Electrical model of dielectric barrier discharge homogenous and filamentary modes

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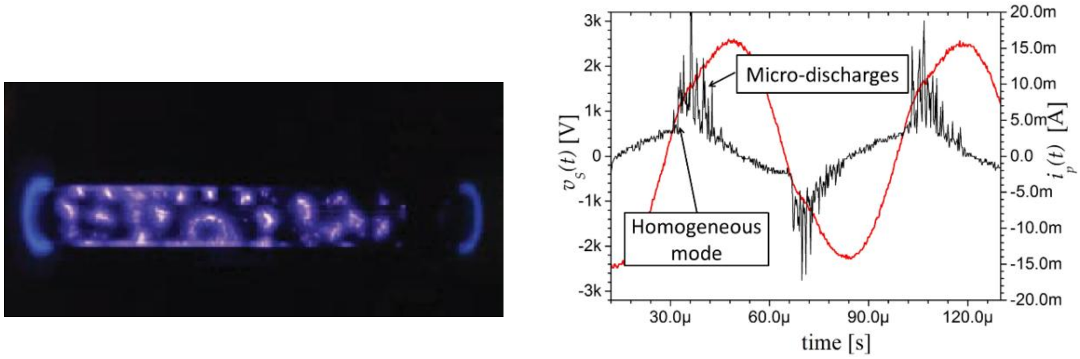
Abstract. This work proposes an electrical model that combines homogeneous and filamentary modes of an atmospheric pressure dielectric barrier discharge cell. A voltage controlled electric current source has been utilized to implement the power law equation that represents the homogeneous discharge mode, which starts when the gas breakdown voltage is reached. The filamentary mode implies the emergence of electric current conducting channels (microdischarges), to add this phenomenon an RC circuit commutated by an ideal switch has been proposed. The switch activation occurs at a higher voltage level than the gas breakdown voltage because it is necessary to impose a huge electric field that contributes to the appearance of streamers. The model allows the estimation of several electric parameters inside the reactor that cannot be measured. Also, it is possible to appreciate the modes of the DBD depending on the applied voltage magnitude. Finally, it has been recognized a good agreement between simulation outcomes and experimental results.

1. Introduction

Dielectric barrier discharge (DBD) has been utilized in many research and industrial fields as an interesting technology due it combines the characteristics of the non-thermal plasma with the advantage of operating at atmospheric pressure, besides that small research reactors can be scaled to industrial reactors. This type of discharge has been used successfully in applications such as pollution control, polymer processing, medicine, fluorescent lamps, ultraviolet lamps, etc. Figure 1(a) shows an argon atmospheric pressure DBD established in a coaxial reactor. While its applied voltage and resulting electric current waveforms are depicted in Figure 1(b), where it can be distinguished the homogeneous and filamentary modes in the current curve.

The DBD can be modeled using computer numerical methods based on continuity equations coupled to the Poisson equation and boundary conditions. However, it should be necessary to make several considerations related to the gas ionization to simulate the physical process. The aim of these models is to study the physical-chemical process discharge, mainly the phenomena associated with the electron conservation, the spatiotemporal evolution of chemical species, electric field along the axis discharge, etc. One of the disadvantages of these computer models is that they are complex, require great computing power and consume considerable time [1]. Instead, there are DBD models based on the use of electric circuits [2], [3], [4], [5] which are mainly composed by a high voltage power supply coupled to a reactor or cell implemented by passive components and the discharge process emulated by switches, dependent current sources and passive elements also. This class of models allows obtaining the dynamic relationships between external parameters (applied voltage, total current, flow and gas type, dielectric materials and reactor configuration).

There are several models of electric discharge DBD for example: Kogelschatz [6], uses a variable resistor, which represents the channels of microdischarges, Valdivia-Barrientos [7], proposes a method in which superimposes the microdischarges to the displacement current, Flores-Fuentes [2] and Chen [8] used a concept of power law, Pal [9] implements a model that uses multiple switches to reproduce the current peaks of the DBD, Kudryavtsev [10] uses a diode bridge model and a source of DC voltage, Naude [11] uses two Zener diodes and an RC circuit, among others.



(a) (b)

Figure 1. Dielectric barrier discharge, (a) cylindrical reactor photography, (b) current and voltage waveforms.

2. Proposed Model

The proposed model does not represent the physical conditions of a DBD but aims to reproduce the electrical signals to serve as support in the optimal design of electric power converters. Besides the model allows obtaining relevant electrical functioning parameters such as voltage discharge, power efficiency, etc. which are useful for scaling of even other applications. When there are many filaments in the discharge process, the plasma is a mixture of glow and filamentary discharges. When the whole system is properly adjusted the filamentary discharge can be suppressed, since the visible streamers and filaments disappear, as a consequence, the discharge becomes more homogeneous. The waveform of the current can remain with few peaks as a result of instabilities caused by irregularities in the electrode edges, dielectric imperfections, water vapor and oxygen species in the plasma [8].

A double dielectric barrier parallel plate reactor with a space gap for containing the gas is powered by an alternating current to generate the DBD discharge. Equivalent electric circuit considers the dielectric plate as a capacitive element C_d and the gas inside the gap corresponds to a capacitive component C_g. When the DBD develops, the proposed model operation is divided into two stages: off and ignition. When voltage applied to the reactor is less than the breakdown gas voltage the reactor impedance is mostly capacitive and can be modeled by the dielectric capacitance C_d in series with the gas capacitance C_g, as it can be seen in Figure 2(a), since the applied voltage is a sinusoidal waveform the current maintains the same form but phase shifted by 90°. The ignition phase is represented by the circuit of figure 2(b), where the reactor current can be defined by equation (1), where the current reactor $i_{DBD}(t)$ is constituted by the addition of three components: current in the gas background $i_g(t)$, current due to homogeneous mode $i_h(t)$ and filamentary current due to microdischarges $i_f(t)$.

$$i_{DBD}(t) = i_g(t) + i_h(t) + i_f(t) \tag{1}$$

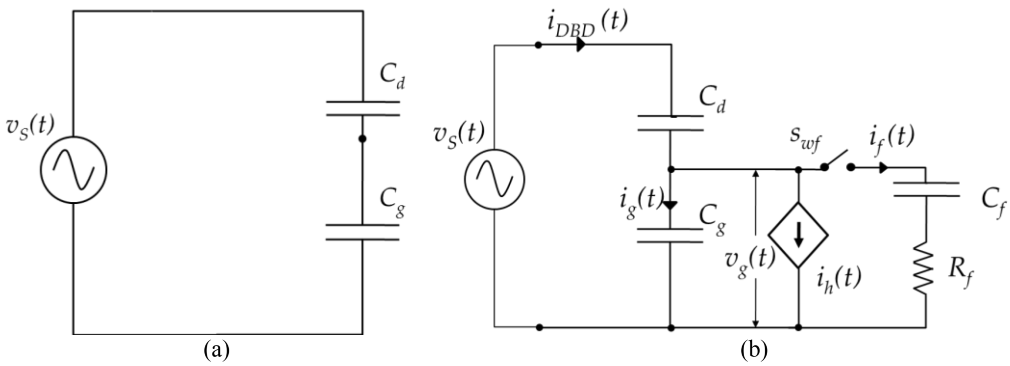


Figure 2. DBD electric model, (a) off stage circuit, (b) ignition stage circuit.

2.1. DBD homogenous mode

The ignition stage begins when the applied voltage inside the gap $v_g(t)$, surpasses the gas breakdown voltage magnitude V_b, at this moment the current $i_h(t)$, turns in an exponential form due to the changes in gas conductivity. The high voltage involves an intense electric field that produces ionization and transportation of charges. Thus this phenomenon is modelled by a power law proposed by Roth [12]:

$$i_h(t) = i_o \left(\frac{v_g(t)}{V_b}\right)^{\alpha} \tag{2}$$

The electric current $i_h(t)$ is implemented in the electric circuit model by a current source controlled by the gap voltage $v_g(t)$ and α is the rate of change of current with respect to time di_h/dt which takes values between 2 and 12, and i_o is the current density due to the continuous emission of electrons from the cathode.

2.2. DBD filamentary mode

When the dielectric has a non-uniform surface, there are areas where the electric field becomes more intense, leading to the development of microdischarges. First, a primary electron by inelastic collisions develops an electrons avalanche and consequently a weakly ionized conductor channel, trough the gap in a few nanoseconds [13], [14], [15]. Then electron accumulation attracted by the positive electrode on the dielectric surface causes the extinction of the local electric field and by the way the ending of the current associated with the electronic avalanche. The number of microdischarges depends fundamentally on the power density, a typical amount of is about 10^6 per cm^2 per second [6]. The proposed model represents the current due to the appearance of microdischarges by the commutation effect of an *RC* circuit, in which a switch connects and disconnects both the capacitor C_f and resistor R_f, as can be seen in Figure 3(a). The control circuit of s_{wf} is shown in Figure 3(b), in order to activate s_{wf} a pulse generator with a nanoseconds period defines the main frequency, this signal is applied to an "and" logic gate with a signal generated if and only if the gap voltage $v_g(t)$ surpasses the gas breakdown voltage level V_b. When s_{wf} is closed, the voltage $v_g(t)$ is supplied to C_f and R_f, applying the laws of Kirchhoff is established the following equation:

$$v_g(t) = V_{Cf} + V_{Rf} \tag{3}$$

Whereas the width of a microdischarge is on the order of nanoseconds while the period of signals that energize the reactor are on the order of microseconds, it can be assumed $v_g(t)$ constant, therefore the above equation can be rewritten as:

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$$v_g(t) = \int i_f(t)\,dt - V_{Cf}(0) + R_f \cdot i_f(t) \tag{4}$$

Solving the above equation for the filamentary current $i_f(t)$ and considering the initial voltage of $C_f = 0$ is obtained:

$$i_f(t) = \left(\frac{V_g}{R_f}\right) e^{-\frac{t}{R_f C_f}} \tag{5}$$

Microdischarges can reach peak currents of the order of 0.1 A, considering the proposed circuit, the maximum amplitude of $i_f(t)$ is obtained at time $t = 0$, then, the amplitude depends on $I_{fmax}= V_g/ R_f$ and solving equation for R_f:

$$R_f = \frac{V_g}{I_{fmax}} \tag{6}$$

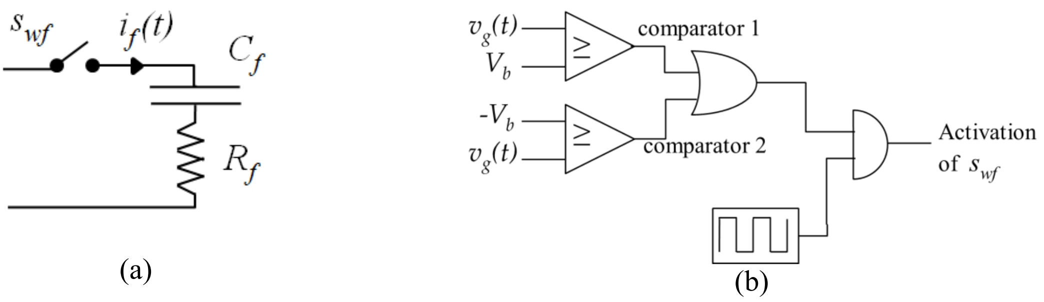
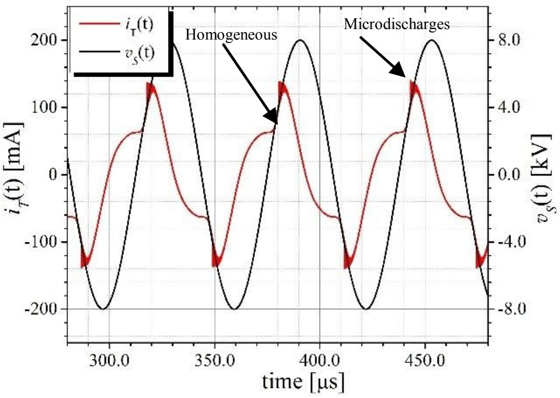


Figure 3. (a) Microdischarge proposed model implemented by an RC circuit, (b) the control circuit of s_{wf}.

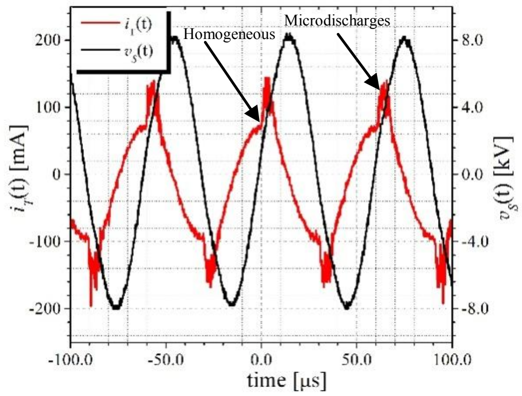
3. Simulation and Experimental Results

The experimental setup consists of a circle parallel plate reactor, where both electrodes are stainless steel with 18 cm diameter, each electrode is covered with dielectric tempered glass with a thickness of 2 mm and a space gap of 2 mm to contain the gas. The working gas is N_2 with a flow of 1 L/min. The reactor is energized by a sinusoidal signal with an amplitude of 16 kV peak to peak at a frequency of 16 kHz. The model has been implemented in Simulink/Matlab® taking into account the physical dimensions of the reactor (C_g= 112 pF, C_d= 253 pF) and the voltage specified in experimentation. The electrical signals obtained by simulation are shown in Figure 4(a) whereas experimental waveforms can be appreciated in Figure 4(b).

Through the proposed model, the curve in Figure 5 was obtained, considering the graph it can be seen six different points denoted by letters A to F. The DBD starts at the point A, where the current remains almost constant until the voltage reaches a value of 3 kV, from this point current, starts to increase exponentially to the point B, reaching its maximum, while the voltage remains nearly constant, then the current decreases from point C until point D, where the current crosses by zero and becomes negative, υ_g remains positive due to the phase shift that occurs between current intensity and voltage due to a predominantly capacitive load, until the voltage reaches zero volt. From point D voltage becomes negative until the point E where it stabilizes while the current has an exponential behavior, then decrease to zero crossing at point F where the current becomes positive while the voltage is negative. Finally, the current becomes positive while the voltage decreases to return to the starting point A.



(a)



(b)

Figure 4. Reactor current and voltage waveforms, (a) simulation outcomes, (b) experimental results.

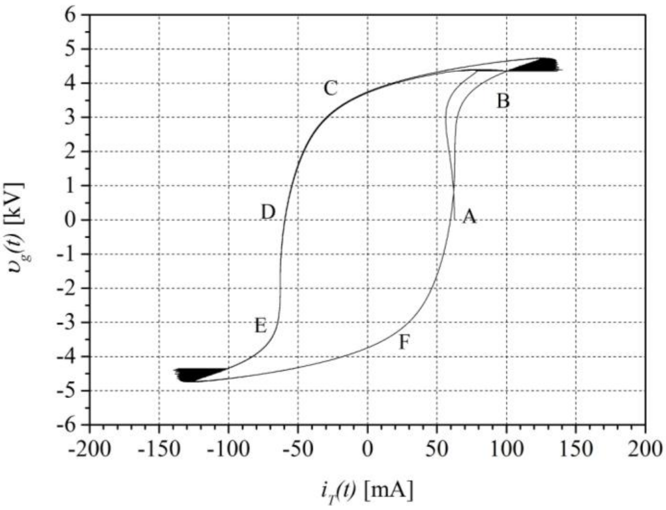


Figure 5. Estimated voltage-current discharge curve resulting from the proposed model.

Signals currents and voltages within the reactor are shown in Figure 6 since it can be seen that the space gap voltage $v_g(t)$ is phase shifted relative to the applied reactor voltage $v_s(t)$, the homogeneous mode starts at point B when $i_h(t)$ increases exponentially. Finally, during the filamentary mode, it has been observed a higher voltage level than that corresponding to the start of the homogeneous mode.

4. Conclusion

The proposed model includes the electrical behavior of both modes of a DBD: homogeneous and filamentary. From the model it has been observed that the homogenous mode starts at lesser voltage level than the filamentary mode voltage level, this could be due to the effect of the increased electric field which begins to produce ionization by changing the gas conductivity and generating displacement of electrical charges, the last are associated with the electric current increase during the homogeneous mode. If the voltage level continues increasing the electric field will become even more intense, and the protrusions of dielectric could present the tip effect, forming conducting current channels (microdischarges). Moreover, the presence of humidity in certain regions of the space gap could produce that the local conductivity is increased favoring the appearance of microdischarges.

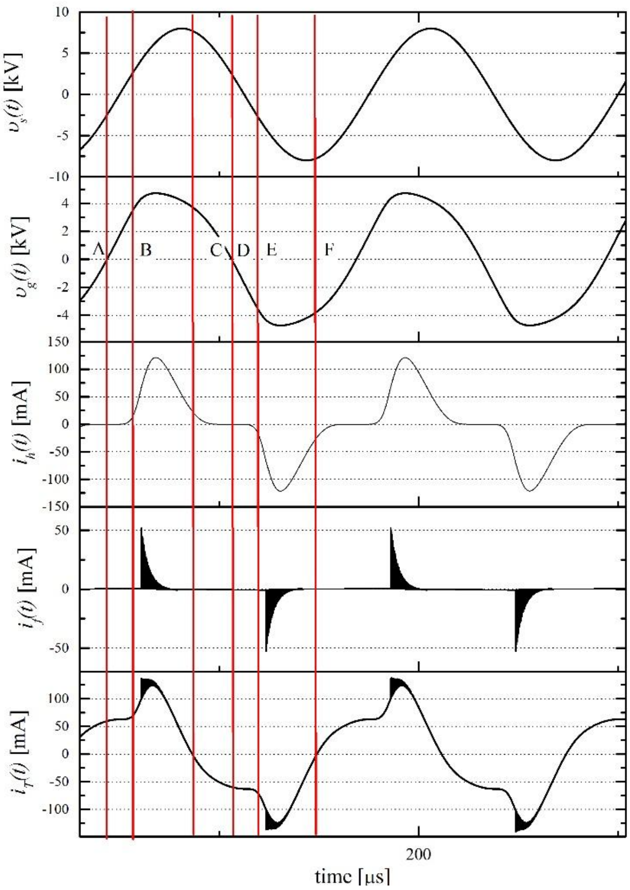


Figure 6. Waveforms inside the reactor obtained from the modelled DBD.

5. References

[1] Fang Z, Qiu Y, Zhang C, and Kuffel E 2007 *J. Phys. D: Appl. Phys.* **40** 1401
[2] Flores-Fuentes A, Peña-Eguiluz R, López-Callejas R, Mercado-Cabrera A, Valencia-Alvarado R, Barocio-Delgado S and de la Piedad-Beneitez A 2009 *IEEE Trans. Plasma Sci.* **37** 128
[3] Fang Z, Ji S, Pan J, Shao T and Zhang C 2012 *IEEE Trans. Plasma Sci.* **40** 883
[4] Pal U N, Gulati P, Kumar N, Prakash R and Srivastava V 2012 *IEEE Trans. Plasma Sci* .**40** 1356
[5] Yao Y, Zhang Z T, Yu Z, Xu S J, Yu Q X and Zhao J S 2013 *J. Phys. Conf. Ser.* **418** 012023
[6] Kogelschatz U. 2003 *Plasma Chem. Plasma P.* **23** 1
[7] Valdivia-Barrientos R, Pacheco-Sotelo J, Pacheco-Pacheco M, Benítez-Read J S and López-Callejas R 2006 *Plasma Sourses Sci. Technol.* **15** 237
[8] Chen Z Y 2003 *IEEE Trans. Plasma Sci.* **31** 511
[9] Pal U N, Gulati P, Kumar N, Prakash R and Srivastava V 2012 *IEEE Trans. Plasma Sci.* **40** 1356
[10] Koudriavtsev O, Wang S, Konishi Y and Nakaoka M 2002 *IEEE Trans. Ind. Appl*. **38** 369
[11] Naudé N, Cambronne J P, Gherardi N and Massines F 2005 *J. Phys. D: Appl. Phys.* **38** 530
[12] Roth J R 1995 *Industrial Plasma Engineering: Volume 1: Principles* (London: Taylor & Francis)
[13] Meek J M 1940 *Phys. Rev.* **57** 722
[14] Xu X and Kushner M J 1998 *J. Appl. Phys.* **84** 4153
[15] D. Braun, V. Gibalov and G. Pietsch 1992 *Plasma Sources Sci. Technol.* **1** 166