

PORTABLE & LOW COST GIGA-WATT PULSED POWER SOURCE FOR INTENSE ELECTRON BEAM GENERATION

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Abstract

An alternative approach for applications requiring production of intense electron beam without using conventional configuration of Marx/Tesla accompanying Pulse Forming Line has been explored. The developed portable system utilizes four stage Blumlein pulse forming network made from inexpensive commercially available URM-67 coaxial cables having characteristic impedance of 50Ω . All stages are charged in parallel and then synchronously discharged through single low inductance railgap switch. Use of low jitter ($<5\text{ns}$) railgap switch allows synchronization with other events and improves reproducibility of the system.

Each stage of Blumlein is configured as eight parallel pulse forming network, with a resultant output impedance of 6.25Ω per stage. For four stages the output impedance is therefore 25Ω . A 24V battery driven 50kV DC to DC Converter has been used for charging the system. The generator is capable of delivering power up to 200kV, 4kA across matched load of 50Ω . The voltage pulse duration and rise time are 50ns and 8ns respectively.

In the presented paper, generator construction has been described and performance of the system is evaluated to realize adverse effect of parasitic impedance on the voltage gain and pulse shape. Also its operation has been simulated by PSPICE circuit simulator program and good agreement has been obtained between simulated and experimental results.

The entire cost of the generator including raw material and labor is under US \$2500. Other than low cost of the generator, added advantage of cable based system is that - the slow DC charging of transmission line to a known voltage eliminates the possibility of diode voltage prepulse in electron beam generation experiments. Applications of this pulse generator also include flash X-ray generation, breakdown tests, ion implantation, streamer discharge studies, ultra wideband generation etc.

I. INTRODUCTION

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Four stages of coaxial Blumlein consisting of eight pieces of transmission lines per stage are charged in parallel and then discharged synchronously in series in to the matched load by using low inductance railgap switch. The output pulse finally results in the gain of four times the charging voltage across matched load.

The pulser has been constructed using standard coaxial cables as they have well defined impedance, transmission line characteristic, reliable and are straightforward to work with. Use of coaxial cables also provides significant degree of flexibility in obtaining various pulse widths, voltages and impedance transformations. Cables are also inexpensive and easy to replace in the event of breakdown. Charging of the coaxial transmission line is done using 100W SMPS powered by 24V DC Panasonic batteries which makes the system portable. It converts the DC input to 50 kV/ 2mA as output. The total weight of power supply including batteries is less than 3Kgs. A block diagram showing the basic parts of the pulser is shown in figure-1

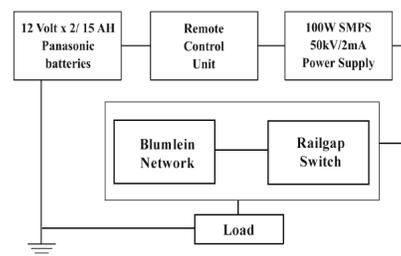


Figure 1. Basic components of Blumlein Pulser

II. GENERATOR DESIGN

Schematic of single stage Blumlein is shown as under –

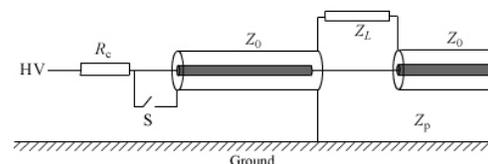


Figure 2. Single Stage Blumlein

As shown in figure 2, single stage Blumlein consists of two sections of transmission lines of equal length and same characteristic impedance. Here, the line is first charged up to voltage V, when the switch S is closed the wave starts and travels along first section of the transmission line.

After the transition time 't₀' a second wave is excited which travels along another section of the line. Both waves are reflected at the inhomogeneities of the line. The potential difference across matched load produced by these waves appears as a square pulse which has amplitude of 'V' and time duration '2t₀'. The results of such theoretical analysis are mathematically presented as under –

The output voltage of Blumlein is –

$$V_o = \frac{2VZ_L}{Z_L + 2Z_o} \dots\dots Eq. (1)$$

Hence, for matched load condition i.e. $Z_L = 2Z_o$, $V_o = V$. Where as in open load condition i.e. $Z_L \gg Z_o$, $V_o = 2V$.

The transition time along one section of line is given by –

$$t_0 = \frac{l\sqrt{\epsilon_r}}{c} \dots\dots Eq. (2)$$

Where l = length of each section of transmission line
 ϵ_r = Dielectric constant of the insulation used
 c = Velocity of light

Thus, the pulse width 'T' is twice the time taken by electromagnetic wave to travel the length of coaxial line in dielectric medium i.e. –

$$T = 2t_0$$

Characteristic impedance of the transmission line is given by –

$$Z_o = \sqrt{\frac{L}{C}} \dots\dots Eq. (4)$$

Where L and C are the inductance and capacitance of the coaxial line per unit length.

The energy per pulse (E_p), delivered to the load (Z_L) is –

$$E_p = \frac{TxV_o^2}{Z_L} \dots\dots Eq. (5)$$

Here, 'T' is the pulse length and 'V_o' is the amplitude.

The schematic diagram of four stage cascaded Blumlein configuration is shown in figure-3. Each stage is constructed by connecting two transmission lines in series. The principle of operation of the device remains the same as mentioned i.e. all the four stages consisting of eight transmission lines per stage are charged in parallel and discharged synchronously in series in to the load by a single railgap switch at the device input. The series addition which persists for twice the line propagation time leads to an output voltage of NV. Where, 'N' is the

number of stages employed and V being the voltage up to which line is charged.

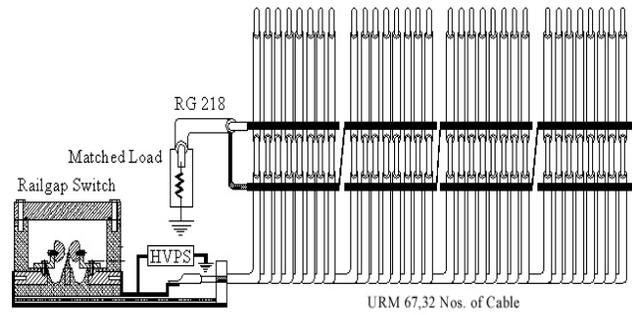


Figure 3. Schematic of four stage Cascaded Pulser

For matched load condition, load impedance of the cascade should be –

$$Z_L = N \times Z_o \dots\dots Eq. (6)$$

Here, each stage has been constructed using eight nos. of coaxial transmission line having identical length of 10m and then divided into two halves of 5m each. Chosen cable for this application is URM67, which has characteristic impedance of 50Ω. The equivalent characteristic impedance per stage becomes 6.25Ω.

The double transit time for 5m length of cable implies pulse duration of 50ns. Each stage of the transmission line contributes 6.25Ω to the total output impedance of the generator. Hence, with four stages the total output impedance of the pulser becomes 25Ω. For matched load condition, load impedance should be twice of generator impedance therefore $Z_L = 50 \Omega$.

As the distributed cable capacitance is of the order of 100pF/m, hence the total cascaded Blumlein capacitance is calculated as – $10m \times 32 \times 100pF/m = 32nF$. At a charging voltage of 50kV, the total energy stored in the system is ~ 40 Joules.

III. FABRICATION AND TESTING

The pulser has been constructed by stacking four Blumlein stages having cable length of 10m each. Selected coaxial cables of URM67 grade has characteristic impedance of 50Ω and is rated for 40kV. Polyethylene is used as insulation between the conductors having dielectric constant (ϵ_r) of 2.3. From each line, outer sheath of the cable has been removed from the centre to create two sections of transmission lines of 5m length, with a common core conductor. Then, the outer braid at both ends of each transmission line module is removed for a distance sufficiently long to enable operation of the pulser at charging voltages up to 50kV without flash over. One end of all the four Blumlein stages is terminated to a single railgap switch and the charging terminal is directly connected. The winding

arrangement along with experimental layout has been shown in figure 4.



Figure 4. Experimental layout of the Cascaded Pulser

Railgap switch has been used instead of spark gap because multichannel spark formation along the length of rail gaps leads to very low switch inductance. The initiation of several simultaneous spark channels along the switch length depends upon rate at which the electric field changes within the gap. Fundamentally, streamers have to be started before the gap closure (~20ns) to ensure multichannel operation. Due to this reason, trigger pulse rise time of greater than 5kV/ns is applied to the midplane knife edge trigger rail.

An oscillogram of the output voltage pulse of cascaded Blumlein pulser, when charged up to voltage of 30kV is shown in figure -5.

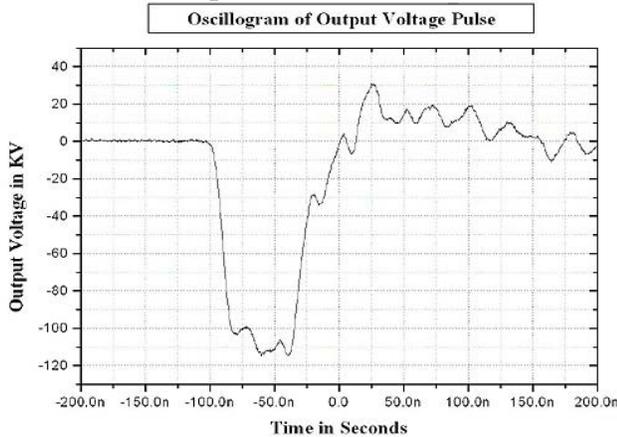


Figure 5. Oscillogram of Output Voltage

The voltage was measured to have value of 110kV across matched load of 50Ω using 1000X RC compensated high voltage probe (make – North Star,

model – PVM5) having bandwidth of 90MHZ. This results in producing system gain of 3.66 which corresponds to voltage gain efficiency of 91.66%.

IV. PERFORMANCE ANALYSIS

Regarding the pulser configuration (as shown in figure – 2), voltage gain efficiency of the system is reduced by presence of parasitic line impedance (Z_p). It exists between the outer part of the shield and ground.

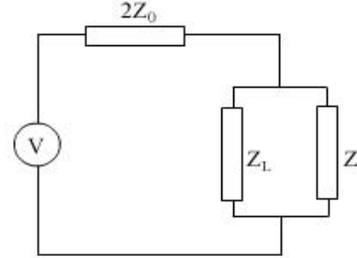


Figure 6. Equivalent circuit with Parasitic Impedance

Though, the parasitic impedance (Z_p) appears parallel with load impedance (Z_L). Hence, it reduces the gain of the system. In addition to affecting the voltage gain efficiency, it also causes trailing reflections after the square pulse which can be observed in the oscillogram. Thus to achieve higher system efficiency, the parasitic impedance (Z_p) should be much larger than characteristic impedance (Z_0) of the transmission line. Moving the system well above ground plane and inductively winding the cable on an insulated former does this, so that impedance of outer part of the jacket remains high.

Evaluation of parasitic impedance is necessary in order to assess the voltage gain of the pulser. It is equivalent to the shield cable impedance given by $\sqrt{L/C}$, where L and C are inductance and capacitance of the cables wounded inductively on a insulated former.

On the basis of constructional parameters equivalent inductance and capacitance with respect to ground plane are given as –

$$L = \frac{4\pi^2 \mu_r n^2 r_L^2 10^{-7}}{\ell} \text{ (Henry) } \dots\dots \text{Eq. (7)}$$

$$C = \frac{24 \times 10^{-12} \ell}{\log\left\{\frac{2h}{r_c}\right\}} \text{ (Farads) } \dots\dots \text{Eq. (8)}$$

Combining equation 1 and 2 gives – $Z_p = \sqrt{\frac{L}{C}}$

Here μ_r is the relative magnetic permittivity, h is the spacing between the outer part of the coaxial winding, 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 10m length of the cable wound on a PVC former having diameter of 20cms (i.e. $a = 0.10\text{m}$) gives sixteen number of turns. Since the outer diameter of the URM67 cable is 10mm, winding length (ℓ) of about 16cms is obtained for the cable length of 10mtrs. Since the cable outside diameter is much smaller than the PVC former diameter hence the approximation $a \approx r_L \approx r_c$ can be made.

As the spacing between the outer part of the coaxial winding and ground plane is 1m, calculated inductance and capacitance from equation 1 and 2 are $63.10\mu\text{H}$ and 2.95pF respectively. Though each stage has 8 nos. of cable therefore L and C per stage is $63.10\mu\text{H}/8$ and $2.95\text{pF} \times 8$ respectively. Thus, estimated parasitic impedance of the system per stage is 578.11Ω .

V. PSPICE SIMULATION

In order to investigate the reflections associated with the waveform as shown in figure 5, analysis and realization of the pulser has been done using circuit simulator program PSPICE. Modeling of the pulser has been done considering the parasitic impedance of the cable formed by shielding itself and ground plane. By using the estimated values of L and C model has been simulated with $Z = 578.11\Omega$ having one way transit time of 25ns.

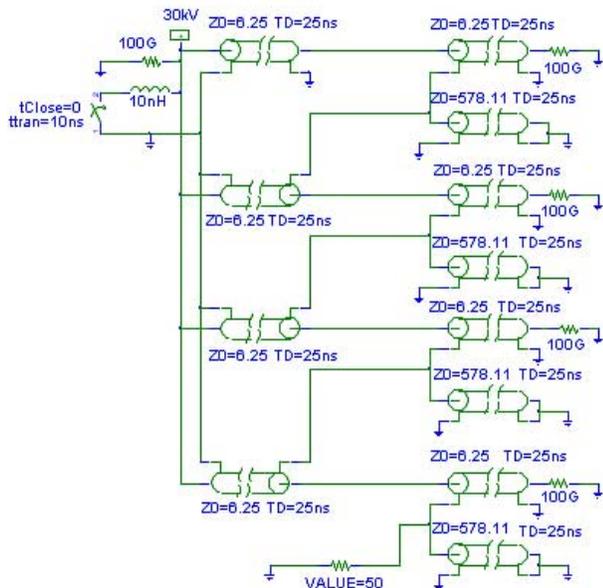


Figure 7. Modeling of cascade blumlein considering parasitic impedance of cables

Figure - 8 shows the simulated output voltage pulse for an initial charging voltage of 30kV. The output pulse amplitude is of 110kV which is lower than the expected value i.e. 120kV. Effect of parasitic impedance contributes significant power loss in the device.

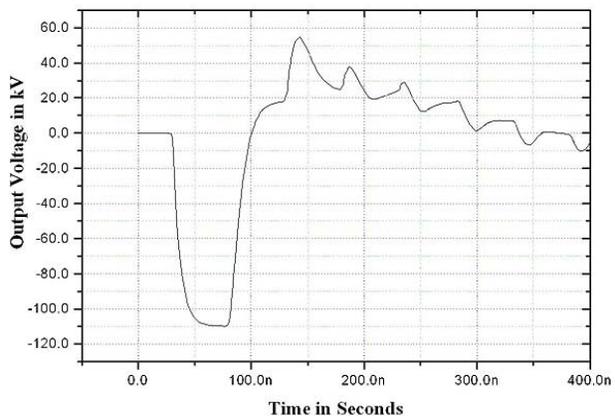


Figure 8. Simulated voltage pulse under actual condition

VI. SUMMARY

Pulsed Power Sources to be used for intense electron beam generation have typical requirements of unidirectional voltage in few hundreds of kV, currents in the range of few kAmps and pulse durations ranging from 30ns to 150ns. Considering these requirements, developed blumlein generator provides a cost effective and simple alternative. In the present configuration it has stacked considerably well giving 91.66% voltage gain with good flat top and rise time.

Simulation of the generator shows that PSPICE modeling is well in agreement with experimental results. Further improvements in the modeling can be done by taking in to account small inductances associated with the system like - at Input/Output connections and considering coaxial cables as lossy transmission lines.

VII. REFERENCES

- [1] I. C. Somerville, S. J. Mcgreagor and O Farish, "An efficient stacked – Blumlein HV pulse generator" Meas. Sci. Technol. Vol. 1, no. 9, pp. 865-868, sep 1990.
- [2] S. J. Mcgreagor, J M Koutsoubis and S M Turnbull, "The design and operation of a compact high voltage, high pulse repetition frequency trigger generator" Meas. Sci. Technol. Vol. 9, pp. 1899-1905, Aug 1998.
- [3] F A Tuema, S. J. Mcgreagor and R A Fouracre, "The design and performance of a low impedance, self matched transmission line pulse generator" Meas. Sci. Technol. 9, pp. 1989-1993, Oct 1998.
- [4] J. O. Rossi, M. Ueda and J.J. Barroso, "Design of a 150kV, 300A, 100Hz Blumlein Coaxial Pulser for long pulse operation", IEEE Trans. on Plasma Science Vol. 30, no. 5 pp. 1622-1626, Oct 2002.