Design and test of the Trigger Vacuum Switch and its Trigger Source for Oil Well Stimulation Device

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***Abstract*—A trigger vacuum switch (TVS) is developed to satisfy the stability and high temperature working environment (above 120 degrees) requirements for the discharge switch in oil well pulse discharge stimulation device. Compared with the self-breakdown switch, TVS can greatly improve the working life and stability of the whole device. The TVS is designed with multi-rod electrode system to improve the ability of current carrying and with suitable main electrode to improve the DC withstand voltage at the same time, and then the size of the TVS is devised. Besides, its electric field uniformity is optimized, developing suitable main electrode chamfer by theoretical calculation and simulation study. Performance parameters for the prototype can reach working voltage of 25kV, the peak current capacity of 30 kA/100 μs, the outer diameter of 68mm.After 1000 life time experiments, its triggering characteristics and DC withstand voltage level is still good, which shows that the TVS fully meets the requirements of the Oil Well Stimulation Device. Aimed at the high temperature working environment of the TVS, the trigger circuit is devised. In that the common thyristor and diode working under high temperature is not reliable, there is a trigger scheme with a three electrode spark gap instead of the thyristor controlling the trigger of the TVS. The trigger capacitance charges from the main circuit charge capacitance, which can simplify the circuit and has no potential isolation problem. With the simulation study and experimental test, it shows that the trigger scheme is feasible.**

***Index Terms*—Trigger vacuum switch, Life time experiment, Trigger circuit, High temperature environment**

I. INTRODUCTION

With the increase of the age of oil well, the deposition of non-soluble salts and the increase of viscosity of crude oil will cause the blockage of oil seepage channel and the decline of oil production. Therefore, it is necessary to carry out the solution to restore the oil production capacity. The pulse discharge device applied for oil well plugging removal and stimulation uses the high voltage and large current pulse discharge in liquid of liquid-electric effect principle [1] to produce powerful pulse pressure wave, mainly being composed of the converter (boost rectifier), the electric power storage unit (pulse capacitor bank), the discharging unit (the main discharge switch) and the discharge electrode [2,3]. When the device works, firstly storage capacitors are charged to a predetermined value by the boost rectifier. And then a control signal is given by the trigger control system to trigger the main discharge switch. After the switch being of conduction, storage capacitors discharge through the liquid gap between the discharge electrodes. The functions of the main discharge switch in the circuit: one is isolation, separating the discharge circuit from the high voltage while charging; the other is connecting the circuit quickly while discharging, making the capacitors discharge to the load.

- The working environment of the pulse discharge device applied for oil well plugging removal and stimulation is poor. The maximum operating depth is of 3000m,and the maximum working temperature is of 120℃, withstanding great pressure at the same time. In order to realize oil well pulse discharge, the relatively harsh demands are made on the equipment and technologies [4,5].And the requirements which are proposed to the main discharge: great through-current capability, quick conduction, work stability, long service life, small volume (the device is encapsulated in a tube whose outside diameter is less than 70 mm), being able to work in a wide temperature and pressure ranges. At present, the main discharge switch is more likely to adopt three electrode switch, field distortion switch or self-breakdown switch [2-6]. But these switches have some problems, such as working unsteadily, the large breakdown dispersion, the life being not long enough and so on. However, adopting the trigger vacuum switch (TVS) as the main discharge switch can greatly improve the working life time of the equipment (average reliable conduction times are more than 10000 times), and further improve the whole trigger circuit working stability [7]. The trigger vacuum switch is a kind of new switching devices, combining vacuum switch technology with three electrode spark gap technology. And its characteristics is using vacuum as the insulation and arc quenching medium among the main contact, and using the special designed trigger electrode to control switch for quick making [8,9]. It have many advantages, such as wide working voltage range, great through current capacity, triggering simply, rapid media recovery, compact structure, high working reliability, long life time, low price and so on. TVS has obtained widespread application of the best in pulsed power technology field [10-13].

In this paper, a miniaturization TVS used in the oil well pulse discharge stimulation device of 25 kV voltage level was designed on the basis of the past TVS design experience. And a series of experiments were carried out on the prototype performance. The results show that the developed TVS fully meet the requirements for oil well pulse discharge stimulation device. At the same time, because most of semiconductor devices cannot work reliably under high temperature, the trigger circuit is studied aimed at the high temperature working environment of the TVS. The designed trigger circuit in this paper didn’t use any semiconductor device, using a three electrode spark gap instead of the thyristor to control the trigger of the TVS. And the trigger capacitance charged from the main circuit charge capacitance. Based on the simulation, the trigger circuit prototype is developed. Conduction tests for TVS are done with the prototype .The results shows that the trigger circuit works steadily and reliably, fully meeting the trigger requirements of TVS working in high temperature environment.

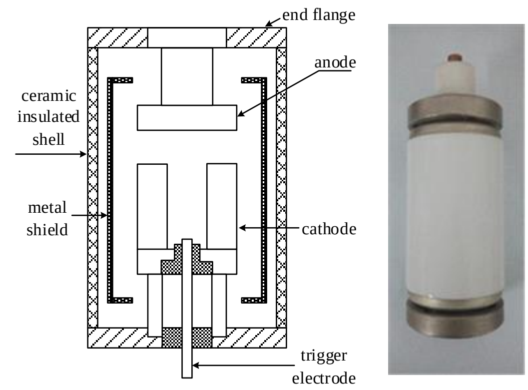
II. DESIGN AND TEST OF THE TVS

A. *Experimental Setup*

The designed triggered vacuum switch (TVS) is used in oil well plugging removal and stimulation pulse discharge device as the main discharge switch, encapsulated in a tube whose outside diameter is less than 70 mm. The maximum operating depth is of 3000m,and the maximum long-term operating temperature is of 120℃. Specific design targets for TVS are as follows:

- The working voltage of 25 kV
- The through-current capacity of 30 kA /100μs
- The pulse repetition frequency of 10 /min
- The outer diameter of not more than 68mm
- The maximum working temperature of 120℃
- The reliable conduction times of 5000 times

The internal structure schematic diagram of the TVS are shown in Fig.1 (a). The TVS prototype shape are shown in Fig.1 (b). As shown in Fig.1 (a), the TVS is composed of ceramic insulated shell, metal shield, multi-rod main electrode (cathode and anode), trigger electrode and end flange. The ceramic insulation shell is to ensure the TVS external insulation performance; the metal shield can make TVS internal electric field distribution more uniform and avoid the metal vapor generated while burning arc to deposit on the inner surface of the insulation shell so as to ensure the insulation strength of the TVS inner surface; main electrodes are made of CuCr30, with two pairs of annular staggered arrangement touch referring to the generation of the eight main discharge gaps (four rod-rod gaps, four rod-plate gaps); the trigger electrode is connected with the external trigger source, generating initial plasma by the ceramic surface flashover to trigger the gap.



(a)TVS structure schematic (b) TVS prototype

Fig. 1. Diagram of TVS internal structure and prototype

1) Arcing area

The cathode erosion rate of CuCr is about $3.8 \times 10^{-5} g/c$.For pulse current of 30kA/100μs, the maximum Coulomb transfer amount is 3C. If calculate according to the designed life time of 5×10^{3} times, the erosion amount of CuCr is to

$$3.8 \times 10^{-5} \times 3 \times 5 \times 10^{3} = 0.57\text{g},$$

Transform it into volume:

$$0.57/7.22=0.078\text{cm}^3.$$

The contact erosion limit is of 3mm, so the effective arcing area of TVS:

$$\text{S} \geq \frac{0.078}{0.3} = 0.26\text{cm}^2.$$

2) Gap distance

According to the simulation and the results of the current withstand voltage test [14], when the highest local field strength within the TVS reaches 10kV/mm (40kV DC voltage), the main gap is very likely to be of breakdown. It is assumed that the local field strength distortion coefficient [15] of the designed TVS is 3, then for the TVS working under 0~25kV, the gap distance d should be guaranteed

$$d > 25 \times 3 \div 10 = 7.5mm.$$

The rod-rod gaps distance can be selected of 10mm and the rod-plate gaps distance can be selected of 12mm.

If calculate according to the minimum breakdown voltage of 24kV, the maximum local field intensity must be controlled not to exceed

$$24 \div 12 \times 3 = 6kV/mm.$$

3) Main electrode design

The shell diameter of the TVS should not be more than 68 mm, the distance between the electrode and the shield is at least 5mm, the shield thickness should be at least 1mm, the distance between shield wall and the inner ceramic tube should be at least 2.5mm, and the ceramic tube shell thickness is at least 5 mm. So the maximum dimension of the electrode base diameter is

$$68 - (5 + 1 + 2.5 + 5) \times 2 = 41mm$$

The rod-rod distance is 10mm. As shown in Fig.2, for TVS with two-pair rod electrode，the maximum of the rod electrode thickness is

$$\left(41 - 10\sqrt{2}\right) \div 2 = 13.4mm.$$

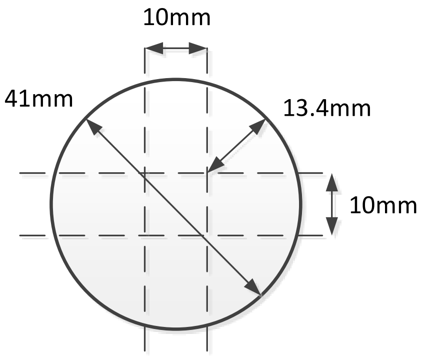


Fig. 2. Rod electrode thickness design

4) Main electrode chamfer and electric field uniformity

In order to improve the voltage withstand ability of TVS, choosing an appropriate chamfer can make the electric field distribution as uniform as possible. The electrostatic field simulation model is established as shown in Fig.3, the two main electrodes being applied to the voltage excitation of 25kV and 0kV respectively, and the shield being applied to the floating potential excitation.

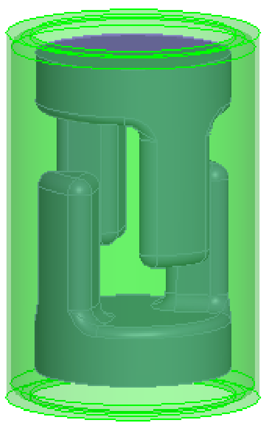


Fig. 3. The electrostatic field simulation model

Supposing that the chamfer of the electrode base, great lateral edge and the top edge are all 3mm, calculate the electric field distribution [16]. The maximum field intensity of the entire TVS is 10.6kV/mm (located at the top of the electrode), and in most of the region, the electric field intensity is 4-7.2kV/mm. The field intensity distribution of the electrode longitudinal section is shown in Fig.4, showing that the maximum of the local field intensity is 7.2kV/mm located at the top of the rod. Considering that the simulation maximum value is very close to the highest local field intensity of 6kV/mm calculated above, a bigger chamfer value is selected: the upper rod electrode chamfering radius is 4mm, rod electrode lateral ribs chamfering radius is 5mm, electrode base chamfering radius is 5mm.

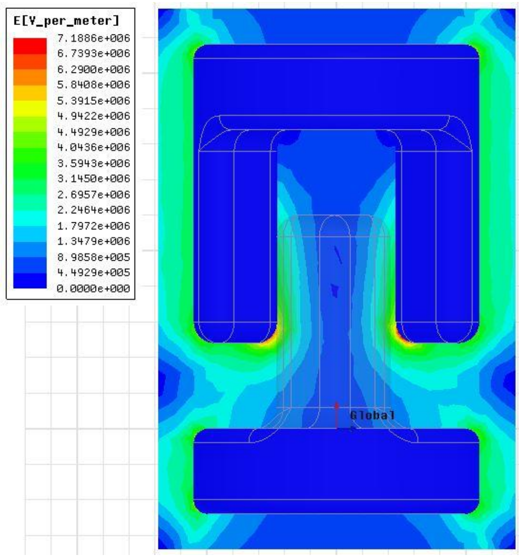


Fig. 4. Diagram of field intensity distribution of the electrode longitudinal section

In the design of TVS vacuum arc extinguishing chamber, the insulation between the electrode and the metal shield should be taken into consideration. Reasonable shielding cover size can improve the electric field distribution in the arc chamber. Based on the empirical formula of the local discharge field intensity:

$$E = Kd^{0.45} \text{ (K=19.33)},$$

When the distance between the electrode and the shield is of d=5mm,

$$E=39.9\text{kV/cm}=3.99\text{kV/mm}.$$

The electric field distribution of the upper and lower surface of the electrode base calculated by stimulation is showed in Fig.5 and Fig.6. It can be seen that the highest local field intensity of the upper and lower surface of the electrode base is found to be 3.9kV/mm, which is close to the highest value of the discharge field intensity calculated above. So the discharge between the metal shield and the electrode base plate will not occur.

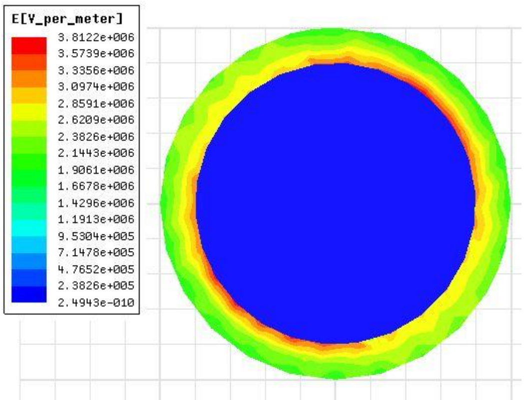


Fig. 5. Diagram of field intensity distribution of the electrode base upper surface

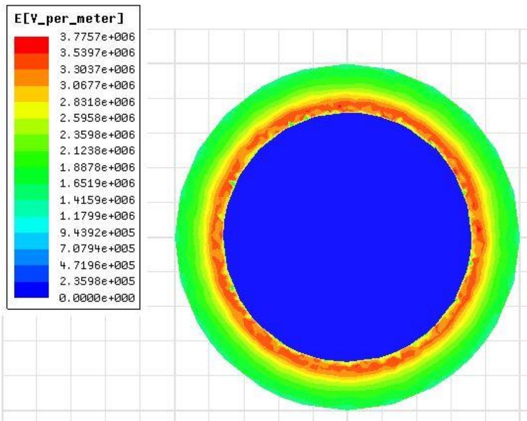


Fig. 6. Diagram of field intensity distribution of the electrode base lower surface

B. Trigger and conduction performance study on the designed 25kV TVS

1) Test circuit for 25kV TVS

The main circuit for the 25 kV TVS through-current/lifetime test is shown in Fig.7, where the charging capacitors bank C：150μF, inductor L：68μH; silicon heap D：100kV.

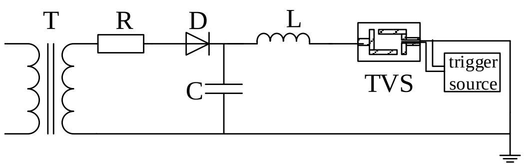


Fig. 7. Diagram of the main circuit for through-current/lifetime test

The trigger circuit diagram used in TVS electrical properties measurements is shown in Fig.8 [17,18]. In the diagram, T_1 is a boosting transformer, D_1 is a high-voltage silicon heap, and R_1 is a charging resistor; C_1 is the primary energy-storage capacitor for the pulse transformer T_2, and the capacitance is 3 μF /4kV; silicon SCR serves as the discharge switch of the primary capacitor C_1 and its conduction is controlled by pre-amplifier control circuit using optical fiber; D_2 is the freewheeling diode used to prevent transformer winding to oscillate when C_1 is discharging; T_2 is a pulse transformer that generates a high voltage pulse output functioning along the triggering surface of TVS; secondary capacitor C_2 is mainly used to ensure the stability of the pulse transformer output voltage. The working principle of the whole trigger circuit is as follows:

Primary energy-storage capacitor C_1 is charged by the half wave rectifier circuit composed of T_1, D_1 and R_1. After the completion of charging to C_1, the thyristor SCR is controlled to conduct, which leads to the C_1 discharging to the pulse transformer T_2. And then secondary winding of T_2 generates a high voltage pulse output functioning along the triggering surface of TVS. Since the secondary capacitor C_2 is connected in parallel with both ends of the trigger electrode and the cathode, T_2 will continue charging to C_2 until the voltage on C_2 reaches the breakdown voltage of the trigger surface. When the voltage on C_2 is higher than the breakdown voltage of the trigger surface, insulation breakdown will occur on the surface, C_2 and T_2 discharging to the trigger surface simultaneously. Due to the existence of small capacitance capacitor C_2, a trigger current with high amplitude and rising time about hundreds ns will flow through the surface, so that large amounts of initial plasmas can be released to use for TVS conduction.

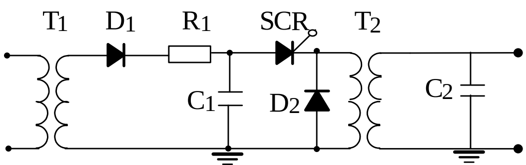


Fig. 8. Diagram of the trigger circuit

In the experimental test, the main circuit charging capacitor is charged with the initial voltage, and then the TVS is controlled to conduct by the trigger circuit. Monitor the main current, trigger time-delay and trigger current, and use the oscilloscope whose model is TBS2042 /200M to record the voltage and current waveforms. The test monitoring equipment contains P6015 high voltage probe, PERSON110 CT current sensor (ratio is 1000:1), PEM current probe (0.05mV/A).

2) Performance test and results

a. Trigger and conduction test

Add the charging voltage of the main circuit charging capacitor to 25kV, and then control the TVS to trigger and conduct taking advantage of the trigger circuit. The main circuit current waveform is shown in Fig.9, and the trigger current waveform is shown in Fig.10. As shown in Fig.9, the peak value of the main circuit current is 35.6 kA and the pulse width is 340μs.

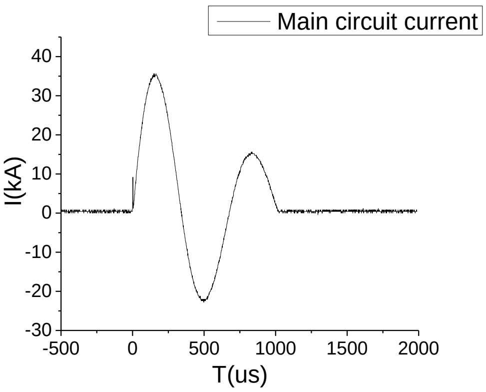


Fig. 9. The main circuit current waveform

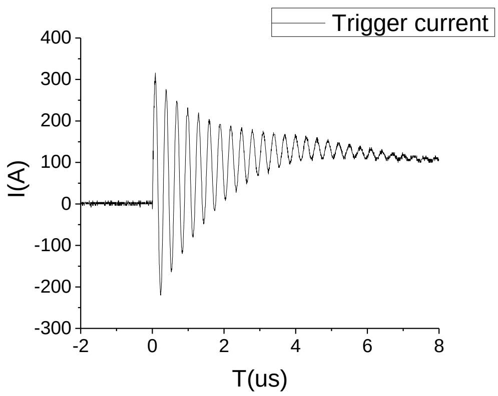


Fig. 10. The trigger current waveform

b. Trigger time-delay test

The trigger time-delay is defined as the time difference from the moment when the trigger voltage waveform starts rising to the moment when the main current starts rising smoothly. In order to measure the trigger time-delay, still add the charging voltage of the main circuit capacitor to 25kV, and then control the TVS to trigger and conduct. The trigger time-delay waveform is obtained as shown in Fig.11, where CH_1 shows the trigger voltage waveform and CH_2 shows the rising edge waveform of the main circuit current. The trigger time-delay is about 4μs.

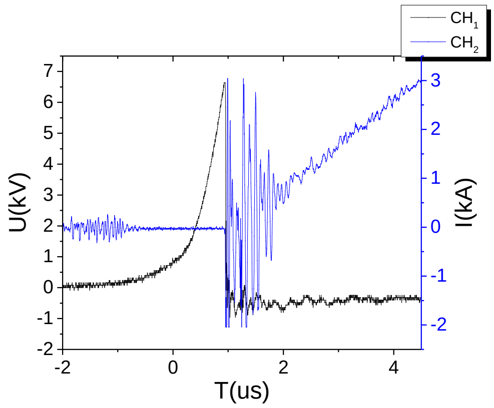


Fig. 11. The trigger time-delay waveform

c. DC voltage-withstand test

During the process of test on the trigger vacuum switch, a DC voltage-withstand test should be done to the trigger vacuum switch after every 10 through-current tests. Use the DC voltage-withstand generator to rise voltage on the both ends of the trigger vacuum switch slowly until the switch is of breakdown, and then record the breakdown voltage. The breakdown voltage data distribution is shown in Fig.12. After test, it is can be seen from the Fig.12 that the DC voltage-withstand level of the trigger vacuum switch is basically maintained at about 75kV.

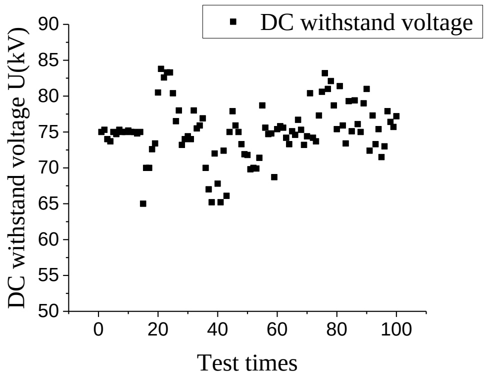


Fig. 12. Diagram of DC voltage-withstand distribution

d. Life time test

1000 times the trigger and conduction tests on the designed TVS are carried out making use of the experimental test platform shown in Fig.7 in order to test the life time of the TVS. The waveforms and data corresponding to the main circuit current, trigger time-delay, and trigger current are recorded for each test. And after every 10 times of the trigger and conduction tests, a DC voltage-withstand test will be done (in accordance with the relevant national standard requirements) to verify whether the insulation of the trigger vacuum switch is in good condition. The TVS can be triggered and conducted every time in the 1000 tests, and after the 1000 life time tests all the trigger and conduction performance is still good, which shows that the TVS has a long life time.

III. Design and Study of the Oil Well Trigger Source

The designed TVS works in the underground high temperature environment (the maximum long-term operating temperature is of 120℃), thus the corresponding trigger source components must be selected using high temperature resistant devices. Because most of semiconductor devices cannot work reliably under high temperature, the commonly used typical trigger circuit (As shown in Figure. 8) is not available. So the trigger circuit is studied aimed at the high temperature working environment of the TVS. In this paper, a trigger circuit without any semiconductor device is designed, using a three electrode spark gap instead of thyristor to control the trigger of the TVS. And the trigger capacitor charged from the main circuit charge capacitor, which can simplify the circuit and has no potential isolation problem.

A. Trigger circuit design

The designed TVS trigger source of series trigger capacitors charging from the main capacitor used in oil well is shown in Fig.13. Capacitor C_1 is primary energy-storage capacitor and is charged by the half wave rectifier circuit composed of T_1、R_1 and D_1; C_2 and C_3 are trigger capacitors, connected in series and then used in parallel to two ends of the TVS main electrode through a resistor R_0; R_4 and R_5 are divider resistors, ensuring the voltage distribution of C_2 and C_3 after charging; GAP can choose three electrode spark gap, controlling the discharge of C_3 to the trigger electrode of TVS with a trigger signal given by C_4; the relay is used to control the discharge of C_4 to the trigger electrode of GAP ; T_2, D_2 and R_2 consist of a half wave rectifier circuit to charge for C_4; R_3 is current-limiting protection resistor.

The basic idea of the designed trigger method: the conduction of relay put the energy into the trigger electrode of GAP, which make the GAP conduct; then the conduction of GAP put the energy into the trigger electrode of TVS, which make the TVS conduct. Discharge on three stage and conduct step by step. When there is no breakdown in the water gap, the gap presents resistance characteristics. So when the charging device charges the main capacitor C_1, trigger capacitors C_2 and C_3 are charged by C_1 through R_0 and the water gap at the same time. After the completion of charging to the whole circuit, the voltage on both ends of the series capacitors C_2 and C_3 is up to 30kV and the respective voltage on C_2 and C_3 is distributed in inverse proportion to their own capacitance, the voltage on C_3 being higher than the breakdown voltage of GAP. When the charging to C_4 is completed, the relay is controlled to conduct and then C_4 discharges to the trigger electrode of GAP, making the GAP conduct. After the conduction of GAP, C_3 discharged upon the trigger surface of TVS, which generate Initial plasma. Due to the voltage on capacitor C_2 can't mutate, in the process of C_3 discharging that is the process of TVS triggering, the voltage on both ends of TVS main electrode can be maintained at a high level until the main electrode is of breakdown, and then the TVS is of conduction. Finally, after the conduction of TVS, voltage on the C_1 is applied to the water gap until the gap is of breakdown, and then the entire circuit conduction, resulting in shock pressure wave in the water.

The advantages of this trigger scheme are that the trigger capacitors C_2 and C_3 charges from the main circuit charge capacitor C_1 without potential isolation problem, the trigger circuit possesses less circuit devices and the structure of the circuit is simple. Technical difficulty lies in the development of GAP and its drive control device.

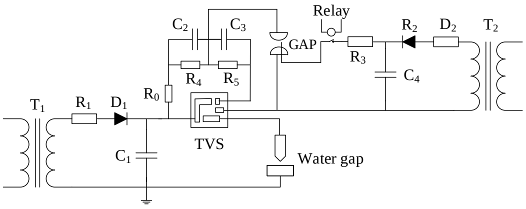


Fig. 13. The diagram of the TVS trigger circuit of series trigger capacitors charging from the main capacitor used in oil well

B. Trigger circuit simulation

The designed trigger circuit scheme shown in Fig.13 is simulated in order to verify whether the scheme is feasible and whether the circuit can trigger the TVS and further cause the discharge of the water gap. The simulation model is established as shown in Fig.14. In the model, TVS, GAP and water gap are all replaced by ideal switch, in which the water gap is equivalent to a resistor before the conduction; trigger capacitors C_2 and C_3 are set containing the same capacitance; resistors R_2 and R_3 are set the same resistance. After charging to the whole capacitors in the circuit by 30kV AC supply through a half wave rectifier circuit is completed, respectively control the GAP, TVS and water gap to conduct, in which the conduction time of TVS is set for 10μs lag behind the GAP conduction and the conduction time of water gap is set for 15μs lag behind the GAP conduction.

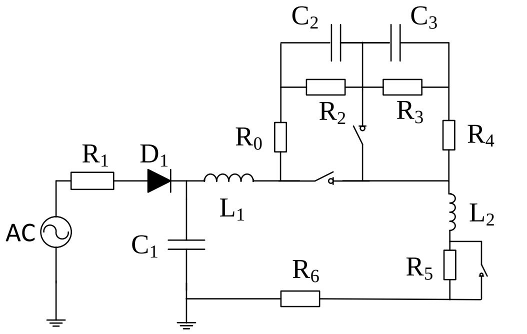
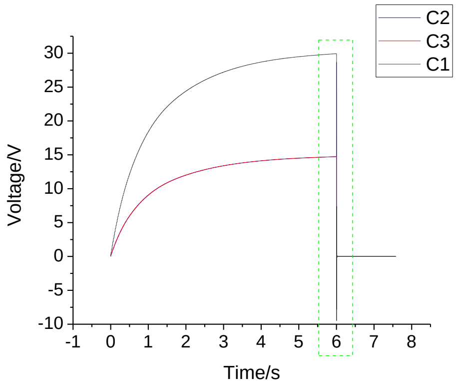
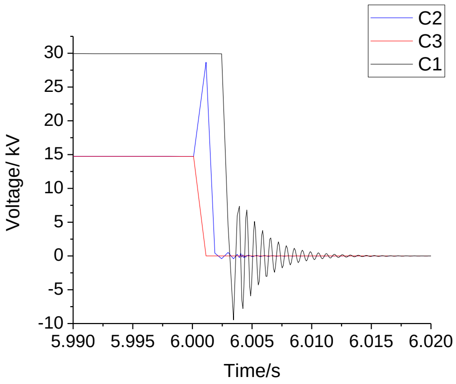


Fig. 14. The simulation model of the TVS trigger circuit used in oil well

The simulation results are shown in Fig.15, Fig.16 and Fig.17. The waveforms of voltage on capacitors C_1, C_2 and C_3 are shown in Fig.15, in which the Fig.15 (b) shows the capacitors voltage waveforms at trigger conduction moment marked out by the green imaginary line in Fig.15 (a); Fig.16 shows the waveform of the main circuit current; The waveforms of voltage on TVS and water gap are shown in Fig.17, in which the Fig.17 (b) shows the voltage waveforms at trigger conduction moment marked out by the green imaginary line in Fig.17 (a). From the simulation results, it can be seen that: when the main capacitor C_1 is charged, trigger capacitors C_2 and C_3 can be charged normally in inverse proportion to their own capacitance; in the process of trigger, main capacitor C_1 generates no overvoltage and trigger capacitors C_2 and C_3 can discharge normally; the designed trigger circuit can trigger TVS and further cause the conducting of the water gap. The simulation results show that the designed TVS trigger circuit of the series trigger capacitors charging from the main capacitor can mainly meet the requirements of the oil well pulse discharge stimulation device.



(a) Capacitors voltage waveforms



(b) Capacitors voltage waveforms at trigger conduction moment

Fig. 15. Waveforms of voltage on capacitors C_1, C_2 and C_3

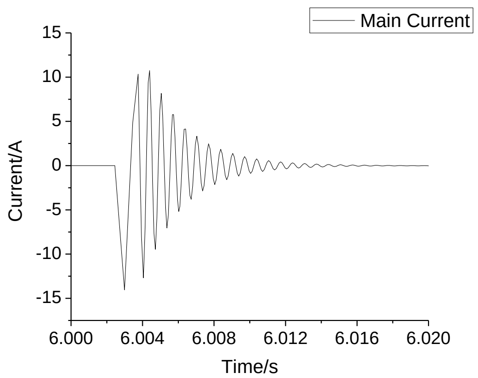
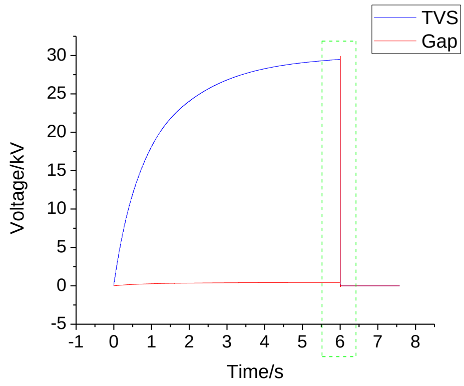
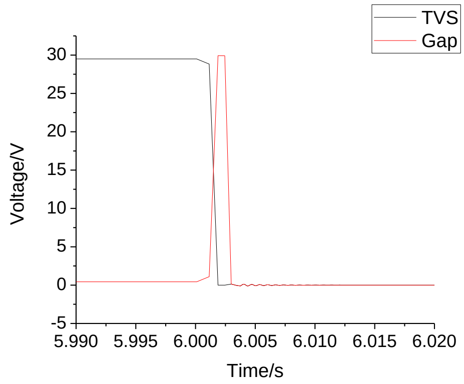


Fig. 16. The main circuit current waveform



(a) Waveforms of voltage on TVS and water gap



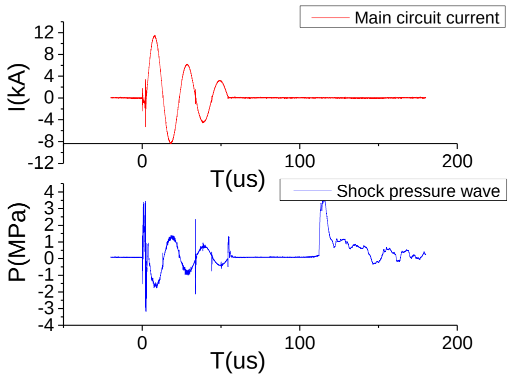
(b) Voltage waveforms at trigger conduction moment

Fig. 17. Waveforms of voltage on TVS and water gap

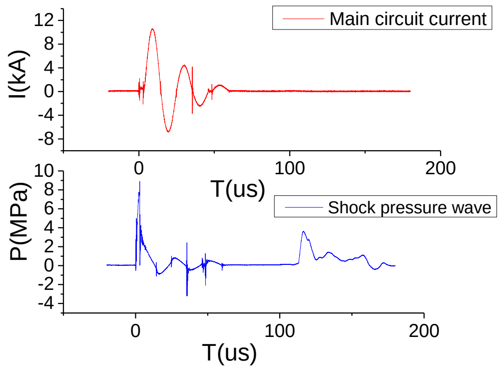
C. Experimental test

The experimental platform is set up to test the trigger scheme according to the designed trigger circuit shown in Fig.13, where GAP is selected to use three electrode spark gap whose trigger gap is 5mm air gap. After the completion of charging to the whole circuit, the TVS trigger source is used to apply the trigger signal to the GAP. Waveforms of the shock pressure wave and the main circuit current are recorded by the oscilloscope. The waveforms of the test results are shown in Fig. 18, where the Fig. 18 (a) shows waveforms of the shock pressure wave and the main circuit current obtained using the designed TVS trigger source of series trigger capacitors charging from the main capacitor and Fig. 18(b) shows waveforms obtained using the typical TVS trigger source (As shown in Figure. 8).

From the experimental test waveforms, it can be seen that waveforms obtained using two kinds of different trigger modes are not very different from each other and that the designed TVS trigger circuit of the series trigger capacitors charging from the main capacitor can normally trigger TVS and further achieve the discharge of the water gap, mainly meeting the requirements of the oil well pulse discharge stimulation device.



(a) Waveforms obtained using the designed TVS trigger source of series trigger capacitors charging from the main capacitor



(b) Waveforms obtained using the typical TVS trigger source

Fig. 18. Waveforms of the shock pressure wave and the main circuit current

IV. Conclusion

In this paper, a multi-rod trigger vacuum switch of 25 kV voltage level used in the oil well pulse discharge stimulation device as the main discharge switch was designed on the basis of the past TVS design experience. The electric field uniformity is analyzed by simulation, developing suitable main rod chamfers by theoretical calculation and simulation study. The developed TVS possesses a through-current capacity of 30 kA/100µs and an outside diameter of 68mm. After 1000 life time tests, the DC voltage withstand level and the trigger-conduction performance of the TVS are still good. The developed TVS fully meet the requirements of the main discharge switch in the oil well pulse discharge stimulation device.

Aimed at the high temperature working environment of the designed TVS, the trigger source is studied. The designed trigger source does not contain any semiconductor device, using a three electrode spark gap instead of the thyristor control the trigger and conduction of the TVS; trigger capacitors directly charge from the energy storage capacitor in bleeder form, which can simplify the circuit and has no potential isolation problem. Based on the simulation, the trigger source prototype is developed. Conduction tests for TVS are done with the prototype .The results shows that the trigger circuit fully meet the trigger requirements of TVS working in in the oil well pulse discharge stimulation device.

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