Emission Current Characteristics of Triggered Device of Vacuum Switch*

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Abstract The characteristics of the triggered vacuum switch (TVS) are obviously influenced by the emission current $i_e$ and emission charge of the trigger device. In this paper, an RC charge collector is designed, and the characteristics of emission current $i_e$ and collecting charge $Q_e$ of the trigger device are studied. The experimental results indicate that the emission current $i_e$ which is produced by the initial plasma has both positive and negative components, and the polarity of the emission current $i_e$ depends mainly on the polarity of the bias voltage $U_{Bias}$. The emission current $i_e$ and collecting charge $Q_e$ increase with the increase of the trigger voltage $U_{tr}$ and the bias voltage $U_{Bias}$. The emission efficient $\eta$ increases linearly with the increase of the bias voltage $U_{Bias}$. When the gap distance is 15 mm and bias voltage $U_{Bias}$ is 160 V and trigger voltage $U_{tr}$ is 2.6 kV, the emission efficiency $\eta$ reaches 6%.

Keywords: emission current, collecting charge, triggered device, vacuum switch

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(Some figures may appear in colour only in the online journal)

1 Introduction

The triggered vacuum switch (TVS), also called the triggered vacuum gap, is developed based on the technology of the vacuum gap and the triggered spark gap. It has been widely applied in pulsed power technology, lightning impulse generator, electromagnetic launch, laser pump excitation source, and impulse for overvoltage protection.

The TVS was first studied by Lafferty in 1966 [1]. He did numerous research studies on the TVS, especially on TVS coated with hydride as trigger materials. In the 1970s, some scholars did experiments on the trigger characteristics of the TVS with different trigger materials [2–5]. At present, the application research of the TVS has been carried out by scholars all over the world [6–8]. The research results show that the TVS with the surface flashover trigger device is easier to be triggered than others [9–13]. However, the use of the TVS is limited due to its disadvantages of operating instability and inaccuracy. It is well known that the trigger device is used to emit the initial plasma into the vacuum gap and to speed up the breakdown of the TVS. When a high trigger impulse is applied, the initial plasma is produced due to the surface flashover on the trigger dielectric material of the trigger device. Then, the initial plasma expands into the vacuum gap of the TVS, and when the initial plasma charge arrives at the anode, additional charged particles and electrons may be generated, which enhances the cathode electron emission ability. When the emission charge reaches or exceeds a critical value, breakdown of the TVS happens. So, the emission current $i_e$ produced by the trigger device and the collecting charge $Q_e$ emitted by the trigger device are essential requirements for the TVS.

In this paper, the collecting and measuring method of $i_e$ and $Q_e$ are put forward and an RC charge collector is designed; then the characteristics of $i_e$ and $Q_e$ are experimented and analyzed.

2 The structure of TVS and charge collector

The structure of the TVS and the collecting circuit of emission charge of the trigger device of the vacuum switch are shown in Fig. 1.

From Fig. 1, it can be seen that the TVS consists of two copper electrodes (anode and cathode) of 60 mm in diameter, which are separated by a poly-methyl methacrylate (PMMA) hollow cylinder insulator. The anode, the cathode and the PMMA hollow
cylinder insulator are assembled together with O-ring sealing. A hole of 6 mm in diameter is designed in the middle of the cathode for installing the trigger electrode. The cathode and the trigger electrode are insulated by a barium titanate dielectric disk with 12 mm in outer diameter and 4 mm in inner diameter, respectively. The vacuum environment of the TVS is maintained at $1.3 \times 10^{-3}$ Pa by a vacuum experimental system consisting of a rotary vane vacuum pump and an oil diffusion pump.

$$Q_e = \int_0^{\infty} i_e(t) dt.$$ (1)

3 Experiments and discussion

3.1 Characteristics of emission current

The characteristic of the $i_e$ (which is formed by the initial plasma produced by the trigger device) is mainly influenced by $U_{tr}$, $U_{Bias}$, and the vacuum gap $D_{gap}$, as shown in Fig. 3. The experimental conditions are as follows: $U_{tr}$ is 2.6 kV and $D_{gap}$ is 15 mm.

From Fig. 3, it is shown that $i_e$ increases with the increase of $U_{Bias}$; the reason is that the initial plasma is attracted by the electric field force produced by $U_{Bias}$. When $U_{tr}$ is the same, the emission speed of the initial plasma is the same, but part of the initial plasma charge with lower initial velocity or lower kinetic energy cannot reach the collecting electrode when $U_{Bias}$ is lower. When $U_{Bias}$ increases, the electric field force is strengthened and more initial plasma charge can be drawn to the collecting electrode. Because $U_{Bias}$ is positive voltage, the electrons can be attracted and the ion is hampered around the cathode, thus $i_e$ is negative current. When $U_{Bias}$ increases, the electric field between two main electrodes is strengthened, which makes more electrons be collected by the collecting electrode, as shown in Fig. 3(a). On the other hand, when $U_{Bias}$ is negative voltage (as shown in Fig. 3(b)) and $U_{Bias}$ increases, more and more ions are attracted to the collecting electrode, therefore $i_e$ is positive current.
3.2 Influences of trigger voltage on emission current and collecting charge

The relations between $Q_e$, $i_e$ and $U_{tr}$ are shown in Fig. 4. The results show that $Q_e$ and $i_e$ increase with the increase of $U_{tr}$ at the beginning, but when $U_{tr}$ is larger than 10 kV, $Q_e$ and $i_e$ change little.

From Fig. 4(a) and (b), it is demonstrated that $Q_e$ and $i_e$ with negative trigger pulse applied are larger than that with positive trigger. The reason is that the trigger current increases with the increase of $U_{tr}$. The increment of $i_{tr}$ means that the surface flashover current of the trigger device increases. Thus, more initial plasma is emitted into the vacuum gap. When more initial plasma is emitted into the vacuum gap of TVS, the trigger delay and jitter can be shortened, which agrees with Green’s investigation [10].

![Fig. 4](image)

(a) Collecting charge, (b) Emission current

Fig. 4 Emission charge and emission current of the initial plasma

From Fig. 4, it can also be seen that $Q_e$ and $i_e$ with negative trigger pulse applied are larger than that with positive trigger. The reason is that electrons are easily emitted from the trigger electrode when the trigger electrode is at negative potential. More electrons can be emitted and more effective secondary collision occurs. Thus, more initial plasma can be emitted into the vacuum gap.

3.3 Influences of bias voltage on emission current and collecting charge

The influence of $U_{Bias}$ on $Q_e$ and $i_e$ under the condition of $D_{gap}$ of 15 mm is shown in Fig. 5.

![Fig. 5](image)

(a) Positive bias voltage, (b) Negative bias voltage

Fig. 5 The collecting charge vs the bias voltage

When the TVS operates in the state of mode A$^+$ (positive $U_{Bias}$ and positive $U_{tr}$ are applied), positive electric field is set up, and the initial plasma from the trigger device is emitted, but the initial emission electrons are divided into two parts: one part of the initial electrons are attracted to the collecting electrode and the other part of the initial electrons are neutralized by the positive trigger electrode. When the TVS operates in the state of mode A$^-$ (positive $U_{Bias}$ and negative $U_{tr}$ are applied), almost all the initial electrons are attracted to the collecting electrode. So, $Q_e$ and $i_e$ with TVS operating in mode A$^+$ are larger than that in mode A$^-$. When the TVS operates in the state of mode B$^+$ (negative $U_{Bias}$ and positive $U_{tr}$ are applied), negative electric field is set up, the initial plasma from the trigger device is emitted, and almost all the initial ions of the initial plasma are attracted to the collecting electrode. When the TVS operates in the state of mode B$^-$ (negative $U_{Bias}$ and positive $U_{tr}$ are applied), the initial emission ions are divided into two parts: most of the initial ions are attracted to the collecting electrode and the other part are neutralized by the negative trigger electrode. So, $Q_e$ and $i_e$ with TVS operating in the state of mode B$^+$ is larger than that in mode B$^-$. Because of the larger mass of ions and low running velocity, these two situations show no obvious difference.
3.4 Influences of vacuum gap distance on emission current and collecting charge

$D_{\text{gap}}$ has significant influence on $Q_{e}$, and the relations between $Q_{e}$ and $D_{\text{gap}}$, $U_{\text{Bias}}$ (with same $U_{\text{tr}}$) are shown in Fig. 6.

From Fig. 6(a) and (b), it can be seen that $Q_{e}$ decreases with the increase of $D_{\text{gap}}$, and then $Q_{e}$ enters into a stable stage when $D_{\text{gap}}$ is larger than 13 mm. When $D_{\text{gap}}$ is less than 5 mm, $Q_{e}$ can also enter into another stable stage. The results can be explained as follows:

a. When $D_{\text{gap}}$ increases, only part of the emission electrons or ions have sufficiently high energy to reach the collecting electrode, so $Q_{\text{gap}}$ decreases with the increase of $D_{\text{gap}}$.

b. When $U_{\text{Bias}}$ increases, the electric field between two main electrodes increases, more emission electrons or ions can be attracted to the collecting electrode, so $Q_{e}$ and $i_{e}$ increase with the increase of $U_{\text{Bias}}$.

![Graphs showing the relation between emission charge and gap distance](a) Positive bias voltage, (b) Negative bias voltage

**Fig.6** The relation between emission charge and gap distance

3.5 Emission ratio of trigger device

The initial plasma is produced by the surface flashover trigger device, but not all the initial plasma is collected by the charge collector. In this paper, we define the ratio of $Q_{e}$ to the all emission charges $Q_{tr}$ as the emission efficiency $\eta$. The relation between $\eta$ and many influencing factors, including $U_{\text{tr}}$ and $U_{\text{Bias}}$ ($D_{\text{gap}}=15$ mm) is shown in Fig. 7.

![Graphs showing the relation between $\eta$ and $U_{\text{tr}}$ or $U_{\text{Bias}}$](a) $\eta$ vs $U_{\text{tr}}$, (b) $\eta$ vs $U_{\text{Bias}}$

**Fig.7** The relation between $\eta$ and $U_{\text{tr}}$ or $U_{\text{Bias}}$

4 Conclusion

Based on the characteristics of the emission current of TVS with a surface flashover device, an RC charge collector is designed. The collecting charge $Q_{e}$ of the initial plasma is obviously affected by the trigger voltage $U_{\text{tr}}$ and the bias voltage $U_{\text{Bias}}$ and the vacuum gap distance $D_{\text{gap}}$. The experimental results show that the collecting charge $Q_{e}$ of the initial plasma increases linearly at the beginning with the increase of the trigger voltage $U_{\text{tr}}$ and the bias voltage $U_{\text{Bias}}$. The collecting charge $Q_{e}$ enters into a stable stage when the trigger voltage $U_{\text{tr}}$ reaches a certain value and increases continuously. The emission efficiency $\eta$ deceases with the increase of the trigger voltage $U_{\text{tr}}$ under the condition of zero $U_{\text{Bias}}$. It is also found that the emission efficiency decreases with the increase of $U_{\text{Bias}}$. From Fig. 7, it is shown that $\eta$ is less than 10%, and $\eta$ decreases with the increase of $U_{\text{tr}}$ (as shown in Fig. 7(a) and $U_{\text{Bias}}$ (as shown in Fig. 7(b)). It is also found that $\eta$ with negative trigger pulse applied is larger than that with positive trigger. These experimental results can be explained as follows:

a. With the increase of $U_{\text{tr}}$, the resistance of the surface flashover channel decreases greatly, which leads to larger consumption in the trigger circuit itself, and the collecting charge $Q_{e}$, which can spread into the vacuum gap and arrive at the collecting electrode decreases accordingly.

b. With the increase of $U_{\text{Bias}}$, the electric field is enhanced and more plasma charges are attracted by the collecting electrode, so $Q_{e}$ increases.
\( \eta \) increases with the increase of the bias voltage \( U_{\text{Bias}} \). When the gap distance \( D_{\text{gap}} \) is 15 mm, the bias voltage \( U_{\text{Bias}} \) is 160 V and the trigger voltage \( U_{\text{tr}} \) is 2.6 kV, the emission efficiency \( \eta \) reaches 6%.

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