The Influence of Electrode Surface Mercury Film Deformation on the Breakdown Voltage of a Sub-Nanosecond Pulse Discharge Tube

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Abstract A sub-nanosecond pulse discharge tube is a gas discharge tube which can generate a rapid high-voltage pulse of kilo-volts in amplitude and sub-nanoseconds in width. In this paper, the sub-nanosecond pulse discharge tube and its working principles are described. Because of the phenomenon that the deformation process of the mercury film on the electrode surface lags behind the charging process, the mercury film deformation process affects the dynamic breakdown voltage of the tube directly. The deformation of the mercury film is observed microscopically, and the dynamic breakdown voltage of the tube is measured using an oscillograph. The results show that all the parameters in the charging process, such as charging resistance, charging capacitance and DC power supply, affect the dynamic breakdown voltage of the tube. Based on these studies, the output pulse amplitude can be controlled continuously and individually by adjusting the power supply voltage. When the DC power supply is adjusted from 7 kV to 10 kV, the dynamic breakdown voltage ranges from 6.5 kV to 10 kV. According to our research, a kind of sub-nanosecond pulse generator is made, with a pulse width ranging from 0.5 ns to 2.5 ns, a rise time from 0.32 ns to 0.58 ns, and a pulse amplitude that is adjustable from 1.5 kV to 5 kV.

Keywords: sub-nanosecond pulse generator, mercury film deformation, gas discharge, breakdown voltage, pulse parameter

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1 Introduction

Under the action of electric force, liquid deformation will occur. If an electrode is made of conductive liquid, under the action of the electric field, the liquid electrode’s radius of curvature will decrease with a rise in the electric field. When a strong electric field is applied, a very small tip on the liquid electrode surface will appear. Then, from the tip, a mass of field-emission electrons or field-emission ions will occur. This phenomenon is widely used in liquid metal electron sources or liquid metal ion sources \cite{1,2,3}, etc.

In 1985, researchers at Xi’an Jiaotong University invented a sub-nanosecond pulse discharge tube \cite{4} with a characteristic structure of mercury film electrodes. Since the invention of the tube, it has been widely applied in many scientific research areas, such as high-voltage technology \cite{5}, electromagnetic missiles \cite{6}, ground penetrating radar \cite{7}, electromagnetic pulse sterilization \cite{8}, dielectric barrier discharge photographic technology \cite{9,10} and dielectric barrier discharge fingerprint acquisition technology \cite{11,12,13,14,15}.

In the sub-nanosecond pulse discharge tube, as a result of mercury film deformation under the action of the electric force, a mercury tip with small a radius of curvature is formed on the electrode surface. Field-emission electrons emit from the tip. Through high-pressure hydrogen gas, these electrons produce an electron avalanche of a higher multitude, and create a complete breakdown of hydrogen at the sub-nanosecond scale. In the early days, attention was mostly paid to the effect of the electric field on the tip shape, and whether this tip can produce field-emission electrons, but not the dynamic process of tip deformation, or the effects of the dynamic process on the high-voltage sub-nanosecond pulse generator’s output parameters.

Nevertheless, according to our recent study \cite{16}, the dynamic process of mercury film deformation would directly affect the breakdown voltage of the tube. Now, further studies in this paper show that the breakdown voltage of the tube is not only variable, but also related to the DC power supply voltage, the charging resistor and the charging capacitor. What is more, the output parameters of the pulse generator can be successfully managed by controlling the dynamic process of mercury film deformation.

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2 The sub-nanosecond pulse discharge tube

2.1 The structure of the sub-nanosecond pulse discharge tube

Fig. 1 contains a structure diagram and a photograph of the sub-nanosecond pulse discharge tube. The tube is filled with \( \text{H}_2 \) at 15 atm, and has a spark gap of 0.25 mm. Using a special wetted technique, a layer of mercury film covers the solid electrode surface.

![Fig. 1 A structure diagram (a) and a photograph (b) of the sub-nanosecond pulse discharge tube](image)

2.2 The working principle of the sub-nanosecond pulse discharge tube

A high-voltage sub-nanosecond pulse generator based on the sub-nanosecond pulse discharge tube is made up of several parts: a DC power supply with an adjustable output voltage, an appropriate set of coaxial metal structures to produce the required pulse waveform and pulse parameters, and a fast pulse test device consisting of a sampling oscilloscope and a coaxial attenuator (75 dB). The corresponding working schematic diagram is shown in Fig. 2(a), and its equivalent circuit in Fig. 2(b).

![Fig. 2 The pulse generator and its output pulse. (a) A schematic diagram of the pulse generator, (b) the equivalent circuit of the pulse generator, and (c) a typical pulse waveform (X: 0.5 ns/div; Y: 200 mV/div; the amplitude attenuates 5623 times)](image)

Obviously, Fig. 2(b) is an electric charging and discharging circuit. The DC power supply, \( E_a \), and the charging resistors, \( R_a \), as well as coaxially distributed capacitance, \( C_a \), form the charging circuit. Capacitance, \( C_a \), sub-nanosecond pulse discharge tube, \( G \), as well as coaxially matched load resistors, \( R_L \), form the discharge circuit. The capacitor, \( C_a \), is charged by the DC power supply, \( E_a \), through the charging resistors, \( R_a \). When the capacitance, \( C_a \), is charged to the breakdown voltage of the tube, a breakdown occurs in the tube. Then, the energy stored in the capacitance, \( C_a \), is released quickly through the load resistor, \( R_L \), and the tube, \( G \). Thereafter, a sub-nanosecond pulse with several kilo-volts in amplitude is formed on the load resistor, \( R_L \). The pulse amplitude and width depend on the value of capacitance, \( C_a \). In order to test the pulse parameters with the SQ-27 sampling oscilloscope, the pulse amplitude must be attenuated by a coaxial attenuator of 75 dB. Fig. 2(c) shows the typical output pulse waveform of the pulse generator.

2.3 The role of mercury in the discharge process

First of all, mercury film can effectively protect the solid electrode from bombardment by charged particles, so as to extend the life of the discharge tube. Secondly, under the action of the electric field, the mercury film electrode surface happens to deform, creating a very small tip on the electrode surface. Earlier studies \([17,18]\) have shown that when the discharge tube is about to break down, the radius of curvature of the
electrode tip can approach a 20 angstrom order of magnitude. In general, the breakdown voltage of the discharge tube is higher than 6 kV. So field-emission electrons will be emitted from this small tip. The field-emission electrons go through high-pressure hydrogen gas, producing an electron avalanche of high multiplication. Thus, the discharge tube can completely discharge at the sub-nanosecond scale. Thirdly, the shape of the mercury film tip has a self-repairing capability in the non-discharge period, so every discharge of the tube is very stable.

3 The phenomena of mercury film deformation

3.1 Microscopic observation of mercury film deformation

With the DC power supply voltage $E_a$ rising, the changing in the surface shape of the mercury film electrode is observed using a microscope. The changing process is shown in Fig. 3.

![Fig.3 Mercury film deformation: (a) the starting state of the mercury film electrode; (b) the mercury film electrode surfaces at a lower $E_a$ value; (c) the mercury film electrode surfaces at a higher $E_a$ value; and (d) when $E_a$ rises near to the breakdown voltage, a significant small tip appears on the mercury film electrode surface](image)

It is found in our experiments that the radius of curvature of the mercury film tip gradually decreases as $E_a$ gradually rises. As shown in Fig. 3, the mercury film shape does not change significantly at the beginning (Fig. 3(a) and (b)). When $E_a$ rises close to the breakdown voltage of the tube, a small tip clearly appears on the mercury film electrode surface (Fig. 3(c) and (d)). When $E_a$ continues to rise, a breakdown occurs in the tube.

3.2 Measurement of the dynamic breakdown voltage

In order to study the effect of mercury film deformation on the output pulse parameters of the pulse generator, a concept of dynamic breakdown voltage of the tube should be introduced.

With the electric charging voltage $U_c$ gradually increasing, the voltage on the electrodes rises gradually. As a result of this, as well as of the gradually diminishing radius of curvature of the mercury film electrode, the mercury film electrode surface’s electric field $E$ also gradually increases. When the electric field on the surface of the mercury film tip reaches the breakdown field strength, $E_s$, a breakdown will occur. Fig. 4 presents a sketch of the charging process of the electric charging voltage $U_c$, and the surface electric field $E$, of the mercury film electrode over time.

![Fig.4 The mercury film deformation process lags behind the charging process](image)

Generally speaking, the $E_s$ and $U_c$ curves in Fig. 4 should be synchronous. When the charging time reaches $t_1$, the surface electric field of the mercury film tip reaches the breakdown field strength $E_s$, and then a breakdown will occur. The voltage on the discharge tube is the static breakdown voltage $V_{s1}$.

In fact, because mercury film deformation is essentially the movement of liquid, the mercury film deformation process is slower, compared with the electric charging process. In other words, when the charging voltage $U_c$ gradually rises, the mercury film deformation may not be able to keep up with the charging voltage. That is, compared with the charging process, mercury film deformation has a time lag. In Fig. 4, when the charging process is not very slow, the relationship between the mercury film electrode surface electric field and time is not curve 1, but curve 2. Due to the time lag of mercury film deformation, the rise rate of curve 2 is slower than curve 1. When the mercury film electrode surface electric field $E$ reaches the breakdown electric field $E_s$ of the tube, the charging voltage has risen to
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In this way, the real breakdown voltage of the tube is $V_{s2}$ instead of $V_{s1}$. Evidently, when the DC power supply voltage $E_a$, the charging resistor $R_a$, or the charging capacitor $C_a$, changes, the charging process will change. Once the charging process changes, the value of $V_{s2}$ will also change. In other words, the breakdown voltage of the tube is not fixed, but relevant to $E_a$, $R_a$ and $C_a$. Therefore, $V_{s2}$ is called the dynamic breakdown voltage of the tube.

In order to measure the dynamic breakdown voltage of the tube, a sampling resistor $r$ is stringed into the charging circuit, as shown in Fig. 2. Measuring the voltage waveform $U_r$ on the sampling resistors $r$, with an oscilloscope, the waveform $U_r$ is as shown in Fig. 5. This waveform essentially represents the charging process $U_c$.

The charging voltage $U_c$ on the capacitor $C_a$, can be expressed as:

$$U_c(t) = E_a(1 - e^{-\frac{t}{R_aC_a}}). \quad (1)$$

After a time period $T$, $U_c$ reaches the dynamic breakdown voltage $V_{s2}$. So the dynamic breakdown voltage $V_{s2}$ is as follows:

$$V_{s2} = E_a(1 - e^{-\frac{T}{R_aC_a}}). \quad (2)$$

In other words, if we measure the charging cycle $T$, the dynamic breakdown voltage $V_{s2}$, can be calculated from formula (2).

### 4 Factors affecting the dynamic breakdown voltage

The charging cycle $T$ is measured separately when the charging resistance $R_a$ is 30 MΩ, 47 MΩ and 62 MΩ. The charging capacitor $C_a$ ranges from 5 pF to 95 pF, and the DC power supply voltage, $E_a$, ranges from 7 kV to 10 kV. Then, the dynamic breakdown voltage can be calculated by formula (2). The relationships among the dynamic breakdown voltage and $E_a$, $R_a$ and $C_a$ are shown in Fig. 6.

![Fig.5 The electrical charging process of the pulse generator](image)

![Fig.6 The effect of $E_a$, $R_a$ and $C_a$ on the dynamic breakdown voltage](image)

Fig. 6 clearly indicates that the faster the charging process, the higher the dynamic breakdown voltage. The measured results indicate that there is a time lag in the mercury film deformation process.

### 5 Control of pulse amplitude using mercury film deformation

In the early days, researchers thought that the breakdown voltage of the sub-nanosecond pulse discharge tube was static, and its static breakdown voltage depended on the structure of the tube itself, regardless
of the charging circuit [19,20]. Therefore, once a tube was selected, the output pulse amplitude and width of the pulse generator were determined only by the capacitance, $C_a$. The larger the $C_a$ capacitance, the higher the pulse amplitude and the wider the pulse width. The DC power supply voltage $E_a$ would only affect the repetition frequency of the pulse.

Because it is very difficult to adjust the values of the capacitance $C_a$ continuously in practice, the pulse amplitude cannot be adjusted continuously. Furthermore, once the distribution capacitance $C_a$ is changed, the pulse amplitude will be changed as well as the pulse width. In other words, the pulse amplitude cannot be controlled separately. For these reasons, the application of this pulse generator is limited in some ways. However, it has now been found that there is a dynamic breakdown voltage for the tube, and this is related to the charging circuit. Therefore, the pulse amplitude is not only related to the distribution capacitance $C_a$, but also related to the parameters in the charging circuit, such as the DC power supply voltage $E_a$, the capacitance $C_a$, and the charging resistance $R_a$.

In other words, besides the value of the distribution capacitance $C_a$, the DC power supply voltage $E_a$ can also be used to control the pulse amplitude. Because the value of the DC power supply voltage can be continuously adjusted easily, the pulse amplitude can also be continuously adjusted.

In order to verify that the pulse amplitude is not only related to the capacitor $C_a$, but also related to the DC power supply voltage $E_a$, a measurement is made of the output pulse parameters at $R_a = 47 \, \text{MΩ}$. The measurement results are shown in Fig. 7.

As can be seen from Fig. 7, when either the capacitance $C_a$ or the value of $E_a$ is increased, the pulse amplitude is increased. Because it is very easy to change the value of $E_a$ continuously, the pulse amplitude can be continuously changed expediently to some extent. It is also found in Fig. 7 that when $E_a$ changes, the pulse width and rise time are almost unchanged, especially when the capacitance $C_a$ is smaller than 40 pF. In other words, as long as the DC power supply voltage, $E_a$, is adjusted continuously, it will be possible to control the pulse amplitude continuously and individually.

### 6 Conclusions

The concept of the dynamic breakdown voltage of the sub-nanosecond pulse discharge tube has been elaborated. It has been proved that the mercury film deformation process mainly affects the dynamic breakdown voltage of the tube. Because the mercury film deformation process always lags behind the charging process, the dynamic breakdown voltage is related to the DC power supply voltage. The output pulse amplitude is also related to the DC power supply voltage. Therefore, the pulse amplitude can be controlled continuously and individually by adjusting the DC power supply voltage continuously.

In this study, the capacitor $C_a$ ranges from 5 pF to 95 pF, and the resistor $R_a$ is 30 MΩ, 47 MΩ and 62 MΩ. When the DC power supply is adjusted from 7 kV to 10 kV, the dynamic breakdown voltage is measured and found to vary between 6.5 kV and 10 kV. In addition, a high-voltage sub-nanosecond pulse is created, with the pulse width ranging from 0.5 ns to 2.5 ns, the rise time ranging from 0.32 ns to 0.58 ns and the pulse amplitude adjustable from 1.5 kV to 5 kV. Due to the limitations of our experimental conditions, the DC power supply can only reach 10 kV, but it is predicted that if the DC power supply can be adjusted to a higher value, the pulse amplitude is likely to be much higher.
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