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Article

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Impedance matching study of surface dielectric barrier discharge plasma generator

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Abstract

The plasma produced by Dielectric Barrier Discharge (DBD) has a very important application in the field of aerodynamics. The plasma generator needs high-voltage and high-frequency power supply. Due to the existence of internal resistance of the power supply, the impedance characteristics of the generator do not match the power supply. The voltage at both ends of the generator is extremely low. Besides, due to the existence of reactive power, most of the energy transported by the power source is reflected, resulting in extremely low energy conversion efficiency of the power source. In the paper, the mechanism of DBD plasma generator is analysed and on the equivalent circuit is received. And then different frequency impedance characteristics of generator and impedance matching circuit by using LR and the LCR respectively is studied. The results show that the equivalent resistance of plasma generator on frequency change is not obvious. The generator is capacitive and tends to 0 with increasing frequency. When LR is matched, resistance increases with the frequency change is not big, and reactance increases gradually, but its value is small, in the range of $n\Omega$. In general the plasma generator impedance is virtually pure resistive. When LCR is matched, the impedance characteristic gradually changes from the inductive to capacitive with the increase of frequency.

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Keywords: Impedance matching; Dielectric barrier discharge (DBD); LR; LCR

1. Introduction

Our findings showed that the plasma generated by Dielectric Barrier Discharge (DBD) can transform the electrical energy into the kinetic energy of air without mechanical moving parts, to realize the flow control of boundary airflow. It avoids the disadvantages of complex structure, easy wear, failure, noise and vibration of traditional mechanical equipment, and has a broad application prospect in the field of aerodynamics, such as aircraft takeoff and landing and wind power generation.

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Because the voltage applied to the plasma generator is high frequency and high voltage sine wave, and the internal power resistance exist in the power source, most of the supply voltage will fall at both ends of the resistance, and the voltage on both ends of the generator is extremely low when the impedance characteristics of the generator do not match the power supply. Or, due to the large amount of reactive power, the energy transmitted by the power supply to the generator is reflected, resulting in low energy conversion efficiency of the power supply. Therefore, it is necessary to match impedance in parallel between the power supply and the plasma generator. At present, many units at home and abroad have studied the impedance matching of plasma, Chen [1] used PSpice software to model and simulate the OAUGDP driver system, and analysed the impedance matching under different conditions. Kunwar Pal Singh, etc. (2019) of the university of Florida studied the influence of frequency on the impedance characteristics of asymmetric plasma generator, and proposed the calculation formula of energy conversion efficiency of power supply. Song et al. [2] of domestic air force engineering university simulated the electrical characteristics of the plasma flow control experimental system, and modelled the plasma discharge as a segmented nonlinear voltage control current source sub-module, which solved the key problem of the electrical characteristics simulation of the plasma flow control system, and simulated the plasma flow control experimental system.

In this paper, the mechanism of surface DBD plasma generator is analysed, and its circuit equivalence is carried out. The impedance characteristics of the generator under different frequencies are studied, and then LCR circuit is used for impedance matching, achieving better results.

2. Structure and discharge mechanism of surface DBD plasma generator

Fig. 1 shows the structure section of surface DBD electrode, the front and back electrodes are linear metal electrodes covered on the dielectric plate, distributed on both sides of the electrode plate, and the width is w_1 and w_2 , respectively. d is the horizontal distance between the two electrodes, s is the thickness of the electrode, and t is the thickness of the dielectric plate. In the discharge loop, the front electrode is connected to the high voltage end, and the back electrode is encapsulated and grounded by insulating medium.

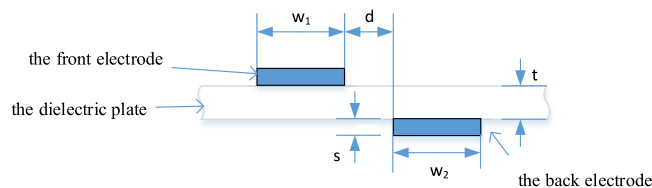


Fig. 1. Structural schematic diagram of surface DBD plasma generator.

In terms of discharge mechanism, the surface DBD still uses the dielectric barrier to restrict the free growth of current between two electrodes, and prevent the formation of spark or arc between electrodes. So, it belongs to non-thermal equilibrium discharge under high pressure. When the positive electrode is the cathode, the electron moves towards the anode under the action of the external electric field, and constantly collides with the gas molecules in the movement, which ionizes them and produces many new electrons. These electrons accumulate on the surface of the medium and interact with the positive charges in the discharge space to create an additional electric field that is opposite to the applied electric field. With the increase of accumulated charge in the medium, the effect of additional electric field is also enhanced, and the total field strength between air gaps will decline. When the field strength between air gaps drops to the breakdown field strength smaller than that of gas, discharge is interrupted. The DBD is powered by high-frequency ac power supply. The polarity of the front and back electrodes is reversed in the second half cycle of the power supply. So, the entire discharge process can be continued continuously.

During discharge, a large amount of discharge charge is accumulated on the surface of the dielectric plate, and form a virtual electrode in addition to the front electrode and the back electrode. In this paper, the discharge circuit parameters are equivalent and the discharge circuit model is established.

3. The equivalent circuit

As the back electrode of the plasma generator is encapsulated, the discharge is carried out only in the discharge space near the front electrode. During discharge, charge accumulation and release continuously occur on the surface

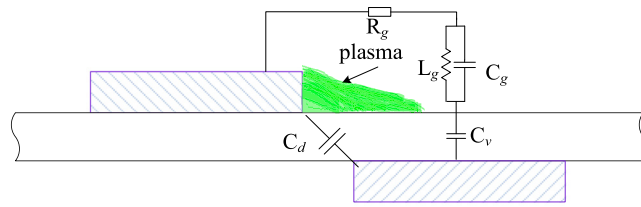


Fig. 2. Equivalent parameters of surface DBD.

of the dielectric plate, and virtual electrodes are formed on the surface of the dielectric which affects the development of discharge process. The equivalent parameters of the surface DBD during discharge are shown in Fig. 2.

In the above figure, C_d is the equivalent capacitance between two electrodes, where, the value is determined by the structure of the electrodes and is independent of whether the circuit discharge is carried out or not. C_v is the equivalent capacitance of virtual electrode and back Electrode. Its value is determined by the thickness of the dielectric plate, the relative dielectric constant of the dielectric and the area covered by the plasma on the dielectric surface, and it changes with the intensity of the discharge. The energy consumption in the discharge process is represented by the air gap equivalent resistance R_g , the inductive properties of electrons oscillating between electrodes are replaced by equivalent inductance L_g and the capacitance between the virtual electrode and the front electrode is represented by the equivalent capacitance C_g . All the values are affected by discharge intensity.

Because of the mismatch between power supply and plasma generator, impedance matching is needed, and LCR circuit is generally used for compensation as shown in Fig. 3. The matching impedance in the circuit is in parallel with the parameters of matching impedance is adjusted to match the impedance in circuit.

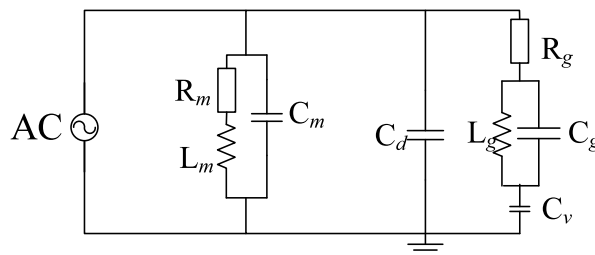


Fig. 3. Equivalent circuit with matching block.

In the equivalent circuit of the plasma generator shown above,

$$Z_1 = R_1 + X_1 = R_g + \frac{1}{j\omega C_v} + \frac{1}{\frac{1}{j\omega L_g} + j\omega C_g} = R_g + j\left(-\frac{1}{\omega C_v} + \frac{\omega L_g}{1 - \omega^2 C_g L_g}\right) \tag{1}$$

$$Z_2 = X_2 = -j\frac{1}{\omega C_d} \tag{2}$$

The equivalent impedance of the plasma generator is

$$Z_p = R_p + X_p = \frac{1}{\frac{1}{R_1 + jX_1} + \frac{1}{jX_2}} = \frac{R_1 X_2 (X_1 + X_2) - R_1 X_1 X_2 + j[X_1 X_2 (X_1 + X_2) + R_1^2 X_2]}{R_1^2 + (X_1 + X_2)^2} \tag{3}$$

Similarly, the matching impedance part of the circuit is

$$Z_{meq} = R_{meq} + X_{meq} = \frac{1}{\frac{1}{R_m + j\omega L_m} + j\omega C_m} = \frac{R_m + j(\omega L_m - \omega^3 L_m^2 C_m - \omega C_m R_m^2)}{(1 - \omega^2 C_m L_m)^2 + \omega^2 R_m^2 C_m^2} \tag{4}$$

$$Z_{eq} = R_{eq} + X_{eq} = \frac{1}{\frac{1}{R_p + jX_p} + \frac{1}{R_{meq} + jX_{meq}}} = \frac{R_p^2 R_{meq} + R_p R_{meq}^2 + R_p X_{meq}^2 + R_{meq} X_p^2}{(R_p + R_{meq})^2 + (X_p + X_{meq})^2} + j \frac{R_p^2 X_{meq} + R_{meq}^2 X_p + X_p^2 X_{meq} + X_p X_{meq}^2}{(R_p + R_{meq})^2 + (X_p + X_{meq})^2} \tag{5}$$

4. Impedance characteristics of surface DBD plasma generator

Tański et al. [3] researched the equivalent circuit of the plasma generator in Fig. 3. According to the conclusion of this paper, the parameters of this paper are selected as follows: $C_d = 1 \text{ pF}$, $L_g = 1 \text{ pH}$, $C_g = 1 \text{ nF}$, $C_v = 1 \text{ pF}$. The structure of plasma generator and the magnitude and frequency of applied voltage determine the intensity of discharge, therefore, the equivalent resistance R_g of the circuit is selected as $0.1 \text{ }\Omega$, $1 \text{ }\Omega$ and $10 \text{ }\Omega$ respectively for data comparison.

DBD can be started with high voltage frequencies ranging from 50 Hz to million Hz and Fig. 4 shows the impedance characteristics of a surface DBD plasma generator at different frequencies. It can be seen from the figure that R_p keeps $0.025 \text{ }\Omega$, $0.25 \text{ }\Omega$ and $2.5 \text{ }\Omega$, respectively, when R_g is $0.1 \text{ }\Omega$, $1 \text{ }\Omega$ and $10 \text{ }\Omega$. That is to say, the equivalent resistance is not affected by frequency variation, and its value is related to the equivalent resistance of the circuit. In the three cases, the equivalent reactance value X_p is negative, indicating that the load exhibits capacitive effect. When the frequency is low, its value is in million level. With the increase of frequency, the amplitude decreases gradually, and finally decreases to zero. The three curves coincide basically, indicating that the reactance characteristics are not affected by the equivalent resistance of the circuit at this time. The capacitance characteristic of the circuit is mainly determined by the capacitance C_d between the two plates. With the increase of frequency, the reactance value decreases, so the X_p decreases to zero.

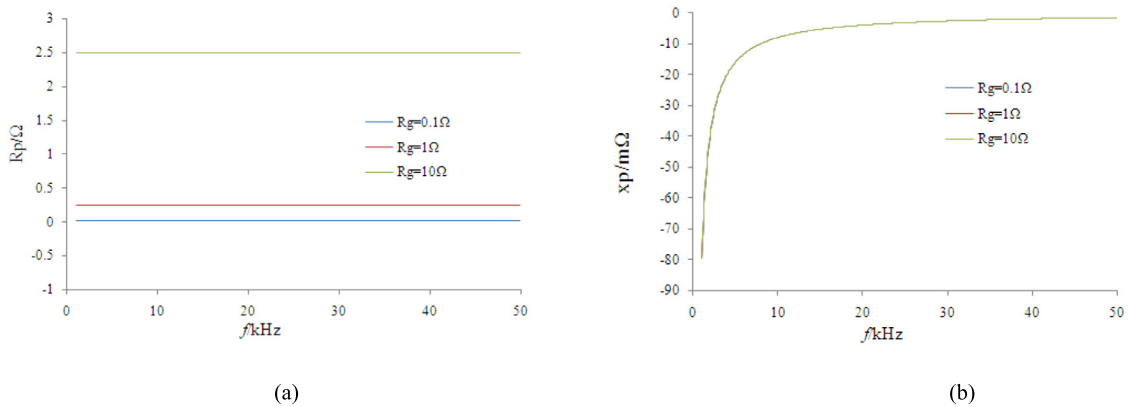


Fig. 4. Impedance characteristics of plasma generator at different frequencies.

5. Impedance matching of plasma generator

Fig. 4 shows that when the frequency is low, the R_p and X_p of the plasma generator are quite different, and the power mismatch between the plasma generator and the power supply is easy to occur, resulting in the low voltage at both ends of the plasma generator, or the energy cannot be completely consumed by reflection on the plasma generator. LR or LCR circuits are usually used to match the impedance of the generator, so that the impedance of the circuit decreases, and then the impedance of the plasma generator can be easily conjugated with the impedance of the power supply by Liu et al. [4]. Fig. 5 is the impedance characteristic curve of the circuit matched with LR circuit. Currently, $R_m = 0.1 \text{ }\Omega$, $L_m = 0.1 \text{ pH}$ and R_g choose $0.1 \text{ }\Omega$, $1 \text{ }\Omega$ and $10 \text{ }\Omega$ respectively. The results are shown in Fig. 5. That is to say, the equivalent resistance of the circuit has little effect on the impedance of the matching circuit.

In the circuit, R_{eq} remains unchanged at $0.1 \text{ }\Omega$, while X_{eq} increases gradually with the increase of frequency, but its value is smaller, within the range of nano Ω . Therefore, in the lower frequency range, the plasma generator is

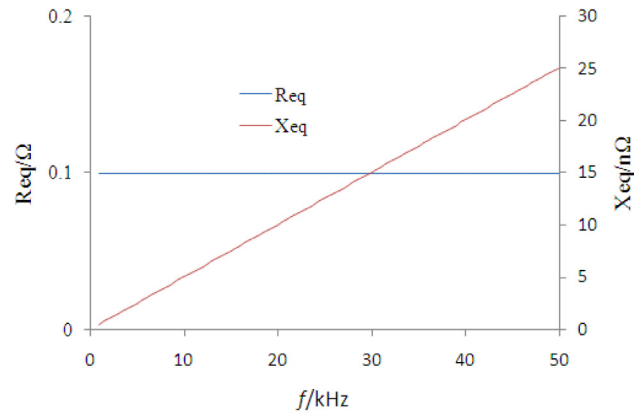


Fig. 5. LR circuit matching.

matched by LR impedance, and $Z_{eq} = 0.1 \Omega$ remains unchanged. At this time, it is also connected with an internal resistance of 0.1Ω , which can achieve the maximum power conversion efficiency.

In addition, LCR matching can be carried out in the circuit. Because the impedance characteristic of the plasma generator is capacitive, a larger inductance is chosen at this time, and $R_m = 0.1 \Omega$, $L_m = 100 \mu\text{H}$, $C_m = 100 \mu\text{F}$. Fig. 6 shows the equivalent circuit impedance characteristics after LCR. R_{eq} has a peak value at the frequency $f = 5 \text{ kHz}$. With the increase of frequency, it increases gradually near the zero value, reaches the peak value, and then begins to decrease rapidly. Then, with the increase of frequency, R_{eq} tends to zero. There are positive and negative peaks in X_{eq} . With the increase of frequency, the value increases gradually from 0 to the maximum, then decreases gradually, and then decreases to 0 near $f = 4 \text{ kHz}$. The impedance characteristics change from inductive to capacitive. Thereafter, X_{eq} continues to decrease to the minimum, then increases, and finally approaches to 0, but the load thereafter. It has always been an inclusive feature.

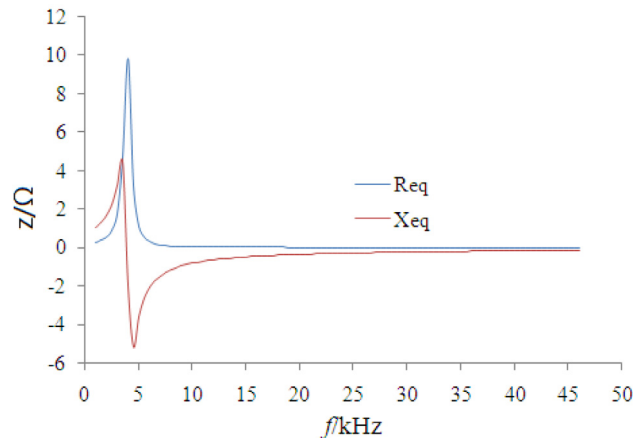


Fig. 6. LCR circuit matching.

6. Conclusions

Based on the discharge mechanism of plasma generator, this paper points out that the accumulation of electrode charge will form a virtual electrode on the surface of the dielectric, so that the circuit equivalent of the planar DBD plasma generator is obtained. The impedance characteristics were analysed and the influence of LR and LCR impedance matching on the impedance characteristics was studied. The following conclusions were obtained:

(1) The equivalent resistance of plasma generator does not change obviously with frequency and its value changes with circuit resistance. The generator has a capacitive property, which gradually approaches 0 with the increase of frequency.

(2) When LR matching is used, the resistance does not change much with the increase of frequency, but the reactance increases gradually, but its value is small. In the range of nano Ω , the impedance of plasma generator can be basically pure resistivity.

(3) In LCR matching, impedance characteristics gradually change from sensibility to capacitance with the increase of frequency.

(4) When matching the power of the plasma generator, it is necessary to select an appropriate matching mode based on the characteristics of the power source and the frequency range of the power.

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