AC-Feedback Electrostatic Voltmeter Operation

Dr. Maciej A. Noras

Abstract An AC-feedback electrostatic voltmeter (ESVM) is an inexpensive tool which provides good measurement accuracy of surface voltage and charge. It provides precision similar to DC-feedback voltmeter along with the convenience and low price of a fieldmeter. This paper describes the principle of the Trek AC-feedback technology.

1 Introduction

Measuring electrostatic quantities poses rather special problems because electrostatic systems are generally characterized by high resistances and small amounts of electrical charge. As a result, conventional electronic instrumentation cannot normally be used for surface charge and voltage measurements, especially in those applications where the measured surface cannot be contacted.

One of the most versatile and least expensive tools for electric voltage and charge measurements is a fieldmeter. A fieldmeter is a ground referenced measuring device in which readings are inversely related to the distance from the probe to the surface or object under test. This is one of the limiting factors of all fieldmeters and if accurate readings are to be obtained, the distance from the field-meter probe to the surface under test must be precisely known and maintained, or, alternately, the fieldmeter calibration must be performed before every measurement at the specified spacing. The measurement geometry is extremely important, because the presence of the measuring instrument and nearby grounded objects alters the electrostatic field. Another limiting factor is the voltage difference between the fieldmeters sensor and the tested surface. If the distance between the surface and the meter is too close, an electrical discharge between the two may occur.

DC-feedback electrostatic voltmeters (ESVM) use a DC voltage feedback to their sensor probe housings to null the electric field between the charged surface and the probe. Compared with fieldmeters, this method minimizes capacitive loading of the charged surface and more accurately reports the electric potential of the tested object. DC-feedback voltmeters supply voltages equal to measured voltage levels back to the sensor. These voltages can be as high as 10 [kV] or more. The DC ESVM also has to be capable of following sudden changes in measured voltages, utilizing high speed amplifier circuitry for that purpose. All these requirements influence the cost of the DC-feedback ESVM.

An AC-feedback electrostatic voltmeter [1–3] is an instrument that combines the low cost of the electrostatic fieldmeter with the accuracy of DC-feedback electrostatic voltmeter. Its construction allows for elimination of high voltage circuitry that is a major cost driver for DC-feedback ESVMs. At the same time AC-feedback voltmeter offers spacing-independent measurements with better accuracy and repeatability than fieldmeters.

2 Theory of AC-feedback

A parallel-plate capacitance model is very frequently used for description of operation of the DC-feedback ESVM [4–7], (Figure 1). The sensor (a.k.a. Kelvin probe) vibrates sinusoidally in the direction perpendicular to the tested surface and the current flowing to and from the probe changes proportionally to the amplitude and frequency of that vibration:

$$I = U \cdot \frac{dC}{dt} =$$

$$= U \cdot \frac{d}{dt}\left(\frac{\epsilon\epsilon_0 A}{D_0 + D_1 \cdot \sin(\omega t)}\right) =$$

$$= \text{-}U \cdot \epsilon\epsilon_0 A \cdot \frac{D_1 \omega \cos(\omega t)}{[D_0 + D_1 \sin(\omega t)]^2} \quad (1)$$

U is the voltage between the plate and the sensor,

A is the surface area of the capacitive sensor-to-plate coupling,

ϵ is the relative electric permittivity of the material between the plate and the sensor, $\epsilon \approx 1$ for air,

ϵ_0 is the electric permittivity of vacuum, $\epsilon = 8.85 \cdot 10^{-12}$ [F/m],

D_0 is the average distance between the plate and the sensor,

D_1 is the amplitude of vibrations [m],

ω is the circular frequency of vibrations, $\omega = 2\pi f$ [rad/s], where f is a frequency in [Hz].

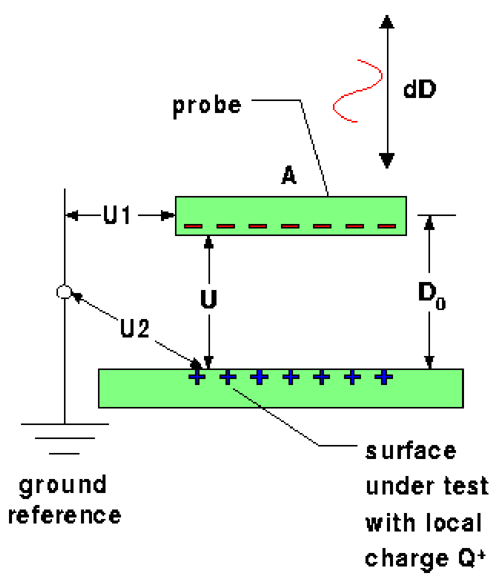

Figure 1: Parallel-plate capacitor.

In the DC ESVM this current is nullified by bringing the value of the voltage U to zero. It is done by increasing the voltage on the sensor (U_1 in Figure 1) to the voltage level of the surface under test (U_2). If the current I equals zero, it means that $U_1 = U_2$, voltage U_2 is then measured and considered a true representation of the voltage on the tested surface.

AC-feedback voltmeter uses a different method for the current I cancellation. An additional current signal I' is fed to the probe sensor in order to obtain that effect:

$$\begin{aligned} I &= \text{-}U \cdot \epsilon\epsilon_0 A \cdot \frac{D_1 \omega \cos(\omega t)}{[D_0 + D_1 \sin(\omega t)]^2} + I' = \\ &= 0 \end{aligned} \quad (2)$$

The current I' is produced by an internal generator circuit:

$$I' = C \cdot \frac{dU_t}{dt}, \quad (3)$$

where C is expressed as:

$$C = \frac{\epsilon\epsilon_0 A}{D_0 + D_1 \cdot \sin(\omega t)}$$

The internal generator supplies current signal not only to the sensor but also to the body of the probe:

$$I'' = C_{probe} \cdot \frac{dU_t}{dt}, \quad (4)$$

For the round body probe, the capacitance C_{probe}, formed between the probe and the surface under test is equal to:

$$C_{probe} = \frac{2\pi \cdot L}{\cosh^{-1}\left(\frac{D_0+R}{R}\right)}, \quad (5)$$

where L is the length of the probe, R is the radius of the probe. All other capacitive couplings between the probe and surroundings are

AC-Feedback Electrostatic Voltmeter Operation

assumed to be negligible. The current I'' is not used for nullification of the current I at the sensor. I'' is a current with constant amplitude which depends only on the distance D_0 between the probe and the tested surface and presents an additional, fixed load to the internal signal generator. The current I , detected on the sensor, is being zeroed by the current I' delivered directly to the sensor. Thus, combining equations 2 and 3:

$$\frac{\epsilon\epsilon_0 A}{D_0 + D_1 \cdot \sin(\omega t)} \cdot \frac{dU_t}{dt} = \\ = U \cdot \epsilon\epsilon_0 A \cdot \frac{D_1 \omega \cos(\omega t)}{[D_0 + D_1 \sin(\omega t)]^2} \quad (6)$$

$$\frac{dU_t}{dt} = U \cdot \frac{D_1 \omega \cos(\omega t)}{D_0 + D_1 \sin(\omega t)} \quad (7)$$

If the voltage U_t is sinusoidal, i.e.:

$$U_t = U_{t0} \cdot \sin(\omega_1 t) \quad (8)$$

$$\frac{dU_t}{dt} = U_{t0} \cdot \omega_1 \cdot \cos(\omega_1 t) \quad (9)$$

Assume that voltage U_t and vibration of the sensor have the same circular frequencies, $\omega_1 = \omega$, and compare equations 7 and 9.

$$U_{t0} \cdot \omega \cdot \cos(\omega t) = U \cdot \frac{D_1 \omega \cos(\omega t)}{D_0 + D_1 \sin(\omega t)}$$

$$\frac{U_{t0}}{U} = \frac{D_1}{D_0 + D_1 \sin(\omega t)} \quad (10)$$

If the amplitude of sensor vibration D_1 is small compared to the distance between the plate and the sensor D_0, the equation 10 becomes:

$$\frac{U_{t0}}{U} = \frac{D_1}{D_0} \approx const,$$

within a certain range of distances D_0 (Figure 2). Notice that this semi-linear region is extended if the amplitude of vibrations D_1 is being reduced. Use of D_1/D_0 scaling factor allows for a voltage of relatively low amplitude U_{t0} to represent much higher voltage U present on the plate. There is no need for high voltage circuitry. It is extremely important to remember that this relationship is valid only within the certain, specified range of sensor-to-plate distances. If D_0 is comparable to the amplitude of vibrations of the sensor D_1, the above $\frac{D_1}{D_0} \approx const$ statement becomes invalid.

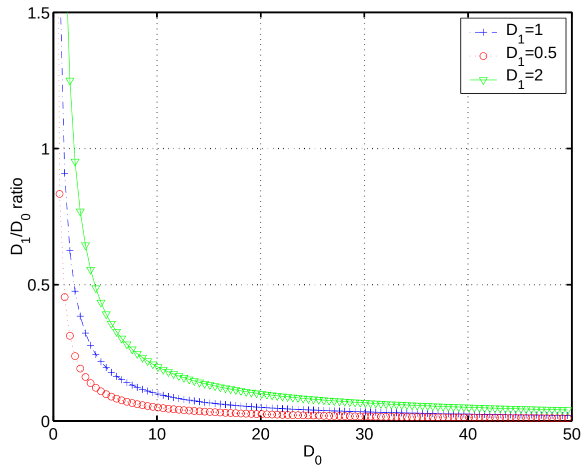

Figure 2: Influence of the sensor-to-plate distance D_0 on the current cancellation condition for various amplitudes of vibrations of the sensor D_1.

3 Conclusions

The distance D_0, for which AC-feedback voltmeter achieves its maximum accuracy, is limited by several factors. First factor is the $\frac{D_1}{D_0}$ ratio which determines the minimum plate-to-sensor spacing. Another element limiting that minimum is the voltage difference between the plate and the sensor. Notice that, unlike in the DC-feedback ESVM, AC-feedback technique does not bring the potential on the sensor to that of the surface under test.

TREK, INC. • 11601 Maple Ridge Road • Medina, NY 14103 • Tel: (585) 798-3140
Call: 1 800 FOR TREK • FAX: (585) 798-3106 • E-mail: sales@trekinc.com • Web: www.trekinc.com

AC-Feedback Electrostatic Voltmeter Operation

There is a possibility of an electric discharge between the sensor and the plate, which can lead to damage of the voltmeter.

There is also a limit regarding the maximum distance D_0. It depends on the size of the sensor, if an influence of environmental conditions can be considered negligible. If the sensor is too far from the tested surface, it becomes capacitively coupled to the surrounding, i.e. test equipment, furniture, etc. An additional constraint for AC-feedback ESVMs pertains to the type of surfaces that can be examined with accuracy specified by the manufacturer. If capacitance between the tested object and the earth ground is comparable to or less than the probe-to-ground capacitance, the AC-feedback voltmeter readings become inaccurate [8]. The AC signal generated by the AC feedback is being induced on the surface due to the capacitive coupling between the probe and the surface under test. The AC component present on the tested object creates an error offset voltage.

References

[1] B. T. Williams. High voltage electrostatic surface potential monitoring system using low voltage a.c. feedback. U. S. patent no. 4797620, 1989.

[2] D. M. Zacher. Feedback-based field meter eliminates need for HV source. *EE Eval. Eng.*, pages S43–S45, November 1995.

[3] D. Pritchard. Electrostatic voltmeter and fieldmeter measurements on GMR recording heads. In *EO/ESD Symposium Proceedings*, volume EOS-22, pages 499–504, Ananheim, CA, September 2000. EOS/ESD.

[4] W. A. Zisman. *Rev. Sci. Instrum.*, 3:367–368, 1932.

[5] Foord T. R. Measurement of the distribution of surface electric charge by use of a capacitive probe. *J. Sci. Instrum. (J. Phys. E)*, 2(2):411–413, 1969.

[6] F Rossi, G. I. Opat, and A. Cimmino. Modified Kelvin technique for measuring strain-induced contact potentials. *Rev. Sci. Instrum.*, 63(7):3736–3743, 1992.

[7] M. Wolff, A. E. Guile, and D. J. Bell. Measurement of localized surface potential differences. *J. Sci. Instrum. (J. Phys. E)*, 2(2):921–924, 1969.

[8] M. A. Noras. *AC-feedback electrostatic voltmeter measurements. Optimal measurement conditions*. Trek, Inc., 2002.

TREK, INC. • 11601 Maple Ridge Road • Medina, NY 14103 • Tel: (585) 798-3140
Call: 1 800 FOR TREK • FAX: (585) 798-3106 • E-mail: sales@trekinc.com • Web: www.trekinc.com