Experimental Study of the Electrical Breakdown characteristics in air at near-atmospheric pressure under Axial Magnetic Fields

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Abstract: *In the present paper, an attempt was made to investigate the effect of axial magnetic field on electrical breakdown characteristics in air at near - atmospheric pressure. The presence of the magnetic field decreases the breakdown voltage and increases the leakage current. The effect of magnetic field on the breakdown voltage characteristics shows a marked dependence on the gap spacing, gap pressure, electrode configuration and the type of applied magnetic field.*

Key Words: *Electric field, axial magnetic field, electrical breakdown, compressed air, vacuum.*

1. Introduction

The electrical breakdown of gases has been, since long time, the subject of many studies. The interest in these studies is the effect of the magnetic field on the characteristics of electrical breakdown. The influence of a magnetic field applied perpendicularly to the electric field on the breakdown mechanism in gases has been studied for many years[1-7], and a good recent review of the subject was given by Heylen [8], but the influence of a magnetic field applied longitudinally to the electric field on the breakdown mechanism in air did not receive the same attention [9-15]. The interest in studying the magnetic field effect 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 [16-19]. 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. These researches included the study of magnetizes plasma discharge at different working parameters such as the pumping gases, the materials and the geometry of electrodes, gas pressure, chamber temperature, humidity of discharge chamber and the type of applied voltage [19-30]. Tan *et al* [21] investigated a new method of measuring the secondary electrons emission by two Faraday cups with and without presence of a magnetic field. One Faraday cup detects the electrons emerging perpendicularly to the target surface and magnetic field lines, while another cup detects electrons flowing along the field lines. The electrical breakdown is presented by Petraconi *et al* [19] at low-pressure of argon and nitrogen gases under the influence of an external longitudinal magnetic field. The influence of the secondary electron emission on the breakdown voltage in micro discharges on the plasma display panel is investigated by making use of the Townsend sparking criterion. Auday *et al* [20] presented an experimental study of the effective secondary emission coefficient for rare gases and copper electrodes. The influence of the magnetic field on the characteristics of electrical breakdown and on the properties of Townsend discharge is motivated as an important mechanism for measuring the Paschen curves, ionization efficiency coefficients, secondary electrons emission and the minimum breakdown voltages with and without applying an axial magnetic field [31, 32]. For the author's best knowledge, the effect of applying an axial magnetic field on the breakdown behavior of air is very important for HV technology because of practical applications for such as axial magnetic field vacuum interrupters for contactors and circuit-breakers [33, 34]. In the present paper, an attempt was made to investigate the effect of axial magnetic field (AMF) on electrical breakdown characteristics in air at near - atmospheric pressure.

This paper is organized as follows. In Section 2, experimental technique and test arrangement are provided. Section 3 presents the review of motion of a charged particle in combined fields (both electric & magnetic). In Section 4, experimental procedure and test results have been provided. In Section 5, discussion about the results has been provided. Finally, Section 6 concludes the paper.

2. Experimental Technique and Test Arrangements

Two kinds of experimental set-up were used in the present study, one for the experiments carried out in the vacuum as shown in Fig. 1, and the other for the experiments carried out in the compressed air as shown in Fig.2.The test container (test cell) has been prepared to study the effect of applying axial magnetic fields AMF to the test gap, on electrical breakdown characteristics in air at near - atmospheric pressure.

The test cell was made of a transparent acrylic tube (Plexiglass) to facilitate visual observation, and having an outer diameter of 150 mm, inner diameter of 140 mm and its length is 300 mm. The electrode gap used was a plane-plane brass electrode, with the possibility of adjusting the tested gap distance to the required value. The plane was a circular disc of 50 mm diameter and 5 mm thickness. In the present study, both AC and DC magnetic field were used. The axial magnetic field was created by a solenoid with 2500 turns and the length of the coil 250 mm. Solenoid is positioned coaxially to the test chamber to generate an axial magnetic field.

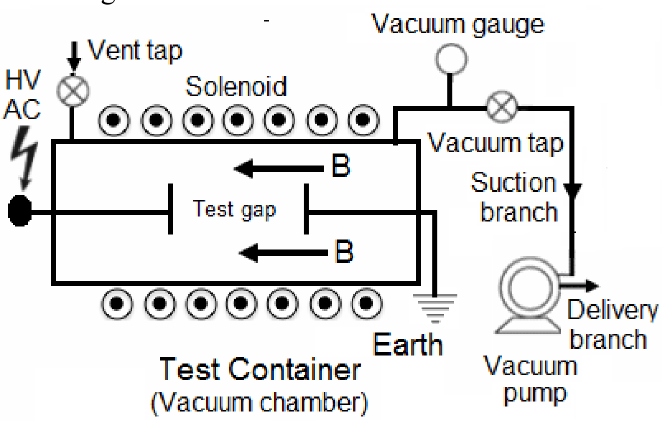

Fig.1 Experimental set-up used for the tests carried out in the vacuum chamber

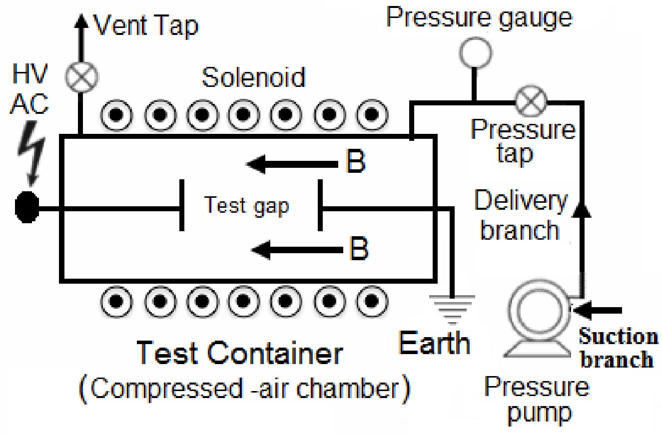

Fig.2 Experimental set-up used for the tests carried out in the compressed- air chamber

The coil was energized by variable DC and AC current supply. The diameters of solenoid coincide with the outer diameter of the test tube. The magnetic flux density could be changed by increasing the passing current through the solenoid. The magnetic flux density B was measured by using the axial B-probe (Leybold, 516 61) with the Teslameter (Leybold,516 62 ranging from 0.01 *mT* to 2T). The pressures employed in this study extends from 0.02*105 to 5*105 *Pa*. Atmospheric air is pumped into compressed-air chamber by air compressor of maximum value of 15*105 *Pa*,While the vacuum chamber was evaluated by vacuum pump of maximum value of 0.03*105 *Pa*. In this study, A 100 *kV*, 20 *kVA*, 50 *HZ* test transformer is used for AC measurements. AC breakdown voltage kVrms was measured by means of a capacitive divider. AC voltage used was AC between one terminal and earth. The mean value of breakdown voltage was calculated by means of five voltage applications.

3. Review of Motion of a Charged Particle in Combined Fields (Both Electric & Magnetic

Before discussing the results, it would be better to review a little bit of electric and magnetic forces both affect the trajectory of charged particles. Force due to both electric and magnetic forces will influence the motion of charged particles. However, the resulting change to the trajectory of the particles will differ qualitatively between the two forces. Below we will quickly review the two types of force and compare and contrast their effects on a charged particle.

1-Parallel Electric and Magnetic fileds :-

When both electric and magnetic fields act simultaneously on an electron, no force is exerted due to the magnetic field and the motion of the electron is only due to the electric field intensity .Note :- No force is exerted due to the magnetic field, since if the electron moves parellel to the magnetic field ; the value of $\varphi = 0$; $\therefore f_m = q.BV \sin 0$; $f_m = 0$

The electron moves in a direction to the fields with a constant acceleration.

If the electric filed is along the Y–axis and magnetic filed is along the Y – axis, the motion of an electron is specified by

$$V_y = V_{oy} \;; \qquad y = V_{0y}\, t - ½\, a t^2$$

where, $a = q.E/m$ = the magnetic of the acceleration.

If a component of velocity V_{ox} is perpendicular to the magnetic filed exists, initially this component along with the magnetic filed will set the electron in a circular motion.The Radius of the circular path is independent of the elecric field, but the velocity along the field changes with time. As a result of this the elctron travels in a helical path with the pitch changing with time.

2-Perpendicular Electric and Magnetic Fields

Consider an electron starting from rest at the origin. Let the magnetic field be directed along '–Y' direction and the electric field be directed along the '–X' direction. The electron directed along the '+X' axis due to the electric filed. The force due to the magnetic field is always normal to B, Hence, lies in a plane parellel to the XZ plane and there is no component of force along the Y direction, and Y component of acceleartion is zero. Thus the motion along ' Y ' is given by :

$F_y = 0$; $V_y = V_{oy}$; $y = V_{oy}\, t$

Assuming that the electron starts at the origin:

1) Since the initial velocity is zero, the initial magnetic force is zero and due to the electric field the electron is directed along the '+X' axis.

2) As the electron is accelerated in +X direction, the force due to the magnetic field is no longer zero. There will be a component of this force which is proportional to the ' X ' component of velocity and will be directed along the +Z axis.

3) The path will thus bend away from the +X direction towards the '+Z' direction.

4) The electric and magnetic force interact with one another the net force will finally make the electron to travel in a cydoidal path.

4. EXPERIMENTAL PROCEDURES AND TEST RESULTS

The test procedures were carried out under different cases, as follows:

A. BREAKDOWN VOLTAGE TEST

This test has been achieved under different procedures:

First Test: With the test gap TG at 10 mm, the breakdown voltage kVrms (BDV) was measured for different gap pressures of 1.0, 0.8, 0.6, 0.4 and 0.2 ×105 Pascal under specified axial magnetic field AMF. The above procedure was repeated for different AMF's of 0.0, 0.03, 0.06, 0.09 and 0.12 Tesla. The obtained results are presented in Fig.3. From this figure, it is clear that the BDV decreases as the AMF increases. The effect of AMF decreases as the gap pressure decreases. The BDV becomes insensitive to any increase of AMF for gap pressures above 0.6x105 Pa nearly. The gap pressure range in this figure ranges from 1x105 to 0. 2x105 Pa under constant main gap distance of 10 mm, if we use pressure gap scale pd which ranges from pd= 2x105 Pa. mm to pd = 10x105 Pa. mm, according to Paschen curves for various gases [p108, 36] curve 2 for air which is to the right of Paschen minimum. Therefore, our results are correct.

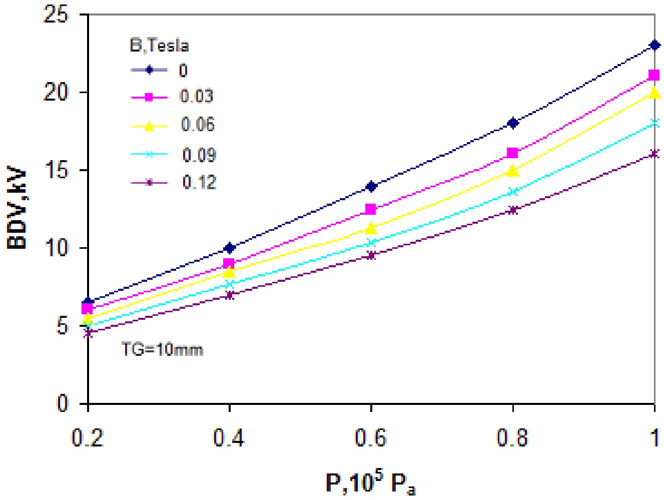

Fig.3 Variation of the breakdown voltage with gap pressure in vacuum for various DC axial magnetic field.

Second Test: With the TG at 10 mm, the BDV was measured for different gap pressures of 1, 2, 3, 4 and 5 × 105 Pa under specified AMF. The above procedure was repeated for different AMF's of 0, 0.03, 0.06, 0.09 and 0.12 Tesla. The obtained results are presented in Fig. 4. From this figure, it is clear that the BDV for a given gap pressure value decreases with increase in AMF. The decrease in the BDV value in the presence of AMF is more pronounced for gap pressures above 3x105 Pa nearly.

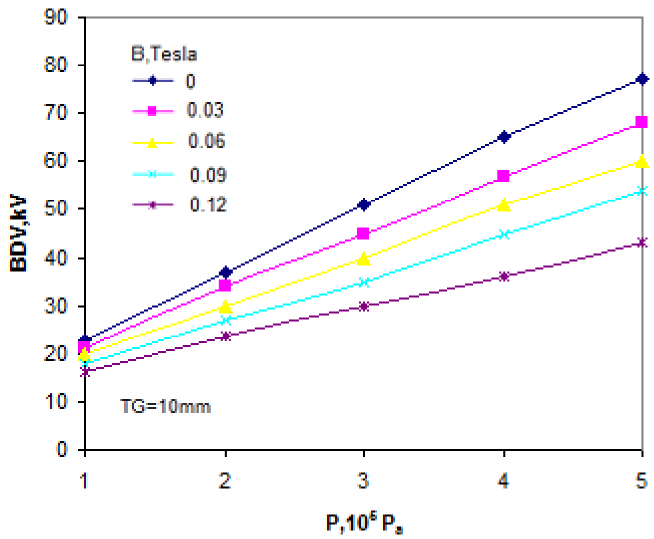

Fig. 4 Variation of the breakdown voltage with gap pressure in compressed air for various DC axial magnetic field.

Third Test: With the TG at 10 mm and gap pressure at 1× 105 Pa, the test results are taken and given in Fig.5. From this figure, it is clear that the B.D.V decreases as the DC or AC magnetic field increases, the decrease in the BDV is larger for AC field rather than under DC field. Also, the breakdown voltage value with D.C magnetic field is higher than that with AC field.

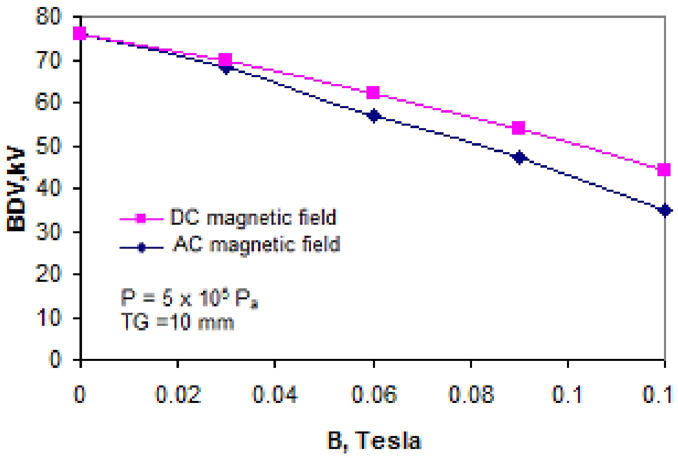

Fig.5 Relation between AC breakdown voltage of the test gap and axial magnetic field of different mode.

Fourth Test : In this study, two types of electrode configurations were used to simulate the test gap TG. The first type was formed of plane-plane electrodes. The second type was formed of needle - needle electrodes. This test was carried out under a constant TG distance of 10 mm. The gap pressure used was 5 ×105 Pa. The breakdown voltage under different AMF's of 0, 0.03, 0.06, 0.09 and 0.12 Tesla was recorded. The above procedure was repeated for different electrode configuration. The test results were recorded and given in Fig.6. From this figure, it is clear that the effect of AMF on the BDV depend on the electrode configuration. From this figure, we can also see that the BDV decreases as the AMF increases. The effect of axial magnetic field AMF on the BDV is more pronounced in non-uniform electric field gaps compared with that in uniform field gaps.

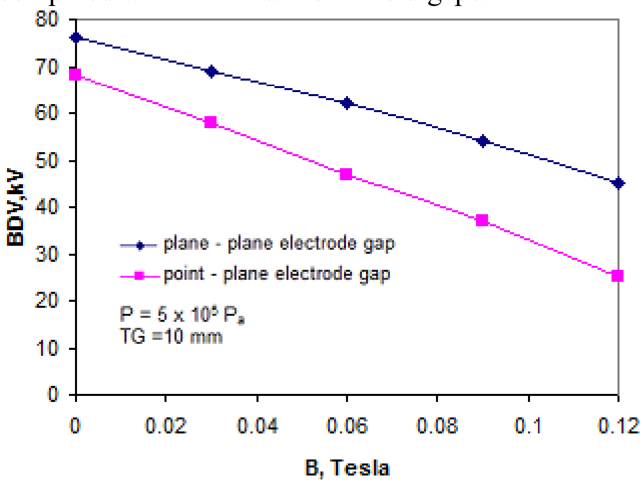

Fig.6 Effect of DC axial magnetic field variation on the breakdown voltage in uniform and non-uniform field gaps.

Fifth Test: The degree of vacuum used in this test was 1×105 Pa .The BDV for different axial magnetic fields AMF's of 0.0, 0.03, 0.06, 0.09 and 0,12 Tesla were obtained for different T.G distances of 10, 20 and 25 mm as shown in Fig.7. From this figure, it is clear that the increase of the AMF has the effect of decreasing the BDV of the TG. The BDV-AMF characteristics assume a linear relation, the slope of this relation increase as the MG distance increases.

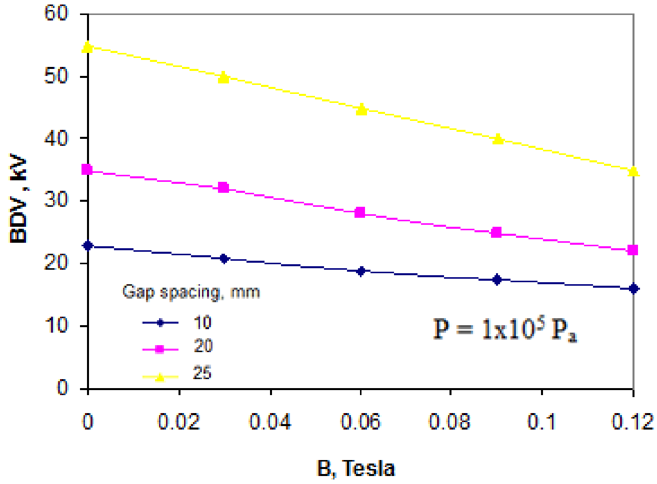

Fig.7 Effect of DC axial magnetic field variation on the breakdown voltage under different gap spacing.

B. LEAKAGE CURRENT TEST

A 100 kV, 20 kVA , 50 HZ test transformer is used for DC measurements . The DC is obtained by rectifying AC voltage with a 140 kV high voltage diode and a 6nF regulating capacitor. The DC voltage polarity used, in this work, was positive with respect to earth. The plane electrode was earthed through a digital multi –meter (IWATSU-7411) for measuring the leakage current.

Sixth Test: The leakage current can be read directly on the micro-ammeter. The test was carried out under constant TG distance of 10 mm. All tests were carried out under a fixed main applied voltage of 21 kVAC. The leakage current was measured for different gap pressures under specified AMF's. The above procedure was repeated for different AMF's of 0.0, 0.03, 0.06, 0.09 and 0.12 Tesla, The obtained results are presented in Fig. 8. It is clear that as the AMF, the leakage current increases. The increase in leakage current value is more pronounced as the air pressure increases. The axial magnetic field AMF makes the actual gap distance decrease, which leads to the maximization of the leakage current.

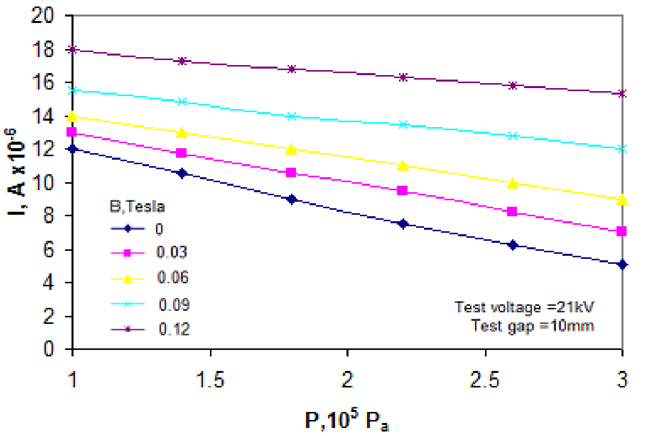

Fig.8 Variation of the leakage current with gap pressure with and without applying the axial magnetic field intensity.

5. RESULTS AND DISCUSSIONS

The electrical breakdown characteristics of air at near-atmospheric pressure in the presence of an axial magnetic field AMF are discussed. From the results obtained throughout this work, the axial magnetic field decreases the breakdown voltage BDV. Also, the axial magnetic field increases the leakage current. The effect of AMF on the BDV characteristics shows a marked dependence on the gap spacing, the gap pressure, the electrode configuration and the type of applied magnetic field.

The BDV is lower when the magnetic field is applied, this can be explained as follows: the current density can be increased by the magnetic field, due to the effective increase in the gas pressure. This is related to the fact that the presence of the magnetic field increases the apparent gas pressure and thus decreasing the mean free path, hence more excitation and ionization processes occurred and consequently, decreasing the breakdown voltage and increasing leakage current. The decrease of the breakdown voltage in the magnetic field results from the increase in the number of collisions between the primary electrons and neutral gas atoms [17].

Also, the reduction of the breakdown voltage when a magnetic field was applied can be interpreted through that the lateral diffusion of electrons would be hindered by the B-field, thereby reducing losses and enhancing the ionization efficiency [30]. This effect is equivalent to a change of the operating gas by another of lower ionization potential.

The lowering in breakdown voltage with B can be explained as follows: in the presence of a magnetic field B, the breakdown is facilitated by the magnetic confinement of electrons which reduces the electron losses and effectively increases the collision frequency between electrons and the gas particles in the inter-electrode space, thus increasing the ionization efficiency. The presence of the magnetic field enhances the secondary ionization coefficient. This effect is equivalent to a decrease of the work function of the cathode material [39, 40].

When a magnetic field is applied to the electric field, the effect of magnetic field on the BDV is more pronounced in non-uniform electric field gaps compared with that in uniform field gaps, this is because in uniform field the free electrons are only acted upon the Coloumbs force, while in non- uniform field the free electrons are acted upon by both the Lorentz force and the Coloumb force, hence Larmor precessions are formed in non-uniform field. As a result of Larmor movement the electron will have much longer path length to travel. The electrons can circumrotate for many periods before traveling out of the ionization region, thereby increasing the number of ionization collisions by electron avalanche. The concentration of both ions and electrons are greatly elevated in the region, thereby decreasing the breakdown voltage and increasing leakage current. Also, as a result of Larmor movement, a kind of "magnetic ring" is formed at cathode surface, which "traps" the electrons that are accelerated away from cathode by the electric field [19, 35, 37-38].This above interpretation depends on that the uniform electric field is one whose magnitude and direction are the same at all points in space, and it will exert the same force of a charge regardless of the position of the charge in space. But the non uniform electric field is one which is not uniform, i.e. it has either different magnitudes or different directions or both are different in a given region of space.

When a magnetic field is applied to the electric field gaps, the decrease in the BDV is larger for AC magnetic field rather than under DC magnetic field, this is due to the periodic reversal of magnetic pole polarity which takes place when AC magnetic field is applied, and thus the direction of the magnetic force reverses frequently, while this does not happen in DC magnetic field. Also, this may be explained through that magnetic field varies with time, and then an additional electrical field is produced according to Faraday's law.

When a magnetic field is applied to the electric field gaps, the effect of AC magnetic field on the BDV is more pronounced in long gap spacing compared with that in short gap, since the inter- electrode spacing increases; the number of collisions between the released electrons with the air molecules is decreased, thus the confinement of electrons by the magnetic field is enhanced. This, in turn, reduces the electron losses and effectively increases the collision frequency between electrons and the gas particles in the inter-electrode space, thus increasing the ionization efficiency.

6. CONCLUSIONS

The effect of the applied magnetic field on the electrical breakdown characteristics, as outlined in this study, shows a marked dependence on the gap spacing, the gap pressure, the electrode configuration and the type of applied magnetic field. The presence of the magnetic field decreases the breakdown voltage and increases the leakage current. The results obtained throughout this work, from a practical point of view, are not-applicable in vacuum switchgear. While on the other hand, these results can be used as an effective method to improve the collection efficiency of electrostatic precipitators (ESPs) as a result of the magnetically enhanced corona discharge. Especially these days, more and more countries are beginning to limit the emissions of micron and sub-micron aerosol particles using the technique of magnetically enhanced negative corona discharges, for the purpose of capturing fine aerosol particles, are presented. More research work is still required to explore some of the still unclear sides of electrical ionization and breakdown of liquids, gas and solids in an axial field, e.g. improving of circuit breaker design to suit the existence current during circuit breaker operation under normal or short circuit conditions to initiate magnetic field in the axial axis of the main circuit breaker poles in order to increase the level of restrike voltage value of the circuit breaker clearance.

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