



Electric-potential-measurement-based methodology for estimation of electric charge density at the surface of tribocharged insulating slabs



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ABSTRACT

The auto-compensated electrostatic induction probe (ACEIP) is widely used for measuring the electric potential at the surface of conductive or insulating bodies. The aim of this paper is to elaborate a methodology for using this probe in view of performing the estimation of electric charge density at the surface of tribocharged insulating slabs. In such cases, the electric potential is not uniformly distributed on the surface under investigation. Metallic plates trimmed with different shapes were used to characterize the probe. Thus, a first series of experiments enabled a crude evaluation of the shape and size of the area “seen by the probe”: a 10-mm-diameter circle. Other experiments served to determine the transfer function that relates the value measured by the probe to the potential of a small area of constant electric potential located at a well-defined distance from it. By dividing the surface under investigation into a large number of small elementary areas, it was possible to use this transfer function to express the potential measured by the ACEIP as the sum of the contributions of each such element. An inverse matrix computation method enabled the estimation of the actual surface electric potential. Based on the results of a final set of experiments, the distribution of the electric charge density was estimated for slabs charged by corona-respectively triboelectric-effect.

1. Introduction

Surface charge density (SCD) measurements on insulators have been under study for more than fifty years [1–3]. In high-voltage engineering, the charge deposited on the surface of solid insulators may influence the dielectric strength, as it reduces the flashover voltages [4]. Evaluation of SCD can be of interest in biotechnologies, too, at it can lead to a better understanding of biomolecular interactions on surfaces, as well as DNA hybridization and protein binding in microarray technologies [5]. Such measurements can be of use in monitoring of aged insulators, assessment of polyethylene films and fibrous dielectrics, evaluation of electrostatic risks, development of electrets, adjustment of Xerox-photography processes [1–3,6–9]. Knowing the charge distribution generated by rubbing is vital for characterizing the tribological behavior of sliding machine parts, as well as the efficiency of tribo-electrostatic generators employed for energy harvesting [10,11].

The electric charge can be directly measured using Faraday pails, planar charge meters, and atomic force microscopes. Each method has its own advantage and disadvantage, for example atomic force microscopy can probe local charge density with high resolution but is time-

consuming and can cover a small area [12]. Plate charge-meters provide measurements of adequate range and precision, but lack resolution and consume a considerable amount of energy.

The electric potential associated to the charge at the surface of insulators can be measured with either a contact or a non-contact probe of an electrostatic voltmeter. The non-contact probe has been widely used as it disturbs to a less extent the electrostatic state of the object under investigation [13–18].

The vibrating probe technique was introduced in the 1960s [14] and later developed for a scanning technique [15]. An electrode of known area is vibrated in the electric field generated by the charge. This induces a signal proportional to the SCD. The most widely-used variant of this device is the auto-compensated electrostatic induction probe (ACEIP). The electronic circuits of the voltmeter adjust the potential of the metallic case of the probe at a value that nullifies the electric field in its vicinity. When the surface under study is a metal plate connected to a voltage supply and the probe is close to it (i.e., less than 3 mm, according to manufacturer's specifications), the electric field can be considered uniform. The zero-field condition implies a zero potential difference between the case of the probe and that surface. The voltage displayed by the electro-static voltmeter is equal to that of the surface

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[19–22].

The situation is much more complicated when the probe scans non-uniformly charged insulators. The geometry of the system formed by the probe and the investigated object may influence the readings. In such cases, one major recommendation is to keep to minimum the distance between measured body and probe [23,24].

ACEIP being the standard for non-contact surface potential measurements [25], the aim of this paper is to elaborate a methodology in view of using this device for evaluating the electric charge density at the surface of tribo-charged polymer plates [16].

The challenge is to handle the situations when the electric charge is non-uniformly distributed at the surface of the samples.

2. Theoretical model

Two problems have to be solved to enable the use of ACEIP for SCD measurements: (1) Obtain the cartography of the actual distribution of the electric potential at the surface of the body under investigation; (2) Find the conversion ratio of the local value of the electric potential into an electric charge density.

The first problem is difficult, as the value indicated by the ACEIP connected to an electrostatic voltmeter depends on the distribution of the electric potential (or the electric charge) on a certain area “seen by the probe” [20,26]. The contribution of the local value of the electric potential in a point L to the value measured by the probe located in a point P is proportional to the reverse of the distance between L and P . Therefore, it can be considered that the probe “sees” only the potential within a circular zone of radius r_{max} to be determined by experiments.

In the most general case, the Green function expresses the potential generated in a given point by a volume distribution of electric charge and by a surface distribution of electric potential, as follows (Fig. 1):

$$\Phi(r) = \frac{1}{\epsilon} \int_V \rho(r') G dV - \oint_S \Phi_S \frac{\partial G}{\partial n} dS \quad (1)$$

where: $G = \frac{1}{4\pi r - r'}$; $\Phi(r)$ is the electric potential to be evaluated in a point defined by the vector r ; $\Phi_S(r')$ is the electric potential in a point defined by the vector r' on a closed surface S ; n is the normal to the surface directed outwards; $\rho(r')$ is the electric charge density in a point defined by the vector r' in a volume V . In particular, if there are no charges in the region of concern (i.e., $\rho = 0$) the potential is determined by Φ_S alone.

In case that the surface potential is null (i.e., $\Phi_S = 0$), the value of Φ depends only of the contribution of the charge. The Green function can be applied when the boundary conditions are well defined but the model is very difficult to use for complex geometries.

Several researchers addressed this problem using a multi-point measuring technique [24–28], in which the surface under investigation is divided up into a large number of elementary areas, and the potential read by the probe is linked to the real potential of each such element by a transfer function (Fig. 2). The methodology described hereafter was inspired by their work.

Thus, the probe measures the electric potential above each surface element. These elements do not have to be square, but they should be small enough for the electric potential (or electric charge density) to be

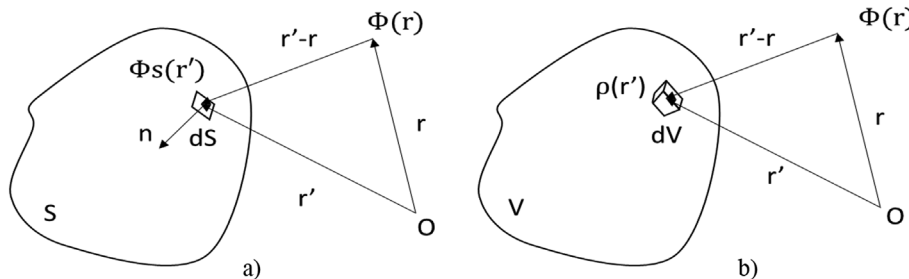


Fig. 1. Principle of calculation of Green's function when $\Phi(r)$ is the electric potential in a point defined by the vector r , and: (a) $\Phi_S(r')$ is the potential in a point defined by the vector r' on a closed surface S ; n is the external normal to the surface; (b) $\rho(r')$ is the charge density in a point defined by the vector r' in a volume V .

constant at the surface of each of them. According to the theorem of superposition, the potential measured by a probe at a given coordinate is the sum of the contributions of each element.

For a well-known surface geometry and a constant electric potential (or electric charge density) distribution, the relation between the potential $\Phi(x_k, y_l, h)$ read by the probe located in a point of coordinates (x_k, y_l, h) and the actual surface potential $\Phi_S(x_i, y_j, 0)$ of a small area $A(x_i, y_j)$, the center of which is located in $(x_i, y_j, 0)$, can be expressed as:

$$\Phi(x_k, y_l, h) = A(x_i, y_j) \cdot \Phi_S(x_i, y_j, 0) \cdot f(x_k - x_i, y_l - y_j, h) \quad (2)$$

where $f(x_k - x_i, y_l - y_j, h)$ is the transfer function between Φ and Φ_S . This function is dependent of the vector R which defines the relative position of the center of mass of the surface $A(x_i, y_j)$ with respect to the probe.

If the surface under investigation is divided in equal areas, the relation between the potential read by the ACEIP and the surface potential can be defined as a matrix equation:

$$\Phi = A \cdot \Phi_S \cdot F \quad (3)$$

where Φ is a matrix with the size $(1, \nu)$ which includes the values of the potential read by the probe at every given position, A is a constant, equal with the area of the entire surface under investigation; Φ_S is a matrix with the size $(w, 1)$, composed of the values of the surface potential in each elementary area, F is the matrix of the elementary transfer functions f . The matrix size for F is (ν, w) . If F is known, equation (3) can be used to compute Φ_S (i.e. the distribution of surface potential), using different methods of matrix solving. One of the major original contributions of the present work when compared to [26] is that the elementary transfer functions f are not estimated by computation, but determined using an experimental approach that will be described later in the paper.

For the situation considered in the present work, a constant ratio exists between the local value of the electric potential and the charge density at the surface of thin insulating slabs above a grounded back-plane.

3. Materials and methods

3.1. Instrumentation

The measuring device concerned by this study is an ACEIP (Trek, Model 3450), connected to an electrostatic voltmeter (Trek, Model P0865). The device can measure the electrical potential measurement in the range 0 to ± 10 kV, with accuracy better than $\pm 0.1\%$ of full scale value, and with a speed of response better than 0.2 ms for 1 kV step change.

The voltmeter was connected to an acquisition card NI USB 6210. The probe was placed in a 3D axis device (operating procedure described in Refs. [29,30]) which can assure its three-dimensional movement with a precision of 0.01 mm. Synchronization between the position of the probe and measured values was made using Labview software. The principle of this type of probe has already been explained in the Introduction.

To facilitate the interpretation of electric potential displayed by the voltmeter when the probe scans the surface of non-uniformly charged

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