Best choice of insulation gas medium for MMGS in fast linear transformer driver

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ABSTRACT
Gas spark closing switch is one of the most important components for a fast linear transformer driver (FLTD). In this paper, we describe the investigation of insulation gas media for a multi-gap multi-channel gas spark closing switch. A six-gap gas switch with corona needles was tested in a typical FLTD brick with two capacitors of 40 nF and a load resistor of about 10 Ω. Corona discharge current, self-breakdown voltage distribution, and triggered breakdown performance were tested when the gas switch was filled with air, N\textsubscript{2}, CO\textsubscript{2}, SF\textsubscript{6}/N\textsubscript{2}, and C\textsubscript{4}F\textsubscript{7}N/N\textsubscript{2}. When C\textsubscript{4}F\textsubscript{7}N/N\textsubscript{2} was applied, there was no abnormal breakdown with low voltage found in the whole test process; the trigger breakdown delay time and switch jitter were very stable, and no pre-fire was found during about 2000 triggered shots. Therefore, we think the C\textsubscript{4}F\textsubscript{7}N/N\textsubscript{2} gas mixture with a very little amount of C\textsubscript{4}F\textsubscript{7}N can dramatically improve the switch performance. It is valuable and easy to realize the application of C\textsubscript{4}F\textsubscript{7}N/N\textsubscript{2} mixture in large scale pulsed power facilities.

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I. INTRODUCTION
Fast linear transformer driver (FLTD) is one of the developing direct drive technologies to generate high voltage high current pulse with a rise-time of 100 ns or so. It is of much importance for x-ray flash photography, Z-Pinch, inertial confinement fusion (ICF), etc.\textsuperscript{1,2} The typical feature of the FLTD based pulse generator is that it consists of tens to hundreds of thousands of primary discharge loops, which are called bricks. These bricks are arranged in parallel and in series in a certain type and are triggered in a specific timing sequence to generate the required high power pulses.\textsuperscript{3,4} According to recent progress, pulsed power facilities are developing toward large scale, higher power, faster front, and repetition rate. Gas spark switches for FLTD are required to be fired with high stability and reliability under a charge voltage of ±100 kV, peak conducting current of tens of kiloamperes, lifetime of the order of 10\textsuperscript{7}, pre-fire probability of the order of 10\textsuperscript{−6}, repetitive rate of 0.1 Hz, and so on.\textsuperscript{5}

To satisfy these strict requirements, a compact three-electrode gas switch, UV pre-ionization gas switch, plasma injection gas switch, multi-gap multi-channel gas switch (MMGS), etc., have been proposed and investigated in recent years. The MMGS with corona needles can provide corona discharge current through the gas gap to improve the voltage distribution along the inner surface of the switch chamber. The related research indicated that the MMGS with corona needles can be steadily operated over 50 000 shots, which are far more than other switches achieved.\textsuperscript{6,7} Dried air or pure nitrogen was usually chosen as the insulating gas medium, and pre-fires were still frequently found in these studies. In a word, although many efforts have been made in China and other countries, it remains difficult to reach the requirements for FLTD applications.

As we know, corona discharge on the needle tip in different gas media is different.\textsuperscript{10} This means that there exists a way to solve the problem by choosing proper gas medium. Therefore, in this paper, we focus on the corona discharge characteristics and firing performance of a MMGS in different gas media, aiming to find the best choice of gas medium for the MMGS with corona needles.

II. CONFIGURATION AND TEST SETUP
The configuration of MMGS tested in this paper is shown in Fig. 1. The switch mainly consists of high voltage electrode, intermediate electrode, switch chamber, corona needles, anchoring balls,
There are two high voltage electrodes and five intermediate electrodes, forming six gas gaps in series. The height of intermediate electrodes is 20 mm. These intermediate electrodes are fixed in the V shaped grooves on the inner wall of the switch chamber by anchoring balls made of PMMA. The length of each gap is equally set to 5 mm, and the total gap length of the switch is 30 mm. Corona needles (stainless steel needles with a length of 6 mm and a diameter of 0.9 mm) are screwed onto the electrodes, except for the positive high voltage electrode. There is just one gas inlet for pumping insulating gas in or out. A trigger pin is screwed onto the trigger electrode (one of the intermediate electrodes). The diameter of this MMGS is about 130 mm, and the total height is 150 mm.

Air and \( \text{N}_2 \) are general insulation gas media for pulsed power gas switches. Because of its high electrical strength, SF\(_6\) is often used as insulation gas in some electric equipment. However, SF\(_6\) has a significant greenhouse effect and is often mixed with \( \text{N}_2 \). As a possible environmentally alternative gas, \( \text{C}_4\text{F}_7\text{N} \) has a GWP value of about one tenth of that of SF\(_6\) and the dielectric strength of \( \text{C}_4\text{F}_7\text{N} \) is twice that of SF\(_6\). In recent years, it has been widely concerned and studied. Therefore, gas types to be studied in this paper mainly include dried air, pure \( \text{N}_2 \), CO\(_2\), and six types of gas mixtures (1%SF\(_6\)/99%\( \text{N}_2 \), 3%SF\(_6\)/97%\( \text{N}_2 \), 5%SF\(_6\)/95%\( \text{N}_2 \), 1%\( \text{C}_4\text{F}_7\text{N} \)/99%\( \text{N}_2 \), 3%\( \text{C}_4\text{F}_7\text{N} \)/97%\( \text{N}_2 \), and 5%\( \text{C}_4\text{F}_7\text{N} \)/95%\( \text{N}_2 \)).

The experimental circuit of the corona discharge current measurement is shown in Fig. 2. The capacitor (40 nF) was charged by a 120 kV DC high voltage source via a 1.5 M\( \Omega \) resistor. The six-gap gas switch to be tested, together with a 100 M\( \Omega \) resistor and a micro-ampere meter, was connected to the capacitor in parallel. Corona discharge current was measured by using the micro-ampere meter, and the charge voltage was measured by using a resistance voltage divider. To protect the \( \mu \text{A} \) meter, a gas discharge tube (GDT) was applied across the switch and micro-ampere meter.

The schematic of the test stand for the self-breakdown and triggered breakdown test of six-gap MMGS is shown in Fig. 3.

During the experiment, the test stand is submersed into a grounded tank filled with transformer oil. The oil tank provided ground potential in the test, which is similar to the actual situation in the FLTD cavity. In the self-breakdown test, the gas switch was...
filled with certain gas medium of 0.1–0.3 Mpa, the capacitors are automatically charged by a ±120 kV high voltage DC source until the gas switch breaks down. The load resistor is about 10 Ω.

In the triggered breakdown test, the capacitors were automatically charged to about ±100 kV by a high voltage DC source. Then, a trigger pulse (100 kV amplitude and 10 ns rise time) provided by the trigger generator was sent to the trigger pin. The trigger pulse and discharge current were measured by using a voltage divider and a Rogowski coil, respectively. After each shot, the gas inside the switch chamber was pumped out by a vacuum cavity and then refilled again by a gas supply via valves. The waveforms of trigger pulse and discharge current are shown in Fig. 4. The trigger delay time $\Delta t$ is defined as the time interval between the arrival of trigger pulse and the start point of discharge current.

III. RESULTS AND ANALYSIS

The values of corona discharge current of the six-gap gas switch with different gas media and charge voltages are shown in Fig. 5.

It is indicated that the value of corona discharge current linearly increases according to the increase in applied voltage. The initial voltage of corona discharge in pure N$_2$ is much lower than that of other gas media. It is noticeable that the slope of the I-U curves in pure N$_2$ is obviously steeper than other gas media. This means that the corona discharge in air, CO$_2$, SF$_6$/N$_2$, and C$_4$F$_7$N/N$_2$ is more stable than in pure N$_2$.

It is known that the electron affinity of a pure nitrogen molecule is very low, which makes it difficult for nitrogen to absorb electrons generated by corona discharge on the needle tip. As a result, the corona discharge develops rapidly and the corona current in pure N$_2$ is much higher. On the contrary, the electron affinity of O$_2$, CO$_2$, SF$_6$, and C$_4$F$_7$N is much higher than that of pure N$_2$. Therefore, it is easier for these gas media to absorb electrons near the needle tip. Then, a layer of negative ions will be formed around the region of the needle tip. The electric field near the needle tip will be dramatically
The MMGS was fired in self-breakdown mode for 100 shots in different conditions. The results of self-breakdown voltage in air, N$_2$, CO$_2$, SF$_6$/N$_2$, and C$_4$F$_7$/N$_2$ are shown in Figs. 6–10. The significant difference between Figs. 6–8 and Figs. 9 and 10 is whether there exist very low breakdown voltage shots. The lowest self-breakdown voltage is about 165 kV, while the average value is about 200 kV. This means that abnormal self-breakdown (usually called pre-fire in pulsed power technology) may occur before the charge voltage reach up to 200 kV. It will dramatically affect the reliability and stability of pulsed power facility with multiple gas switches.

We did not find any abnormal shot with a very low breakdown voltage when the MMGS was filled with SF$_6$/N$_2$ and C$_4$F$_7$/N$_2$. The dispersion of self-breakdown voltage in Figs. 9 and 10 is obvious lower than that in Figs. 6–8.

Then, the triggered breakdown performance was studied. The MMGS was filled with air, N$_2$, 1%SF$_6$/99%N$_2$, and 1%C$_4$F$_7$/99%N$_2$; the charge voltage was set to ±100 kV. By adjusting the gas pressure in the switch chamber, the working coefficient (ratio of charge voltage and self-breakdown voltage with certain gas pressure) in the experiments ranged from 60% to 90%. The MMGS was fired over 100 shots under each condition. The switch delay time is defined as the time interval between the arrival of trigger pulse and the start point of discharge current. The standard deviation of delay time is defined as a switch jitter. The experimental results are shown in Table I.

The trend of the delay time and jitter with the decline of the working coefficient is almost the same when the MMGS was filled with four types of gases/gas mixtures. The most important is the delay time, and the jitter is very stable when 1%C$_4$F$_7$/99%N$_2$ is used as insulation gas. We did not find any abnormal shots, such as pre-fire, non-triggered, or late triggered during the entire test process, which includes about 2000 triggered shots.

According to the experimental results, the gas mixture with a very little amount of SF$_6$ or C$_4$F$_7$N can dramatically improve the switch performance, especially to avoid pre-fire. For the consideration of the greenhouse effect, C$_4$F$_7$N/N$_2$ maybe better than SF$_6$ or SF$_6$/N$_2$. Although according to some research studies, C$_4$F$_7$N is a toxic gas, it is valuable and easy to realize the application of the C$_4$F$_7$N/N$_2$ mixture with a very little amount of C$_4$F$_7$N, especially for large scale pulsed power facilities. We think that the result is important and valuable for pulsed power systems with multiple gas switches.

### IV. CONCLUSION

In this paper, we presented a comparison study of several gas media of a six-gap MMGS for FLTD. From the aspects of corona discharge current, self-breakdown voltage, triggered breakdown performance, and environment consideration, C$_4$F$_7$N/N$_2$ with a very little amount of C$_4$F$_7$N is the best choice of gas medium for MMGSs in FLTD. The most impressive thing is that when C$_4$F$_7$N/N$_2$ was applied, there was no abnormal breakdown with low voltage found in the whole test process. The trigger breakdown delay time and

| Working coefficient (%) | Air | N$_2$ | 1%SF$_6$/99%N$_2$ | 1%C$_4$F$_7$/99%N$_2$ |
|--------------------------|-----|-------|-------------------|-----------------------|
|                          | Delay (ns) | Jitter (ns) | Delay (ns) | Jitter (ns) | Delay (ns) | Jitter (ns) | Delay (ns) | Jitter (ns) |
| 90                       | 55.49 | 1.30   | 55.82 | 1.24 | 53.70 | 1.24 | 53.89 | 1.41 |
| 80                       | 59.31 | 1.24   | 58.35 | 1.58 | 56.03 | 1.22 | 55.85 | 1.30 |
| 70                       | 63.45 | 2.49   | 63.63 | 5.37 | 61.56 | 1.86 | 62.43 | 2.31 |
| 60                       | 68.47 | 2.68   | 75.81 | 11.60 | 67.28 | 2.91 | 63.65 | 2.86 |
switch jitter were very stable, and no pre-fire was found during about 2000 triggered shots. The triggered performance of long-term operation is still under test, and subsequent results will be reported in the future.

**DATA AVAILABILITY**

The data that support the findings of this study are openly available in Mendeley datasets at https://doi.org/10.17632/kcwrkJxztp.5.

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