Closing performances of double-gap laser-triggered vacuum switch

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Abstract
To develop high-voltage-pulsed power switches with better performances, a multi-gap laser-triggered vacuum switch is proposed in this study. Based on established test prototype for double-gap laser-triggered vacuum switch, closing processes of double-gap laser-triggered vacuum switch are discussed combined with laser-produced plasma. Closing performances of double-gap laser-triggered vacuum switch under different gap polarity configurations, operating voltages, laser energies and laser split ratios are investigated. Closing time delay characteristics of double-gap laser-triggered vacuum switch and single-gap laser-triggered vacuum switch are compared later. The test results prove that, affected by the imbalanced developed initial plasma between gaps, double-gap laser-triggered vacuum switch with two positive gaps and 1:1 laser split ratio presents best closing performances than other switches. With the rise of laser energy, closing delay time and jitter time of double-gap laser-triggered vacuum switch both decrease, while the influences from increasing voltages are weak. Closing delay time of P–P type double-gap laser-triggered vacuum switch can be controlled within 103 ± 1.5 ns under 90 mJ laser energy, and it is about 10 ns longer than single-gap laser-triggered vacuum switch. For some direct current applications with changing voltage directions, P–N type double-gap laser-triggered vacuum switch with 1:1 laser split ratio shows more stable closing performances. In addition, closing performances of double-gap laser-triggered vacuum switch can be further improved by optimizing the developments of initial plasma in series gaps.

1 | INTRODUCTION

Laser-triggered vacuum switch (LTVS) is a pulsed power closing switch developed combined the technical advantages of electrically triggered vacuum switches (ETVS) and laser-triggered gas switch (LTGS) [1, 2]. Under the interactions of pulsed laser beam with target materials, abundant initial plasma can be generated to close vacuum gap rapidly [3–5]. Compared to LTGS and ETVS, relative preferable time-delay characteristics, larger current capacities and wider operating voltage ranges can be obtained with designed LTVS [6–9]. With expanding applications of pulsed power technologies, requirements for the closing switches are also changed. LTVS shows excellent developing potential in the fields of high current switching under wide voltage ranges, such as direct current (DC) power system protections, static protections, electromagnetic launch systems and so on [10–14].

Prior works have documented the advantages of proper parameters on improving the performances of LTVS. Such as the delay time of LTVS proposed by Sandia Lab (gap distance 0.5 mm, breakdown voltage 6 kV) can be controlled within 100 ns under 20 μJ laser energy by optimizing its target materials [15]. R. G. Fellers et al. fabricated a 100 kV LTVS while the delay time is less than 1 μs [16]. Z. He et al. designed a 27 kV multi-rod LTVS with 12 mm gap distance, and the trigger delay time reaches 17 ± 2 ns [17, 18]. M. Liao et al. optimized the target configurations of LTVS to decrease its delay time [19, 20]. Limited by the non-liner grown
insulation capacity of vacuum gaps, there are few high-voltage-triggered vacuum switches employed in pulsed power facilities so far.

However, the developing pulsed power system calls for more comprehensive and better performances of closing switches. For example, the switches employed as auxiliary switch in high-voltage DC circuit breakers are required with higher hold-off voltage, wider operating voltage ranges and larger current capacities. Single-gap LTVS is able to satisfy most of requirements except for the high-voltage application. Previous researches on multi-break vacuum circuit breakers found that the breakdown voltage of vacuum switches can be improved efficiently by connecting multiple short vacuum gaps in series [21, 22]. To utilize the advantages of LTVS to develop high-voltage pulsed power switches with better operating performances, a multi-gap LTVS (MLTVS) composed of multiple series connected laser-triggered vacuum gaps is proposed in this study.

Operating performances of LTVS mainly depend on the properties of laser-produced plasma (LPP), in other words, the initial plasma in vacuum gap. The differences among LPP in each vacuum gap would certainly affect the closing process of MLTVS. Based on the features of proposed MLTVS, this study investigates the closing process of a double-gap LTVS (DLTVS) with the established test prototype. Closing performances of DLTVS under different gap polarity configurations, laser split ratios, laser energies and operating voltages are studied. Influences from the imbalanced developed LPP between gaps on the closing processes are analysed. Closing delay time of DLTVS and single-gap LTVS are compared and discussed later.

2   DESIGN OF MLTVS

2.1  The developed 30 kV single-gap LTVS

A 30 kV LTVS is developed based on previous works; the schematic drawing of LTVS is shown in Figure 1. Recorded operating parameters of the switch are listed in Table 1. Trigger delay time of the switch reaches 35 ± 2 ns under 15 mJ laser energy with 1.1 mm² laser spot area on target surface. Service life of LTVS is over 2000 times while the charges through the switch are above 50 C per pulse. The ageing of LTVS is mainly caused by the loss of target materials based on test results. For the purpose of industrial applications, a fibre-optic trigger system for the LTVS is designed and experimentally tested, as shown in Figure 2. The max output laser energy from optical fibre reaches 16 mJ (1064 nm & 10 ns). Laser spot area onto target reaches 1 mm² after the long distance collimation-focus system (over 150 mm). The LTVS products can be reliably closed under ±200 V operating voltages with the optical fibre. Compared to the gas switch and its fibre trigger system in [23], the designed trigger system for LTVS is simpler and easier to be regulated to suit for different type of LTVS.

FIGURE 1  Schematic of laser-triggered vacuum switch

TABLE 1  Operating parameters of the LTVS

| Parameter             | Value                                |
|-----------------------|--------------------------------------|
| Operating voltage     | 0.05–30 kV                           |
| Current capacity      | 60 kA (3 ms)                         |
| Charge per pulse      | 100C                                 |
| Service life          | Over 2000 shot                       |
| Trigger delay time    | 35±2 ns (15 mJ, 1064 nm)             |
| Trigger threshold     | 5.8 mJ (1 nm² spot, 250 V, by optical fibre) |

Abbreviation: LTVS, laser-triggered vacuum switch.

2.2  Schematic diagram of proposed MLTVS

Based on the operating parameters of LTVS and the features of MLTVS, a ±120 kV four-gap LTVS is designed in this study, as shown in Figure 3. Four series connected 30 kV LTVS are separately located at the vertices of an isosceles trapezoid. With above structural arrangements, the voltage distributions
among four gaps can be relatively uniform without voltage grading methods based on electric fields simulation. For practical applications of the four-gap LTVS, there would be voltage grading methods employed to promise its reliability. Besides, four-gap polarities in the switch can be adjusted with requirements. There are laser channels set at the centre hole of insulators and pillars. Four vacuum gaps can be triggered synchronously with designed spatially laser path or optical fibre trigger system. The estimated operating voltage ranges of four-gap LTVS are about ±500 V–120 kV.

Closing processes of MLTVS are affected by different factors related to the properties of LPP in each gap, including gap polarity, operating voltage, laser energy, and so on [24]. For different conditions in Figure 3, laser beams shoot into series gaps almost at the same time. Then the closing processes of these vacuum gaps and their interactions due to the different LPP properties would lead to complex closing processes of the switch. The increase of gap amounts could certainly result in further more complicated closing processes of MLTVS.

To simplify followed researches on MLTVS, closing performances of a DLTVS are studied in this paper. Compared to the four-gap LTVS, closing process of DLTVS is relative simpler. But the interaction principles between gaps and the regulating methods for imbalanced LPP during their closing periods are similar. Researches on DLTVS can provide suggestions for the developments of four-gap LTVS. Similar with the four-gap LTVS in Figure 3, DLTVS can be directly constructed with two single-gap LTVS in series. However, to conveniently change various influence factors, test prototype of DLTVS is developed based on the double gaps detachable vacuum chamber in this study. Based on previous works on LTVS, there are few operating parameters differences between the chamber and the sealed LTVS except for shielding and stray capacitance.

3 | EXPERIMENT SETUP

3.1 | Test platform for DLTVS

Structures of the DLTVS prototype and its electrode are presented in Figure 4a. The vacuum chamber is sealed with atmosphere by high transmittance quartz glasses on the top sides of two hollow conducting rods in upper triggered gap (UTG) and lower triggered gap (LTG). Gas pressure in the chamber is maintained below \(2 \times 10^{-5}\) Pa by pumps. Two laser beams shoot into the chamber through the centre holes of conducting rods and electrodes, and separately focus onto the surface of target materials in UTG and LTG finally. The target materials in this paper adopt the powder mixtures of Ti and KCl. The powder mixtures are compressed to be conical targets. The targets are assembled into the 5 mm centre hole at electrodes, as shown in Figure 4b. Target depths in two gaps are both set to 1 mm beneath electrode surface to decrease arc erosions. The arc control electrodes are employed to promise the current capacity and service life of DLTVS. Based on massive results, there are few influences from the electrode on closing delay time of LTVS compared to plate electrode. The surface materials of electrodes are CuCr50. Gap distances in UTG and LTG are adjusted to 2 mm, and the breakdown voltages of each vacuum gap are about 18 kV as measured.

Schematic diagram of test platform for the closing performances of DLTVS is presented in Figure 5. Pulse current can be generated with RC circuit, while the capacitance of \(C_0\) is 8.9 \(\mu\)F, and \(R_L\) is 11.85 \(\Omega\) non-inductive resistor. Equivalent inductance of test circuit \(L_d\) is about 5.6 \(\mu\)H. Two vacuum gaps in the DLTVS are separately paralleled with 9 M\(\Omega\) high-voltage resistors \(R_1\) and \(R_2\) to grade their operating voltages. \(P_{11}\), \(P_{12}\) (Tek P6015 A) and \(C_1\) (Tek TCP202 A and CT-4) in test circuit are voltage probes and current probe. Laser trigger system adopts Nd:YAG laser head to generate pulsed laser beam with 1064 nm wavelength and 10 ns pulsed width. The laser beam is spatially divided, reflected and finally focused onto the conical targets surfaces in two gaps. Laser spot areas on two conical target surfaces are both adjusted to 1.1 mm\(^2\). The generated linearly polarized state laser beam from laser head is Gaussian beam. The polarization states of laser beam
can be regulated by waving the wave plate in laser path. Thus the ratios of laser energy into two gaps, in other words, laser split ratios between two vacuum gaps after spectroscope can be adjusted. Influences of laser polarization states on trigger performances of the switch are neglected in this study. The pulsed laser signals are caught by laser detector.

3.2 Analysis on the closing process of DLTVS

Previous works on the trigger performances of LTVS proved that, after the decomposition of target materials under laser ablation, plasma diffusions in positive polarity vacuum gap at initial period mainly depend on electrons and negative ions (Cl⁻), while the plasma diffusions in negative gap mainly depend on positive ions (Ti⁺ and K⁺). For the DLTVS in this study, there are three gap polarity configurations, including P–P type, P–N type and N–N type, as shown in Figure 6. By changing connection methods of electrodes in vacuum gaps, closing performances of DLTVS can be studied.

Closing waveform of P–P type DLTVS under 60 mJ laser energy is shown in Figure 7. Laser split ratio is adjusted to 1:1. Operating voltage on DLTVS is 13 kV. \( I_C \) is the current signal smoothed by fast fourier transform filter. \( U_{\text{int}} \) is the pulsed laser signal caught by laser detector.

The voltage on DLTVS \( U_{\text{DLTVS}} \) begins to decline accompanied with voltage on UTG \( U_{\text{UTG}} \) at 38 ns since the rise of laser signal in Figure 7. Meanwhile, \( I_C \) also decreases below zero with oscillations due to the collisions of initial plasma with electrodes in two vacuum gaps. Voltage on LTG \( U_{\text{LTG}} \) begins to drop at 65 ns after the laser shot. At 175 ns since the rise of \( U_{\text{int}} \), \( U_{\text{DLTVS}} \) almost drops to zero, as \( U_{\text{UTG}} \) and \( U_{\text{LTG}} \) are about to decline to zero too. And the smoothed \( I_C \) starts to rise above zero. The switch can be completely closed at the moment. Based on sufficient test results under different conditions, the switches can’t be reliably closed until \( I_C \) rise above zero monotonically.

Researches on single-gap LTVS normally employ the trigger delay time to present its operating performances [17–19]. Trigger delay time is defined as the time duration from the initiation of laser signal to the beginning of voltage fall of LTVS, as the \( t_1 \) illustrated in Figure 7. Combined with plasma diffusion process of LTVS in Figure 8, abundant LPP can be generated immediately due to the laser materials interactions [25, 26]. LPP diffuse into vacuum gap with high velocities under the accelerations of target explosions and gap electric fields [27, 28]. The collisions of LPP with electrode surface would benefit to the formations of initial discharge channels in vacuum gaps, leading to the voltage fall of switch [29, 30]. Due to the strong interactions of laser with target materials under sufficient laser energy, abundant initial plasma can be generated with highly enough initial velocities and complex compositions [31, 32]. The followed collisions of LPP with electrode surface involve in complicate physical processes, leading to oscillations of current and voltage signals of the switch during voltage fall period based on massive results. And the oscillations of current prove that there are no stable discharge channels formed in vacuum gaps at the period.
FIGURE 8  Plasma diffusion in vacuum gap at initial period. (a) Photo of LPP in LTVS and (b) schematic of LPP diffusion. LPP, laser-produced plasma; LTVS, laser-triggered vacuum switch

(a) photo of LPP in LTVS  (b) schematic of LPP diffusion

For the closing process of DLTVS in Figure 7, though the fall time of $U_{LTG}$ is 27 ns beneath $U_{UTG}$, $U_{DLTVS}$ and $I_C$ begin to drop with $U_{UTG}$. The declines of $U_{DLTVS}$ and $I_C$ manifest that there are unstable initial discharge channels formed in the switch to transfer charges. The differences of voltage fall time between gaps are mainly caused by the imbalanced developed LPP in two gaps. And the imbalanced developments of LPP would also result in different tendencies of voltages on two gaps during the voltage fall periods. Affected by the complex developing processes of LPP, there are fluctuations of $U_{DLTVS}$ accompanied with $U_{LTG}$ when $I_C$ is about rising above zero, enlarging the time duration of closing process. Until the monotonically rise of $I_C$, DLTVS can be closed with relative stable discharge channels in series gaps, and the voltages on two gaps decline to zero. The closing delay time of DLTVS is defined as the time duration from the rise of laser signal to the moment of current signal $I_C$ rise above zero, as the $t_2$ illustrated in Figure 7. In addition, the peak value of initial current $I_C$ during voltage fall period increases with the rise of applied laser energies and operating voltages. The directions of initial current change with vacuum gap polarities.

Figure 9 presents the relationships of voltage and current on DLTVS with transferred charges $Q_C$. $Q_C$ is calculated with the integration of un-smoothed $I_C$, as shown in Equation (1). $Q_C$ begins to decline below zero while $U_{DLTVS}$ starts to drop due to the collisions of LPP with electrodes. The decline of $Q_C$ also proves that there are unstable discharge channels formed to transfer initial charges. The transferred initial charge reaches $-30 \mu C$ in 137 ns. $Q_C$ starts to rise monotonously at 175 ns after laser shot. Meanwhile, $I_C$ is about to rise above zero with weak oscillations, and the switch is closed.

$$Q_C = \int_0^t I_C dt$$

(1)

Based on above analysis, it is suggested to employ the closing delay time of DLTVS to represent its performances. Closing process of DLTVS depends on the closing processes of each single gap in the switch. The different tendencies of voltage waveforms of two gaps during the closing period indicated that there are dynamic charge transfers between gaps. The dynamic charge transfers are mainly caused by the imbalanced developed LPP in each gap, leading to the unstable charge transfers of DLTVS at initial period. The generations and developments of LPP mainly rely on the laser materials interactions and electric fields in vacuum gaps. Thus the differences of LPP under different conditions would lead to various tendencies of voltage waveforms, affecting the closing processes of DLTVS.

For example, Figure 10 presents the closing processes of DLTVS under different gap polarity configurations and laser split ratios. Laser energies on these DLTVS are 60 mJ. For the switches with same polarity gaps in Figure 10a,b, LTG is triggered ahead of UTG under the double of laser energy. More LPP can be generated in LTG compared to UTG. $U_{LTG}$ almost declines to zero before the fall of $U_{DLTVS}$ due to the initial discharge channels cannot be formed in DLTVS until the reliable trigger of UTG. For the P–N type DLTVS in Figure 10c, the negative polarity LTG can be triggered ahead of positive UTG under 40 mJ laser energy, leading to the decline of $U_{LTG}$. Affected by the plasma diffusion mechanisms in different polarity gaps, the developments of initial plasma in subsequently triggered UTG under higher voltages can be accelerated. LPP in UTG is relatively more abundant than that in LTG during the rising period of $U_{LTG}$ based on test results. The rise of $U_{LTG}$ could also accelerate the developments of LPP in LTG, leading to the steeply drop to zero of $U_{LTG}$ before $U_{UTG}$. Closing process of the DLTVS in Figure 10d is similar with the N–N type switches. The positive UTG is triggered ahead of negative LTG under higher laser energy, and $U_{UTG}$ declines to zero before the trigger of LTG. Though voltage waveforms of two gaps in Figure 10 differ a lot due to
their operating conditions, the switches could not be reliably closed until the voltages on two gaps are both about to decline to zero, and $I_C$ starts to rise above zero monotonously.

This paper adopts the closing delay time of DLTVS to present its operating performances. The closing delay time $t_2$ and jitter time $t_j$ are calculated with (2) and (3), and the test count $n$ for each condition is set to 5.

$$t_2 = \frac{n \sum t_{2i}}{n} \quad (2)$$

$$t_j = \sqrt{\frac{n \sum (t_{2i} - t_2)^2}{n}} \quad (3)$$

4 | CLOSING TIME-DELAY CHARACTERISTICS OF DLTVS

4.1 | Closing performance of DLTVS with different gap polarity configurations

To investigate the influences of imbalanced developed initial plasma between gaps on the closing performances of DLTVS, closing time delay characteristics of DLTVS with different gap polarity configurations are compared. The test results are shown in Figure 11. Laser split ratios between two gaps are adjusted to 1:1. Operating voltages on the switches are 6 kV. The DLTVS with two positive gaps shows best closing performances than the other switches. Closing delay time of P–N type DLTVS are shorter than N–N type switch. Closing delay time of the P–P type DLTVS can be controlled within 103 ± 1.5 ns under 90 mJ laser energy. Besides, with the rise of laser energies, the decline rate of closing delay time of these switches both get slowly.

The imbalanced developments of LPP in two series connected gaps are mainly attributed to the different strengths of laser materials interactions and the differences of gap electric fields. Similar laser materials interactions strengths can be obtained in two gaps with 1:1 laser split ratio, while effects of polarization states of the laser beams are neglected. With the rise of laser energy, the laser material interactions in two gaps both can be strengthened. More LPP with higher initial velocities are generated under the effects of stronger materials explosions, benefiting to the rapidly closing of two vacuum gaps. Under sufficient laser energy, the amounts of generated LPP are abundant to fill up vacuum gaps quickly and their velocities are highly enough. The effects of rising laser energy on strengthening laser materials interactions get relatively
saturated. Thus the decline rates of closing delay time of DLTVS gradually get slow as laser energy increase. Under same electric fields strengths, diffusion mechanisms of LPP in vacuum gaps differ with gap polarities, in other words, the directions of electric fields. Due to electrons and negative ions in LPP are with relative lighter weights and faster initial velocities compared to positive ions in LPP, the accelerating effects of gap electric fields on the developments of LPP in positive gap are more effective than that of negative gap. And relative stable discharge channels can be formed quickly in positive gap. In addition, due to the differences of LPP in same polarities gaps are relative small, the dynamic charge transfers between gaps in P–P type switches are weak than the P–N type switch, also benefiting to the reduction of closing delay time. Therefore, P–P type DLTVS shows best closing performances compared to the others.

4.2 Closing performance of DLTVS under various laser energies and operating voltages

Affected by the changed operating voltage directions in some DC applications, P–N type DLTVS with 1:1 laser split ratio would present more stable performances than other switches, for example, auxiliary switch in DC circuit breakers. Closing time delay characteristics of P–N type DLTVS under different laser energies and operating voltages are shown in Figure 12. Laser split ratio between two gaps is 1:1. With the rise of laser energy, closing delay time and jitter time of DLTVS both decrease. Closing delay time of P–N type switch under 90 mJ laser energy reaches 136 ± 2 ns. Besides, under sufficient laser energy, the closing performances of DLTVS under different voltages show slightly differences.

By enlarging laser density on target surfaces, more LPP with higher initial velocities can be generated under stronger laser materials interactions. Closing processes of vacuum gaps both can be accelerated. The differences of imbalanced developed LPP in two polarities gaps could be gradually reduced. Thus the dynamic charge transfers between gaps could be accelerated and relatively weakened, benefiting to reducing the closing delay time of DLTVS. In addition, under sufficient laser energy, effects of increasing electric fields strengths on accelerating the developments of LPP can be relative weakened, as the initial velocities of LPP are highly enough. Thus the DLTVS under different voltages show similar closing performances.

Compared to closing delay time, trigger delay time of DLTVS under different voltages shows slightly differences while applied voltage ranges are from 4 to 12 kV. Thus the differences of voltage fall time durations of DLTVS under above voltage ranges would gradually approach to zero. Combined with Equation (4), the voltage decline rate of DLTVS \( \frac{du}{dt} \) increases with the rise of applied laser energies and operating voltages while the oscillations of \( U_{DLTVS} \) are neglected. \( C_s \) is equivalent capacitance of the circuit. Combined with Equations (1) and (4), \( I_C \) and \( Q_C \) at initial period can be enlarged with higher \( \frac{du}{dt} \). Thus more stable discharge channels can be

\[
I_C = C_S \frac{du}{dt} \approx C_S \frac{U_{DLTVS}}{t_2 - t_1} \tag{4}
\]

4.3 Closing performance of DLTVS with different laser split ratios

Except for influences from gap electric fields, laser materials interactions also play key roles on the closing processes of DLTVS. By changing the laser energy into two gaps, closing performances of the P–N type DLTVS with different laser split ratios are compared, as the results shown in Figure 13. The switch with 1:1 laser split ratio shows much shorter closing delay time and lower jitter time than the other switches. With the rise of laser energy, the closing delay time differences of the switches with 1:1 and 1:2 laser split ratios are gradually reduced. Jitter time of these P–N type DLTVS are controlled within 4 ns under 90 mJ laser energy. Besides, due to the higher triggered thresholds of negative gap, the switch with 2:1 laser split ratio cannot be reliably closed when laser energy is beneath 35 mJ.

Ignoring the influences from laser polarization states, the strengths of laser materials interactions in vacuum gaps can be relatively balanced by uniformly dividing laser energy in the switch. The imbalanced developments of LPP in two polarity gaps can be relatively alleviated, profiting to shorten the dynamic charge transfers processes between vacuum gaps. Closing performances of P–N type DLTVS can be improved. Based on above results, the differences of developed initial plasma in different polarity gaps cannot be simply decreased by enlarging the laser energy into negative gap to two times than that of positive gap. Though the gradually saturated laser materials interactions in vacuum gaps under sufficient laser energy would benefit to reduce closing delay time differences.
between P–N type DLTVS. Besides, the developments of LPP would be severely imbalanced when the voltage directions on P–N type switch (with 1:2 laser split ratio) changes, leading to worse performances of DLTVS, as shown on the closing performances of switch with 2:1 laser split ratio.

5  |  DISCUSSION

Based on above researches, closing performances of DLTVS are affected by laser materials interactions in each gap, gap electric fields and the dynamic charge transfers between gaps. By optimizing the gap polarity configurations and laser split ratios in the switch, closing performances of DLTVS can be improved. The P–P type DLTVS with 1:1 laser split ratio shows best closing time delay characteristics than the others. But compared to the 4 mm single-gap LTVS, closing performances of DLTVS are still not satisfied under same external conditions, as the comparisons of DLTVS with single-gap LTVS are shown in Figure 14. Laser spot areas in LTVS are also adjusted to 1.1 mm². With the rise of laser energy, closing delay time of these switches both decrease. When laser energy is above 75 mJ, closing performances of positive LTVS and negative LTVS show slightly differences because of gradually saturated laser materials interactions strengths and relatively weakened effects from electric fields directions. Affected by the lower laser densities into series gaps and the dynamic charge transfers between gaps, closing delay time of the P–P type DLTVS are about 10 ns longer than single-gap LTVS under 90 mJ laser energy, and the jitter time of these switches are both controlled below 1.6 ns. Besides, due to the laser densities on target surfaces in LTVS are about double times than that of DLTVS, the service life of DLTVS seems to be longer than single-gap LTVS.

Compared to single-gap LTVS, closing performances of DLTVS are still required to be improved in some degree. For the developments high-voltage LTVSs with better performances, further researches on the MLTVSs ought to focus on optimizing the imbalanced developments of LPP in series gaps. The influences from dynamic charge transfers need be reduced to improve the closing performances. The switches are suggested to connect multiple positive short vacuum gaps in series and equally dividing the laser energy into each gap based on above results. In addition, for some DC applications with changing operating voltage directions, the switches are supposed to be composed of same amounts of positive gaps and negative gaps in series to promise its reliability, and the laser split ratio in the switch needs to be optimized.

6  |  CONCLUSIONS

Relative stable closing performances can be obtained with the proposed high-voltage DLTVS. Based on above studies, the following conclusions can be drawn:

i. Closing performances of DLTVS are determined by the developments of LPP in each single gap. Laser materials interactions in vacuum gaps, gap electric fields and dynamic charge transfers between gaps would both affect the closing processes of DLTVS.

ii. The P–P type DLTVS under 1:1 laser split ratio shows best closing performances than the other switches due of the relatively balanced developments of LPP in two gaps. Closing delay time of the P–P type DLTVS reaches 103 ± 1.5 ns under 90 mJ laser energy.

iii. With the rise of laser energy, closing delay time and jitter time of DLTVS both decrease. Under sufficient laser energy, there are slightly influences from the rising operating voltages (4–16 kV) on the closing performances of DLTVS. For some DC applications with changing voltage directions, the P–N type switch under 1:1 laser split ratio shows more stable closing performances.
iv. Closing delay time of the P–P type DLTVS is about 10 ns longer than the single-gap LTVS under 90 mJ laser energy, and jitter time of the switches can be controlled within 1.6 ns. Closing performances of DLTVS can be further improved by optimizing the imbalanced developed LPP in series gaps.

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