Electrical Breakdown in Low-Pressure Nitrogen in Parallel Electric and Magnetic Fields

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Abstract - *The influence of magnetic field on electrical breakdown characteristics for low- pressure nitrogen discharges is investigated by applying a magnetic field B parallel to the electric field E. Paschen curves were obtained (at a fixed value of d and variable p) and the secondary electron emission coefficient (γ), the first Townsend ionization coefficient (α) and the ionization efficiency (η), were plotted with respect to the variation of the reduced field (E/P). To observe the effect of the magnetic field these curves were plotted for fixed values of B=0 T and B=0.072 T. A Helmholtz coil was used to produce a uniform magnetic field (B) parallel to the discharge axis. We observed that the magnetic field B applying along the discharge axis promoted a reduction of the breakdown voltage .The breakdown is facilitated by the magnetic confinement of electron which reduces the electron losses and effectively increases the collision frequency between electrons and the gas particles at a given reduced field, thus increasing the ionization efficiency. The presence of the axial magnetic field does not lead to the variation of Townsend coefficients significantly at the conditions of the B-field and reduced field E/P investigated. Overall it is concluded that the DC electrical breakdown of the gases is facilitated if a longitudinal magnetic field is applied along the discharge axis.*

Index Terms **–** *Paschen curve, Townsend coefficient, electrical breakdown, magnetic field.*

I. INTRODUCTION

For the purpose of exploring the better understanding of the complex mechanisms of gas discharge, the characteristics of electrical breakdown of several gases under the effect of applied magnetic field have been subjected in many researches. The electrical breakdown of gases has been, since long time, the subject of many studies [1-4]. The interest in these studies is the effect of the magnetic field on the characteristics of electrical breakdown and on the properties of a Townsend discharge is motivated by a necessity of gaining a better understanding of the complex mechanisms of gas discharge phenomena and also because the B-field may contribute favourably for dealing with practical problems associated with the use of this kind of discharge for plasma processing technologies [5-6]. However, for the author's best knowledge, the influence of an axial magnetic field in low vacuum has not yet been widely introduced. A knowledge of the effect of applying an axial magnetic field on the breakdown behaviour of low vacuum is very important for h.v. technology because of practical applications such as vacuum interrupters for contactors and circuit-breakers. In the present paper, the influence of magnetic field on electrical breakdown characteristics for low- pressure nitrogen discharges is investigated by applying a magnetic field B parallel to the electric field E. Paschen curves were obtained (at a fixed value of d and variable p) and the secondary electron emission coefficient (γ), the first Townsend ionization coefficient (α) and the ionization efficiency (η), were plotted with respect to the variation of the reduced field (E/P). This study contributes Townsend discharge regime at a new values of magnetic field, plane-parallel electrode separation and gap pressure. In this work, breakdown potentials in N2 under the presence of an external longitudinal magnetic field were measured in the Townsend discharge regime. In this regime the electrons in the tail of the energy distribution function have enough energy to ionize the gas atoms. The secondary electrons thus produced can also obtain a sufficient amount of energy from the electric field to ionize atoms and produce new electrons. This gives rise to an avalanche-like growth of the degree of ionization. For this to occur, the loss of electrons should be rather small. The electron losses occur by recombination with ions as a result of diffusion toward the walls and also, as in the case of electronegative gases, as a consequence of the formation of negative ions. We have developed an experimental device to observe the effect on the gas breakdown, of a magnetic field parallel to the electric field. We expected the lateral diffusion of electrons to be hindered by the magnetic field consequently reducing losses and enhancing the ionization efficiency in the Townsend regime. In fact, as the experimental results show, this phenomenon was confirmed by the reduction of the breakdown voltage when a magnetic field was applied . Thus Paschen curve obtained at the conditions of the B-field and reduced field E/P investigated in this work is not-applicable in vacuum switchgear, on the other hand the B-field may contribute favorably for dealing with practical problems associated with the use of this kind of discharge for plasma processing technologies .

II. EXPERIMENTAL TECHNIQUE AND TEST ARRANGEMENTS

The experimental set-up used in this work is shown in Fig. 1.The Pyrex glass chamber of 100 mm internal diameter and 400 mm length was preliminarily evacuated to pressure below 10^{-4} Torr. Plane-parallel stainless steel electrodes (5mm diameter) were used in this work. This study has been confined to a relatively low pressure range (0.02 to 0.2) Torr, i.e. (medium vacuum). The DC used was obtained from 0 to 5 kV DC test set (negative polarity with respect to ground). A low intensity B- field (0- 0.072 Tesla, in the direction of the electric field, could be produced by the Helmholtz coil. Helmholtz coil used in this work consists of two circular coaxial coils, each of N=220 turns and radius R=5.5cm,separated by a distance S=R. The two coils carry equal currents **I** in the same direction. DC current source used in this work was obtained from current source (0 - 30A). The breakdown voltage measurements were made at zero B-field and 0.072 Tesla .The DC magnetic field B (in Teslas) is measured as follows:

$$B = \frac{8\mu_0 N.I}{5\sqrt{5}R} Wb/m^2 or\ (Tesla,T)$$

where: I = current flowing in each coil
R = radius of the coil
N= number of turns in each coil
uo= 4πx10-7 H/m

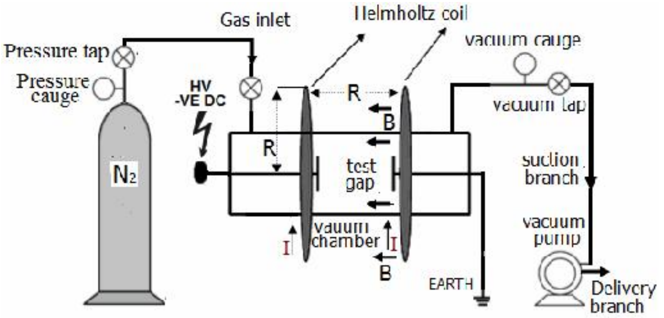

Fig. 1 Schematic diagram of the experimental setup

III. EXPERIMENTAL RESULTS AND DISCUSSIONS

The electrical breakdown has been investigated for low- pressure nitrogen discharges under the influence of an external longitudinal magnetic field B (in the direction of the electric field E). The test procedures were carried out under different cases, as follows:

A. Breakdown voltage and Paschen curve

The gas breakdown voltage V_B was determined as a function of the product **pd**. The measurements were made for nitrogen discharge at a fixed value of **d** =50 mm and variable **p** in the range (0.02 to 0.2) Torr (medium vacuum). To observe the effect of the magnetic field these curve were plotted for fixed values of **B**=0 T and **B**=0.072T . Measurements are carried out for pressure * electrode gap (p*d) products from 0.1 to 1 Torr. Cm, for gap fixed at 5cm. Paschen curves with and without applying the axial magnetic field B are shown in Fig.2. Overall, the results show that the effect of the magnetic field on the paschen curves is to reduce the breakdown voltage, especially on the region of paschen's minimum{$V_{b(min)}$, $(Pd)_{min}$}.This effect can be attributed to the higher efficiency of the secondary ionization processes at the conditions of the pressure P and reduced field E/P investigated. At lower values of Pd, on the left side of the minimum, the effect of the B-field is reduced because in this region the breakdown is governed primarily by the electrode materials properties rather than by ionization process in the bulk of the gas .Also, on the left side of the minimum paschen curves, V_B decreases fast when increasing Pd which can be attributed to the increase in the collision frequency between electrons and neutral atoms or molecules. However, on the right side of the minimum, the breakdown voltage increases gradually when increasing Pd, which can be attributed to the decrease in the ionization cross-section, making the electrons to require more energy in order to achieve the breakdown of the discharge gap [9].It is seen from this figure that the breakdown voltage values are lower with magnetic fields than without parallel magnetic field. The lowering in breakdown voltage with B, can be explained as follows: in the presence of a magnetic field B, the electron free path across the residual gas is lengthened and also the lateral diffusion of the electrons can be reduced. These combined effects imply that the losses of electrons are reduced and they can now make more collision with the gas molecules than they could do in the absence of the magnetic field [5]. Namely, it can be said that the lowering of breakdown voltage in the presence of a parallel magnetic field, can be interpreted through that the lateral diffusion of electrons to be hindered by the magnetic field ,consequently reducing losses and enhancing the ionization efficiency in the Townsend regime.

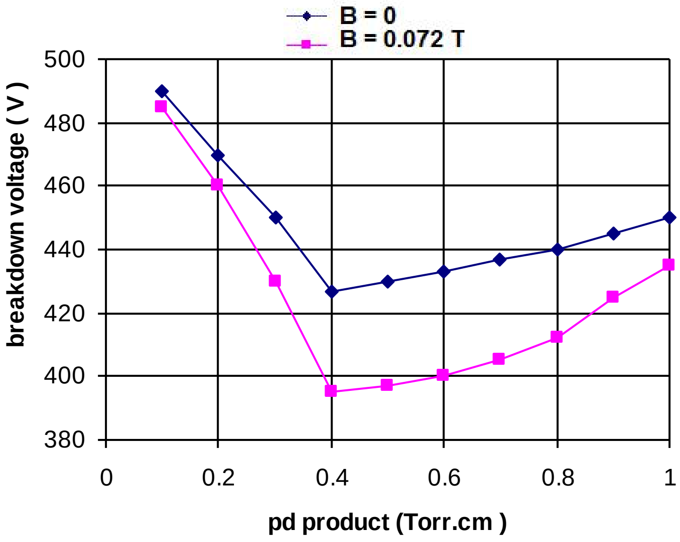

Fig. 2 Breakdown voltage (V_B) from nitrogen as a function of pd (Paschen curves) with an without applying the axial magnetic field (B)

B. Variation of α with E/P

Fig.3 shows the first Townsend coefficient α (the number of ionizing collisions per cm) as a function of reduced electric field E/P for nitrogen N2 with and without applying the axial magnetic field B. It has been observed that, the first Townsend coefficient α is decreased by a magnetic field , compared with its value at zero magnetic field , and the reduction of the α value is more pronounced in low reduced electric field E/P rather than in high reduced electric field E/P .At higher values of E/P(i.e.at lower values of Pd), the effect of the B-field is diminished because in this region the breakdown is governed primarily by the electrode material properties rather than by ionization in the bulk of the gas. Overall, the presence of the axial magnetic field does not lead to the variation of first Townsend coefficient α significantly .Also the influence of magnetic field diminishes in high reduced electric field E/P.

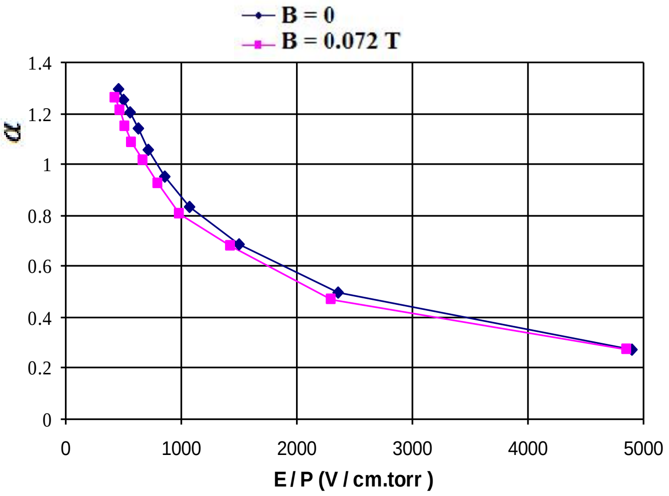

Fig. 3 Variation of the primary ionization coefficient α with E/P-obtained from data in Fig. 3 with and without applying the axial magnetic field (B).

Fig.4 shows the first Townsend coefficient α/p as a function of reduced electric field E/P for nitrogen N2 with and without applying the axial magnetic field B, the values of α – coefficients coincide with one another.

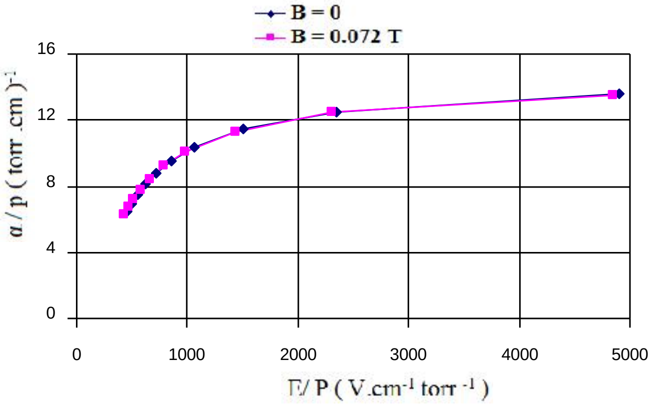

Fig.4 The first Townsend coefficient α/p as a function of reduced electric field E/P.

C. Variation of γ with E /P

Fig. 5 shows the second Townsend coefficient **γ** as a function of reduced electric field E/P for nitrogen N_2 with and without applying the axial magnetic field B. The values of secondary electron emission coefficients **γ** are calculated from the Paschen curves Fig.3 and represented in Fig.5. It is usually observed that the curves of **γ** with (E/P) has a minimum values [8] but in the investigated experimental range of reduced field in this work the ascending branches of curves are only obtained .The presence of the axial magnetic field does not lead to the variation of secondary ionization coefficient **γ** significantly. In addition, it can be seen that the second Townsend coefficient **γ** values are higher with magnetic fields than without parallel magnetic field. For low values of reduced electric field that difference disappears .The increase of the reduced electric field leads to the rising value of secondary ionization coefficient γ, and the presence of magnetic field results to the amplifying of γ. In addition, it can be concluded that the influence of magnetic field diminishes in low reduced electric field. The increase of Townsend coefficient **γ** in the presence of a parallel magnetic field can be interpreted through that the emission of secondary electrons is enhanced by the confinement effect promoted by the application of a magnetic field.

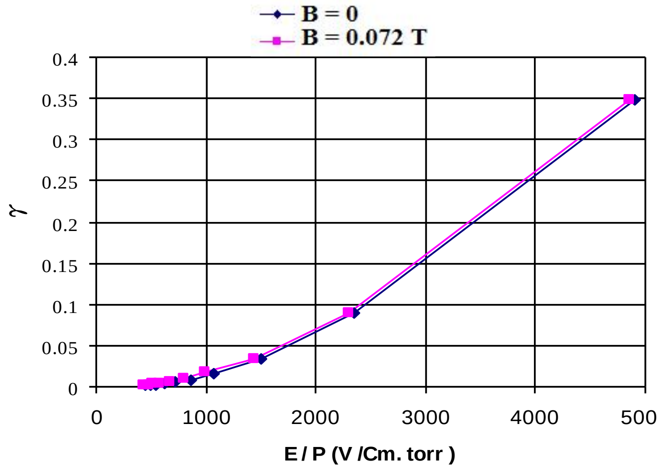

Fig. 5 Variation of the secondary ionization coefficient γ with E/P-obtained from data in Fig. 3 with and without applying the axial magnetic field B.

D. Variation of η with E/P

Fig.6 shows the ionization efficiency η as a function of reduced electric field E/P for nitrogen gas N_2 with and without applying the axial magnetic field B. The ionization coefficient η can be defined as the number of ionization events caused by an electron in passing through a potential difference of 1 V which can be expressed as η = α/E. The presence of the axial magnetic field does not lead to the variation of ionization efficiency η significantly. This result is in agreement with the results of Figures 3 and 4, and it also was expected because the value of the ionization efficiency depends on the inverse of ionization potential of the gas . In addition, it can be seen that the ionization efficiency η values are higher with magnetic fields than without parallel magnetic field. For low values of reduced electric field that difference disappears. The increase of ionization efficiency η in the presence of a parallel magnetic field can be interpreted through that the lateral diffusion of electrons would be hindered by the B-field, thereby increasing the ionization efficiency [10].

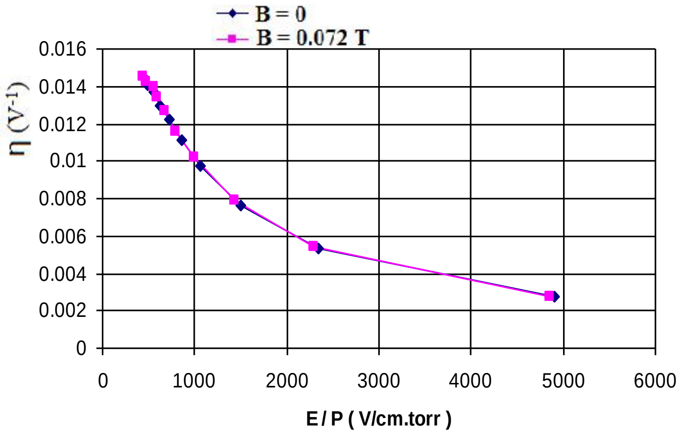

Fig. 6 Ionization coefficient (η) as a function of E/P-obtained from data in Fig. 3 with and without applying the axial magnetic field B.

IV. CONCLUSIONS

The breakdown voltages in low pressure gases have been measured for nitrogen discharges using plane – plane parallel stainless steel electrodes. We have investigated the influence of a longitudinal magnetic field on the Paschen curves and on the Townsend parameters . we observed that the magnetic field B applying along the discharge axis promoted a reduction of the breakdown voltage .The breakdown is facilitated by the magnetic confinement of electron which reduces the electron losses and effectively increases the collision frequency between electrons and the gas particles at a given reduced field, thus increasing the ionization efficiency. The presence of the magnetic field enhances the secondary ionization coefficient γ at a given E/P value. This effect is equivalent to a decrease of the work function of the cathode material. While on the other hand the first Townsend coefficient α is decreased. The presence of the axial magnetic field does not lead to the variation of Townsend coefficient significantly at the conditions of the B-field and reduced field E/P investigated .Overall , it is concluded that the DC electrical breakdown of the nitrogen gas N2 is facilitated if a longitudinal magnetic field is applied along the discharge axis. Thus Paschen curve at the conditions of the B-field and reduced field E/P investigated in this work is not-applicable in vacuum switchgear. While on the other hand the B-field may contribute favourably for dealing with practical problems associated with the use of this kind of discharge for plasma processing technologies .

REFERENCES

1. A. von Engel, “Ionized Gases”, *Oxford-Clarendon Press*, Second Edition,1965.

2. E. Nasser, “Fundamentals of gaseous ionization and plasma electronics”, *John Wiley & Sons*, Inc, 1971.

3. E.W. Mac Daniel, “Collision Phenomena in Ionized Gasses”, *John Wiley & Sons*, 1964.

4. J.Isidorovic, “Paschen curves and spatial distribution of emitted light of glow discharge in the air”, *Acta Phys*, Pol.A88 Supplement, S-37,1995.

5.G.Petraconi,H.S.Maciel,R.S.Pessoa,G.Murakami,M.Massi,C. Otani,W.M.I.Uruchi,B.N.Sismanoglu, Longitudinal magnetic field effect on the electrical breakdown in low pressure gases”, *Braz.J.Phys*.Vol.34no.4b sao Paulo Dec.2004.

6. Arian Fateh Borkhari and Kiomars Yasserian , “Influence of the hot filament on the electrical breakdown characteristics in the presence of Ar/N2” , *Journal of Theoretical and Applied Physics*, 7:5, 2013

7.Sabah I. Wais, Raghad Y. Mohammed, Sedki O. Yousif ,“ Influence of Axial Magnetic Field on the Electrical Breakdown and Secondary Electron Emission in Plane-Parallel Plasma Discharge”, *World Academy of Science*, Engineering and Technology, Issue 0056, PP.1304-1309, August 2011.

8.Radmilovic M, Radjenovic , Radjenovic B,“The effect of magnetic field on the electrical breakdown characteristics”, J *Phys D: Appl Phys*, 39:3002-3007,2006.

9. G. Auday, Ph. Guillot, J. Galy and H. Brunet, “Experimental study of the effective secondary emission coefficient for rare gases and copper electrodes”, *J. Appl. Phys.* 83(11), 5917-5921, 1998.

10.Singh,G. and Chaturvedi,S., “Two- Dimensional PIC simulation of spark gaps with longitudinal magnetic fields”,*Pulsed power converence, IEEE*, 627-630, June 2005.