Design and Construction of a150kV/300A/1μs Blumlein Pulser

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Abstract:- Blumlein pulsers are well suited devices for high voltage pulse generation in the range of nanoseconds or microseconds. They consist of pieces of transmission lines charged in parallel and discharged synchronously in series into the load by using a single switch. The main problems with this type of circuit are the presence of the shield cable impedance that contributes to the power loss of the device and the requirement of long lengths of lines for operation in the microsecond range. In view of that, this paper presents a construction method that minimizes these losses and reduces the generator size by using coaxial lines coiled up on cylindrical tubes. In particular, we report the construction of a 150kV/300A/1μs Blumlein pulser that has been carried out in our laboratory, including a PSPICE simulation of the output pulse voltage of the generator.

Key-words: - Blumlein, pulse generator, transmission line, high voltage, coaxial cable, switch tube

1 Introduction

Blumlein devices are high voltage generators made of pieces of transmission lines and normally used in a great variety of applications such as in lasers, high power microwave generators and x-ray generation [1-2]. They are capable of generating high voltage pulses of several hundreds of kV in the nanosecond or microsecond ranges. Basically they consist of transmission lines (strip lines or coaxial cables) that are charged in parallel and discharged synchronously in series into the load. For example, Fig. 1 shows a 3-stage coaxial pulser where a single switch at the input makes the voltage commutation of the lines. The pulser structure is constructed by stacking three Blumlein lines, each one consisting of two transmission lines connected in series with an active line on the left to be switched and a passive line on the right (see Fig.1). Since the passive lines are only used for storing the charge voltage they may be replaced by capacitors. The principle of operation can be summarized as follows: in the initial state the lines are positively charged, but the net output voltage is zero because of the initial voltage vector opposition as indicated in Fig. 1. As soon as the switch is closed, the pulse voltages propagate down the active lines. After a propagation delay time the pulses arrive at the output where reflections occur converting the initial vector opposition to a series addition that remains for twice the line propagation time. This leads to an output voltage of 2nV for an open end or nV for the case of a load $2nZ_0$ matched to the generator output, where n is the number of

Blumlein lines and Z_0 is the characteristic impedance of the transmission line.
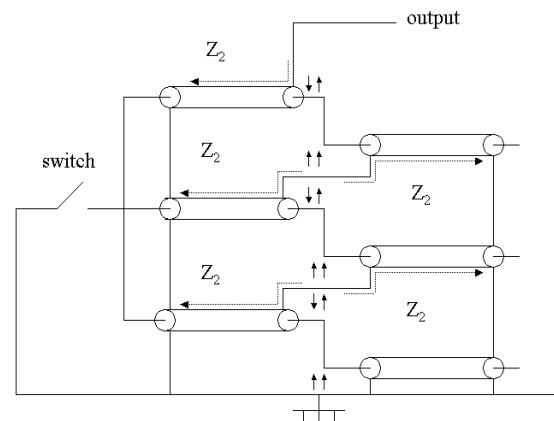
Figure 1. A 3-stage coaxial Blumlein pulser showing the cable shield impedance path (Z_2) and voltage vector commutation.

Regarding the pulser configuration circuit, there are two important impedances in a cable, the normal inner impedance (i.e. the cable characteristic impedance Z_0) and the impedance of the outer part of the shield (see impedance Z_2 in Fig.1). The impedance of the outer part of the cable can allow some current to reach ground without going through the load. If the outer impedance can be made large, for example by winding the cable on a former so that the inductance of the outer part of the jacket be larger, reducing the output current and, thus,

contributing less to the overall power loss of the Blumlein. In this paper we present a design method to make $Z_2 >> Z_0$ [3] as well as the current phase of construction of a high voltage Blumlein pulser (150kV/300A/1μs) that has carried out in our laboratory. Also we have included a PSPICE simulation of the output voltage pulse considering the shield cable impedance Z_2.

2 Pulser Design and Construction

The requirements of our pulser design are: 150 kV/300 A with pulse duration of 1 μs. Thus the pulser load of 500 Ω requires a design with 10 pieces of a 50-Ω coaxial cable (or 5-stages). To ensure a high breakdown voltage, we choose the coaxial cable URM67/50Ω with the maximum rating of 40 kV. Considering a 5-stage pulser and its output nominal voltage 150 kV gives a maximum charging voltage of 30 kV, below the cable breakdown voltage. The length of each transmission line is 100 m as the selected cable URM 67 has a double transit time of 10 ns/m, which implies in the pulse duration of 1 μs. To increase the device gain efficiency, the coaxial lines may be wound around insulated tubes as shown by the cross sectional view of the pulser supporting structure in Fig. 2. Each pair of insulated tubes on the same plane makes up a stage of the pulse generator, where the active and passive lines are coiled up respectively on the left and right tubes. Two ground planes made by thin copper plates put on both lateral sides of the structure provide the same value of the shield cable impedance for all lines (actives and passives) in the stack. Using this structure layout we can calculate the secondary mode impedance for each line from the coaxial coil inductance and the equivalent coaxial capacitance with respect to the ground plane such as [4]:

$$L = \frac{4\pi^2 \mu_r n^2 r_L^2 10^{-7}}{l} \quad [H] \quad (1)$$

$$C = \frac{24 \times 10^{-12} l}{\log\left(\frac{2h}{r_c}\right)} \quad [F] \quad (2)$$

Combining (1) and (2) gives

$$Z_2 = \frac{129\pi \, n \, r_L}{l} \sqrt{\mu_r \log\left(\frac{2h}{r_c}\right)} \quad [\Omega] \quad (3)$$

where μ_r is the relative magnetic permittivity of the coil core medium, h is the spacing between the outer part of the coaxial winding and the ground plane, l is the winding length, r_L and r_c are respectively the mean and outer radii of the winding and N is the number of turns. Using a length L_c=100 m of a coaxial cable wound on a PVC supporting tube with radius a = 0.2 m gives an estimated number of turns N = 80 ($L_c/2\pi a$). Since the outside diameter of the coaxial cable URM 67 is 10 mm a winding length of about 0.8 m is obtained. Thus making the approximation a≈r_L≈r_c (since the cable outside diameter is much smaller than the support tube radius) and setting the parameter h = 0.5 m we obtain from (1) that Z_2 is on the order of 7 kΩ. The estimate of Z_2 in the pulser design is necessary to assess the voltage gain of the Blumein pulser as shown in the next section. Fig. 3 shows a picture of the pulser structure that has been recently assembled in our laboratory.
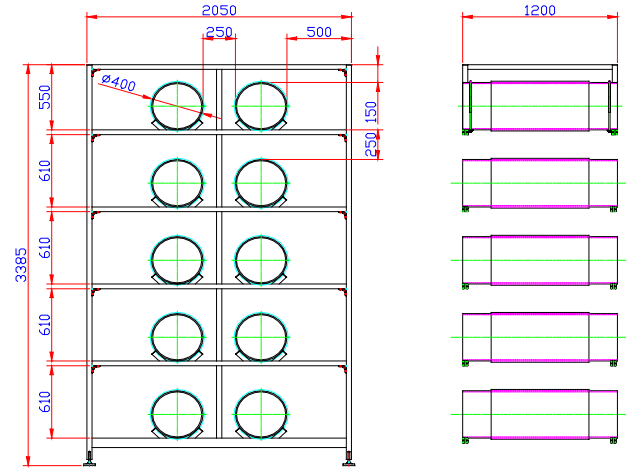
Figure 2. Cross sectional view of the pulser supporting structure with dimensions in mm.

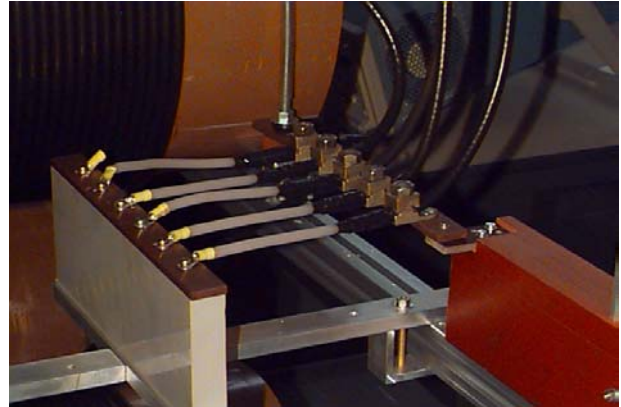**Figure 3.** Picture of the pulser structure assembling.

To charge the coaxial cables we use a charging high voltage power supply with negative polarity since the Blumlein pulser will be applied to ion

acceleration experiments such as plasma immersion ion implantation. The main specifications of the power supply are: maximum output voltage of 35 kV (below the cable breakdown voltage) and constant charge rate of 8 kJ/s. As the distributed cable capacitance is on the order of 100pF/m, the total Blumlein structure capacitance is calculated as 100m×10×100pF/m=100 nF. At a charging voltage of 30 kV the total energy stored in this capacitance is on the order of 45 J ($W=CV^2/2$), which gives a maximum pulse repetition rate on the order of 177 Hz for a power supply charge rate of 8 kJ/s.

To operate as a switch we have recently purchased a thyratron tube from EEV. To select the tube model, the maximum voltage/current ratings at the device input as well as the pulse repetition rate are required. The maximum charging voltage (35 kV) defines the voltage rating. The current parameter is found by calculating the total current when five cables are short-circuited. For example, a single 50 Ω coaxial cable contributes 600 A and, thus five such cables produce a total current of 3 kA through the switch. Taking into account the expected repetition rate of 100 Hz, the voltage and current operating parameters (30 kV/3 kA) the thyratron tube CX1722 with voltage/current/frequency capabilities of 35 kV/5 kA/200 Hz meets the requirements. The switch incorporates a glass envelope single gap tube that conducts in the reverse direction (hollow anode version). This is an important switch characteristic for applications such as ionic implantation where non-linear loads lead to reversal reflected voltages at the generator input side.

Finally, a point of great concern in the pulser design is related to the stray impedances in the connections at the cable ends. Mainly at the switch connections, stray inductance must be kept as small as possible in order to avoid an excessive increase in the pulse rise-time. To make a low inductance connection at the device input the coaxial cable shieldings are stripped back by 300 mm and soldering the inner conductors to a cooper plate. Then the shieldings are connected to a second cooper plate separated from the first one by the stripped shielding distance of 300 mm as seen in the picture of Fig.4. The same technique can be applied to make the output connections where the shieldings (or the inner conductors) of adjacent cables are joined and the shieldings of the upper and lower most cables are connected to the load. The second problem in the connections is the resonance frequency between the stray capacitance and inductance, which can lead to a decrease in the voltage gain and peak voltages causing cable ends to arc, even though the charging voltage is kept below the cable breakdown voltage.

The solution for this consists in increasing the spacing between two adjacent turns on the coil former in order to maintain the stray capacitance as small as possible. On the other hand, as an adverse effect this can decrease somewhat the secondary mode impedance since the coil length is increased.


Figure 4. Picture of the low inductance connection at the input cable ends.
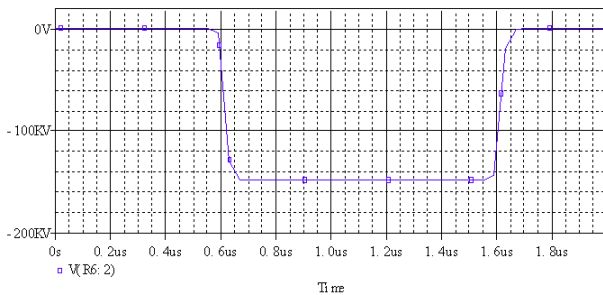
3 PSPICE Pulser Simulation

In this section the PSPICE simulation of the output pulse voltage assesses the performance of the device. For the simulation, the pulse generator is modeled by ideal coaxial lines with characteristic impedance Z_0= 50 Ω and transit time δ = 500 ns connected to a resistive matched load of 500 Ω. The open ends of the passive lines are simulated through high value resistors to avoid node list problems in the PSPICE simulation. First, we have considered an ideal case without the presence of the parasitic lines represented by the cable shielding impedance Z_2. Fig.5 shows the simulation circuit used in this case and Fig.6 gives the correspondent simulated output pulse voltage. Note in Fig. 6 that a flat pulse with amplitude of –150 kV with duration of about 1μs is obtained for an initial charge of –30 kV as expected. In this simulation the transient time in the switch model determines the pulse rise and fall times on the order of 0.2 μs.

Second, we have modeled the cable shield impedances by parasitic lines laid between the adjacent Blumlein stages. This is so because the cable shield impedance Z_2 represents the characteristic impedance of a transmission line formed by the shielding itself and the ground plane. As the cable shieldings are connected to the ground at one end the parasitic lines are short-circuited at their input in the model. These lines in the lower stages have characteristic impedance equal to half

the shield cable impedance as two impedances Z_2 are in parallel according to Fig.1, except for the top stage. In this case, the parasitic line characteristic impedance is equal to the shield cable impedance. In the model, all the parasitic lines have the same transit time given by $T = \sqrt{LC}$, where L and C are respectively the coil inductance and capacitance defined by (1) and (2) in section 2. Using the same parameters given in this section we tested the model with Z_2=7 kΩ and T=18 μs. Fig.7 gives the modified model circuit including the cable shielding lines and Fig.8 shows the simulation of the output pulse voltage in a longer time scale of 20 μs. Note that in this case the parasitic lines cause an unbalancing in the system and because of that there are reflections. As a result they cause some power loss in the device as the output pulse amplitude of –135 kV is lower than expected. Thus to obtain the required output voltage of 150 kV it is necessary to increase the initial charging voltage of the coaxial lines up to approximately 33 kV.
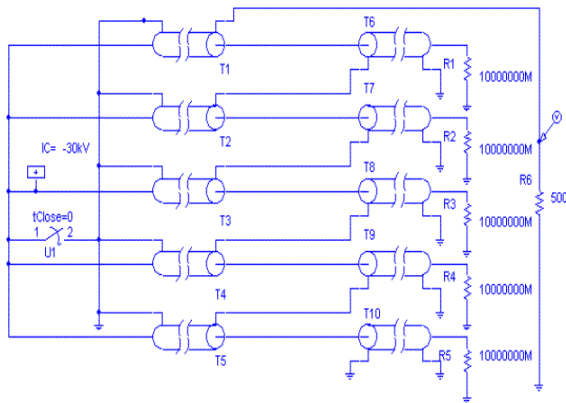
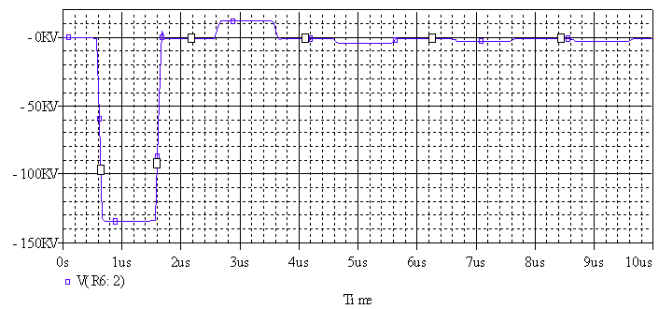**Figure 5.** PSPICE circuit model of the ideal Bumlein. Pulser.

Figure 6. Output pulse voltage simulation of the ideal Blumlein pulser.
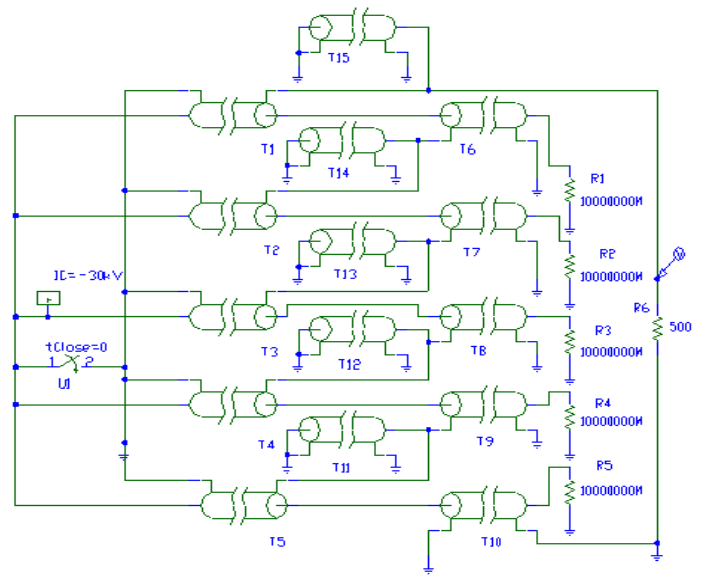
Figure 7. PSPICE circuit model including the cable shielding impedance.

Figure 8. Simulation of the output voltage pulse including the cable shield impedance.

4 Conclusions

In this work we have presented the design and construction of a 150 kV/300 A high voltage Blumlein pulse generator for long pulse operation on the order of 1 μs. Basically the pulser has been built by connecting long lengths of transmission lines coiled up on insulating tube formers to minimize the adverse effect of the shield cable impedance on the voltage gain of the device. Although the device is not ready yet to be put into operation, we have demonstrated the possibility of obtaining voltages in excess of 130 kV for lower charge voltages as low as 30 kV. To verify the pulser gain, we have made a simulation of the output pulse voltage including the effect of the shield cable impedances that are modeled (as well the cables) by ideal transmission lines.

On the other hand, with a pulse-forming network (PFN) design we could obtain the same output

voltage, but at a higher cost because of the pulse transformer required to step up the output voltage. Moreover, due to the stray inductance of the pulse transformer windings the pulse rise time could also be adversely increased.

Acknowledgment

References

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