

Can Static Electricity be Measured?

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Ever since my first EOS/ESD Symposium in Las Vegas in 1983 I have wondered why intelligent people presenting interesting papers describing cleverly executed experiments with useful results keep insisting on using non-existing concepts and warped units when presenting their findings.

Some of my (maybe now former) friends may already have guessed that I am hinting at such things as *the voltage of a plastic box*.

There is no such thing.

Or a surface resistivity measured in *ohms per square*.

There is no such thing. (The one and only unit is ohm (Ω)).

This, and a lot more, is discussed in this paper.

Is this then just a hair-splitting exercise ?

I hope not.

Rather, this is an attempt to put some things together in a more comprehensive context to make the concepts and their interrelations more digestible.

I do well know that it may all end up a Don Quijote crusade against windmills.

Because these “windmills” are so comfortable and familiar.

So who cares if the flour is polluted by unhealthy additives.

I hope you do.

Lyngby, September 1998

Niels Jonassen

The artwork is done by my friend O. Broo Sørensen.

Most of the figures are from my book *Electrostatics*, (Chapman & Hall, 1997)

CAN STATIC ELECTRICITY BE MEASURED

?

Niels Jonassen

INTRODUCTION

The title could also (and probably more correctly so) be: *Is it possible from measurements to deduce or predict the effects and behavior, harmful and beneficial, of electrostatic charge distributions ?*

Either version of the question may seem impertinent when you consider the immense number of static measurements being performed and the number of results being reported in order to characterize materials and processes.

Nevertheless, quite a few commonly used procedures may lead to results that are next to worthless in assessing for instance electrostatic risks.

This is true of many exercises in measuring static fields and even more so when dealing with the rather elusive concept of voltage of insulating objects.

This paper will try to give an overview of fundamental electrostatic concepts and electrostatic effects and most importantly of electrostatic metrology, especially what can and what cannot be measured.

FUNDAMENTAL CONCEPTS

Charge, field, voltage and capacitance

The basic electric concept is **charge**, a property of certain elementary particles, like the protons in the nuclei of any element and the electrons found in certain regions around the nuclei. The (positive) charge of a proton has the same numerical value as that of an electron (negative), namely

$$e = 1.6 \times 10^{-19} \text{ C}$$

If a body has an excess of electrons it is said to be negative, if it has a deficit of electrons it is positive.

The number of electrons participating in the charging of any macroscopic body is huge.

Some characteristic values are given below.

If a charged particle of a powder is sticking to the wall of a container or a tube the charge may be about 10^{-14} C , meaning that several hundred thousands of electrons have been exchanged.

If a person is charged to such a voltage that she may receive a shock by touching a water tap, her charge is at least 10^{-7} C or, in other words, more than 10^{12} electrons have been exchanged in her charging.

If a powder, like sugar or flour, is sliding down a tube, be it metal or plastic, the net charge on the powder is often about $10^{-7} \text{ C} \cdot \text{kg}^{-1}$.

If a plastic sheet is being rubbed by a cloth the charges separated may again be about 10^{-7} C.

A direct measurement of a charge would in principle mean a counting of the number of electrons (missing or in excess) involved, and such a process is obviously impossible. The only way charges make themselves known is through the forces by which they interact.

If a charge “feels” a(n electric) force the charge is said to be in an **electric field**.

If the force on the charge Q is F , then the field strength E is defined by

$$\mathbf{F} = Q\mathbf{E} \quad (1)$$

The field itself is caused by other charges.

If a charge q is located within a very small region (a point charge) in a distance r it will create an electric field E given by

$$E = \frac{q}{4\pi\epsilon r^2} \quad (2)$$

where ϵ^1 is the permittivity at the distance r .

The field is directed away from the charge for a positive charge and towards it for a negative charge.

In Fig. 1 is shown the variation of the field with distance.

Let us look a little critically at eqs. (1) and (2).

Eq. (1) might give the impression that the strength of an electric field might be measured by placing a “test charge” Q in the field and measuring the force F on the charge. This, however, is not possible. Even if a known charge Q could be selected, the force F would in all practical cases be far too small to be measured with a reasonable accuracy.

Eq. (1) only serves as a definition of the concept of field strength², not as an instruction on how to measure the field.

But before going into considerations of measurements, let’s look more closely at the concept and properties of fields.

Eq. (2) expresses one of the simplest relationships between charge and resulting field, and in fact it does not only give the field from a more or less theoretical

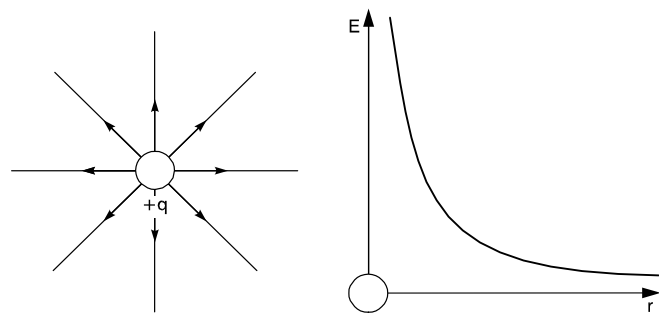


Fig. 1

1 In vacuum (and air at atmospheric pressure) $\epsilon = \epsilon_0 \approx 8.85 \cdot 10^{-12} \text{ F} \cdot \text{m}^{-1}$.

2 It is not unusual that an equation of definition is unsuitable for measuring the quantity being defined. If a current I creates a total magnetic flux Φ_B in a circuit, the inductance L of the circuit is defined by the equation

$$\Phi_B = LI$$

but nobody in her right mind would use this equation for directly determining the inductance.

point charge but also the field outside any uniform, spherical charge distribution with a total charge q .

Let us now assume that we have established some charge distribution, the field from which should be given by (2), and we then try to measure the field or just plot its dependence of distance from the charge.

We will then most certainly find that (2) is not fulfilled.

This is caused by the almost unavoidable distortion of the field by the measuring equipment.

To put it simply:

“What you measure is not what you want to measure”.

Well, hardly ever.

More about this when we talk about the principles of field measurements.

But even in the absence of the disturbing effect of meters, fields hardly ever decrease with the square of the distance from the charge as suggested by (2).

If we for instance have a(n undisturbed) cylindrical charge distribution with the linear charge density μ ($\text{C}\cdot\text{m}^{-1}$) the field strength E at a distance from the axis will be

$$E = \frac{\mu}{2\pi r} \quad (3)$$

i.e. decreasing with the first power of the distance.

If we have a plane charge distribution with the charge density σ ($\text{C}\cdot\text{m}^{-2}$) the field near the plane is

$$E = \frac{\sigma}{2\varepsilon} \quad (4)$$

i.e. independent of the distance as long as the distance is small compared to the dimensions of the charge distribution, as suggested in Fig. 2.

This situation may almost be achieved by a charged sheet of plastic, and it does not matter if the charge is on one side or the other or on both sides as long as the total charge density is σ .

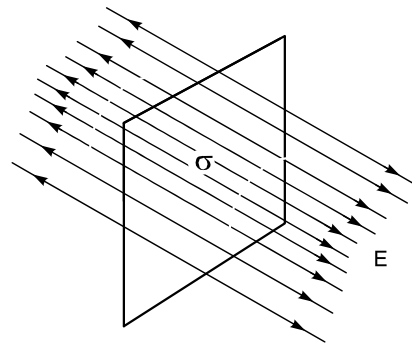


Fig. 2

If the material charged is a conductor the field close to the surface (with the charge density σ) is

$$E = \frac{\sigma}{\epsilon} \quad (5)$$

The discrepancy between (4) and (5) is only apparent. Without going into details the difference is caused by the fact that the field inside a conductor is zero, and thus you can not “see” the charge on the backside of the conductor, Fig. 3.

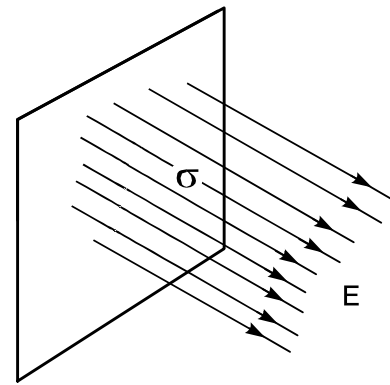


Fig. 3

It appears as if eqs. (4) and (5) would offer a way of determining the local charge density by measuring the field close to the charged surface.

We would then have

$$\sigma = 2\epsilon E \quad (6) \quad \text{for an insulator,}$$

and

$$\sigma = \epsilon E \quad (7) \quad \text{for a conductor.}$$

If, however, the insulator is a thin sheet the relation between the charge density and the surface-near field is rather given by eqs. (5) and (7) than by (4) and (6), since the field distribution near the field meter in this situation would be more like Fig. 3 than Fig. 2.

In the case of a charged conductor, the relationship between surface density and the field strength near the surface is definitely given by eqs. (5) and (7), but the field strength measured and consequently the charge density calculated may be very different from (normally larger than) the corresponding undisturbed quantities.

Let us now turn to another important concept, **voltage or potential**.

When dealing with batteries, power supplies and generators, voltage, or more precisely voltage difference, is a property which can be put on a label and carried around with the apparatus, ready to cause a current when applied across a conductive path.

This is all well understood and the numerous applications so familiar to everybody that people don't suspect difficulties in understanding when the question of voltage appears in static electric connections.

But when dealing with static electricity, voltage is a rather elusive property of a static field.

It can only be used meaningfully and, above all, only be measured when we are talking about conductors.

To appreciate this fact we have to look at a little theory.

If a charge Q is placed in an electric field E , Fig. 4, the force F on the charge is

$$\mathbf{F} = Q\mathbf{E} \quad (1)$$

If the charge is moved from point A to point B the field will do a work W_{AB} given by

$$W_{AB} = Q \int_A^B \mathbf{E} \cdot d\mathbf{a} = Q[V_A - V_B] \quad (8)$$

The quantity

$$V_A - V_B = \int_A^B \mathbf{E} \cdot d\mathbf{a} \quad (9)$$

is called the **voltage difference**, or **potential difference**, between A and B.

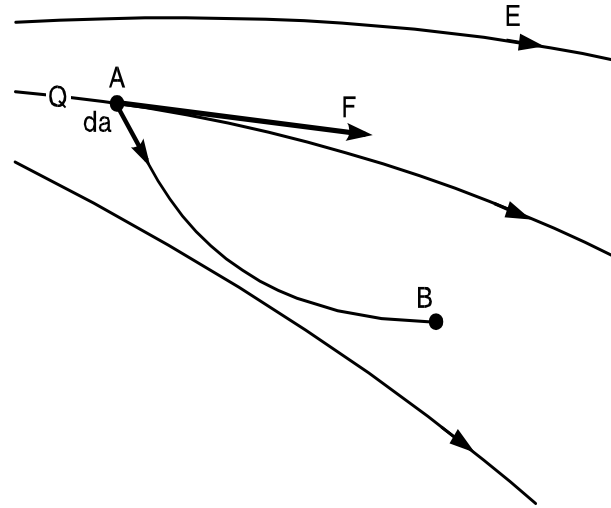


Fig. 4.

Eq. (9) only defines voltage differences. In order to define the voltage or potential of a point we have to choose another point, or collection of points, to have the potential zero.

Traditionally we choose any point at an infinite distance from our charge to have zero potential, since the field strength at all such points is infinitely small, and consequently the voltage difference between these points is zero, according to (9).

Since the field in the ground is also zero, all ground points have the same potential as the infinitely far points, i.e. zero.

We thus have the definition of the voltage V_P of a point P

$$V_P = \int_P^\infty \mathbf{E} \cdot d\mathbf{a} \quad (10)$$

According to (8), the dimension of voltage difference (and voltage) is work/charge with the unit joule/coulomb, $J \cdot C^{-1}$ which is called volt, V, i.e.

$$1 \text{ volt} = 1 \text{ joule/coulomb}$$

It follows from eq. (9) that field strength may be expressed in the unit volt/meter, $V \cdot m^{-1}$. On the other hand, eq. (1) defines the dimension of field strength as force/charge with the unit newton/coulomb, $N \cdot C^{-1}$. There is, however, no discrepancy between these two statements, since

$$1 V \cdot m^{-1} = 1 J \cdot C^{-1} \cdot m^{-1} = 1 N \cdot m \cdot C^{-1} \cdot m^{-1} = 1 N \cdot C^{-1}$$

As explained above, voltage is a property of a point in an electric field. Let us now examine if it is possible to use the concept of voltage to (partly) characterize a charged body, be it an insulator or a conductor.

In Fig. 5 is shown a charged insulator placed near a grounded plane.

Suppose the insulator an uneven charge distribution, with positive as well as negative blotches of charge.

If we integrate the field strength from the point P_1 to ground we get a positive quantity V_1 which is the (surface)-potential of P_1 .

If we do the same thing for the point P_2 we get a negative value, and although there might be cases where this exercise will lead to potentials with the same sign, the quantity will vary from point to point over the surface of the insulator.

Hence there is no common value for the potential of an insulator.

Or put more plainly:

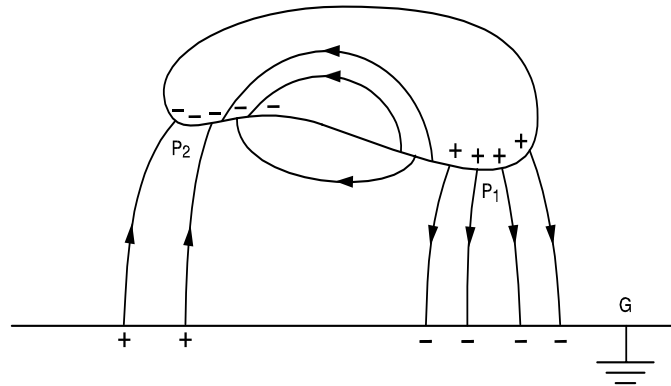


Fig. 5.

A charged insulator can never be characterized by a number of volt³

Let us now turn to the case of a charged conductor.

In Fig. 6 is shown a positively charged conductor A in the vicinity of a grounded plane G. The charge q will distribute itself on A in such a way that the field strength is perpendicular to the surface and is zero inside A

According to (9) the potential difference between any point in or on the conductor is zero, or any point P in or on the conductor then has the same potential

$$V_P = \int_P^G E \cdot da \quad (11)$$

V_P (or just V) is called the potential of the conductor.

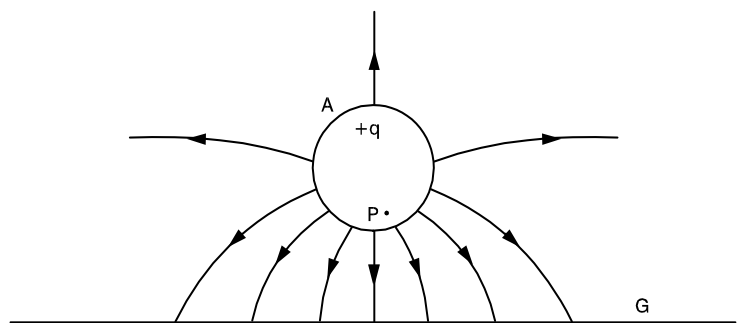


Fig. 6

³ In all fairness it should be mentioned that there is an exception to this rule. That of a charged electret or of a charged photodrum.

If the charge q is changed, the field around A will change proportionally but keep its shape.

Hence also the voltage of A will be proportional with q which is normally written

$$q = CV \quad (12)$$

The factor C is called the capacitance of the insulated conductor (or capacitor) relative to ground. C has the dimension of charge/voltage with the unit coulomb/volt which is called farad, F, i.e.

$$1 \text{ F} = 1 \text{ C} \cdot \text{V}^{-1}$$

The capacitance of any insulated conductor may be written

$$C = \epsilon L \quad (13)$$

where ϵ is the permittivity of the material through which the field extends itself (when the conductor is charged) and L is a function with the dimension of length determined by the geometry of the conductor and its surroundings.

The best known form for a capacitor is the parallel plate capacitor, Fig. 7, with the capacitance

$$C = \epsilon \frac{A}{d} \quad (14)$$

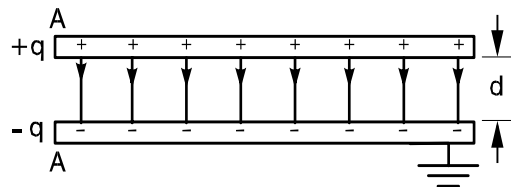


Fig. 7

The capacitance of common insulated conductors can often be conveniently estimated by use of eq (14).

Like that of a standing person, Fig. 8

If her shoe size and sole material and the material of the floor is known, her capacitance may be estimated to, say 200 pF.

If it is measured electrically (or rather electrostatically) we may find it to be 300 pF, indicating that her feet is responsible for 60 - 70 % of her capacitance and hence also for the location of the same percentage of a possible charge.

The capacitance of an insulated conductor is an important parameter in characterizing the effects of a static charge distribution.

It should be mentioned that, like the concept of voltage, capacitance can only be applied to conductors, but as it appears from eqs. (13) and (14) the capacitance of a given conductor or set of conductors also depends upon the dielectric properties of the surrounding or intercapacitive medium.

If we thus have two samples of identical shape and size of different (insulating) materials and we place two metal electrodes on the same places of the samples we may have two widely different capacitances. The difference is caused solely by the different properties of the insulators.

Nevertheless the insulators, themselves, have no capacitance.

Not until electrodes have been placed on (or even just in the neighborhood of) the insulating samples, does the concept of capacitance have a meaning.

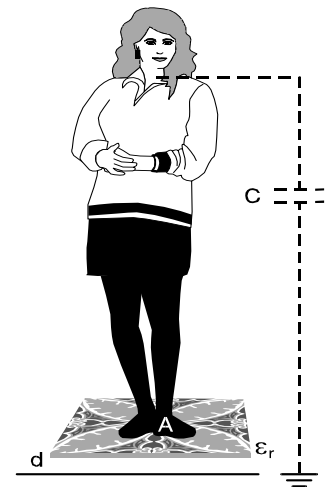


Fig. 8

EFFECTS OF STATIC ELECTRICITY

Let us now look at what effects a static charge distribution may have.

It appears that all known effects are caused by the electric field.

Charge, per se, has no known direct effect, and voltage is just another, often very practical, way of characterizing the field.

Static cling

If a charged material, like a sheet of plastic or paper, comes near the surface of a conductive (or semi-conductive) body, the field from the material will induce an opposite charge on the body, Fig. 9.

Let us suppose that the two surfaces are (more or less) parallel, and that the charge density on the charged material is σ , the induced charge density will be $-\sigma$ and the field between the two surfaces will approximately be given by

$$E = \frac{\sigma}{\epsilon} \quad (5)$$

The charged material will experience a force f_u per unit area given by

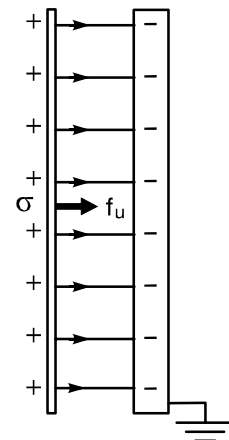


Fig. 9