Electrostatic risk and specification of field and voltage limits for insulating web materials

Kelly Robinson * and Jeremy Smallwood *

1 Electrostatic Answers LLC, 15 Piping Rock Run, Fairport NY 14450-9596, USA
2 Electrostatic Solutions Ltd, 13 Redhill Crescent, Southampton SO16 7BQ, UK
E-mail: jeremys@static-sol.com

Abstract. Evaluation of electrostatic risk in production insulating web systems rely on electrostatic field or voltage measurements. Field meter measurement at the centre of a web span gives a direct evaluation of electrostatic risk from net web surface charge density. Surface voltage measured on the web against a grounded conductor can reveal the distribution of charges on each web film surface independently. Considerations for measurement instruments are given.

1. Introduction
Electrostatic field and voltage measurements are used for evaluating electrostatic risks, [1] including in insulating sheet web production systems. The instruments used are typically hand-held non-contact “electrostatic voltmeters” [2]. The most common types are “field mill” or capacitive electrostatic field meters calibrated to give voltage readings when held at a prescribed distance from a large planar equipotential surface. The calibration distance of these instruments is commonly 2 cm, 2.5 cm or 10 cm and they typically have voltages ranges of 0-2 kV or 0-20 kV. Other types include true non-contact electrostatic voltmeters that use nulling techniques to give voltage readings up to 2 kV relatively independent of the distance between the target surface and the sensor over a short distance of a few millimeters.

Setup, measurement and interpretation of fields and voltages in web systems are commonly misunderstood. The web voltage is often assumed well defined, and measurements made using different instruments assumed to give similar results. In practice the web voltage depends on proximity to the meter, the earthed user and earthed machine parts. The web voltage varies with position in the process and field meters calibrated to read voltage at different distances from the web can be expected to give different readings. This paper reviews the principles of measurement, specification of field or voltage limits and instruments for successful determination of electrostatic risk by field measured at an open web span, and voltage measured with the web material against a grounded metal surface such as a roller.

2. Theoretical analysis
Seaver [3] explained the principles and practice of measurements and interpretation of results made on web surfaces. The analysis is based on the assumption that an area A of a thin web surface can be modelled as one electrically isolated plate of a capacitor having capacitance C and holding a charge Q, with the meter forming the earthed second plate with equal area A at a distance dm from the web surface (figure 1). This model assumes a uniform field between the meter and the web. The web is assumed to
have a single layer surface charge density $\sigma = Q/A$. This analysis assumes that the meter is an earthed conductive non-contact electrostatic field meter, e.g., of “field mill” type, and that the results may be reported either as electrostatic field $E$ as or a voltage $V$. The field and voltage are related by the distance between the web and meter as $E = V/d_m$. The charge and capacitance are related by $CV = Q$. The capacitance of the parallel plate capacitor is given by $C = \varepsilon_0 A/d_m$, where $\varepsilon_0$ is the permittivity of the air $(8.9 \times 10^{-12} \text{ Fm}^{-1})$ between the capacitor plates. Combining these equations leads to

$$E = \frac{V}{d_m} = \frac{1}{\varepsilon_0 A} \frac{\sigma}{\varepsilon_0}$$

So, the field is directly related to web charge density and is theoretically independent of the distance between the web and the meter, and the dimensions of the meter. As the web voltage $V$ is $E/d_m$ the web voltage changes with distance between the web and the meter. Meters held at different distance from the web will in theory see the same field but different voltage. A field meter calibrated to read voltage at 25 mm will report a voltage of 5000 V for a field of 0.2 MVm$^{-1}$, whereas a meter calibrated at 100 mm (also common) will report 20 kV.

In practice, other objects around the web such as the capacitance between the web and the user’s body $C_b$ and other earthed conductive machine parts are significant. These capacitances are effectively in parallel with the meter capacitance $C$ and reduce the field strength and voltage seen by the meter leading to underestimation of the web charge density. If we consider that the effect of the earthed user’s body on the web area $A$ as a parallel capacitance $C_b$ at a distance $d_b$, the total capacitance is $C + C_b$, the web voltage $V'$ and the field seen by the meter $E'$ is given by $Q = CV = (C + C_b)V'$, leading to

$$E' = \frac{V'}{d_m} = \frac{Q}{(C + C_b)d_m} = \frac{CV}{(C + C_b)d_m} = \frac{C}{(C + C_b)} E$$

$$\frac{E'}{E} = \frac{C}{(C + C_b)}$$

If $C_b << C$ then the ratio $E'/E$ is nearly 1 and when $C = C_b$, the ratio $E'/E$ is 0.5. If $C_b >> C$ then the ratio $E'/E$ approaches a fraction $C/C_b$. To minimize error, the meter must be held close to the web and any conductive support (e.g. the user’s hand) or machine parts remain as far from the web as possible.

The field remains the same between the web and any other large conductor such as a roller as the distance between them reduces. If the charge density at a free span of web material has been established to be below the threshold of risk for electrostatic discharges from the material, this also theoretically true for any other large quasi planar object.

The assumption that the web can be treated as a single layer of charge on the web surface is invalid at a position where the web passes around a metal roller (Figure 2). A web has top and bottom surfaces $t$, $b$ separated by the material thickness $d$ and permittivity $\varepsilon = \varepsilon_0 \varepsilon_r$, where $\varepsilon_r$ is the material relative permittivity. Each web surface is likely to have different charge density $\sigma_t$, $\sigma_b$.

In figure 2 the web surface $t$ is approaching and eventually makes contact with the roller surface. At the same time the capacitance $C_t$ increases, the top surface voltage $V_t$ reduces with $d_t$ and becomes zero with $d_t$ at contact. The capacitance $C_b$ of an area $A$ of the web having charge density $\sigma_t$ and web material thickness $d$ is given by $C_b = \varepsilon_0 \varepsilon_r A/d$. The surface voltage $V_b$ measured on surface $b$ at the roller is

$$V_b = \frac{\sigma_b A}{C_{tb}} = \frac{\sigma_b d}{\varepsilon_0 \varepsilon_r}$$
If the charge density \( \sigma_b \) is 2 \( \mu \text{Cm}^{-2} \), the relative permittivity of the web material \( \epsilon_r \) is about 3 (for example PET), and the web thickness \( d \) is 100 \( \mu \text{m} \), the surface voltage seen by an electrostatic field or voltmeter is around 7.6 V. So, the web voltage measured over an earthed metal roller is rather low, proportional to web thickness and inversely proportional to web material permittivity. An instrument capable of measurement of low voltages with good resolution (around \( \pm 0.1 \text{V} \)) is required. To interpret this measurement, the web thickness and permittivity must be taken into account. The meter is normally be positioned many times the web thickness away from the web surface and has little effect on the voltage result. It is only the charge density on the external web surface that is measured.

To prevent ignition risks from charged insulators in industrial processes, it is usual to ensure that electrostatic discharges cannot occur to the surface to nearby conductors. For breakdown and discharge, the voltage across an air gap must exceed 300 V. The field strength must exceed about 3 \( \text{MVm}^{-1} \) corresponding to a surface charge density of about 25 \( \mu \text{Cm}^{-1} \). If the charge density is established to be below the threshold at one region on the web, it will remain safe until the next point where charge can be gained, e.g. by contact with a roller. In practice a lower threshold should be used to allow for errors in measurement. Seaver used a threshold of 2 \( \mu \text{Cm}^{-2} \) giving an order of magnitude margin for error and corresponding to a surface field strength of 0.3 \( \text{MVm}^{-1} \). If this is measured mid span using a field meter calibrated to read voltage at distance \( d_m \), a voltage limit of \( E d_m \) must be used. For a meter calibrated at 2.5 cm, this gives a voltage limit of 5 kV. For a meter calibrated at 10 cm the corresponding voltage limit is 20 kV.

If the charge density is measured at the roller the voltage limit must be calculated with knowledge of the web thickness and permittivity for each circumstance. The measurement only includes the external surface charge density. The internal surface charge density must also be accounted by some means.

The model is based on field between large quasi-planar surfaces, but most field meters as used (without a “guard” plate) represent a smaller surface. Electrostatic field from regions surrounding the web material area are likely to focus on the earthed meter and elevate the electrostatic field measured. Secker [4] found that with a 150 mm diameter guard plate a field meter with 40 mm diameter sensing aperture gave correct field readings at distances between about 30 mm and 80 mm from the charged surface. Without a guard plate, readings changed nearly linearly over that range, being approximately correct at about 40 mm distance.

The model does not account for increased field strength due to a small radius conductive object approaching the web surface. Intermediate size items such as bolt heads or other machine features can give highly intensified field at the item surface causing risk of brush discharges from the charged web surface [1] The allowed web charge density may need to be reduced by more than one order of magnitude. At the extreme, small diameter fibres can be used as passive ionisers to help neutralize excessive fields by corona discharge from their tips.

In contrast, the web surface voltage over a metal roller surface is relatively independent of proximity to machine features unless the feature is very close to the web surface. The risk of an electrostatic discharge remains insignificant providing the web surface charge density is within the allowed limit.
Earthed rollers may accumulate some voltage while running due to charge generation and resistance to earth. This voltage must be subtracted from the web surface voltage for more accurate measurements.

3. A practical example

These measurements were used to evaluate charging on a web (figure 3). The incoming web material (polyethylene (PE) thickness $d = 4.5 \text{ mm}$, relative permittivity $\varepsilon_r = 2.2$) passed around three metal rollers. The mid span field $E$ was measured using a Monroe 257D electrostatic field meter. The net surface charge $\sigma_t + \sigma_b = \varepsilon_0 E$ was found to be $0.88 \, \mu\text{Cm}^{-2}$.

![Figure 3](image_url)

**Figure 3.** Example charge density measurement by free span field and roller surface voltage

The average roller voltages $V_1$, $V_2$, of the underlying metal rollers 1 and 2 were monitored at exposed roller surfaces using a Trek 368 electrostatic voltmeter and subtracted from the web surface voltages measured at the rollers $V_t$ and $V_b$. The top charge density $\sigma_t$ and $\sigma_b$ were calculated from measurements yielding +0.22 and +0.91 $\mu\text{Cm}^{-2}$ respectively. The sum of these gave 1.13 $\mu\text{Cm}^{-2}$ total charge density which compares well with the total 0.88 $\mu\text{Cm}^{-2}$ measured from the mid span field measurement.

4. Conclusions

Electrostatic measurements on insulating materials depend on the interaction of instruments with the electrostatic fields. Field meter instruments calibrated to read voltage act on underlying assumptions that are not valid in this case. Evaluation of risk of electrostatic discharges can be based on the surface charge density. For quasi planar surfaces this must be less than 25 $\mu\text{Cm}^{-2}$. Accepting a maximum surface charge density of 2 $\mu\text{Cm}^{-2}$ gives a margin of safety, but this should be reduced if small radius conductors are present. Surface charge density can be evaluated using an electrostatic field meter measurement in a free span of the web or a voltage measurement at a metal roller in contact with the web. The first method requires an earthed field meter measurement made in a position as far as possible from the user’s body or machine parts. If calibrated as a voltmeter, the corresponding voltage limit requirement for the meter (usually several kV) must be calculated. The result gives the net value of charge density on both sides of the web.

Surface charge density on one side of the web material can be measured at a metal roller using a non-contact electrostatic voltmeter capable of low voltage measurements, preferably having resolution of around 0.1 V. The maximum allowed surface voltage should be calculated knowing the permittivity and thickness of the web material, and subtracting any roller voltage. The charge on both web surfaces should be evaluated.

References

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