Current multiplication by using multiple thyristors

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This paper presents a circuit topology to obtain current multiplication by using multiple thyristors. To gain insight into this technique, an equivalent circuit model is introduced. Proper operation of the topology was demonstrated by experiments on a small-scale setup including three thyristors. One thyristor is triggered by a trigger circuit; the other two are autotriggered and require no external trigger circuit. The three thyristors could be synchronized automatically in sequence. During the closing process, the discharging of the energy storage capacitors via the thyristors is prevented. The discharging starts when all thyristors are closed, and the currents through each thyristor are simultaneous and identical. The output current is exactly three times the switching current. © *2008 American Institute of Physics.* [DOI: 10.1063/1.2949236]

I. INTRODUCTION

Heavy-duty, repetitive, solid-switch pulsed power generation is an emerging technology for the generation of powerful electrohydraulic discharges. These discharges can be applied for high-resolution seismic imaging and water treatment.[1–3] A recently introduced single-thyristor based repetitive pulsed power system is able to generate peak currents into the discharges of over 20 kA.[1] To increase the current level into the discharges to much higher levels (>100 kA range), multiple thyristors have to be used due to the limited capacity of a single device. When multiple thyristors are used in parallel, critical issues are how to synchronize them within a short time interval and how to obtain a good current balance among individual devices. Switch failures can be easily caused by the overcurrent caused by poor switch timing. Carefully selecting switches with similar specifications may reduce the overcurrent problem, but it is not a failure-free solution. This article presents and demonstrates a failure-free topology, by which a large current pulse can be realized by multiplying the currents through each thyristor. Testing was carried out on a small-scale setup including three thyristors. Experiments show that multiple thyristors can be synchronized automatically, and excellent current balance can be obtained. Moreover, to gain insight into the principle of this technique, an equivalent circuit model will be introduced.

II. EXPERIMENTAL SETUP AND RESULTS

Figure 1 shows the schematic of a testing setup with three thyristors. Three identical capacitors C_1–C_3 are charged in parallel via resistors R_1–R_6, and interconnected to three transmission lines line_1–line_3 via three thyristors th_1–th_3. The transmission lines are made from coaxial cables (Z_0=50 Ω) wound on ferrite toroids. Moreover, they are connected in parallel to a resistive load at the output side. Thyristor th_1 is manually triggered by closing switch S. The other two thyristors th_2 and th_3 are used as autotriggered switches (similar to spark gaps[4,5]), by placing a breakover diode (BOD) in series with a resistor R_T between their anodes and gates. A BOD is a gateless thyristor. It is designed to breakdown and conduct at a specific voltage in excess of several kilovolts and is used to protect applications.[6] When the transient overvoltage across th_2 and th_3 exceeds the BOD breakover voltage (which is chosen below the voltage rating of thyristors), the BOD becomes conductive and provides a trigger current, which turns on the thyristor. The value of this trigger current is limited by the resistor R_T, in series with the BOD. Once the thyristor is turned on, the parallel-connected RC snubber will provide the holding current to keep it conductive until all thyristors are closed. Three diodes D_1–D_3 are used to complete the energy transfer from the capacitors to the load when oscillation occurs. Within the present testing circuit, two diacs stacked in series were used as BODs, with a clipping voltage of about 90–100 V. C_1–C_3 have values of about 1.88 μF; R_T is 5 kΩ; R and C are 1 kΩ and 2 nF, respectively; the resistance value of the load is about 1.25 Ω; and the charging resistors R_1–R_6 were about 7 kΩ.

Figure 2 shows the typical voltages over thyristors (th_2

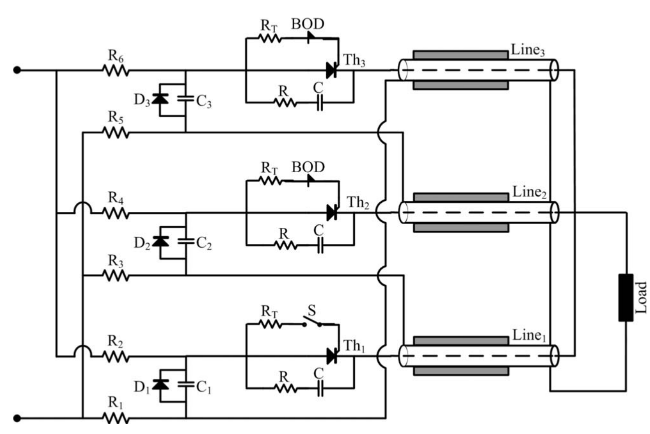

FIG. 1. The schematic of the experimental setup with three thyristors.

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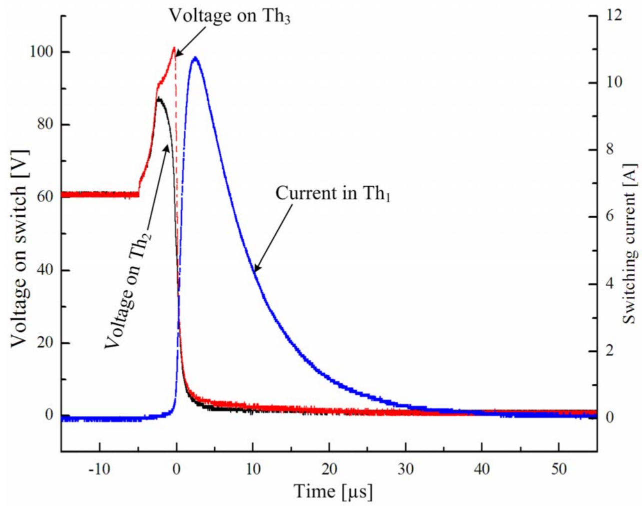

FIG. 2. (Color online) The typical voltages across thyristors th_2 and th_3 and the typical switching current in th_1 before, during, and after the switching process.

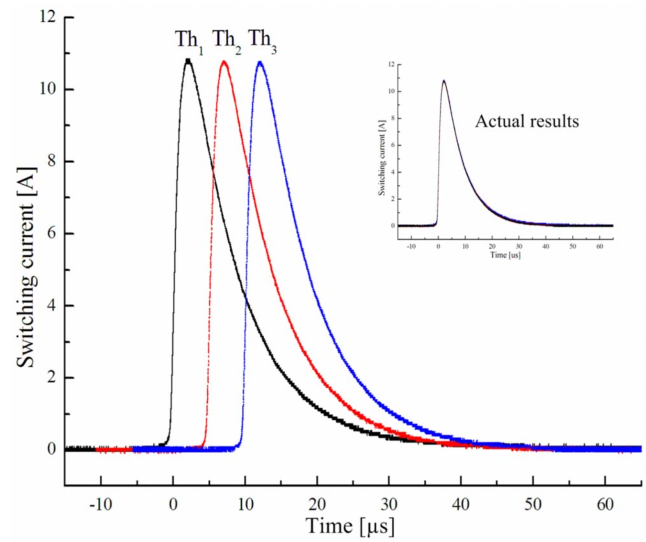

FIG. 3. (Color online) Typical switching currents in thyristors $th_1 - th_3$. They are shifted from each other for clarity; actually they are simultaneous and identical.

and th_3) and the switching current in th_1. They clearly show the working process of the thyristors before, during and after the synchronization. Initially, the capacitors are charged to 60 V. Thyristor th_1 was closed first by closing switch S manually. As expected, the closing of the first th_1 leads to overvoltage across thyristors th_2 and th_3, which forces the two BODs to conduct and turn on th_2 and th_3 sequentially within a time interval of 4.6 μs. The voltage over th_3 when it closed was 100 V, which is below the maximum theoretical value of 180 V since the BOD already broke before the maximum value has been reached. During the closing process, the switching current in th_1, as shown in Fig. 2, was very small due to the large inductance formed by the coaxial cables, which prevents the discharging of the capacitors (see also next section for a more detailed description). After all thyristors have been closed, the cables behave like a current balance transformer and the switching currents increase and the capacitors discharge into the load rapidly and simultaneously.

Figure 3 shows the switching currents in all thyristors $th_1 - th_3$. Note that the three curves are shifted in time for clarity; actually they overlap (see small plot within the figure). As can be seen, the time needed for all switches to close is about 4.6 μs, however, the switching currents are simultaneous and identical. Figure 4 gives the relationship between the switching current and the output current. Note that, again, both curves are shifted in time. It can be seen that they are simultaneous and the output current is three times the switching current, as expected.

From the experimental results, it can be seen that multiple thyristors can be synchronized with the present technique. Although they are switched on consecutively within a relatively long period, the discharging through each thyristor can only start when all the thyristors are closed. Moreover, an excellent current sharing can be obtained, thus no overcurrent will cause failures of individual devices. Today, thyristors with integrated BODs are commercially available.[7,8] It is believed that by using the present technique, pulses on the order of microseconds can be generated that meet various voltage and current requirements.

III. CIRCUIT MODEL

To gain insight into the mechanism of the technique, the equivalent circuit model shown in Fig. 5 can be used. Here the three transmission lines are represented by three identical 1:1 transformers $K_1 - K_3$, respectively. The winding inductance and the mutual inductance of each transformer are L and M, respectively. Now one can derive the following equations for three different situations: (i) switch S_1 is closed and S_2 and S_3 are open; (ii) switches S_1 and S_2 are closed and S_3 is open; and (iii) all switches $S_1 - S_3$ are closed.

(i) Switch S_1 is closed and switches S_2 and S_3 are open

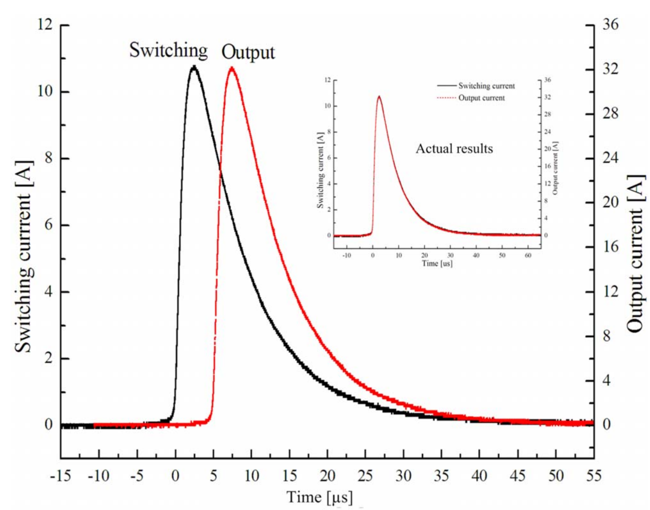

FIG. 4. (Color online) Relationship between the switching current and the output current. They are shifted from each other for the clarity; actually they are simultaneous.

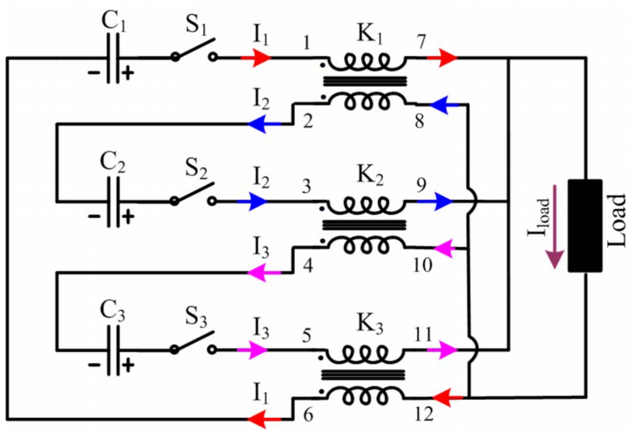

FIG. 5. (Color online) Equivalent circuit model of the three-switch circuits.

$$I_1(s) = \frac{V_c(s)}{2sL+Z},$$

$$V_{s_2}(s) = V_{s_3}(s) = \frac{3V_c(s)}{2}\left[1 - \frac{Z/sL + 2(1-k)/3}{2 + Z/sL}\right], \quad (1)$$

(ii) switches S_1 and S_2 are closed and switch S_3 is open

$$I_1(s) = I_2(s) = \frac{V_c(s)}{s(2-k)L+2Z},$$

$$V_{s3}(s) = 3V_c(s)\left[1 - \frac{2Z/sL + 2(1-k)/3}{(2-k)+2Z/sL}\right], \quad (2)$$

(iii) switches S_1–S_3 are all closed

$$I_1(s) = I_2(s) = I_3(s) = \frac{V_c(s)}{2s(1-k)L+3Z},$$

$$I_{\text{load}}(s) = 3I_1(s). \quad (3)$$

In the above equations, Z is the load impedance; k is the coupling coefficient of the transformers; $V_C(s)$ is the Laplace form of the voltage on the capacitors; $I_1(s)$, $I_2(s)$, $I_3(s)$, and $I_{\text{load}}(s)$ are the Laplace forms of the currents in switches S_1–S_3 and in the load respectively; $V_{S2}(s)$ and $V_{S3}(s)$ are the Laplace forms of voltages on switches S_2 and S_3, respectively. Under the assumption that $k \approx 1$, from Eqs. (1)–(3) one can conclude that (i) when the first switch S_1 is closed and the other switches S_2 and S_3 are open, the current in S_1 will be negligible (as shown in Fig. 2) when $\omega L \gg Z$; the closing of the first switch S_1 will lead to an overvoltage over the other switches (S_2 and S_3) that are open (as shown in Fig. 2), and the theoretical voltages on S_2 and S_3 could be up to about 1.5 times the charging voltage; (ii) when switches S_1 and S_2 have been closed and while switch S_3 is open, the switching current in S_1 and S_2 can be still kept very small (as shown in Figs. 2–4) provided that $\omega L \gg Z$; and the voltage on S_3 will continue to increase (as shown in Fig. 2), theoretically it can be up to three times the charging voltage; (iii) after all three switches have been closed, the currents in S_1–S_3 are identical (as shown in Fig. 3) and determined by the leakage inductance and the load; the current in the load is three times the current in each switch, as shown in Fig. 4. Now the discharging of each capacitor can be represented by an equivalent circuit model shown in Fig. 6, where the capacitor discharges into the load with a value of $3Z$ via an inductance $2(1-k)L$.

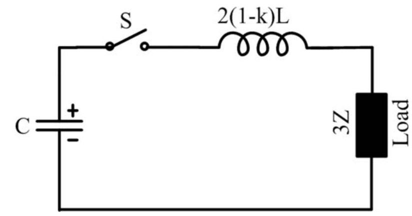

FIG. 6. Equivalent circuit model for the discharging through each switch after all the thyristors have been closed.

In principle, the circuit topology shown in Fig. 1 can be extended to any number of switches (m). After all m switches have been closed, the current in each switch and the current in the load can be expressed as:

$$\begin{cases} I_j(s) = \dfrac{V_C(s)}{2s(1-k)L+mZ} \\ I_{\text{load}}(s) = mI_1(s) \end{cases} \quad \text{where } j = 1,2,\ldots,m. \quad (4)$$

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