Analysis of Magnetron Discharge Regions in Vacuum Chamber under Test

Raina Tzeneva[1], Peter Dineff[2]

Abstract - **A cold cathode magnetron ionization principle is employed to measure the pressure within the vacuum interrupter by using existing interrupter elements as 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 the positive ion current is studied. The magnetron discharge of *G. Phillips* (1898) is used, and the magnetic field is oriented along the direction of the electrodes of a vacuum interrupter. Using appropriate modeling of the electric and magnetic field, the characteristic plasma toroidal regions in the space of the vacuum apparatus are determined.**

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

I. INTRODUCTION

Nowadays, the best principle of indirectly measuring the pressure inside a vacuum envelope is that of the magnetron. A cold cathode magnetron ionization principle is employed to measure the pressure within the vacuum interrupter by using existing interrupter elements as principal parts of an ionization gauge and by immersing the vacuum circuit apparatus in a magnetic field, Fig. 1 [2, 3, 5, 6, and 8].

Measuring the pressure in factory made *vacuum circuit interrupters* (*VCI*) has always been a great problem for the manufacturers of vacuum switchgear during its shelf life, which is longer than ten or twenty years. The *VCI* cannot maintain the pressure inside itself during all that time, and customers want to be sure that the pressure in the vacuum envelope will not be increased considerably for this period. That is why there is a need of a technique that will permit detecting any residual pressure alterations in *VCI*, [6, 7].

The *VCI* comprises an evacuated and sealed envelope, a pair of separable contacts or electrodes within that envelope, which can move from an engaged position to a spaced-apart position in order 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 that electrode [3, 6, 7].

There are two possible cases of a diode ionizing gauge for measuring the pressure inside the *VCI*-vacuum envelope with the participation of *MVCS* as a cathode, Fig. 1:

♦ *MVCS* as the cathode of a cold cathode ionizing gauge performs the role of a collector for measuring the ion current, and the two contacts of *VCI* are closed and have the same potential, i. e. together they form the anode of the ionizing gauge, Fig. 1a;

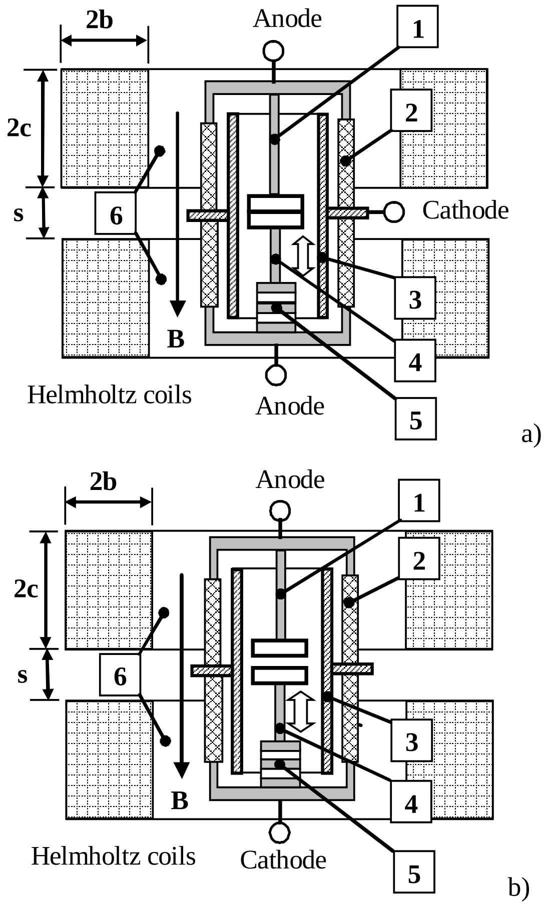

Fig. 1. Sectional view of the vacuum interrupter employed as a diode ionization gauge for indirect pressure measurement within the vacuum sealed envelope when an exterior electrical connection to the metallic vapor-condensing shield (*MVCS*) is either available (a) – closed electrodes and negative potential at *MVCS*; or unavailable (b) – opened electrodes and floating potential at *MVCS*.

1 – fixed electrode; **2** – insulating cylinder; **3 -** metallic vapor-condensing shield; **4** – movable electrode; **5** – sylphon; **6** – *Helmholtz* coils.

---

[1] Raina T. Tzeneva is with the Department of Electrical Apparatuses, Faculty of Electrical Engineering, Technical University of Sofia, 8 Kliment Ohridski Blvd., 1000 Sofia, Bulgaria, E-mail: tzeneva@tu-sofia.bg.

[2] Peter Dineff is with the Department of Electrical Apparatuses, Faculty of Electrical Engineering, Technical University of Sofia, 8Kliment Ohridsk iBlvd., 1000 Sofia, Bulgaria, E-mail: dineff_pd@abv.bg.

- *MVCS* participates indirectly in the measurement, staying at floating potential, Fig. 1b; this case is characteristic for many of the modern *VCI*, *MVCSs* of which have not any tap outside the *VCI* vacuum sealed envelope.

In both cases the *VCI* vacuum envelope is immersed in a constant magnetic field oriented along the axis of the electrodes, which corresponds to the well-know circuit of *G. Phillips* (1898) for the ignition of a magnetron discharge, Fig. 2 [4].

Measuring the pressure in the sealed envelope with the help of the *VCI* contact system transforms *VCI* into a magnetron-type diode ionization gauge.

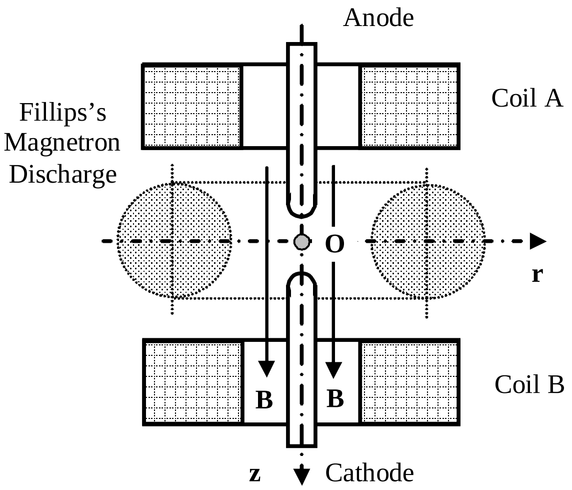

Fig. 2. Spatial arrangement of the *Fillips*'s magnetron ionizing discharge.

The possibility of placing the evacuated *VCI* envelope fully in a relatively uniform magnetic field created by two *Helmholtz* coils, coaxially situated, allows investigating the conditions provided by the electrodes and *MVCS* for the ignition and the burning of the magnetron discharge.

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

II. GENERAL FORMULATION OF INVESTIGATIONS

The vacuum circuit interrupter is immersed in the magnetic field of two *Helmholz* coils, coaxially situated above each other, the magnetic flux density **B** of which is oriented along the axis of the vacuum device, Fig. 1.

The metallic vapor-condensing shield has a rotationally symmetric shape and is placed in such a way in the space inside the interrupter that creates a labyrinth transition from the space before the insulating cylinders to that inside *MVCS* that it ensures the necessary protection of the insulating cylinders from metal vapors and metallization, Fig. 1.

The so selected technical solution provides a relatively uniform magnetic field in the space of the vacuum sealed envelope and similar conditions for the manifestation of the cathode magnetron ionization principle in the three characteristic regions of burning of the magnetron discharge depending on gauge construction, Fig. 3:

- the higher region of discharge between the flange of the fixed contact and the upper part of *MVCS*, or in the region of the higher labyrinth sealing, Figs. 3 and 4;
- the central region of discharge between the touching contacts and *MVCS*, Fig. 3, or in the region between the open contacts and between them and the central part of *MVCS*, Fig. 4;
- the lower region of discharge between the flange of the movable contact, sylphon and lower part of *MVCS*, or in the region of the lower labyrinth sealing, Figs. 3 and 4.

Lucek and *Pearce*, [3], were the first to find out that modifying the flange design in order to create the labyrinth transition leads to instability of the magnetron discharge and of the cathode current measured.

Our investigations, [7], performed on modern designs of vacuum interrupters indicated that in this case it is most appropriate to use the circuit of inverse magnetron ionizing discharge where *MVCS* is the cathode, as it is shown in Fig. 1a.

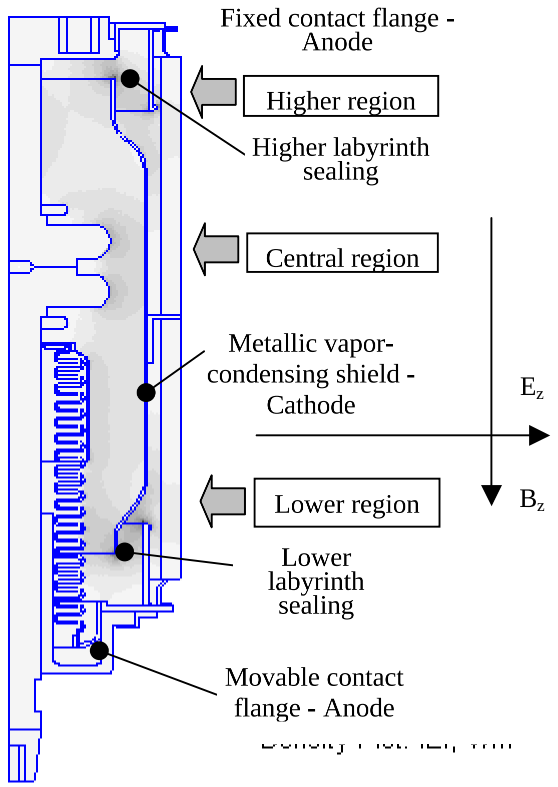

Fig. 3. Picture of the distribution of electric field intensity value |E| in the space of the *VCI* closed contact system – anode, and *MVCS* - cathode.

III. RESULTS AND DISCUSSION

The role of *MVCS in* the two main case of measuring is investigated: ♦ the measurement circuit or the first model according to Fig. 3 and ♦ the measurement circuit or the second model according to Fig. 4.

Using modern software products based on the numerical method of boundary elements, two distributions of the electric field intensity |**E**| have been obtained, each of them corresponding to the selected variant of the pressure measurement by measuring the positive ion currents, Figs. 3 or 4. The relatively uniform magnetic field makes visible the regions of burning of the magnetron ionizing discharge that form the total positive ion current.

It is known that the height of the cycloid h_e, along which the free electron drifts in a plane transversal to the direction of magnetic field ***B***, and gains energy $e.V_i$, sufficient for an α- or electron impact ionization, is defined as follows:

$$h_e\, E_r \geq e\, V_i \quad \text{or} \tag{1}$$

$$h_e\, E_r = 2\, \mu_0^{\,2}\, \frac{m_e}{e}\, \frac{E_r^{\,2}}{B_z^{\,2}} \geq e\, V_i\,, \tag{2}$$

where $\mu_0 = 4\,\pi\, 10^{-7}$ H/m is the magnetic constant; $m_e = 9.11 \times 10^{-31}$ kg – the electron mass; $e = 1.602 \times 10^{-19}$ C – the electron charge; E_r – the radial component of the of electric field intensity; B_z – the axial component of the magnetic field; V_i – the first ionization potential.

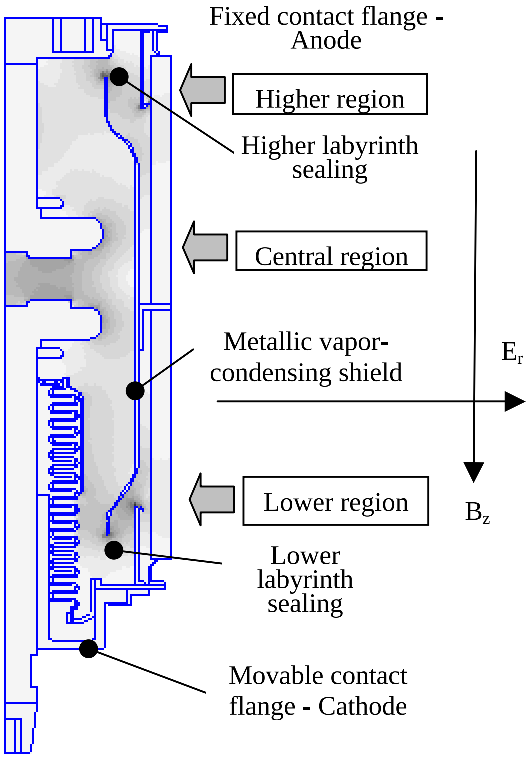

Fig. 4. Picture of the distribution of electric field intensity value |E| in the space of *VCI* at open contact system and *MVCS* under the action of a floating potential.

The first ionization potential for oxygen is $V_i\,(O_2) = 13.618$ V, and for nitrogen - $V_i\,(N_2) = 14.534$ V, which allows calculating the critical ratios of the magnetron ionization for oxygen and nitrogen, respectively:

$$\text{for oxygen: } \left(\frac{E_r}{B_z}\right)_{cr} \geq 1102\ , \text{kV/(T m)} \tag{3}$$

$$\text{for nitrogen: } \left(\frac{E_r}{B_z}\right)_{cr} \geq 1138\ , \text{kV/(T m)} \tag{4}$$

This permits to determine the conditions of magnetron ionizing discharge in different regions depending on the magnetic field created, the *Helmholtz* coils having the following geometrical parameters, Fig. 1: 2 R$_2$ = 375 mm; 2 R$_1$ = 255 mm; 2 b = 60 mm; 2 c = 60 mm; s = 9, 19, 29, 39, 49, 59, or 69 mm. The number of turns in each of the two coils is 150.

The seven models of the magnetic field (s = var) allow determining the values of its axial component B_z for various distances s between coils. Maximal magnetic flux density B_z in the lower region does not depend on the distance between coils, s ∈ [9…69] mm: B_z = 0.0086 T.

Maximal magnetic flux density B_z in the central region diminishes with increasing distance s - s/B_z, mm/T: 9/0.0117; 19/0.0114; 29/0.0110; 39/0.0107; 49/0.0103; 59/0.0099; 69/0.0096.

Maximal magnetic flux density B_z in the higher region demonstrates analogous behavior, but is of values lower than those in the central region of the interrupter - s/B_z, mm/T: 9/0.0113; 19/0.0111; 29/0.0108; 39/0.0105; 49/0.0102; 59/0.0098; 69/0.0096.

The magnetic field is most homogeneous in the space of the interrupter investigated at s = 69 mm.

Calculated critical values of intensity $(E_r)_{cr}$ of the electric field – at $h_e\, E_r = e\, V_i$, for s = 69 mm, for oxygen and nitrogen, respectively, are shown in Table 1 for the different regions of magnetron ionizing discharge.

TABLE 1

REGION OF MAGNETRON IONIZING DISCHARGE	OXYGEN	NITROGEN
	E_R, kV/m	E_R, kV/m
MODEL OF MEASURING (CLOSED ELECTRODE, AVALABLE SHIELD)		
Higher discharge region	10.58	10.92
Central discharge region	10.58	10.92
Lower discharge region	9.48	9.79
MODEL OF MEASURING (OPENED ELECTRODE, UNAVALABLE SHIELD)		
Higher discharge region	10.58	10.92
Central discharge region	10.58	10.92
Lower discharge region	9.48	9.79

Data in Table 1 allow making the following conclusions: *first*, the two regions of the vacuum interrupter – the higher and central ones – have same critical values of intensity E_r, irrespective of the measurement circuit; *second*, it is possible to determine the space of burning of magnetron ionizing discharge in the three regions of *VCI*, irrespective of the measurement circuit for critical intensity E_r; *third*, the lower region of magnetron ionizing discharge has a critical ignition voltage which is considerably lower.

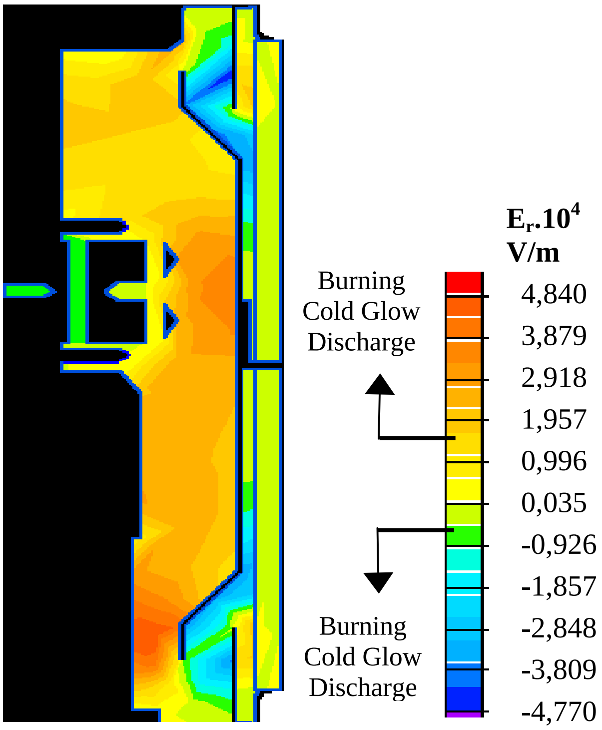

Fig. 5. Spaces of magnetron ionizing discharge in the higher (a), central (b), and lower (c) regions of the evacuated envelope at closed contact system of *VCI* and *MVCS* – cathode.

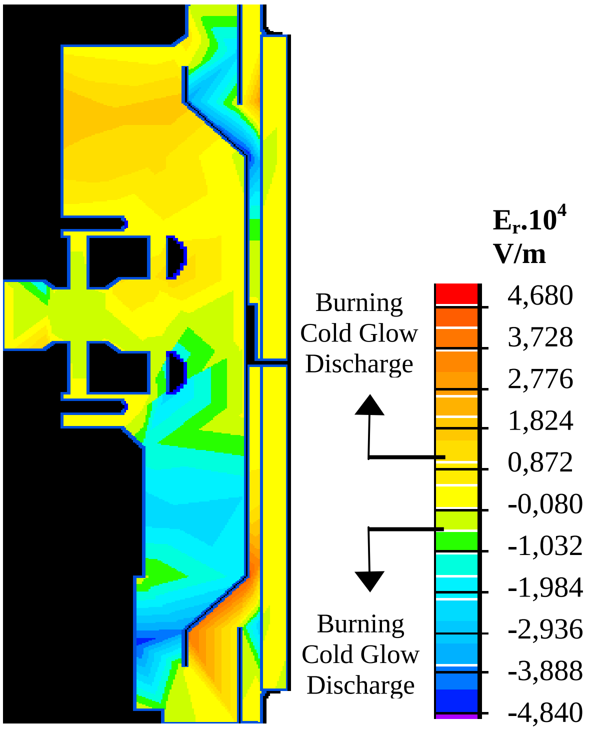

Fig. 6. Spaces of magnetron ionizing discharge in the higher (a), central (b), and lower (c) regions of the evacuated envelope.

The presented distribution of radial component E_r of the electric field in a cross-section symmetrical to the axis of the vacuum interrupter permits – by using the software product *Photo Shop 6* – determining the volume of the space of intensive ionization and burning of magnetron ionizing discharge: it is 85 % of the whole volume (Fig. 5) and 35 % of the whole volume (Fig. 6), respectively.

To our regret, the method of measurement with a closed contact system remains inapplicable to modern vacuum interrupters because most often the metallic vapor-condensing shield or *MVCS* has not any tap outside the vacuum envelope. Accordingly, it becomes mandatory to use the second method, i. e. that of measuring with an open contact system. However, it provides a considerably smaller magnetron ionizing volume, which also means lower sensibility.

IV. CONCLUSION

The magnetron ionizing method of indirect pressure measurement by focused action of the magnetic field in the central region of *VCI*, patented by *Watrous* (1971), does not provide any real advantages as the lower region is characterized by a more strongly expressed ionization. In that case of measurement, the almost equivalent higher region of magnetron air ionization, i. e. that of oxygen and nitrogen should not be ignored as well [4, 7].

The modeling investigation performed has shown that this pressure measurement can be realized locally in the same way in the region of each of the two labyrinth transitions of the vacuum interrupter.

The simultaneous use of all three characteristic regions of magnetron ionizing discharge (with the participation of *MVCS*) in measuring the pressure by means of the discharge current increases strongly the sensitivity of the magnetron method of pressure measurement.

The movable contact region, together with that of the lower labyrinth transition, or the lower region of the vacuum interrupter remains the most active region of magnetron air ionization, irrespective of the method of measurement.

REFERENCES

[1] G. L. Saksaganski, *Electro-Physical Vacuum Pumps*, Moscow, Energoatomizdat, 1988 (in Russian).

[2] J. D. Cobine and J. M. Lafferty, Vacuum Device Gas Measurement Apparatus and Method, US-Patent Appl. No 3,495,165, Patented Feb. 10, 1970.

[3] P. Dineff, *Electrotechnology. Introduction to Electrotechnology*, Technical University, Sofia, Bulgaria, 2000 (in Bulgarian)

[4] P. A. Redhead. Ionization Vacuum Gauges, US-Patent Appl. No 3,051,868. Patented Aug. 28, 1962.

[5] W. W. Watrous, Method and Apparatus for Measuring Pressure in Vacuum Interrupters, US-Patent No 3,575,656, Patented Apr. 20, 1971.

[6] Zhao Zjyu et al., “Study on Internal Pressure Measurements in Vacuum Interrupters”, *Proceedings of XIX ISDEIV*, pp. 775-778, China, 2000.

[7] R. Tzeneva, P. Dineff, “Most Possible Zones for Discharge Initiation in a Vacuum Circuit Interrupter under Test”, *XXXIX International Conference on Information, Communication and Energy Systems and Technologies ICEST’2004 Proceedings of Papers*, v. 2, pp. 537-540, Bitola, Macedonia, 16 – 19 June, 2004.