Most Possible Zones for Discharge Initiation in a Vacuum Interrupter under Test

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Abstract - **Nowadays, the best method to measure the pressure inside a vacuum circuit interrupter designed to operate at pressures of 10^{-4} Torr and lower is the magnetron. A cold-cathode magnetron ionization principle is employed to measure pressure within the vacuum interrupter through the use of the existing interrupter elements as the principal parts of an ionization gauge and by immersing the vacuum apparatus in a magnetic field.**

The role of a metallic vapor-condensing shield of tubular configuration as a collector of positive ion current for creating the characteristic torus-shaped plasma regions in the internal space of a vacuum apparatus is revealed by appropriate modeling of the electric and magnetic fields.

Keywords - **Cathode magnetron ionization principle, Magnetron pressure measurement method, Metallic vapor-condensing shield, Vacuum circuit interrupter.**

I. INTRODUCTION

Measuring the pressure in a *vacuum circuit interrupter* (*VCI*) has always been a great problem for manufacturers of vacuum switchgear. A factory-made *VCI* is not able to maintain its internal pressure forever, yet its shelf life is longer than ten or twenty years and customers want to be sure that pressure in the vacuum envelope won't increase considerably during this period. Thus, one needs a technique that can provide detection of residual pressure alteration in *VCI*, [6].

Nowadays, the best method of measuring the pressure inside a vacuum envelope is the magnetron. A cold-cathode magnetron ionization principle is employed for measuring the pressure within the vacuum interrupter by using the existing interrupter elements as the principal parts of an ionization gauge and by immersing the vacuum circuit apparatus in a magnetic field.

The *VCI* comprises an evacuated sealed envelope, a pair of separable contacts or electrodes within the envelope, which are movable from an engaged position to a spaced-apart position to define an arcing gap therebetween, and a *metallic vapor-condensing shield* (*MVCS*) of tubular configuration surrounding the gap and electrically isolated from at least one of the electrodes by an evacuated space surrounding said electrode [3, 6, 7].

There are four possible cases of realizing a diode ionizing gauge for measuring the pressure inside the *VCI* vacuum envelope with the participation of *MVCS* as a cathode of a cold-cathode ionizing gauge, Fig. 1, or as an anode – not shown as an execution variant in Fig. 1:

♦ As a cathode *MVCS* performs the part of a collector for measuring the ion current, and the two contacts of *VCI* are closed and have the same potential, i. e. they represent an anode, Fig. 1a;

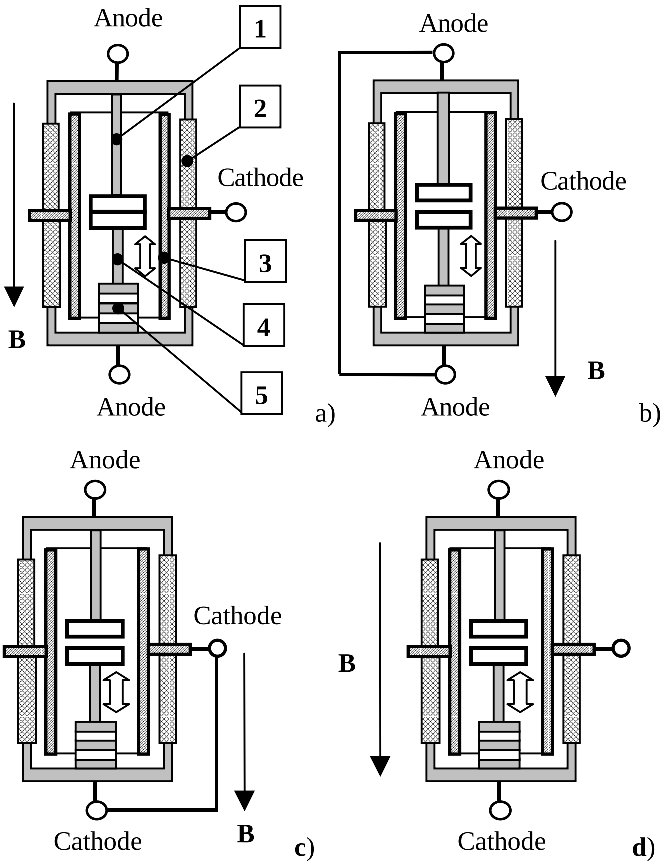

Fig. 1. Principal parts of a vacuum circuit interrupter performing the part of a diode ionization gauge (a) for measuring the pressure inside the vacuum sealed envelope and the way of participating of the metallic vapor-condensing shield (*MVCS*): **a** – for a closed electrode system and negative potential at *MVCS*; **b, c** - for an opened electrode system and negative potential at *MVCS*; **d** – for an opened electrode system, *MVCS* having a floating potential.

1 – fixed electrode; **2** – insulation cylinder; **3** - metallic vapor-condensing shield; **4** – movable electrode; 5 - bellows.

♦ *MVCS* may be a cathode again, depending on its electrical connection to one of the two electrodes, Fig. 1c;

♦ *MVCS* participates indirectly in the measurement, remaining with a floating potential, fig. 1d. This case is

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characteristic for *VCI*, the *MVCS* of which has no terminal outside the vacuum-sealed envelope of *VCI*.

T. Lee (1957) patented a triode ionizing gauge for measuring the pressure, but these technical solutions dropped off in the subsequent development of this issue, [6].

All variants shown are realizable only in the presence of an electric terminal of *MVCS* outside the vacuum envelope.

In all described cases of measurement *MVCS* performs the part of a cathode that collects positive ions moving towards it. The arrival of these positive ions at the cathode results in a current flowing through the cathode. The magnitude of this current is indicative of the pressure in the interrupter, Fig. 1.

THE TASK of the present work consists in revealing the participation of the metallic vapor-condensing shield in the occurrence and maintenance of a cold-cathode magnetron discharge in the space between the anode and the cathode of an ionizing gauge inside the evacuated envelope of *VCI.*

II. GENERAL FORMULATION OF THE INVESTIGATIONS

From the theory of Penning's discharge it is well known that at using weak magnetic fields – having minimal magnetic flux density **B** below 20 mT – and at pressures below 10^{-4} Torr a maximally uniform distribution of the negative volumetric charge is obtained. Under these conditions the discharge exists in its steady state without any electromagnetic radiation. The percentage of the electron component in the cathodic (discharge) current does not exceed a few hundredths. The theoretical model agrees well with the results from the experimental investigations, [1].

Discharge current I_p varies with applied anode potential V_a in the following manner [1]:

$$I_p = M\left[2\left(V_a - V_0\right) - V_0\left(\frac{r_a}{l^2}\right)\right] a\ p\ l_a \tag{1}$$

$$M = \frac{1 + \left(1 - \frac{\beta^2}{2\,\omega^2}\right)^{0.5}}{2\left(1 - \frac{\beta^2}{\omega^2}\right)^{0.5}} \tag{2}$$

$$\beta^2 = 2\,e\left(V_a - V_0\right)/\,m_e\,r_a^{\,2} \tag{3}$$

$$\omega = e\,B\,/\,2\,m_e \tag{4}$$

where p is the pressure; a – a constant that depends on the nature of the gas; V_0 – the potential at the center of the *Penning's cell*; e, m_e – the electron charge and mass; r_a, l_a – radius and length of the *Penning's cell.*

From Eq. (1) it follows a conclusion, which is important for the measurement of pressure p, namely that the intensity of Penning's discharge is constant in the so-called first regime of burning:

$$\frac{I_p}{p} = const \ \text{ or } \ I_p = k\ p\,, \tag{5}$$

where k is a coefficient depending on gauge construction.

This relationship lies at the basis of the operation of the ionization vacuum gauges of the so-called Penning's vacuum gauges, [5].

There are also patented proposals of including the cold-cathode ionization gauge as a separate measurement element in the construction of *VCI*, [3, 6].

Measuring the pressure in a sealed envelope by means of the contact system of *VCI* transforms the Penning's gauge into a magnetron-type diode ionization gauge, Fig. 2.

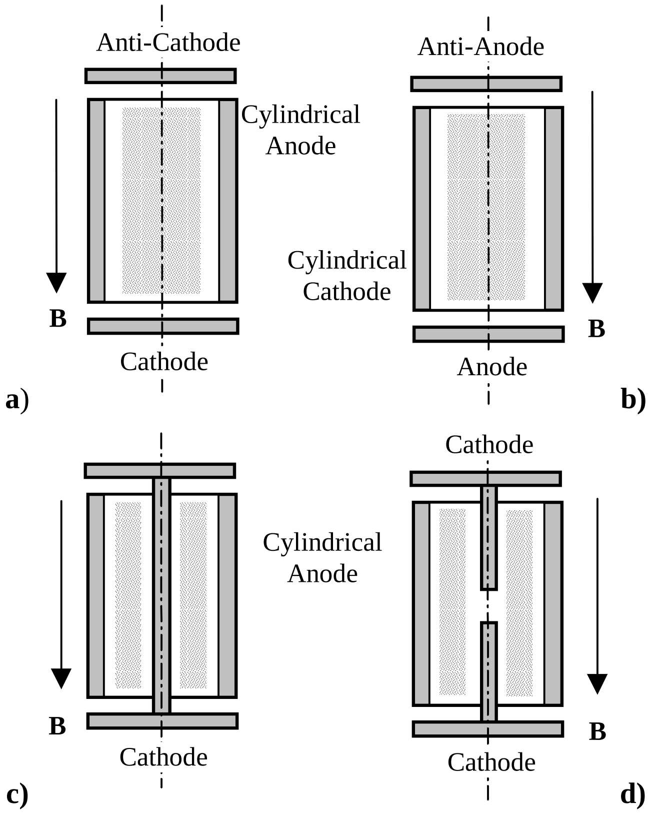

Fig. 2. Principal configurations of Penning's discharge - basic (**a**) and inverse (**b**), and of the magnetron ionizing discharge - basic with one cathode (**c**) and basic with a two-part cathode - cathode and anti-cathode (**d**) in a diode ionizing gauge.

The principle of permanence of discharge intensity I_p remains in force also for the basic and inverse cold-cathode magnetron ionization discharge, which allows performing the pressure measurement in *VCI* under the same conditions.

The difference consists in the manifestation in this case of a power law instead of the linear one [3, 7]:

$$\frac{I_p}{p^n} = const \ \text{ or } \ I_p = k\ p^n\,, \tag{6}$$

where n is the exponent, the value of which most often is $n = 1.1$ in the most frequently used constructions.

As Eq. (6) has been obtained empirically from the investigation of real constructions, it should be assumed the understanding of the fact that the increase in exponent *n* mirrors not only the transition to magnetron ionization discharge, but also the rotational non-cylindrical form of *MVCS*, the creation of a labyrinth transition from the space inside *MVCS* to the volume in front of the insulation cylinders with the purpose of protecting it against metal vapors, etc., Fig. 4.

Lucek and *Pearce* [3], have already informed about the fact that modifying the construction of flanges with the purpose of creating the labyrinth transition leads to instability of the magnetron discharge and cathodic current. Our investigations performed on such modern constructions indicate that in this case it is most appropriate to use the circuit of inverse magnetron ionizing discharge, i. e. *MVCS* becomes a cathode in accordance with Fig. 1a.

III. RESULTS AND DISCUSSION

The *MVCS* role is examined in two basic cases of measurement: ♦ the measurement circuit or the first model in accordance with Fig. 1a and ♦ the measurement circuit or the second model in accordance with Fig. 1d.

A vacuum circuit interrupter is immersed in the magnetic field of two Helmholz's coils located co-axially with respect to each other, the magnetic flux density of which is directed along the axis of the vacuum device, Fig. 3a.

Using modern software products, simulation is conducted for the 2D-distribution of the axially symmetrical magnetic field of Helmholz's coils, in which *VCI* is immersed.

The technical solution selected creates a relatively uniform magnetic field all through the volume of the vacuum sealed envelope, which ensures the same conditions for the manifestation of the cathode magnetron ionization principle in different regions of discharge burning, Fig. 3b.

This allows estimating the effect of the three characteristic zones of the magnetron ionizing discharge in the volume of *VCI* upon the magnitude of the positive ion current consisting respectively of three components, each of them corresponding to one of the following discharge regions:

♦ higher region of discharge between the fixed contact flange and the top part of *MVCS* – in the region of the upper labyrinth sealing;

♦ central region of discharge between the contacts that touch each other and *MVCS* for the first model of measuring or in the intercontact region and between the opened contacts and the middle part of *MVCS*;

♦ lower region of discharge between the movable contact flange, bellows and bottom part of *MVCS* – in the region of the lower labyrinth sealing, Fig. 4.

By using software products based on the numerical method of finite elements, two distributions of electric field intensity |**E**| are obtained. Each of these distributions corresponds to the selected variant of pressure measurement performed by measuring the positive ion current, Fig. 4.

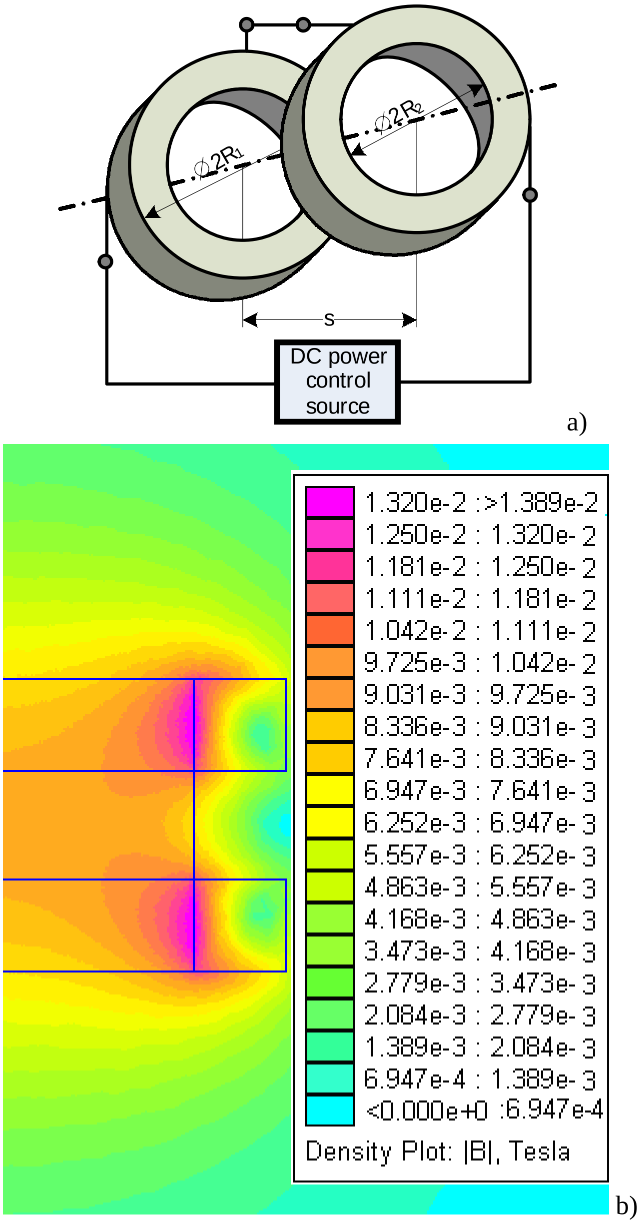

Fig. 3. Modeling the distribution of the magnitude of magnetic flux density **B** along the axis of the two Helmholz' s coils (**a**), one of which is placed under the other and which create a relatively uniform magnetic field (**b**) in the whole volume of the vacuum circuit interrupter.

The relatively uniform electric field makes visible the regions of burning of the magnetron ionizing discharge, which form the common ion current. Moreover, from the magnitude of the intensity of electric field **E** in the corresponding region it is possible to estimate, although roughly, the contribution of each region to the value of the common ion current.

In both cases of participation of *MVCS* in the circuit of measuring the pressure in *VCI*, as a basic element of the magnetron ionization gauge, it is possible to take into account the strong influence exerted by the two regions of labyrinth transitions of the vacuum sealed envelope upon the cathodic current.

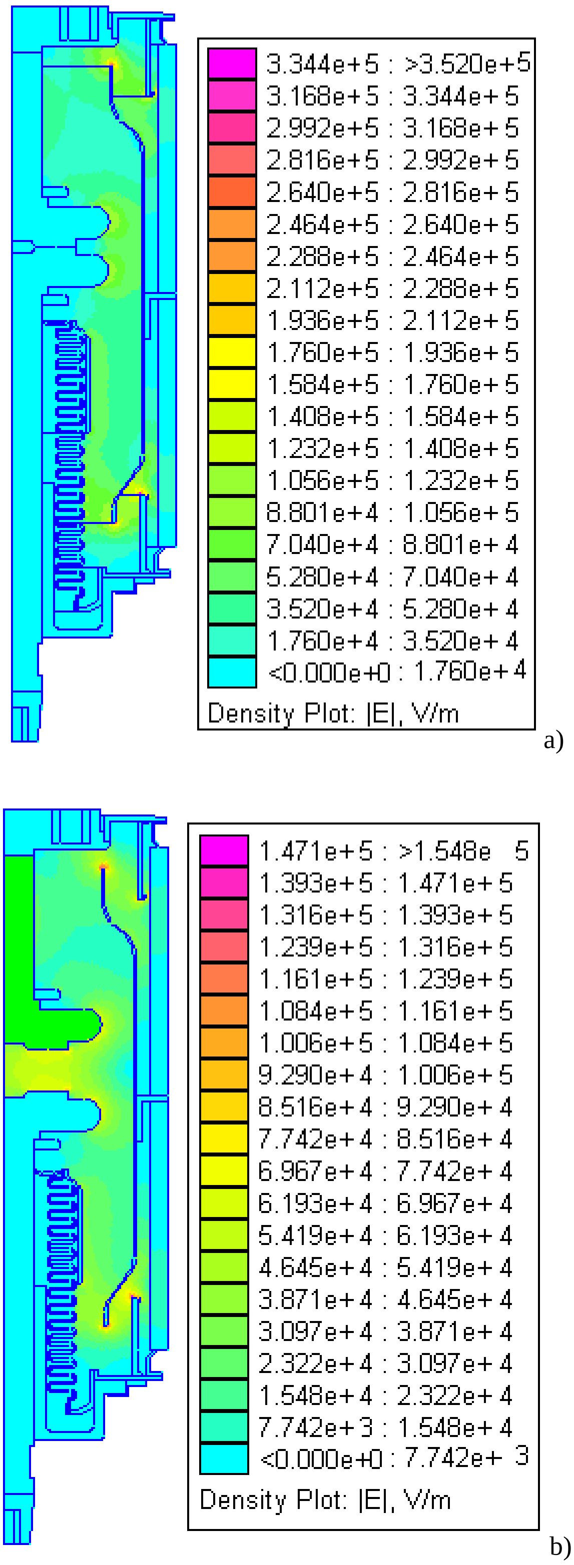

Fig. 4. Distribution picture for the magnitude of the electric field intensity |**E**| in the volume of *VCI* for a closed contact system and *MVCS* electrically powered as a cathode (**a**) and left in the state with floating potential (**b**).

The maximal values of intensity |E| of the electrical field in the corresponding regions of the magnetron ionizing discharge are shown in Table 1.

In both cases of investigation it is obvious that the contribution of the lower labyrinth transition and the bellows region to the magnitude of discharge current is considerably higher – with 91 percent (model 1) and with 64 percent (model 2) – with respect to the central region of the discharge.

TABLE 1.

REGION OF MAGNETRON IONIZING DISCHARGE	MAXIMAL VALUE OF ELECTRICAL FIELD INTENSITY, V/m
MODEL OF MEASURING 1	
Higher discharge region	219
Central discharge region	121
Lower discharge region	232
MODEL OF MEASURING 2	
Higher discharge region	134
Central discharge region	86
Lower discharge region	142

For the labyrinth transition shown above this difference is considerably smaller – respectively with 80 percent (model 1) and with 56 percent (mode 2), Table 1.

The difference between the two central zones of the magnetron discharge amounts to about 41 percent in favor of the circuit with *MVCS*-cathode.

IV. CONCLUSION

Watrous (1971) patented a magnetron circuit for direct pressure measurement with local action of the magnetic field in the central zone of *VCI*, [7].

The investigation performed indicates that this may be even more successfully carried out locally also in the zone of each of the two labyrinth transitions.

The simultaneous involving of the three characteristic discharge regions with the participation of *MVCS* increases sharply the sensitivity of the magnetron method of pressure measurement.

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