PSpice Simulation of Atmospheric Pressure Air Glow Discharge Current-Voltage Characteristic

Peter D. Dineff[1], Diliana N. Gospodinova[2] and Elisaveta D. Gadjeva[3]

Abstract – **The current-voltage characteristic of an Atmospheric Pressure Air Glow (*APAG*) discharge has been simulated by commercial circuit simulation software such as PSpice®. PSpice model has been developed for the plasma discharge in a *APAG* discharge applicator, which consists of two parallel electrode plates with a small gap between electrodes. At least one of the electrodes is covered by a dielectric barrier.**

An *APAG* discharge operating gap can be modeled as an electric capacitor without plasma, as an air gap containing plasma. The cold plasma itself has been modeled as a voltage-controlled current source that switches on when the voltage across the air gap exceeds the value of the discharge ignition voltage.

The simulation current-voltage behavior agrees with the experimental data from an actual parallel-electrode-plate plasma generator. It has been found that in different operating regimes, the discharge current of the *APAG* discharge plasma generator is described by a voltage linear law.

Keywords – **Atmospheric pressure air glow (*APAG*) discharge, cold plasma, one-atmosphere glow discharge, plasma ignition voltage, voltage-controlled current source, current-voltage behavior, current-voltage characteristic.**

I. INTRODUCTION

[1]The characteristics of many electrical systems can be simulated with proprietary computing tools such as *PSpice*®. Devices employing cold plasmas are embedded in electrical systems in many situations. It is advantageous to simulate the complete system, including the plasma as phenomena, with such commercial software. Previous paper regarding the computational simulation of high pressure plasma in air discharge were investigated, [2, 3, 4].

Normally the *APAG* discharge plasma system for plasma-chemical modification of low energy surfaces consists of a power supply, transformer, impedance matching network, and plasma applicator. This electrical system was an object of simulation with such computational tools [2, 4].

In an electrical discharge system, the inductors and capacitors, in the impedance matching network, the power supply, and the transformer are ordinary electrical components and have well-developed *PSpice* models. However, there is no available electrical model in *PSpice* for the plasma *APAG* discharge, so a principal simulation task is to develop such a model, [3, 4, 6].

J.-R. Roth introduced, on the base of the observed phenomenological characteristic of the normal glow discharge voltage-current behavior, the name "*one-atmosphere uniform glow discharge*" (OAUGD). Other cases of such behavior have been often reported in the contemporary literature. The normal glow discharges, as the dielectric-barrier discharges, ignite and burn at constant plasma ignition (or burning) voltage, [2].

R. Gadri shows that an atmospheric *RF* glow discharge in helium exhibits the same phenomenology as a current source, and its output current follows a power law of the applied voltage [2].

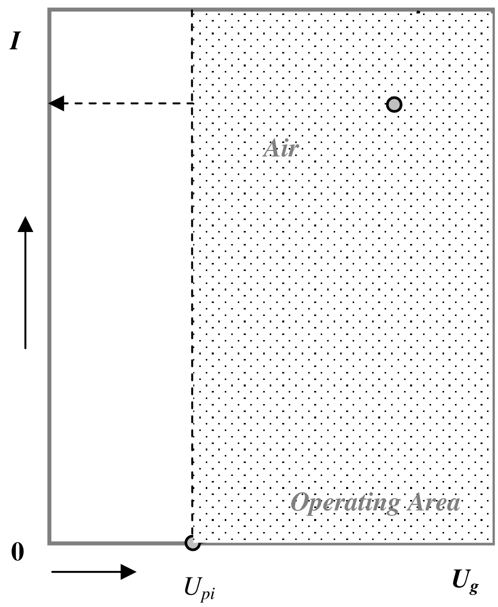

Fig. 1. Power law model of current-voltage behavior of an *APAG* discharge according to *J. Roth.*

J. Roth reported that the current-voltage (I-U) relationship of the high-power atmospheric pressure air glow discharge was $I \propto U^2$, and $I \propto U^3$, depending on the operating regime - the output current *I* is defined in Eqn. 1 by a power law function of the difference between the gap voltage U_g and the plasma initiation voltage U_{pi}, in order to simulate the current-voltage behavior in the operating range, Fig. 1 [2]:

$$(1) \qquad I \begin{cases} =0, \text{ for } U_g < U_{pi} \\ \alpha\left(U_g - U_{pi}\right)^n, \text{ for } U_g > U_{pi} \end{cases} ,$$

where *n* is an integer that ranges from 1 to 12 in different air glow discharge plasma devices.

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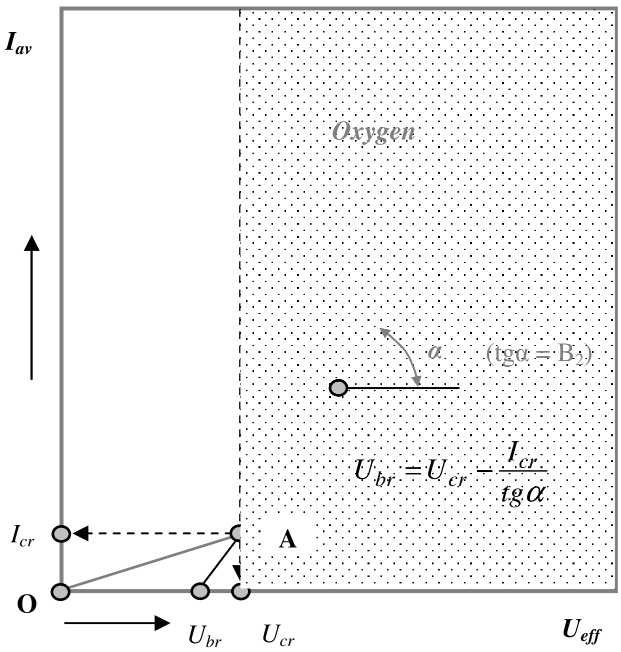

Fig. 2. Linear model of the current-voltage behavior of an *APAG* discharge in oxygen according to *I. Emelyanov*.

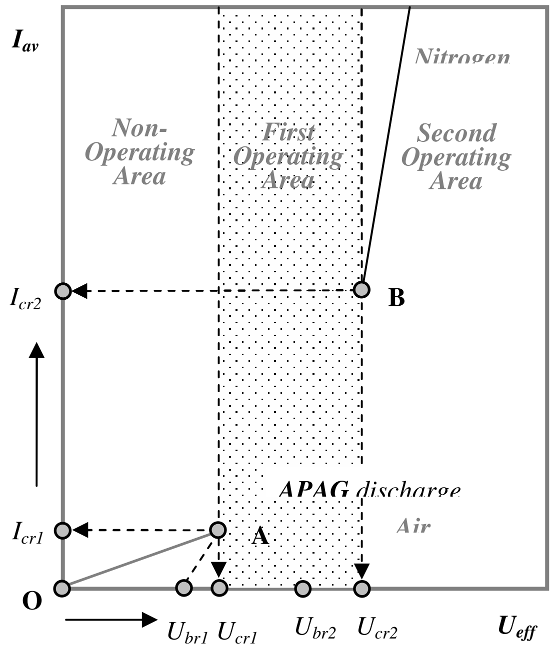

Fig. 3. Linear polynomial model of the current-voltage behavior of an *APAG* discharge in oxygen after *P. Dineff - D. Gospodinova.*

I. Emelyanov assumed that the current-voltage relationship of the atmospheric pressure glow discharge in oxygen was $I_{av} \propto U_{eff}$ - the output average current I_{av} is defined in Eqn. 2 by a linear law function of the gap effective voltage U_{eff} , Fig. 2 [3],:

$$(2) \qquad I_{av} \begin{cases} = B_1\, U_{eff} \;\; for\, U_{eff} < U_{cr}/\sqrt{2} \\ = B_2\, U_{eff} + A \;\; for\, U_{eff} > U_{cr}/\sqrt{2} \end{cases} .$$

P. Dineff and *D. Gospodinova* reported that the current-voltage relationship of the atmospheric pressure air glow discharge - *APGD*, was $I_{av} \propto U_{eff}$ for every of both operating areas of relationship - the first operating area being that of the ozone- and oxygen-containing non-equilibrium air plasma, and the second operating area being that of nitrogen oxides (NO_x)-containing non-equilibrium air plasma, Fig. 3 [3]:

$$(3) \qquad I_{av} \left\{ B_0\, U_{eff} \;\; for\, U_{eff} < U_{cr1}/\sqrt{2} \right.$$

$$I_{av} \begin{cases} = B_1\, U_{eff} + A_1 \;\; for\, U_{eff} > U_{cr1}/\sqrt{2} \\ = B_2\, U_{eff} + A_2 \;\; for\, U_{eff} > U_{cr2}/\sqrt{2} \end{cases}$$

In this paper, specific circuit *PSpice* models and *PSpice* simulation of the current-voltage relationship of *APAG* discharge plasma parallel-plate cold plasma generator have been obtained with the proprietary circuit simulation software *PSpice* and compared with experimental data.

II. PSPICE MODEL FOR SIMULATION OF CURRENT-VOLTAGE RELATIONSHIP FOR PARALLEL-PLATE *APAG* DISCHARGE PLASMA GENERATOR

A parallel-plate *APAG* discharge plasma generator consists of two parallel metal electrode plates with a small gap between them. One of the electrodes is covered with a dielectric plate or coating.

The *APAG* discharge burns at constant drop of voltage U_{br} across the operating gap. *J. Roth* introduced the name "*one-atmosphere uniform glow discharge*" (OAUGD®). This fact is confirmed by multiple researchers [1, 2, 3].

At the same time, however, the current-voltage behavior of a parallel-plate *APAG* discharge plasma generator is governed by a power law in the Roth's model of current-voltage behavior. In order to satisfy the requirement for constancy of the voltage drop across the operating gap during the period of burning of the *APAG* discharge, the current-voltage relationship should vary linearly with the increase of the applied voltage.

This requirement is met in the *Emelyanov*'s linear model of current-voltage behavior of the *APAG* discharge in oxygen.

P. Dineff and *D. Gospodinova* have proposed a linear polynomial model of current-voltage behavior of the *APAG* discharge in air that contains two operating areas corresponding to the elementary processes (dissociation, ionization, and chemical processes) conducted with the participation of oxygen - non-equilibrium ozone- and oxygen-containing plasma, and to the elementary processes conducted with the participation of nitrogen - non-equilibrium nitrogen-oxides-containing plasma, Fig. 3 [3].

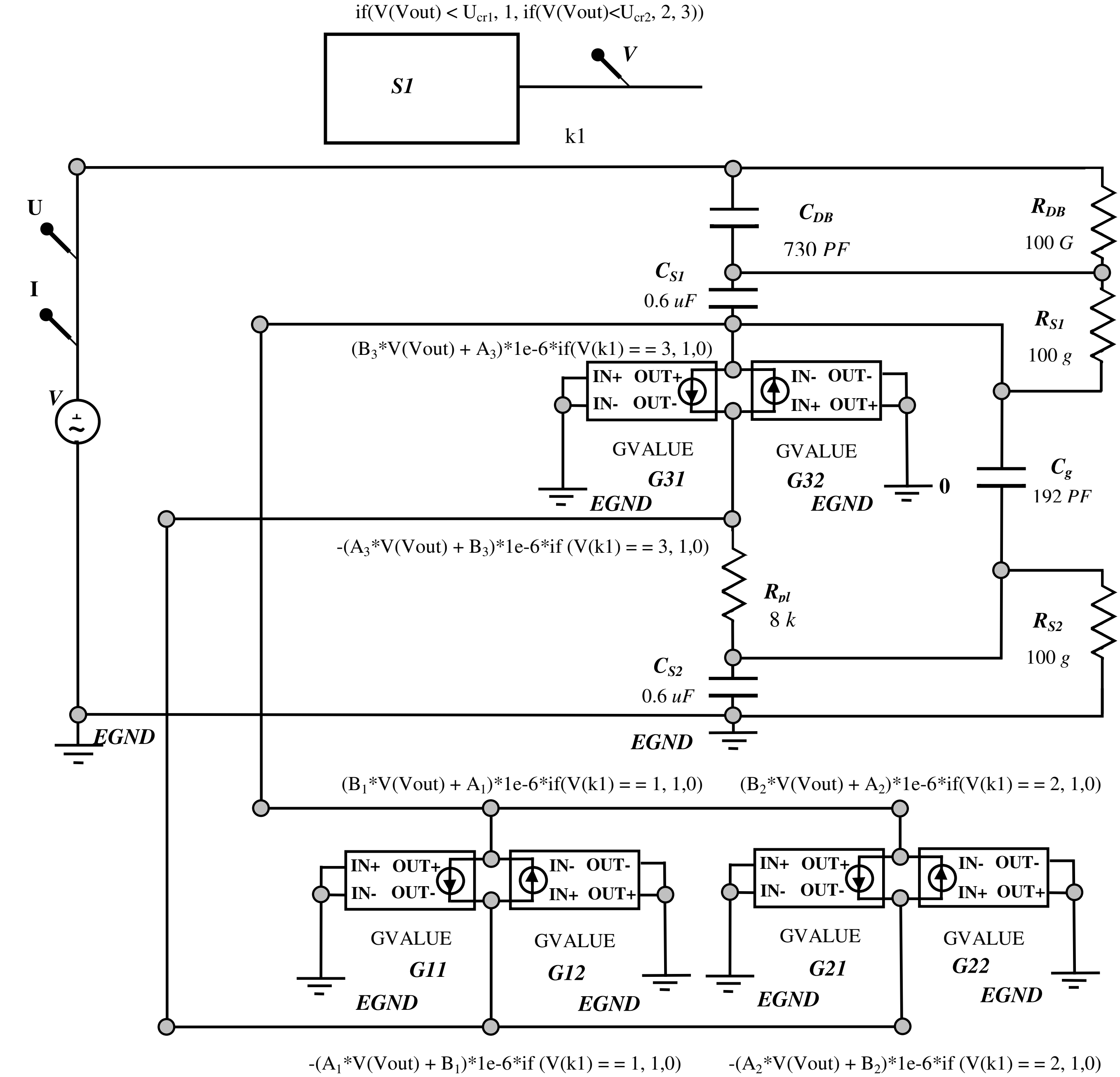

Fig. 4. *PSpice* circuits simulation model for an *APAG* discharge plasma generator current-voltage behavior.

This model reflects adequately the specificity of an *APAG* discharge current-voltage behavior and represents on the basis of equality all areas of the characteristic – the first non-operating area (before discharge ignition) and the two operating areas of burning *APAG* discharge.

All this imposed the creation of a new *PSpice* schematic model for an *APAG* discharge plasma generator, which is governed by the following general relationship reflecting the stationary regime of burning of the *APAG* discharge in both operating areas:

$$(2)\quad \begin{cases} \Delta I = I_{av} - I_{cr1} = B_1 \left(U_{eff} - U_{cr1}\right) & for\ U_{cr1} < U_{eff} < U_{cr2} \\ \Delta I = I_{av} - I_{cr2} = B_2 \left(U_{eff} - U_{cr2}\right) & for\ U_{eff} > U_{cr}. \end{cases},$$

Based on the phenomenology of *APAG* discharges, the *APAG* plasma discharge in the operating gap can be itself modeled as a voltage-controlled current source that is switched on as long as the voltage across the gap exceeds the value of the plasma ignition voltage U_{br} [3].

The simulation schematic model is constructed on using dependent current sources GVALUE (from the library abm.slb), for which the control is preset as a mathematical expression (linear relationship), Fig. 4.

The control of the three pairs of dependent current sources *G11* and *G12*, *G21* and *G22*, and *G31* and *G32*, one for each half-wave of the harmonically varying voltage of the ideal voltage source *V*, is realized by voltage-controlled switch *S1* (*operator for data statements*): the pair *G11* and *G12* operates when the voltage is below the critical voltage U_{cr1}, the pair *G21* and *G22* when the voltage is below the critical voltage U_{cr2}, and the pair *G31* and *G32* when the voltage is higher than U_{cr2}, Fig. 4.

Table 1. Results from accomplished simulations

Active Power P_A, W	**Active Power** P_A, W	**Active Power** P_A, W	
Experimental current-voltage relationship	*PSpice simulation polynomial linear law model*	*PSpice simulation power law model*	
		n = 1.6	n = 12
28.1	27.0	38.0	36.0
Relative error, %			
base	**- 3.9**	**+ 35.2**	**+ 28.1**

The values of the critical voltages of discharge ignition, U_{cr1} and U_{cr2}, are entered for each operating area; they have been calculated in a known manner from the current-voltage relationship [3].

The behavior of the model in time (*Transient Response*) as a result of the effect of the voltage across the electrodes that varies harmonically with determinate frequency (50 Hz) with time is investigated, Fig. 6.

An *AC analysis* is assigned additionally by defining the active power p_A by means of the selected format, Table 1.

In accordance with [4], more comparative investigations are performed on the PSpice simulation power-law model of a burning *APAG* discharge, developed by *P. Dineff* and *D. Gospodinova,* for two different values of the power exponent *n*, Table 1.

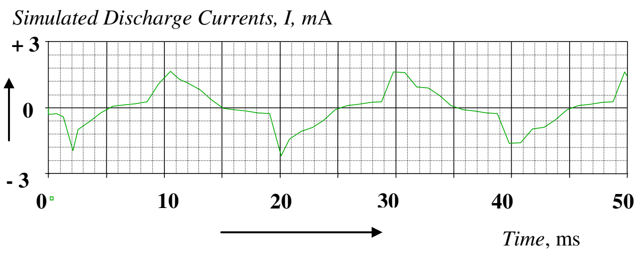

Fig. 6. Simulated discharge currents for an *APAG* discharge plasma parallel-plate generator according to *PSpice* simulation polynomial linear law model (U_{eff} = 12 kV; 50 Hz; δ_{bar} = 3 mm; δ_{gap} = 3 mm).

A voltage U_{eff} is assumed in such a way that simulation will be realized in the transition area between the two operating areas, namely 12 kV, because a maximal relative error in simulation is expected for this transition area.

Results presented in Table 1 demonstrate the improved accuracy (- 3.9 %) of the proposed simulation model of the *APAG* discharge current-voltage behavior. At the same time the lowest value of relative error (+ 35.2 %) is obtained for the highest values of the power exponent - $n = 12$.

III. Discussion and Conclusion

The simulation verifies that the amplitude of the simulated discharge current is determined by four independent variables - the values of the critical parameters - the voltages U_{cr1} and U_{cr2}, currents I_{cr1} and I_{cr2}**;** dielectric barrier capacitance C_{DB}, and applied voltage U_{eff} across the operating gap. It has been found, too, that the polynomial linear law simulation model has a minor relative error compared to the power law simulation model.

We have developed a satisfactory PSpice circuit model for the *APAG* discharge plasma generator current-voltage behavior simulation.

The variant calculations which allow following the effect of parameters of the electrode system or the electric circuit, e. g. those of the matching series capacitor, upon the *APAG* discharge current-voltage behavior for different frequencies may be especially valuable.

Acknowledgement

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