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Accuracy of the measurement of electric charge transferred during ESD with capacitive loaded discharge electrode

***Abstract**. In the paper there was presented the theoretical analysis of the accuracy of the measurement of the electric charge transferred through the plasma channel of electrostatic spark discharge by applying the discharge, metallic ball electrode loaded with the high quality capacitor. It was proved that applying the measurement capacitor of sufficiently high capacity, the error of the charge measurement could be freely decreased.*

***Streszczenie.** W artykule przedstawiono teoretyczną analizę dokładności pomiaru ładunku elektrycznego przenoszonego przez kanał plazmowy w czasie iskrowego wyładowania elektrostatycznego, za pomocą metalowej, kulistej elektrody wyładowczej, obciążonej nisko-stratnym kondensatorem Wykazano, że zwiększając pojemność kondensatora, można dowolnie zmniejszać błąd pomiaru spowodowany indukowaniem ładunku w obwodzie pomiarowym w czasie zbliżania sondy do obiektu naelektryzowanego, przed wystąpieniem wyładowania.(**Dokładność pomiaru ładunku elektrycznego przenoszonego podczas wyładowania elektrostatycznego, za pomocą elektrody wyładowczej obciążonej pojemnościowo**).”*

Keywords: electrostatics, electrostatic discharge**,** electrostatic charge transfer, charge measurement, transferred electrostatic charge
Słowa kluczowe: elektryczność statyczna, wyładowanie elektrostatyczne, przenoszenie ładunku, pomiar ładunku elektrostatycznego

Introduction

According to the BIA’s [1] statistics and the other [2], the electrostatic discharges (ESDs) were the source of about 8.5% ignition of dust explosive atmospheres. Probably, the statistics for gas atmospheres are similar. For this reason the prevention of electrostatic discharges in the vicinity of explosive atmospheres is an obligation for the employers [3] in European Union.

In general, the assessment of the risk of explosion initiated ESD is based on the comparison of the potential energy of possible ESD with the minimum ignition energy (MIE) of the explosive atmospheres. There ere a few basic kinds of ESDs (capacitive sparks, brush discharges, propagating brush discharges (PBD), cone discharges). The sparks occurs between conducting objects if the potential difference is higher than 300 V. Prevention of the sparks is relatively simple, it is achieved by bonding and earthing of all conducting objects (including human) in the hazardous zones. Despite of that more than 90% of dust ignition accidents caused by ESDs are the result of spark discharges [4].

The brush discharges which are able to ignite the gaseous and vapours atmospheres only (energy less than 4 mJ), usually occurs between the electrified insulators and conducting objects. The need the electrostatic potential difference several kilovolts at least. At this case the risk assessment with discharge energy cannot be apply, as the discharge is not full and the electric capacity and potential of the insulating materials cannot be well defined. For this case the other method (see Fig. 1) based on the measurement of an electric charge transferred by ESD was developed and applied [5]. It is much more convenient and accurate than the other methods. This method can be used for sparks between the conductors also, and seems to be more exact than that one based on MIE. Currently, there are available in technical standards the values of minimum ignition energies and minimum ignition charge (MIQ) as well.

To measure the transferred charge, the discharge electrode of the probe have to be approached to the electrified object up to the moment at which ESD appeared. Generally, the charge of the object should be discharge through the measurement circuit, where it should be measured. The probe of the meter consists of the metallic ball electrode (diameter of the order of 15-25 mm), earthed by measurement low value resistor R_m (order of 0.5 – 2 Ohm). To measure the charge transferred during the ESD, the voltage drop across R_m has to be integrated. Because of the very short time of ESDs (from several nanoseconds up to a few microseconds), the integrator has to be very rapid. The most commonly used integrators were a digital, wideband (above 300 MHz) oscilloscope equipped with the integrating software.

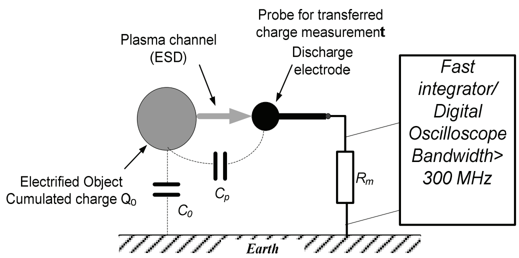

Fig.1. An electrical diagram of the circuit for measuring the electric charge transferred during provoked electrostatic discharge (ESD). C_0 – stray capacitance to the earth of the charged object, C_p – capacitance between the electrified object and the discharge electrode of the probe, R_m - special, high quality measurement standard resistor

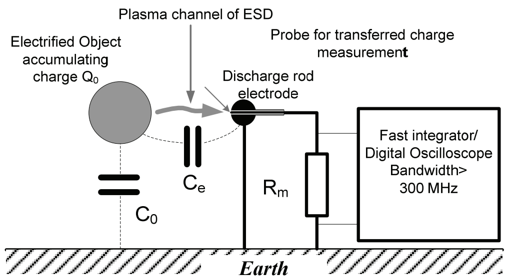

Fig.2. An electrical diagram of the circuit for measuring the electric charge transferred during provoked electrostatic discharge (ESD), with shielded discharge electrode

During last years, there appeared some papers [e.g. 7, 8, 9] pointing at the serious disadvantage of the circuitry shown in Fig. 1. When the probe was being approached to the electrified object, there appeared an increasing during approaching, the stray electric capacitance between the object and a discharge electrode. The part of the charge which was moved from the system to this stray capacitance, was discharge during the ESD directly by the plasma channel and did not flow through the resistor R_m, resulting the significant charge measurement negative error (even up to -80 – -90% for the small electrified objects).

To avoid this problem, the special construction of the probe electrode, as shown in Fig. 2 was recommended [1, 7, and 8]. The metallic ball electrode was drilled, and in the internally insulated hole, there was placed real discharge electrode (thin rod rounded at the end). The directly earthed ball acts as an electrostatic shielding and as the creator of the proper field distribution around the electrode. In fact it acts as an additional stray capacitance in parallel with the capacitance of the electrified object. In that circuit, whole charge transferred by ESD through the plasma channel hast to flow through the measurement resistor R_m, so the measurement accuracy dependent only on the accuracy of the integration voltage drop across the resistor and the accuracy of the measurement of that voltage.

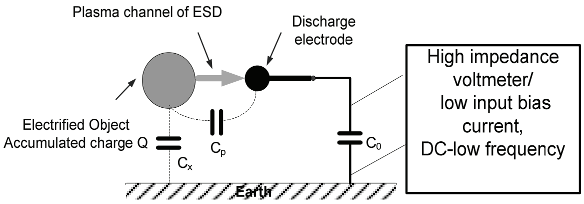

Fig.3. The circuit for measuring the electric charge transferred during provoked electrostatic discharge (ESD) with application the measurement capacitor and electrostatic voltmeter

To avoid the necessity of applying fast and expensive integrators, here was presented another method, as shown in Fig. 3. If replace the resistor R_m with the high quality capacitor C_m, there would be no need to use fast integrator. The role of integrator plays capacitor. If the time constant of the capacitor alone is of the order of 10^4 s or more, it can hold the voltage sufficiently long to make possible readout the results with a low frequency, high impedance electrostatic voltmeter. To assess the accuracy of this method, the presented below analysis was made.

Analysis

In this chapter the analysis of the accuracy of the method of measurement of the transferred ESD charge with the circuitry shown in Figs. 3. and 4. was presented. For the analysis the model of this circuitry, as shown in Fig. 4, was applied.

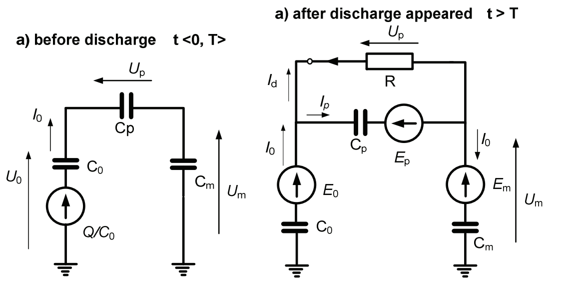

Fig. 4. Models of the transferred charge measuring with the capacitive integrator C_m. a) model used before the ESD, at the and of approaching the probe to the electrified object; b) model used just after ESD began. R – the model of the resistance of the plasma channel.

A few assumptions which simplified the analysis were put:
- the charged object was a metallic and the discharge was a spark,
- stray inductances were omitted,
- the resistance of the plasma channel was put to be linear and constant.

In the author's opinion, those assumption would not influence the final results of the analysis.
The analysis consisted of two time phases:
- the time period before the ESD (0 - T),
- the time period covering duration of the ESD (t >T).

The model diagram concerning the first phase was shown in Fig. 5a, and for the second phase in Fig. 5b.

t < T

The circuit in Fig. 5a was described with the following equation system of Laplace transforms of the currents, voltages and impedances (*s* – Laplace operator):

(1)
$$U_0 = \frac{Q}{sC_0} - \frac{1}{sC_0} I_0 = \frac{Q}{sC_0}\frac{C_0 - C}{C_0}$$
$$\frac{1}{C} = \frac{1}{C_m} + \frac{1}{C_0} + \frac{1}{C_p}$$

(2)
$$U_p = \frac{Q}{sC_0}\frac{C}{C_p}$$

(3)
$$U_m = \frac{Q}{sC_0}\frac{C}{C_m}$$

At the time moment $t = T$, the model diagram is changed to Fig. 5b. The e.m. forces E_x, representing the level of the charging of capacities, were introduced according to the formula (Eq. 4):

(4)
$$E_x(s) = E_x = L^{-1}(u_x(t))_{|t=T}\frac{e^{-sT}}{s},$$

where L^{-1} is the inverse Laplace transform.

The calculated values of e.m. forces at the moment t = T, for all the capacities had the following forms:

(5)
$$E_0 = \frac{Q}{C_0}\frac{C_0 - C}{C_0}\frac{e^{-sT}}{s};$$

(6)
$$E_m = \frac{Q}{C_0}\frac{C}{C_m}\frac{e^{-sT}}{s}; \quad E_p = \frac{Q}{C_0}\frac{C}{C_p}\frac{e^{-sT}}{s}.$$

The presented analysis aimed at evaluation of the relative difference between the value of the electric charge (Q_d) transferred by ESD through the plasma channel (represented in Fig. 4 by channel resistance R) and the charge Q_m accumulated at the measurement capacitor C_m. It was calculated in the following way:

(7)
$$Q_d = \int_T^{\infty t} i_d(t)\,dt \qquad Q_m = C_m u_m(t \to \infty)$$

(8)
$$\delta = \frac{Q_m - Q_d}{Q_d}.$$

The model shown in Fig. 5b was described with the following equation system:

(9)
$$1)\ E_0 - \frac{1}{sC_0}I_0 - E_p - \frac{1}{sC_p}I_p - E_m - \frac{1}{sC_m}I_0 = 0$$
$$2)\ I_d R_d - E_p - \frac{1}{sC_p}I_p = 0$$
$$3)\ I_0 = I_d + I_p$$

From the (Eqs. 5-7) it was found that:

(10)
$$E_0 - E_m - E_p = 0$$

For the presented analysis the calculation of the values of the currents flowing through the plasma discharge channel (I_d) and through the measurement capacitance (I_m) and the voltage drop across the measurement capacitance (U_m) were necessary and sufficient:

(11)
$$I_0 = Q\frac{CC_y}{C_0(C_y - C_p)\tau}\frac{1}{s+\alpha}e^{-sT};$$
$$\alpha = \frac{C_p}{(C_p - C_y)\tau};\ \tau = RC_p;\ C_y = \frac{C_m C_0}{C_m + C_0}$$

(12) $$I_d = Q\frac{C}{C_0\,\tau}\left[\frac{C_y}{\left(C_y-C_p\right)}\frac{1}{\tau\,(s+\alpha)}\frac{1}{\left(s+\frac{1}{\tau}\right)}+\frac{1}{\left(s+\frac{1}{\tau}\right)}\right]e^{-sT}$$

(13) $$U_m = E_m - \frac{1}{sC_m}I_0 = = Q\frac{C_m}{C_0C_m}\left[1-\frac{C_y}{\left(C_y-C_p\right)\tau}\frac{1}{s+\alpha}\right]\frac{e^{-sT}}{s}$$

Calculating the reverse Laplace transforms, the necessary currents, charges voltage in the time domain were derived:

(14) $$i_d(t) = Q\frac{C}{C_0\tau}e^{-\alpha(t-T)}$$

The value of the charge transferred through the plasma channel during ESD was:

(15) $$Q_d = \int_T^{\infty} i_d(t)\,dt = Q\frac{C}{C_0}\frac{\left(C_p-C_y\right)}{C_p} = Q\frac{C_p-C}{C_0+C_m}$$

The voltage drop after ESD across the measurement capacitor C_m was:

(16) $$u_m(t) = Q\frac{C}{C_0C_m}\left[1(t-T)-\frac{Cy}{\left(C_y-C_p\right)\tau}e^{-\alpha(t-T)}\right]$$

(17) $$u_m(t\to\infty) = Q\frac{C}{C_0C_m}\ .$$

The value of the charge accumulated in the measurement capacitor was:

(18) $$Q_m = C_m u_m = Q\frac{C}{C_0} = Q\frac{1}{1+\frac{C_p}{C_0}+\frac{C_0}{C_m}}$$

The relative error of the measurement of the transferred charge Q_d by assuming that measured $Q_d = Q_m$ was derived from (Eqs. 7, 8, 14-16):

(19) $$\delta = \frac{Q_m-Q_d}{Q_d} = \frac{C_y}{C_p-C_y} = \frac{1}{1+\frac{C_0}{C_p}+\frac{C_m}{C_p}} \to_{|C_m >> C_0, C_p} \frac{C_p}{C_m}$$

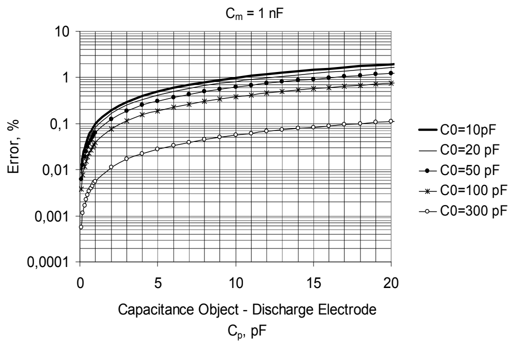

Fig. 5. Dependence of the error of measurement of charge transferred by ESD on the circuit capacitances C_0 and C_p at C_m =1nF

Discussion and conclusions

On the basis of (Eq. 19) it can be concluded that accuracy of the measurement of the transferred charge could be freely improved by increasing the measurement capacitance C_m. The dependence of the measurement relative error on capacitances C_0 , C_p and C_m was shown in Fig. 5 and 6.

On the basis of the made analysis it could be stated that applying of the integrating capacitor in place of the resistor was possible and had the following advantages:

- there is no need to use the expensive wideband digital oscilloscopes, which could be difficult to apply at the field measurements,
- increasing the value of the capacitance C_m results increasing the time duration of holding the measured charge in C_m or applying worse quality voltmeter.

The important disadvantage of that method is a lack of possibility of checking if multiple discharges were provoked. At the oscilloscope method this is visible at once. This problem could be resolved by adding to the probe a fast counter of the received pulses.

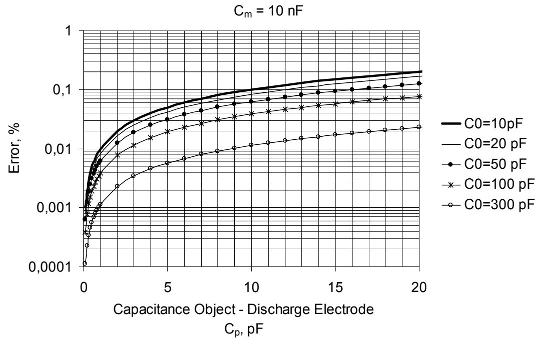

Fig. 6. Dependence of the error of the measurement of charge transferred by ESD on the circuit capacitances C_0 and C_p at C_m =10 nF

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REFERENCES

[1] BIA-Report: „*Dokumentation Staubexplosonen. Analyse und Einzelfalldarstellung*", HVBG, 11/97, Sankt Augustin, 1997

[2] Taylor D.M., Secker P.E., Industrial electrostatics. Fundamentals and measurements. Research Studies Press LTD, Taunton, 1994

[3] Kondej, D., Gawęda, E. 2006, Wybuchowość pyłów metali na przykładzie pyłów aluminium. *Bezpieczeństwo pracy. Teoria Praktyka*. (in Polish) nr 10 (421), CIOP-PIB, 12-15

[4] Directive 1999/92/EC of the European Parliament and of the Council of 16 December 1999 on minimum requirements for improving the safety and health protection of workers potentially at risk from explosive atmospheres (15th individual Directive within the meaning of Article 16(1) of Directive 89/391/EEC). OJ EU, L 23/5728.1.2000

[5] Jones, T., B., King, J., L., *Powder handling and electrostatics.*, Lewis Publishers, Chelsea, Michigan, 1991

[6] von Pidoll, U., Brzostek, E., Froechtenigt, H.-R, Determining the incendivity of electrostatic discharges without explosive gas mixtures. *IEEE Transactions on Industry Applications*, 2004, vol. 40, 6, 1467- 1475

[7] Chubb, J.N., Measurement of charge transfer in electrostatic discharges. *Journal of Electrostatics*, 2006, vol. 64, 321 – 325

[8] Walmsley, H.L., Induced-charge errors in charge-transfer measurement. *Journal of Electrostatics*, 2009, vol. 67, 320 – 325

[9] Holdstock, P., Does charge transfer correlate with ignition probability? *Journal of Physics*: Conference Series 142, 2008, 01/2009

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