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ЭЛЕКТРОНИКА И РАДИОТЕХНИКА

TIME DELAY OF A FIELD-BREAKDOWN TRIGGERED VACUUM SWITCH WITH FLAT ELECTRODES

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Triggered vacuum switch (TVS) is one of the important switch apparatuses in the field of pulsed power system. The field-breakdown will bring long lifetime of TVS under rated working conditions. However, the load of trigger will be heavy, leading to the large time delay and jitter time. In this paper, a field-breakdown TVS sample with flat electrodes was fabricated and its time delay was tested. Initial plasmas play an important role in the turning-on process of TVS, so the time delay from the control signal to the switching-on of TVS is discussed in the trigger system time, the motion time and the collapse time, where the motion time and the collapse time are the needed time for the generation and development of the initial plasmas. Test results show that, under positive working mode, the trigger system time is about 34–36 μs with positive trigger pulse, while 39–41 μs with negative trigger pulse, which prove that the polarities of trigger pulse have nothing to do with the trigger system time almost, and the long trigger system time is mainly owing to the limited performances of trigger pulse transformer. The motion time is about 50 ns and almost stable, due to the definite trigger gap. The collapse time is about 100–300 ns, which is decreased with the rise up of main gap voltage, exponentially. In negative working mode, both of the motion time and collapse time are about 10 μs, due to the ions of initial plasmas becoming the main moving particles in the main gap, no longer the electrons as positive working mode.

1. INTRODUCTION

Triggered vacuum switch (TVS), also named triggered vacuum gap, is developed based on the technology of vacuum gap and triggered spark gap. It has been applied widely in the field of high pulsed power technology, due to the merits of compact structure, convenient operation, high-reliability, high current carrying and high charge transferring capability, etc. [1–5].

Although the pseudospark switches and high pressure spark discharges have achieved tens of kilovolts hold-off voltage, transfer kilo-ampere current, and have much shorter time delay and jitter time (tens of nanoseconds or less), the switch structures and their trigger systems are so large and complicated, unsuitable in the compact and limited spaces. However, TVS is adopted, such as the field of electromagnetic launch (EML) [6, 7].

As control demand, the time delay and trigger reliability of TVS become more and more important. Lafferty found that time delay of TVS was about 1–2 μs [1]. Kamakshaiah and Rau concluded some methods to reduce the time delay [8]. Warren et al. considered that the time delay consisted of two parts, i.e., wait time and collapse time, which was accordant with the researches of Green et al., although the definition was not the same [2, 9]. Kil-soo and Tae-Ho proposed a high power vacuum rotary arc gap closing switch with time delay of 10.8 μs and jitter time of 2–3 μs [10]. Dougal and Morris presented a type of magnetically delayed vacuum switch, whose time delay varied from tens to hundreds of nanoseconds [11]. Liao et al. proposed a trigger pulse, which could restrict the jitter time within 2μs and its time delay was 16 μs [12]. Ling et al. and Dong et al. presented the delay results between hundreds and thousands of nanoseconds [13, 14].

These reports show that the time delay of TVS is quite different due to the different TVS samples, and they all focused on the surface-breakdown TVS almost, whose trigger lifetime is limited. Its short time delay is mainly owing to the easy breakdown of surface in the trigger gap. However, as the simplest structure and long lifetime, the report of time delay of field-breakdown TVS with flat electrodes is scarce, especially under the negative working mode.

Although the transfered charge per shot of the flat electrodes is less than that of the other electrode shapes, it is cheap, simple and the field-breakdown can extend its working lifetime. Because there is no filling material between the trigger pin and the main electrode for the field-breakdown TVS, the pollution of metal vapor as in surface-breakdown switches can be avoided, which is benefit to the long lifetime.

In this paper, such a kind of TVS was fabricated, and TiH_2 was coated on the surrounding surfaces of

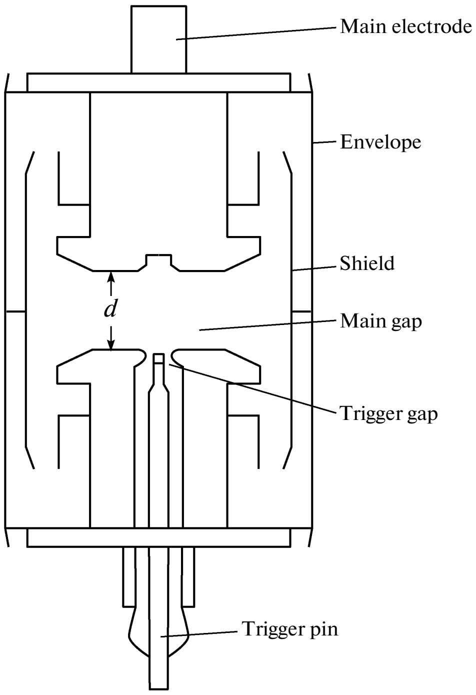

Fig. 1. Structure of field-breakdown TVS with flat electrodes.

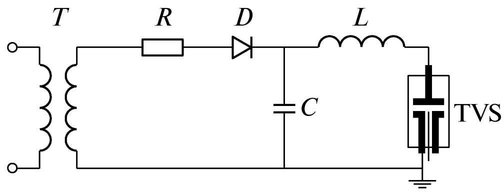

Fig. 2. Time delay experiment set up.

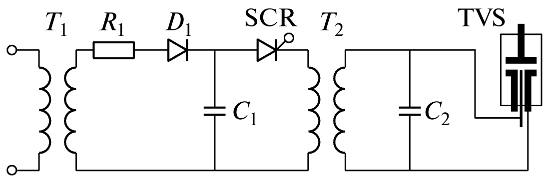

Fig. 3. TVS trigger circuit.

trigger gap, which can improve the trigger reliability and reduce the trigger pulse peak value needed in the field-breakdown.

2. TVS STRUCTURE AND TIME DELAY EXPEREMENT SET UP

The detailed structure of a field-breakdown TVS is shown in Fig. 1. It is mainly made up of an insulated envelope (ceramic or glass materials), a metal shield, a pair of main electrodes with main gap of d, and a trigger pin. The envelope keeps the inner vacuum degree at 1.33×10^{-4} Pa commonly, and isolates the main electrodes. Metal shield can adjust the distribution of electric field and protects the inner surface of the envelope, keeping metal vapor away, which will reduce its dielectric strength.

Main electrodes transmit the heavy current, their structure design is important to the charge transfer ability of TVS. The trigger pin is connected to the trigger pulse, generating initial plasmas. There is no filling material in the trigger gap and the initial plasmas are generated due to the high voltage trigger pulse, so it is called the field-breakdown TVS. Some parameters of the TVS sample: diameter of main electrodes 50 mm; distance of main gap 20 mm; diameter of trigger hole 6 mm; diameter of trigger pin 5 mm; distance of trigger gap 0.5 mm; work voltage 0.1–40 kV; current peak 60 kA; repetition rate 0.2 Hz; recover rate 200 A/μs.

The turning-on process of TVS includes two primary parts, i.e., trigger and main gap switching-on [1, 2]. Trigger process supplies initial plasmas for the main gap. In field-breakdown TVS, initial plasmas come from the point discharge of trigger pin and its needed time is called the motion time of t_1.

With the help of electric field of main gap, the charged particles enter the main gap, and cause glow discharge. Along with the rapid increase of current density, glow discharge is developed to arc discharge. Metal arc is created and the TVS switches on at last. This process is continual and its needed time is called the collapse time of t_2. When the arc current decreases to zero, the TVS will be switched-off, automatically.

The time delay experiment was set up as Fig. 2, where T is the step up transformer, R is the current-limiting resistance, D is the high voltage diode, C is the main capacitor, and L is damping inductance. TVS works in the positive mode, i.e., the main electrode without trigger pin is connected to the positive terminal of capacitor and the other main electrode is earthed. If the TVS is reversed, that is negative working mode.

The positive trigger pulse is formed by the trigger circuit shown in Fig. 3, where SCR is the silicon controlled rectifier, C_1 is the capacitor of pulse discharge, and C_2 is the capacitor of energy storage which can enlarge the trigger current. When the output terminals of T_2 to the trigger pin are reversed, the negative trigger pulse also can be obtained. The control signal is a 5 V step signal and the fiber-optic is used to isolate the control signal from the high voltage of main loop. The high voltage probe of P6015A and digital storage oscilloscope of TDS 2022B are adopted in the experiment.

3. RESULTS OF TIME DELAY

3.1. The trigger system time

The trigger system time means the time duration between the output of trigger signal and the peak value of trigger pulse. It includes two parts, i.e., the time de-

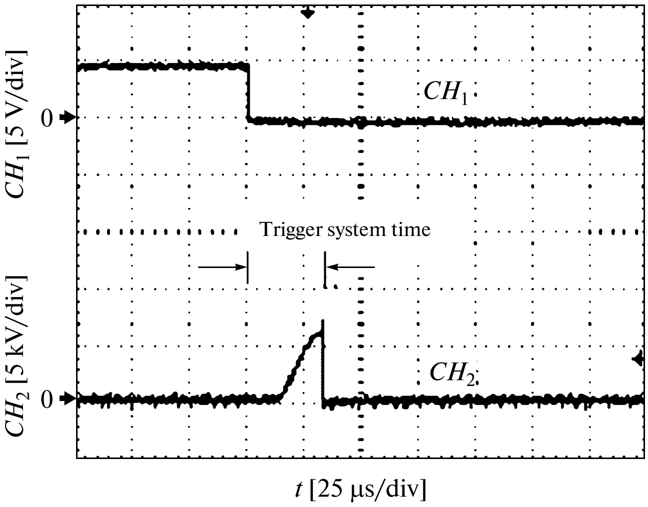

Fig. 4. The trigger system time when positive trigger pulse.

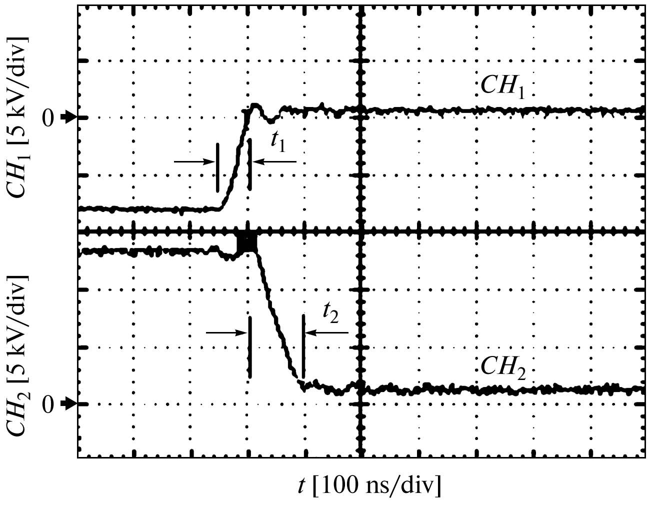

Fig. 5. Motion time of CH1 and collapse time of CH2 under positive working mode.

lay of trigger circuit (action time of fiber-optic, diode, SCR, etc.) and the rise time of the trigger pulse.

When TVS works in the positive mode, a positive trigger pulse is shown in Fig. 4, where CH_1 is the 5 V control signal and CH_2 is a 7 kV high voltage trigger pulse. It is shown that the trigger system time is about 35 μs, which is made up of the time delay of trigger circuit, about 15 μs and invariable, and the rise time of trigger pulse, about 25 μs and variable, due to the peak value of field breakdown. A statistical result of the trigger system time is shown as Table 1, which means the trigger system time fasten on about 35 μs, with jitter time of ±1 μs. On the other hand, the trigger system time when negative trigger pulse is about 39–41 μs, shown in Table 2, with jitter time of ±1 μs, too.

Under the same working condition, the comparison of Table 1 and Table 2 proves that the trigger system time has no strict relationship with the polarities of trigger pulse. The difference of time delay in the Tables is due to the higher trigger pulse peak value needed for the negative trigger pulse, about 10 kV.

Test results also show that the time delay of trigger circuit is always 15 μs, which is oblivious in many papers [1, 10–14]. The rise time of trigger pulse, whether positive or negative, is variable and limited in the jitter time of ±1 μs. However, the long rise time of trigger pulse is due the limited performances of trigger pulse transformer, where the ignition coil is adopted. If the trigger pulse transformer is designed specially, the rise time of trigger pulse can be reduced sharply. So the trigger system time and its jitter time can be improved evidently.

3.2. The motion time of t_1

During the motion time of t_1, the initial plasmas are generated, which spends the time from the peak value of trigger pulse to the breakdown beginning of the main gap voltage across the TVS. It is the first stage of the process of switching-on TVS. Under positive working mode, its typical waveform is shown as CH_1 in Fig. 5. It should be explained that the step up wave of CH_1 is a negative trigger pulse in fact and the peak value of trigger pulse is under the base line in CH_1. So, the peak value of trigger pulse is –8 kV and it spends about 50 ns from the –8 kV to the zero, which is also the beginning of collapse time of t_2 in CH_2.

Test results show that, when the TVS can be triggered stably, it is no use to increase the trigger voltage for the reduction of t_1. The trigger voltage is due to the field breakdown at the top of trigger gap. Otherwise, it will be discharge at the bottom of trigger gap if increase the trigger voltage to an ultra high value, leading to the switching failure because the initial plasmas are restricted in the long and narrow bottom of the trigger gap. So the t_1 is almost invariable and the average velocity of initial plasmas can be estimated as 10 mm/μs.

If the working mode is negative, the t_1 will be much longer. The trigger process is shown as Fig. 6, where CH_1 is the trigger pulse and CH_2 is the collapse of negative main voltage of –2 kV. CH_1 tells that the trigger gap is breakdown at 7 kV and from the peak value to zero it spends about 10 μs, i.e., $t_1 = 10$ μs. It is obvious that the motion time of negative mode is much longer than that of positive mode. And the average velocity of initial plasmas here is about 0.05 mm/μs.

Table 1. The trigger system time when positive trigger pulse

Time delay, μs	34	34.5	35	35.5	36
Repeated tests	6	12	19	11	5

Table 2. The trigger system time when negative trigger pulse

Time delay, μs	39	39.5	40	40.5	41
Repeated tests	4	16	20	15	5

Table 3. Collapse time t_2 of different main gap voltage with positive working mode

Voltage, kV	1.8	2.3	3.0	4.4	6.0
t_2, ns	280	240	200	140	100

3.3. The collapse time of t_2

The second stage of turning-on of TVS is the time required for the main gap voltage across the TVS to fall to the minimum value. This time delay is known as the collapse time of t_2, which is shown as CH_2 in Fig. 5 and Fig. 6. It records the initial stage of the development of main gap current and the current begins to rise just at the minimum value of the main gap voltage.

The t_2 in Fig. 5 is about 100 ns under positive working mode. Statistical tests show, that the t_2 has good relationship with the main gap voltage and it is decreased in negative exponent with the increase of main gap voltage, i.e., $t_2 = KU^{-0.9} = 5 \times 10^{-4}\, U^{-0.9}$, where K is due to the structure of TVS and trigger pulse [5]. The detailed data are shown in Table 3.

The distance of main gap for the initial plasmas to cross is 20 mm, so the average velocity of initial plasmas in the main gap can been calculated, shown as Fig. 7. It is in a range of 70–200 mm/μs due to the different main gap voltage of 1.8–6 kV.

We can also get the t_2 of negative working mode from the CH_2 of Fig. 6. From the peak value of –2 kV to the zero, it spends about 10 μs and the average velocity is only 2 mm/μs. So it is obvious that the collapse time of negative working mode is much longer than that of positive working mode. That is why most of papers just report the time delay of positive working mode.

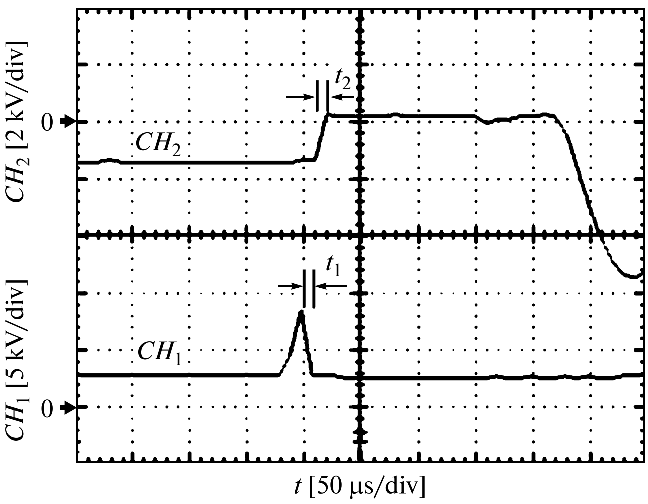

Fig. 6. Motion time of CH_1 and collapse time of CH_2 under negative working mode.

4. DISCUSSIONS

Both of the positive pulse and negative pulse are useful to trigger the TVS and the trigger system time under different pulse polarities are almost the same. For the same TVS sample, the small trigger gap is stable, so the breakdown voltage of trigger gap is almost the same and has nothing to do with the working polarities.

However, the motion time and the collapse time under different working modes are influenced by the different developments of initial plasmas, shown as Fig. 8, where the left one is the positive working mode, while the right one is the negative working mode.

Many researches focused on the characteristics of positive working mode and found that the time delay here is the smallest [9, 14]. That is because the initial plasmas are generated near the main cathode. The surface of cathode is covered by the positive ions of initial plasmas, while the electrons are dispelled to the main gap by the positive electric field. So the ion sheath is generated near the main cathode and it is useful to bring cathode spots. Meanwhile, the electrons of high density cause breakdown of main gap in a short time due to the high velocities of electrons (70–200 mm/μs).

If the working mode is negative, the time delay will be much longer. That's because the cathode spots generated by initial plasmas are located on the surface of anode and they will not participate in the discharge of main gap. The new cathode spots should be set up again on the main cathode surface by the vacuum breakdown.

Thus, its delay is made up of the needed time of positive ions crossing the main gap, the time of generating ion sheath layer and the time of setting up new cathode spots. Because the velocities of positive ions

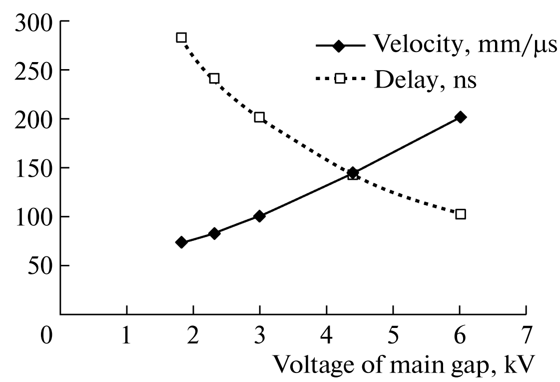

Fig. 7. Velocities of initial plasmas during collapse time.

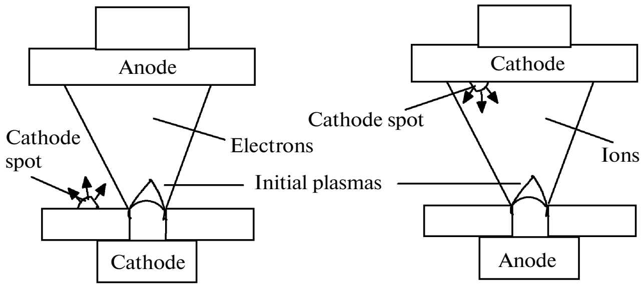

Fig. 8. Developments of initial plasmas under polarities

are much lower than that of electrons, the needed time for ions crossing the same main gap is much longer.

The crossing time is also influenced by the voltage of main gap. However, the influence is much less than the influence of same voltage of main gap under positive working mode.

So the motion time and collapse time under positive working mode can be ignored, if the trigger system time is long. And in order to get more precise control, it is needed to reduce the time delay of trigger circuit and improve the performance of trigger pulse transformer.

5. CONCLUSIONS

As a simple, compact and convenient controlled vacuum switch with long lifetime, the time delay of field-breakdown TVS with flat electrodes is studied. From the control signal to the voltage collapse of main gap, the time delay is divided into three parts, i.e., the trigger system time, the motion time and the collapse time.

Under positive working mode, the trigger system time is about 34–36 μs with positive trigger pulse, while 39–41 μs with negative trigger pulse, which prove that the polarities of trigger pulse have nothing to do with the trigger system time almost, and the long trigger system time is mainly owing to the limited performances of trigger pulse transformer. The motion time is about 50 ns and almost stable, due to the confirmed trigger gap. The collapse time is 100–300 ns, which is decreased with the rise up of main gap voltage, exponentially. In negative working mode, both of the motion time and collapse time are about 10 μs, due to the ions of initial plasmas are become the main moving particles in the main gap, no longer the electrons as positive working mode.

The trigger system time is much longer than the motion time and collapse time in the positive working mode, so the later two time delay can be ignored. However, both the motion time and collapse time are long in the negative working mode, so it is necessary to consider the three parts of time delay completely in the field of control demand.

There are only hundreds of nanoseconds in positive working mode and 20 μs in negative mode, if considering the time delay of TVS itself. Further work should be done to improve the trigger circuit and trigger pulse transformer.

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