MATHEMATICAL MODEL OF A DIELECTRIC BARRIER DISCHARGE IN ATMOSPHERIC PRESSURE HELIUM SUPPLIED BY A MULTICELL INVERTER

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Abstract

A dielectric barrier plasma discharge (DBD) in helium at atmospheric pressure is modelled in the case of a parallel plate reactor supplied by a multicell voltage source inverter, which, in this case, is composed by three commutation cells, whereby it is called a three cell inverter (TCI). The novelty of the present study lies in simultaneously simulating: (a) the power supplied by a static converter distinct from a linear amplifier, (b) the coupling transformer response and (c) the discharge behaviour itself. The main aim of such a simulator is developing a comprehensive MATLAB®/Simulink model of the archetypal discharge within two flat parallel electrodes separated by a narrow gap. These are covered with a thin dielectric coating which is electrically represented by a capacitor. The plasma discharge is simulated by a voltage controlled current supply that is activated as soon as the gas breakdown voltage is surpassed. The discharge is modelled by a *V-I* exponential dependence characterised by a factor α, in turn, dependent on the Townsend ionisation coefficients. Specifically produced experimental results validate the theoretical predictions of the model which can be adjusted in order to include discharges in other gases, predicting the respective optimised experimental conditions.

Keywords: DBD, multicell VSI, plasma system model, voltage controlled current source, voltage current exponential dependence.

Presenting Author's biography

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1 Introduction

Dielectric Barrier Discharges (DBD) are usually generated between two parallel electrodes in a gas at atmospheric pressure. The power sources most frequently used for DBD generation are able to provide high AC voltage outputs from some tens of Hz [1] up to the order of several kHz [2]. For this purpose, several authors resort to resonant inverters either in a half-bridge configuration [3] or in a full-bridge one, operating at tens of kHz [4]. This paper presents a Matlab®/Simulink model and several simulation results from it when applied to a system constituted by a DBD reactor with parallel plates. The latter is biased by a coupling transformer whose primary is driven by a voltage power supply configured on the basis of a half-bridge three cell inverter (TCI).

2 Electrical model

Figure 1 shows the circuit representation of the considered reactor and the DBD. A dielectric sheet between the actual plates is represented by two capacitors (C_{d1} and C_{d2}). A voltage-controlled current-source (G_p) stands for the discharge dynamic impedance which represents the behaviour of the plasma discharge. Therefore, as long as the applied voltage across the gap exceeds the gas breakdown voltage, the current-source is turned on, and its output value increases as a function of the voltage, according to the power law discussed in [5]. C_g and R_g are, respectively, the capacitance and the resistance of the gas.

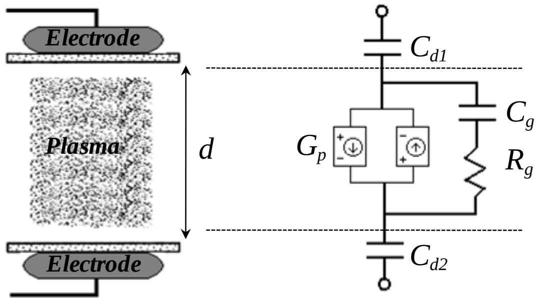

Fig. 1 The DBD cell (left) and its electrical model (right)

There are a several reported simulation studies of the electric characteristics of plasma discharges [6, 7]. We have focused on a versatile model in order to change the simulation parameters so to fit the characteristics of the experimental plasma discharge behaviour.

2.1 The MCI as a power supply

A half-bridge TCI configuration has been improved with a parallel plate DBD reactor as a load (Figure 2).

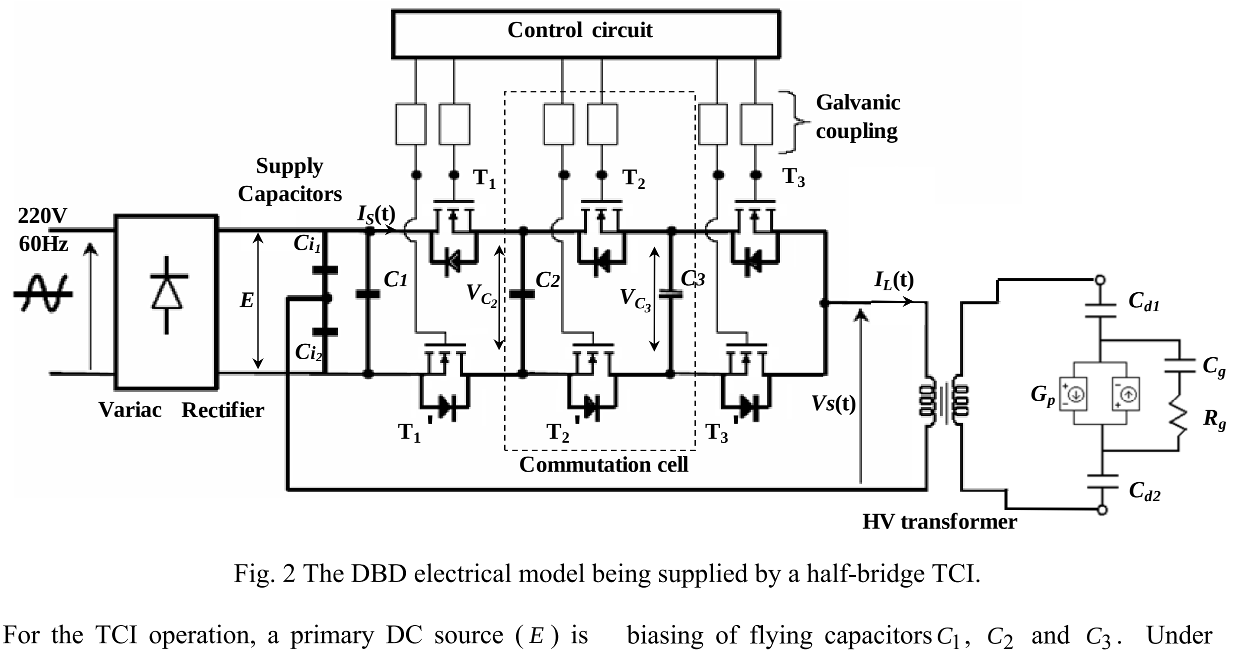

Fig. 2 The DBD electrical model being supplied by a half-bridge TCI.

For the TCI operation, a primary DC source (E) is required. The inverter is supplied by a bipolar voltage source composed by the capacitors C_{i1} and C_{i2}, so that $V_{C_i} = E/2$. Through the appropriate commutation of the cells it is possible to generate a quasi-sinusoidal output signal $V_S(t)$ [8]. The commutation cells are structured by two MOSFETs associated to freewheel diodes, connected in parallel, and their operation requires several control sequences preceded by the biasing of flying capacitors C_1, C_2 and C_3. Under balanced circumstances, the voltages across each of them are: E, $2E/3$ and $E/3$, respectively. Meanwhile, the average current in each switch can be defined as:

$$I_{P_{avg}} = D_n I_S(t) \tag{1}$$

where: $I_S(t)$ is the input current of each TCI switch and D_n is the work cycle of the n-th switch, determined by the T_{on}/T ratio. Here T_{on} is the activity period of the switch, the signal period is $T = 1/f_{sw}$ and the switching frequency is f_{sw}=200 kHz.

TCI stability is achieved when the work cycles of its commutation cells reach the same duty cycle, while the relative phase of the control signals is kept at 120°. The commutation signals at the TCI switches are generated by means of a sinusoidal pulsed width modulation (PWM) technique with an f_{sw} carrier signal frequency and an f_0 modulation one. Thus, the PWM is able to produce the signals to the MOSFET transistors T_1, T_1', T_2, T_2', T_3 and T_3', each pair of their respective complementary (same subindex) switch signals being mutually 120° out of phase.

In order to calculate the capacitance values required to limit the voltage through the switches, a designer estimation of the ripple voltage ΔV_{Ck} is required. Thus, the capacitance of floated C_k turns out to be:

$$C_k = \frac{I_s(t)}{2n f_{sw} \cdot \Delta V_{Ck}} \qquad (2)$$

2.2 Electrical modelling of the DBD

As in any DBD reactor process, the present one evolves through two main phases: *discharge off* and *discharge on* (ignition and Townsend regimes). Therefore, the reactor can be represented by (see Figure 1): a) the gas capacitance C_g and gas resistance R_g ; b) the equivalent capacitances of each one of dielectrics C_{d_1} and C_{d_2}, whereby $C_d = C_{d1} + C_{d2}$, and c) the discharge current $I_{dis}(t)$ modelled by a voltage controlled current-source. The $I_{dis}(t)$ value equals the sum of ignition ($I_{dis-ign}(t)$), and Townsend ($I_{Townsend}(t)$) currents. So, the input current to the reactor, $Ig(t)$, is either the sum of those in block G_p and in the capacitor C_g or the discharge off current ($I_{dis-off}(t)$). Thus:

$$Ig(t) = I_{dis}(t) + I_{dis-off}(t) \qquad (3)$$

In the discharge-off case, the current $I_{dis-off}(t)$ depends on the applied voltage $V_s(t)$, and is affected by capacitances C_d and C_g, as well as R_g, in the form:

$$I_{dis-off}(t) = \frac{C_d C_g}{C_d + C_g} \frac{dVs(t)}{dt} + \frac{V_s(t)}{R_g} \qquad (4)$$

The ignition discharge is given by:

$$I_{dis-ign}(t) \begin{cases} = 0 & , Vg(t) < Vb \\ \propto (V_s(t)/Vb)^{\alpha} & , Vg(t) > Vb \end{cases} \qquad (5)$$

where: $V_s(t)$ is the voltage being delivered by the MCI to the load, Vb is the breakdown voltage, $Vg(t)$ is the voltage through the gas and α is a coefficient which depends on several discharge characteristics. At this stage, $Ig(t)$ remains small until the breakdown point. From then on, the current increases its slope according to the value of the exponent α (see Eq. (5)). Finally, in the Townsend regime, the current becomes:

$$I_{Townsend}(t) = C_d \frac{dVs(t)}{dt} \qquad (6)$$

The turn-on potential Vb depends on the breakdown field E_t which is a characteristic of each specific gas, the electrode material, pressure and gap space [9]. In order to determine Vb, it is necessary to consider α, which is given by:

$$\alpha = Ap \exp(-Bp / E_t) \qquad (7)$$

where: p is the pressure in Torr and the coefficients A, B and E_t/p are defined specifically. Several of these coefficients are listed in Table 1.

Table 1 Ionization coefficients and the application regions.

Gas	A [cm·Torr]$^{-1}$	B V/cm·Torr	E_t/p V/cm·Torr
He	3	34	20-150
Ar	12	180	100-600
N_2	8.8	275	27-200
Aire	15	365	100-800

These coefficients can be introduced as arguments in the block function f(u) of the voltage controlled current source (G_p) model, depicted in Figure 3.

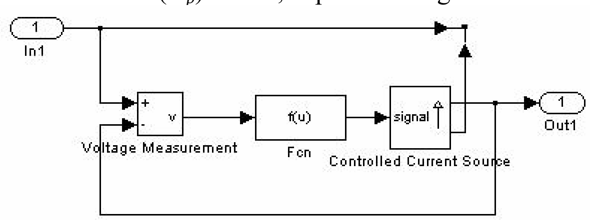

Fig. 3 Simulation model of the voltage controlled current source (G_p).

3 Simulation and experimental results

An important element of the TCI is its high voltage power transformer as it isolates the converter from the high voltage circuit (DBD reactor) and increases the voltage applied to its primary winding.

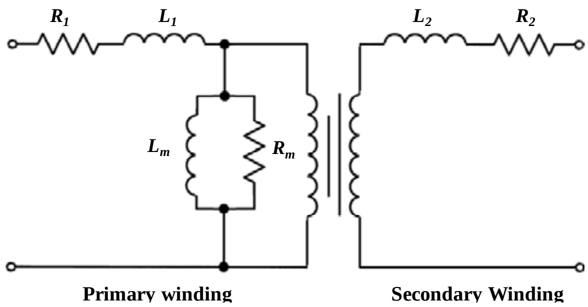

Fig. 4 Transformer model.

The transformer model, shown in Fig. 4, consists of two coupled coils wound on the same core. This takes into account the winding resistances (R_1, R_2) and the leakage inductances (L_1, L_2), as well as the magnetizing characteristics of the core, which is modelled by a linear (R_m , L_m) branch.

In order to define the transformer parameters it is necessary to specify their *per unit* (*p.u.*) magnitudes. The values are based on the transformer rated power P_n in VA, nominal frequency f_n in Hz, and nominal voltage V_n in Vrms, of the corresponding winding. For each winding, the *p.u.* resistance and inductance are defined as:

$$R(p.u.) = \frac{R(\Omega)}{R_{base}}, \; L(p.u.) = \frac{L(H)}{L_{base}} \tag{8}$$

The base resistance and base inductance used for each winding are:

$$R_{base} = \frac{(V_n)^2}{P_n}, \; L_{base} = \frac{(R_{base})^2}{2\pi \cdot f_n} \tag{9}$$

For the magnetization resistance R_m and inductance L_m, the p.u. values are based on the transformer rated power and on the nominal voltage of the primary winding.

The parameters imposed on the simulation in the case of a Helium discharge are listed in Table 2. The values of R_1, L_1, R_2, L_2, R_m and L_m have been calculated so to determine the parameters of the coupling transformer. By contrast, R_{xtr}, $L_{primary}$, $L_{secondary}$ and K_{xtr} are actual measured values.

Table 2 Parameters used in simulation of the DBD system.

Ideal Transformer in MATLAB® model			
$R_1 = 0.026\Omega$	$L_1 = 3.3H$	$R_2 = 0.0066\Omega$	$L_1 = 1H$
$L_m = 500H$	$R_m = 500\Omega$		
Non-ideal transformer real measurements			
$R_{xtr} = 0.1\Omega$	$L_{primary} = 50\mu H$	$L_{secondary} = 2mH$	
$K_{xtr} = 30$			
Parallel plate DBD reactor values calculated from experimental data.			
$C_{d1} = 6.5nF$	$C_{d2} = 6.5nF$	$C_g = 1.3nF$	$R_g = 0.01\Omega$

Finally, C_{d1}, C_{d2}, C_g and R_g were calculated from published experimental data [10]. According to our observation of the parallel plate DBD reactor, the dielectric capacitance can be calculated by applying the expression $C_d = \varepsilon_0 \varepsilon_r S/l$. So, for an industrial glass dielectric $\varepsilon_r = 2.7$, and from the DBD reactor characteristics (thick between plates $l = 0.2$ cm and the surface plate $S = 113\,\text{cm}^2$) the DBD reactor capacitance becomes $C_d = 13$ nF. In fact, the value of the plasma sheet capacitance C_g is around ten times lesser than C_d [11]. The R_g value was slightly undervalued at the time of the current discharge.

The resulting current and voltage discharge waveforms for the simulation process are shown in Figure 5. Figure 6 presents the respective experimental signals.

Then, Figures 7 to 9 display the experimental and simulated results from the discharge evolution under an increasing output inverter voltage $V_s(t)$ in order compare the effectiveness of the proposed model.

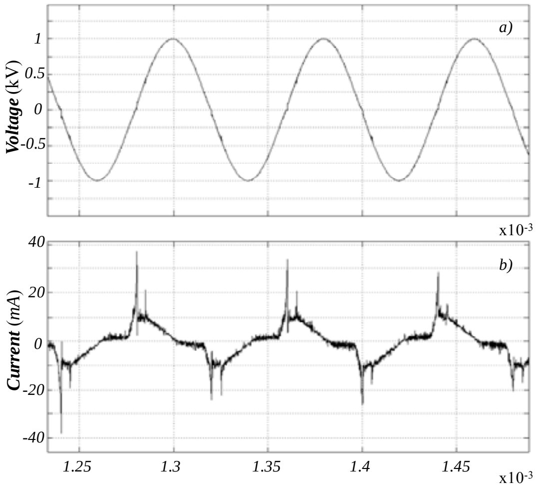

Fig. 5 Simulation results (frequency 12.5 kHz, α=12): a) applied voltage $V_s(t)$, b) discharge current.

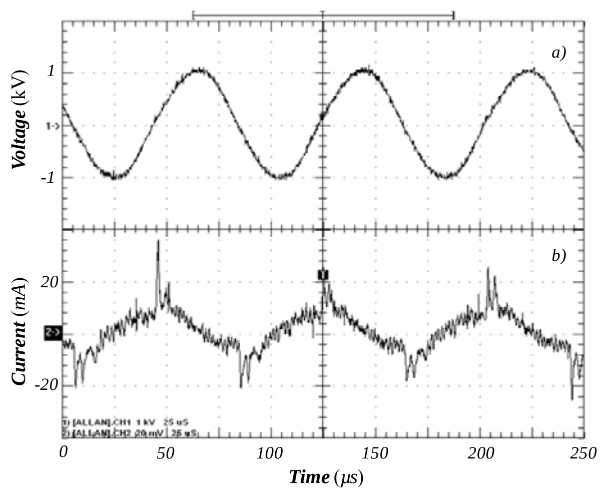

Fig. 6 Experimental results from the reactor (12.5 kHz frequency, transformer primary 75V/9A) a) applied voltage $V_s(t)$, b) discharge current.

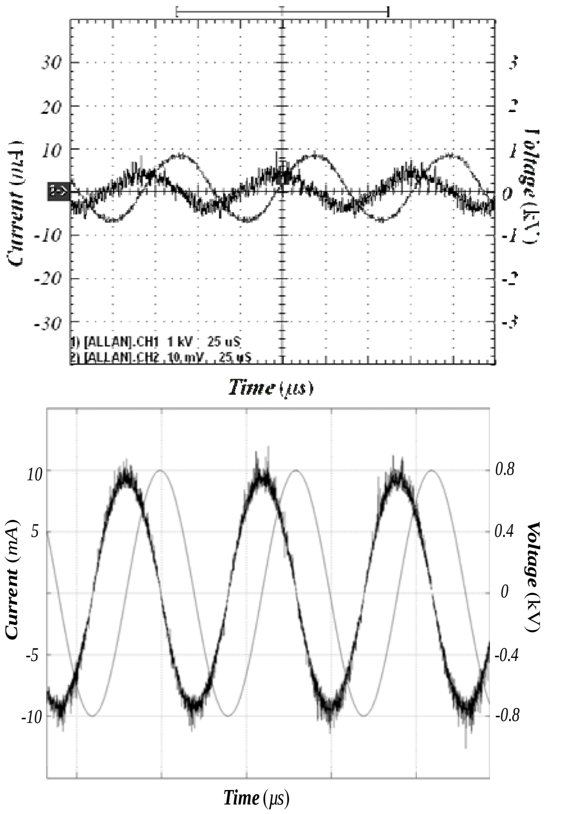

Fig. 7. Comparison of experimental (top) and simulation (bottom) results at 12.5 kHz. The parameters of the voltage transformer primary side are 35V/6A, with α=9.

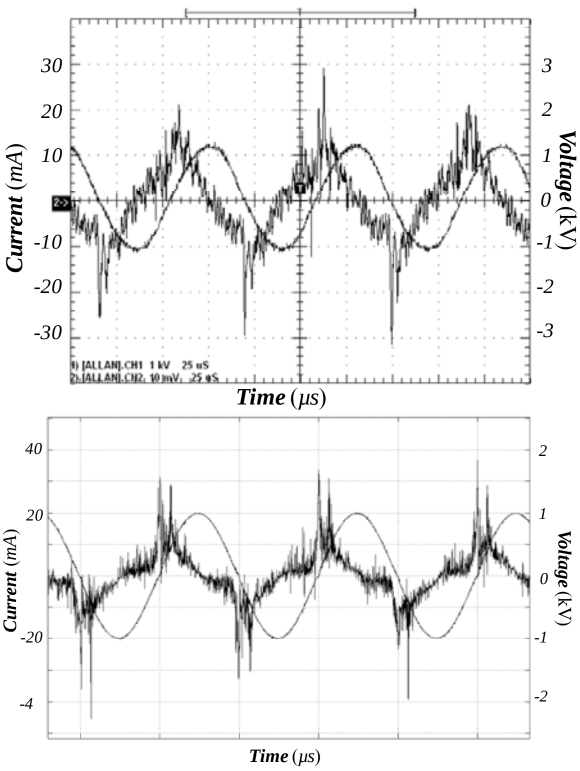

Fig. 8 Comparison of experimental (top) and simulation (bottom) results at 12.5 kHz. The parameters of the voltage transformer primary side are 70V/8A with α=9.

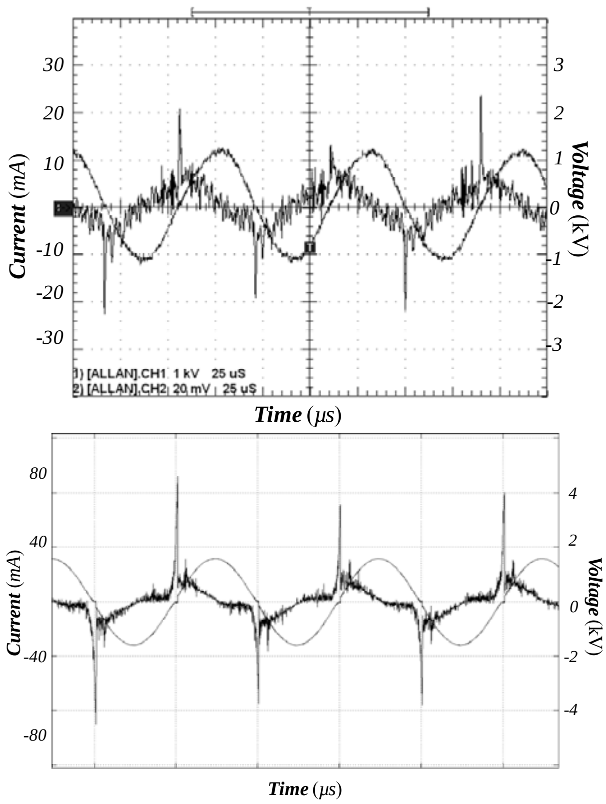

Fig. 9 Comparison of experimental (top) and simulation (bottom) results at 12.5 kHz. The parameters of the voltage transformer primary side are 110V/9A; the coefficient α=9

4 Conclusions

A satisfactory MATLAB® model of a plasma discharge in a parallel plate DBD reactor operated with Helium gas at atmospheric pressure has been developed. The simulation predictions agree both qualitatively and quantitatively with the experimental data provided that the *I–V* power law exponent is chosen to fit the particular reactor geometry and the plasma work conditions.

The MATLAB® simulation shows that the voltage and current amplitudes applied to the DBD reactor supplied by a half-bridge TCI are determined by the gas factor α which, in turn, depends on both the gas pressure and the geometry of the reactor. The behaviour of this factor follows a current-voltage power law and constitutes a phenomenological characteristic of a normal glow discharge. The results of the simulation model suggest that the characteristics of the power supply and the transformer coupling are fundamental factors of the experimental performance.

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