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ORIGINAL RESEARCH

Design and Performance of a Compact Marx Generator for Two-Electrode Gas Switch Used in ICF Power Conditioning System

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Abstract As the high-current, high-coulomb transfer two-electrode graphite gas switch had no trigger electrode and must be triggered by a nanosecond pulse, a compact Marx generator was developed to produce a nanosecond rise-time, voltage level around 100 kV negative pulse to trigger the gas switch. This paper presented the structure of the compact Marx generator and the performance used in ICF power conditioning system. The effect of the ultraviolet radiation was utilized to decrease the amplitude of the breakdown voltage of the spark gaps. Coaxial structure of the metal shell was employed to reduce the inductance of the Marx generator. Additional isolation circuits were improved to prevent the electromagnetic disturbance which was significant for the application of the two-electrode graphite gas switch. The results showed that the designed compact Marx generator was suitable and have been successfully used as the trigger generator in ICF power conditioning system.

Keywords Marx generator · Two-electrode gas switch · Pulse generation · Nanosecond pulse

Introduction

Two-electrode graphite gas switch has been widely used in inertial confinement fusion (ICF) power conditioning system for its excellent anti-ablation performance [1, 2]. Since with no separate trigger electrode, a trigger generator and a saturable ferrite magnetic switch were used to trigger the two-electrode gas switch by providing an overvoltage nanosecond pulse across the switch gap [3]. Several approaches were appropriate to produce the nanosecond pulse, including pulsed transformer, high-voltage capacitor discharge circuit and Marx generator. The Marx generator had the advantages of wide span of physical size and output capability which had been widely used to produce high voltage trigger pulse [4, 5]. However, the conventional Marx generator was not applicable to trigger the two-electrode gas switch due to the special discharge circuits of the ICF power conditioning system.

The ICF power conditioning system is a modular capacitive energy storage system that provides energy to flashlamps loads through a coaxial transmission line system requiring nearly 100 miles of high-voltage cable [6]. In order to increase the overall efficiency of the laser and stabilize the drive characteristics of the flashlamps, pre-ionization of the flashlamps method is used and precedes the main driven current pulse by approximately 300 microseconds [7]. The basic circuit of the ICF power conditioning system is shown in Fig. 1, a low-energy pre-ionization lamp check circuit (PILC) is used to produce a microsecond pre-ionization current pulse, as the PILC pulse had to transmit a long coaxial transmission line and directly overvolting the flashlamps, the reflected voltage wave could be inevitably transmitted back into the main discharge circuit, result in electromagnetic disturbance and high pre-fire probability of the trigger generator.

The compact structure of the Marx generator with metal tube that served as the return conductor can produce very fast rise-time voltage [8]. Previous studies have showed that proper design of the stray capacitance and the inter-stage capacitance could results in nanosecond rise-time

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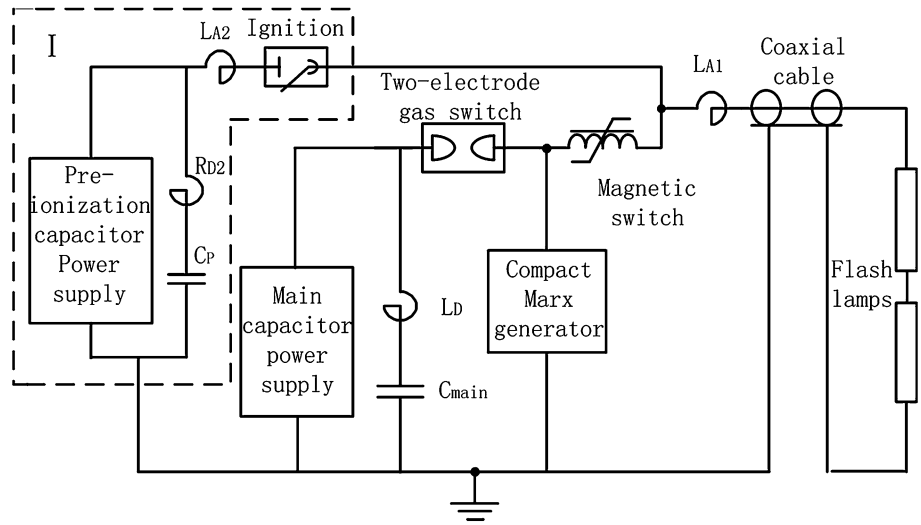

Fig. 1 Schematic of the typical ICF power conditioning system. (C_{main}: main storage capacitor, LD: Damping inductor, LA1: ballast inductor, LA2: *PILC inductor*, RD2: PILC resistor, Cp: PILC storage capacitor, I: PILC discharge circuit)

with several hundred kV output voltage [9]. As lack of the isolation device between the main discharge circuit and the trigger generator, the insulation failure of the trigger generator could be happened when the main discharge high current pulse flowing through. Thus additional circuit components were required to isolate the main discharge high current pulse.

Based on the analysis above, a compact Marx generator with additional isolation circuits were developed and evaluated. As the difference of the PILC electromagnetic disturbance and the effect of the main discharge current pulse, different isolation circuits were designed. The transient voltage produced by the PILC pulse on the output cable of the Marx generator was measured, and the output parameters of the Marx generator were obtained. The results showed that the designed compact Marx generator could isolate the electromagnetic disturbance successfully and work properly as the trigger generator in ICF power conditioning system.

Ceramic capacitors and spark gaps are selected for the advantages of lower inductance and fast closure time [10]. The basic equivalent circuit of the Marx generator is shown in Fig. 2, as the amplitude of the overvoltage on the next stage spark gap is mainly decided by the ratio of the capacitance C_{sw} and C_s, the increasing of C_s could increase the amplitude of the overvoltage on the follow-up spark gaps, which is very effective on the voltage multiplication [11]. Thus compact coaxial reflux metal chamber and high pressure dry air are used to increase the stray capacitance C_s and decrease the discharging inductance.

As the compact structure is sufficient to keep the discharging inductance of the Marx generator be small, the breakdown stability of the spark gaps become important for the entire system reliability. The ultraviolet has been proven to be effective on reducing and stabilizing the self-breakdown voltage of spark gaps when operating [12], thus the optical line-of-sight structure of the spark gaps is used to decrease the self-breakdown voltage of the spark gaps.

Design of the Compact Marx Generator

Basic Design

The Marx generator generally consists of several capacitors and switches, each capacitor charged by a high voltage power supply though charging resistors. When the first stage switch is breakdown, the next stage switch withstand almost double of the charging voltage and induce the switch turned on, This process is going on until all the switches are closed, then all capacitors are connected in series to produce a high voltage pulse. In order to achieve an output pulse with nanosecond rise-time, the inductance of the Marx generator's discharge circuit must be small.

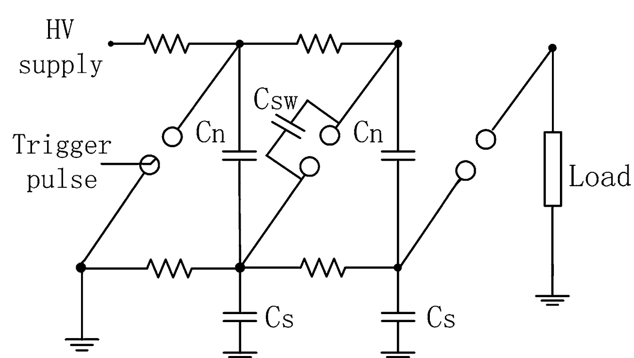

Fig. 2 The basic Marx generator circuit. (Csw: equivalent capacitance of the spark gap, Cs: stray capacitance, Cn: discharge capacitor)

When the first stage spark gap breakdown, the ultraviolet radiation is produced and ionized the rest of the unbreakdown spark gaps to decrease the self-breakdown voltage. In order to increase the intensity of the ultraviolet radiation, an auxiliary discharging capacitor is used between the first stage spark gap.

Based on these principles, a compact Marx generator was designed. Two trigatron gas switches were used as the first and second stage spark gaps, both of them were triggered simultaneously to increase the triggering reliability of the Marx generator. The rest of gas switches were two electrode self-breakdown spark gaps and the electrode material was high grade 304 stainless, uniform electric field was applied to eliminate corona discharge, the radius of these spherical electrodes was 10 mm and the gap distance was 2.2 mm, the internal structure was shown in Fig. 3. The self-breakdown voltage of the stage spark gaps change with pressure was shown in Fig. 4. The result showed that the self-breakdown voltage was linear with the pressure, and the scatter of the self-breakdown was very low.

The range of the operating voltage of the spark gaps was closely related to the triggering reliability of Marx generator, high working coefficient (the ratio of the operating voltage and self-breakdown voltage) could induce a high misoperation probability of the Marx generator. As the effect of the ultraviolet radiation and double trigger structure, the lowest working coefficient can decrease to 0.65, which was lower than the conventional Marx generator [13].

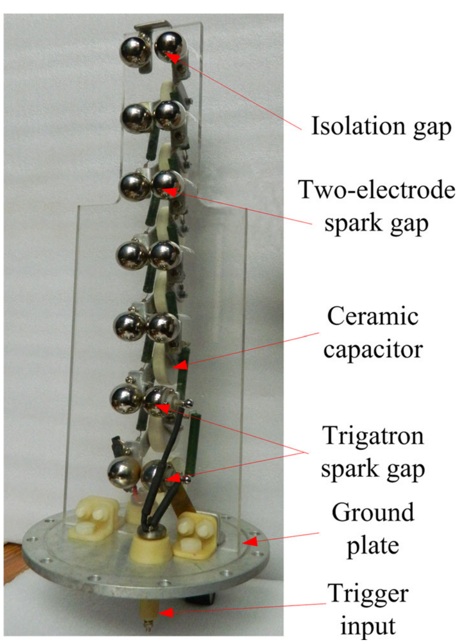

Fig. 3 Internal structure of Marx generator

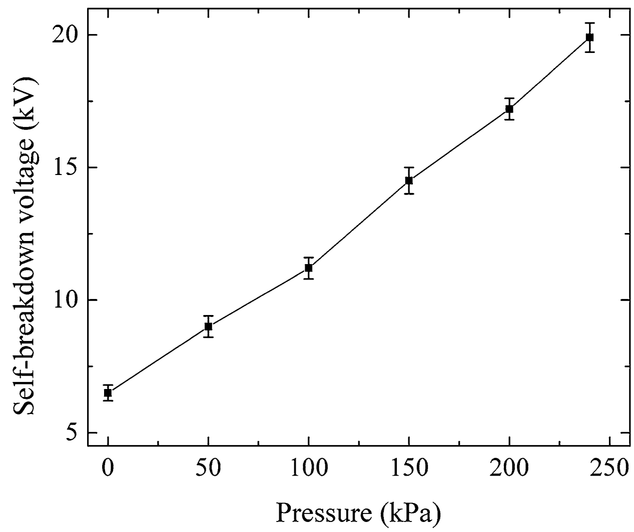

Fig. 4 Self-breakdown voltages of the Marx generator versus dry air pressure

Design of the Additional Isolation Circuits

Since the compact Marx generator was connected directly to the main discharge circuit, the PILC pulse and the main discharge pulse could transmit back into the last stage spark gap of the Marx generator and cause a pre-fire operation. Thus isolation circuits were necessary, as the operating voltage of the Marx generator had been applied when the PILC pulse flowing through the main discharge circuit, the isolation circuits need to guarantee the last stage spark gap cannot be disturbed. An isolation gap was sufficient to prevent the Marx generator from the disturbance. The isolation gap was designed as a self-breakdown two-electrode spark gap. In order to stabilize the output voltage, the E-field was designed a slightly uneven electric field, and was placed in an optical line-of-sight of the Marx generator's spark gaps, the structure was shown in Fig. 3. The gap distance was 12 mm, the DC self-breakdown voltage and impulse breakdown voltage change with pressure were shown in Fig. 5. In order to guarantee high reliability of the Marx generator, the self-breakdown voltage under working pressure 240 kPa was designed 50 kV to isolate the disturbance.

When the two-electrode gas switch was triggered by the Marx generator, the main discharge high current pulse was formed and could induce a high potential on the output cable of the Marx generator. While the isolation gap has been turned on and cannot isolate the disturbance any more, if the failure of the ceramic capacitors or resistors happened during discharging, the high current pulse could flow through the fault components to the Marx generator's ground, result in a terrible accident. Therefore a blocking capacitor was required to isolate the Marx generator from the main discharge circuit. As the ceramic capacitor had

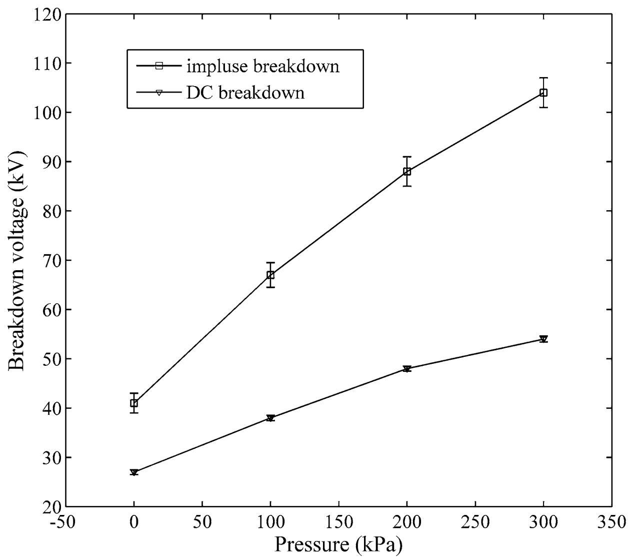

Fig. 5 Self-breakdown voltages of the isolation gap under itself output pulse and DC voltage

excellent high frequency response performance and can block low frequency pulse, high voltage ceramic capacitor was very appropriate for our application. The ceramic capacitor can block the microsecond high current pulse and let the nanosecond trigger pulse pass through which meant no effects on the output performance of the Marx generator, thus a high-voltage ceramic capacitor was chosen as the block capacitor, the electrical specifications were given in Table 1, and the overall schematic was shown in Fig. 6.

Measurement of the Compact Marx Generator in ICF Power Conditioning System

In order to verify the design rationality of the additional isolation circuits, the effects of the PILC pulse and the main current pulse on the Marx generator were analyzed in shenguang-III (SG-III) ICF power conditioning system. The charging voltage of the PILC capacitor was 23.5 kV, the reflected voltage waveform on the output cable of the Marx generator produced by PILC pulse was measured by using a HV probe(NORTH STAR: PVM-5) and the results were shown in Fig. 7. It can be seen that the voltage amplitude can reach 37 kV, the isolation gap must withstand this transient voltage, or not could cause a pre-fire operation of the Marx generator, this phenomenon happened when the isolation gap was not mounted. The designed self-breakdown voltage of the isolation gap was 50 kV which was high enough for this application. The effect of the main discharge current pulse cannot be evaluated directly for safety consideration, as the charging voltage of the main capacitors was 23.5 kV, the voltage waveform on the flashlamps can be measured directly, the result was shown in Fig. 8. We can see that the highest potential on the flashlamps was about 15 kV, this indicated that the potential on the output cable of the Marx generator was less than 23.5 kV, for the reflecting voltage waveform cannot be formed, thus the operating voltage of the ceramic capacitor was designed 50 kV to guarantee a high reliability of the Marx generator.

Table 1 Specifications for the compact Marx generator

Number of stages	6
Charging voltage	13.5 kV
Working coefficient	0.65
Pressure	240 kPa
Marx stage capacitor	10 nF/20 kV
Auxiliary discharging capacitor	5 nF/20 kV
Isolation ceramic capacitor	850 pF/100 kV
Stored energy	5.5 J
Output impedance	50 Ω
Pulse rise time (10–90 %)	17 ns
Pulse width (FWHM)	95 ns
Height of the Marx	140 mm
Diameter of the Marx	35 mm

Characteristics of the Compact Marx Generator

The output voltage waveform of the compact Marx generator was measured with a HV probe, the charging voltage was 13.5 kV, which produced approximately 65 % of the self-breakdown voltage across the gaps in 240 kPa of dry air, the load was a two-electrode gas switch with capacitance about 40 pF, the results showed that the amplitude of the output pulse was about 100 kV and the rise time (10–90 %) was 17 ns. The delay time was defined as the interval between the time of the first stage trigatron switch breakdown and the time of the initial of the output pulse, the measured voltage waveform were shown in Fig. 9. The jitter was calculated as the standard deviation of the delay time. The observed average delay time and jitter of the output pulses were approximately 38 and 1 ns. The results showed that the output pulse build-up time was very small and stable, which indicated that the ultraviolet radiation method was very effective.

As the magnitude of the output pulse can influence the breakdown probability of the two-electrode gas switch, the scatter of the output pulse become an important parameter. The repeatability performance of the output pulse was obtained by overlaying twenty voltage waveforms and the results were shown in Fig. 10. The standard deviation of the magnitude of output voltage was 5.3 kV, and the scatter of the rise time was also calculated, the standard deviation

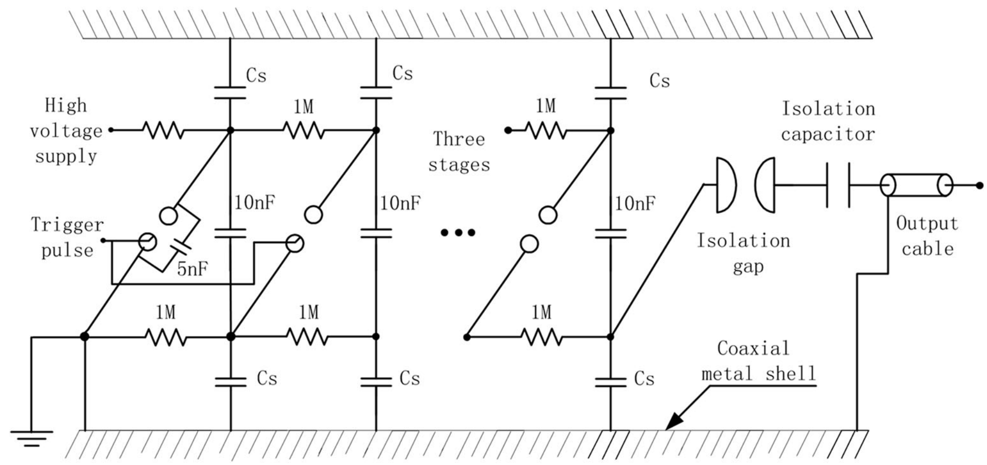

Fig. 6 Overall scheme of the compact Marx generator

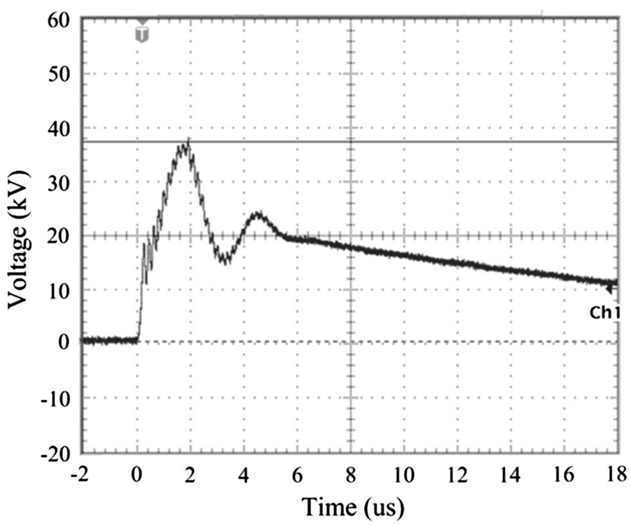

Fig. 7 The reflected voltage waveform on the output cable of the Marx generator

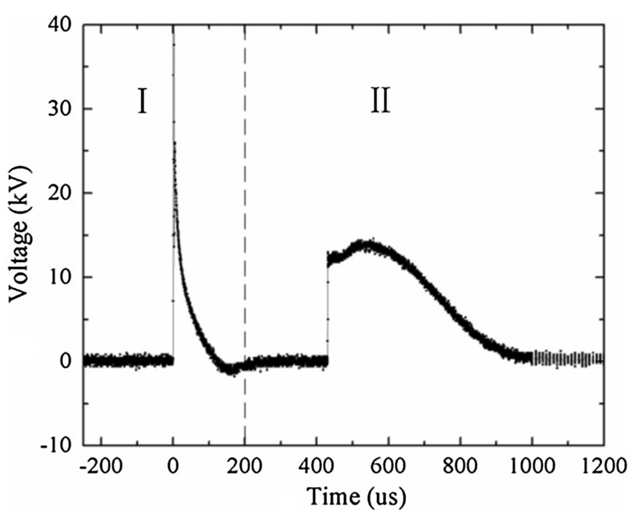

Fig. 8 Voltage waveform on the flashlamps (I: PILC discharge pulse; II: main discharge pulse)

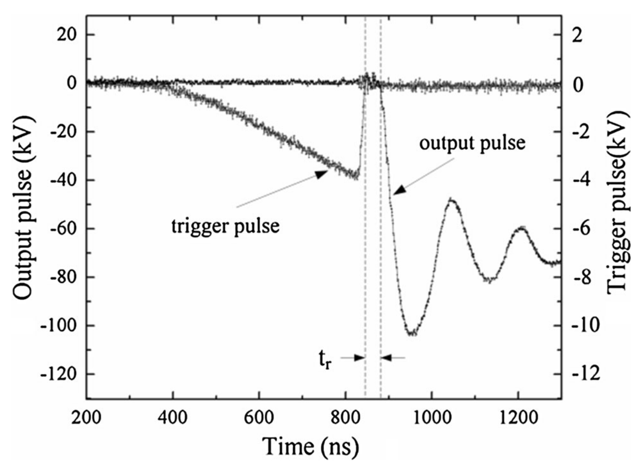

Fig. 9 Waveforms of the output pulse and the trigger pulse

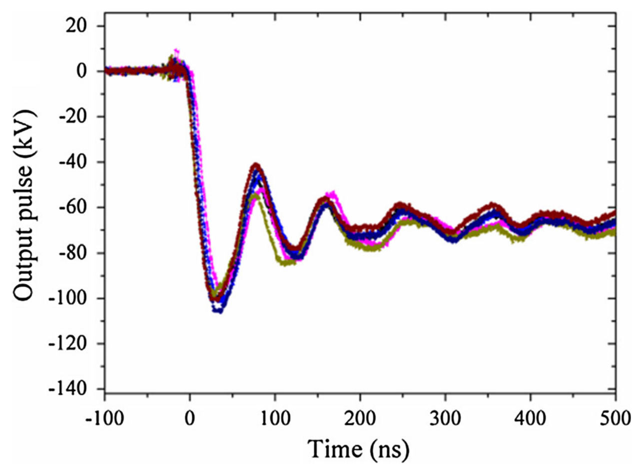

Fig. 10 Overlay of twenty output voltage waveforms

of rise time was less than 0.3 ns. After operating the Marx generator over 10,000 shots, no damage of the electrodes in gas switches and stable output performance were observed.

Conclusion

In this paper, a compact Marx generator with nanosecond rise-time was designed and tested for the two-electrode graphite gas switch. In order to eliminate the disturbance of the PILC pulse and the main discharge current pulse, a carefully designed isolation gap with 50 kV self-breakdown voltage and a high-voltage isolation ceramic capacitor were selected and evaluated. The reflected voltage waveform produced by PILC pulse on the output cable of the Marx generator was measured, the results showed that the amplitude of the reflected voltage can reach 37 kV. The performance of the compact Marx generator was also measured, a stable fast rise-time nanosecond pulse was obtained. The reproducibility of the output pulse was good and no damage of the electrodes were observed after operating over 10,000 shots, which indicated that the designed compact Marx generator was suitable for the two-electrode gas switch in ICF power conditioning system.

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