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Citation for published version (APA):

DOI:
10.1063/1.2176080

Document status and date:
Published: 01/01/2006

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:
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Download date: 08. Mar. 2020
Novel multiple-switch Blumlein generator

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(Received 2 December 2005; accepted 22 January 2006; published online 10 March 2006)

The Blumlein generator has been one of the most popular pulsed-power circuits. The pulse forming lines are charged simultaneously, and then discharged via a single switch, such as a spark gap. The generator can be used for single pulse or at a high repetition rate. However, for large pulsed power generation, one critical issue for such a single-switch based circuit topology is related to large switching currents. In this article, we propose a novel Blumlein circuit topology based on multiple switches. The pulsed forming lines are charged in parallel and then are synchronously commutated via multiple switches. No special synchronization trigger circuit is needed for the proposed circuit topology; this robust circuit topology is simple and very reliable. A prototype multiple-switch Blumlein generator with two spark-gap switches has been experimentally evaluated with both resistive and corona plasma loads. In terms of the switching currents, it is observed that the two switches can be synchronized within 2–3 ns. The energy conversion efficiencies are 82% and 76.8% for a matched resistive load and a plasma reactor, respectively. © 2006 American Institute of Physics. [DOI: 10.1063/1.2176080]

I. INTRODUCTION

The Blumlein circuit is commonly used for generating square voltage pulses. One of its advantages is that the output voltage on a matched load is equal to the charging voltage.1 Conventionally, the pulse forming lines are charged in parallel and synchronously commutated by a single switch, such as a spark gap.2–5 For such a single-switch based generator, the main problem when increasing the power is the large switching current. Multiple switches are preferred in heavy-duty pulsed power systems. The critical issue for multiple switches is how to synchronize them.

In this article, we introduce a novel multiple-switch based Blumlein generator. The charged pulse forming lines can be synchronously commutated by multiple switches and no synchronization trigger is needed. Experiments are performed on a two spark-gap switch based generator. Both a resistive load and a bipolar corona plasma reactor are used to evaluate it.

II. SINGLE-SWITCH BLUMLEIN

Figure 1 shows a typical example of a single-switch based Blumlein. It consists of four identical coaxial cables (lines 1–4), a spark-gap switch S, and a load. The lines 1 and 2 are used in parallel, which is identical to a single line with a characteristic impedance of 0.5Z0, where Z0 is the characteristic impedance of the cables. This is also true for the lines 3 and 4. With a matched resistive load, the output voltage and pulse duration will be V0 and 2τ, respectively, where V0 is the charging voltage, and τ is the transit time of the one cable. The switching and output currents are 2V0/Z0 and V0/Z0, respectively. Figure 2 shows an example of such output characteristics. The four pulse forming lines are 4.5 m long RG217 cables, the switch is an LCR triggered spark gap,6 the charging voltage is 27 kV, and the resistive load is 49.8 Ω. The shown waveforms are the voltage on the inner conductor of lines 1 and 2 at the switch side. One can easily see that the switching current is nearly twice the output current. The switching current would increase significantly when using a larger number of stacked Blumleins (i.e., to increase the power) or a low characteristic impedance cable.

III. MULTIPLE-SWITCH BLUMLEIN CIRCUIT TOPOLOGY

Figure 3 gives an example of a two-switch based Blumlein circuit topology. It consists of four identical coaxial cables (lines 1–4), two switches S1 and S2, and a load. At the right side, the lines 1 and 2 are interconnected via switches S1 and S2. Magnetic cores are placed around the outsides of the lines 1 and 2 to increase the secondary mode impedance (the wave impedance between the outer conductors of lines 1 and 2). The four identical lines are charged simultaneously up to V0. Whenever one of the two switches closes, there will be a voltage pulse traveling between the outer conductors of lines 1 and 2, which overcharges the other switch that is still not closed yet. As a result, the other switch is closed subsequently.

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After all switches are closed, lines 1 and 2 discharge simultaneously, and the EM waves are excited inside lines 1 and 2. The switching current per switch is \( V_0 / Z_0 \). After the transit time \( \tau \), the excited EM wave reaches the load. In an ideal case, i.e., with a matched load, a square pulse with 2\( \tau \) duration will be obtained. The output voltage and current are \( V_0 \) and \( V_0 / Z_0 \), respectively. The main advantages of this circuit topology are that no special synchronization trigger is needed and that the energy stored in the lines 1 and 2 cannot be significantly discharged until all the switches are closed. In comparison with the single-switch circuit in Fig. 1, the switching current in each switch is reduced by a factor of 2.

In fact, the circuit principle described in Fig. 3 can be used for any number of stacked Blumleins. Figure 4 gives an example of a four-switch stacked Blumlein generator. It consists of eight identical coaxial cables (lines 1–8), four switches \( S_1 \) to \( S_4 \), and a load. Magnetic cores are used around lines 1–4. At the right side, the lines 1–4 are interconnected via switches \( S_1 \) to \( S_4 \). At the left side, the four lines 5–8 are connected in parallel, which are identical to a single line with a characteristic impedance of 0.25\( Z_0 \). The output current is 2\( V_0 / Z_0 \), but the switching current per switch still is \( V_0 / Z_0 \), which is reduced by a factor of 4 compared to the single-switch circuit.

### IV. EXPERIMENTS AND DISCUSSIONS

To verify the proposed circuit topology and to study the synchronization characteristics, a two-switch Blumlein generator was developed. Testing was conducted on both a resistive load and a bipolar plasma reactor.

**Test with a resistive load.** The schematic diagram of the testing setup with a resistive load is shown in Fig. 5. The four identical lines are made from 4.5 m long RG217 cable. The length of magnetic cores around lines 1 and 2 is about 1 m. Switch \( S_1 \) is an LCR triggered switch, while switch \( S_2 \) is a self-breakdown spark gap. The 49.8 \( \Omega \) resistive load is a high-voltage recorder (HVR) disk type resistor. The diode \( D \) and inductor \( L_0 \) are used to charge the lines. The power supply is a three-step resonant charging system developed earlier in our group.

Figure 6 gives typical voltage waveforms of \( V_1 \) and \( V_2 \), where \( V_1 \) and \( V_2 \) are the voltages on the inner conductors of lines 1 and 2 at the switch side. It clearly shows the voltage transient before, during, and after the synchronization of \( S_1 \) and \( S_2 \). The four lines are charged up to 26.8 kV. The triggered spark gap \( S_1 \) is closed first, and then the voltage on the inner conductor of line 2 rises to 44.5 kV, which forces the self-breakdown spark-gap switch \( S_2 \) to close. The rise time of 29 ns (from 26.8 to 44.5 kV) of the overvoltage pulse indicates that the switch \( S_2 \) closes 29 ns after switch \( S_1 \) closes.

Figure 7 shows the current waveforms of \( I_s_1 \), \( I_s_2 \), and \( I_\text{out} \), where \( I_s_1 \) and \( I_s_2 \) are the switching currents of the switches \( S_1 \) and \( S_2 \), and \( I_\text{out} \) is the output current. The two switching current pulses are almost identical, and their time delay is around 2–3 ns. Thus, one can conclude that the currents in both switches are synchronous within 2–3 ns. In addition, the switching current is approximately equal to the output current. It is reduced nearly by a factor of 2 in contrast to that shown in Fig. 2. Figure 8 shows the typical waveforms of the output voltage \( V_\text{out} \) and current \( I_\text{out} \). The rise time and width are around 20 and 50 ns, respectively. And the peak output voltage and current are 25.5 kV and 510 A, respectively. It can be seen that, although multiple switches may close within a large time delay, their outputs are nearly synchronous and identical in terms of their switching currents. This
unique feature is the same as that of a voltage pulse generator based on multiple switches and a transmission line transformer.\textsuperscript{9,10}

To evaluate the energy conversion efficiency, the output power $P_{\text{out}}$, the output energy $E_{\text{out}}$, and the energy conversion efficiency $\eta_R$ are calculated according to the following equations:

\[ P_{\text{out}} = V_{\text{out}} I_{\text{out}}, \]
\[ E_{\text{out}} = \int P_{\text{out}} dt, \]
\[ \eta_R = \frac{E_{\text{out}}}{E_{\text{total}}} = \frac{E_{\text{out}}}{0.5 C_H V_0^2}. \]

In Eq. (3), $E_{\text{total}}$ and $C_H$ are the energy stored in the four lines and the total capacitance value of the four lines (1.8 nF), respectively. The typical output power and energy waveforms are shown in Fig. 9. The output peak power and energy are 13 MW and 0.568 J, respectively. The calculated energy efficiency $\eta_R$ is 82%. The energy loss is mainly caused by the spark gaps and the current in the secondary mode.

Test on a bipolar corona plasma reactor. An interesting application of this technique is generation of bipolar corona plasma, which can be used for flue gas cleaning.\textsuperscript{11} The schematic diagram of the setup with a corona reactor is shown in Fig. 10. Compared to the circuit shown in Fig. 5, the resistive load is replaced by a corona reactor, and the inductor $L_1$ is
added for charging the lines. The inductor $L_1$ is designed to have high impedance during the pulse forming process. The corona plasma reactor consists of two steel “saw-blade” arrays. Each array includes nine steel saw blades connected in parallel. The length of each saw blade is 80 cm, and the distance between two arrays is about 8 mm. Details of the reactor are shown in Figs. 11(a) and 11(b). Because the potentials on the two arrays are positive and negative, respectively, during plasma generation, we call this a bipolar plasma reactor. Figure 11(c) shows a time integrated (0.5 s) photo of the generated corona plasma, which was taken by a normal charge-coupled device (CCD) camera.

Figure 12 plots the typical waveforms of the switching currents $I_{s1}$ and $I_{s2}$ in switches $S_1$ and $S_2$, respectively. As observed with a resistive load, there is no problem at all for the synchronization. Figure 13 shows the typical plasma voltage and current waveforms. The peak values of voltage and current are 29 kV and 506 A, respectively. Figure 14 gives the typical waveforms of plasma power $P_{\text{plasma}}$ and energy $E_{\text{plasma}}$. The peak value of plasma power is 12 MW, and there is nearly no reflection after the first power pulse, which means that most of the electrical energy is transferred into plasma. In order to evaluate the efficiency of plasma generation, two kinds of efficiency are defined. One is the energy efficiency $\eta_{\text{plasma}}$ similar to $\eta_R$; another one is relative efficiency $\eta$. They are calculated by the following equations:

$$\eta_{\text{plasma}} = \frac{E_{\text{plasma}}}{E_{\text{total}}} = \int P_{\text{plasma}} dt \int 0.5C_H V_0^2,$$  

$$\eta = \frac{\eta_{\text{plasma}}}{\eta_R}.$$  

In Eqs. (4) and (5), $E_{\text{plasma}}$ is the energy absorbed by the corona plasma. With the present setup, the energy efficiency $\eta_{\text{plasma}}$ is in the range of 73.2%–76.8%, which agrees with the previous works, and the relative efficiency $\eta$ is in the range of 89.3%–93.7%, which means the plasma reactor was well matched compared to that in the resistor load.


