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# Experimental investigations on triggering characteristic of TVS under DC and AC load

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**Abstract** Triggered vacuum switches (TVSs) have fast growing applications in the field of power system and pulse power. The relation between triggering parameters of triggering system, such as triggering voltage and triggering power, between the triggering time delay and its scatter of TVS had been obtained through series of experiments. The result can be adopted as the steering for high-power controller design and application of TVS. A steepened high-voltage triggering pulse is introduced in the main high-voltage generating circuit. As a result, the triggering time delay and its scatter can be decreased remarkably. Synchronous switch technology is imported to control the triggering phase at the crest of applied voltage on TVS. The Triggering characteristic of TVS under alternating current (AC) and direct current (DC) load has been investigated emphatically. Given the identical triggering parameter of triggering system, DC condition is prior to AC on the triggering probability and stability markedly. Such conclusion can be drawn, for AC condition, TVS would require much for the triggering system.

**Keywords** triggering characteristic, delay effects, direct current (DC) and alternating current (AC) load, triggered vacuum switch (TVS)

## 1 Introduction

Triggered vacuum switches (TVSs), which are also named as triggered vacuum gaps (TVGs), have fast growing applications in the field of power system and pulse power. A closing switch is the necessary controlling device of power supply of an electromagnetic launcher (EML) system and synthetic making test of high-voltage circuit

breakers for short-circuit current introduce, which should have the ability to quickly connect the circuit and precisely control the moment of connection. It also should isolate the high-power storage and then close the circuit at a set time.

TVS gets fast development in recent years, which attributes to its many advantages. High insulation level of vacuum medium and the fast diffusion of post-arc plasma make TVS have the ability to turn on and off high voltage and high current with higher frequency. Electrodes and triggered pin are sealed in the vacuum chamber and free from outside disturbance, which ensures the reliability of TVS. Arcs running in vacuum have very low arc voltage that leads to much lower energy input to the arc and thus result in a lower electrode erosion rate.

In our research, a series of experiments have been carried out on the sample TVS with direct current (DC) and alternating current (AC) load between main electrodes. The triggering and delay characteristics of TVS were emphatically expounded in each case. An elaborated circuit for controlling the TVS is proposed herein. The triggering energy of the controller can be adjusted conveniently. By means of changing the triggering energy, experimental results show that the delay and jitter times decrease with increasing triggering energy. The delay and jitter times decreases magnificently with the increasing voltage in the main gap. By increasing the main-gap voltage, the triggering probability increases. With the same DC and AC amplitude, the DC case has better performance in triggering and delay characteristics than AC one. With enough triggering energy, it is possible to fire the TVS in both load condition.

## 2 Experimental circuit setup

### 2.1 Sample TVS

Typical structure and practical photo of TVS are shown in Fig. 1. The electrode material is copper-chromium alloy (50 wt%). The triggered pin is made out of molybdenum and with coat of hydride titanium.

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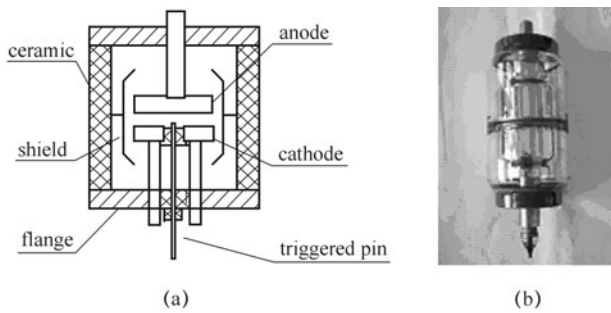


Fig. 1 (a) Typical structure of TVS; (b) practical photo of TVS

Under normal conditions, TVS is at OFF state, which implies an insulating gap between the main electrodes. When TVS is triggered, a high voltage pulse is applied to a triggered pin that is attached to one of the main electrodes. This pulse causes dielectric breakdown between the main electrodes and subsequently forms arc plasma there. The arc plasma propagates quickly from one main electrode to another main electrode as a result of the so-called vacuum diffusion in the applied electric field and finally establishes the arc plasma between the two main electrodes. At this stage, the TVS is regarded to be at ON state. For an alternating current, arc will be extinguished at a current zero, and a TVS can thus turn off automatically [1].

## 2.2 Experimental circuit

In order to investigate the triggering characteristics of TVS, two types of the test circuit setup were introduced in our research, which were named as TYPE1 and TYPE2. In circuit TYPE1, DC voltage load was applied between TVS's anode and cathode. Moreover, in circuit TYPE2, the load voltage applied between TVS's anode and cathode is AC type [2].

As shown in Fig. 2(a),  $LC$  constitutes the resonant circuit. Moreover, pulsed capacitor is used as the energy stored component, whose capacitance is  $8.7 \mu\text{F}$ . In Fig. 2,  $L$  is an inductance that is about  $6.2 \mu\text{H}$ ;  $T_1$ ,  $T_2$  are

transformers, and the parameters are  $220 \text{ V}/110 \text{ V}$  and  $110 \text{ V}/10 \text{ kV}$ . The polarity of the main gap of TVS is positive, and the triggered pin is located in the cathode. High-voltage dividers and oscillograph are used to measure the triggering pulse voltage and the voltage between the anode and cathode of TVS simultaneously.

For the sake of assessing the triggering characteristic of TVS under AC load, as shown in Fig. 2(b), a refined test circuit has been adopted, in which phase detect unit (PDU) is introduced. Based on the synchronous closing technology, the phase of applied voltage between the main electrodes of TVS is detected in real time, thus, it can control the time of triggering command sent of TVS at the crest of applied voltage.

## 3 Triggering and control system of TVS

### 3.1 Triggering circuit setup for TVS

Triggering circuit for TVS used in our research is provided in Fig. 3. The upper part of Fig. 3 is the typical triggering circuit set used in other research [3]. According to the function of the electrical arrangement, the upper part triggering circuit can be marked off two sections. One section is called high-power pulse generating circuit, which includes the components as current limiting resistance  $R_{01}$ , charge diode  $D_{01}$ , energy storage capacitance  $C_{01}$ , silicon controlled rectifier (SCR), and high-power pulse transformer  $T$ . The other section of the upper part is called low voltage and current sustaining circuit, which includes current sustaining  $D_{c1}$ ,  $R_{c1}$ ,  $C_{c1}$ ,  $R_{x1}$ , and  $D_{x1}$ .  $R_{c1}$  and  $C_{c1}$  constitute the low voltage and current sustaining branch. The function of  $R_{x1}$  and  $D_{x1}$  is to charge  $C_{c1}$ .

The working process of the upper part in Fig. 3 is discussed as follows. When the triggering command of TVS is sent, SCR will start action and induce capacitance  $C_{01}$  to discharge. Therefore, an induced high-power pulse will ignite the triggering gap of TVS. If the triggering pulse is strong enough, the low voltage and current sustaining

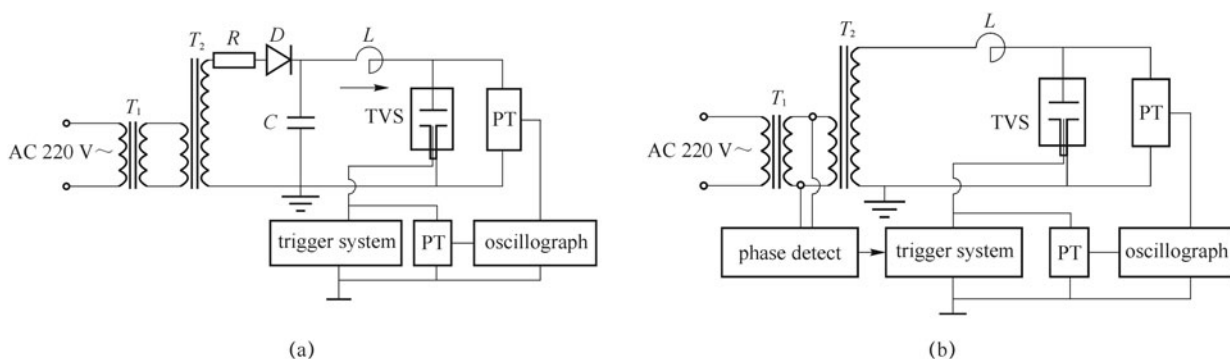


Fig. 2 Experiment circuit setup for TYPE1 DC load and TYPE2 AC load applied between TVS's main electrodes. (a) Test circuit setup TYPE1; (b) test circuit setup TYPE2

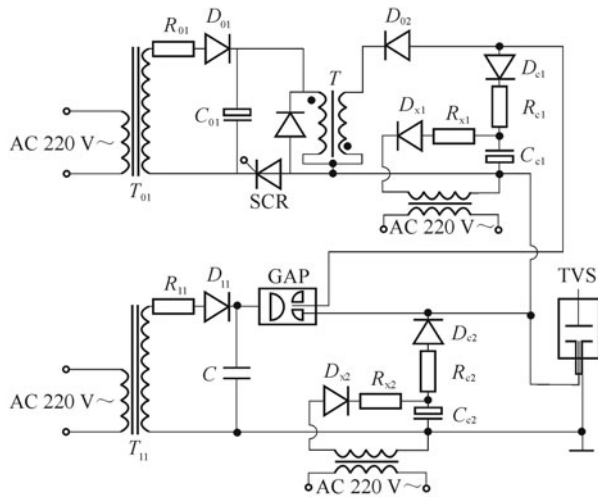


Fig. 3 Triggering circuit setup of TVS

circuit will work.  $C_{c1}$  discharges through its conducting channel, and a high-current pulse will be generated.

From the above illumination, we know the upper circuit in Fig. 3 can trigger TVS independently. In order to decrease the triggering time delay and its scatter and improve the triggering characteristic of TVS further, a steepened high-voltage triggering pulse generating circuit is introduced as the lower part of Fig. 3. The working principle of this segment is similar with the upper one, which adds a spark gap GAP. When GAP is fired, the charged high-power capacitor  $C$  could discharge directly and could result to a rapid breakdown between the main electrodes of TVS. In this way, a high reliability of trigger will be achieved.

Typical pulse waveforms generated by the upper and lower part, as is shown in Fig. 3, are given in Fig. 4. The oscillogram shown in Fig. 4(a) is no-load triggering pulse generated by the upper and lower part of triggering circuit, respectively, in Fig. 3. When these pulses between the

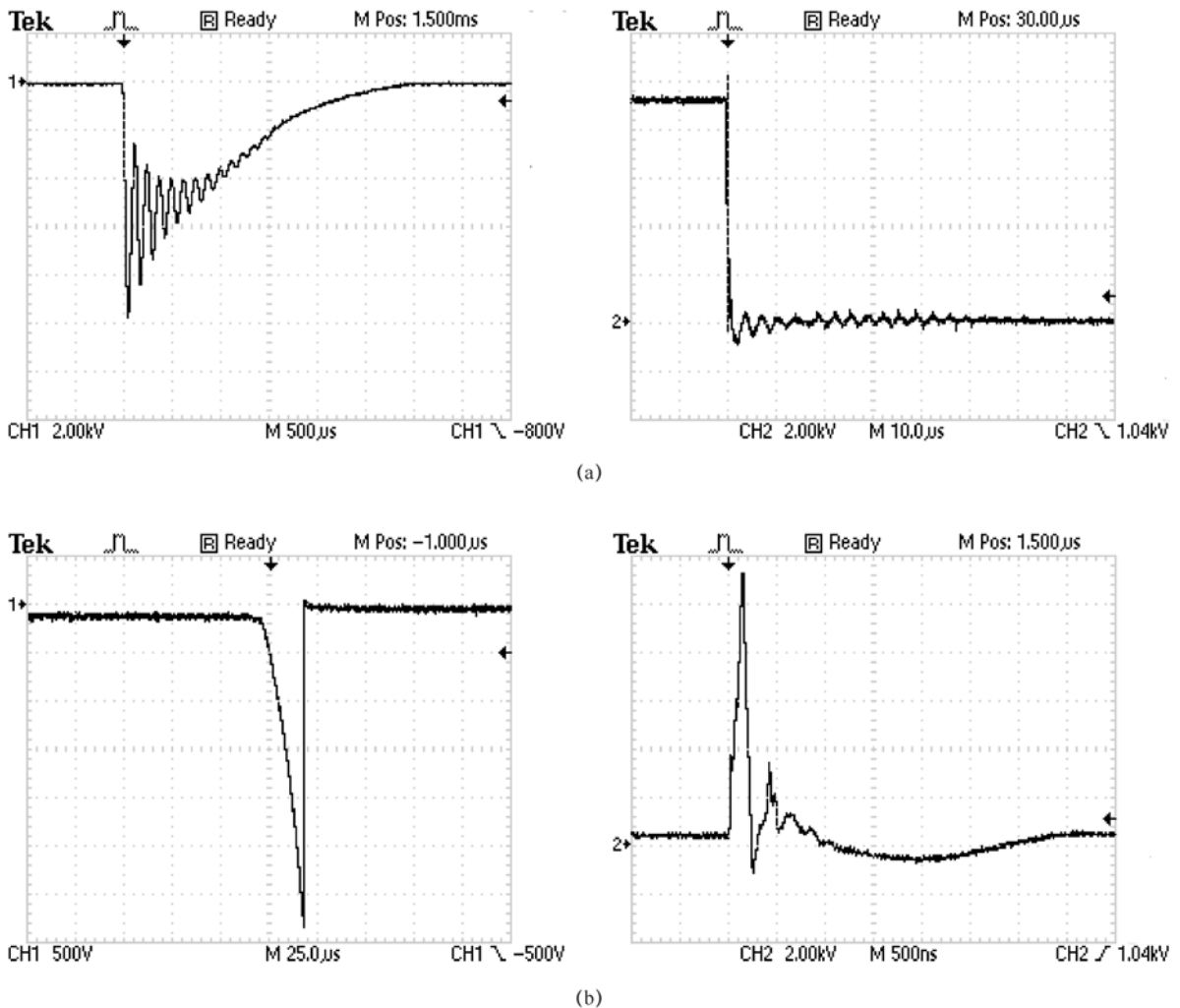


Fig. 4 Triggering pulse generated by upper and lower part in Fig. 3 triggering circuit setup. (a) No-load triggering pulse generated; (b) pulse between cathode and triggered pin of TVS generated

cathode and triggered pin of TVS are applied, the measured waveform are provided in Fig. 4(b) for the upper and lower part. In Fig. 4(b), the current sustaining branch  $D_{c1}$ ,  $R_{c1}$  and  $C_{c1}$  (or  $D_{c2}$ ,  $R_{c2}$  and  $C_{c2}$ ) have functions to produce a dense initial plasma for TVS' triggering period.

### 3.2 Controller of TVS

Digital signal processor TMS320LF2407A is adopted as the CPU of the test controller in our research. The control and data signal transmitted are all by optic-fiber, thus the control accuracy and security can be guaranteed. The photo of the test controller and test field are shown in Fig. 5.

## 4 Triggering time delay characteristic of TVS

Formation and development mechanisms of initial plasma are different for triggering states. For the surface discharge, initial electrons come from the triple-junction of metal, insulator, and vacuum. When an external pulse is applied to the trigger, a high pulse field appears between the trigger and the main electrode. Some electrons emit out from the triple junction and jump along the insulator surface. The secondary electrons form a sustained discharge and initiate the plasma. Some coatings can even make a discharge under some tens of volts on the insulator. Duration from discharge beginning to form a self-sustained discharge  $t_{d1}$  is presented as follows [4]:

$$t_{d1} = \frac{\pi\lambda\gamma_d C_d}{4J^2 U^2} (T_{cd} - T_0)^2, \quad (1)$$

where  $\lambda$ ,  $\gamma_d$ ,  $C_d$ , and  $T_{cd}$  are thermal conductivity, density, specific heat, and critical temperature of insulator (or coating material);  $T_0$  is environment temperature;  $U$  and  $J$  are voltage and current density on the trigger.

After the initial plasma formed, whether it can be developed into a self-sustained discharge depends on some other conditions. When the triggered pin embeds in

cathode (firing on the cathode), the main electrodes discharge time delay can be well approximated by [4,5]

$$t_{d2} = kd \left( 1 + \frac{R}{d} \right) I_f^{-\alpha}, \quad (2)$$

where  $k$  is a factor depending on the trigger assembly design,  $I_f$  is the maximum amplitude of the triggering current,  $d$  is the distance between anode and cathode,  $R$  denotes the distance from the tip of triggered pin to cathode surface, and the factor  $\alpha$  within the range of 0.5–1 depends on the mechanism of plasma scattering into the vacuum gap of TVS.

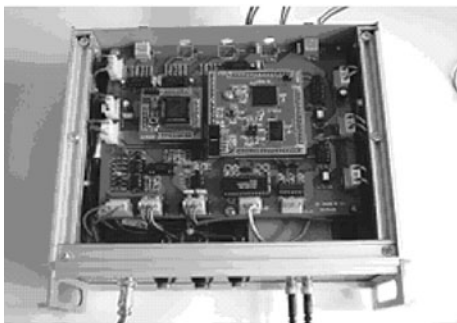
Measured triggering time delay of TVS in our research is 25  $\mu$ s. The time delay to trigger TVS is defined as the elapsed time between the application of the triggering command and the complete voltage collapse to its minimum value across the main gap. It has a little difference with the definition of Warren [6].

The typical result is shown in Fig. 6, where CH1 denotes the triggering command from controller, and CH2 stands for the voltage between the anode and cathode of TVS. The test condition is as follows: the polarity of applied triggering pulse is positive, as the charged voltage in capacitor  $C$  is positive in Fig. 3. The voltage applied between the main electrodes is DC 8 kV. The peak value of triggering pulse is 12 kV, and the charged high-power capacitor  $C$  (in Fig. 3) is composed of two capacitance of 3900 pF/100 kV connected in parallel.

## 5 Result discussion

### 5.1 Triggering characteristic of TVS

A large number of experiments reveal that the improvement in the structure and controller of TVS is an effectual way to decrease the delay and jitter times. By changing the capacity and charged voltage of  $C$  in Fig. 3 and also changing the voltage across the anode and cathode of TVS, the relation between triggering time delay, jitter time, and triggering energy, voltage between main electrodes of TVS



(a)



(b)

Fig. 5 (a) Photo of test controller; (b) photo of test field

can be achieved. Figures 7 and 8 illustrate the relationship of the above mentioned parameters.

Triggering energy provided by the triggering system can be adjusted conveniently. The triggering energy can be calculated through

$$W = \frac{1}{2}C' U^2, \quad (3)$$

where  $C'$  is the capacity of  $C$ ,  $U$  is the charge voltage of  $C$ , and  $W$  is the triggering energy stored in  $C$  (as shown in Fig. 3). Changing  $C'$  and  $U$  can achieve different triggering energy for TVS.

In Fig. 7, the voltage across the main electrodes of TVS is maintained at 7 kV. We can see the triggering time delay and jitter time acutely decrease with the increasing of the triggering energy. Until triggering energy reaches some extent, the delay time and jitter time decrease slowly and trend to a constant value. In Fig. 8, the capacity of  $C$  maintains at 15600 pF (3900 pF×4), and the charge voltage on  $C$  is 15 kV. Therefore, the triggering energy is maintained at about 1.76 J. Figure 8 shows the effect of voltage across the main electrodes on delay time and on jitter time.

It can be seen that the delay time and jitter time decrease magnificently with increasing the voltage across the main electrodes. When TVS is triggered, the initial plasma will be injected into the gap between the anode and cathode, and a plasma sheath can be formed quickly. It is due to the enhancement of the electric field near the electrode surface [7,8]. The sufficiently large electric field causes the explosive formation of cathode spots [9], which generate metal vapor, ions, and electrons to conduct the main discharge current. The larger the voltage across the main electrodes is, the stronger the electric field between the main gaps will be. The electric field has the contribution to the diffuse velocity of the initial plasma in TVS; thus, with the increasing of the voltage across the main electrodes, the conducting time of TVS sharply decreases, as is shown in Fig. 8.

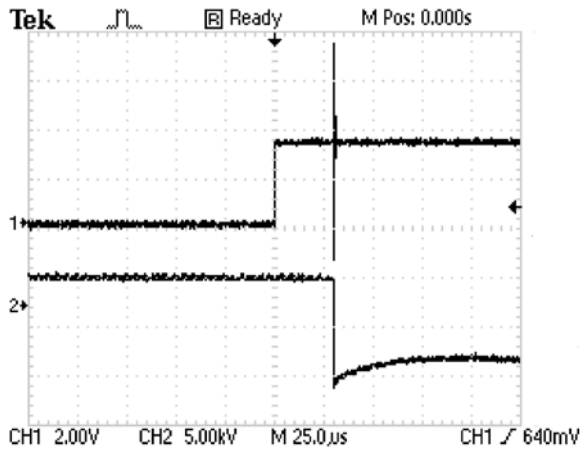


Fig. 6 Oscillogram of triggering time delay for TVS

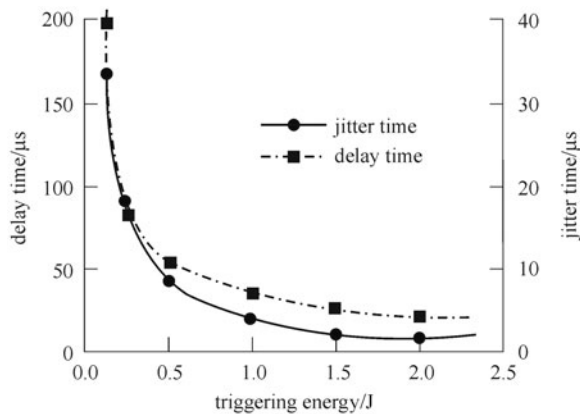


Fig. 7 Effect of triggering energy on delay time and jitter time

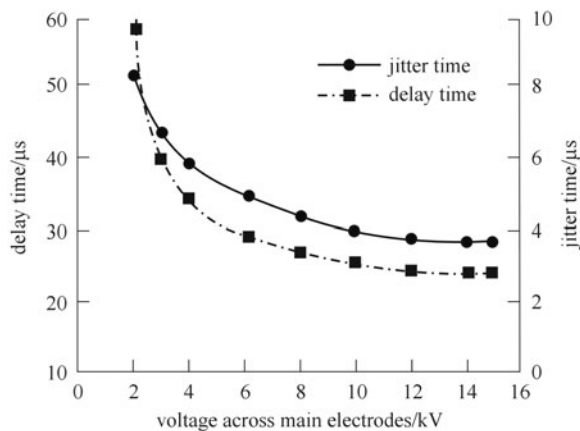


Fig. 8 Effect of voltage across main electrodes of TVS on delay time and jitter time

### 5.2 Triggering under AC condition

Synchronous switch technology is imported to control the triggering phase at the crest of applied voltage on TVS. Figure 9 shows the triggering phase control of TVS under

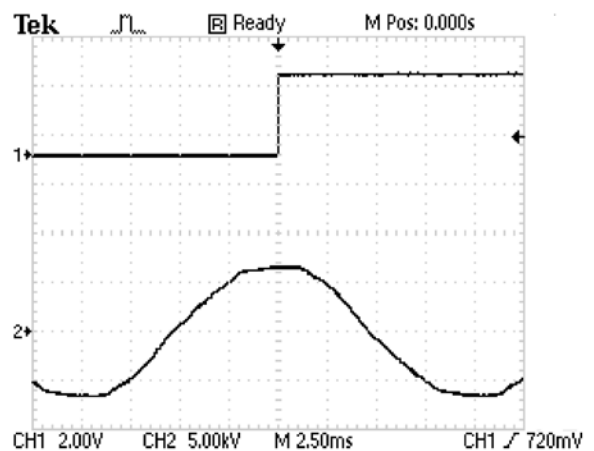


Fig. 9 Phase control of TVS triggering under AC load

AC load. As is shown in Fig. 9, CH1 stands for the triggering command from CPU, and CH2 denotes the AC voltage load between the main electrodes of TVS. The controller detects the phase of the voltage across the main electrodes in real time. When the zero of the reference voltage is detected, after a set of time delay, CPU sends the triggering command and control TVS to act at an expectant phase.

Figure 10 presents the test result of TVS triggered at the crest of applied voltage, where CH1 stands for the triggering command, and CH2 stands for the applied AC voltage load. In Fig. 10(a), the peak value of applied AC voltage is 5 kV, and in Fig. 10(b), the peak value of applied AC voltage is 8 kV. As we can see in Fig. 10, the triggering characteristics are strongly affected by the voltage between the main electrodes under AC load. The triggering extent is much larger in Fig. 10(b) than in Fig. 10(a).

In order to compare the triggering characteristic of TVS under AC condition with DC one, the parameters of triggering system and controller are maintained identical, and the peak value of applied voltage in AC condition is set equal to DC condition. The sample numbers are 60002, 60020, and 60029. Tables 1 and 2 are the results with the voltage across the main electrodes of TVS at 4 kV and 7 kV, respectively, where No.1/No.2 stands for succeed shot times/total shot times.

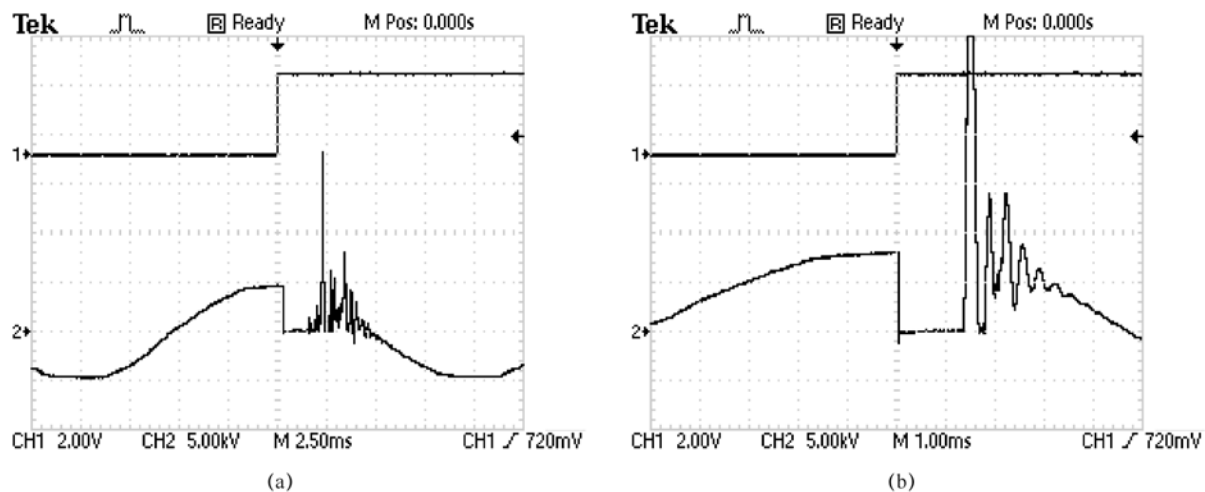
From the data in Tables 1 and 2, we can see that the triggering characteristic of TVS in DC condition is prior to AC one on the triggering probability and stability

markedly. Such the conclusion can be drawn, for AC condition, TVS would require much for the triggering system.

## 6 Conclusion

Delay characteristics of TVSs were experimentally verified in the cathode mode (firing on the cathode) of operation. A refined triggering and control system for TVS is proposed herein. The triggering power of the controller can be adjusted conveniently by changing the capacity of power storage capacitor and the charge voltage on it. With the increasing of the triggering energy, the delay and jitter times of TVS drastically decrease. The experimental results show that the delay and jitter times effected magnificently by the applied voltage across the main electrodes. By increasing the applied voltage, the triggering probability increases accordingly. The improvement in the structure and controller of TVS is an effectively way to decrease the delay time and jitter time.

The triggering characteristic of TVS under AC and DC load has been investigated emphatically. Given the identical triggering parameter of triggering system, DC condition is prior to AC one on the triggering probability and stability markedly. Such the conclusion can be drawn, for AC condition, TVS would require much for the triggering system.



**Fig. 10** Results for TVS triggered under AC load. (a) Peak value of applied voltage is AC 5 kV; (b) peak value of applied voltage is AC 8 kV

**Table 1** Triggering pulse crest at 10 kV under DC and AC load

sample number	main gap voltage: 4 kV		main gap voltage: 7 kV	
	DC	AC	DC	AC
60002	7/10	0/10	9/10	1/10
60020	9/10	0/10	10/10	3/10
60029	8/10	0/10	9/10	1/10

**Table 2** Triggering pulse crest at 15 kV under DC and AC load

sample number	main gap voltage: 4 kV		main gap voltage: 7 kV	
	DC	AC	DC	AC
60002	8/10	0/10	10/10	2/10
60020	9/10	1/10	10/10	5/10
60029	9/10	0/10	10/10	3/10

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