DEVELOPMENT OF A 75 COULOMB TRIGGERED VACUUM SWITCH

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Abstract

We designed, fabricated, and tested sealed-off triggered vacuum switches (TVSs) used as an ETC-gun switch. To fabricate the sealed-off TVS, we developed processes of the fabrication such as part machining, chemical cleaning, ceramic to metal and metal to metal brazing, metal welding, baking, getter processing and test procedures. The fabricated switches were tested with capacitor banks of 100 kJ and 300 kJ. The prototype switches were successfully tested up to 20 kV peak charging voltage, 109 kA peak current, 1.5 ms pulse-width, and 75-coulomb integrated charge transfer at 300 kJ capacitor bank. Compared to other reported similar switches, the tested switch showed high quality electrical characteristics in high operating voltage, high charge transfer, and long pulse operation.

I. INTRODUCTION

The switching technology in all of the pulse power systems is considered significant. Improvement of the switching technology affects all pulse power technology fields in military as well as civilian works. Required conditions of the switch in ETC-guns and other high power civilian applications are low-cost, high-coulomb transfer, long lifetime, low jitter, environmentally friendly, and sealed-off system that can be operated in any position and easily replaceable [1]. TVS are extremely robust devices that can survive over-voltage, over-current, and reverse-current fault that would destroy other types of switching devices [2]. Through study of different pulsed high power switches, we selected a triggered vacuum switch (TVS) to investigate as an ETC-gun switch. It consists of six trapezoidal electrodes, a ceramic outer chamber, a copper screen, a getter and a trigger.

II. A TRIGGERED VACUUM SWITCH

A. Design and Fabrication

Figure 1 shows a schematic of the TVS. Anode and cathode of the switch consist of three trapezoidal rods that are positioned alternatively. Each rod has a width of 24 mm and a height of 39.5 mm. Gaps between the electrodes are 9.6 mm. The electrodes are made of oxygen free high conductivity copper (OFHC). A trigger pin made of OFHC is inserted in the center of the cathode. A ceramic feed-through is used to insulate the trigger pin and the cathode. An OFHC screen is placed between the electrodes and the ceramic chamber to protect the ceramic surface from metal coating. Getters are welded on outer skirts of metal screen to maintain internal vacuum. Diameter and height of the TVS assembly are 134 mm and 165 mm, respectively.

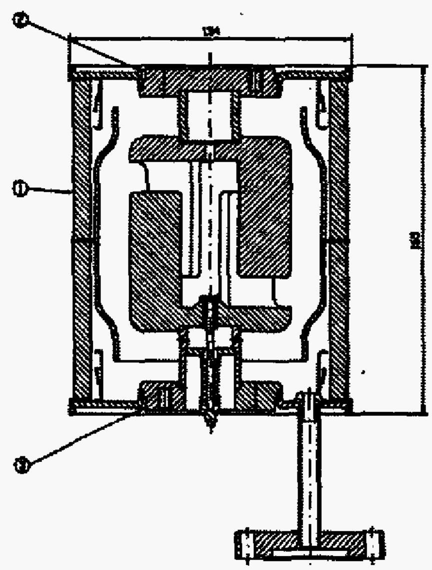

Figure 1. A schematic drawing of the TVS (1) Ceramic chamber, (2) Anode, (3) Cathode.

We developed a fabrication procedure of the TVS as shown in Figure 2 [4, 5]. Parts of the switch were chemically cleaned and polished before spot welding and brazing. We then assembled the spot-welded and brazed electrodes and ceramic chamber. The assembled electrodes and the chamber were then welded together. The assembly was tested on its leaking to confirm vacuum tightness. Before the next degassing and activation processing, we conditioned the trigger pin under vacuum of low 10^{-6} Torr of air so that the ceramic gap between the trigger pin and the cathode had enough metal coating on the ceramic surface of the trigger insulation. The typical measured resistance between the trigger pin and the

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cathode was about several hundred kΩ ~ several MΩ after the conditioning. Under the same vacuum condition, the TVS was tested for hold-off voltage up to 40 kV, and then it was high voltage conditioned by applying voltage with 5 MΩ charging resistor from 5 kV to 35 kV with 5 kV step increase in case the leakage current was less than 1 µA. The TVS was then placed in a baking furnace for degassing of component of TVS and activation of getters. The TVS was baked at 600 °C for about 24 hours. Internal pressure of the TVS was low 10^{-6} Torr during the baking. After cooling down the TVS, and the internal pressure of the TVS was about 10^{-9} Torr, the switch was then pinched off. To strengthen screw holes, helicoils were inserted into the holes. Figure 3 shows a picture of the fabricated TVS.

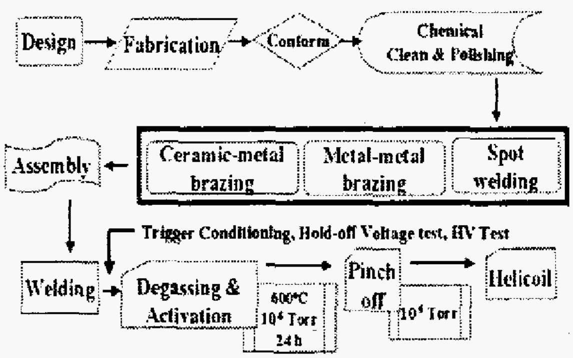

Figure 2. Fabrication procedure of the TVS.

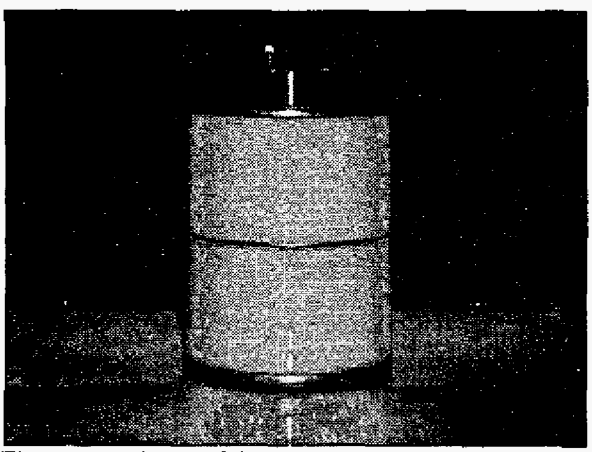

Figure 3. A picture of the fabricated TVS at the pal.

B. TVS test

B.1 Short Pulse Test

We applied a 5 kV peak-voltage pulse to trigger the TVS. When the switch was triggered, peak current of the trigger pulse was 400 A with 6.5 µs pulse-width. The TVS was tested to verify its charge and current transfer capability. For the test, we used a 100 kJ capacitor bank that had total capacitance of 100 µF with a maximum charging voltage of 44 kV. Current and voltage were measured with a current transformer with a 0.001 V/A sensitivity and a 5 dB attenuation and a voltage probe with a 1000:1 sensitivity. Typical waveforms of voltage and current are shown in Figure 4. In Figure 4, the charging voltage is 30 kV and the peak switching current is 90 kA. Current pulse-width of the first half sine-wave is about 100 µs. Total integrated transferred charge through the switch was 74-coulomb.

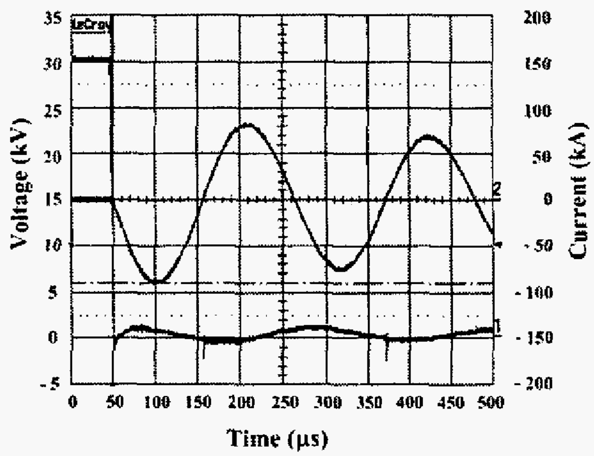

Figure 4. Typical waveforms of voltage(CH1, capacitor charging voltage 30 kVpeak) and current(CH2, 90 kApeak, half-cycle width 100 µs) TVS.

B.2 Long Pulse Test

To test long pulse switching characteristic of the TVS, a 300 kJ capacitor bank was used.

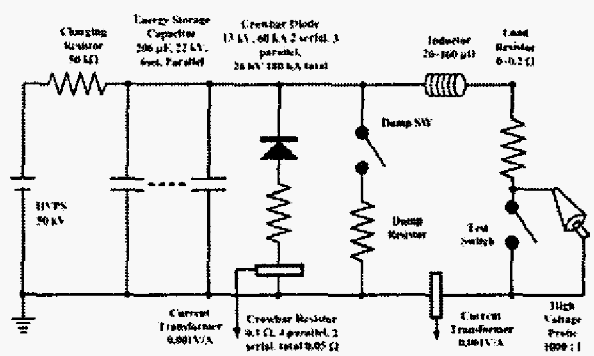

Figure 5. Long pulse test circuit diagram of the TVS.

Figure 5 shows a schematic diagram of the long pulse test circuit. Figure 6 shows a picture of the long pulse test setup. The capacitor bank consists of six capacitors 206 µF, 22 kV capacitors. An inductor, which can be varied from 20 to 160 µH, and a load resistor, which can be varied from 0 to 0.2 Ω were connected in series between the capacitor bank and the TVS. Figure 7 shows typical waveforms of current and voltage for the long pulse test of the TVS. Charging voltage was 20 kV. Inductance of 20 μH without the load resistance was used during the test. The switched peak current was 109 kA with total 1.5 ms pulse-width. Energy and charge in the capacitor bank were about 250 kJ and 75-coulomb. Current and voltage were measured with a current transformer with a 0.001 V/A sensitivity and 50 □ impedance and a voltage probe with a 1000:1 sensitivity. Switching delay time was about 3.2 μs that was measured from the time of trigger command signal to the turn on time of TVS. Maximum switching jitter was about 2 μs.

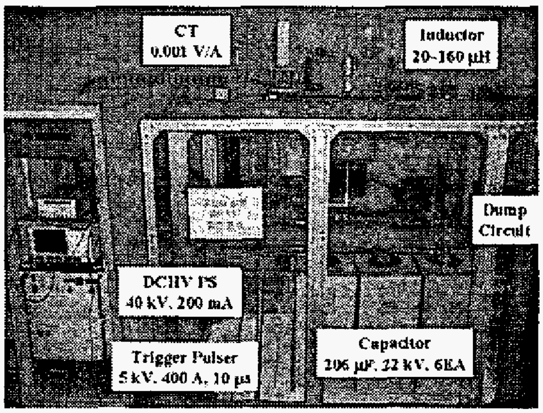

Figure 6. Long pulse test set-up of the TVS.

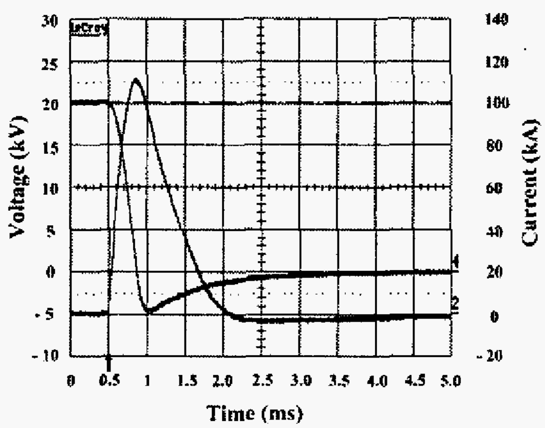

Figure 7. Long pulse test waveforms of voltage (CH4, capacitor charging voltage 20 kVpeak) and switching current (CH2, 109 kApeak). Total switching pulse-width is about 1.5 ms. Transfer charge is 75 C.

B.3 Summary of Test Results

Table 1 summarizes test results of the TVS. As given in the table, the TVS was tested up to operating voltage of 30 kV, peak current of 109 kA, charge transfer of 75-colomb, pulse-width of 1.5 ms, and di/dt of 10.5 kA/μs

Table 1. TVS test summary.

Parameter	unit	Test Result					
Cap.bank		100 kJ				300 kJ	
Inductor /Resistor	μH/Ω	0/0	10/0	10/0	0/0.125	80/0.25	20/0
Voltage	kV	10	20	30	20	20	20
Current	kA	105	63	90	52	42	109
Half Period	ms	0.02	0.1	0.1	0.08	1.2	1.5
Coulomb	C		3	74	2	25	75
di/dt	kA/s	10.5	1.5	1.8	1.3	0.1	0.2
Diode Phenomena		Non	Non	Non	Non	Ok	Ok

C. Diode phenomena and voltage drop of TVS

We observed diode phenomena with the test switch. The diode phenomena were investigated by using a 100 kJ capacitor bank. Five different combinations of the series inductance and load resistance values were used for the test. Typical waveforms of the diode phenomenon at 20 μH without the load resistance are shown in Figure 8. Figure 8 shows typical waveforms of current and voltage for the short pulse test of the TVS. Charging voltage was 12 kV and discharge current was 28 kApeak.

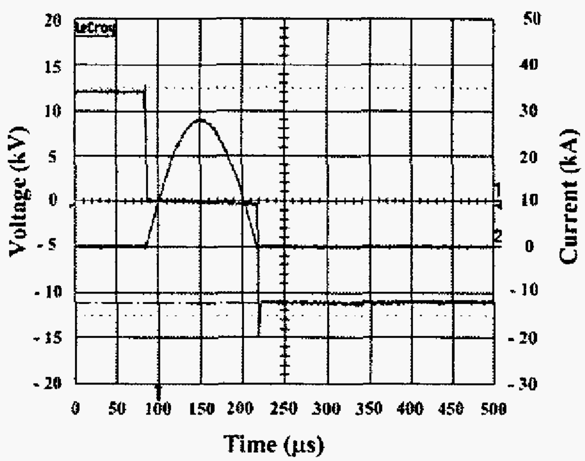

Figure 8. Typical waveforms of the diode phenomenon. (CH1, cross switching voltage 12 kVpeak) and current(CH2, 28 kApeak). Total switching pulse-width is about 134 μs.

For the combination of a 5 μH inductor and a 0.1 Ω resistor, the diode phenomena occurred with 96% probability for 50-shot tests at below 10.8 kV/μs and 236 A/μs. With a 10 μH inductor without the resistor, the diode phenomena were always observed for 25-shot tests at below 12.5 kV/μs and 268 A/μs. With a 5 μH inductor without the resistor, the diode phenomena were always observed for 25-shot tests at below 11.1 kV/μs and 352 A/μs. With a 15 μH inductor without the resistor, the diode phenomena were always observed for 50-shot tests at below 13.3 kV/μs and 344 A/μs. With a 20 μH inductor without the resistor, the diode phenomena were always observed for 50-shot tests at below 13.2 kV/μs and 257 A/μs. Results of the measured dv/dt versus di/dt are plotted in Figure 9. It is generally considered that the diode phenomenon is only a strong function of di/dt. However, the test result shows that the diode phenomenon is also a strong function of dv/dt as well. Similar test can reportedly be found in other references [2].

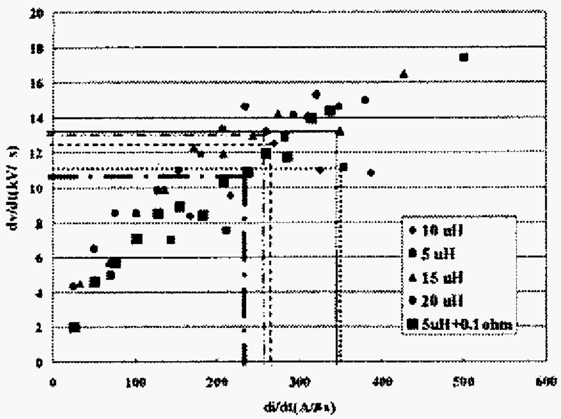

Figure 9. Plot of the rate of current decay, di/dt, versus the rate of inverse voltage, dv/dt, of the tested TVS for five different experimental conditions. The points with the crossing lines represent maximum values to observe high probability of rectifying characteristic of the TVS with the given experimental condition.

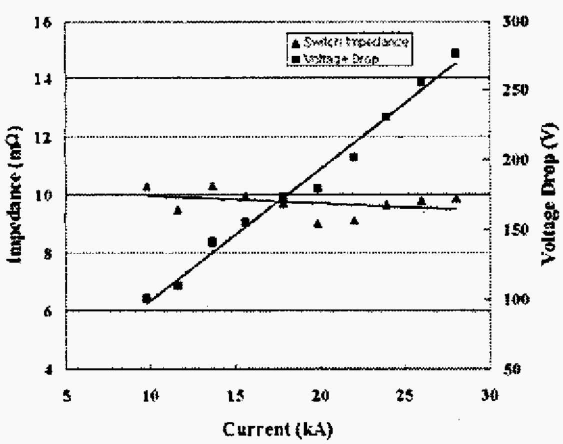

Figure 10. Plot of the switch voltage drop versus peak switch current with 20 μH inductance load.

Switching voltage drop of the TVS was also measured with the 20 μH inductance load. Figure 10 shows the plot of switching voltage drop and impedance as a function of switch current. As shown in the figure, the switching impedance was maintained at around 10 mΩ.

III. SUMMARY

We designed, fabricated, and tested a high current, a high voltage, and a high coulomb TVS. The TVS was tested up to operating voltage of 30 kV, peak current of 109 kA, charge transfer of 75-colomb, and pulse-width of 1.5 ms at 300 kJ capacitor bank. Switching delay time was about 3.2 μs. The tested TVS showed high performance in terms of high operating voltage, high current as well as charge transfer capability, and long pulse operation. Diode phenomena were found that they were not a sole function of rate of current decay, di/dt, but also a strong function of rate of reverse voltage rise, dv/dt. The switching impedance of the TVS was measured as about 10 mΩ.

IV. REFERENCES

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