



Analysis of Electric Circuit Model on Atmospheric Pressure Dielectric Barrier Discharge (DBD) Plasma

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Abstract— Analysis of Electric Circuit Model on Atmospheric Pressure Dielectric Barrier Discharge (DBD) Plasma has been simulated using the Simulink-Matlab R2010a software. Plasma reactor being used as the basis to determine the parameters in the circuit is in the coaxial form made of pyrex glass with an iron rod as the active electrode and spiral copper wire as passive electrode. The reactor was filled with argon gas with the flow rate of 2 L/s. Simulation circuit model which was prepared based on a DBD equivalent circuit, operated in a voltage range of 1.0 kV to 6.0 kV for frequency of 10 kHz to 66 kHz. Electrical characterization was performed to describe the plasma discharge that occurs in the reactor. The datas of supply voltage and current, as well as voltage and current discharge, was used to determine the average power during one period. From the simulation was obtained an increase in supply and discharge currents with increasing of frequency at the same operating voltage. Discharge power has increased in a specific voltage and increased frequency. It is obtained the average discharge power for 5.5 kV of 11.28 W and 10.90 W at a frequency of 21 kHz and 24 kHz, respectively. The highest efficiency obtained from the simulation that achieved at voltage of 1 kV and frequency of 45.7 kHz is equal to 56.59%.

Keywords — electrical circuit model, dielectric barrier discharge, atmospheric pressure, electrical characteristic, simulation model approach.

I. INTRODUCTION

1.1. EQUIVALENT MODEL OF DBD

DBD is one of the two methods that have been extensively used to generate non thermal plasma at atmospheric pressure, in addition to corona discharge. Corona discharge has many applications in industry, in which excitation or charged species concentrations required is relatively small. In contrast, DBD discharge is defined for wider plasma-chemistry applications. Barrier discharge which also referred as a silent discharge is characterized by the present of an isolator layer between two electrodes, plane or cylinder, which is connected to a source of alternating voltage [1]. Dielectric barrier discharges is an easy way to generate non-thermal or non-equilibrium plasma at atmospheric pressure [2]. The main advantage of this type of electrical discharges is that the conditions of non equilibrium plasma at atmospheric pressure gas can be produced in an economical and reliable way.

This feature has led a number of important applications including ozone generation, pollution control, plasma chemical gas deposition and surface activation, excitation at eksimer lamps and surface modification on a wide variety of materials [3]. The discharge appears on dielectric barrier discharges can be either a filament or homogeneous depend on the experimental conditions such as gas discharge, gas pressure, gas gap, the surface properties of the dielectric, and a voltage waveform [4].

There are two types of equivalent models to DBD, i.e. physical and electrical models. Physical model involves the ionization process of various gases, this model is considered more difficult and time consuming. While the electric model is more appropriate and simpler, in which the plasma discharge is usually treated as an equivalent electrical circuit that represents the relationship between the reactor configuration and the electrical parameters. Electric models were used to study the phenomenon of DBD in the variation of the voltage waveform and the applied gas pressure. UN Pal et.al has proposed a simulation model based on the electrical circuit equivalent for DBD cells contain argon gas by comparing the characteristics of DBD discharge in experimental and simulation. This model was implemented using Matlab/Simulink which involves the applied discharge conditions. The results of the simulation model were then compared to the experimental results [2].

Research on the characteristics of DBD have been carried by a number of researchers either through experiments or simulation models using Matlab/Simulink. The Matlab/Simulink model were developed to express the interaction between parallel plate reactors and high-voltage sinusoidal source [5]. In their research, R Valdivia et al stated that electric models of DBD with cylindrical configuration in Matlab Simulink software may be used as a diagnostic tool of dynamic behavior of the reactor. This model allows the estimation of some internal electrical parameters of the discharge generated only by the use of electrical values which can be measured externally (i.e. applied voltage and total electric current). The dynamic behavior of discharge is equal to the developed simulation model and the curve of each variable associated with the signals shown experimentally. Tao Xiaoping et al. reported the results of experimental investigations of the electrical characteristics of DBD by using glass and alumina as the dielectric materials. Based on the Lissajous curve of charge vs voltage, it was found that the discharge power with alumina as a dielectric material is greater than when using glass as a dielectric materials, for the same applied voltage. In addition, the voltage vs current curve with glass and alumina as dielectric materials reinforces the fact that dielectric barrier behaves as a semiconductor material for the specific applied voltages [6]. In addition, UN Pal et al. proposed a coaxial DBD tube made of quartz filled with argon gas and an electric model to characterize the discharge. The proposal takes into account the geometry of the DBD tube, gas space, and the material properties of the dielectric barrier. Sinusoidal voltages up to 2.4 kV with a frequency of 20 to 100 kHz is applied to the electrodes for the generation of micro discharge [2].

From the description, the problem is how the compatibility between the electrical characteristic of DBD plasma reactor, using the pyrex tube as a dielectric material with argon gas as the gas source, and the results obtained from the simulation of Matlab/Simulink.

II. METHODS

2.1. EXPERIMENTAL SETUP

The scheme of cylindrical DBD cell with argon as input gas is shown in Figure 1(a), whereas Figure 1(b) shows a vertical cross section schematic of DBD cell consists of a pyrex tube. The outer surface of tube wrapped by a copper wire as the outer electrode. The length of the copper wire windings is 190 mm. At the center of the tube axis, iron rod fitted with a radius of 3.70 mm as the inner electrode. The high voltage signal was connected to the inner electrode, while the outer electrode was grounded. The radius of tube is 21.975 mm with thickness of 3.15 mm. Gas gap was 18.275 mm with tube length of 290 mm.

The experiment series was set by referring to the experimental set up used by Valdivia et al [7], and is shown in Figure 2. Plasma reactor is in the form of cylinder with a dielectric material made of pyrex glass. DBD plasma was generated using AC high voltage in the range of 1 to 6 kV with a frequency up to 66 kHz. Electrical characterization was performed by measuring the current of source. The flow of gas was observed by using a *flowmeter*. The applied current and voltage waveforms were visualized using an oscilloscope.

2.2. ELECTRICAL MODEL AND ANALYSIS

An equivalent circuit model of plasma reactor is required to analyze characteristics of DBD plasma reactor. The equivalent circuit model is in accordance to the used reactor model configuration. The experimental results need to be confirmed by the results of simulation using Simulink/Matlab software.

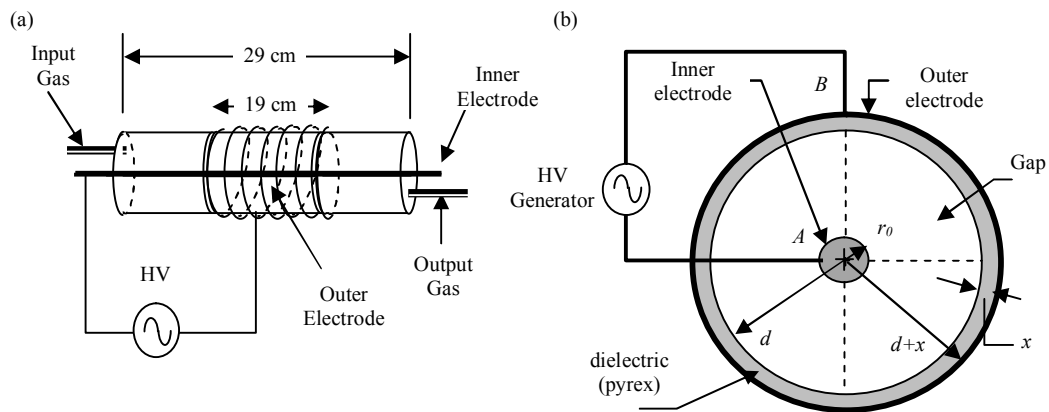


Figure 1. (a) scheme of DBD reactor skema reaktor, (b) vertical cross section of DBD reactor

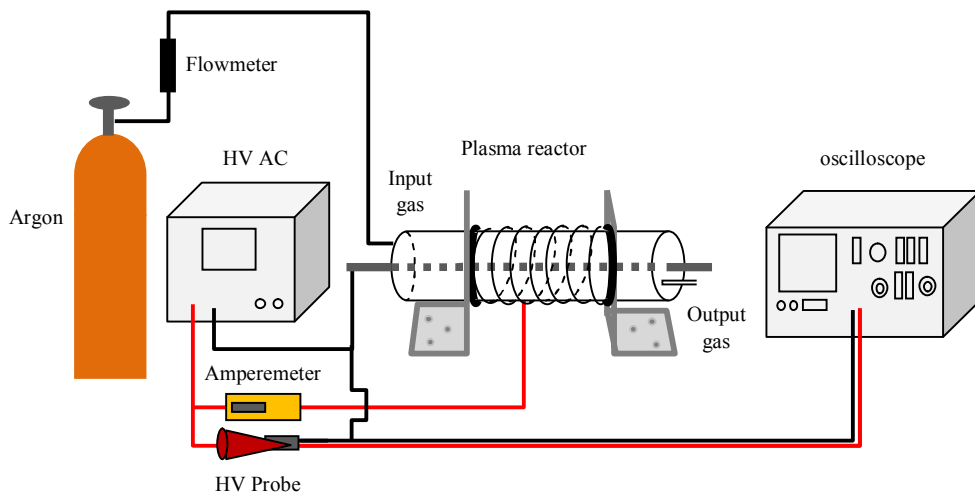


Figure 2. Experimental set up

2.3. EQUIVALENT ELECTRICAL CIRCUIT

Equivalent circuit series of DBD tube was set referring to electrical series used by Valdivia et al [7] which coupled with a modification. The equivalent circuit series was shown in Figure 3.3, while the electrical circuit model applied in Simulink/Matlab was shown in Figure 3.4. Modification on the equivalent circuit in this study was conducted by connecting the circuit with the voltage and current measuring devices. Therefore, in this study, there are four blocks of the additional scope which represent a measuring tool, respectively. Scope 3 and 4 serve to measure voltage and current, respectively, in the gas gap or discharge. While scope 1 and 2 serve to measure total voltage and total current, respectively, in the series.

Equivalent electrical circuit model consists of two capacitors connected in series. Capacity of tubular dielectric barrier and gas gap were denoted as C_g and C_d . Capacitances of C_g and C_d were with a cylindrical capacitor approach using equations (1) and (2),

$$C_g = \frac{2\pi\epsilon_0\epsilon_{r1}l}{\ln\left(\frac{d}{r_0}\right)}, \quad (1)$$

$$C_d = \frac{2\pi\epsilon_0\epsilon_{r2}l}{\ln\left[\frac{(d+x)}{d}\right]} \quad (2)$$

whereas $\epsilon_{r_1} = 1.0005172$ and $\epsilon_{r_2} = 4.5$, which denote the relative permittivity of argon and pyrex glass, respectively [8]. By entering these values into equations, capacitances of C_g and C_d obtained value results of 5.936 pF and 355.073 pF, respectively.

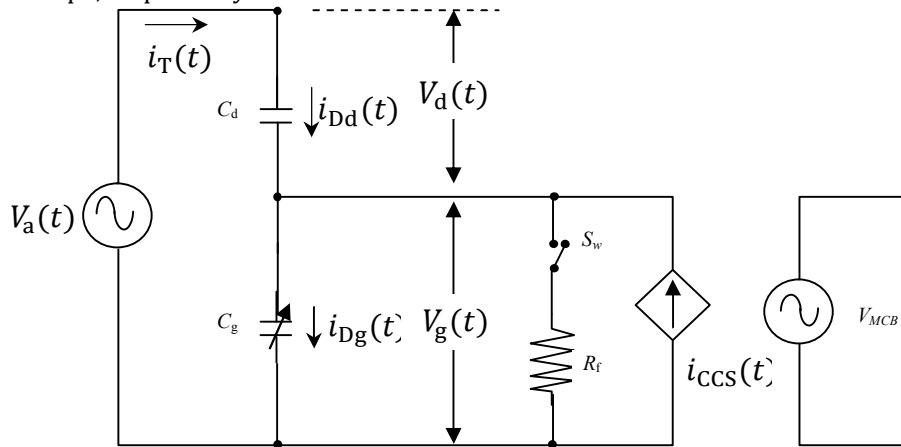


Figure 3. Equivalent circuit model of DBD tube

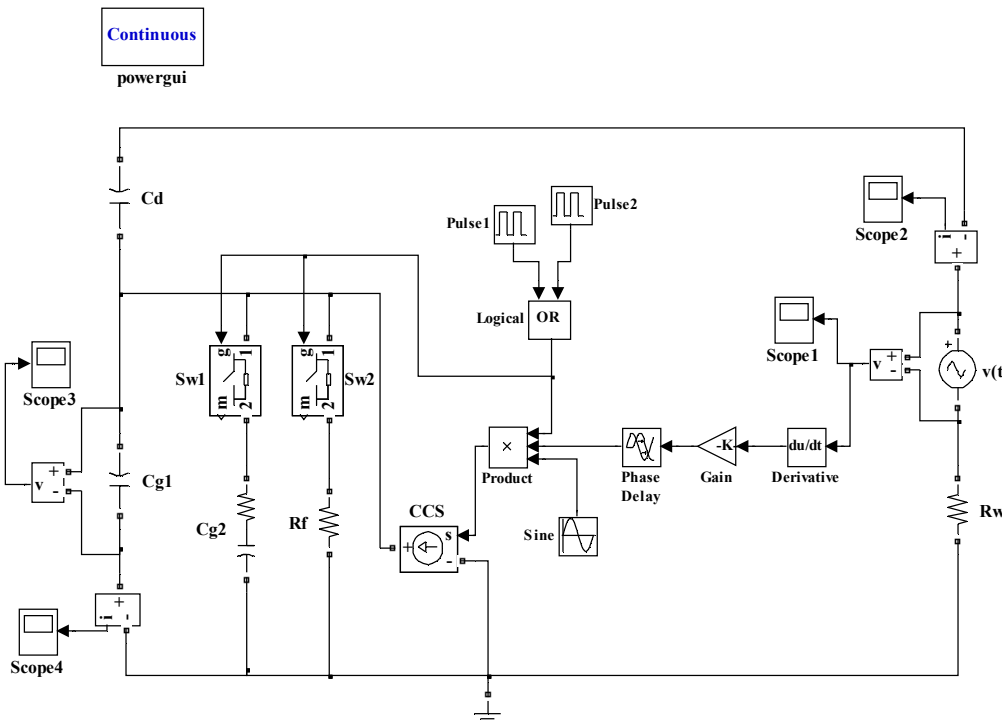


Figure 4. Simulation model in Simulink

Simulation model in Simulink was shown in Figure 4. The simulation model is based on the equivalent electrical circuit model in Figure 3, regardless of the properties of the gas, but more emphasis on the electrical operating conditions of the circuit. The parameters that generate micro discharge ignition and extinction were taken into account [2].

III. RESULT AND DISCUSSION

3.1. SIMULATION RESULT

3.1.1. VOLTAGE AND CURRENT WAVEFORMS

The characteristics can be investigated by measuring the applied voltage, current, and power consumption in DBD. The investigation on the electrical characteristics may be conducted in two ways, i.e. by conducting an experiment and by using an electrical simulation approach.

In Figure 5 (a) by using a frequency of 21 kHz, the current amplitude obtained was in the range of 102.53 mA with a breakdown voltage of 503.33 V. Whereas, at the frequencies of 22 kHz, 23 kHz, and 24 kHz, the electric current amplitude in each series are 104.14 mA; 104.81 mA; and 105.24 mA with the breakdown voltage of 500.99 V, 498.77 V, and 496.67 V.

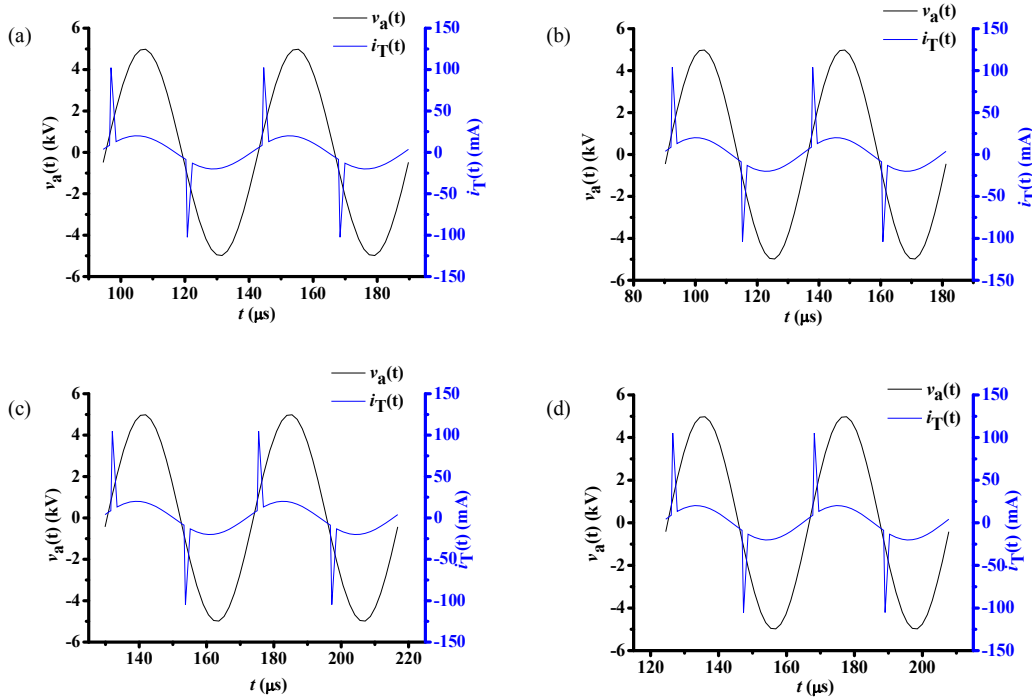


Figure 5. Voltage and current waveforms at frequencies of (a) 21 kHz, (b) 22 kHz, (c) 23 kHz, and (d) 24 kHz.

It suggests that for the same voltage applied to the DBD provides a higher current for a higher frequency. The sharp increase in electrical current was indicating an excessive charge flow either in dielectric material or in the gas gap. The electric current increases has occurred periodically and indicate a micro discharge that occurs in DBD which is a filament discharge. Both of the relationship between the total current amplitude and frequency, and the relationship between the total current amplitude and voltage, can be seen in Figure 6.

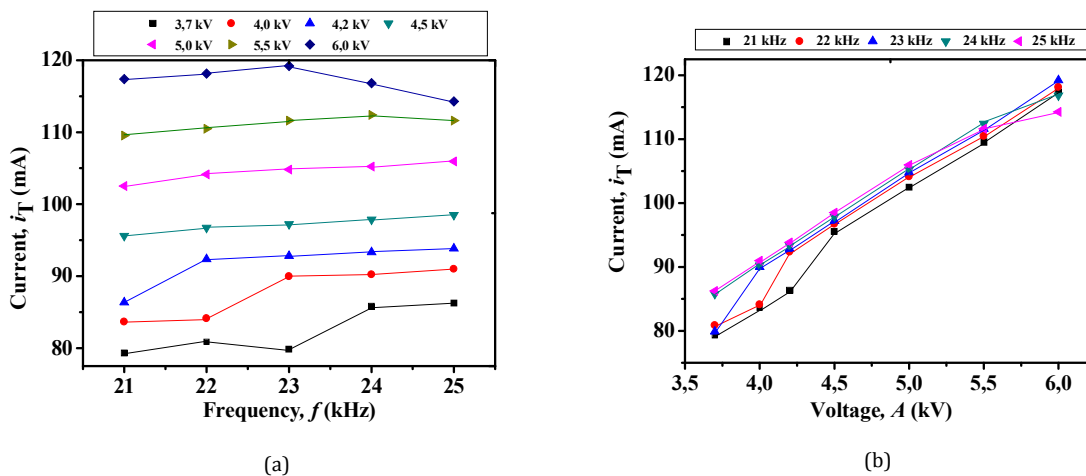


Figure 6. (a) The graph of current vs frequency, and (b) current vs voltage

Figure 6 (a) describes the relationship between the maximum current from the voltage source, for some applied voltages, and frequency. Figure 6 (b) shows the relationship between the current amplitude, from the voltage source, and the applied voltage for some frequency. It indicates the increase in maximum current for each operating frequency with the voltage increases. The increase in current, either as the operating frequency is increased or when the applied voltage is increased, will affect the discharge plasma generated in the reactor.

The current increases will cause the discharge generated be greater. In addition, the time to emerge and extinction of the discharge is dependent on the applied voltage and frequency.

3.1.2. DISCHARGE POWER

The simulation model may also be used to determine the average power when the discharge occurs. The input power and consumption power respectively can be determined using the equation (3) and (4).

$$P_{sup}(t) = V_a(t)I_T(t) \tag{3}$$

$$P_{dis}(t) = V_g(t)I_{Dg}(t) \tag{4}$$

Whereas the average power input and discharge power follow the equations (5) and (6).

$$\langle P_{sup} \rangle = \frac{1}{T} \int P_{sup}(t) dt \tag{5}$$

$$\langle P_{dis} \rangle = \frac{1}{T} \int P_{dis}(t) dt \tag{6}$$

The electrical energy used for one discharge can be determined by using the equation approach (7)

$$W_{dep} = \frac{\langle P_{dis} \rangle}{2f} \tag{7}$$

Figure 7 shows that the the discharge power increases when the operating voltage increases. Based on the simulation results obtained, three electrical parameters i.e. $v_T(t)$, $i_T(t)$, and $P_{dis}(t)$ for the argon gas has been shown in Figure 5, 6, and 7. It provides important information about the electrical system response to the multiple voltage source and frequency. The view of predicted electric system can be determined before the actual system be applied [9]. The uniform current form with the higher value causes the glow discharge becomes brighter. Meanwhile, the electric field becomes stronger due to the increased in power and frequency. The function of parameters in the case of argon gas discharge is clearly different from the other gases. For the higher V_{bd} , the voltage source should send more power to generate discharges.

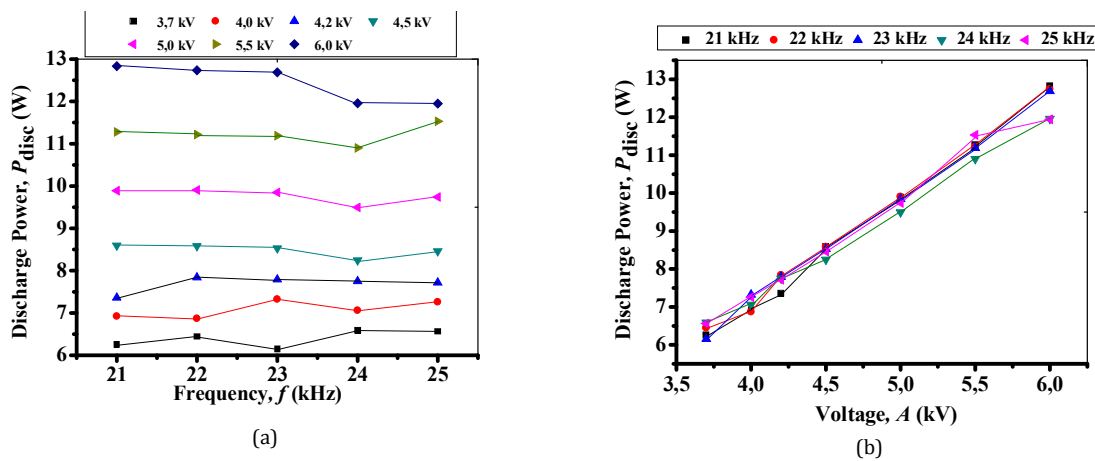


Figure 7. Average power consumption vs (a) frequency and (b) voltage

3.2. EXPERIMENT RESULT

The experimental data for comparison obtained from the research conducted by Pal et al [2] and Valdivia et al [7]. The use of these data based on the similarity of voltage and operating frequency. In this experiment, the voltage, which connected to a coil copper wire as the outer electrode and an iron rod as the inner electrode, was slowly increased manually. The argon gas flow rate was set at 2 L/min. The image of the discharge with the argon gas source is shown in Figure 8. These pictures show that the filament discharge is seen more clearly by the increase in applied voltage. These results reinforce the previous studies, among others is the research carried out by Pal et al. [2].

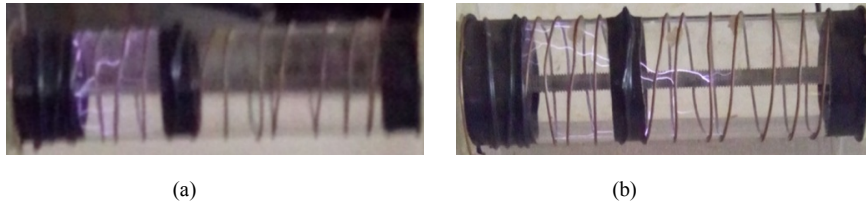


Figure 8. Discharge in DBD tube with argon gas at a voltage of (a) 2 kV, and (b) 2,5 kV

The electric field generated through the discharge gap in the breakdown area has caused the charge accumulation on the dielectric surface and it happens in a very short time interval. The other glow discharge in the same channel will occur after emerging the local electric field generated by the applied voltage. The process of ignition and extinction in the local channels is repeated every half cycle before the voltage polarity changes occur [10].

3.2.1. VOLTAGE AND CURRENT WAVEFORMS

Dielectric Barrier Discharge (DBD) is composed of a lot of discharge filaments and occurred within tens of nanoseconds [11]. The experimental datas obtained by Pal et al and Valdivia et al were used for comparison to the simulation results. The simulation result conducted by Pal dkk [2] for an operating voltage of 1 kV with a frequency of 45.7 kHz and the simulation results of this research can be seen in Figure 9. Based on Figure 9(b) and the data obtained, the maximum current when the discharge occurred was 57.13 mA. The supplied power and the average discharge power for each cycle was 3.69 W and 2.09 W, respectively. Therefore, the reactor efficiency obtained was 56.59%. While Figure 9(c) shows the maximum current of 66.33 mA to the average discharge power of 3.34 W with supplied power of 9.16 W. It provides a lower efficiency of 36.51%.

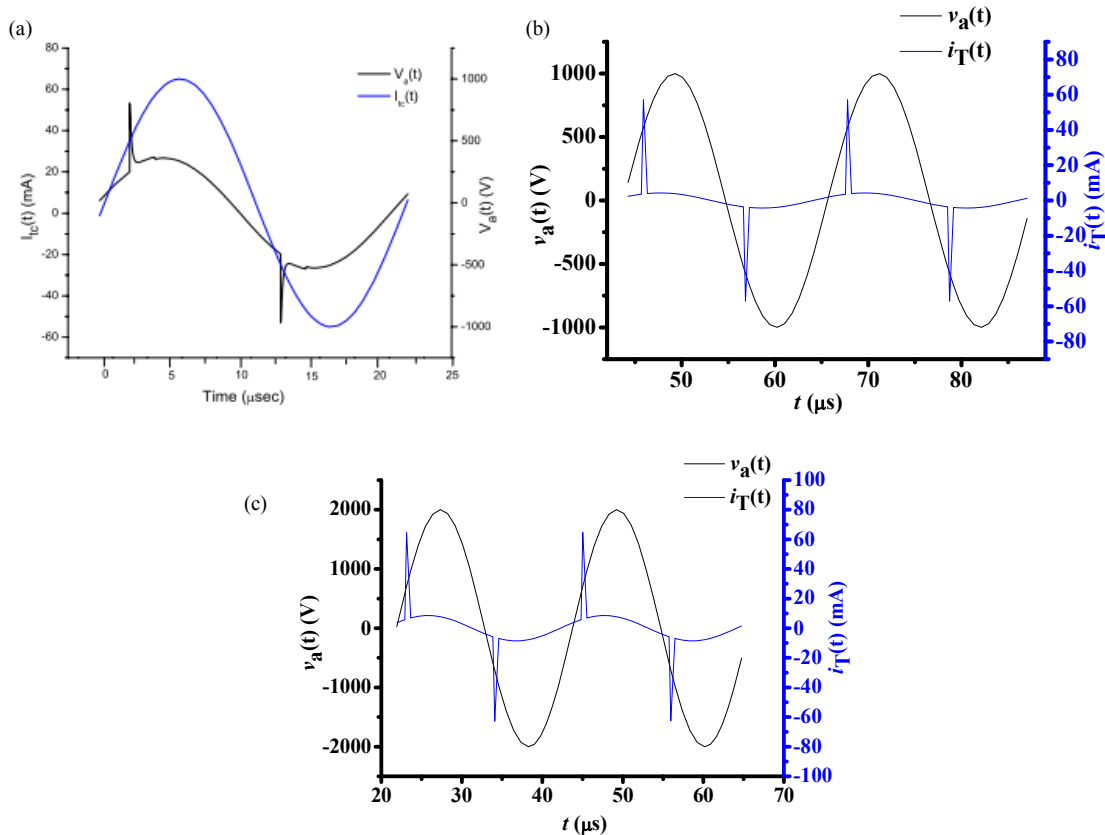


Figure 9. Current and voltage waveforms in the micro discharge at frequency of 45.7 kHz (a) based on the experiment by Pal et al (2010) with voltage of 1 kV, (b) simulation voltage of 1 kV, and (c) voltage 1 kV.

Meanwhile, the research conducted by Valdivia et al (2006) using a coaxial reactor consisting of a Pyrex tube, an inner electrode in the form of stainless steel rod, and an outer electrode in the form of hollow wire wrapped around the tube, indicating that the applying of voltage and frequency affect the current waveform. The current accumulation occurs at certain specific times. Valdivia obtained an applied voltage of 1505 V with a frequency of 19 kHz and maximum current of about 80 mA. While for the voltage and frequency of 1230 V, 46 kHz and 1240 V, 66 kHz, Valdivia et.al have found that the current amplitude when the discharge occurred of about 90 mA and 135 mA, respectively. The results of the simulation conducted by Valdivia et al [7] showed the maximum current, when the discharge occurred, increases with the increases of frequency, the resulting values are 0.065 A; 0.1 A; and 0.15 A. The simulation results using the same voltage and frequency to the research conducted by Valdivia et al can be seen in Figure 10. (a), (b) and (c). While the maximum efficiency of reactor was obtained when the reactor operated at a voltage of 1 kV and a frequency of 66 kHz.

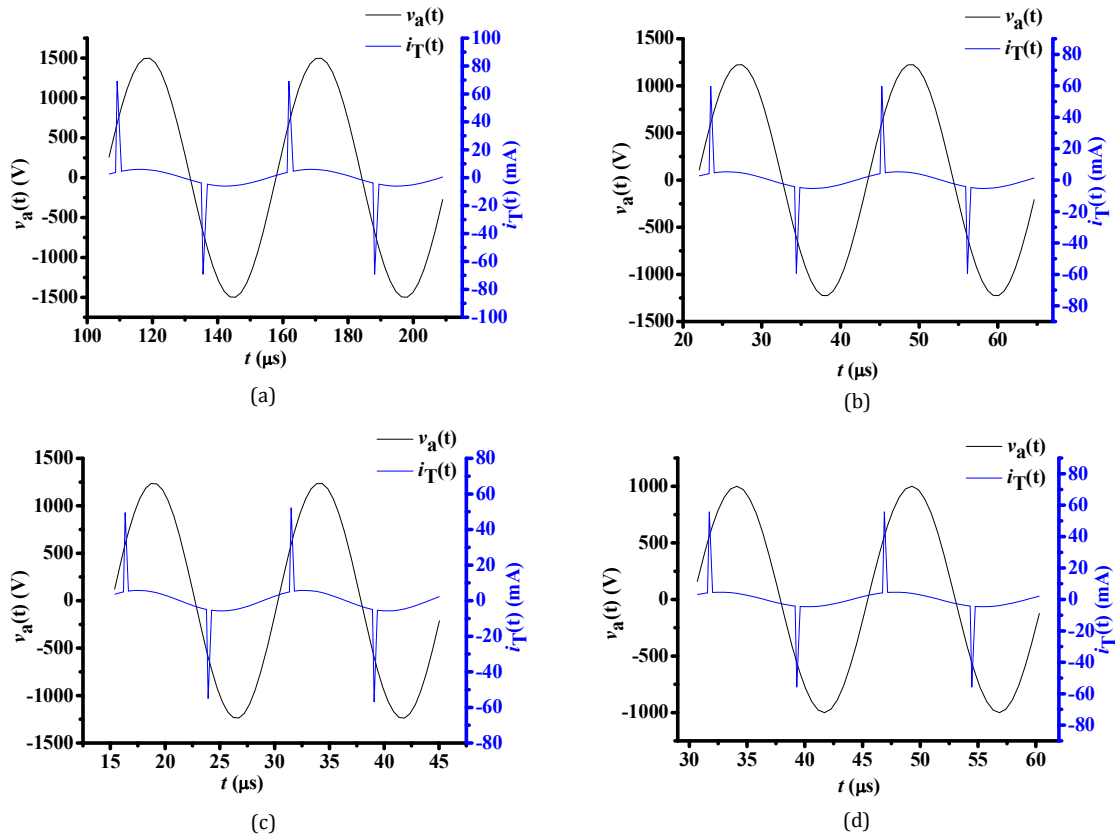


Figure 10. The simulation results at a voltage and frequency of (a) 1505 V, 19 kHz; (b) 1230 V, 46 kHz; (c) 1240 V, 66 kHz; and (d) 1000 V, 66 kHz

IV. CONCLUSIONS

Based on the results of this study, it can be concluded that there is an accumulation or sharp increase in electric current when the discharge occurred. An amplitude current of 104.81 mA has been obtained for the applied voltage of 5 kV and frequency of 23 kHz, while the frequency of 25 kHz was obtaining the amplitude current of 105.96 mA. The use of electrical simulation models of DBD may provide the electrical parameters which serves as the information before running the actual reactor. The calculation result of discharge power efficiency according to the simulation model for applied voltage of 5 kV with frequency of 21 kHz and 22 kHz were obtained approximately 21.53% and 21.55%, respectively. For the voltage of 1 kV; 45.7 kHz and 1.5 kV; 19 kHz respectively provide an efficiency of 56.59% and 49.13%. While the results of the research by Pal et al. [2] with a voltage of 1 kV applications; 45.7 kHz, was obtained average power efficiency of 32.1%, and and the results obtained by Valdivia et al [7] using 1.5 kV; 19 kHz was 34.8%.

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REFERENCES

- [1] U. Kogelschatz, "Filamentary, Patterned, and Diffuse Barrier Discharges," *IEEE Transactions on Plasma Science*, vol. 30.4, pp. 1400–1408, 2002.
- [2] U.N. Pal, M. Kumar, M.S. Tyagi, B.L. Meena, H. Khatun, and A.K. Sharma, "Discharge analysis and electrical modeling for the development of efficient dielectric barrier discharge," *J. Phys: Conference Series 208*, IOP Publishing, 2010.
- [3] K.G. Kostov, R.Y. Honda, L.M.S. Alves, and M.E. Kayama, "Characteristics of Dielectric Barrier Discharge Reactor for Material Treatment," *Brazilian Journal of Physics*, vol. 39.2, pp. 322–325, 2009.
- [4] F. Massines, A. Rabehi, P. Decomps, R.B. Gadri, P. Ségur, and C. Mayoux, "Experimental and theoretical study of a glow discharge at atmospheric pressure controlled by dielectric barrier," *J. Appl. Phys.*, vol. 83.6, pp. 2950–2957, 1998.
- [5] C. Zhang, T. Shao, Y. Yu, Z. Niu, P. Yan, and Y. Zhou, "Comparison of Experiment and Simulation on Dielectric Barrier Discharge Driven by 50 Hz AC Power in Atmospheric Air," *Journal of Electrostatics*, vol. 68, pp. 445–452, 2010.
- [6] T. Xiaoping, L. Rongde, and L. Hui, "Electrical Characteristics of Dielectric-Barrier Discharges in Atmospheric Pressure Air Using a Power-Frequency Voltage Source," *Plasma Science and Technology*, vol. 14.8, pp. 723–727, 2012.
- [7] R. Valdivia, J.P. Sotelo, M. Pacheco, J.S. Benítez, and R.L. Callejas, "Analysis and Electrical Modelling of A Cylindrical DBD Configuration at Different Operating Frequencies," *Plasma Sources Sci. Technol.*, vol. 15, pp. 237–245, 2006.
- [8] D.R. Lide, *Handbook of Chemistry and Physics*, 84th-ed., CRC Press, 2004.
- [9] A.L. Fuentes, R.P. Eguiluz, R.L. Callejas, A.M. Cabrera, R.V. Alvarado, S.B. Delgado, and A.P. Beneitez, "Electrical Model of an Atmospheric Pressure Dielectric Barrier Discharge Cell," *IEEE Transaction on Plasma Science*, vol.37.1, Pp.128-134, 2009.
- [10] W.H. Tay, S.L. Yap, and C.S. Wong, "Electrical Characteristic and Modelling of a Filamentary Dielectric Barrier Discharge in Atmospheric Air," *Sains Malaysiana*, vol.43.4, Pp.583-594, 2014.
- [11] N. Gherardi, G. Gouda, E. Gat, A. Ricard, and F. Massines, "Transition from glow silent discharge to micro-discharge in nitrogen gas," *Plasma Source Sci. Technol*, vol.9, Pp.340-346, 2000.