A Study on Equivalent Circuit Model of RF Discharge Based on Multi-Physics Field

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Abstract ─ Belongs to EMC problems, the equivalent circuit model of RF discharge is studied. By establishing the correlation between circuit parameters of equivalent circuit and plasma characteristics, this paper conducts a brief analysis on the RF discharge mechanism with different frequencies.

Index Terms ─ Equivalent circuit model, multi-physics simulation, RF discharge.

I. INTRODUCTION

Once loses control and precaution, excessive electromagnetic energy not only cause electromagnetic interference, but also have a damaging effect on some specific targets, which is generally known as hazards of electromagnetic radiation. The US military standard MIL-STD-464C [1] has proposed HERF (Hazards of electromagnetic radiation to fuel), but the mechanism of HERF still lacks in-depth studies yet.

HERF is an interactive result of multiple physical fields including electromagnetism, plasma science, combustion science, hydrodynamics and thermodynamics. From the macroscopic chronological perspective of the interaction, the mechanism of HERF can be roughly divided into three processes: electromagnetic coupling, discharge and ignition. When the discharge coupled by electromagnetic is sufficient to ignite, the HERF problem will occur and cause unpredictable damage.

There is still a lot of work about the hazard mechanism of HERF like electromagnetic coupling, discharge and combustion, and the RF discharge is one of the keys. Since the discharge of HERF comes from electromagnetic coupling instead of ESD (electro-static discharge), this process belongs to RF discharge. The breakdown characteristic of RF discharge is very different from ESD due to different frequency. There is a critical frequency during RF breakdown process [2]:

$$f_{c0} = \frac{\mu_e E}{\pi d}, \tag{1}$$

where E is the amplitude of the alternating electric field, d is the distance between the gap and μ_e is the electron mobility. While the frequency is higher than f_{c0}, free electrons cannot reach the electrode before the polarity of the electric field changes, which may reduce the electron dissipation rate, and change the breakdown characteristics. However, the specific regular of this process is unclear yet.

To quantitatively study the characteristics of RF discharge, it is necessary to extract core parameters of the discharge. Many scholars have carried out research [3-5] and experiments [6-9] on the relationship between the discharge parameters and the circuit parameters including voltage, current, equivalent plasma resistance from voltage and current. But these equivalent circuit models of discharge are conductivity models, which are only suitable for DC discharge, and not suitable for the RF discharge problem discussed in this paper.

According to the previous qualitative research [10] and reference [11], RF discharges have different physical characteristics with different frequencies. As the definition of current and electron, current can evaluate the characteristics of electron number density during RF discharge.

Aiming to overcome the quantitative research of RF discharges, this paper studies and analyzes the breakdown characteristic of RF discharge under the same amplitude with different frequency. Because the traditional electromagnetic simulation software cannot calculate the discharge breakdown model, multi-physics simulation software COMSOL is selected. This paper gives the calculation method of the equivalent AC capacitance form the discharge structure considering a typical structure of aircraft fuel tank oil-inlet and nozzle. By analyzing the equivalent circuit, the gas conductivity can be clearly seen and the discharge characteristic under different frequencies can be obtained. Finally, the breakdown characteristics of RF discharge in the whole frequency band are analyzed and summarized through a large number of simulations.

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II. EQUIVALENT CIRCUIT MODEL BASED ON ELECTROMAGNETIC FIELD THEORY

A. Equivalent circuit model

Unlike the stable electric field of DC discharge, the electric field of the RF discharge is alternating where the frequency determines the characteristics of the breakdown process. After the RF discharge occurs, the gas medium has a capacitive effect because of the RF electromagnetic field, so the equivalent circuit structure of RF discharge is different from the DC discharge.

In addition to the conductance component of the plasma gas, there is the AC capacitance component equivalent from the high frequency electromagnetic structure. So, the equivalent circuit structure of the RF discharge is a capacitor parallel conductance circuit like Fig. 1.

According to the characteristics of the parallel circuit, the total terminal current is divided into two parts:

1) The current of the capacitor is the displacement current, which is generated by the neutral medium after the breakdown of the gas. While the electron density of gas is small, the displacement current can be constant during the breakdown process;

2) The current of the conductance is the electron current, which is generated by the free electron motion after breaking down. The conductance can characterize the plasma characteristics of gas breakdown discharge. The equivalent conductance in this paper can be calculated from the total terminal current, excitation voltage and equivalent capacitance, and it is one of the most important parameters.

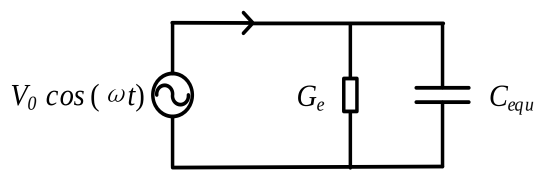

Fig. 1. The equivalent circuit model of RF discharge.

B. Equivalent AC capacitor structure

There are three necessary conditions for the accidental ignition of fuel by electromagnetic radiation [12]: proper ratio of fuel vapor and air, discharge produced by Electromagnetic radiation which has enough length and heat to ignition. These conditions indicated that HERF may occur in the gap between the carrier aircraft fuel tank oil-inlet and nozzle.

Referring to the structure of aircraft fuel tank oil-inlet and nozzle [13-14], two concentric cylindrical plates are selected as the two poles of discharge reactor. With a thin layer of dielectric attached on the metal surface of fuel tank oil-inlet and nozzle, two dielectric plates are added outside the gap to compose the model like Fig. 2. The electromagnetic field between the two cylindrical electrode plates is approximately uniform in the θ direction.

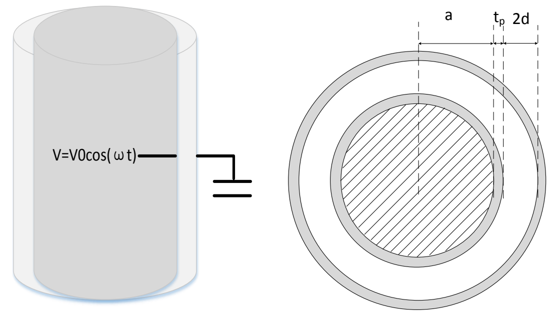

Fig. 2. Cross-sectional structure of the cylinder.

The inside radius of cylindrical plate a is 145mm, the dielectric layer thickness t_p is 0.1mm, the gap between aircraft fuel tank oil-inlet and nozzle $2d$ is 1.8mm and the length of the cylinder l is 150mm. Since l is much longer than the gap $2d$, the edge effect of electromagnetic field distribution can be ignored in the simulation process. So, the three-dimensional simulation model can be simplified to one-dimensional axisymmetric model.

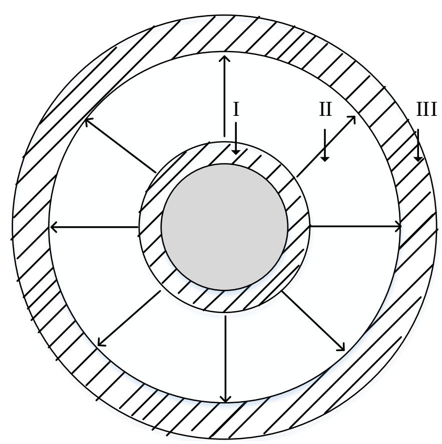

Fig. 3. The gap structure of the cylinder when $z = l/2$.

The gap structure can be simplified as the cross-sectional distribution when $z = l/2$ like Fig. 3, half of the distance between two plates is d, and the thickness of plates is t_p. Because no free charge distributes in I, II and III regions, the field line of electric displacement vector should be continuous, and it is easy to know that the modulus of electric displacement vector in region I, II, and III regions is inversely proportional to the radius:

$$|D| = \frac{A}{r}, \tag{2}$$

where D is the electric displacement vector, A is a constant and r is the radius.

So, the electric fields in the direction of the r-axis can be calculated:

$$E_{\mathrm{I}} = E_{\mathrm{III}} = \frac{A_1}{r}, \quad (3)$$

$$E_{\mathrm{II}} = \frac{A_2}{r}, \quad (4)$$

where $E_{\mathrm{I}}, E_{\mathrm{II}}, E_{III}$ are the electric fields of the three region.

Here are the boundary conditions in $z = 0$:

$$V_0 = -\int_0^{2d+2t_p} E_r(z,t)|_{z=0} dr, \quad (5)$$

$$D_I|_{r=a+t_p} = \varepsilon_0 \varepsilon_r E_I = \varepsilon_0 \varepsilon_g E_{II} = D_{II}|_{r=a+t_p} . \quad (6)$$

The key parameter can be calculated:

$$\begin{cases} A_1 = \dfrac{V_0}{ln\frac{(a+t_p)+(a+2t_p+2d)}{a(a+t_p+2d)} + \frac{\varepsilon_r}{\varepsilon_g} ln\frac{(a+t_p+2d)}{(a+t_p)}} \\ A_2 = \dfrac{\varepsilon_r}{\varepsilon_g} A_1 \end{cases}, \quad (7)$$

where V_0 is the amplitude of the excitation voltage, a, t_p, d are the structural parameters as Fig. 2 shown, ε_g is the relative dielectric constant of the gas and ε_r is the relative dielectric constant of the dielectric layer. In this paper, ε_g is 1 and ε_r is 10.

Terminal voltage and terminal current are obtained by integration of electric and magnetic fields in the gap:

$$\begin{aligned} \mathrm{u} &= \int_a^{a+2t_p+2d} E_r dr \\ &= \left[\mathrm{A}_1 \ln\frac{(a+t_p)(a+2t_p+2d)}{a(a+t_p+2d)} \cos\left(\beta_r \frac{l}{2}\right) + \right. \\ &\left. \mathrm{A}_2 \ln\frac{a+t_p+2d}{a+t_p} \cos\left(\beta_g \frac{l}{2}\right)\right] \cos \omega t, \end{aligned} \quad (8)$$

$$\mathrm{i} = -2\int_0^{2\pi} H_\theta r d\theta = -\frac{4\pi A_1}{\eta_r} \sin\left(\beta_r \frac{l}{2}\right) \sin \omega t. \quad (9)$$

According to the AC capacitance theory [15], with the increase of the frequency, different order Taylor expansions of the trigonometric function can obtain different equivalent circuit model. For example, the first-order approximation is a capacitance model, and the second-order approximation is a capacitive-inductor series circuit model.

Take the first-order approximation as an example and put the structural parameters into the equation. The first-order approximate cut-off frequency calculation result is 60MHz and the capacitance is 0.669nF:

$$\beta_r \frac{l}{2} < 5\% \cap \beta_g \frac{l}{2} < 5\% , \quad (10)$$

$$\mathrm{C} = \frac{2\pi\varepsilon_0\varepsilon_r l}{\ln\frac{(a+t_p)(a+2t_p+2d)}{a(a+t_p+2d)} + \frac{\varepsilon_r}{\varepsilon_g}\ln\frac{a+t_p+2d}{a+t_p}} . \quad (11)$$

The equivalent conductance is calculated from the terminal current and capacitance by multi-physics simulation results, and it is affected by the degree of ionization. Therefore, the RC equivalent circuit can identify discharge breakdown characteristics. The conductance represents the degree of ionization between the gap, and the terminal current represents the discharge characteristics.

III. RF DISCHARGE MECHANISM

A. Parameters of simulation model

The plasma module of multi-physics simulation in COMSOL was selected to analyze the mechanism of RF discharge [16]. The excitation signal is $\mathrm{V} = -600[\mathrm{V}]\sin(\omega t)$, the gaseous pressure is 1 atmosphere and the temperature is 400K [17].

According to research, the conductance of the equivalent circuit model grows in proportion to the frequency, which means that the degree of ionization is proportional to the frequency. And there are five different breakdown physical characteristics found under the same excitation voltage with different frequency.

B. Terminal current

Referring to the foregoing analysis, the waveform of the total terminal current on the electrode can represent the breakdown characteristic of discharge and determine whether breakdown occurs and analyze the degree of ionization.

According to the simulation results below, the first-order approximate cut-up frequency of the equivalent capacitance, there are five different waveforms of the terminal current generated by the excitation of 600V, representing different breakdown characteristics.

1) 1 Hz ~ 23.4 kHz: as shown in Fig. 4, the terminal current from simulation result is completely consistent with the analytical solution of the extracted capacitor, which means that the current of the equivalent conductance component is almost negligible and there is no breakdown.

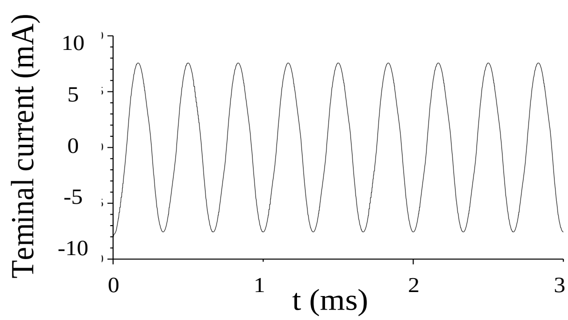

Fig. 4. Terminal current at 3kHz.

2) 23.4 kHz ~ 120 kHz: compared with the values above, the cyclical mutation of terminal current illustrates cyclical discrete breakdown. There is a process of breakdown, maintenance, and extinction during every half cycle like Fig. 5.

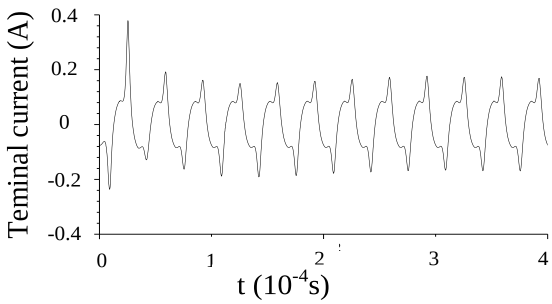

Fig. 5. Terminal current at 30kHz.

3) 120 kHz ~ 1.5 MHz: as shown in Fig. 6, the duration of breakdown per half cycle is getting longer and longer, until the plasma from collision is enough to maintain a continuous breakdown the excitation of 600V.

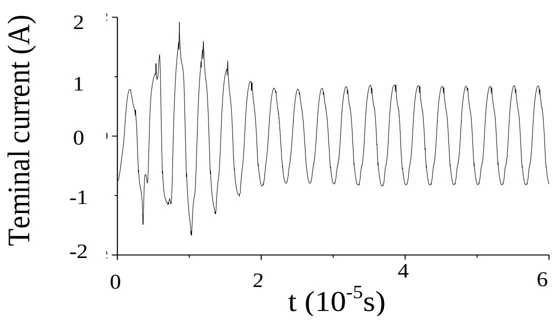

Fig. 6. Terminal current at 300kHz.

4) 1.5 MHz ~ 12 MHz: Fig. 7 indicates that the continuous collision of electrons will accumulate more new electrons, which may increase the ionized plasma over time. The initial current value is the same as the displacement current, which means that the accumulated plasma is not enough to breakdown argon at the initial stage of accumulation effect.

Under this special accumulation effect, the breakdown process is gradual and there is no clear breakdown state. It is necessary to determine a certain threshold to judge whether electrons are accumulated enough.

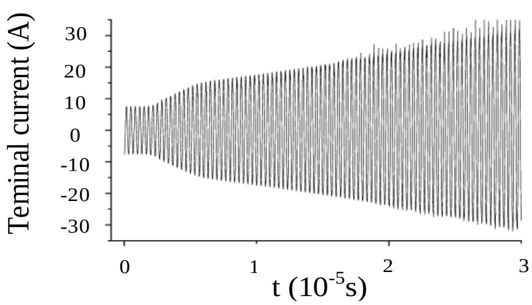

Fig. 7. Terminal current at 3MHz.

5) 12 MHz ~ 60 MHz: as shown in Fig. 8, under these frequencies, the accumulation effect will lead to a qualitative change while it reaches a certain level, which is called electron avalanche effect breakdown. The ionization of electrons will suddenly intensify when electron avalanche effect breakdown occurs.

It is worth noting that the cut-off frequency calculated by the Equation (1) is 12.1 MHz, which is the same as the multi-physics simulation result, the accuracy of the plasma portion can be verified.

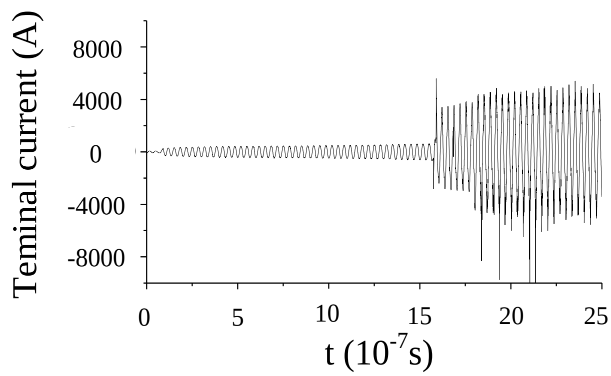

Fig. 8. Terminal current at 30MHz.

C. Equivalent conductance

The equivalent conductance of the ionized gas can be solved based on the total terminal current and the displacement current. The conductance can analyze the conductivity of the plasma and the breakdown characteristics. Following is a brief analysis from conductance.

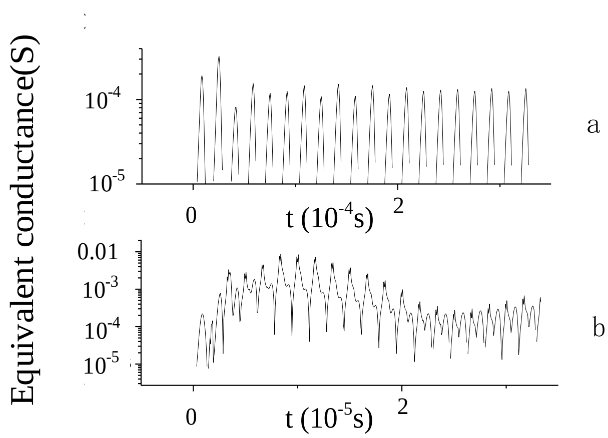

Fig. 9. Conductance of cyclical discrete breakdown at 30kHz (a), and continuous breakdown at 300kHz (b).

Figure 9 indicates the case of periodic discrete breakdown and continuous breakdown. During the cyclical discrete breakdown process, the conductance changes discretely between a small conductance at breakdown and infinitesimal conductance at unbroken.

Under the condition of the continuous breakdown, the gas remains in a conductive state, and the conductivity at larger magnitude of the excitation voltage is greater than when the amplitude is small.

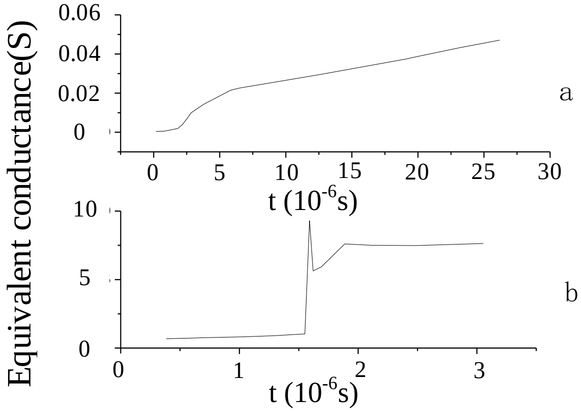

Fig. 10. Conductance of accumulation effect at 3MHz (a), and avalanche effect at 30MHz (b).

As shown in Fig. 10, during the cumulative effect and avalanche effect breakdown process, the conductivity of the gas gradually increases with the breakdown process at the same excitation voltage amplitude. This proves the most essential difference between RF discharge and DC discharge, and that RF discharge is more harmful to the HERF problem.

IV. CONCLUSION

A method of multi-physics simulation is proposed to analyze the mechanism of RF discharge. Through the equivalent models, some important conclusions can be obtained by simulation results.

When the structure of Aircraft Fuel Tank oil-inlet and Nozzle is coupled by the RF field, its electromagnetic structure can be equivalent to different orders LC circuit under different frequency.

There are different breakdown characteristics with different frequencies at the same excitation voltage, and the characteristics can be analyzed by the equivalent circuit. In general, the higher the frequency, the breakdown will be easier, and the degree of ionization will be higher.

Research shows that there are five different breakdown states under different frequencies excited at 600V. With cumulative effect, high frequency discharge process appears above 1MHz, the degree of ionization changes significantly. With electron avalanche effect, high frequency discharge process appears above 10MHz, the degree of ionization will suddenly intensify nearly 10 times. And these situations are related to the breakdown time.

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