Study of Laser-Triggered Vacuum Switch with a Six-gap Rod

Zucheng Huang1,2, Bin Xiang3, Yun Zong4, Xiangwei Cao5, Xiaopo Mao5,6, Zhenghao He1, Jinjiao Kong3 and Yaodong Zhang3

1 State Key Laboratory of Advanced Electromagnetic Engineering and Technology (Huazhong University of Science and Technology), Wuhan, Hubei, 430074, China
2 Guangzhou Zhiguang Electric Co., Ltd., Guangzhou, Guangdong, 510000, China
3 State Grid Hubei Electric Power Co., Ltd. Electric Power Research Institute, Wuhan, Hubei, 430077, China
4 Communication Engineering Department, Shijiazhuang Information Engineering Vocational College, Shijiazhuang, Hebei, 050035, China
5 China Tobacco Hubei Industrial of Cigarette Material Co., Ltd., Wuhan, Hubei, 430040, China
6 E-mail: mxp2004@163.com

Abstract. In this paper, the triggered polar material structure of the Laser Triggered Vacuum Switch (LTVS) was redesigned and the shape of the main electrode was improved. At last, we know that when the gap length of the LTVS is 12mm and the withstand voltage is 30kV, the LTVS is successfully conducted with 5kV gap voltage and 10mJ laser whose wavelength is 1064nm. Meanwhile, jitter time of the switch is approximately 2ns and the conduction time is approximately 20ns. By comparing the gap voltage, capacitance value, laser power and laser wavelength, the implications of such improvements on the jitter time and conduction time of the switch are discussed.

1. Introduction
Laser Triggered Vacuum Switch (LTVS) is one kind of high power pulse switch which can hold high voltage and large current. Compared with electrical triggered vacuum switch, it is not affected by electromagnetic interference, and thus it was not to be erroneously triggered. Furthermore, its trigger energy is low, because lasers are used to trigger [1-2]. In 1988, P.J.Brannon and D.F.Cowgill adopted the mixed material to trigger the vacuum switch, the mixed material was titanium powder (Ti) and potassium chloride (KCl), Ti could absorb the laser heat well and transfer to KCl, and then KCl sublimated to form K+ and Cl- under the action of electric field force, the vacuum switch therewith was not conducted [1]. In 1989, P.J.Brannon and M.E.Riley proposed two kinds of vacuum switch device, thermal device firstly generated initial current, and then ions regeneration device accumulated current [3].

In this paper, the conduction time and jitter time of the LTVS with redesigned trigger polar structure and main electrode structure were analyzed with different trigger pole structure, main electrode structure, electrode gap voltage, laser energy, laser wavelength and capacitance value.
2. Experiment equipment and technology

2.1. Optical setup and experiment circuit

Figure 1 is a diagram of experimental optical setup and figure 2 is a diagram of the LTVS experiment circuit.

![Figure 1. Diagram of experimental optical setup.](image1)

![Figure 2. Diagram of the LTVS experiment circuit.](image2)

In figure 1, the power source controls ND: YAG laser, a variable attenuator are used to get different wavelength of lasers, two beams are produced after the beam splitter, a beam is detected by photodiode detector, the signal is passed to the oscilloscope to get trigger signal, the other beam trigger the target material. In figure 2, energy storage circuit comprises of AC220V, a voltage regulator, a transformer, a protect resistance, a silicon stack and a storage capacitor; discharge circuit consists of a load, a LTVS and storage capacitor.

2.2. Trigger polar

Trigger pole is the biggest difference between the laser triggered vacuum switch and the electrical triggered vacuum switch. Its material composition and cathode location decide the conduction energy, process and success rate. By literature [1] and [2], the trigger pole is constituted by the mixture of the titanium powder (8um in diameter) and the potassium chloride (300um in diameter). Firstly, the titanium powder absorbed laser energy and transferred to potassium chloride, and then potassium chloride crystal sublime [4], when the surface temperature of potassium chloride is 250°, at last, under the action of electric field, the potassium chloride is ionized, accompanied by the movement of chlorine ion to the anode, and the movement of potassium ion to the cathode, which constitutes the initial plasma.

| Number | Time/s | Pressure/kN | Quantity | Note            |
|--------|--------|-------------|----------|-----------------|
| 1      | 180    | 50          | 10       | Very Loose      |
| 2      | 180    | 60          | 10       | A Little Loose  |
| 3      | 180    | 70          | 10       | Strong          |
| 4      | 180    | 80          | 10       | Some Deformation|

2.5g titanium powders and 2.5g potassium chloride are mixed and made into cylindrical structure under a definite pressure (as showed in table 1). Number 3 is the best choice, that is to say, the mixture is made into cylindrical shape by the 70kN pressure in 180 seconds.
Trigger pole material was put into the flat form vacuum switch, as showed in figure 3. Through the anode round hole, the laser irradiated the trigger pole installed in the cathodic area. The distance between the top of the trigger pole and the top of the cathode is $D$, $D$ is respectively held to 3mm, 2mm, 1mm, 0.5mm and 0mm. When the trigger pole is fixed on the outside of the cathode, the distance between the top of the trigger pole and the top of the cathode is $d$, $d$ is respectively took for -1mm and -2mm.

2.3. Main electrode
The main electrode material is CuCr50, which possesses ablation resistance, powerful current capacity and good degassing capacity. Furthermore, when main gap distance is 12mm, withstand voltage is $30kV$, internal vacuum is $1 \times 10^{-5}Pa$. Compared with the plane form, the six-gap rod form LTVS in which three anode rod and three cathode rod are in circular permutation could avoid the agglomeration of arc, make arc move continuously in multiple clearances and effectively improve the current capacity of LTVS [5], as shown in figure 4.

3. Experimental results and analysis
In figure 5, CH1 is laser trigger signal, CH2 is switch voltage waveform. The conduction time of the switch is defined as the time interval between the arrival of the trigger laser pulse and the decline point of the voltage. The jitter time is defined as the standard deviation of the conduction time measured in 20 shots.
3.1. The distance between the top of the trigger and the top of the cathode
The energy of the laser derived from the Nd:YAG is 10mJ and the wavelength is 1064nm, the gap voltage is 5kV, the capacitance is 40uF. The conduction time and jitter time in different distance level are shown in figure 6 and figure 7 respectively.

![Conduction Time vs Distance](image1.png)

**Figure 6.** Distance vs conduction time.

![Jitter Time vs Distance](image2.png)

**Figure 7.** Distance vs jitter time.

Figure 6 and figure 7 showed that the greater the distance, the longer the jitter time and the conduction time, especially when the trigger pole mounted in the cathodic area. While the distance between the top of the trigger polar and the top of the cathode is -2mm, -1mm and 0mm, the variation of the conduction time and jitter time were both small, especially, when the distance is -2mm, the conduction time is 20ns and the jitter time is 2ns. The reason is that the initial plasma could quickly move to the main electrode under the effect of electric field, impact the main electrode and lead to the avalanches effect, and then the switch turned off [6]. If the distance was greater than 0mm, the conduction time and the jitter time became very long. That’s because when the trigger polar was put into the cathode, not only did quite a number of initial plasma disappear inside the cathode but also the effect of the initial plasma on main electron was unstable and insufficient, the conduction time and jitter time became longer because of lacking of initial plasma. So the method that the trigger polar is fixed on the outside of the cathode was advantageous, the change of conduction time and jitter time is not very obvious, but conical surface area is bigger than the cylindrical surface area, the greater surface area accompanied by greater utilization rate, the longer service life of the switch, so the conical trigger material is the better choice.

3.2. The relationship between the conduction time and jitter time and gap voltage
As showed in figure 8 and figure 9, when the laser energy is 10mJ, figure 8 is conduction time vs gap voltage and figure 9 is jitter time vs gap voltage, which demonstrates the conduction time is not affected strongly by the gap voltage. However, the greater gap voltage is, the shorter jitter time is, the
faster the speed of initial plasma, the bigger the energy of collision with electrodes, the more obvious the electron avalanche effect. When the gap voltage is lower than 50V, switch cannot be stop which means the ion regeneration mechanism of gap voltage can't make the initial plasma produce electrode avalanches.

![Figure 8. Conduction time vs gap voltage.](image1)

![Figure 9. Jitter time vs gap voltage.](image2)

3.3. The relationship between the conduction time and jitter time and the capacitor value
When laser energy is 10mJ, laser wavelength is 1064nm, gap voltage is 5kV, figure 10 is conduction time vs capacitor value and figure 11 is jitter time vs capacitor value, which demonstrates the conduction time and jitter time is not affected strongly by the capacitor value.

![Figure 10. Conduction time vs capacitor value.](image3)

![Figure 11. Jitter time vs capacitor value.](image4)

3.4. The relationship between the conduction time and jitter time and the laser energy
When the gap voltage is 5kV, laser wavelength is 1064nm, figure 12 is conduction time vs laser energy and figure 13 is jitter time vs laser energy. The higher laser energy, the shorter jitter time and conduction time, but the more trigger material cost. When the laser energy is less than 600uJ, switch can't be closed, which shows that laser energy is insufficient and consequently initial plasma derived from the heat mechanism is insufficient to make the switch closed. When the laser energy is less than 10mJ, conduction time and jitter time change significantly, which shows that the secondary electron produced by collision between initial plasma and electrode is not stable and the avalanche effect lag. When energy is higher than 10mJ, the range of the variation of conduction time and jitter time tends to be stable. Considered the trigger material cost, the 10mJ of laser energy is appropriate for trigger switch.
3.5. The relationship between the conduction time and jitter time and the laser wavelength
At the same time, in figure 12 and figure 13, compared the two sets of laser wavelength, 1064nm and 532nm, when the laser energy is less than 5mJ, the laser wavelength of 532nm can’t close the switch. However, when the laser energy is greater than 5mJ, the conduction time and jitter time of the laser wavelength of 532nm is shorter than the other one. By the equation:

$$ E = h \nu $$

(1)

$$ \nu = c / \lambda $$

(2)

Equation (2) is taken into (1):

$$ E = h \frac{c}{\lambda} $$

(3)

E is the single photon energy, h is Planck's constant, \( \nu \) is the photon frequency, c is the speed of light, \( \lambda \) is the wavelength. When the laser energy is a constant value, the longer the laser wavelength, the lower the single photon energy, the photoelectric effect is palpable. When laser energy is lower than 5mJ, the initial plasma generated by the photoelectric effect is deficient. The 1064nm wavelength of the laser generated the initial plasma by the laser ablation.

4. Summary
In this paper, with the unique trigger polar structure and the electrode structure, LTVS can reduce the conduction time and jitter time and withstand high voltage and large current, the speed of dielectric recovery is fast. The following conclusions were obtained:

1. The conduction time and jitter time are shorter when the trigger pole material is fixed on the outside of the cathode than that of fixed on the inside of the cathode. Meanwhile, the loss of the initial plasma is very little and the time that the initial plasma impact electrode is short, electrode avalanche effect is obvious. In addition, the conical structure is effective to increase the trigger area and the life of trigger pole.

2. The LTVS with six-gap rod form could avoid the arc agglomeration and make arc move continuously in multiple clearances which effectively improve the current capacity of LTVS.

3. The relationship between the conduction time and jitter time and gap voltage: The greater the gap voltage, the shorter the jitter time. That’s because the initial plasma is faster, the energy derived from the collision between the initial plasma and the electrode is more. The conduction time isn’t affected strongly by the gap voltage.

4. The relationship between the conduction time and jitter time and the capacitor value: The conduction time and jitter time aren’t affected strongly by the capacitor value.

5. The relationship between the conduction time and jitter time and the laser energy: The greater laser energy, the shorter conduction time and jitter time are, but the cost of trigger material is more. When the laser energy is greater than 10mJ, the conduction and jitter time tend to be stable. Therefore, appropriate laser energy is 10mJ considered the trigger material cost.
(6) The relationship between the conduction time and jitter time and the laser wavelength: The conduction time and jitter time of the laser wavelength of 532nm is less than the laser wavelength of 1064nm.

Acknowledgments
This work is supported by The National Natural Science Foundation Program of China (51377071) and Huazhong University of Science and Technology Independent Innovation Research Funding (HUST: 2010JC018). The authors would like to thanks Associate Prof. Wang Ying.

References
[1] Paul J and Cowgill D 1988 Low-jitter laser-triggered vacuum switch using a composite target. Apr 1988 IEEE Transactions on Plasma Science 16(2) 325-327
[2] Mao X, He Z, Wang Y, et al, 2014 Research on the interaction of primary plasma and main electrode for laser triggered vacuum switch IEEE Transactions on Plasma Science 42(11) 3592-3597
[3] Paul J and Merle E 1989 A model for the operation of a laser-triggered vacuum low-Inductance switch IEEE Transactions on Plasma Science 17(6) 859-862.
[4] Okuyama F, Wong S and Rollgen F 1985 Emission of positive ions from KCl and NaCl crystals exposed to high electric fields Surface Science 151 131-136
[5] Mao X, He Z, Wang Y, et al, 2015 Research on the time delay characteristics of the laser triggered vacuum switch IEEE Transactions on Plasma Science 43(6) 2005-2010
[6] Huang Z, Xiang B, Cao X, et al, 2018 Research on the Prebreakdown Current of the Laser-Triggered Vacuum Switch IEEE Transactions on Plasma Science 46(2) 410-414