Investigation on a novel multiple-switch pulsed power technology

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INVESTIGATION ON A NOVEL MULTIPLE-SWITCH PULSED POWER TECHNOLOGY*

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Abstract

This paper discusses a novel multiple-switch pulsed power technology. By using transmission lines, multiple switches can be synchronized like in a MARX generator. To gain insight into this technology, an equivalent circuit model was developed, a two-switch experimental setup and a prototype pulsed power source with four gas spark-gap switches have been constructed. The four-switch setup includes 16 coaxial cables, four in parallel in each stage. This setup has been operated at a repetition rate of 50 pps with over 1.4 kA switching current. The principle, experimental setup and experiment results will be given in this paper.

I. INTRODUCTION

For large pulsed-power generation, multiple-switch based circuit topologies are often used to produce either a high voltage or a large current pulse or their combination. When the multiple switches are used in series, e.g. the Marx generator, large pulsed-power generation is realized by producing a higher voltage pulse. On the other hand, when the multiple switches are used in parallel, for instance in a capacitor bank, large pulsed-power generation is realized by producing a large current pulse. Obviously, the most critical issue for utilization of multiple switches is how to synchronize them. Generally, a specially designed synchronization trigger circuit is often needed.

A novel multiple-switch circuit topology for pulsed power generation was proposed by K.Yan in 2003 [1]. By means of a transmission line, multiple switches can be synchronized like in a MARX generator. The new circuit topology was first verified in a small model with three spark gap switches [1]. The new topology is attractive to be used to design a long-life large (100kW) pulsed power source for corona industrial applications, such as gas cleaning [2]. To gain insight into the technology, an equivalent circuit model was developed, and a two-switch experimental setup and a prototype pulsed power source with four switches have been constructed, and some measurements have been done. In this paper, both the principle and the experimental results will be given.

II. PRINCIPLE OF THE MULTIPLE-SWITCH CIRCUIT

Figure 1 shows the schematic diagram of a multiple-switch circuit with two spark-gap switches S_1 and S_2 and a two-stage transmission line transformer (TLT). The identical capacitors C_1 and C_2 are charged in parallel and are connected to the transmission line via switches at the input side. At the output side, the transmission lines are connected in series, and the output impedance is $2Z_0$. Z_0 is the impedance of the transmission line. Magnetic cores are placed around the transmission line to increase the impedance Z_s, which is defined as the wave impedance between the two adjacent stages of the TLT as seen from the input side.

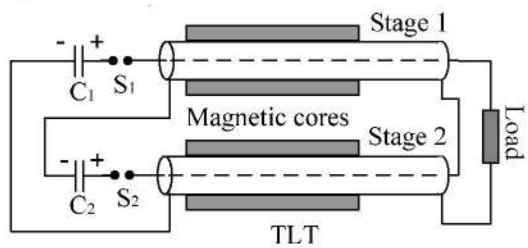

Figure 1. Schematic diagram of a multiple-switch circuit with two spark gap switches and a TLT

Whenever one of the two switches is closed, the other one will follow automatically. To figure out the synchronization mechanism, the equivalent circuit referred to the input side was developed for the ideal situation, where the length of the transmission lines is infinite, and the inductances induced by the connection leads can be neglected (Fig. 2).

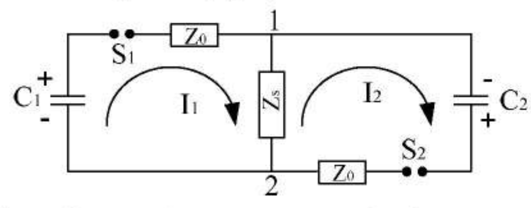

Figure 2. Equivalent circuit referred to the input side

Assume that the impedance Z_s is much larger than Z_0, (which is practically realized by using magnetic cores around the coaxial cables) and the switch S_1 is the one

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that closes first, then a voltage drop occurs across Z_s. This voltage drop is equal to $[Z_s/(Z_0+Z_s)] \times V_0 = V_{12} \approx V_0$, where V_0 is the charging voltage on the capacitors. At the same time, if the stray capacitance over the switch S_2 is much smaller than capacitor C_2, the voltage across switch S_2 rises to $V_0+V_{12} \approx 2V_0$, and this voltage will remain until S_2 is closed. The capacitor C_1 discharges only very slowly before the switch S_2 closes due to the large Z_s.

After all the switches are closed, with reference to the equivalent circuit in figure 2 one can obtain the following equations:

$$I_1(t)\cdot(Z_0+Z_s)-I_2(t)\cdot Z_s = V_0-\frac{1}{C_0}\cdot\int_0^t I_1(t)\cdot dt \quad (1)$$

$$I_2(t)\cdot(Z_0+Z_s)-I_1(t)\cdot Z_s = V_0-\frac{1}{C_0}\cdot\int_0^t I_2(t)\cdot dt \quad (2)$$

Where $I_1(t)$ and $I_2(t)$ are the currents flowing in switch S_1 and S_2 respectively, e.g. the currents in stage 1 and 2, and C_0 is the value of the identical capacitors C_1 and C_2. Solving these two equations, one can obtain the solutions of $I_1(t)$ and $I_2(t)$ as follows:

$$I_1(t)=I_2(t)=\frac{V_0}{Z_0}\cdot\exp\left(\frac{-t}{Z_0\cdot C_0}\right) \quad (3)$$

From equation (3), it can be seen that the currents are the same in each stage of the TLT, and then the voltage drop across Z_s is zero and the transmission lines at the input side are put in parallel equivalently. This equivalent circuit model is not exactly accurate in practice due to the finite length of the TLT, but it's good enough to understand the principle of the new multiple-switch pulsed power circuit.

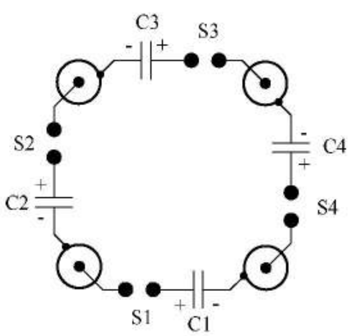

Figure 3. Schematic diagram at the input side of a four-switch pulsed power system

The multiple-switch circuit topology can be used to generate a large-power pulse either at a high voltage or at a large current or at their combination. Figure 3 shows the schematic diagrams at the input side of a four-switch system. It consists of four spark gap switches (S_1, S_2, S_3 and S_4) and four identical capacitors (C_1, C_2, C_3 and C_4) and a four-stage TLT. Figure 4 shows the options for schematic diagram at the output side of the system. In circuit (a), (b) and (c) the transmission lines are connected in series and in parallel and in combination (series and parallel) respectively; in circuit (d) the transmission lines are used to drive independent loads. These four circuits in figure 4 give identical output power. However, the output voltage for circuit (a), (b) and (c) respectively are four times, equal to and twice the switching voltage V_0. And the corresponding output currents are equal to, four times and twice the switching current I_0.

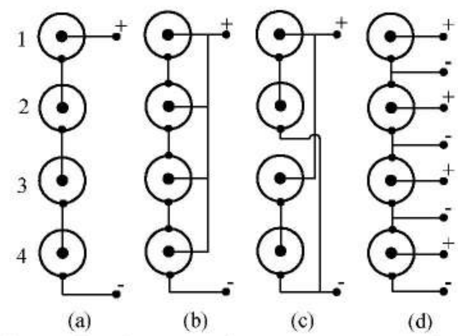

Figure 4. Schematic diagram at output side of a four-switch pulsed power system

Furthermore, as additional options, the capacitors can be replaced by transmission lines, and the spark gap switches can be replaced by solid –state switches.

III. TWO-SWITCH EXPERIMENTAL SETUP AND EXPERIMENT RESULTS

Figure 5 shows the schematic diagram of the main circuit of the experimental setup. It consists of a resonant charging circuit and a two-switch pulsed power circuit.

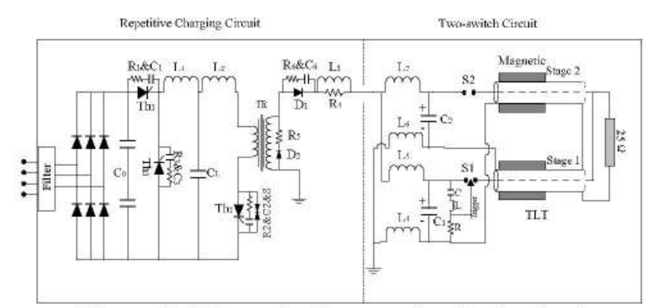

Figure 5. Schematic diagram of main circuit of experimental setup with two switches

The resonant charging circuit was developed earlier by our group [3]. It finishes one charging period through closing thyristors Th1, Th2 and Th3 consecutively. The output voltage ranges from 20kV to 40kV with a repetition rate up to 1 kHz.

The two-switch circuit consists of four 100 μH air-core inductors $L_{4\text{-}7}$, two 1.3 nF Murata high-voltage capacitors, two gas spark-gap switches, a 2-stage TLT and a 25Ω high-voltage disc resistor. As for the two switches, one is a self–breakdown spark gap switch, and the other one is a triggered spark gap switch [4]. The TLT is made from 1.5 meter long coaxial cable RG217 and at the output side the

TLT is connected in parallel and matched by a 25Ω resistor load. The magnetic cores (MP4510) are placed around the cables to increase the impedance Z_s. The length covered by the magnetic cores on each cable is 1 meter.

On this two-switch experimental setup, both voltages on the high-voltage capacitors and the current in each stage are measured. For the voltage measurements, the Northstar high voltage probe PVM-1 was used (ratio 1000:1, band width 80 MHz). With regard to the current measurement a fast Pearson current probe was used (model 6600 sensitivity 0.1V/A and usable risetime is 3.5 ns).

Figure 6 gives the typical waveform of the voltage on the positive ends of capacitors C_1 and C_2. The capacitors C_1 and C_2 are charged to 23 kV. The trigged spark gap S_1 is closed firstly, then the voltage on the positive end of C_2 rises up to nearly 44 kV, which forces the self breakdown spark gap switch S_2 to close.

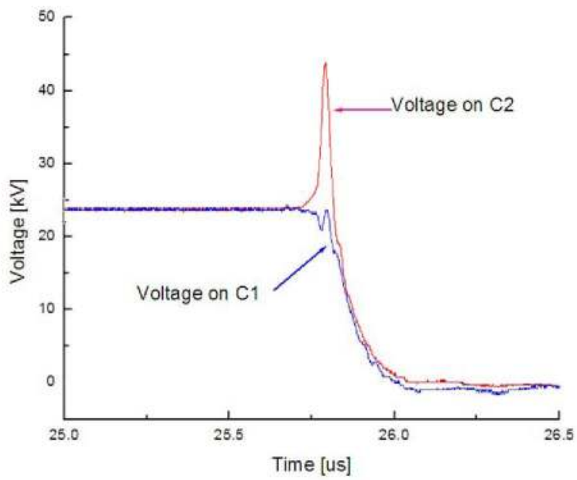

Figure 6. Typical waveform of potential on the positive ends of capacitors C_1 and C_2

Figures 7 and 8 show the typical waveforms of the currents in both stages of the TLT. In the case shown in figure 7, the capacitors C_1 and C_2 are identical, and have a value of 1.3 nF. The current in both stages of the TLT are almost same, which means that the currents in both stages are indeed synchronized. The risetime of the current pulse is about 25 ns. And the fall time of pulse, e.g. the time required for current to drop from 90% peak value to 10% peak value, is about 130ns, which is approximately equal to 2τ (τ is defined as time constant and equal to Z_0C_0.). It can be seen that the equation (3) obtained from the equivalent circuit model mentioned above is roughly accurate. In the case shown in figure 8, the capacitors C_1 and C_2 are 2.6 nF and 1.3 nF respectively. It can be seen that there is an oscillation at the end of the pulse due to the finite length of the TLT. This shows that selecting identical capacitors is necessary to achieve a pulse shape without oscillations.

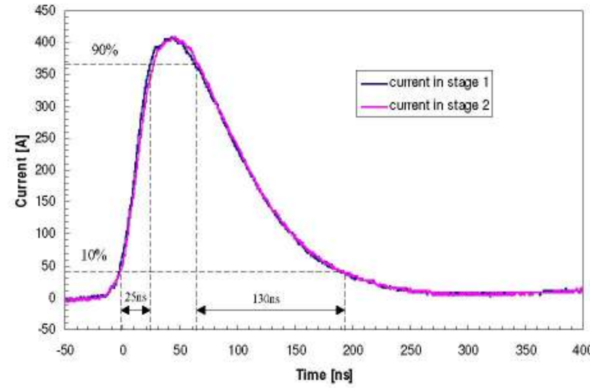

Figure 7. Typical waveforms of currents in stage 1 and stage 2 when C_1 and C_2 are 1.3nF.

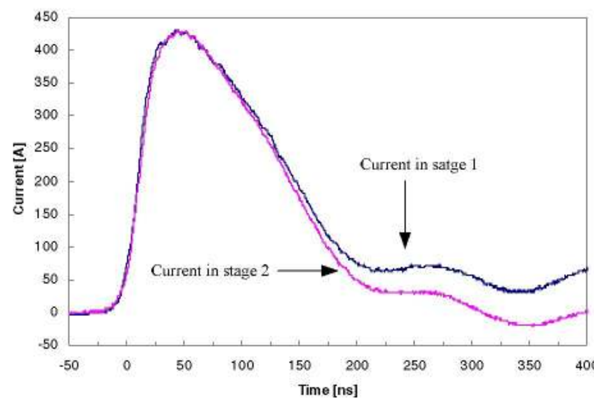

Figure 8. Typical waveforms of currents in stage 1 and stage 2 when C_1 and C_2 are 2.6 nF and 1.3nF respectively.

IV. PROTOTYPE OF A FOUR-SWITCH PULSED POWER SOURE

Figure 9 and 10 show the schematic diagram and a photograph of the four-switch pulsed power system. In this system, the charging circuit is same as that used in the two-switch system. The four-switch pulsed power circuit comprises of 8 inductors L_{4-11}, 4 high-voltage capacitors C_{1-4}, 4 gas spark-gap switches and a 4-stage transmission line transformer.

The eight 100 μH air-core inductors are used to charge the high capacitors and also serve as high impedance during the synchronization of the switches. The capacitors are Murata capacitors with 40 kV DC rating.

All four switches are gas spark-gap switches put into one cavity. One of the four switches is triggered; the other three are self-breakdown spark gaps. For the triggered spark gap, the distance of trigger gap is 2 mm, and the main gap is 10 mm. As for the self-breakdown spark gaps, the distance of gap is 10 mm.

Each stage of the transmission line transformer is made from four parallel 1.5m long coaxial cables (RG 217), and at the output side, the four parallel coaxial cables are connected to a 12.5 Ω resistor load. Magnetic cores are placed around each cable to increase the impedance Z_s, and the length of the cores is about half meter.

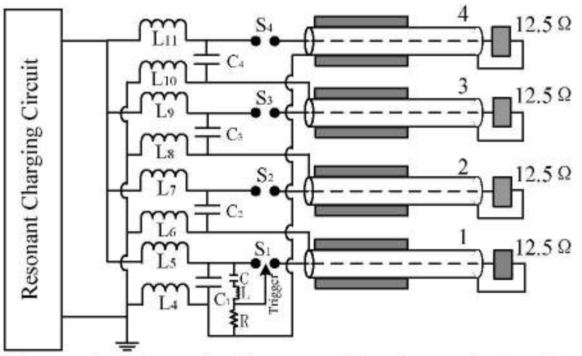

Figure 9. Schematic diagram of the four switch pulsed power system

Figure 10. Photograph of the four-switch pulsed power system

Figure 11 gives typical switching current waveform under the conditions with four 1.3 nF capacitors connected in parallel in each stage. From Figure 11, it can be seen that the risetime is over 50ns, which is caused by the lead connection. In order to obtain fast pulse with a risetime of about 20ns, more improvement on compactness of the system has to be done. Further voltage and current measurements in the four-switch setup are being prepared, and experimental results will be reported in future.

This system has operated at a repetition rate of 50Hz for half an hour with the switching current of over 1.4 kA, and no failure occurred. The target performance on this system is to obtain 2 kA switching current in each switch with about 20ns rise time at 1 kHz.

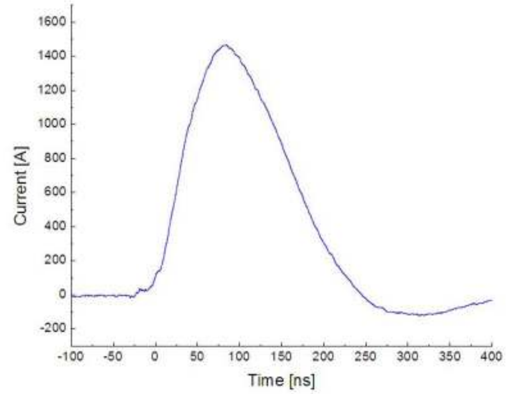

Figure 11. Typical switching current waveform

V. SUMMARY

The equivalent circuit model for analyzing the novel multiple-switch pulsed power circuit was developed. An experimental setup with two spark-gap switches and a prototype of a four-switch pulsed-power source have been constructed, and experimental results are given. The equivalent circuit model is roughly accurate. The currents in each stage indeed can be synchronized by the transmission lines, and this multiple-switch circuit can be used to drive independent loads. To obtain a good pulse shape, selecting identical capacitors is necessary. For generating fast and large pulsed power by multiple switches, much attention must be paid to making the complicated high-voltage mechanical structure very compact.

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