th altitude is taken,

\[ t_{i,n} \] — \( t \) when the last sample of \( i \)th altitude is taken;

\[ \Delta v_{i,j} \] — Offset of the meter.

In Fig. 3.10, ① indicates the manual operation to turn a spacer to one of its horizontal ends to start sampling. ② and ③ show the moments when the spacer is rotated one turn horizontally for sampling and moved vertically to another \( z \)-coordinate (see §3.3.4). ④, ⑤, ⑥ and ⑦ represent the interfaces in the flow chart.
3.3 MEASURING PROGRAM

\[ v_o = u_h \]

\[ t_{i,1} = t \]

\[ x_{i,j} = u_h, \sigma_{s_{i,j}} = u_{s} \]

\[ u_h = x_{i,j} + s_h? \]

\( N \)

\[ j = j + 1 \]

\( N \)

\[ v_{s1} + v_{s2} = 1? \]

\( Y \)

\[ t_{i,n} = t \]

\( N \)

Stop?

\( Y \)

\[ i = i + 1 \]

\( 2 \)

\[ x_{i,j} = (x_{i,j} - v_o) \frac{x_m - x_o}{v_m - v_o} + x_o \]

\( 3 \)
3.3.4 To run the program

While the program is being executed, actions have to be performed at the proper time, such as those indicated by ①, ② and ③ in Fig. 3.10. These factors were of course taken into account in the program. The user just has to follow the instructions the computer gives during measurement. The computer will prompt with beeps and give the commands on the screen. The following can help the user to understand the performance and the execution of the program.

After starting, the first prompt is to input the scale of the meter to be used for the calibration:

Input scale factor of the meter:  

Then the question appears:
3.3 MEASURING PROGRAM

Change the original data $<Y/*>$?

If changes need to be made for a newly replaced spacer, $Y$ is typed, otherwise any other key is typed. In the former case, new values are keyed in according to the relevant prompts on the screen.

To allow the computer to read in the starting time $t_a$ and the corresponding deviation $v_a$ of the meter, the following instruction should be followed:

Unlock the meter and press a key,
Then open the probe!

Thereafter, the spacer can be moved from a proper position. If it is not at one of the horizontal ends, the computer will react with:

Turn to one horizontal end, please!

The action taken here is indicated by $\text{①}$ in Fig. 3.10. As soon as an end is reached, it displays:

Start!

which tells the user to turn the spacer to another horizontal end for the program to take samples (②). After the spacer has been turned 360°, one gets a chance to end the program or to change the vertical position of the spacer so that the measurement can be continued. In the meantime, while the spacer is being moved vertically (③), the computer prints out the present vertical coordinate for reference:

\[ z = ###.## \text{ mm} \]

Press "S" to stop, or any other key to continue ...

As soon as $S$ is typed, the following appears:

Close the probe and press a key,
Then lock the meter!
The end time $t_b$ and the corresponding deviation of the meter $v_b$ are read in after this key is pressed.

Finally, the file names under which the data is to be stored have to be defined and some description can be placed in the front of a file. When the computer draws the results graphically on the screen, the scale factors of the coordinates (the divisions of the axes) are determined automatically by the program.

### 3.4 Programs for Data Processing

Several other programs were developed in the present work to process the measured data. By means of these programs, the measured results can be presented with various coordinate pictures, therefore the accumulation can be studied in different aspects. Each program is designed to present an image on the monitor. This image can be printed by a printer, if necessary. The data array for an image and the image itself can be saved and used again.

#### 3.4.1 Three-dimensional presentation

When using the measuring program, we detect the charge distribution on a surface and store it as the charge density at each location together with its coordinates. To present this distribution graphically, a program has been developed which is capable of drawing three-dimensional figures; therefore a clear image can be directly established.

The images are drawn in perspective with three axes as follow:

- $\sigma_S$ — Surface charge density ($\mu C/m^2$),
- $X$ — Horizontal (circumferential) geometrical coordinate ($mm$),
- $Z$ — Vertical (altitude) geometrical coordinate ($mm$).

This coordinate system is illustrated in Fig. 3.11. For the sake of convenience, it is called the $X-Z-\sigma_S$ (system), whereas the coordinate system on an actual plane is called the $X'-Y'$ (system). Now an $X-Z-\sigma_S$ image will be presented in an $X'-Y'$ plane.
Figure 3.11: Three-dimensional coordinate \((X-Z-\sigma_S)\) system: \(\sigma_S\rightarrow\) charge density, \(X\rightarrow\) horizontal coordinate, \(Z\rightarrow\) vertical coordinate at the surface

The main procedure here is to transform the three coordinates in \(X-Z-\sigma_S\) into two in \(X'-Y'\). An image is obtained by the new transformed coordinates. As we know, a \(\sigma_S \sim X\) curve is always at a plane parallel to the \(X'-Y'\) plane, while the origin of each plane changes according to its \(Z\) coordinate. Because of the way we place the \(Z\) axis, the data transformation should be, geometrically:

\[
\begin{align*}
X' &= AX + B \frac{Z}{\sqrt{2}} \\
Y' &= C \sigma_S + D \frac{Z}{\sqrt{2}}
\end{align*}
\]

(3.2)

where \(A, B, C, D\) are constants depending on the scale factors of the axes. Using (3.2), every location in \(X-Z-\sigma_S\) can be transformed into a location in \(X'-Y'\). Then, the relevant segments can be drawn which constitute the curves along each circumference of a spacer and those along each height of the spacer.

Another essential procedure is to make a picture appear three-dimensional. To achieve this, the segments, which are behind those on a plane in front, have to be invisible. In the program, after (3.2) is applied, the drawing is conducted from the lowest coordinate of \(Z\) to the highest. Meanwhile, the computer determines whether a segment
within a curve should be drawn or not by comparing it to those which have appeared on the screen. The procedure is illustrated in Fig. 3.12. The variables in this figure are:

\( X_i' \) — An \( X' \) coordinate, where the end of a segment is placed,
\( Y_i' \) — \( Y' \) at \( X_i' \),
\( M_i \) — Maximal \( Y' \) at \( X_i' \),
\( m_i \) — Minimal \( Y' \) at \( X_i' \);
\( i \) — Counter of sequential segment in a curve;
\( l \) — Total segments in a curve.

After a data array has been introduced, the scale factor and the sign for the \( \sigma_s \) axis can be defined manually via the keyboard, or automatically by the computer. Hence, a proper comparison can be performed. The range of the \( Z \) axis is sampled from the minimal altitude to the maximal altitude, the \( X \) axis presents the entire length of a circumference. In §4, this program is frequently used to show the test results.

### 3.4.2 The mean charge density

Charge accumulations at a surface vary greatly, even under identical stresses and dielectric properties. To correlate the charge accumulation with macroscopic parameters, such as field strength or the permittivity of the dielectric, a mean value under identical conditions is preferred [59,76,77]. For the axisymmetrical arrangements employed in the present work, the condition along each circumference of a spacer is identical, therefore the charge accumulation at a certain altitude can be presented by its mean density.

The mean density \( \overline{\sigma_{S_i}} \) at an altitude \( Z_i \) is defined as:

\[
\overline{\sigma_{S_i}} = \frac{1}{n} \sum_{i=1}^{n} \sigma_{S_{i,j}}
\]

(3.3)

where the parameters are the same as in § 3.3. In the program, the mean density \( \overline{\sigma_S} \) and the maximum and the minimum of the charge
Figure 3.12: A fraction of the flow chart of the three-dimensional program
density at \(Z_i\) are calculated and are presented together within one image.

In order to compare the distributions of different tests, a program has been developed which can read several data files and draw the mean curves together in one image.

### 3.4.3 Relative total charge

Charges are accumulated at a surface until the accumulation becomes saturated and a stable condition is achieved. In this condition, however, local charges would redistribute themselves owing to the high charge-induced fields [48,75]. This makes it impossible to describe the saturation with the growth of a local charge density (more detail can be found in §4.2). A proper quantity has to be introduced to study the saturation phenomenon.

If the charge distribution over an area is of the same polarity, the total charge there will change little because the area receives little net charge after the charge accumulation has been saturated. Correspondingly, the integration of the measured quantity \(u_2\) over this area approaches a constant. The growth of this integration can then be employed to determine whether an accumulation is saturated or not. It is also useful to observe the accumulation process and the decay phenomenon of surface charges. With a cylindrical spacer, this integration can be presented as:

\[
I_u = \sum_{i=1}^{n} \bar{u}_{2,i} \cdot 2\pi r \Delta Z_i
\]  

(3.4)

where \(I_u\) is the integration of the measured quantity \(u_2\), \(\bar{u}_{2,i}\) is the mean of \(u_2\) in the area \(2\pi r \Delta Z_i\), whereas \(r\) and \(\Delta Z_i\) are the radius of the spacer and the \(i\)th distance element along the vertical coordinate \(Z\) respectively.

For a certain spacer, the \(2\pi r\) is a constant and plays no part when the accumulation process is observed. Removing this constant yields:
\[ \bar{Q} = \sum_{i=1}^{n} \frac{u_{2,i}}{U_{0}} \Delta Z_i \]  

(3.5)

The values of \( \bar{Q} \) at different times can then be compared and an accumulation rate as well as a decay rate are thus determined. This is performed in §4.2. Because \( \bar{Q} \) corresponds to the total charge over the area, it is defined here as the relative total charge for the use in §4 though \( \bar{Q} \) is not dimensionless. However its values are usually normalized in §4, based on the value at a certain time, then a dimensionless quantity results.

### 3.5 Surface Roughness

As indicated in §1.2.2, the micro structure of a spacer surface affects the performance of GIS. This micro structure is described in terms of surface roughness\(^1\). Before we demonstrate the influence of surface roughness on the charge accumulation in §4.6, the techniques to produce surface roughnesses are described in this section. The various definitions of surface roughness and its measurement are described in Appendix B.

#### 3.5.1 Application of abrasive sheets

Several kinds of sandpaper with varying grits were used to produce roughnesses on pieces of PMMA of which the original roughness was 0.3\( \mu \text{m} \). This material is fine, homogeneous in density and softer than filled epoxy resin, so that the roughness can be developed by sandpapering and can be determined more precisely than with epoxy. It was found that the produced roughness increases somewhat with increasing roughness of the sandpaper (see the first five terms in Table 3.1). Higher roughnesses were developed when using other more roughly coated abrasives and abrasives with hard rough surfaces (the surfaces themselves being rough and hard, not sand-coated). The results are

---

\(^1\)The average height of the protrusions on a rough surface [78].
Table 3.1: Surface roughnesses $R_t$ produced by rubbing with abrasive sheets

<table>
<thead>
<tr>
<th>Type or grit</th>
<th>Roughness, $R_t$ ($\mu m$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.0</td>
</tr>
<tr>
<td>1C</td>
<td>5.4</td>
</tr>
<tr>
<td>1G</td>
<td>5.8</td>
</tr>
<tr>
<td>2</td>
<td>5.8</td>
</tr>
<tr>
<td>3</td>
<td>5.8</td>
</tr>
<tr>
<td>Cushion, fine</td>
<td>4.5</td>
</tr>
<tr>
<td>Cushion, middle</td>
<td>6.0</td>
</tr>
<tr>
<td>SIA,P220</td>
<td>8.0</td>
</tr>
<tr>
<td>100</td>
<td>15.0</td>
</tr>
<tr>
<td>100/2</td>
<td></td>
</tr>
<tr>
<td>3M210, P120</td>
<td>20</td>
</tr>
<tr>
<td>3M210, P80</td>
<td>27</td>
</tr>
</tbody>
</table>

shown in Table 3.1. The disadvantage of this method is that a homogeneous surface cannot be developed. Even by the naked eye, large grooves are observed on the surface, as shown in Fig. 3.13.a.

3.5.2 Application of pearl jets

Air or water jets with fine glass pearl (or sand) can produce rough surfaces more homogeneously. The roughness produced depends on both the pearl grit and the jet speed. Table 3.2 gives the results produced by several jets. Microscopic examination shows that a rough surface is produced homogeneously, see Fig. 3.13.b.
### 3.5 Surface Roughness

![Micrographs of roughened PMMA surfaces](image)

**Figure 3.13:** Micrographs of roughened PMMA surfaces: a. by abrasive sheet SIA, P220, b. by pearl jet NK60

### Table 3.2: Surface roughnesses $R_t$ produced by blasting with jets

<table>
<thead>
<tr>
<th>Jet</th>
<th>Pearl grit</th>
<th>Roughness, $R_t$ (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>NK60</td>
<td>17.5</td>
</tr>
<tr>
<td></td>
<td>100-200</td>
<td>7.0</td>
</tr>
<tr>
<td>Water</td>
<td>GK40-80</td>
<td>6.5</td>
</tr>
<tr>
<td></td>
<td>GK50-100</td>
<td>15.0</td>
</tr>
<tr>
<td></td>
<td>105-210</td>
<td>15.0</td>
</tr>
</tbody>
</table>

### Application to an Epoxy Spacer

The cylinders of epoxy resin used throughout the thesis have an original surface roughness of 0.5μm. The influence of the surface roughness of a spacer is here studied using a spacer with different roughnesses on its side surface. For this purpose, the circumference of the spacer is vertically divided into three equal parts. One of them possesses the original roughness; the other two are roughened by a water jet (GK 40-80) and an air jet (NK 60) respectively. The former produced a
roughnesses of 7.0\(\mu m\), while the latter was 13.0\(\mu m\).

This spacer will be stressed using the electrode arrangement with toroids, as seen in the next chapter. The charge accumulations at different parts of the surface will be compared to determine the influence of the surface roughness.

### 3.6 Test Procedure

The test procedure is described with regard to:

- Sample preparation,
- \(SF_6\) input,
- Voltage application,
- Measurement.

The samples are painted with conductive paint at their end sections, including the recesses forming the inserts. Then their surfaces, as well as the surface of the electrodes, are cleaned with chlorothene and then with alcohol. After being dried in air for several hours they are placed inside the tank. Thereafter the calibration of the vertical coordinate is performed.

\(SF_6\) is introduced immediately after the tank has been evacuated to a pressure of \(< 10 \text{Pa}\). The pressure of \(SF_6\) is 100\(k\text{Pa}\). Before any voltage is applied, at least 24 hours is spent ensuring a stable condition inside the tank.

A voltage is applied when all the three plugs, for position output, for power supply, and for operating system, as indicated in §3.1.3, have been disconnected. Meanwhile the probe has been driven to the extreme end and shielded by the shutter.

After a spacer has been stressed under voltage for a certain period, the voltage is removed and the high voltage electrode is earthed. Then all three plugs are inserted and the probe is moved to a separation of 5\(mm\) away from the surface of the spacer. These procedures take about 3 ~ 5 minutes.
3.6 TEST PROCEDURE

The measurement is conducted according to the program as described in §3.3.4. Depending on the total number of samples, this takes place within 4 ~ 5 minutes.

If the same spacer is to be stressed for another period at the same voltage, the plug-in mechanisms on the tank are taken off again and the voltage is put on immediately. The preceding procedure is repeated. Tests at another voltage are performed after the accumulated charges have decayed below a certain density, which may take several days.
Chapter 4
Experimental Observations

This chapter deals with the test results. To clarify the design of each test, a review is given first in terms of influencing factors. This review and the test results supply comprehensive observations on the charge accumulation.

4.1 Factors Affecting Charge Accumulation

4.1.1 Spacers and materials

Most of the investigations have been conducted with cylindrical spacers of epoxy resin. Some of them were with inserts [51, 54, 59, 65, 76], as shown in Fig. 4.1 [51], while others were not [64, 74, 75, 86, 88, 89]. Other materials used were teflon (i.e. PTFE: polytetrafluoroethylene) [65, 66, 89], nylon [65, 66] and PMMA (polymethyl methacrylate) [93].

A spacer material may influence charge accumulation via its permittivity. As is known, the introduction of spacers with different
permittivities changes the initial field and, therefore, the processes of charge production and the transit. A high permittivity of the material results in a high field deformation. This effect caused a much higher accumulation on a nylon spacer ($\epsilon_r = 3.8$) than on a teflon spacer ($\epsilon_r = 2.1$) in a rod-plane electrode arrangement [87].

In [54] it is shown that fillers in epoxy have little effect on the charge accumulation, although with $Al_2O_3$ filler the charge distribution is more inhomogeneous. This may be a result of the inhomogeneous distributions of the ohmic conductivity and the dielectric permittivity of the material.

The difference between the accumulated charge densities on different materials may reflect the effect of the surface conductivity of the materials. The surface conductivities of nylon and teflon are $\sim 10^{13}\Omega$ and $\sim 10^{16}\Omega$ respectively. In a quasi-homogeneous field, where the angle between the surface and the field lines is small, the accumulation on a nylon spacer is smaller and more homogeneous than that on a teflon spacer [65,66].

All the above studies were performed using small-scale samples. As is known, discharge mechanisms vary with the spacing between electrodes [4]. The condition of pre-discharges would thus differ when the scale changes. Actual GIS possess much larger spacers than those mentioned above. It would be doubtful to evaluate the performance of GIS with the conclusions obtained from small-scale models.
4.1 FACTORS AFFECTING CHARGE ACCUMULATION

In the present work, large-scale arrangements, as those shown in Fig. 3.3 and Fig. 3.7, have been established. An intensive study has been carried out using spacers of epoxy resin, which is the most widely used material for spacers in GIS. Other materials such as PVC were also employed, see §2 and §4.5.

4.1.2 Applied voltages

DC Stresses are mostly applied to study the accumulation. A higher applied voltage will result in a higher charge accumulation [54,66]. As the polarity of the voltage is reversed, the charge distributions will reverse too [66,76]. The details can be found in §4.2.

Ootera and others changed the polarity of voltage during stress at a conical spacer in SF₆ at 400kPa [71]. The results showed that a larger amount of charge is accumulated if the reversal is from negative to positive polarity (both stress duration being 30 minutes). However, as the stress was reversed from positive to negative, the original negative charge distribution by the positive stress changed little. These results seem to suggest that negative charge is apt to accumulate, or to stick to the surface. Using a small sample in a quasi-homogeneous field (teflon spacer between recessed electrodes without insert), Bektas, however, found no effects of the pre-stress of an opposite polarity [66].

AC stress usually results in poor accumulations as concluded by the present author [80]. Though charge of one certain polarity (negative) is apt to deposit on the surface, see above, the period of AC stress is still too short for the surface to get charged significantly. However, Sudhakar [74] indicated that in a non-uniform (rod-plane) field, the charging increased and the patterns became more complex with increasing AC voltage and duration. Both positive and negative charges coexisted and no single polarity charges dominated on the surface (up to \( \sim 2\mu C/m^2 \)).

Impulse stresses can result in charge accumulations too. Under a switching impulse (25/350\( \mu s \)) [91,93] or a longer one (2/50000\( \mu s \)) [56], two or three shots are enough for the accumulation to get saturated.
The accumulations increase with increase impulse voltage [75]. By means of a point-ring arrangement on a sample surface, the accumulations under negative impulses are stronger and more uniform [56]. Under a lightning impulse, on the other hand, the voltage must be high enough to produce corona to charge the surface [48].

As indicated in §1.3, much denser charge accumulation occurs under DC stress. The study with this stress is, therefore, very worthwhile. In this chapter, most of the tests were performed under DC stresses. The accumulation mechanisms under DC stresses are studied in the following chapter. However, tests have also been performed under AC stresses to examine the influence of charge accumulation on spacer performances in AC GIS (see §4.7).

### 4.1.3 Electric field and its distribution

The applied field on a spacer surface depends on the configuration of the system. Field components, i.e. the normal and the tangential ones along the spacer surface have been studied to explain the accumulation of charge.

To show the effect of the normal component of the field $E_n$, Fujinami and others designed a post spacer profiled along electric lines (therefore with poor $E_n$) stressed with inserted electrodes. They detected poor accumulations at most parts of the spacer surface, and found that even the breakdown voltage of inverse polarity, when the accumulation intensifies the field midway at the surface, remains unchanged [76]. On the other hand, Stoop et al. used an arrangement with negligible $E_n$ (cylinders between plane electrodes without insert). Quite high accumulations were detected [88]. Further measurements indicated that there is no essential relation between $E_n$ and the charge distribution [48,66].

Local charges may also be accumulated on a spacer surface by means of surface conduction. In this case the tangential component $E_t$ of the field may play a role in charge accumulation [51,52].

Whether the normal component of the field, or the tangential one
4.1 FACTORS AFFECTING CHARGE ACCUMULATION

dominates charge accumulation is studied with the tests in §4.3 and §4.4. The deduction of the mechanisms of charge accumulation is elaborated in chapter 5.

4.1.4 Surface conditions

Not only the surface conductivity of a spacer, but also its roughness plays a role in the accumulation. Fujinami et al. gave some results [76] showing that more charges accumulated on the surface with increasing surface roughness. The onset voltage for a certain density decreases with increasing surface roughness [52]. This can be explained by micro-discharges at the surface. However the scatter of data is quite large, even with identical surface roughness. This scatter could have masked the observations concerning the surface roughness mentioned here. In §4.6, more measurements are conducted on this aspect with specially developed surface roughnesses.

The measurements in [86] showed that a particle increases the accumulation around it. This was explained by micro-discharges at the tips of the particles.

4.1.5 Other factors

GASES AND PRESSURE

It seems that the influence of gases and their pressure on the accumulation is not so significant [54]. Bektas indicated that there is no essential change in the charge distributions obtained in air and in SF6 under similar conditions [66]. However, the pressure does influence the decay rate of surface charges. The higher the gas density, the higher the decay rate [65,89].

TEMPERATURE

Using a cathode at 100°C and an anode at 50°C, Knecht found no marked change on the charge accumulation as compared to room tem-
perature [54]. This implies that field emission is not a dominant factor, or that 100°C is not high enough to release significant thermal emission. In the presence of a nearby γ-irradiation, similar conclusions were drawn [66].

Feeding the electrode in GIS (central conductor in a coaxial system) with 6kA current can raise the temperature, both of the electrode and in the test vessel. When the temperature in the vessel was changed from 15°C to 35°C in this way, no significant influence was detected [79]. This is explained by the large scatter of charge accumulation: the change of the surface conductance due to the change in temperature, as well as the electrode emission, are not strong enough to be observed because of the accumulation scatter.

In the present work, artificial protrusions were introduced on the surface of the cathode to study the role that field emission plays in the accumulation. The test is performed in §4.5.

## 4.2 Fundamental Observations

### 4.2.1 Charge distribution and development

Charge distributions differ in practice, also with the same field design. Every time a spacer is replaced by one with the same material and dimensions, a different distribution appears. Undetectable micro-constructions at the surfaces of the electrodes and in the vicinity of the spacer surface play important roles here. Moreover, as shown below, the exact charge distribution differs from time to time, even within the same test. Therefore, the reproducibility of a charge distribution pattern is quite poor from one test to another.

To give an example, a solid spacer between electrodes with toroids, as shown in Fig. 3.3 (the distance of the toroids from the electrodes $s$ equals 0mm), is stressed to show charge distributions in this section. Fig. 4.2 gives the result at $+125kV$ voltage for 300 minutes. As can be seen, though the field is axisymmetric, the accumulation along a circumference at one altitude is not identical at all. For instance,
4.2 FUNDAMENTAL OBSERVATIONS

Figure 4.2: Charge accumulation at $+125kV$ for 300 minutes in $SF_6$ of 100$kPa$ (toroids, $s=0$): a. distribution, b. mean density with scatter, where $X$ represents the circumferential coordinate and $Z$ is the vertical coordinate

at $z = 55mm$ the accumulation can be $\sim +8.0\mu C/m^2$ but it can be $\sim -0.3\mu C/m^2$ as well. The distribution over the surface is quite inhomogeneous. However, charges of identical polarity dominate the accumulation over a particular area. In the present case, no negative charge was detected at $z > 55mm$.

The development of this distribution is illustrated in Fig. 4.3 where the charge distributions at different moments $t_{app}$ during the test are presented. It is shown that, with increasing stress time $t_{app}$, more charges were accumulated, especially at the locations where the peaks in charge density appear. Most of these peaks appeared in the first 30 minutes and dominated the profile of an accumulation thereafter. In other words, the accumulation profile is mainly determined in the first 30 minutes at a stress. With increasing $t_{app}$, most peaks (positive and negative ones) increase and the inhomogeneity of the distribution becomes more obvious.

However, charge redistribution occurs throughout the duration of a test. It is interesting to note the accumulation at the vicin-

\footnote{The results are presented in terms of charge density. In some cases $9\mu C/m^2$ surface charge can induce a field of $1kV/mm$ in the gas and has a considerable effect on the field configuration, see second part of §6.2.}
$t_{app} = 30\text{min.}$

$p = 8.4\mu\text{Cm}^3/\text{div.}$

$t_{app} = 60\text{min.}$

$p = 10.5\mu\text{Cm}^3/\text{div.}$

$t_{app} = 90\text{min.}$

$p = 11.3\mu\text{Cm}^3/\text{div.}$

$t_{app} = 120\text{min.}$

$p = 11.4\mu\text{Cm}^3/\text{div.}$

$t_{app} = 150\text{min.}$

$p = 12.7\mu\text{Cm}^3/\text{div.}$

$t_{app} = 180\text{min.}$

$p = 14.8\mu\text{Cm}^3/\text{div.}$
4.2 FUNDAMENTAL OBSERVATIONS

$t_{app.} = 210\text{min.}$

$t_{app.} = 240\text{min.}$

$t_{app.} = 270\text{min.}$

**Figure 4.3:** Growth of surface charges at $+125kV$ in $SF_6$ of 100$kPa$ (toroids, $s=0$)

ity of $z = 54mm$ and $x = 94mm$, where a peak appeared and increased gradually up to $\sim +13.1\mu C/m^2$ when $t_{app.} = 180min$. This peak decreased thereafter continuously, even to the negative polarity of $\sim -0.3\mu C/m^2$.

Fig. 4.4 and Fig. 4.5 show again the relations of the distributions of 30 minutes and those several hours later at other applied voltages. Obviously, the outlines (the contour), and the polarities, were defined in the first 30 minutes, in spite of redistributions later. The saturated distributions in Fig. 4.2, Fig. 4.4 and Fig. 4.5 also show the influence of increasing voltages on the saturated distributions, that is further discussed in §4.2.2.
\[ t_{app.} = 30\text{min.} \quad \text{and} \quad t_{app.} = 180\text{min.} \]

**Figure 4.4:** Comparison of the charge distribution after 30 minute stress with the saturated one at \(+75kV\) in \(SF_6\) of \(100kPa\) (toroids, \(s=0\))

\[ t_{app.} = 30\text{min.} \quad \text{and} \quad t_{app.} = 180\text{min.} \]

**Figure 4.5:** Comparison of the charge distribution after 30 minute stress to the saturated one at \(+100kV\) in \(SF_6\) of \(100kPa\) (toroids, \(s=0\))

Stressing at reversed polarity results in a reversed charge distribution. Fig. 4.6 shows the growth of surface charges at \(-125kV\). Obviously, the profiles of the distributions are quite similar compared to those in Fig. 4.3, but the charge polarity at each location is reversed. Conclusions are drawn in the succeeding subsection about the differences in polarity.
4.2 FUNDAMENTAL OBSERVATIONS

\[ t_{app.} = 240\text{min.} \]

\[ t_{app.} = 300\text{min.} \]

\[ t_{app.} = 360\text{min.} \]

\[ t_{app.} = 420\text{min.} \]

Figure 4.6: Growth of surface charges at \(-125kV\) in \(SF_6\) of \(100kPa\) (toroids, \(s=0\))

4.2.2 Saturation

The growth of surface charges has been shown above. Anyhow this growth would stop after a certain period at a stress, then the net charge on the surface hardly increases. To study charge accumulation at a certain stress, it is important to measure the densities at this condition. For instance, if the accumulations at two different stresses are to be compared, an erroneous conclusion can be drawn if the accumulations are still under growth.

In terms of mean charge density (defined in §3.4.2), Fig. 4.7 shows again the growth of surface charges at \(-125kV\), as has been presented
Figure 4.7: Mean charge density at different moments at $-125kV$ derived from Fig. 4.6

in Fig. 4.6. Obviously, most of the charge is accumulated in the first four hours. A stress for longer time will increase the quantity, but the rate slows down. There is no significant difference between the quantity after six hours of stress and that after seven hours. The accumulation is, in fact, saturated. Little charge will be further accumulated, though the total charge may fluctuate, continuously, at that stress.

In §3.4.3, a variable, the relative total charge $\tilde{Q}$, was introduced to describe this saturation ((3.5)). Whether accumulation is still under growth can then be determined by the increase of this variable. In Fig. 4.8, the increases of the relative total charge, integrated from $z = 50mm$ to $z = 85mm$, at several stresses are given. Obviously, $\tilde{Q}$ increased fast at first, then the increase rate decreased gradually. However, the charge is not constant after it was saturated, in agreement with the instability of the distribution under this condition.

The saturation time $t_s$ and the relative total charge $\tilde{Q}$ versus stresses are summarized in Fig. 4.9. As is shown, both quantities increase with increasing applied stress at both polarities. The saturation times under negative stresses are about 200 minutes longer than those under positive ones. The absolute total charges are also higher
Figure 4.8: Relative total charge $\tilde{Q}$ versus stressing time $t_{app}$, at various voltages in $SF_6$ of 100kPa (toroids, $s=0$)

under the negative stresses where the accumulations are negative.

4.2.3 In summary

- Charge accumulations at a surface are inhomogeneous. The scatter along a circumference can be quite large although the electric field is identical.

- The profile of the charge distribution as well as the polarity of the accumulation are mainly determined within the first 30 minutes.

- Local charge redistributions take place continuously, no matter an accumulation has been saturated or not. The total charge over an area increases before saturation and still fluctuates continuously afterwards.

- Saturation time increases with increasing applied voltage.

- The accumulation at an opposite stress is opposite in polarity,
Figure 4.9: Saturation time $t_s$ and the relative total charge $\tilde{Q}$ versus applied voltage $U$, derived from Fig. 4.8

with quite a similar profile. Saturation times for negative accumulation are longer and the total absolute charges are also higher.

4.3 Spacers with Opposite Normal Fields

This section presents the test results of charge accumulation on two cylindrical spacers with opposite normal fields (equal in amplitude and opposite in direction at the spacer surfaces). In §3.2.2, the test arrangements were designed: one is with toroids when the distance between the toroids and the plane electrodes $s$ is 5mm (Fig. 3.3); the other is with inserts whose radius $r$ is 27mm (insert A, Fig. 2.10). The field distributions along the two spacers are redrawn in Fig 4.10.
Figure 4.10: Field distributions at +100kV with toroids at s=5mm and with insert Λ; the normal fields are opposite (duplicate of Fig. 3.5)

As mentioned in §3.2, if the normal field would dominate the charge accumulation the local polarity of the accumulated charges should change as the normal field changes its direction at a dielectric surface. Besides, local charge densities might also respond to the strength of the normal field, depending on how strong the relation were between them. In this section, the two spacers are stressed with voltages of 125kV in both polarities.

4.3.1 With toroids at s = 5mm

The results under positive and negative stresses are given in Fig. 4.11 and Fig. 4.12 respectively. Compared to the results in the preceding section, the scatter here is much larger. At each circumference of the spacer the accumulation can be both positive and negative, though the fields are identical. The axial distribution of the mean density changes its polarity at the negative stress (Fig. 4.12.b) at z≈50mm, where the normal stress changes polarity. It is interesting to note
Figure 4.11: Charge accumulation with toroids at $s=5\, mm$ and at $+125\, kV$ for 420 minutes in $SF_6$ of $100\, kPa$: a. distribution, b. mean density with scatter.

Figure 4.12: Charge accumulation with toroids at $s=5\, mm$ and at $-125\, kV$ for 480 minutes in $SF_6$ of $100\, kPa$: a. distribution, b. mean density with scatter.

that the axial distributions differ a lot at different horizontal positions, even reverse the polarities all the way along the whole height. For instance, at negative stress (Fig. 4.12.a) and $x=0\, mm$ the accumulation goes first negatively and then positively. But at $x=150\, mm$, it goes the other way: from positive to negative, see Fig. 4.13.
4.3 SPACERS WITH OPP. NORM. FIELDS

\[ \sigma_5, 7.7 \mu C/m^2/dv. \]

\[ \begin{align*}
  \text{x=150mm} \\
  \text{x=0mm} \\
  \text{Z,25mm/div.}
\end{align*} \]

**Figure 4.13:** Axial distributions of surface charge at different circumferential positions \( x \) (derived from Fig. 4.12.a)

### 4.3.2 With insert A

Figure 4.14 and Fig. 4.15 show the results obtained with insert A at both polarities. The accumulations here are weaker than those with toroids. Both distributions of the mean density change polarity at the middle of the surface and are opposite to each other. In quite a large area the accumulations are weak with a small scatter.

By comparing these results (in Fig. 4.14 and Fig. 4.15) with those in the preceding subsection (in Fig. 4.11 and Fig. 4.12), it can be seen that the polarity at a circumference at the spacer surface changes less with inserts than with toroids. Under a certain stress, the accumulations are opposite in polarity in the two subsections, except the two points in Fig. 4.11.b when \( z<50mm \).

### 4.3.3 In summary

Under the conditions that the normal fields are opposite whereas the tangential fields and their derivatives (therefore the profiles) are identical in sign (not equal in amplitude), the following conclusions can be drawn:
Figure 4.14: Charge accumulation with insert A at $+125kV$ for 400 minutes in $SF_6$ of 100kPa: a. distribution, b. mean density with scatter

Figure 4.15: Charge accumulation with insert A at $-125kV$ for 410 minutes in $SF_6$ of 100kPa: a. distribution, b. mean density with scatter

- The mean charge densities are reversed in polarity.
- An accumulation with toroids is denser and more inhomogeneous than that with inserts.
4.4 Spacers with Identical Tangential Fields

This section presents the test results of charge accumulation on two cylindrical spacers along which the tangential fields are completely identical both in amplitude and in direction. In §3.2.2, the design of the test arrangements is given: one is with toroids at $s=0\text{mm}$ (Fig. 3.3) and the other is with insert B ($r=16\text{mm}$, Fig. 2.10). The field distributions along the two spacers are redrawn in Fig 4.16.

![Graph of tangential fields](image)

**Figure 4.16**: Field distributions at $+100\text{kV}$ with toroids at $s=0\text{mm}$ and with insert B: the tangential fields are identical (duplicate of Fig. 3.6)

This test was arranged to study the role that the tangential component of a field plays in charge accumulation. If the tangential field were the dominant factor, the accumulation should differ little with these two arrangements.

The applied voltages are $150\text{kV}$ of both polarities.
4.4.1 With toroids at $s = 0$

This arrangement is the same as described in §4.2, except that a new spacer was used. Fig. 4.17 and Fig. 4.18 give the results. With increasing stresses, much denser accumulations result than those at 125$kV$ (Fig. 4.2 and Fig. 4.6). The mean densities change their polarities midway at the surface though the scatter is large.

**Figure 4.17:** Charge accumulation with toroids at $s=0\text{mm}$ and at $150kV$ for 420 minutes in $SF_6$ of 100$kPa$: a. distribution, b. mean density with scatter

**Figure 4.18:** Charge accumulation with toroids at $s=0\text{mm}$ and at $-150kV$ for 420 minutes in $SF_6$ of 100$kPa$: a. distribution, b. mean density with scatter
4.4.2 With insert B

Figure 4.19 and Fig. 4.20 give the results with insert B. As can be seen, most charges were accumulated in the vicinity of \( x = 0 \text{mm} \). Under positive stress the accumulation there is positive at low altitude \( z \) and changes to negative midway at the surface. The accumulations in the present case are much weaker than those presented in the preceding subsection with toroids. The maximal density at the positive stress is only 8% of that with toroids. At a certain voltage, the charge

![Figure 4.19: Charge accumulation with insert B at +150kV for 380 minutes in \( SF_6 \) of 100kPa: a. distribution, b. mean density with scatter](image)

![Figure 4.20: Charge accumulation with insert B at −150kV for 410 minutes in \( SF_6 \) of 100kPa: a. distribution, b. mean density with scatter](image)
accumulations are reversed at the surfaces of the two spacers.

4.4.3 In summary

- Identical distributions of tangential fields by the two arrangements do not result in similar accumulation distributions. The polarities of the mean densities of the accumulated charges follow the change of the normal field, not that of the tangential field.
- The accumulation with toroids is stronger and more inhomogeneous than that with inserts.

4.5 Effects of Protrusions at Electrodes

In order to study whether field emission plays an important role in charge accumulation, a PVC spacer was stressed in $SF_6$. The spacer had aluminum electrodes (Fig. 3.7) with two artificial protrusions on the surface of the cathode. The spacer is shown in Fig. 2.5.6 and the field distribution without the protrusions is shown in Fig. 3.8.

The protrusions were made of steel. They are 1 mm in diameter, and 4 mm in height including the sharp pointed tips which are 1 mm high. These protrusions were glued on the cathode surface at different circumferential and radial positions. They are 10 mm and 26 mm away from the spacer surface respectively.

4.5.1 The accumulation

The results were recorded with an $X - Y$ recorder (Fig. 2.6), instead of a computer. For the qualitative study in this section, the measured quantity $u_2$ is not transformed into charge densities. Fig. 4.21 shows the results at a stress of $+200 kV$ for 50 minutes, where $p_1$ is the location of the protrusion 10 mm away from the spacer surface ($x = 160 mm$), and $p_2$ is that of the other ($x = 370 mm$). As is shown, each protrusion indeed results in a denser accumulation in its vicinity.
It is interesting to note that the accumulations in these vicinities possess both negative peaks and positive ones along the surface though only negative charges are expected to be emitted by the protrusions. This will be explained in §5.5.1 after the mechanisms of charge accumulation have been studied.

### 4.5.2 Lichtenberg figures

The charge distribution was also verified using powders of sulphur and lead oxide after the tank was opened 4200 minutes after the stress was removed. The results are shown in Fig. 4.22, where a. presents the distribution in the vicinity of \( p_1 \), b. presents that at \( p_2 \) and c. at another site (\( x = 357\, mm \)). The Lichtenberg figures show that if one charge peak appears, another peak with an opposite polarity will also appear at the same vertical line on the surface. The local distributions in the two-peak regions are, in some degree, of mirror symmetry. After 4200 minutes of decay, little charge existed in the centre areas of the locations where peaks had occurred (see §4.9).
Figure 4.22: Lichtenberg figures of the charges shown in Fig. 4.21 after 4200 minutes decay: a. at $p_1$, b. at $p_2$, c. at the other site

4.5.3 In summary

- Protrusions at the electrodes result in denser accumulations in their vicinities.
- Charge peaks of positive and negative polarities co-exist along the same vertical line on the surface.

4.6 Effect of Spacer Surface Conditions

A spacer has been treated with pearl jets ($\S$3.5) so that it possesses three roughnesses $R_t$, i.e. $13.0\mu m$, $7.0\mu m$, and the original one of $0.5\mu m$, on three equal divisions of its side surface. This spacer is assembled between the electrodes with toroids ($s = 0$) and stressed with $+150kV$ for 460 minutes. The field distribution by an applied stress is identical in the three regions (Fig. 3.4), though the roughnesses are different.

Figure 4.23 shows the charge accumulation after this stress. In order to avoid the error at the boundaries between the regions, the data $5mm$ away from both boundaries were taken into account only. By comparison of the results, it can be seen that increasing roughness has no significant influence on the mean density, especially in regions
4.6 EFFECT OF SPACER SURFACE CONDITIONS

Figure 4.23: Charge accumulation with several roughnesses of the spacer surface in $SF_6$ of 100kPa: a. distribution, b. mean density with scatter
II and III. The differences between the mean densities of the three surface roughnesses are well within the scatter (see also Fig. 4.17.b under the same conditions).

The charge accumulation in region I is obviously more scattered than in other regions. High charge peaks appear in this region. According to the results shown in Fig. 4.17 under similar conditions, these peaks may even be higher. In regions II and III, the accumulation is more homogeneous at each circumference (where the field is identical). The densities in the two regions have no significant difference, no matter how rough the surface is. The scatter is shown again in terms of the standard deviations\(^2\) \(S\) in Fig. 4.24. As can be seen,

![Graph showing standard deviation S for different roughnesses](image)

**Figure 4.24:** Standard deviation \(S\) of the accumulated charges presented in Fig. 4.23

the standard deviation \(S\) in region I is always larger than in other regions. At \(z = 71\,mm\), it is more than 4 times higher in region I than in other regions, while the difference between \(S\) in region II and III is small. This may result from the treatment (i.e. the blasting) on the spacer surface, not the roughness itself. Region I possesses

\[ S = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (x_i - \bar{x})^2} \], \(x_i\) is one of \(n\) samples, \(\bar{x}\) is the sample mean.
the original surface finish, while the other two were blasted with the pearl. After the surface is blasted, the charge accumulation becomes more homogeneous.

In §4.2, it has been indicated that the large scatter of charge accumulation is due to undetected micro structures at the surfaces of the electrodes or to that of the spacer surface. The influence of the treatment on the spacer surfaces seems to suggest that the micro structure of the spacer surface is more responsible than that of the electrode. To confirm this, other tests were conducted when a spacer is stressed using the same electrodes, but the relative position of the anode differs 180° from each other. Fig. 4.25 gives the results. The

![Figure 4.25: Comparison of the charge accumulations when the anode is turned 180° in SF₆ of 100kPa (with toroids at s = 5mm, at +125kV): a. stressed for 420 minutes at a position, b. the anode was turned 180° and stressed for 270 minutes](image)

second test (Fig. 4.25.b) was conducted without any precharge on the surface (after the surface charge shown in Fig. 4.25.a had decayed for one month). It shows that both the amplitudes and the distributions of the two tests are quite similar, therefore the surface conditions of the spacer are more responsible for the large scatter of charge accumulation than the micro condition of the electrode surfaces.

**In summary**

- Artificial surface roughness has no significant influence on the
charge accumulation. The differences in the results are well within the scatter.

- Influence comes from the variation in the surface conditions of the spacer by the sandblasting. If the surface is treated, no matter how rough it is, the accumulation becomes more homogeneous.

- The micro surface structure at the spacer is more responsible for the large scatter of charge accumulation than that at the electrode.

### 4.7 AC Stresses

As mentioned in §1.3, charge accumulations in AC GIS are much smaller, therefore little has been done with AC stresses. However, the study of AC stresses is necessary to reveal the pre-discharge conditions for surface flashover under AC stresses, and it is useful in improving the understanding of the mechanisms of surface charge accumulation.

Using small acrylic and teflon samples, it was found that the accumulation under a quasi-uniform field is not noticeable [66,74]. However, if the field configuration is rod-plane, an AC stress results in substantial surface charges on the acrylic sample, though the influence of those charges on the impulse flashover voltages is not significant [74].

In this section, epoxy spacers are stressed at with voltages. Both virgin spacers and a spacer with previous surface charges are employed. The surface roughness of the electrodes are varied as well.

#### 4.7.1 Virgin spacers

Two virgin spacers were stressed between the electrodes with toroids. The first one was stressed with an AC voltage of $70.7kV_{eff}$ ($100kV_{Max}$) for 60 minutes, at $s = 0mm$. The second one was stressed with AC $88.4kV_{eff}$ ($125kV_{Max}$) for 360 minutes, at $s = 5mm$. The field distributions for both tests can be found in Fig. 3.4. The experimental
results are shown in Fig. 4.26. It is shown that negative charges are favourably accumulated at an stress. With the first virgin spacer the charges were accumulated somewhat homogeneously all over the surface, though the accumulation is weak (the magnitude is $< |$  

![Figure 4.26: Charge accumulation on virgin spacers at AC stresses in $SF_6$ of 100kPa (with toroids): a. 70.7$kV_{eff}$ for 60 minutes at $s=0$, b. 88.4$kV_{eff}$ for 360 minutes at $s=5mm$](image)

1.1μC/m²$|$); while with the second virgin spacer, no noticeable charge was detected over the surface but for the location of $z = 73mm$ and $x = 66mm$ where a peak of $-1.2μC/m²$ in density appeared. The two spacers were made from the same epoxy rod. No remarkable difference can be found between the surfaces under the microscope.

### 4.7.2 Spacer with precharges

**PRECHARGES**

After the peak density as shown in Fig. 4.26.b had decayed to $\sim-0.5\mu C/m²$ (1030 minutes after the AC voltage was removed), the spacer was stressed again with $-DC 125kV$ for 480 minutes and achieved much denser charges on the spacer. These charges decayed quite quickly just after the stress was removed and then decayed progressively slower with time. After of 5000 minutes decay, no noticeable decay could be detected any more in several hours (see §4.9). A some-
what stable charge distribution was then achieved. Fig. 4.27.a shows this charge distribution after 5280 minutes decay.

**AC STRESS**

With these precharges on the spacer surface, an AC stress of $70.7kV_{eff}$ was applied for 150 minutes. Fig. 4.27.b gives the results. In Fig. 4.27.c, the mean densities in Fig. 4.27.a and b are presented. Just as in the case where a virgin spacer was used, the AC stress has little influence

*Figure 4.27:* Effect of AC voltage at precharges collected by DC (toroids at $s = 5mm$, in $SF_6$ of 100$kPa$): a. before AC, b. after 150 min. AC at $70.0kV_{eff}$, c. mean values
on the previous charge profile, except that it adds some amount of negative charges ($< | - 0.6 \mu C/m^2|$) to the surface close to the upper electrode.

### 4.7.3 Lichtenberg figures

In addition to the above tests, Lichtenberg figures were produced after an AC stress to verify the accumulations at AC stresses. For this purpose, the spacer as shown in Fig. 2.10.6 (with insert B, instead of toroids) was stressed for 280 minutes at $141.4 kV_{eff} (200 kV_{Max})$. Then the tank was opened and sulphur and lead oxide powders were sprayed on the surface 130 minutes after the voltage was removed. It was found that the sulphur powder adhered distinctly to some locations on the surface. On most areas of the surface the adherence is nil. The result is shown in Fig. 4.28. This Lichtenberg figure verifies the weak accumulation at AC stresses, and the negative polarity of the accumulation if there is any.

**Figure 4.28:** Lichtenberg figure after an AC stress at $141.4 kV_{eff}$ for 280 minutes with insert B in $SF_6$ of 100 kPa
4.7.4 Rougher electrode surfaces

Rougher electrode surface will increase the charge emission [23] and therefore affect the charge accumulation. The weak accumulation at AC stress might be enhanced if the electrode surface roughness is increased. All the above tests were performed with brass electrodes whose surface roughness is 0.5$\mu$m (see §3.2.1), while in this subsection the same electrodes are roughened by blasting with jet NK60 and a roughness of 15.0$\mu$m is achieved.

WITH TOROIDS

Only the toroids, not the plane electrodes, were roughened. The separation of the toroids from the plane electrodes $s$ was zero. The breakdown voltage was determined as 135$kV_{eff}$ compared to 178$kV_{eff}$ when the electrode surface roughness is 0.5$\mu$m (decreases 24%). Fig. 4.29 shows the charge accumulation with different surface roughnesses of the electrode at a same spacer. Obviously, as the electrode surfaces were smooth, quite weak accumulation was detected, while with the rougher electrodes several negative peaks appear and the largest reaches $| - 2.2 \mu C/m^2|$. It was found that the charge accumulation

![Diagram](image_url)

**Figure 4.29:** Charge accumulation with roughened electrodes in $SF_6$ of 100$kPa$ compared to that with smooth electrodes (toroids, $s = 0$mm): a. electrode surface roughness $R_t = 0.5 \mu m$ at AC 145$kV_{eff}$ for 380 minutes, b. $R_t = 15.0 \mu m$ at AC 129$kV_{eff}$ for 240 minutes
even after several breakdowns is still in the order of $-0.1 \mu C/m^2$ if the electrodes are smooth.

The same spacer was also stressed both with protrusions and with copper sheet sleeving the toroid respectively. The protrusions were placed at the top side along the lower toroid with the separation of 1cm between each other. They are sharp pointed, 0.6mm in diameter and 0.5mm in height. The sleeve is 0.2mm thick and 20mm long. The surface of it was roughened with abrasive paper 3M210 P120 and a roughness of only 8.0$\mu m$ was obtained. However the edges of the sleeve will give some distortion to the original field and might also affect the charge accumulation. The toroids are with roughness of 15.0$\mu m$. The results are presented in Fig. 4.30. In both cases,

![Figure 4.30: Charge accumulation in $SF_6$ of 100kPa when the local field is distorted: a. with protrusions at the lower toroid and at AC 130$kV_{eff}$ for 150 minutes, b. with sleeve at the lower toroid and at AC 130$kV_{eff}$ for 210 minutes](image)

some positive charge was detected as well. The effect of protrusions is remarkable. Nevertheless the average accumulation here is lower compared to that without field distortion (Fig. 4.29.b) though the applied voltage is comparable. This might be within the large scatter of charge accumulation. The thin sleeve did not seem to form significant edge grooves at a proper site to supply charge.
WITH INSERT B

This spacer is the same as used to make the Lichtenberg figures in preceding subsection. Fig. 4.31 gives the results. For the voltage application at $R_t = 0.5\mu m$ (the surface roughness of the electrodes), a flashover occurred at $230kV_{eff}$ during the increase of the voltage.

![Figure 4.31: Charge accumulation at the spacer with insert B in SF$_6$ of 100kPa: a. surface roughness of the electrodes $R_t = 0.5\mu m$ at AC $220kV_{eff}$ for 60 minutes, b. $R_t = 15.0\mu m$ at AC $212kV_{eff}$ for 120 minutes](image)

Then the voltage was decreased to $220kV_{eff}$ and endured for 60 minutes. A peak of $-0.3\mu C/m^2$ appeared. At $R_t = 15\mu m$, the highest peak becomes $-14.0\mu C/m^2$ (the circumferential position of the spacer would have been changed). Much stronger accumulation appeared here compared to that with toroids. This might be due to the higher applied voltages and therefore the higher charge emission with inserts.

4.7.5 Discussion

The surface conditions of the second spacer and the electrodes in §4.7.1 were carefully examined under a microscope. No noticeable difference was found in the vicinity of the location where the peak occurred. As indicated in §4.2, undetectable micro structures at the surface and in the vicinity play important roles in the accumulations.
The results also reflect the poor reproducibility of charge accumulations. Compared with the accumulations under DC stress, the accumulations under AC stress are much smaller.

Dense surface charges resulting from DC stress decay in their own way: there is little influence of AC stress on it. The results in the two cases, with and without precharges, suggest that AC stresses can only change the original profile of surface charges a little, whether the original distributions are of significant charges or not. An AC stress results in some amount of negative charges on the spacer surface.

As the surface roughness of the electrodes is increased the charge accumulation becomes substantial due to the enhanced emission at the electrodes. The accumulation tends to be negative. In practice the electrode surface could easily be rougher than 15μm [23] and would be worsened during assembling, therefore denser charge is expected at a comparable voltage. This accumulation deteriorates the original field and it might contribute itself to a flashover to promote a premature leader.

4.7.6 In summary

- When stressing smooth electrodes at AC voltage, the charge accumulation tends to be negative and slight.
- With smooth electrodes, the effect of AC stress on original profile of surface charges is small.
- Charge accumulation increases with increasing surface roughness of the electrodes and attains values when the initial field configuration may be affected.

4.8 Actual Spacer under Atmospheric Conditions

As an example of the application of the two-step method introduced in §2.5, the calibration for an actual GIS spacer (Fig. 2.16) has been
defined (Fig. 2.17). In this section, the charge accumulation at this GIS spacer is studied under atmospheric conditions. The study will be useful in researching the pre-discharge state of the surface flashover in air. It will further be beneficial to the studies with compressed gases. In the following chapter, it will be shown that the accumulation mechanisms in air and in SF₆ are similar.

Both positive and negative DC voltages of 56kV were applied to the central conductor, with the enclosure earthed. All the tests were carried out in air of 20°C, 100kPa and 60% (11g/m³) humidity. The measurements were performed in one radial direction (downward) only, from the conductor to the enclosure, along the spacer surface.

Figure 4.32 shows the charge accumulations after stressing for different durations under positive and negative DC voltages, where r is the radial coordinate from the axis of the conductor (see Fig. 2.16). It can be seen that the charge distributions at both polarities are similar: monopolar charges are deposited only; each charge distribution has a peak near the conductor and the charges have a polarity which is opposite to the applied voltage. There is little increase in the charge density beyond 30 minutes.

For convenience to study the mechanisms of charge accumulation (to be performed in §5), the distribution of the initial normal field along the spacer surface is given in Fig. 4.33 succeeding the test results.

### 4.9 Charge Decay

Once the stress is removed, the accumulated charges will gradually drift away from the surface. The decay characteristic is studied in this section. All the tests were conducted at the condition that the HV electrodes were earthed after each voltage application.
4.9 CHARGE DECAY

Figure 4.32: Charge accumulations on the GIS spacer (Fig. 2.16) in air under 56kV: a. positive, b. negative

4.9.1 Time dependence in $SF_6$

The arrangement with toroids (Fig. 3.3) at $s = 0$ was used. To obtain the decay characteristic, the quantity $\bar{Q}$ (Equation (3.5)), at the surface area of $z=50mm$ to $85mm$, was divided by its value of the first measurement $\bar{Q}_o$ (3 ~ 4 minutes) after a stress. Fig. 4.34 gives the results after the spacer was stressed with $-75kV$ for 420 minutes, with $-100kV$ for 360 minutes, and with $+125kV$ for 300
Figure 4.33: Initial normal field $E_n$ along the GIS spacer (Fig. 2.16) at +56kV

Figure 4.34: Charge decay in $SF_6$ of 100kPa after DC voltage application (toroids, $s = 0$): $\bar{Q}$—relative total charge, $\bar{Q}_0$—initial value of $\bar{Q}$
minutes respectively. As is shown, the accumulated charges in each case decay fast at the beginning, and the decay rate slows down with increasing decay time (the time axis is a logarithmic one). Half of the charges were decayed in 160 minutes. There is no significant difference between the decay rates in these experiments.

### 4.9.2 Distributions during decay in $SF_6$

The decay of the accumulation on the PVC spacer, tested in §4.5, was also determined. Fig. 4.35 shows the distributions along the vertical line at $x = 357mm$, where the accumulation was the strongest. The times at observation are 37 minutes, 1200 minutes and 4050 minutes respectively. At the locations where charge peaks appeared, the decay rate was higher than in the surroundings, so that the peaks changed to recesses during the decay. For instance, at the location where the negative peak took place ($z = 128mm$), a recess appeared after 1200 minutes decay.

The faster decay in the centre of a charge peak has also been indicated by others [89,90,93]. After the density in the centre is equal to that in the periphery, the decay rate is usually equal in the whole region of this peak until the total charges have decayed away. In
the present work, the decay rate in the centres was higher until little charge remained at that place, with quite dense charges surrounding it. This can be seen in the Lichtenberg figures in Fig. 4.22, at the decay time of 4200 minutes and can be explained by the repulsion of the like charges in the localized charge accumulations.

In the case when there is a small amount of charge in a small area surrounded by dense charges, the output of the probe does not approach zero because of the surrounding charges (§2.2.3). In this case, Lichtenberg figures give more effective results.

4.9.3 Charge decay in air

The actual GIS spacer (Fig. 2.16) was tested in air of 22°C, 100kPa and 60% humidity. The decay characteristics at different radial positions $r$ are shown in Fig. 4.36, after a stress of $+DC56kV$ for 30 minutes, where the surface charge is normalized based on the densities at individual positions after 13 minutes decay (the first measurement). The results show, as above, that the surface charges decay rapidly at

![Graph](image_url)

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**Figure 4.36**: Charge decay in air at 60% humidity: $\sigma_S \rightarrow$ surface charge density, $\sigma_{S_0} \rightarrow$ initial value of $\sigma_S$
first. The charge density is halved in about one hour. As the charge densities become smaller, their decay rates slow down.

At the condition that the relative humidity was decreased to 35% (18°C, 100 kPa), the decay differs. At the same voltage for the same period as above, almost no decay can be detected in 24 hours (the data were normalized based on the readings after 10 minutes), except at \( r = 60 \text{mm} \) where the leakage distance is the shortest, see Fig. 4.37. This behaviour is caused by the increase of the surface resistivity at dry conditions (see §5.6).

### 4.9.4 In summary

- In \( SF_6 \) the decay rate of surface charges is the highest at the beginning, and becomes progressively slower later on. Half of accumulated charges decays in some three hours. The rest may stay on the surface for several days with a small decay rate.

- In \( SF_6 \) charges at the centres of the peaks decay faster than those elsewhere. Charge densities in those centres approach
zero with dense charges in the surroundings.

- In air (at 60% humidity and 20°C), similar conclusions to that in the first item were drawn. However, if the humidity is lowered to 35% fast decay was hardly observed.
Chapter 5
Theoretical Aspects

This chapter deals with the physical and theoretical aspects of charge accumulation. The content is:

- Review of theoretical models (§5.1 and §5.2);
- Conclusions on the accumulation mechanisms (§5.3);
- Explanation of charge accumulation by field analysis (§5.4 and §5.5);
- Decay physics of surface charges (§5.6).

5.1 Charge Origins

Charges accumulated on a dielectric surface have certain origins and have been transported via certain paths. They have been proposed in the literature by others. The origins are supposed to be:

a. Natural ionization [51,76];

b. Field emission at protrusions on the electrodes [51,59,76];
c. Micro discharges (at particles) on the dielectric surface [76,86];
d. Partial discharges at the interface between the spacer and the electrodes [41,63].

The paths are:

a. Transportation via space [51,59,76,86];
b. Surface conduction [51,76];
c. Bulk conduction [51,76].

Among the origins, the first, natural ionization, supplies ions within GIS as a result of the attachment of electrons to neutral $SF_6$ molecules. The electrons are released from the $SF_6$ by cosmic ray collisions [11,89]. Under a bias voltage, these ions are driven away from the gas space onto spacers or electrodes, depending on whether a field line is intersected with a spacer surface or not. Ions arriving at a spacer are accumulated there. Measurements indicate that the ionization rate in $SF_6$ by cosmic rays is approximately 100 ion pair/$m^3 \cdot s \cdot Pa$ [12]. This rate is, however, much too low to get a charge density as high as those encountered in the preceding chapter. If an actual accumulation would result from the natural ionization only, the saturation time would be thousands, not several, hours. Hence this origin is not significant in practice.

The other three origins are, in fact, due to the field distortions in GIS, as described in §1.1 and §1.2. These distortions are introduced by protrusions at the electrode surfaces, conductive particles at the spacer surfaces, and poor contacts at the interface between the spacer and an electrode. At the operating stress, the field strength at these sites may be above the breakdown threshold and local discharges take place to supply charges.

The produced charges drift along the electrical lines. Depending on the configuration of the field, the charges may arrive at a spacer surfaces. The charges generated at an electrode need to be transported via the gas space onto a spacer surface, whereas the charges produced at an interface between spacer and electrode can reach the
5.2 ACCUMULATION MODELS

surface by surface conduction. These charges may also reach the surface via the body of the spacer (the bulk conduction). The charges at a particle on the surface may be redistributed by surface conduction.

5.2 Accumulation Models

Charges are released due to the distortions of the field, and are led to a surface by the electric force of the field. Hence the initial field (the field before charge is accumulated) plays an important role in the charge accumulation. Three theoretical models, each of which is related to one of the paths of charge accumulation, have been proposed in the literature. These models are reviewed in the following in separate subsections, and evaluated in §5.2.4.

5.2.1 Charge conduction in spacer body

As has been seen, charges released at an interface of the spacer and an electrode may arrive at the spacer surface by bulk conduction. Charges may also be transferred from an electrode to the bulk of the spacer by contact potential [95] and then drift along the field lines in the spacer and reach the spacer surface from inside.

A model explaining charge accumulation by bulk conduction was proposed in [94]. It was indicated that the gradient in bulk conductivity of the spacer, due to the inhomogeneity of the material and the dependence of the conductivity on the field strength, leads to a charge distribution inside the spacer [94] (similar to §5.4):

$$\rho = -\frac{\varepsilon_d}{\sigma_d} \mathbf{E}_d \cdot \nabla \sigma_d$$

(5.1)

where $\rho$, $\mathbf{E}_d$ are respectively the bulk charge density and the field within the spacer in a steady state; $\sigma_d$ is the bulk conductivity. $\varepsilon_d=\varepsilon_r\varepsilon_0$ represents the permittivity of the spacer material. Migration of these charges onto the spacer surface may cause surface charges [30]. In §5.2.4, it will be shown that this mechanism is not responsible for charge accumulation.
5.2.2 $E_n$ model — charge transport via gas

Interpretation of charge accumulation was based on the charge transport in gas by the author of [54]. This was further emphasized in [59] by the same group and was backed up in [76] by others with more experimental results and developed into a theoretical model. The mechanism is given as follows.

Charges are generated by field emission or micro discharges at the sites of heavy field distortions, including dust particles floating in the gas space. These charges drift along the field line and may finally arrive at the spacer surface, see Fig. 5.1.a. If the conductivity of the spacer is very low (both in the bulk and at the surface), space charges build up at the surface. The accumulated charges will counteract the initial field near the spacer surface so that the normal component of the field is reduced. After a while, a steady state is achieved so that new charges moving along the field lines will no longer touch the spacer surface but sweep over it when the normal field in the gas becomes zero, see Fig. 5.1.b. This steady state corresponds to the saturation of the charge accumulation as defined in §4.2.2. The local charge density can be computed with the following boundary conditions [59,76]:

![Diagram](image-url)
5.2 ACCUMULATION MODELS

\[
\begin{align*}
\epsilon_o E_{n,o} - \epsilon_d E_{n,d} &= \sigma_S \\
E_{n,o} &= 0
\end{align*}
\]

where \( E_{n,o} \) and \( E_{n,d} \) are the normal fields (after saturation) at the gas side and at the bulk side of the spacer respectively, \( \sigma_S \) is the saturated charge density, \( \epsilon_o \) is the permittivity in vacuum (also in \( SF_6 \)) and \( \epsilon_d \) is the permittivity of the spacer material. The first equation is derived by applying the Gauss theorem to the interface; the second one is due to charge accumulation. Consequently in this case \( E_{n,d} \) approaches \( -\frac{\sigma_S}{\epsilon_d} \).

The saturated charge distribution is then correlated to the profile of the initial normal field \( E_n \). The polarity of the accumulated charge is opposed to the polarity of \( E_n \). The resulting normal field in gas caused by the accumulated charges equals \( E_n \) in magnitude, but is opposite to \( E_n \) in direction (so that their superimposition equals zero, see the second equation in (5.2)).

In [76], various types of inserts were used and it was found by them that the tangential component of the field became constant along the spacer surface when \( E_{n,o} \) approaches zero. This is illustrated in Fig. 5.2\(^1\) with one of the spacers. It should be noted that the total field (i.e. the sum of the normal and the tangential fields) also becomes constant as the charge accumulation gets saturated.

5.2.3 \( E_t \) model — charge conduction along spacer surface

Nakanishi et al. supposed that surface conduction is the dominant mechanism in charge accumulation owing to the fact that the accumulation is strongly influenced by the filler and surface treatment of the spacer [51]. This mechanism was illustrated in more detail in [52] by the same authors, with measurements of surface and bulk conductivities.

\(^1\)In order to correspond with the applied voltage by the authors, the field variation at \(-200\,kV\) is illustrated here instead of \(1\,kV\) as in [76].
Figure 5.2: Field variation by charge accumulation as calculated in [76]:
a. spacer with inserts, b. charge accumulation at $-200kV$, c. field variation at $-200kV$

Their results, as shown in Fig. 5.3, indicate that the surface conductivity $\sigma_s$ for epoxy resin in $SF_6$ can be described by:

$$\sigma_s = \sigma_{s,0} e^{b[E_{t,0}]} ,$$  \hspace{1cm} (5.3)

where $\sigma_{s,0}$, $b$ are constants and $E_{t,0}$ are the tangential field along the spacer surface. The surface current density $j_z$ is obtained by:
5.2 ACCUMULATION MODELS

Figure 5.3: Dependence of surface conductivity $\sigma_s$ of epoxy resin on the tangential field $E_{t,o}$ in $SF_6$ as measured in [52]

$$j_z = \sigma_s E_{t,o}$$

(5.4)

The surface charge density $\sigma_{ST}$ accumulated in a period $T'$ is [52]

$$\sigma_{ST} = \int_{T'} - \frac{\partial j_z}{\partial z} \, dt,$$

where $z$ is the coordinate of an axis in the direction of the surface current. This may be, for instance, $Z$ in Fig. 3.3 if a cylindrical spacer is employed. Provided that the charge density is low and does not modify the initial field, the authors concluded² [52]:

$$\sigma_{ST} \propto - T' E_t \frac{\partial |E_t|}{\partial z},$$

(5.5)

where $E_t$ is the initial tangential field. Equation (5.5) agrees to some extent with the results in [51] and [52], see Fig. 5.4. The test arrangement for these experiments is shown in Fig. 4.1.

In the saturation condition, the surface charge is constant. Then [51]

²The original expression in [52] is revised here to make it valid for a coordinate in any direction.
Figure 5.4: Comparison of the measured charge density $\sigma_S$ with a function of the initial tangential field $E_t \frac{\partial |E_t|}{\partial z}$ at $+130kV$ as performed in [52]

$$\frac{\partial j_z}{\partial z} = 0$$ (5.6)

The $E_t$ model correlates the charge accumulation with the initial tangential field $E_t$. The charge distribution corresponds to the product of $E_t$ and the gradient of its absolute value. If $E_t > 0$ and increases (the gradient being $> 0$), negative charge is accumulated; if it decreases along the surface (the gradient being $< 0$), positive charge is accumulated.

5.2.4 Evaluating these models

No matter where charges come from, each of the models emphasizes a certain path of charge accumulation. The distribution of the charges in the individual models is determined by the paths only.

Bulk conduction cannot be an important mechanism due to the fact that the polarity of the measured charge is opposite to the polarity expected of the bulk conduction. This is the case in the ex-
periments discussed in §4, also in the experiments by others, such as those reviewed above [51,52,54,59,76]. For example, if a positive stress is applied to the arrangement of [51] (shown in Fig. 4.1), the direction of the field inside the spacer will be from the anode to the upper half of the spacer surface, and from the lower half of it to the cathode. The charge arrived at the spacer surface via bulk conduction would therefore be positive at the upper surface, and negative at the lower surface. This is not consistent with the measured results (see Fig. 5.4). Hence the bulk conduction cannot be the dominant mechanism for charging the surface.

On the other hand, the charges due to the gradient of the bulk conductivity (see (5.1)) is distributed according to the configurations of the field and the bulk conductivity. They cannot migrate to the surface because the field and the conductivity do not vary in the steady state after saturation; hence this model cannot be employed to explain the charges accumulated at the surface. Owing to the fact that the bulk conductivity of epoxy resin is almost independent of the stress in the normally applied range [52], the bulk distribution of charge is, however, slight compared with that at the spacer surface. This will be further elucidated in §5.4 by field analysis.

The other two models, concerning the surface conduction and the charge transport in the gas, were originally proposed during the same conference [47]. It is interesting to note that the test conditions in the two papers [51] and [54] are similar, see Table 5.1. For this reason, the test results in these papers were also similar (see Fig. 5.2 and Fig. 5.4). The following analysis show the limits of these experiments.

The $E_n$ model emphasizes the effect of the normal component of the field along the spacer surface. If the field lines are directed toward the spacer surface, positive charge is accumulated; otherwise negative charge is accumulated. The accumulation will counteract the initial normal field. As soon as condition (5.2) is satisfied: $E_{n,o} = 0$, charge will no longer be accumulated. This condition also results in a constant tangential field along cylindrical spacers with inserts, as calculated in [76] (Fig. 5.2).

For the cylindrical spacers with inserts as shown in Fig. 4.1 and
Table 5.1: Comparison of test conditions in [51] and [54]

<table>
<thead>
<tr>
<th>Items</th>
<th>[54]</th>
<th>[51]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spacer†</td>
<td>Epoxy resin</td>
<td>Epoxy resin</td>
</tr>
<tr>
<td></td>
<td>$\phi40 \times h40$</td>
<td>$\phi40 \times h40$</td>
</tr>
<tr>
<td>Gas</td>
<td>$SF_6$</td>
<td>$N_2$</td>
</tr>
<tr>
<td>Press. ($kPa$)</td>
<td>100~400</td>
<td>400</td>
</tr>
<tr>
<td>Surface rough.</td>
<td>Original</td>
<td>10 ~ 20$\mu m$</td>
</tr>
<tr>
<td>Stress ($kV$)</td>
<td>100 ~ 400</td>
<td>50 ~ 200</td>
</tr>
</tbody>
</table>

†See also Fig. 4.1 and Fig. 5.1.

Fig. 5.2.a, the above process will result in negative charges at the upper half of the side surface of the spacer, and positive charges at the lower half, under a positive stress.

On the other hand, the $E_t$ model pays attention to the tangential component of the field. In the condition of (5.6), the density of the surface current $j_z$ is constant all over the surface. Then charges must have been accumulated on the surface to vary the field $E_{t,o}$, and the surface conductivity $\sigma_s$ as well, so that a constant current density $j_z = \sigma_s E_{t,o}$ exists. As a result, the surface charge accumulation counteracts the initial tangential field. According to (5.5), this will result in a negative accumulation if the tangential field increases, and a positive accumulation if the latter decreases in the direction of the leakage current.

Using a cylindrical spacer with inserts like those shown in Fig. 4.1 and Fig. 5.2.a, such a field distribution is achieved: where the tangential field $E_t$ decreases, the normal field $E_n$ is negative; where $E_t$ increases, $E_n$ is positive; and when $\frac{\partial E_t}{\partial z} = 0$, $E_n = 0$ (see Fig. 5.2.b). Therefore, the $E_t$ mechanism will result in the same charge distribution, as predicted above with the $E_n$ model: negative charges at the upper half of the spacer surface, and positive charges at the lower half, under a positive stress. Therefore the results in [76] and [52] (see Fig. 5.2 and Fig. 5.4) might be interpreted by either the $E_n$ mech-
anism or the $E_t$ mechanism; the actual dominant mechanism is still unknown.

5.3 Accumulation Mechanisms

5.3.1 Introduction

To evaluate the role the normal field plays, an extra test was performed in [52], where a post spacer, with inserts, was stressed in a coaxial conductor configuration. The authors concluded that the charge pattern does not correspond to the distribution of the normal field, but to the tangential field. However this conclusion was masked by the large scatter of the charge accumulation. Because of the large scatter, an experiment is only valid to reveal the dominant mechanism if the predicted results of the two model are greatly different. This can be achieved if the initial field is so designed that the polarity of the accumulation would be clearly positive if the $E_n$ mechanism were valid, and negative if the $E_t$ mechanism were valid. Then the conclusion is reached by simply comparing the polarity of the measured charge and the polarities predicted by the models.

Such a field can be produced by axisymmetrical arrangements with toroids, not with inserts as in [52]. In the following, the fields designed in §3.2 and the test results presented in §4.3 and §4.4 are employed to reveal the dominant mechanism of the charge accumulation.

5.3.2 Experiments and results

The geometry of the arrangement with toroids is shown in Fig. 3.3. Fig. 3.4 gives the field distributions along the spacer surface.

If the $E_t$ model were valid, a positive voltage should cause negative charges at the upper half of the spacer surface, and positive charges at the lower half.

If the $E_n$ model were be valid, the same positive voltage would cause positive charges at the upper half, and negative charges at the
lower half of the spacer surface.

The two predicted distributions are completely opposite to each other.

The test results under positive voltages can be found in Fig. 4.11 and Fig. 4.17. Similar, but opposite results under negative voltages are shown in Fig. 4.12 and Fig. 4.18. According to the mean densities of the accumulated charge in these figures, the polarity of charge accumulation corresponds obviously to the distribution predicted by the $E_n$ mechanism (except at the lowest two points in Fig. 4.11.b). Consequently the charge transport in the gas is dominant in the charge accumulation.

The results in §4.4 show further that surface conduction of the spacer cannot dominate the charge accumulation. In that section, the charge accumulations were determined with two arrangements which possess an identical tangential field both in the magnitude and in the profile (and therefore the gradient of the field strength), but the normal fields are opposite in polarity and differ 2.3 times in magnitude from each other (Fig. 3.6). The accumulations change their polarity according to the polarity of the normal field and do not follow the prediction of the $E_t$ mechanism.

However, surface conduction may play a role in charge accumulation locally, though not dominant. This can be seen in Fig. 4.12.a. The accumulation at $x = 0$ (redrawn in Fig. 4.13) corresponds to the prediction of the $E_t$ model and is probably caused by surface conduction. Nevertheless, the $E_t$ mechanism does not dominate the charge accumulation, and has therefore less influence on the performance of a spacer.

5.3.3 Influences of field emission and electrode area

By using artificial protrusions on the electrode surface, it has been shown that the field emission from the electrode surface is an important origin of charges (§4.5). The only way for these charges to be
accumulated at the spacer surface is transport in the gas space. This confirms the important role of the $E_n$ mechanism.

Because charge transport in gas is an important path, the emission behaviour at the electrode surface also affects the charge accumulation: the higher the probability of field emission, the stronger the charge accumulation. The charge accumulation is thus determined by both the emission at the electrodes and by the normal field at the spacer. The influence of the field emission can be observed in §4.3, where the two arrangements were used: one with toroids, another with inserts. The normal field were designed to be equal in magnitude, and opposite in polarity all over the spacer surface. The maximal tangential field (and therefore its gradient) is higher with inserts than with toroids, see Fig. 3.5. Under these conditions, the accumulations were opposite in polarity according to the normal field at each arrangement, under both positive and negative stresses (compare Fig. 4.11 with Fig. 4.14, and Fig. 4.12 with Fig. 4.15). However, the accumulations were not comparable in magnitude, though the normal fields were equal. For instance, under the positive stress the maximal density with inserts (Fig. 4.14) is only $\sim 40\%$ of that with toroids (Fig. 4.11).

The difference in tangential fields cannot be responsible for this difference. As discussed in the preceding section, if there were any charge accumulated due to the tangential field, the polarity of the charges would be the same as that due to the normal field, with inserts; and would be opposite with toroids. In other words, the accumulation due to the tangential field will counteract the accumulation by the normal field, if the arrangement is with toroids; but enhance the accumulation if the arrangement is with inserts. From this point of view, the accumulations with inserts in §4.3 should have been stronger than the accumulations with toroids. This is contrary to the results. Therefore, the large accumulations with toroids cannot be due to the tangential field.

This can be explained by the higher field strength at the toroids than at the plane electrodes, and by the large electrode area with toroids. The former increases the emission strength and the latter
gives more probability of the field distortions occurring (electrode area effect, §1.1.2). This, on the other hand, gives a possible explanation for the electrode area effect.

5.3.4 Conclusions

From the present experiments, the following conclusions can be drawn:

- Charge transport in the gas space is the dominant mechanism for charge accumulation. Consequently, $E_n$ is the dominant factor in the field configuration.

- Surface conduction has little influence on the charge accumulation.

- The main charge origin is the field emission at the electrode surfaces. The emission behaviour also affects the distribution and the densities of the accumulation.

In an actual GIS, the electrode surface would be much rougher than that in the present work, therefore the field emission would be stronger. The conclusions drawn here apply to the actual situations.

5.4 Inevitability of Charge Accumulation

Any dielectric material shows dielectric losses under voltage. As long as a loss (leakage) exists in a field, space charges will be accumulated due to the unavoidable variations of the dielectric characteristics in the field. This inevitability is studied in this section.
5.4 INEVITABILITY OF CHARGE ACCUMULATION

5.4.1 Accumulation in inhomogeneous materials

In an electroquasistatic field\(^3\), Maxwell's equations can be presented as

\[
\nabla \times \mathbf{E} = 0
\]

\[
\nabla \cdot \mathbf{D} = \nabla \cdot \epsilon \mathbf{E} = \rho
\]

\[
\nabla \cdot \mathbf{J} + \frac{\partial \rho}{\partial t} = 0
\]

where \(\mathbf{D}\) is the flux density, \(\mathbf{E}\) is the electric field strength, \(\mathbf{J}\) is the current density in the dielectric, while \(\epsilon\) and \(\rho\) are the the dielectric permittivity and free space charge density respectively. \(\mathbf{J}\) obeys Ohm's law:

\[
\mathbf{J} = \sigma \mathbf{E}
\]

where \(\sigma\) is the conductivity of the material.

Equation (5.9) implies that the increase of space charge at a location results from the decrease of current there. It is the leakage current that gives rise to space charge accumulation.

With an inhomogeneous conductivity and permittivity, the statement of Gauss theorem (5.8) and Ohm's law (5.10) becomes

\[
\mathbf{J} \cdot \nabla \frac{\epsilon}{\sigma} + \frac{\epsilon}{\sigma} \nabla \cdot \mathbf{J} = \rho
\]

Elimination of \(\nabla \cdot \mathbf{J}\) between (5.9) and (5.11) gives

\[
\frac{\partial \rho}{\partial t} + \frac{\sigma}{\epsilon} \rho = \frac{\sigma}{\epsilon} \mathbf{J} \cdot \nabla \frac{\epsilon}{\sigma}
\]

When a DC voltage is applied to a system, the leakage current transfers space charges continuously to the space where the current

\[^{3}\text{when the displacement current and the magnetic induction can be ignored [106].}\]
(the electric field) has a component in the direction of a gradient of \( \frac{\varepsilon}{\sigma} \). After a certain time a steady state occurs when the time rates of change are negligible and (5.12) becomes

\[
\rho = \mathbf{J} \cdot \left( \nabla \frac{\varepsilon}{\sigma} \right)
\]  

(5.13)

or

\[
\rho = \varepsilon \mathbf{E} \cdot \left( \frac{\nabla \varepsilon}{\varepsilon} - \frac{\nabla \sigma}{\sigma} \right)
\]  

(5.14)

At this condition,

\[
\frac{\partial \rho}{\partial t} = 0
\]

and consequently

\[
\nabla \cdot \mathbf{J} = 0
\]  

(5.15)

This is the well-known equation of current continuity in the steady state. In this condition, the charge accumulation is said to be saturated.

(5.13) shows that space charge will be developed if the medium in the field is not homogeneous \( \nabla \frac{\varepsilon}{\sigma} \neq 0 \) in the direction of the leakage current. No material, strictly speaking, exists which is perfectly homogeneous or gives no loss under a voltage. Hence, space charge will always be accumulated.

In engineering, each single material is normally idealized to be isotropic. Then the anisotropy appears at the interfaces of materials, such as the gas-solid interface, gas cavities or inclusions in solid materials. Normally at an interface, \( \varepsilon \) and \( \sigma \) change in such a way that \( \frac{\varepsilon}{\sigma} \) is not continuous. This variation is much larger than inside the material. Hence, (5.13) and (5.14) suggest that the charge accumulation in a field is localized at the interface of media; little charge can be accumulated in the "homogeneous" bulk of a medium. This removes the concern of researchers as to whether a detected potential is attributable to the charges at the surface or distributed in the bulk of a spacer [47].
5.4.2 Accumulation at an interface

In this subsection the charge density at a dielectric interfaces will be calculated. For later use in this thesis, a gas-spacer interface as shown in Fig. 5.5 is referred to. The characteristics of the spacer and of the gas are shown in the figure. At this surface, charges are accumulated because of the sudden variations of $\varepsilon$ and $\sigma$. The charge density can be determined by the boundary conditions as given below.

Applying (5.8) and (5.9) (the volume charge density $\rho$ is now replaced by the surface charge density $\sigma_S$) at the interface,

\[
\begin{align*}
\epsilon_o E_{n,o} - \epsilon_d E_{n,d} &= \sigma_S \\
\sigma_o E_{n,o} - \sigma_d E_{n,d} + \frac{\partial \sigma_S}{\partial t} &= 0
\end{align*}
\]

Elimination of $E_{n,d}$ results

\[
\frac{\partial \sigma_S}{\partial t} + \frac{\sigma_d}{\epsilon_d} \sigma_S = \frac{\epsilon_o \sigma_d}{\epsilon_d} E_{n,o} - \sigma_o E_{n,o}
\]

At a steady state,

\[
\sigma_S = E_{n,o} \left( \epsilon_o - \epsilon_d \frac{\sigma_o}{\sigma_d} \right)
\]
or

\[ \sigma_S = E_{n,d} \left( \epsilon_o \frac{\sigma_d}{\sigma_o} - \epsilon_d \right) \]  \hspace{1cm} (5.19)

where the subscript \( n \) indicates the normal components of the variables shown in Fig. 5.5; \( o \) represents those in the gas side, and \( d \) in the spacer side; \( \sigma_S \) is the surface charge density. These two expressions correlate the accumulation to the normal field. Normally in GIS, \( \frac{\sigma_o}{\sigma_d} < \frac{\epsilon_o}{\epsilon_d} \) due to the fact that \( \epsilon_o < \epsilon_d \) and \( \sigma_o > \sigma_d \) ((5.23), see §5.5.1). Therefore, a surface charge accumulation results if there is a normal component of the field.

In the steady state, \( E_{n,o} \) does not have to be zero as presented in equation (5.2) (\( E_n \) model). A small normal field remains normally at the interface to ensure a continuous leakage current.

### 5.4.3 Maxwell’s capacitor

The above conclusions are derived at the steady state. At this condition, the spatial charge (\( \rho \) and \( \sigma_S \)) distribution is constant which is determined according to the variations of the dielectric characteristics. In this subsection, the process of charge accumulation and the transient of the field will be illustrated using a simple configuration, Maxwell’s capacitor, as shown in Fig. 5.6. The space between two

![Figure 5.6: Maxwell's capacitor](image)

parallel electrodes is filled by two layers of material with characteristics as shown in Fig. 5.6. Initially, there is no charge between the electrodes at the interface. The electrodes are assumed long enough
so that the fringing at the edges can be neglected and the fields in the materials are uniform.

When \( t = 0 \), a DC voltage is applied between the electrodes, as shown in Fig. 5.7. From the law of charge conservation (5.9) and Gauss theorem (5.8),

\[
(\sigma_a E_a - \sigma_b E_b) + \frac{d}{dt} (\epsilon_a E_a - \epsilon_b E_b) = 0
\]  
(5.20)

The line integral of the electric field equals the applied voltage:

\[
\int_{-b}^{a} E \, dx = aE_a + bE_b = u(t)
\]  
(5.21)

Eliminate \( E_b \) between these two equations,

\[
(b\epsilon_a + a\epsilon_b) \frac{dE_a}{dt} + (b\sigma_a + a\sigma_b) E_a = \sigma_b u(t) + \epsilon_b \frac{du(t)}{dt}
\]  
(5.22)

For \( t > 0 \), \( u(t) = U \) and \( \frac{du(t)}{dt} = 0 \). The solution to (5.22) is

\[
E_a = \frac{\sigma_b U}{b\sigma_a + a\sigma_b} \left( 1 - e^{-\frac{t}{\tau}} \right) + \frac{\epsilon_b U}{b\epsilon_a + a\epsilon_b} e^{-\frac{t}{\tau}}
\]

where

Figure 5.7: Application of a DC voltage
\[ \tau = \frac{b\varepsilon_a + a\varepsilon_b}{b\sigma_a + a\sigma_b} \]

is a time constant. From (5.21),

\[ E_b = \frac{U}{b} - \frac{a}{b} E_a \]

and from the Gauss theorem

\[ \sigma_S = \frac{U(\sigma_b\varepsilon_a - \sigma_a\varepsilon_b)}{b\sigma_a + a\sigma_b} \left( 1 - e^{-\frac{t}{\tau}} \right) \]

This expression illustrates the transient from the initial capacitive distribution to the steady state expressed in (5.18). The time constant \( \tau \) can be in the order of some hours. In [106] it is shown for instance that the relaxation time of mica (which is caused by multiple interfaces within the mica) is in the order of \( 10^4 \) seconds.

The transients of the field and the surface charge density are illustrated in Fig. 5.8 (provided that \( \varepsilon_b > \varepsilon_a \) and \( \sigma_b > \sigma_a \)).

**Figure 5.8**: Transients of the fields and the surface charge density at the interface after a DC voltage is applied to a Maxwell's capacitor as shown in [106]
5.4.4 In summary

- Charge accumulations occur if there is a dielectric loss in the field \((\mathbf{J} \neq 0)\) and the medium is not homogeneous in the direction of the leakage current.

- The charge is dominantly accumulated at the interface of the media.

- If there is a normal component of the field at one side of an interface, there is a charge accumulation at that place.

- The time constant of the charge accumulation and the transient of the fields can in practical cases be in the order of hours.

5.5 Application of Field Theory

5.5.1 Explaining the test results

In this subsection, efforts are made to interpret the test results presented in chapter 4 using the mechanisms and the field theory deduced in the preceding sections.

It has to be indicated that the loss in a gas, e.g. \(SF_6\), is not caused by a conductive current, but due to charge transport in the gas. The loss in the gases depends strongly on the applied voltage: at a low voltage gases cause little dielectric loss, but if the voltage is so high that ionization takes place at the electrode surface the losses increase sharply. The charges produced at the ionization site will be transported along the field lines to the spacer surface. The charge production also depends on how quickly the produced charges can flow away from the ionization site, due to the shielding effect of the produced charges around this site. Therefore, the loss is not constant in time. This may result in small variations of charge density, or redistributions of surface charge in a steady state. However, if the accumulation in a certain period is to be studied, an average \(\sigma_0\) can still be employed to describe the loss.
As has been seen in §5.3, ionization at the electrode surface is the dominant origin of charge under the test voltage. This can be described as:

\[ \sigma_o > \sigma_d \]  

(5.23)

Substituting (5.23) into (5.19) shows that a positive normal field \( E_{n,o} \) (toward the gas, see Fig. 5.5), results in a negative accumulation. This agrees with the test results presented in §4 and in other papers [51,52,54,59,76]. The scatter could have been caused by undetected variations of the parameters \( \epsilon \) and \( \sigma \) in the vicinity of the interface. This can be described by (5.13) and (5.14). A treatment of the spacer surface removes a thin layer and changes the surface geometry. It may improve the distributions or change the values of \( \epsilon \) and \( \sigma \). The scatter of the charge accumulation is reduced (§4.6).

Protrusions at the electrode surface increase the charge accumulation (§4.5). It is interesting to note that, though the charges of one polarity are supplied by a protrusion, the accumulation over a whole height, at the circumferential side where a protrusion is placed, is enhanced for both polarities (Fig. 4.21). This can be explained as follows. At a positive voltage, the protrusions at the cathode supply negative charges to the surface close to the anode; that will distort the field there, and increases the field at the anode. This process increases the leakage current \( J \) at the protrusion side and the charge density is increased (see (5.13)).

Charges are also released at the electrodes in an AC field (§4.7). The charge transport in the gas is influenced by the mass of the charges. As negative charges are mainly electrons, more negative charges are expected to be accumulated due to the much less mass of them. As a result of the \textit{dynamic} equilibrium of the production and the transportation of the charges of both polarities, the accumulation appears to be slightly negative.

At atmospheric conditions, the inception field strength for ionization at an electrode surface is lower than in \( SF_6 \) (~3kV/mm at the standard reference conditions\(^4\), compared with ~8.9kV/mm·100kPa

\(^4T = 20^\circ, P = 100kPa \) and \( H = 11g/m^2 \) [98].
in $SF_6$), therefore the condition of (5.23) is satisfied at a lower voltage. The test results in atmospheric conditions (§4.8) is well described by (5.13). This can be demonstrated by comparing the test results (Fig. 4.32) with the normal field along the GIS spacer (Fig. 4.33): the distribution corresponds obviously to the normal field at the spacer surface. Because of the lower inception voltage in air, it is expected that the charge accumulation is stronger in air than in $SF_6$ at the same stress.

5.5.2 Special cases

In the following, the expressions for some special cases are derived from the field study performed in the preceding section. Some of these cases are, in fact, the conditions at which the three accumulation models in §5.2 were established. By the derivations in this subsection, it can be seen clearly which aspects were emphasized and which were ignored in each of these models. The discussions also show the applicability of (5.13), (5.14), (5.18) and (5.19) in practice.

1. CONSTANT PERMITTIVITY OR CONDUCTIVITY

Under a DC stress, the permittivity of a dielectric is assumed to be constant in certain field and temperature ranges. Then:

$$\nabla \epsilon_d = 0$$

At this condition, (5.14) become the same as (5.1):

$$\rho = -\frac{\epsilon_d}{\sigma_d} \mathbf{E}_d \cdot \nabla \sigma_d$$

which describes the bulk distribution in a spacer. If the conductivity of a material is strongly dependent on the field, this expression should be employed to study the space charge accumulation.

On the other hand, if the dielectric is ideal, it shows little variation in $\sigma$, e.g. at low applied voltage. However the permittivity may change due to the impurities or inclusions in the dielectric. Then:
\[ \nabla \sigma \approx 0 \]
(5.14) becomes
\[ \rho = \mathbf{E} \cdot \nabla \varepsilon \]  
(5.24)

In practice, some special constructions are produced with different permittivities such as \( \varepsilon \) grading in HV apparatus [4]. At stable conditions at low stress, the space charge may follow the distribution described by (5.24).

2. STRONG SURFACE LEAKAGE

Sometimes strong leakage occurs at the interface of two materials, though both materials possess little conductivity, for instance, at the surfaces of outdoor insulators in salt fog or heavy humidity. In this case, the other components of \( \mathbf{J} \) can be neglected. Provided that the leakage is in a thin layer at the gas side and \( \varepsilon_o = \text{const.} \), (5.13) can be rewritten as
\[ \sigma_S = j_z \frac{\partial}{\partial z} \left( \frac{\varepsilon_o}{\sigma_s} \right) = -j_z \frac{\varepsilon_o}{\sigma_s^2} \frac{\partial \sigma_s}{\partial z} \]

or
\[ \sigma_S = -\varepsilon_o E_{t,o} \frac{1}{\sigma_o} \frac{\partial \sigma_s}{\partial z} \]

with \( j_z \) the surface current density and \( \sigma_s \) the surface conductivity. If \( \sigma_s \) satisfies (5.3),
\[ \sigma_S = -\varepsilon_o E_{t,o} \frac{\partial |E_{t,o}|}{\partial z} \]  
(5.25)

This expresses the surface charge density if surface leakage dominates. The \( E_t \) model in §5.2 is, in fact, based on these assumptions, therefore (5.25) represents the charge density in that model. This mechanism is not significant for the accumulation in GIS.
5.5 APPLICATION OF FIELD THEORY

3. LITTLE LOSS IN SPACER BULK

As indicated in the preceding subsection, the dielectric loss in a gas is strongly dependent on the applied voltage. In fact the loss depends only on how quickly the electrodes can supply charges to the gas, instead of how quickly the charges can be conducted (transported) in the gas. If there is a strong gas ionization in the field, mass charges can be supplied to the gas and, therefore, be driven by the field. The corresponding conductivity $\sigma_o$ is then large. Beyond a certain stress,

$$\sigma_o \gg \sigma_d$$

From (5.19),

$$\sigma_S = -\varepsilon_d E_{n,d}$$

(5.26)

This means that the normal field at the gas side is zero: $E_{n,o} = 0$ (see the first equation in (5.16)). Then the process described in §5.2.2 takes place, and (5.2) applies. Under these conditions the $E_n$ model was developed.

4. LITTLE LOSS IN GAS

Contrary to the above case, if the applied voltage is lower than the inception voltage of gas ionization at any protrusion at the electrodes, or if the electrode surfaces were so smooth that there would be little gas ionization at an operating voltage, the conductivity can be considered to be zero:

$$\sigma_o \approx 0$$

From (5.18),

$$\sigma_S = \varepsilon_o E_{n,o}$$

(5.27)

i.e. there is no normal field at the spacer side: $E_{n,d} = 0$. For an isotropic material $\mathbf{J}$ has the same direction as $\mathbf{E}$, therefore $j_{n,d} = 0$. 


In the vicinity of the interface, there is only a current tangential to the surface to continue the leakage current coming from the spacer bulk. All the field lines from the gas will end at the surface or change their directions along the spacer surface. No field line can penetrate into the spacer bulk in this particular DC case.

If there is little ionization in the gas, say under low stress, and the conductivity of the spacer is higher than that of the gas, a charge accumulation described by (5.27) can take place. However, the amplitude will be too low to be detected by a capacitive probe.

5.6 Decay Mechanisms

5.6.1 Decay mechanisms

As soon as the stress is removed, charge begins to move away. There are three mechanisms possible for charge to decay: bulk conduction, surface conduction and charge neutralization at the surface by natural ionization. Most studies find a relatively fast decay just after the voltage has been removed (some tens of minutes). Thereafter, the decay rate slows down gradually [90,92,93]. Sometimes, the fast decay was not observed [89].

Natural ionization is most responsible for the charge decay in gases [65,89]. During the stage of slow decay, the decay current is quite comparable to that predicted by the natural ionization rate in that gas [89]. This suggests that the charge decay depends on the ionization condition in the gas: the decay rate increases with increasing ionization rate and ion density in the gas. \( \gamma \) irradiation placed in the gas can increase the gas ionization, therefore the decay time can be reduced greatly [65]. The natural ionization rate is different in different gases\(^5\). It is \(~100, ~20\) and \(~23\) ion pair/m\(^3\)-s-Pa in \(SF_6\), air and \(N_2\) respectively [12]. Experiments confirm that the decay rate

\(^5\)The natural ionization rate for a gas is dependent on the average energy expended in creating an ion pair, which is determined in [89] in terms of absorbed dose by a gas (\(pW/kg\)). This is proportional to the density of a gas.
in $SF_6$ is $4 \sim 5$ times higher than that in air and $N_2$ in proportion to the ratios of their natural ionization rates (or, the ratios of their relative densities [65,89,93]).

However, if the surface resistivity is low, say in the range of $\leq 10^{13} \Omega$, the surface conduction will play an important role [65]. In this case, the charge accumulation is much smoother and the charge decays more rapidly after stressing the object.

The mechanism of natural ionization gives an upper limit to the decay time at highly insulating surfaces. This can easily be several days.

As is known, the charge mobilities at the surface, bulk and gas are strongly influenced by the field. Just after the voltage has been removed, and the charge-introduced field is still high, the decay current of each mechanism will also be larger. This may be the cause of the fast decay at the beginning.

### 5.6.2 Discussion

Fig. 4.34 shows the fast decay period in $SF_6$. The decay rate slowed down gradually. After 4 days decay, there was still $\sim 7\%$ charge on the spacer. This result shows that surface conduction is not important in the decay at the surface of epoxy resin in $SF_6$.

Because the negative particles produced by natural ionization are in the form of ions, not electrons, their mobility is the same as the positive particles. Hence the probabilities for the particles in both polarities to arrive at the surface are the same, and the rate to neutralize the charge on the surface is identical for both polarities. Therefore, the decay rates of both negative and positive charges are identical, as shown in Fig. 4.34.

The charge accumulated in air (35% humidity) is quite stable after the voltage has been removed (Fig. 4.37), which is attributable to the low rate of the natural ionization in air. Almost no decay can be detected in 24 hours, except at $r = 60mm$, where the surface leakage distance is short. There might have been a fast decay just after
the stress, as the first measurement could only made after 10 minutes. However, at standard reference conditions when the humidity is increased to 60% (11g/m³), the charge decay is much faster. The charge density is halved in about 1 hour. This is due to the increase in the charge mobility at the surface (surface conduction) by increased humidity [36].
Chapter 6
Effects of Accumulation

Charge accumulation affects the performance of GIS by changing the field distribution and the flashover dynamics. In this chapter, the variation of the field is studied by field calculations both with and without surface charges. To simplify the calculations, the similarity between the field under DC stress and the electrostatic field in an isotropic system is elucidated beforehand. The spacer design criteria are discussed penultimately prior to the summary of the conclusions.

6.1 Similarity between DC and Electrostatic Fields

1.) An explanation of the terms defining the field in different cases is given here.

The electrostatic field describes the field when there is no moving charge in the system (the conductivity of the dielectrics is zero). If the charges appear at the conductors only, the field is called a Laplacian field; if there are charges in the space between the conductors, the field
is called a *Poisson field*. The electrostatic field is determined by the configuration of the dielectric permittivity $\epsilon$. Correspondingly, this field is also called *capacitive field* in the literature. An electrostatic field occurs under AC stress and under fast varying unipolar stress, e.g. impulse voltage or the switching on of DC voltage.

The term *DC field* is employed to indicate the field in the steady state under a DC voltage. Due to the dielectric loss at the *DC case*, the field is determined by the configuration of the conductivity $\sigma$ of the dielectric; and is also called a *resistive field* in the literature.

The DC field is achieved after a DC voltage has been applied for a certain period. This is illustrated in Fig. 6.1. The *initial field*,

![Figure 6.1: Field transitions under a DC voltage $U$: $t_1 \rightarrow U$ is switched on and the field is capacitive, $t_1 \sim t_2 \rightarrow$ the field varies from capacitive to resistive (in several hours), $t_2 \rightarrow$ the field is a resistive one, $t_3 \rightarrow U$ is switched off and the charge-induced field is left and decays slowly (in some cases several days)](image)

at the moment the voltage is put on $t_1$, is determined by $\epsilon$ and is therefore a capacitive field. Thereafter the field gradually changes into a resistive one, until a steady state occurs at $t_2$. At that time, the field follows the configuration of $\sigma$ and the DC case occurs. The surface charge accumulation is, in fact, the inevitable result of the transition ($t_1 \sim t_2$).

Though the DC field is determined by the configuration of $\sigma$, it can also be calculated with the configuration of $\epsilon$, taking the accumulated
charged into account, as will be shown below. From this point of view, the DC field is the combination of the initial capacitive field and the charge-induced field.

2.) The electric field of a system differs at the electrostatic condition and in the DC case due to the different configurations of \( \epsilon \) and \( \sigma \). If the two configurations were the same, i.e. (see (5.13))

\[
\nabla \cdot \frac{\epsilon}{\sigma} = 0
\]

the two solutions would be the same as well. In the following, the similarity between the electrostatic field and the DC field when the configurations of \( \epsilon \) and \( \sigma \) are different is studied with respect to the inevitable charges at the sites where \( \frac{\epsilon}{\sigma} \) changes.

As is known, in an isotropic and homogeneous medium without space charge, both electrostatic and DC fields satisfy the Laplacian equation:

\[
\nabla^2 \Phi = 0 \tag{6.1}
\]

where \( \Phi \) is the potential in the medium. From the mathematical properties of the Laplacian equation, it is known that the solution of it is uniquely specified by the boundary conditions [100,104]. The similarity between the two fields can thus be studied with the boundary conditions at the interfaces, provided that the values of \( \phi \) at the conductors have been given.

For the electrostatic field, the boundary conditions are, taking a spacer-gas interface as an example (see Fig. 6.2):

\[
\left\{ \begin{array}{l}
E_{t,o} = E_{t,d} \\
\epsilon_o E_{n,o} - \epsilon_d E_{n,d} = \sigma_S
\end{array} \right. \tag{6.2}
\]

where \( E_{t,o} \), \( E_{t,d} \) are the tangential fields at both side of the interface; \( E_{n,o} \), \( E_{n,d} \) are the normal fields.

For the DC field, the boundary conditions are:
\[ \begin{align*}
\sigma_o E_{n,o} &= \sigma_d E_{n,d} \\
E_{t,o} &= E_{t,d}
\end{align*} \]

(6.3)

where \( \sigma_o \) and \( \sigma_d \) are the conductivities of the spacer and the gas. The first condition can be explained as: the tangential fields at both sides are identical; while the second condition shows the current continuity at the interface. There may be some charges at the interface, but the DC field is exclusively determined by the configuration of \( \sigma \), therefore the conditions in (6.3) are sufficient for the solution of the field. Of course, the second condition in (6.2) is also satisfied in the DC field. The magnitude of \( \sigma_S \) depends on the difference between the configurations of \( \epsilon \) and \( \sigma \).

The second condition in (6.3) is satisfied automatically if the Laplacian equation (6.1) is solved with the conditions of (6.2), and \( \sigma_S \) in (6.2) satisfies (5.18) (and (5.19)):

\[ \sigma_S = E_{n,o} \left( \frac{\epsilon_o - \epsilon_d \sigma_o}{\sigma_d} \right) \]

Therefore the field distributions must be identical to each other in the two cases described by (6.2) and (6.3).
6.2 EFFECT ON NORMAL FIELDS

More formally, if each material in a system is isotropic and homogeneous, the solution of the electrostatic field incorporating the saturated surface charges at the interfaces is equal to the solution of the conductive DC field. The DC field can thus be obtained by calculating an electrostatic field where $\sigma_S$ satisfies (5.18) (or (5.19)).

3.) In practice, the DC fields can hardly be calculated by the conditions of (6.3) because the conductivity of the gas $\sigma_n$ is not well known, and is strongly dependent on the field as well as any micro distortion to it, especially at the electrode surfaces (§5.3.3 and §5.5.1).

However, the surface charges at each voltage have been determined in §4, therefore the fields can be calculated here with the electrostatic boundary conditions (6.2) with the measured charges. The error by this simulation depends on the precision of the charge measurement, and the decay time when the measurement is performed.

In this study the field calculations were limited to axisymmetric systems because of the limitation of the available computer program. However, the measured charge distributions were not always axisymmetric so that difference between the calculated field and the actual one occurred.

6.2 Effect on Normal Fields

Before the field calculations are performed, some properties of the variations of the normal field are elucidated in this section. As concluded in the preceding chapter, charge accumulation is essentially correlated to the normal component of the field at an interface. After DC voltage has been applied, charges begin to reach the interface from one side. They will counteract the initial normal field at that side and enhance the normal field at the other side. For instance, charges come out of the gas at an epoxy-\(SF_6\) interface, therefore the accumulation reduces the normal field $E_{n,o}$ at this side and enhance $E_{n,d}$ at the other gradually until the steady state is reached. In the following it is shown that the accumulation can never reverse the ini-
tial normal field into another direction, it can only reduce the latter, at the utmost to zero.

The interface shown in Fig. 6.2 is taken as an example. Suppose positive charges were accumulated at this interface (then charges would come out of the spacer bulk). The accumulation would gradually enhance \( E_{n,o} \) and reduce \( E_{n,d} \) until the steady state is reached. Because \( E_{n,o} \) were enhanced and, therefore, would never be reversed, \( j_{n,o} \) would remain identical in its initial direction (Ohm's law (5.10), \( \mathbf{E} \) and \( \mathbf{J} \) are in the same direction in an isotropic medium). This implies that \( j_{n,d} \), on the other side, should also remain in the initial direction to satisfy the continuity equation ((5.15)) at the interface, and \( E_{n,d} \) would not be reversed because of the restraints of the Ohm's law as well. As a result, each of the normal fields remains in the same direction as the initial one. None of them can be reversed by charge accumulation.

However, at extreme conditions, the accumulation can make the normal field equal to zero. This has been shown in §5.5.2 as case 3 and case 4.

To sum up, accumulated charges counteract the initial normal field \( E_n \) at the side from which the charges have come. The resulting normal component of the DC field \( E_{n,o} \) is in the same direction as the initial one, and

\[
0 \leq |E_{n,o}| \leq |E_n|
\]  

(6.4)

With this conclusion in mind, the field calculations are, therefore, mainly utilized to study the variations of the tangential field.

**CHARGE-INDUCED FIELD**

After the applied voltage is removed (beyond \( t_3 \) in Fig. 6.1), the charge-induced field \( E_{\sigma_S} \) is left. The strength of this field is studied in the following using a Maxwell's capacitor, as shown in Fig. 6.3. At the condition that the surface charge is homogeneous over the interface (assumed to be infinite), \( E_{\sigma_S} \) has a normal component only. Then
6.2 EFFECT ON NORMAL FIELDS

![Diagram of Maxwell's capacitor filled by dielectric and gas]

**Figure 6.3:** Maxwell’s capacitor filled by dielectric and gas

\[ a E_{\sigma S,o} = -b E_{\sigma S,d} \]

where \( E_{\sigma S,o} \) is the charge-induced field in the gas and \( E_{\sigma S,d} \) is that in the dielectric. From Gauss theorem,

\[ \varepsilon_o E_{\sigma S,o} - \varepsilon_d E_{\sigma S,d} = \sigma_S \]

Elimination of \( E_{\sigma S,d} \) between the above two equations gives

\[ E_{\sigma S,o} = \frac{\sigma_S}{\varepsilon_o \left(1 + \frac{a}{b} \varepsilon_r \right)} \] \hspace{1cm} (6.5)

The charge-induced field is discussed in the following in three cases.

1. \( a = b \)

   This is the same case as both \( a \) and \( b \) are supposed to approach infinite. At this condition,

   \[ E_{\sigma S,o} = E_{\sigma S,d} = \frac{\sigma_S}{\varepsilon_o \left(1 + \varepsilon_r \right)} \]

   Substitute the values of \( \varepsilon_o \) and \( \varepsilon_r \) of epoxy (in the range of 4 \sim 5) into (6.5), it can be found that surface charge of 1\( \mu \)C/m\(^2\) induces a field of 0.02kV/mm in the vicinity of the interface. For \( SF_6 \) of 100kPa, surface charge will cause breakdown without any external field if it reaches the density of \(~ 400\mu \)C/m\(^2\).

2. \( a \ll b \)

   This is the situation when there is a gas layer between a spacer and the electrode by a poor contact (triple junction problem),
\[ E_{\sigma,s,0} \approx \frac{\sigma_s}{\varepsilon_o} \]

In this case surface charge of \( 9\mu C/m^2 \) induces a field of \( 1kV/mm \) and has a substantial effect on the field in the case of superposition with AC or DC. For \( SF_6 \) of \( 100kPa \), breakdown might occur if the charge density reaches \( \sim 80\mu C/m^2 \).

3. \( a \gg b \)

This case occurs if an electrode is coated by a dielectric layer, when

\[ E_{\sigma,s,0} \approx \frac{\sigma_s}{\frac{a}{b}\varepsilon_r\varepsilon_o} \]

The charge-induced field is \( \frac{a}{b}\varepsilon_r \) smaller than that in the above case and becomes insignificant.

A surface charge at an interface (of e.g. a spacer, see Fig. 6.4) gives different effects depending on where it is located. If it is near

\[ \text{Figure 6.4: Spacer-gas interface between parallel electrodes} \]

one of the electrodes and the relevant field mainly passes through the gas the effect of the charge is small (see field line c); if the field line passes a small air-gap the effect is large (field line d). In the latter case the field inducing effect of a surface charge of \( 9\mu C/m^2 \) is in the order of \( 1kV/mm \) again.
6.3 EFFECT ON TANGENTIAL FIELDS

6.3 Effect on Tangential Fields

Depending on the polarity and the density of the accumulation, different effects on the field can result. The effect of the charge accumulation by the arrangements with inserts and by those with toroids are different. This is shown by the following field calculations.

6.3.1 With inserts

The spacer with inserts (inserts $B$), and the initial field distribution along its surface are shown in Fig. 2.10.b and Fig. 3.6 respectively. The charge accumulation under $+150kV$ is presented in Fig. 4.19. It is shown that positive charges were accumulated close to the cathode and negative charges were accumulated close to the anode. The accumulation will thus increase the tangential field close to both electrodes, and decrease it midway along the surface (the integration over the tangential field is constant).

The calculation was performed by introducing the mean charge density (Fig. 4.19.b) at the spacer surface. Table 6.1 gives the comparison of the tangential fields with and without accumulated charges close to the triple junctions and midway at the spacer surface. It is found that the tangential field increases by less than 2.0% close to the electrodes, whereas it decreases by less than 1.0% midway at the surface. According to the initial distribution in Fig. 3.6, this influ-

<table>
<thead>
<tr>
<th>Position</th>
<th>At triple junctions</th>
<th>Midway at the surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{t,o}, kV/m$</td>
<td>1185</td>
<td>1757</td>
</tr>
<tr>
<td>$E_t, kV/m$</td>
<td>1171</td>
<td>1763</td>
</tr>
<tr>
<td>Variation, %</td>
<td>1.2</td>
<td>0.3</td>
</tr>
</tbody>
</table>
ence would reduce the inhomogeneity of the field, but the effect is not significant.

Under a higher stress, stronger gas ionization takes place, and the corresponding conductivity $\sigma_0$ of the gas increases. More charges are expected and more improvement of the tangential field can result. In an extreme case (case 3 in §5.5.2), the normal field is zero and the tangential field becomes completely homogeneous along the spacer surface (see Fig. 5.2.c).

### 6.3.2 With toroids

The toroid arrangement (Fig. 3.3) was used with distance $s$ between the toroids and the plane electrodes: $s = 0.0m$. From §3.2.2 it is known that at this distance an identical tangential field can be created as that with inserts $B$ (used in the preceding subsection), while the normal fields differ more than 100%. The comparison of the fields can be found in Fig. 3.6. Fig. 4.17 shows the charge accumulation with the toroid arrangement under $+150kV$. According to the mean charge densities in this figure, positive charges were accumulated close to the anode and negative charges were accumulated close to the cathode. This distribution will decrease the tangential field close to both electrodes, and therefore increase it midway at the spacer, which increases the inhomogeneity of the tangential field.

The influence of the charge accumulation on the field is shown in Fig. 6.5, where the solid lines indicate the initial field, the dotted lines are due to the DC field at the steady state. Obviously, the equipotential lines are driven towards the middle of the surface and the field is enhanced there. The distribution of the tangential field, as compared to the initial one, is shown in Fig. 6.6. It can be found that the tangential field decreases $\sim 4$ times (from 1.16 to 0.32$kV/mm$) close to the electrodes, whereas it increases $\sim 10.0\%$ midway at the surface. The field distribution becomes thus more inhomogeneous.

In fact, the actual field is much worse due to the large scatter of charge accumulation (see Fig. 4.17.a). The scatter of the charge distribution is more clearly presented in Fig. 6.7 where the axial distri-
6.3 EFFECT ON TANGENTIAL FIELDS

--- No charge  --- With charge

**Figure 6.5:** Equipotential lines with and without surface charges in the case of toroids at 150kV

Distributions at different circumferential positions are compared. Though the *macro* field was designed the same, the accumulated charges can be positive along a height at one side \((x = 215\, mm)\), but negative at another \((x = 50\, mm)\). This is due to undetected micro structures at the surfaces as indicated in §4.2 and discussed in §5.5.1. Suppose such a undetected factor would dominate a charge accumulation, the charge distribution all over the surface should then be the same as that at \(x = 50\, mm\), or at \(x = 160\, mm\). The former \((x = 50\, mm)\) could result in \(\sim 70\%\) increase of the maximal tangential field close to one
**Figure 6.6:** Tangential fields with surface charges compared with the initial field (from Fig. 3.6) in the case of toroids at 150kV: calculated with the mean charge density and the densities at circumferential positions $x = 50$ and $x = 160$mm

**Figure 6.7:** Charge densities along the spacer surface at different circumferential positions when using toroids at 150kV (see Fig. 4.17.a)
of the electrode; whereas the latter \((x = 160\text{mm})\) would enhance the tangential field by \(~50\%\) (see Fig. 6.6). The real case is, of course, still more complicated.

The influence on flashover voltages is reviewed in Appendix C to correlate the flashover voltages with the field variations.

### 6.4 Spacer Design

#### 6.4.1 Spacer design criteria

Spacers are widely used in GIS to support the conductors. In coaxial GIS, they are shaped as a disc, a cone, a post, a tri-post etc. The basic geometries of these spacers are shown in Fig. 6.8. Among these,

\[a\] a disc, \[b\] a cone, \[c\] a post, \[d\] a tri-post

![Diagram of spacers](image)

**Figure 6.8:** Basic spacer designs in coaxial GIS: \(a\). disc, \(b\). cone, \(c\). post, \(d\). tri-post

the disc-shaped spacer gives the smallest distortion to the field. In an optimum design it performs better than other types of spacers.

A cone-shaped spacer increases the surface distance and therefore gives a better performance against contaminations. It also prevents damage to the spacer surface by an arc.
The post spacer represents the simplest support of the conductor with the advantages of a low cost and a small surface area to collect contamination [6,9].

Each of the spacers has to be well designed so that a satisfactory performance of GIS can be achieved. This requires a field in the presence of spacers to be unfavourable to both initiation and propagation of a breakdown. The necessary condition is a local field strength not exceeding the gas ionization criterion, say $8.9\, kV/mm \cdot 100\, kPa$ for $SF_6$. The most critical locations where a higher field might occur are the triple junctions (§1.2.2). This has to be overcome by proper shaping of the spacers and of the conductors, or by employing spacers with a lower relative permittivity, to reduce the local field strength; the contact should also be improved by casting the spacers directly on the conductors or metallizing the spacer surfaces to be in contact with the conductors [6]. The geometric design to optimize the field distribution is the main subject of this chapter.

At a spacer surface, the voltage distribution is described by the tangential component of the field which is responsible for channel propagation along the surface. As the spacer surface (the leakage distance) is designed longer, the tangential field is smaller, and the probability of a flashover is smaller. To reduce the peak fields along the surface, the tangential field should be designed as homogeneously as possible.

However, the decrease of the field, both at a triple junction and along a spacer surface, is obtained at the expense of an increased field inside the spacer bulk or in the gas space. For instance, if inserts are employed, the stress in the spacer bulk will be increased, though the field at the triple junction is reduced; if toroids are employed, the stress in the gas space is increased. In practice, a compromise between the field decrease along a spacer surface and the resultant field increase in the spacer bulk or in the gas space should be made. Usually, the field is preferably to be designed lower at the spacer surface than inside the spacer bulk or in the gas space. This is due to the fact that the surface performance would more or less be deteriorated after a long-term service due to contaminations, and that a
6.4 *SPACER DESIGN*

surface can be damaged permanently once an arc (breakdown) has occurred on it. Hence proper spacer design should make a possible breakdown channel take place in the gas space, separated from the spacer surface [30].

In summary, the following criteria must be followed by a spacer design:

- Low field at triple junctions;
- A sufficient leakage distance;
- Small field distortion.

### 6.4.2 Optimum design without charge

Before the spacer design is studied with respect to the charge accumulation in the next subsection, the optimization of the Laplacian field is briefly reviewed on the basis of early literature in this subsection.

As is known, the distribution of the field $E_r$ in a coaxial system without a spacer at radius $r$ can be described by (see Fig. 6.9)

$$E_r = \frac{U}{r \ln \frac{r_x}{r_c}}$$  \hspace{1cm} (6.6)

where $U$ is the applied voltage; and $r_x < r < r_e$ according to Fig. 6.9. The field is the strongest at the surface of the inner conductor and decreases with increasing radius $r$.

This field distribution is affected by introducing a spacer. Fig. 6.9 gives a diagram of an interface between spacer and gas. In [43], the dependence of the electrostatic field on the contact angle $\theta$ was calculated. The equipotential lines at the interface are pushed outwards from the conductor towards the enclosure if $\theta$ is less than 90°. The smaller the angle, the more the equipotential lines are affected. In the range of $\sim 55^\circ < \theta < \sim 70^\circ$ (depending on the permittivity of the spacer material), a quasi-homogeneous field is achieved. If, on the other hand, $\theta$ is larger than 90°, the equipotential lines are driven
towards the centre and the field is made more inhomogeneous. This should, of course, not occur in an actual system.

A disc-shaped spacer possesses two interfaces with the gas. For optimum design, the interfaces near the conductor can be designed acute-angled ($\theta < 90^\circ$) until a quasi-homogeneous field is present along the surface. Inserts can then be utilized to reduce the field at both electrodes. The interface can gradually be modified at the inner conductor to further reduce the field there, as shown by the dashed lines in Fig. 6.10. In this way, the use of inserts or toroids can be obviated.

**Figure 6.9:** Interface between spacer and gas with contact angle $\theta$

**Figure 6.10:** Illustration of optimum design of a disc-shaped spacer: dashed lines indicate the modification of the profile to further reduce the field at the inner triple junctions
However, such a spacer represents an optimum design under clean conditions only. It is not valid for the case of contaminations, which can often occur in GIS. For this reason, the authors of [43] designed a spacer which is partly disc-shaped and partly cone-shaped, that increases the leakage distance to 1.75 times that of the gas gap, and makes the field at the inner triple junctions comparable to that of an optimum disc-shaped spacer. With a metal insert at the outer end, the field is also improved there. This spacer, together with its field distribution, is shown in Fig. 6.11. It combines the advantages of

![Diagram](image)

**Figure 6.11:** Composite shaped (disc/cone) spacer with the field distribution, as developed in [43]

the quasi-homogeneous field distribution of the optimum disc-shaped spacer with that of the long leakage distance of a cone-shaped spacer. The performance was almost as good as that of the system without spacer [43].

The pushing effect of an acute-angled spacer is also valid for cylindrical spacers between plane electrodes. This was studied in [44]. By calculations of the Laplacian field, it was found that the equipotential lines at the spacer surface are pushed away from the electrodes, with decreasing contact angle of the spacer $\theta$ (the angle inside the spacer between the interface and the electrode surface). However though the
tangential field close to the electrode is decreased, the normal field increases. Independent of the material permittivity, a contact angle of $\theta = 45^\circ$ results in the smallest total field at the triple junctions. As both ends of the spacer are so designed, the spacer surface midway can be arc-profiled, as shown in Fig. 6.12.

![Diagram of cylindrical spacer](image)

**Figure 6.12:** Design of cylindrical spacer as shown in [44]

In AC GIS the field is determined by the permittivities which is described by an electrostatic field without space charge. The conclusions introduced in this section have therefore to be applied to AC GIS.

### 6.4.3 Spacer design for DC GIS

Spacers of optimized design introduced in the preceding subsection cannot perform well in DC GIS, due to the fact that the field in DC GIS depends on the configuration of the conductivities, instead of the permittivities, of the materials. Such a field is, however, difficult to calculate because of the uncertainty of the conductive behaviour of gases in GIS. Fortunately, it was proved in §6.1 that this DC field is actually the same as the superimposed field of the initial one and the one induced by the surface charges. This charge-induced field has to be taken into account in the design of DC spacers.
The shielding effect of an insert or a toroid near a triple junction can be reduced or enhanced by charge accumulation. If heterocharges are accumulated close to an electrode, the shielding effect is reduced; otherwise it is enhanced. In §5 it has been seen that if the normal component of the field $E_n$ is initially positive (out of the surface), negative charges will be accumulated, and vice versa. Heterocharges can be accumulated close to an electrode if the local polarity of $E_n$ is identical to the polarity of the electrode: positive near the anode and negative near the cathode. An arrangement with inserts produces such a field distribution, therefore the shielding effect will be reduced. On the other hand, $E_n$ with another direction (polarity) close to the electrode, e.g. with toroids, will cause homocharges to be accumulated and the shielding effect is enhanced.

This influence can be described by introducing a field angle $\vartheta$ (instead of the contact angle $\theta$) of the spacer. The field angle is defined as the angle close to the electrode between the spacer surface and the equipotential lines as shown in Fig. 6.13. Then heterocharges are accumulated if $\vartheta < 90^\circ$; and homocharges are accumulated if $\vartheta > 90^\circ$. Hence the above conclusions can be expressed as: if $\vartheta < 90^\circ$, the shielding effect is counteracted by the charge accumulation; and as $\vartheta > 90^\circ$, this effect is enhanced. This conclusion is valid for both anode and cathode.

![Figure 6.13: Field angle $\vartheta$ referring to an equipotential line](image-url)
APPLICATION OF INSERTS

Application of inserts cause \( \vartheta \) to be less than 90°, the shielding effect is therefore reduced. This means that the tangential component of the field \( E_{t,o} \) is increased close to the electrodes, though the normal one \( E_{n,o} \) is reduced ((6.4)) by the accumulated charges. This influence does not have to be harmful because the charge accumulation of inserts does not deteriorate the field distribution (see §6.3.1). That is why the flashover voltage of the spacer does not decrease if the stress polarity is the same as that causing the charges [52].

Charge accumulation reduces the field midway along the surface, while the shielding effect near the electrodes can never be counteracted completely by the accumulated charges. Just after a DC stress is turned on, when the field is still Laplacian, \( E_{t,o} = E_{t} \), the shielding effect makes \( E_{t,o} \) near the electrodes smaller than midway along the surface (see Fig. 3.8 as an example). With the accumulation of charges, \( E_{t,o} \) increases while \( E_{n,o} \) decreases. In an extreme case, \( E_{n,o} \) might approach zero and \( E_{t,o} \) becomes constant along the surface [76] (§5.2.2). This constant field is, in fact, the field without any insert or toroid, or the average field along the surface: \( \overline{E_{t}} \). In other case than this extreme case, \( E_{n,o} \) is smaller than \( E_{n} \) and larger than zero (see §6.2), therefore

\[
|E_{t,o}| \leq |E_{t}|
\]

close to the electrodes, while

\[
|E_{t,o}| \geq |E_{t}|
\]

midway along the spacer surface. This means that \( E_{n,o} \) near the electrodes is never stronger than that midway along the surface and the shielding effect can therefore never be counteracted into zero. Because the field midway is decreased while there is no field intensification near the electrodes the field distribution along the surface seems to be improved to some degree by inserts.

In the above, the scatter of the parameters of the spacer material, both at the surface and in the bulk, has not been taken into account,
which may give rise to unexpected distortions of the field. In §4.6, it has been seen that the surface conditions of the spacers are responsible for the scatter of the accumulated charges. A treatment, e.g. by sand blasting, can largely reduce the scatter. In [52] this improvement was also observed when the applied stress was 3.3 times that in the present work (§4.6).

Care has to be taken during such a treatment because a still rougher surface may cause distortions to the field by the micro variation of the surface profile. In [45], surfaces of small samples (φ10×h10) of epoxy resin were rubbed with emery cloths of grits of #600 and #1000. It was found that the flashover voltage with these samples in SF₆ decreased with increasing surface roughness (the difference in flashover voltage between the samples with the original surface and those with the roughest surface is \(~2.7\%/100\text{kPa}\)). According to the measurements in [78] using other materials, the produced surface roughnesses by these two grits might only be a few μm, though with quite large scatter: gross grooves are produced on the surface by this rubbing process, as found in §3.5. How the surface roughness influences the flashover voltage after a long-term DC stress has not been studied.

**DESIGN WITH TOROIDS**

If the field angle \( \vartheta \) is greater than 90°, homocharges are accumulated close to the triple junctions, that reduces the field close to the electrode and make the field midway along the surface stronger. This has been demonstrated by applying toroids in the preceding sections. The variation of the tangential field can be seen in Fig. 6.6. In other words, some of the shielding effect will be achieved by the accumulated charges.

However, at the inception of a breakdown, homocharges close to an electrode may shorten the spacing and the breakdown channel may easier grow out. Moreover, toroids themselves provide more surface area of electrode. They increase the field strength at the electrode surface and therefore the amount of the accumulated charges. Heavier
homocharges will be accumulated with toroids than with inserts, even if the normal field is the same. The actual field distribution would be quite deformed due to the large scatter of the surface charges (§6.3.2). Hence such a configuration should not be designed and employed in DC GIS.

**SUPPRESSING CHARGE ACCUMULATION**

Another strategy for the design of DC spacers is to reduce the charge accumulation to an amount as small as possible. Then DC GIS can operate at a field approximating a Laplacian one. This simplifies spacer design which can be based on calculations of the Laplacian field only.

From the expression of the density of surface charge \( \sigma_S \) (5.18):

\[
\sigma_S = E_{n,o} \left( \epsilon_o - \epsilon \frac{\sigma_o}{\sigma_d} \right)
\]

it can be seen that suppressing charge accumulation requires

\[
E_{n,o} \to 0
\] (6.7)

or

\[
\left( \frac{\epsilon_o}{\sigma_o} - \frac{\epsilon}{\sigma_d} \right) \to 0
\] (6.8)

where \( E_{n,o} \) is the normal field at the gas side, produced by both the applied stress and the accumulated charges; \( \epsilon_o \) and \( \sigma_o \) are the permittivity and the conductivity of the gas respectively, while \( \epsilon \) and \( \sigma_d \) are those of the spacer material. As indicated in §5.4.2, the condition (6.8) can hardly be satisfied in GIS. A design suppressing charge accumulation has then to be achieved by satisfying condition (6.7).

In §6.2, it was concluded that \( E_{n,o} \) satisfies (6.4):

\[
0 \leq |E_{n,o}| \leq |E_n|
\]
where $E_n$ is the normal component of the initial field, i.e. that introduced by the applied voltage only. Obviously, if $E_{n,0}$ needs to approach zero, $E_n$ shall be zero as well. In this way, the surface charge accumulation will be suppressed.

However this leads to short spacers with insufficient leakage distance. In practice, a good compromise has to be made between the charge accumulation and the leakage distance.

### 6.5 Conclusions

- The DC field in a system with isotropic and homogeneous dielectrics is the same as the electrostatic one, with surface charges at the dielectric interfaces satisfying (5.18) or (5.19).

- Charge accumulation decreases the initial normal field, at the utmost to zero. It can never reverse the normal field.

- Charge accumulation with inserts results in a slight variation of the tangential field. This effect might improve the field distribution.

- The arrangement with toroids results in a charge accumulation which deteriorates the initial tangential field. The tangential component of the field midway along the surface increases in average $\sim 10\%$. The real case is much worse than this because of the large scatter of the surface charges.

The following design of DC spacers could be improved by the following measures:

- DC spacers can be designed with an acute field angle (i.e. $\theta < 90^\circ$) by using inserts.

- A design suppressing charge accumulation might be achieved by choosing the normal field component at the spacer surface relatively small.
Chapter 7
Conclusions

7.1 Conclusions

ON CALIBRATION

1. A two-step method has been developed by which the bulk capacitance inside a dielectric sample can be determined experimentally, so that the calibration of surface charge measurements is improved. This two-step method has further been developed to calibrate a probe whose sensing area is not parallel to the dielectric surface. Charges at a curved surface, such as at the surfaces of actual spacers, can thus experimentally be determined.

ON CHARGE ACCUMULATION

2. Local charge redistributions take place continuously under stress, no matter whether the accumulation has been saturated
or not. The saturation time depends on the applied voltages: the higher the voltage, the longer the saturation time.

3. The micro variations in characteristics at the spacer surfaces are responsible for the large scatter of the charge accumulation.

4. Protrusions at an electrode result in denser charges in their vicinities. Though a protrusion provides charges of one polarity, charge peaks of both polarities can result from it.

5. Arrangements with inserts result in a slight charge accumulation which improves the initial field distribution; accumulations with toroids are much stronger and strongly deteriorate the field.

6. AC stresses result in slight charge accumulations, favourably of negative polarity.

ON THEORETICAL STUDIES

7. Charge transport in the gas space is the dominant mechanism for charge accumulation. The main origin is field emission at the electrode surfaces. The emission behaviour affects the density of the accumulated charges.

8. A theoretical model is proposed which provides the explanation to all above mentioned phenomena. This model correlates the charge density with the leakage current and the field in inhomogeneous dielectrics. It reveals that:

   - Charges are dominantly accumulated at the interfaces of the materials;
   - If there is a normal field component at an interface, charge will be accumulated there.

9. It has been shown that a field under DC stress that is based on leakage current is the same as an electrostatic field with charges at the interfaces. The DC field can
then be easily determined by calculating the electro-
static field with surface charges.

10. Charge accumulation reduces the magnitude of the normal field,
but can never change the polarity of the latter.

ON SPACER DESIGN

11. If the field angle of a spacer (between the interface and the
equipotential lines close to a triple junction) is less than 90° the
shielding effect is reduced by charge accumulation; if this angle
is larger than 90° the shielding effect is enhanced.

12. Inserts, which make the field angle less than 90°, can well be
used in DC GIS.

7.2 On Future Work

1.) There exist many models of surface flashover. They cannot be
applied directly to practice as little effort has been made to correlate
flashover with the surface itself. Charge accumulation at the sur-
face is one of the essential phenomena that influences the flashover.
The variation in the pre-breakdown conditions have been studied in
the present work; the influence of the charge accumulation on the
breakdown process itself is also of importance: the pre-energy (the
charges) existing at the surface may contribute to the breakdown
channel, therefore the input energy demanded by the growth of the
channel from the circuit is changed. The contributions of surface
charges may affect the growth velocity of the channel and the width
of it. Fundamental studies are required to determine the influence of
the surface charges on these parameters.

2.) The influence of a spacer surface on the AC breakdown voltages
might also arise from charge accumulation. Though the detected ac-
cumulation is slight, the accumulation just before breakdown, when
there is much stronger field emission, might be large enough to af-
fect the breakdown voltage. To reveal this, the charge measurements have to be performed under different levels of the applied stress and at different stages of a breakdown.

3.) The original surface conditions of epoxy resin are too inhomogeneous to get rid of localized charge concentrations, which gives rise to unpredicted field distortions in GIS. It would be interesting to industry to find out whether the surface condition can be improved during manufacturing by, e.g., a different or a clearer mould surface (or the isolating agent on it), different cooling times, etc.. This might also be achieved by putting coatings on the spacer surface at a certain time during cooling.

Sand blasting proves to be useful in improving the surface conditions, but it may increase the surface roughness. There are many other ways to treat the spacer surface such as rubbing with abrasives, chemical etching, plasma etching and heat etching [45,78]. Different techniques of these will produce different surface geometries and conditions, therefore the influence may also be changed. Studies are required to correlate the techniques with both the charge accumulation and the dielectric strength. More work is also needed to study the influence of the surface roughness on the dielectric strength in the presence of charge accumulation at the surface.

4.) It seems that charge accumulation can shield a crack at the interface between a spacer and a electrode (i.e. the problem at a triple junction). The deterioration by such a failure may appear different if the stress is increased quite slowly to achieve charge accumulations. This has to be proved by experiments.
Appendices

A. Configuration of the Probe

The geometry of the probe used in the present work is discussed in this appendix. The field configurations in front of the probe are presented for the cases that surface charge is measured and that the probe is calibrated by a metal plate.

In chapter 2, the capacitive probe was introduced in a design where the probe (the core) is flush with the shielding (see Fig. 2.1). However if such a configuration is adopted, the field lines from the surface would reach the probe via the separation between the probe and the shielding, which increases the difference of the effective area $A'$ with the sensing area $A$ and deteriorates the field homogeneity in the separation $h$. A reasonable solution for this problem is to make the

![Diagram of the capacitive probe]

**Figure A.1:** Geometry of the capacitive probe
Figure A.2: Field distributions in front of the probe when the separation $h$ is 5mm: a. charge measuring at a dielectric provided that the surface charge is homogeneous, b. calibration with a metal plate.

shielding somewhat higher than the probe (the probe is recessed in the shielding), so that the field lines between the probe and the shielding can be collected by the shielding. The field homogeneity under the probe is then improved. The proper height of the shielding depends on how broad this separation is. In the present work, the shielding is 1.9mm higher than the probe and round-edged. The separation between the probe and the shielding is 1.4mm. Fig. A.1 shows the geometry of this probe.

In the present work, the separation $h$ between the probe and the charged surface (the distance from the surface to the edge of the shielding) is 5mm. The field configurations, when the probe is used and when the probe is calibrated with a metal plate, are presented in Fig. A.2.
B. Surface Roughness and Measurement

This appendix is included to give the definitions of surface roughness and to introduce the method of measurement. Surface roughness was measured using a profilometer, Tester P5-KV, in this thesis. The following information was obtained from the manual accompanying the meter and some other relevant materials of the manufacturing company (Hommelwerke). Literature [78] was also referred to.

B.1 Terminology and definitions

A surface invariably incorporates structural deviations. This is classified as form error, waviness and surface roughness. The form error indicates the deformation (geometrical error) of a surface; the waviness represents the flatness of a flat surface; while surface roughness describes how smooth a surface finish is.

Figure B.1 shows a surface profile explaining both waviness and

![Surface Profile Diagram](image)

**Figure B.1**: Diagrams of surface profile:  
a. actual profile with both waviness and surface roughness,  
b. roughness profile with waviness filtered out
surface roughness. The surface roughness is concerned in the present study only. During measuring the surface roughness, the waviness is filtered off (Fig. B.1.b) and the data necessary to evaluate the surface roughness are collected. After this filtering, a straight centre line can be introduced for the roughness evaluation, which is obtained when the sum of the areas within the profile above the line is equal to the sum below it.

The filtering depends on the cut-off $\lambda_c$, a term describing the limiting wavelength. Shorter wavelengths than $\lambda_c$ are allotted to the roughness profile and wavelengths longer than $\lambda_c$ to the waviness profile.

There are several definitions of surface roughness. Using the instrument available for the present work, two parameters can be measured: arithmetic mean roughness $R_a$ and maximum peak-to-valley height $R_t$. The definitions are:

$R_a$ The arithmetic average value of the deviation of the roughness profile from the centre line within a certain length (evaluation length, see the succeeding subsection) $l_m$ (Fig. B.2.a):

$$R_a = \frac{1}{l_m} \int_{l_m} |y| \, dx$$

$R_t$ The maximum peak-to-valley height of the roughness profile over the evaluation length $l_m$, as shown in Fig. B.2.b.

$R_t$ was employed in the present work.

Other parameters are also used in practice, such as the mean peak-to-valley height, root mean square roughness, highest peak above the centre line, etc..

**B.2 Measurement using an instrument**

The surface roughness is detected by moving a stylus along the surface in a manner similar to a record player. This is illustrated in Fig. B.3. The stylus is moved over the surface in order to provide a
Figure B.2: Illustration of the definitions of surface roughness: a. arithmetic mean roughness $R_a$, b. maximum peak-to-valley height $R_t$. $l_m \rightarrow$ evaluation length

Figure B.3: Measuring stylus on a rough surface

two-dimensional profile measurement. The vertical displacement of the stylus tip is detected and converted to an electrical signal by a transducer. The electrical signal is then processed to evaluate the surface roughness.

The stylus moves a certain length during a measurement. This is defined as the traverse length $l_t$. The traverse length can be divided into, see Fig. B.4:

Set-up length $l_v$ The first section of $l_t$ that is not used for the param-
Figure B.4: Divisions of traverse length of a stylus: $l_t$→traverse length, $l_v$→set-up length, $l_m$→evaluation length, $l_n$→run-off length, $l_e$→sampling length

...eter evaluation, but used for stimulating the filter.

Evaluation length $l_m$. The section of $l_t$ that is used for parameter evaluation.

Run-off length $l_n$. The last part of $l_t$ just for filter settlings, again not used for parameter evaluation.

Normally, a fifth of the evaluation length $l_m$ corresponds to the sampling length $l_e$, the length for making a single assessment of a parameter, and the sampling length equals the cut-off $\lambda_c$. 
C. Effect of Charge Accumulation on Flashover Voltages

This appendix is included to show the effect of charge accumulation on the flashover voltages which has been studied by others.

A study with inserts was performed in [52,76]. As studied in §6.3.1 with this type of arrangement, the field is in fact improved by surface charges, therefore the accumulation does not deteriorate the performance of a spacer if the stress is of the same polarity as that responsible for the accumulation.

However, as the stress polarity is suddenly reversed the charges accumulated at the surface will increase the inhomogeneity of the field along the surface (as analyzed in §6.3.2 with toroids), so that the flashover voltage decreases.

Fig. C.1 gives the DC flashover voltages at reversal to the opposite polarity [52] and the flashover voltages at switching impulses (S.I.)
which are opposite to the original DC voltages [76] versus the maximal surface charge densities (refer to Fig. 4.1 and Fig. 5.2.a for the test arrangements). It is shown that as the charge density approaches \( \sim 400 \mu C/m^2 \), the flashover voltage decreases \( \sim 50\% \) for a reversed DC stress, and \( \sim 40\% \) for a switching impulse of opposite polarity.

Experiments showed that the slight charge accumulations under AC and impulse voltages have little influence on the flashover strength of an impulse voltage. The influences fall well within the range of the scatter in the breakdown voltages measured with the “up-and-down” method [98] at a given level [74,75].
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Symbols

$A$    sensing area
$A'$   effective area
$C_1$  capacitance within probe separation
$C_2$  input capacitance of probe
$C_3$  bulk capacitance
$D$    electric flux density
d      dielectric thickness
$E$    electric field intensity
$E_{bd}$ breakdown field
$E_d$  field in dielectric
$E_n$  initial field normal to boundary
$E_{n,d}$ normal field in dielectric
$E_{n,o}$ normal field in gas
$E_o$  field in gas
$E_r$  radial field
$E_t$  initial field tangential to boundary
$E_{t,d}$ tangential field in dielectric
$E_{t,o}$ tangential field in gas
e      electron
$H$    humidity

$h$    probe separation, height
$h'$   protrusion height at electrode
$J$    electric current density
$j_z$  surface current density
$K_1$  dividing ratio of voltage by first calibration
$K_2$  dividing ratio of voltage by second calibration
$M$    calibration coefficient
$ar{M}$ matrix of calibration coefficient
$P$    pressure
$R_t$  surface roughness
$r$    radius
$r_c$  radius of conductor
$r_e$  inner radius of enclosure
$Q$    electric charge
$	ilde{Q}$ relative total charge
$S$    standard deviation
$s$    toroid separation
$T$    temperature
t    time
$t_{app}$ stressing time

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$t_s$ saturation time
$U$ DC voltage
$\overline{U}$ potential matrix
$U_{bd}$ breakdown voltage
$u$ voltage
$u_2$ voltage output of probe
$X$ circumferential coordinate
$Z$ vertical coordinate
$\alpha$ ionization coefficient
$\bar{\alpha}$ effective ionization coefficient
$\beta$ deviation angle
$\delta$ photo-emission coefficient
$\epsilon$ dielectric permittivity
$\epsilon_d$ permittivity of dielectric
$\epsilon_0$ permittivity of vacuum
$\epsilon_r$ relative permittivity of

$\eta$ attachment coefficient
$\theta$ contact angle
$\vartheta$ field angle
$\Lambda$ probe response function
$\lambda$ free path of electrons
$\sigma$ conductivity
$\sigma_d$ conductivity of dielectric
$\sigma_a$ conductivity of gas
$\sigma_s$ surface conductivity
$\sigma_S$ surface charge density
$\overline{\sigma_S}$ charge matrix
$\xi$ spacer efficiency
$\rho$ bulk charge density
$\tau$ time constant
$\Phi$ electric potential
$\phi$ diameter
Samenvatting

Ladingsopbouw op een isolatoroppervlak kan het electrische veld sterk veranderen en daardoor de werking van GIS, gas geïsoleerde schakel-systemen, verslechteren. Zowel de verschijnselen als de mechanismen worden in dit proefschrift bestudeerd.

Hoofdstuk 1 geeft een algemene inleiding, waar de problemen uit de praktijk en het doel van dit proefschrift worden beschreven.

Hoofdstuk 2 introduceert de meetmethoden, o.a. de capacitieve meetsonde. Het ijken van de sonde wordt bestudeerd, hetgeen van belang is om een goede meting uit te kunnen voeren. Het ijken wordt tweemaal gedaan, met spanning op een metalen plaat: één keer voor de meting van de capaciteit tussen isolator en sonde, de andere keer voor de meting van de capaciteit binnen de isolator (twee-stappen methode, §2.4 en §2.5). Dit verbetert de nauwkeurigheid van het ijken en maakt het mogelijk om ook de ladingen op gebogen isolatoroppervlakken te meten.

Hoofdstuk 3 behandelt de meetopstelling en het ontwerp van het meetsysteem. De elektroden en de isolatoren werden d.m.v. veldberekeningen ontworpen. Het meetprogramma’s om de gegevens te verwerken worden met Quick BASIC beschreven.

Hoofdstuk 4 presenteert de testresultaten: de verschijnselen van oppervlakteladingsopbouw onder verschillende condities, met aandacht voor de mechanismen verantwoordelijk voor ladingsopbouw en -afbouw. Een overzicht wordt ook gegeven van de factoren die de ladingsopbouw beinvloeden.

Hoofdstuk 5 bestudeert de theorie van de ladingsopbouw. Hier
volgt uit dat het voornaamste mechanisme de ladingsbeweging is langs de electrische veldlijnen. Micro gasionizatie op het electrode oppervlak is verantwoordelijk voor het ontstaan van de lading. Een veldstudie toont aan dat de ladingsopbouw onvermijdelijk is wegens de sprongsgewijze verandering van de dieëlectrische eigenschappen aan het isolatoroppervlak.

Hoofdstuk 6 onderzoekt de invloed van de oppervlakteladingsopbouw op de verandering van de velden. Ook wordt het ontwerpen van isolatoren in dit hoofdstuk besproken.

De belangrijkste conclusies wordt samengevat in hoofdstuk 7 en er wordt een aantal voorstellen gedaan voor toekomstig onderzoek.
T. Jing was born on February 10, 1959 in Shaanxi, China. He graduated from high school in January 1976 and became a teacher in a primary school in August of the same year.

In December 1977, he passed the national university entrance examination and entered Xi'an Jiaotong University in February the following year. He received the B.Sc. and M.Sc. degrees from this university in January 1982 and October 1984 respectively, both in electrical engineering. During 1984~1988 he worked at the High Voltage Division of the Department of Electrical Engineering, Xi'an Jiaotong University, first as an assistant and later as a lecturer.

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Mr. Jing is the recipient of the 1990 Award of Excellence for Significant Contributions to Science and Technology from the State Education Commission of China, an award from Xi'an Jiaotong University and an award from Shaanxi Province, all for the sustained contributions to the fields of gas discharge and calibrations of breakdown in long air gaps he made in Xi'an Jiaotong University. His interests in research include insulation design, gas discharges and their application, high voltage measurements and apparatus design as well as pulsed-power generation.