Macroscopic modeling of the glow dielectric barrier discharge (GDBD) in helium

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ABSTRACT. *The objective of this study is to investigate the mechanisms controlling the glow dielectric barrier discharge (GDBD) using PSIM software. A simulation model was established through the analysis on relevant constraints, such as reactor configuration (gas gap distance, shape of electrode and dielectric barrier thickness), gas properties, and amplitude and frequency of applied voltage. Through this study, it was found that the dynamic behavior of the discharge parameters (such as gas gap voltage and discharge current), with are not measurable in the real process, is study with the electrical simulation model, and the voltage-current curves are also obtained from simulation and used to analyze the evolution trajectory of the homogeneous DBD.*

RÉSUMÉ. *L'objectif de cette étude est de contrôler les mécanismes de la décharge luminescente à barrière diélectrique (GDBD) à l'aide du logiciel PSIM. Un modèle de simulation a été établi en analysant les contraintes pertinentes, telles que la configuration du réacteur (distance inter électrode, forme de l'électrode et l'épaisseur de la barrière diélectrique), les propriétés du gaz ainsi que l'amplitude et la fréquence de la tension appliquée. Cette étude a révélé que le comportement dynamique des paramètres de la décharge (tels que la tension d'espace gazeux et le courant de décharge), qui ne sont pas mesurables dans le processus réel, est étudié avec le modèle de simulation électrique et que les courbes tension-courant sont également obtenu de la simulation et utilisé pour analyser la trajectoire d'évolution du DBD homogène.*

KEYWORDS: *dielectric barrier discharge (DBD), electric model, equivalent electric circuit, gas discharge, homogenous discharge, simulation.*

MOTS-CLÉS: *décharge à barrière diélectrique (DBD), model électrique, circuit électrique équivalente, décharge du gaz, décharge homogène, simulation.*

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1. Introduction

Barrier discharge, sometimes also referred to as dielectric barrier discharges (DBD) or silent discharges possesses essential advantages in surface processing and plasma chemistry. DBD is a low temperature discharge, usually working at atmospheric pressure. DBD plasma is typically obtained between two parallel electrodes separated by a dielectric layer with a gap of some millimeters and excited by alternating current AC voltage with frequency in the range of 10Hz to 100Hz. The dielectric barrier can be made from glass, quartz, ceramics, or polymer coating. The dielectric barrier discharge is very attractive for the applications in plasma technologies especially in ozone generation, surface modification of polymer, plasma chemical vapor deposition, pollution control, excitation of CO_2 laser, excimer lamps, plasma display panels and medical domain like sterilization.

Experimental diagnoses are the usual means by which one can study the characteristics of the discharge and the mechanism of the DBD. Numerous experimental studies on the characteristics and mechanism of DBD under atmospheric pressure have been undertaken. It is shown that the characteristics of the DBD discharge depend on the parameters of the discharge system, such as reactor configuration (gas gap distance, electrode shape and thickness of the dielectric barrier), properties Gas, and the amplitude and frequency of applied voltage (Kogelschatz, 2003; Fridman *et al*., 2006). This results in a large number of studies and experimental research. Consequently, the two models of simulation of the digital and electrical discharge have been developed to study the mechanism and the characteristics of the DBD (Georghiou *et al.*, 2005; Fridman, 2008). The numerical models are mainly based on the continuity equations coupled with the Poisson equation and the boundary conditions, and they are widely used to study the discharge process and the mechanism of the DBD. However, various gas ionization processes should be considered to simulate physical processes in DBD plasma, numerical simulation models are difficult to configure and calculations take a long time.

From an electrical point of view, the DBD system consists of a power supply and a discharge reactor, and both can be modeled by an equivalent electrical circuit. Therefore, the whole DBD system can be modeled by an equivalent electrical model is relatively simple and convenient, and it reveals the interaction between the power supply and the DBD reactor. The use of this type of model, the dynamics of the relationships between external parameters (i.e., applied voltage, total current, gas exploitation, dielectric materials, and arrangements of reactor) and internal electrical parameters (i.e., dielectric voltage, gas voltage, discharge current, displacement current, and transported charges) of the DBD systems under different operating conditions can be obtained; As a result, it considers the dynamics of the electrical behavior of DBD systems, thus not only determining the optimum operating state of DBD reactors but also designing suitable HV power sources for DBD applications.

Several equivalent electrical models have been developed and used to help study the discharge characteristics and behaviors of DBD systems.

Kogelschatz (2003) and Laroussi and Lu (2004) reported a model characterizing DBD, in which the plasma discharge is represented by a temporally variable resistance, and several researchers have used this model to study and analyze the characteristics of the discharge DBD (Nersisyan and Graham, 2004; Bibinov *et al*., 2001), Koudriavtsev *et al*., (2002) presented a model using a diode full bridge and a constant DC voltage source to represent plasma discharge, and they used the model to study the characteristics of a DBD ozone generator. Ponce-Silva *et al*., (2007) used this model to design power supplies for DBD ozone generators, and Sugimura *et al.,* (2006) And Olivares *et al.,* (2006) also used this model to study the characteristics and luminous efficiency of DBD lamps. Naudé *et al.,* (2005) used two Zener diodes and an RC circuit for the DBD model and the model established to study the transition from a Townsend to a filamentary DBD in nitrogen by means of PSpice software. Bhosle *et al.,* (2004 and 2005) presented a model for axisymmetric multifilament mode DBD lamp, in which variable conductance or voltage controlled conductance was used to model the discharge. Chen (2003) developed a model to study the electrical characteristics of an atmospheric pressure homogeneous discharge plasma by means of PSpice software; Two voltage-controlled current sources (CCSs), whose output current obeys the conventional exponential function with discharge voltage, were used for modeling the discharge of two positive and negative periods, Liu and Neiger (2003) proposed a model of the DBD through a theoretical analysis, in which the conduction discharge current of the plasma discharge was represented by a voltage CCS rather than a variable resistance or a diode bridge. This model has been validated for an arbitrary excitation voltage, and it has been used and enriched by researchers to study the discharge characteristics of DBD under different configurations of reactor and power supplies. Based on this model, Valdivia-Barrientos *et al.,* (2006) configured a dynamic model of a cylindrical DBD configuration driven by a high frequency power supply, and the model was implemented in Simulink software and used for studying the influence of frequency On the efficiency of the DBD reactor. Zhang *et al.,* (2010) configured a dynamic model of a plane-parallel configuration of the DBD driven by a 50 Hz power supply and was used to study the effect of various factors on the characteristics of the DBD in atmospheric air; And Pal *et al.,* (2009) configure a model of a DBD configuration of a coaxial argon-filled driven by a high-frequency power supply, and it was used to study the dynamic behavior of the discharge parameters. Flores-Fuentes *et al.,* (2009) used the concept proposed in Liu and Neiger (2003) to configure a model of plane-parallel configuration DBD driven by a high-frequency power supply, in which the discharge plasma was also represented by a voltage CCS which is based on The power law proposed by Chen (2003) and the voltage and current characteristics of the DBD in helium, argon and nitrogen were studied using this model.

DBD can exist in the filamentary mode or in the homogeneous mode, depending on the parameters of the reactor configuration and the power supply. Homogenous DBD can be generated in helium, nitrogen, and neon at atmospheric pressure and could be one of the most used for several industrial applications taking advantage of their uniform plasma characteristics (Fang *et al.,* 2007; Lu *et al.,* 2012), and several simulations numerical studies and experimental studies were also carried out to study the characteristics of the discharge and to understand their mechanism. However, there are few reports about the electrical models characterizing homogeneous DBD (Naudé *et al*., 2005; Chen, 2003; Liu and Neiger, 2003) and there are few reports on the homogeneous electric discharge simulation and comparison of results with those of experimental works (Fang *et al*., 2012).

To solve these defects, this paper established an electric model based on the equivalent electric circuit, and applies it to simulate the plane parallel configuration. With the aim to generate the homogeneous DBD in atmospheric Helium. The findings shed new light on dynamic behavior of the discharge parameters and evolution trajectory of the homogenous DBD.

The remainder of this paper is organized as follows:

Section 2 introduces the electric behavior of DBD represented by an equivalent electric circuit model, section 3 describes the electrical characteristics of atmospheric pressure homogenous discharge plasma (such as gas voltage, discharge current and applied voltage) by means of PSIM software, for facilitates the study of dynamic behavior of DBD, and established to study the transition from a glow to a filamentary DBD in Helium.

2. Electric model

2.1. Equivalent electric circuit

In the literature (Massine *et al.,* 1998; Khamphan *et al.,* 2004) there are several electrical models that are more or less faithful to reality. The purpose of an electric model is to provide an electrical circuit simulable and simple to implement.

The circuit model models the plasma by elements of circuit type (resistance, capacitance, diode ...). Thus, electrical components are used which make it possible to best describe the electrical behavior of the DBD. For example, capacitors for dielectrics, a dissipative element for plasma, etc. Figure 1 below shows some examples of circuit type models.

These models do not allow to have a microscopic vision of the plasma (ion movement, electrons, ...) but rather to have a macroscopic view of things (voltage / current at the terminals of the DBD), which can make it possible to have A global view on all the physical phenomena that can occur within the DBD. The majority of these models are simply adjusted to an operating point. They therefore do not allow modeling the behavior of plasma if the parameters vary strongly, but this modelization makes it easy to implement them in Spice simulation software, with a very fast calculation time.

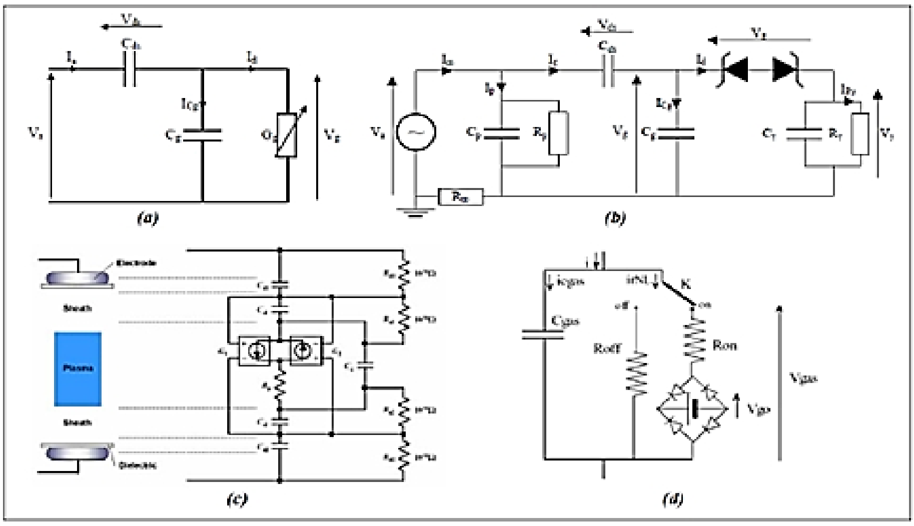

*Figure 1. Example of different models of discharge circuit type:
(A) Equivalent electrical diagram of the discharge (Khamphan, 2004); (B) Townsend discharge model at atmospheric pressure (Naudé, 2005); (C) Dielectric - barrier discharge (Chen, 2003); (D) Dielectric- barrier discharge (Vongphoutone et al., 2001)*

Controlled discharge (DBD), these quantities are not directly measurable and must be calculated from an equivalent electrical diagram (Figure 2).

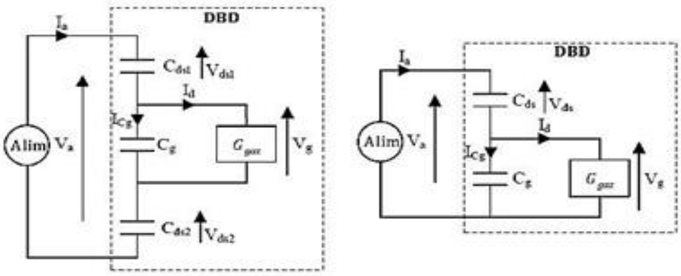

Figure 2. Classical electrical circuit of a DBD

The solid dielectrics which cover each electrode are modeled using the capacitance Cds (which corresponds to the series association of the capacitors C_{ds1} and C_{ds2} which correspond respectively to the capacities of the dielectrics covering the high voltage and the ground).

The values of the different capacities are directly dependent on the section under consideration.

Whether the discharge is switched on or off, the electrode surface (9 cm^2) must be considered.

We can therefore easily calculate the capacitances of the circuit model for an electrode surface of 9 cm^2 and an inter-dielectric space:

$$C_g = \frac{\varepsilon_0 \varepsilon_{rg} S}{d} = 7.96 \text{ pF} \tag{1}$$

$$C_{ds1} = C_{ds2} = \frac{\varepsilon_0 \varepsilon_r S}{d} = 12.41 \text{ pf} \tag{2}$$

$$C_{ds} = \frac{C_{ds1} C_{ds2}}{C_{ds1} + C_{cd2}} = 60 \text{ pF} \tag{3}$$

Where ε_0 is the permittivity of the vacuum ($8.854.10^{-12}$ Fm^{-1}), ε_r is the relative permittivity depending on the milieu (1 in the case of helium 9.6 in dielectrics), S is the surface area of the electrodes (9 cm^2) and d is the inter-dielectric distance (1mm).

From the equivalent electrical circuit of Figure. 2, it is possible to calculate the discharge current as well as the voltage applied to the gas:

$$V_g(t) = V_a(t) - V_{ds}(t) \tag{4}$$

$$V_{ds}(t) = \frac{1}{C_{ds}} \int_0^t I_a(t).\, dt + V_{ds}(0) \tag{5}$$

Knowing Vg, it is thus possible to separate the discharge current, Id, from the capacitive current I_{cg}.

$$I_d(t) = I_a(t) - I_{cg}(t) \tag{6}$$

with

$$I_{cg}(t) = C_g . \frac{dV_g(t)}{dt} \tag{7}$$

The gas having the gas conductance, the gas current and the gas voltage are linked through:

$$I_d = V_g . G_{gas} \tag{8}$$

The phenomenon of conduction in the gas (discharge) is represented by a variable conductance model (Yat, 2012-2013; Diez *et al*., 2007), which is placed in parallel with C_g.

This conductance is governed by a differential equation which imposes the behavior of the gas. It has three terms in its right-hand member (Yat, 2012-2013; Diez *et al*., 2007):

$$\frac{dG_{gas}}{dt} = K_1 . \frac{1}{1+e^{\frac{V_{th}-|V_g|}{\Delta V}}} - K_2 . G_{gas} + K_3 |I_d| \qquad (9)$$

Where G_{gas} is the gas conductance, V_g is the gas voltage, I_d is the conduction current in the gas, Vth is the gas breakdown voltage, ΔV is the voltage Width, K_1 is the breakdown coefficient, K_2 is the excitation coefficient and is the K_3 is the proportionality coefficient (between the gas flow and the conductance).

- The first term (K_1) represents the ionization process linked to gas breakdown; this term operates when the voltage applied to the DBD reaches the breakdown voltage, such as a gate function to dictate when the discharge is to start.
- The second term (K_2) is related to the extinction of the discharge, once the breakdown has passed and any phenomenon likely to sustain the ionization has ceased; This disappearance of the carriers follows a decreasing exponential law, with a time constant equal to:

$$\tau_{extinction} = \frac{1}{k_2} \qquad (10)$$

- The third term (K3) is a term which induces a relation of proportionality between the current of the gas and the conductance, in steady state, that is to say when (dG_{gas} / dt) is equal to zero. The introduction of this term implicitly implies a hypothesis: the current of the gas can maintain the conducting gas in steady state, without there being systematically a new breakdown.

2.2. Simulation model in psim

The parameters of the simulation are presented in Table 1, taking into account the previously calculated gas and dielectric capacities for an electrode surface of 9 cm^2, a dielectric thickness of 0.635 mm, and an inter-dielectric space of 1 mm. The device is powered by a source of sinusoidal voltage from 12 kVcc to 3 kHz.

Table 1. Simulation parameters in PSIM (Enache et al., 2006; Shao et al., 2008)

Parameter	Value
Gas breakdown voltage Vth	4110 V
Voltage Width ΔV	159 V
Breakdown coefficient K1	8.3595
Extinction coefficient K2	$1.7837*10^7$
Proportionality coefficient K3	$2.42 *10^3$

The model of Figure 2 is realized in the software Psim (Figure 3).

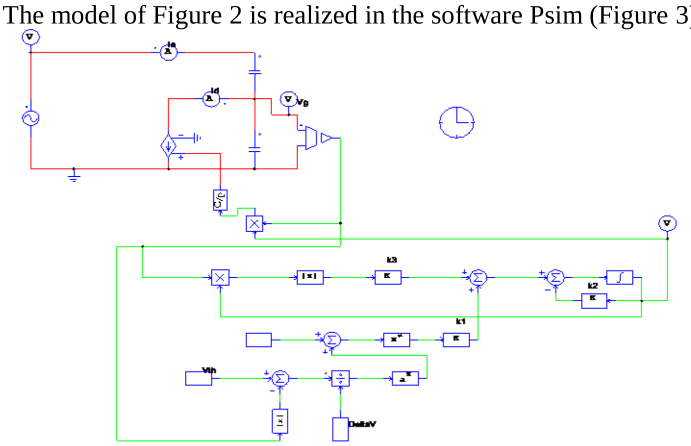

Figure 3. Electrical model of DBD in software Psim

The Psim model takes over the electrical circuit of the DBD. The conductance equation has been reduced to a coefficient circuit in parallel with the gas capacity. It allows us to obtain the characteristics of the different curves of the DBD, that is to say the voltages / currents applied to it, as well as the discharge current, the voltage at the terminals of the gas and the variation of the conductance.

3. Results and discussions

3.1. Electrical characteristics of the discharge

The electrical model of the simulation was carried out on the values of the parameters given in Table 1. The capacitance values Cds and Cg are calculated by substituting the geometry of the DBD cell for formulas (1) and (3), and Are 60pF and 7.96pF, respectively. Figure 4 shows the temporal evolution of the electrical characteristics during two cycles of applied voltage. The discharge current curves and the gas voltage show a model of discharge in the He, which has a single peak current in each half cycle of applied voltage.

This result is obtained by simulating from several works on the homogeneous discharge with dielectric barrier in the He with different discharge conditions (Chen, 2003; Enache *et al.*, 2006; Shao *et al.*, 2008; Zhang *et al.*, 2006). Each peak lasts 5µs with amplitude of 6.7mA. Upon initiation of the discharge, the impedance of the gas varies without the capacitance Cg being modified.

This variation in impedance can therefore be represented by a variable conductance Gg in parallel with the capacitor Cg. The current circulating in the gas is decomposable into two parts: ICg, the current flowing in the capacitor Cg called the displacement current, and Id, the discharge current flowing in the variable conductance called the conduction current. An example of the different waveforms characterizing the discharge can be seen in Figure 5.

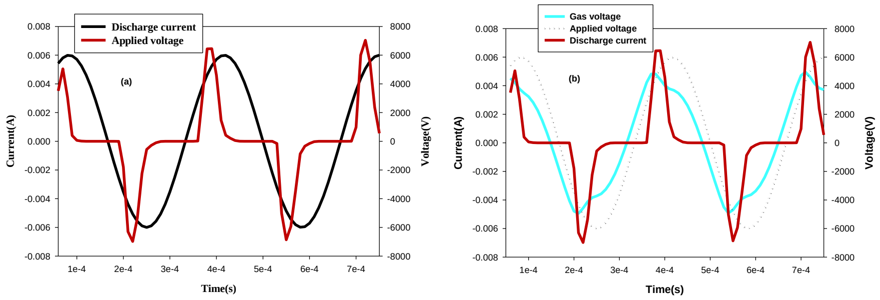

Figure 4. Time evolution of the discharge current and gas voltage during two cycles of applied filed in Helium for an applied voltage of 6 kV, a frequency of 3 kHz and a gap distance of 1 mm

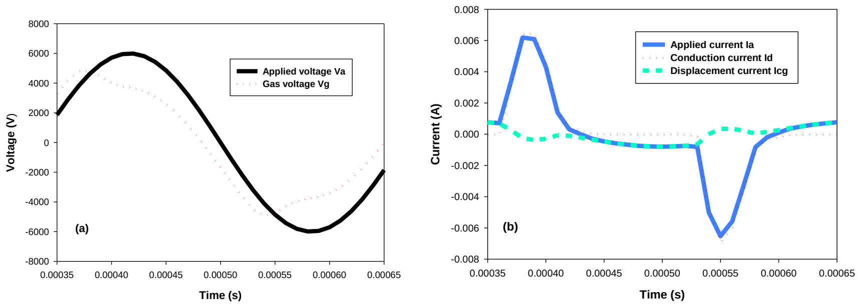

Figure 5. Wave forms a homogeneous DBD

On the basis of the equivalent electrical diagram and the calculation of the internal electrical quantities of the discharge, Figure 6 represents an example of the temporal evolution of the electrical quantities of the atmospheric pressure dielectric barrier discharge in the discharge cell. The gas voltage varies strongly between two peaks of current but is quasi constant for a sufficient value of the current.

Thus, during a half-period, four distinct zones of operation can be observed (Figure 6-a): zone 1 corresponds to the period when the discharge is extinguished, that is to say where there is no ionization in the gas (the gas voltage having not yet reached the starting voltage Vth), zone 2 at the start of the discharge, zone 3 at the interval where voltage Vg is quasi constant and finally The zone 4 at the extinction of the discharge due to the decay of the voltage Va. From the gas voltage and the discharge current it is possible to calculate the gas conductance. As can be seen in Figure 6-b, the conductance varies greatly over a period. When the discharge is switched off (zone 1), the conductance is minimal. A strong increase of the conductance during the initiation of the discharge (zone 2) is then observed before the latter decreases with the decrease of the current (zone 3 and then 4).

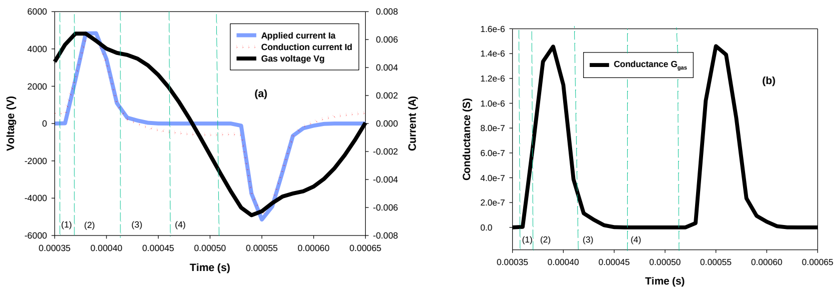

Figure 6. Typical areas of discharge: (a) Voltage/Current; (b) Conductance

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The shape of the voltage / charge Lissajous figure illustrated in Figure 7 is also studied in this work. This curve contains important information about the discharge. As shown in Figure 7, the voltage / charge Lissajous figure for the homogeneous dielectric barrier discharge in the He clearly shows two perpendicular edges corresponding to these two peaks in the discharge current. The form of this Lissajous figure is close to the ideal parallelogram, which comprises four phases. In the first phase (AB) the filaments are created and continue to develop until the voltage reaches its maximum value (plasma on). In the second phase (BC), the value of the voltage decreases and the plasma off'. There is no discharge in this zone until the beginning of the second discharge in which the charge transfer resumes (plasma on) to the third phase (C-D). At the end of the fourth phase (D-A), the voltage decreases again and the plasma remains off until the next discharge (Kogelschatz, 2003).

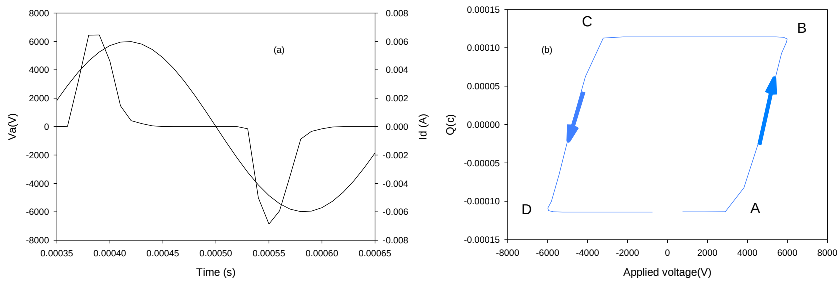

Figure 7. Simulated applied voltage and discharge current Waveforms and Lissajous Figure of Homogenous DBD in He ((a) applied voltage and discharge current, (b) Lissajous figure

3.2. Dynamic behavior of discharge parameters

The voltage-current curves can show the dynamic behavior of the DBD at atmospheric pressure. Some researchers obtained the curves using a numerical simulation and used it to analyze the evolution of homogeneous DBD (Naudé *et al*., 2005; Shao *et al*., 2006). Using the proposed electric model, the voltage-current curves of the homogeneous DBD in He can be easily obtained. Figure 8 shows the curve of the discharge current and the gas voltage obtained from the electrical model simulation. It is shown that it consists of two individual closed loops connected by two lines. Each of the two loops is near the maximum value of the negative and positive voltage cycles, which correspond to the two pulses of the discharge current of Figure 7. On the positive half-cycle of the applied voltage, Vg increases constantly, but Id remains zero. Fracture occurs when Vg reaches point (1) and Id increases sharply, while Vg shows a slight reduction to point (4). According to the conventional gas discharge theory, it is the Townsend discharge mode between (1) and (2). The current growth is stopped at point (4) when the differential conductivity of the gas interval changes from negative to positive. With a positive differential conductivity value, the discharge current begins to decrease while the gas voltage continues to decrease until point (5) is reached and the entire process is completed. Due to its positive differential conductivity, the discharge process between (2) and (4) belongs to the luminescent discharge mode (Zhang *et al*., 2001).

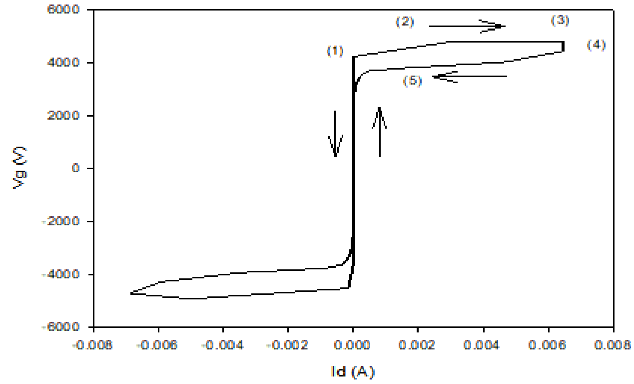

Figure 8. Charactirestics Vg(Id)

In this section we put ourselves under the same conditions as before (sinusoidal voltage 12 KVcc at 3 KHz) in order to study the transition in filamentary mode. The first step consists in reproducing macroscopically a micro-discharge, so we must introduce a strong increase in the local conductivity over a zone corresponding to the diameter of a micro-discharge for this; we have varied the value of the coefficient K2 (coefficient of Proportionality between the discharge current and the conductivity).

Figure 9 shows the Lissajous figure corresponding to the charge as a function of the voltage to distinguish the filamentary regime (Potin, 2011; Tay *et al.*, 2014). According to the curve of the discharge current there are several peaks of the current for each half cycle of the applied voltage corresponding to the filamentary regime.

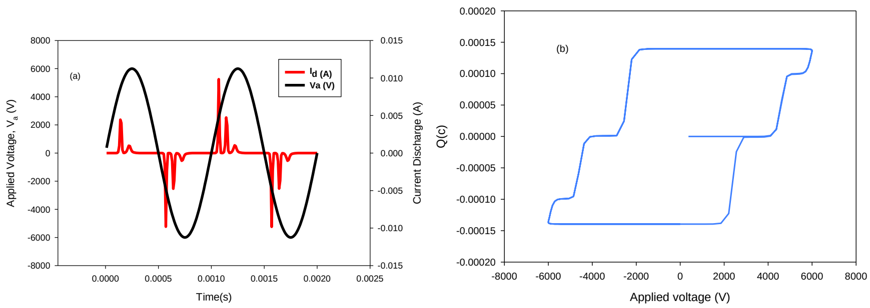

Figure 9. Simulated applied voltage and discharge current Waveforms and Lissajous figure of Filamentary DBD in He ((a) applied voltage and discharge current, (b) Lissajous figure)

4. Conclusion

This work makes it possible to obtain an electric model of the glow discharge with dielectric barrier (DGBD) in helium. The model obtained gives a general view of the electrical behavior of the DGBD, this model is studied using software Psim based on a variable conductance.

The results of the simulation on the DGBD under an applied voltage are presented, among others, the time evolution of the discharge current, the gas voltage and the various current that exist in the DLBD. It is found that the landfills studied function in the homogeneous mode. Therefore, the electrical model is checked to accurately reflect the discharge process, and it can be used as an efficient method for studying the electrical characteristics of the homogeneous DBD. The filamentary regime is indicated by different peaks in the characteristics of the current are confirmed by the Lissajous figure.

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