Indian Journal of Pure & Applied Physics
Vol. 49, January 2011, pp. 64-72

Development of 2.4 ns rise time, 300 kV, ~500 MW compact co-axial Marx generator

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Received 23 February 2010; revised 22 July 2010; accepted 10 November 2010

Compact Marx generators are known for delivering high power in very short duration and do not require any separate pulse shaping components. The design and operation of 10 stage co-axial Marx generator with fast rise time of 2.4 ns, maximum voltage 300 kV, pulse width 20 ns, energy 4.2 J and impedance 71 Ω has been presented. The Marx generator is capable of delivering the peak power of ~500 MW with 100 Ω load. The coaxial geometry is used throughout the system to achieve high value of capacitance and low value of inductance leading to low impedance and also uses single point triggering for erection. The generator is presented with consideration of internal inductance and stray capacitance. The strontium titanate[1] ($SrTiO_3$) capacitors are used in this experiment due to very low derating capacitance at rated voltage, high dielectric strength and high current capacity. This set-up is pressurized by dry nitrogen air for the charging of Marx to −30 kV. The erected series current is measured by using non-inductive 10 mΩ current viewing resistor. This compact Marx is fitted into a stainless steel (metallic) cylinder (102 mm diam, 730 mm total length). The present Marx generator has been operated for the charging of voltage up to −30 kV. The Marx generator is tested at different charging voltages with 50 and 100 Ω ceramic resistive loads. The measured voltage waveforms and the corresponding data have been given. The output parameter of Marx generator is checked by simulation and experiment. The modeling, design and experimental results of coaxial Marx generator are discussed.

Keywords: Fast Marx generator, Coaxial Marx generator, Impulse voltage generator, Pulsed power

1 Introduction

Marx generator is frequently used in many pulsed power applications. It describes the unique circuit design for voltage multiplication. The basic principle of the Marx generator is charging of N number of capacitors in parallel through the charging resistors and discharge them in series. Marx generator is most suitable to drive systems like ultra wide band (UWB) generation[2], flash X-ray radiography experiments[3], coaxial Marx generator for producing intense relativistic electron beam[4] and impulse voltage generator[5]. The typical Goodlet-Marx generator schematic is shown in Fig. 1. The output of the N stage Goodlet-Marx generator to a charging voltage $-V$ is the theoretically $N\times V$. The characteristics of Marx generator are simplicity of the construction, small in size and high efficiency of energy transferred to the load. The coaxial Marx generator has no need to use specific pulsed forming line for pulse compression and it has low internal inductance and hence most suitable driver for above mentioned experiments. Marx generator is capacitive energy storage circuit, which is charged to a given voltage level then quickly discharge and delivering its energy to a load at very high power levels. It is well known that maximum power transfer from the generator to the load occurs if the impedances of the generator Z_o and the load Z_L are matched under these conditions, the potential appearing across the load will be one-half of the erected Marx potential, i.e. the load voltage of 150 kV for the charging voltage of 30 kV and these delivered powers are higher if source impedance kept low.

In this paper, the basic theory and design of coaxial Marx generator and the contribution by the stray capacitance in erection of Marx generator have been described. Simulation is done by using experimental design data. Coaxial geometry used in Marx generator reduces the total circuit inductance which minimize the circuit oscillation, introduces the stray capacitance between inner conductor and the metallic return conductor, which leads to good erection of Marx generator, and leads to compactness of the experimental system. Coaxial Marx generator can be used for coaxial impedance load like a coaxial electron beam generator and coaxial impulse-radiating antenna.

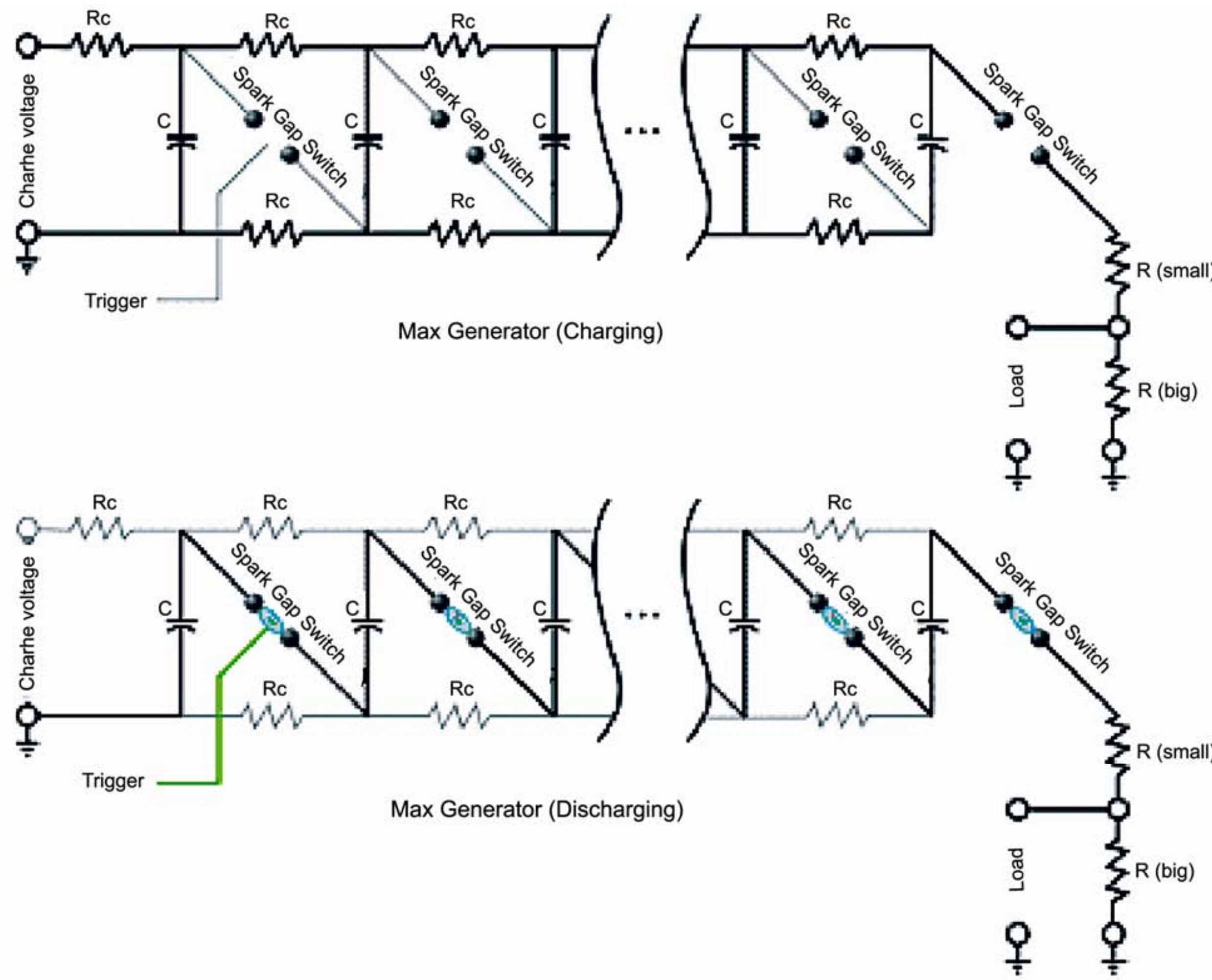

Fig. 1 — Good-let-Marx generator schematic

2 Theory and Design of Co-axial Marx Generator

The Marx generator circuit is simple RLC series circuit and the design of Marx generator is as follows[6].

The period of oscillation, T_{period} and the source impedance, Z of the generator are:

$$T_{\text{period}}=2\pi(L_{\text{eq}}C_{\text{eq}})^{1/2} \quad \ldots(1)$$

$$Z=(L_{\text{eq}}/C_{\text{eq}})^{1/2} \quad \ldots(2)$$

where L_{eq} and C_{eq} are lumped inductance and capacitances of the co-axial Marx circuit.

The critical damping is chosen as a compromise between maximum voltage amplitude and the overshoot as:

$$Z=R_L/2 \quad \ldots(3)$$

where R_L is the load resistance.

In order to find the effective source inductance and capacitance of the Marx generator we have to solve the Eqs 1-3. The stage capacitance and inductance are calculated according to Eqs 4 and 5.

$$L_{\text{stage}}=L_{\text{eq}}/N \quad \ldots(4)$$

$$C_{\text{stage}}=C_{\text{eq}}*N \quad \ldots(5)$$

where N is number of stages.

For the choice of FWHM pulse width is 80% half the period under damped oscillation.

$$T(FWHM)=0.8\pi(L_{\text{eq}}C_{\text{eq}})^{1/2}$$

Stage inductance is calculated by summation of spark gap inductance, internal inductance of capacitor and inductance due to connection.

$$L_{\text{stage}} = L_{\text{sparkgap}} + L_{\text{cap}} + L_{\text{con}} \quad \ldots(5a)$$

Coaxial geometry spark gap inductance is calculated by using following formula:

$$L = l\mu \ln(R_o / R_i) / 2\pi \ (nH) \quad \ldots(6)$$

where R_i is inner conductor radius, R_o is return conductor radius, l is length in cm and μ is permeability.

The stray capacitance for coaxial geometry is calculated by using following formula:

$$C = 24.15\varepsilon_r / \log(D/d) \ (pf/m) \quad \ldots(7)$$

where D is inside diameter of outer conductor in meter, d is outside diameter of inside conductor in meter, ε_r is relative permitivity.

The stray capacitance acts as a major role in Marx generator erection or successive breakdown[7]. The stray capacitance between the two spheres of the spark gap is C_2 and between high voltage and ground on both sides are C_1 and C_3 respectively. The schematic circuit diagram of erection of Marx generator with stray capacitance is shown in Fig. 2. The voltage across *a* and *b* is *Vab,* which is derived by using following formulae:

$$V_{ab} = V_b - V_a = V\left[2 - \left(C_2 / \left(C_1 + C_2 + C_3\right)\right)\right] \quad \ldots(8)$$

$$V_{ab} = V\left[1 + \left((C_2 + C_3) / \left(C_1 + C_2 + C_3\right)\right)\right] \quad \ldots(9)$$

We have to design the generator in which the potential difference across all the consecutive switches becomes twice the charging voltage, otherwise the Marx generator will not erect properly. If the gap is large, $C_2 = 0$, and the voltage across the second sphere gap is $2V$ from Eq. 8, which is the ideal case, since this ensures the breakdown of successive gaps. On the other hand, if $C_1 + C_3$ is small compared to C_2, then the voltage across the second sphere gap is approximately equal to V, so that the breakdown of successive gaps would not occur. Therefore, for good operating conditions, $C_1 + C_3$ must be large, and C_2 small, so that the upper gaps would breakdown simultaneously. In design of Marx generator the ratio of C_2 and C_1 is sufficiently small ($C_2 << C_1$). This can be achieved by placing the ground conductor close to the case of the storage capacitor. Generally, for a small impulse generator, since the sphere gap is small, C_2 is high and $C_1 + C_3$ small, so that the conditions for the breakdown of successive gaps is poor. In this case, C_1 can be deliberately increased to improve breakdown conditions. In the case of large impulse generators, C_2 is small, so that the conditions are favourable for the breakdown of the upper gaps.

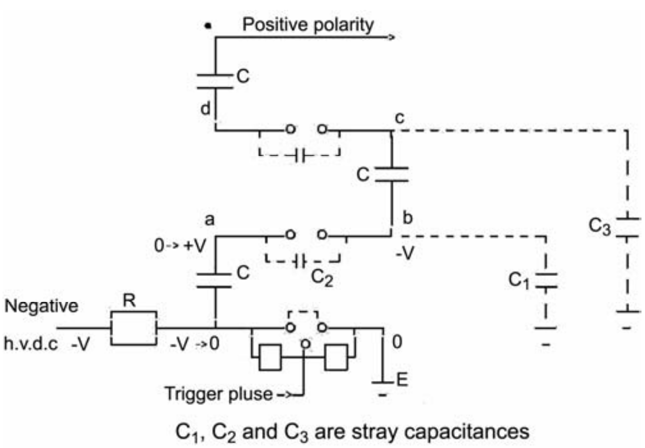

Fig. 2 — Marx generator erection with stray capacitance

3 Experimental Details

3.1 Experimental design data

The Marx generator is constructed in the form of completely coaxial geometry, which can minimize the circuit inductance. The capacitor has been chosen with material of strontium titanate $SrTiO_3$ for high current capacity and very low derating capacitance value at rated voltage and it has high dielectric strength so it becomes compact. The single stage design experimental view of Marx generator is shown in Fig. 3. It consists of one capacitor, two spark gaps, two charging resistors, and Perspex disc that is enclosed by stainless steel cylinder.

Marx generator has been designed in such a way that the distance between the high voltage charging resistor and the ground electrode or plate should have enough clearance. To avoid the breakdown between high voltage charging resistor and ground electrode while charging, aluminium 9 mm diameter spark gap

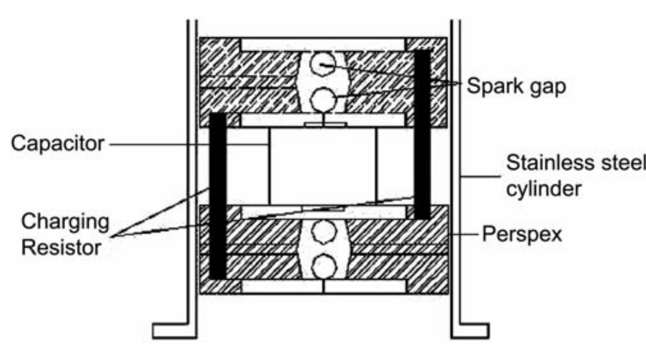

Fig. 3 — Design of experimental view (single stage)

electrodes are connected at both ends of the each capacitor and the two spark gap electrodes are separated by 4 mm distance between them. All the spark gap sphere electrodes and the gap of the each spark gap should be identical, which leads to good erection of Marx generator. The proper value of design of stray capacitance (between high voltage disc and cylindrical return conductor, and between the spark-gap spheres) leads to good erection. The Marx generator test assembly is enclosed by the 95 mm inner, 102 mm outer diameter and 730 mm total length metallic cylinder. The outer case of all the capacitor is extended up to 60 mm diameter by 5 mm thickness aluminium disc, so that the stray capacitance between high voltage disc and cylindrical return conductor is designed 2 pF. The co-axial geometry acts as a transmission line that leads to low inductance system. The inductance per stage of the Marx generator is about 40 to 45 nH. The designed value of stray capacitance between two spheres of the spark gap is 147 femtoF and stray capacitance between the high voltage capacitor case and coaxial return conductor is 2pF. The design parameters of the coaxial Marx generator is given in Table.1

3.2 Simulation

The 10 stage Marx generator circuit is simulated and the Pspice simulation software is used for analysis[8]. The stage capacitance and inductance value of Marx generator is 940 pF and 40 to 45 nH, respectively. The stray capacitance between capacitor outer case and cylindrical return conductor is 2 pF. The spark gap capacitance is 147 femtoF. The simulated 10 stage Marx generator delivers the maximum output voltage of 221 kV at 100 Ω and delivers the maximum current of 2.9 kA at 50 Ω load for the charging voltage of –30 kV. The schematic of Marx generator simulation circuit is shown in Fig. 4. The maximum simulated output voltage and current waveforms at 50 Ω (under damped), 71 Ω (Critical damped) and 100 Ω (Over damped) are shown in Figs 5-10, respectively.

Table 1 — Parameters of co-axial Marx generator

Symbol	Description	Value	Unit
N	Number of stages	10	Nos
V_{cap}	Capacitor voltage	30	kV
T_r	Rise time	2.4	ns
T_{pulse}	Pulse width	20	ns
C_{stage}	Capacitance per stage	940	pF
C_{Marx}	Erected generator capacitance	94	pF
L_{Marx}	Erected generator inductance	475	nH
Z_{Marx}	Marx Impedance	71	Ω
V_{Max}	Maximum output voltage (open circuit voltage)	300	kV
V 100 Ω	Load Voltage at 100Ω for −30 kV charging at 2 bar	221	kV
η_{Marx}	Erection efficiency at 100 Ω	73	%
E_{Marx}	Total energy stored for 30 kV charging voltage	4.2	J
P_{avg}	Average power	210	MW
P_{peak}	Peak power at 100 Ω	488	MW
L	Length	730	mm
D	Diameter	102	mm

3.3 Experimental arrangements

There are 10 stages assembled by staking one upon other in the vertical towering shape. Each stage consists of one 940 pF strontium titanate ($SrTiO_3$) capacitor, two 1 MΩ, 2 W charging ceramic resistor at both the ends of the capacitor and one spark gap switch. Spark gaps are connected to the center of the disc capacitor to achieve the coaxial configuration. Aluminium disc is used between the capacitor and spark gap electrode, which gives electrical connection and mechanical support to capacitor, charging resistor and spark gap electrode. The capacitor in the each module is mounted on the Perspex disc. Every stage Perspex disc is well connected vertically with four limbs of nylon stick, which are tightened at both ends. The entire stack is then enclosed by a cylindrical flanged stainless steel vessel, which acts as return conductor while erection. Both sides of the cylinder are sealed airtight by O-rings. The pressure inlet valve is placed in one side of the flange, which is used to maintain the pressure inside the cylinder and also release the pressure from the cylinder. The pressure gauge is fixed on the generator to measure the inside pressure. The experimental internal view of co-axial Marx generator is shown in Fig. 11.

The lowest stage (first stage) has a trigatron type spark gap. It consists of three electrodes namely main electrode, ground electrode and trigger electrode. The spark plug is used as a trigger electrode, so the trigger pulse is applied to spark plug. The trigger pulse from the pulse transformer triggers the first stage of the Marx generator. The output switch is placed between the last stage of the Marx generator and the load, which is used to isolate the load while charging and also to transfer the full energy to load while erection. The disc type ceramic resistor is used as a load for this experiment. This will dump the full Marx energy at rated voltages. The current viewing resistor (CVR) 10 mΩ, bandwidth 200 MHz, maximum energy of 500J and rise time of 2ns is connected in series with the load.

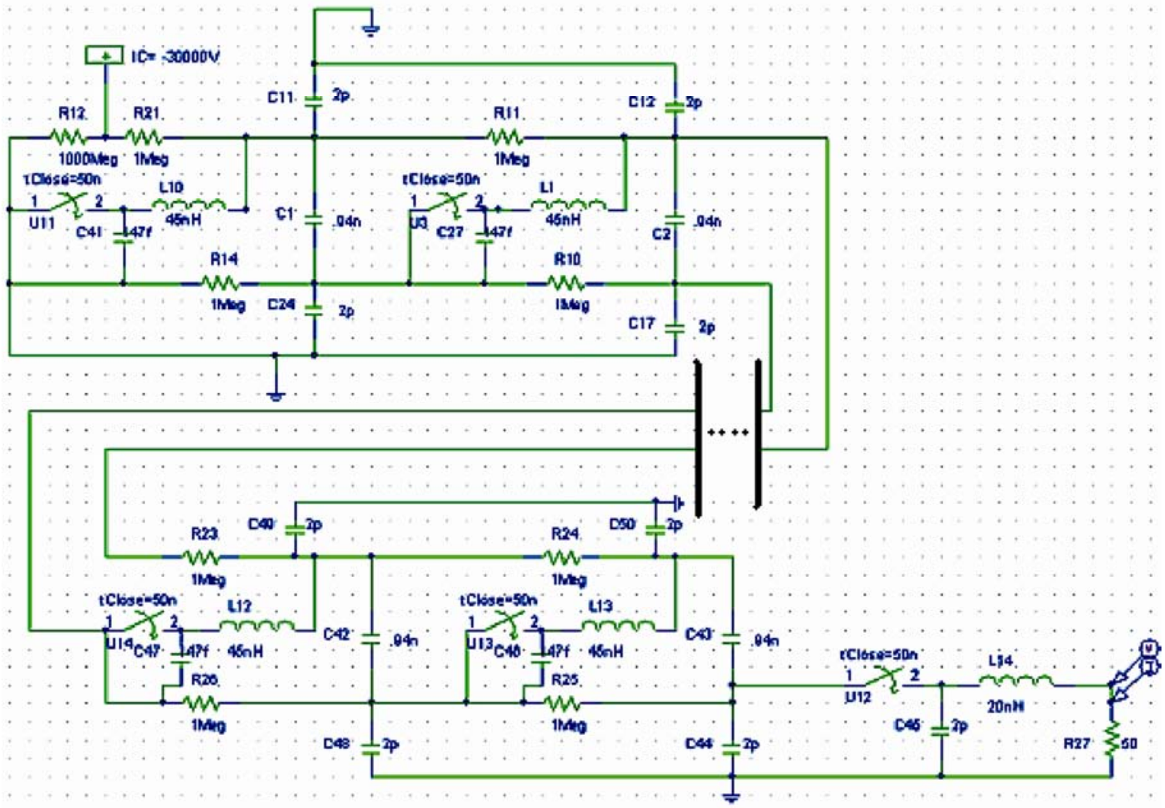

Fig. 4 — Marx generator simulation circuit

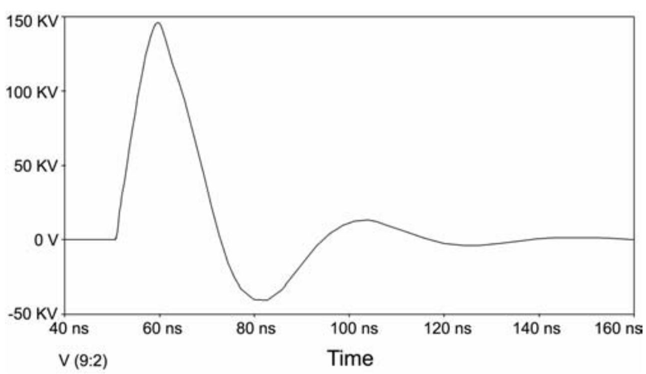

Fig. 5 — Simulated output voltage waveform at 50 Ω

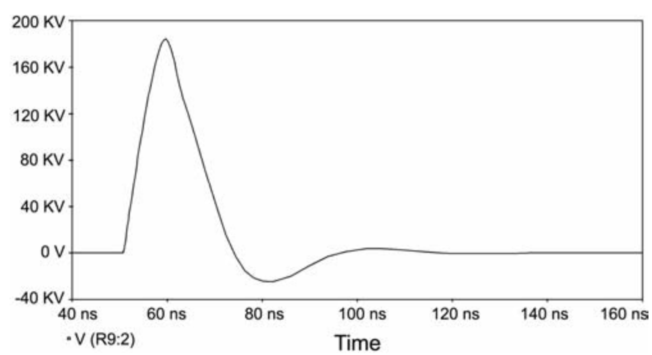

Fig. 7 — Simulated output voltage waveform at 71 Ω

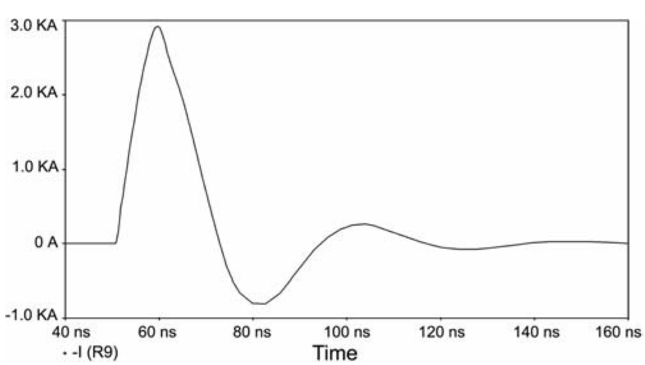

Fig. 6 — Simulated output current waveform at 50 Ω

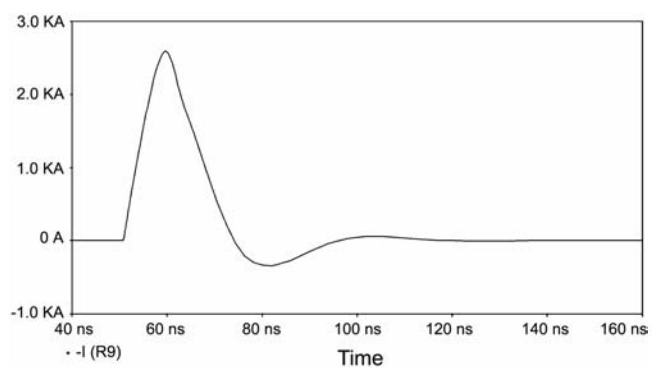

Fig. 8 — Simulated output current waveform at 71Ω

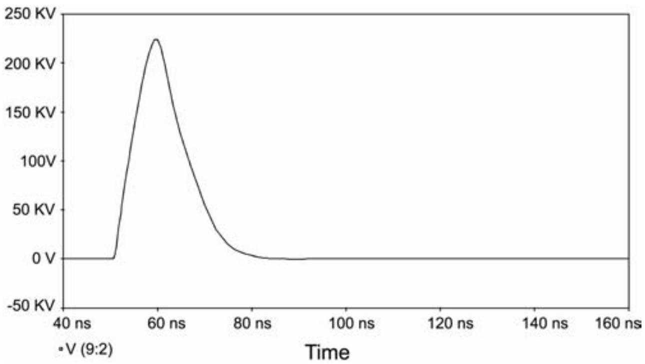

Fig. 9 — Simulated output voltage waveform at 100 Ω

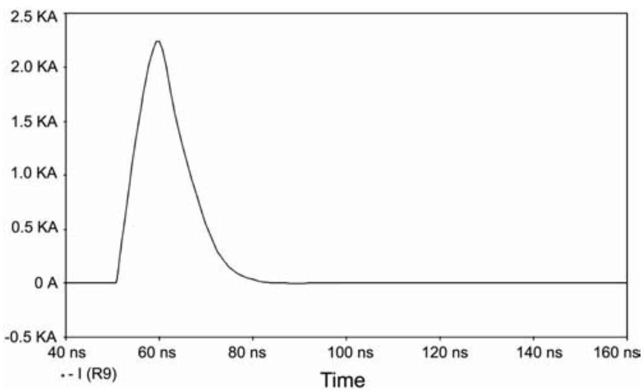

Fig. 10 — Simulated output current waveform at 100 Ω

The generator, load resistor and current viewing resistor (CVR) are connected in series while erection. The CVR and the load are well connected by the threaded joint. The load and the last stage of the Marx generator is contacted by spring fit arrangement for firm fit. The load set-up can be detached easily to change the different value of load. The pure ceramic resistive load 50 Ω with CVR is shown in Fig. 12.

3.4 Test and Results

The first switch is closed by the external trigger pulse and leads to increase the voltage across the next switch and causes the chain reaction of self-breakdown of the consecutive stages. All the capacitors are switched in to a series configuration delivering voltage pulse to the load that is $\eta_{Marx} \times N \times V$ (efficiency of Marx×number of stages × charging voltage). The test set-up of assembled coaxial Marx generator is shown in Fig. 13.

To close the first stage hetropolar operation technique is used[9]. The breakdown time is defined as the time between the arrival of trigger pulse and the appearance of significance current in the main gap. This breakdown time σ_{bd} is minimized using the

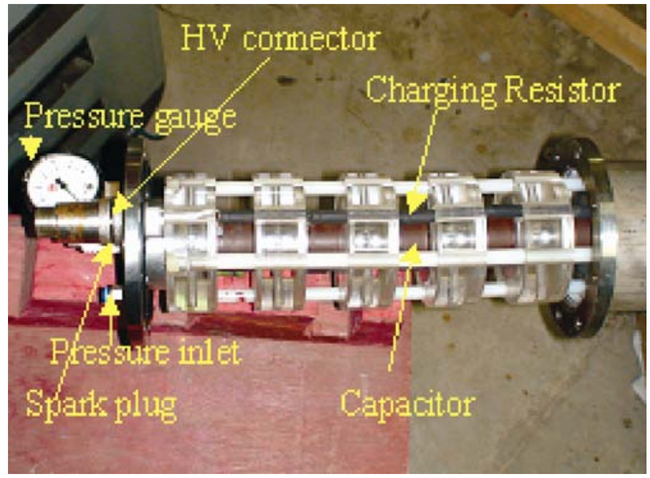

Fig. 11 — Internal view of co-axial Marx generator

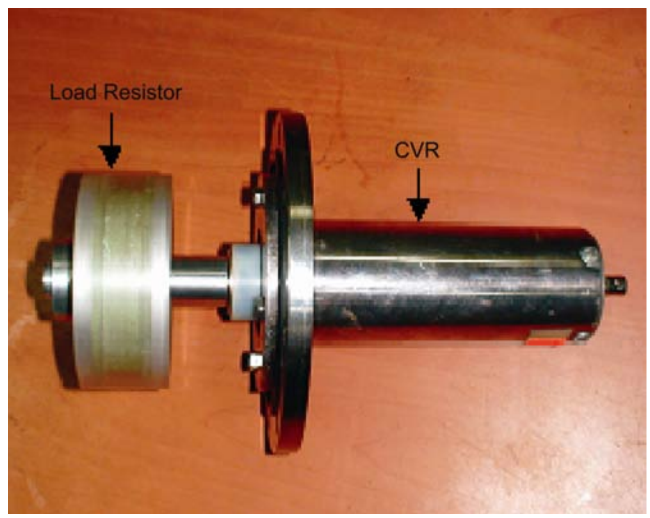

Fig. 12 — Pure ceramic resistive load 50Ω with CVR

Fig. 13 — Assembled co-axial Marx generator

positive triggering pulse with negative main gap voltage (hetropolar operation), i.e. the opposite electrode is at negative potential and trigger electrode is at positive potential. The arc formation takes place between this region of applied voltage across the two electrodes $0.5\ V_{sb} <= (V_g - V_t) < V_{sb}$, where V_{sb} is self-breakdown voltage, V_g is main gap voltage and V_t is trigger voltage. The erection of 10 stage Marx generator is shown in Fig. 14, which is done with out coaxial cylinder. The image is taken from camera operating in bulb mode.

The capacitor of the each stage is charged by −30 kV SMPS powered by 24 V dc battery. To charge the Marx generator above 13 kV the total system has to be pressurized. In order to find the source impedance of the generator, the short circuit test has been conducted. The generator is shorted by eight parallel wires of length 6 cm. Each wire is connected parallel between the center conductor and the return conductor (metallic enclosure). The current transformer is placed around one of the conductors to measure the short circuit current. The short circuit test waveform is shown in Fig. 15.

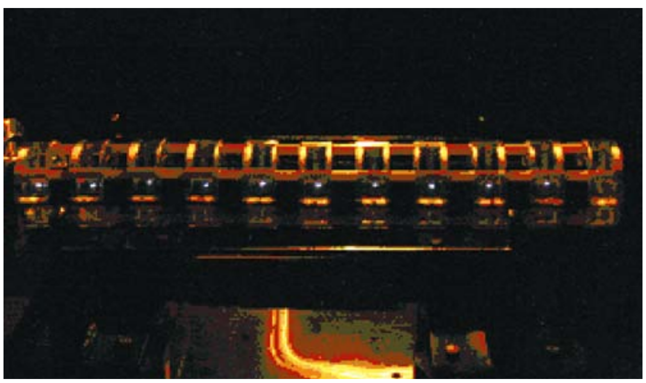

Fig. 14 — Erection of 10 stage Marx generator

From the short circuit test waveform the generator-erected inductance L_{eq} is calculated by using time period of oscillation as given below. The erected capacitance C_{eq} is 94 pF. The source impedance is calculated from the erected inductance and erected capacitance[10].

T oscillation $=2\pi(L_{eq}/C_{eq})^{1/2} = 42$ ns

by solving this equation we get source inductance, $L_{eq} = 475$ nH.

The source impedance $Z=(L_{eq}/C_{eq})^{1/2}=(475 \text{ nH}/94 \text{ pF})^{1/2} = 71\ \Omega$

Marx generator is charged up to -30 kV with dry nitrogen gas pressurized inside the coaxial cylinder. The load resistance has been chosen according to the established source impedance value. The under damped, critical damped and over damped oscillation circuit characteristics can be obtained by choosing the appropriate value of the load resistance. The solid pure ceramic type 50 and 100 Ω as used as load resistor to perform the load test. The load test has been conducted for the different charging voltages with the corresponding pressure levels. The current flowing through the CVR is measured and the corresponding voltage across the pure resistor is calculated. The output current pulse is measured by the lecroy wave runner 6100A 1 GHz bandwidth, 10 GS/s oscilloscope. The maximum output voltage of 221 kV is obtained for the charging voltage of −30 kV with 100 Ω resistive load. The rise time of the

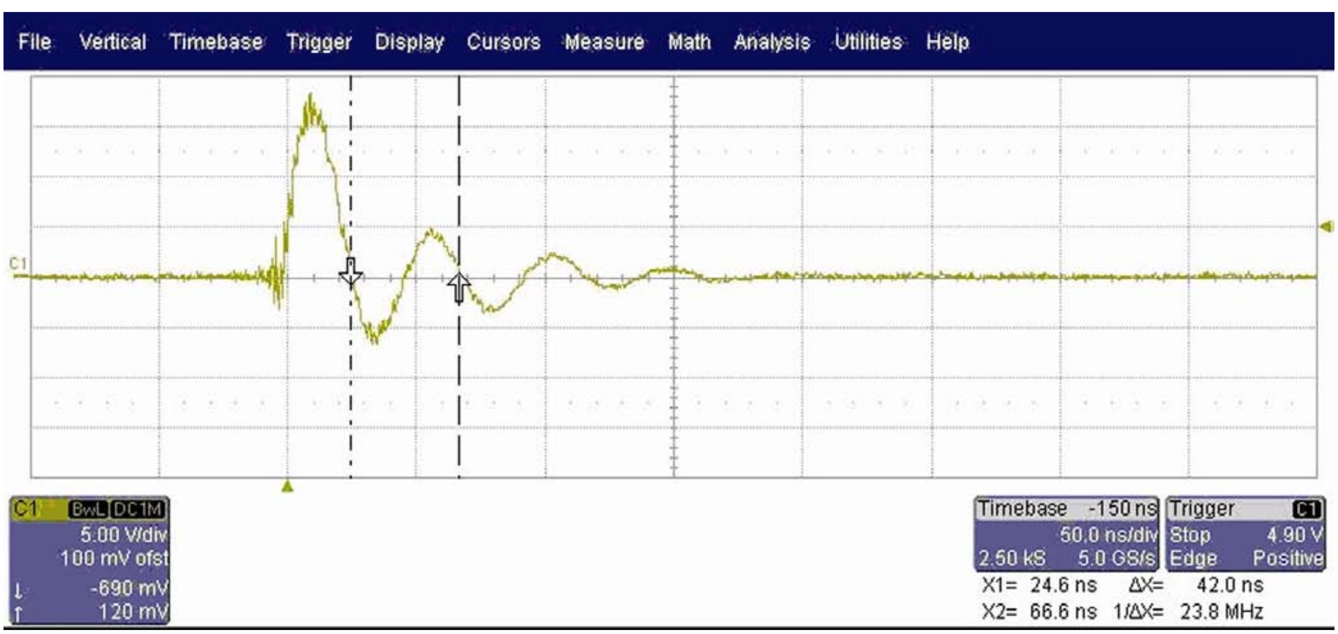

Fig. 15 — Short circuit test waveform

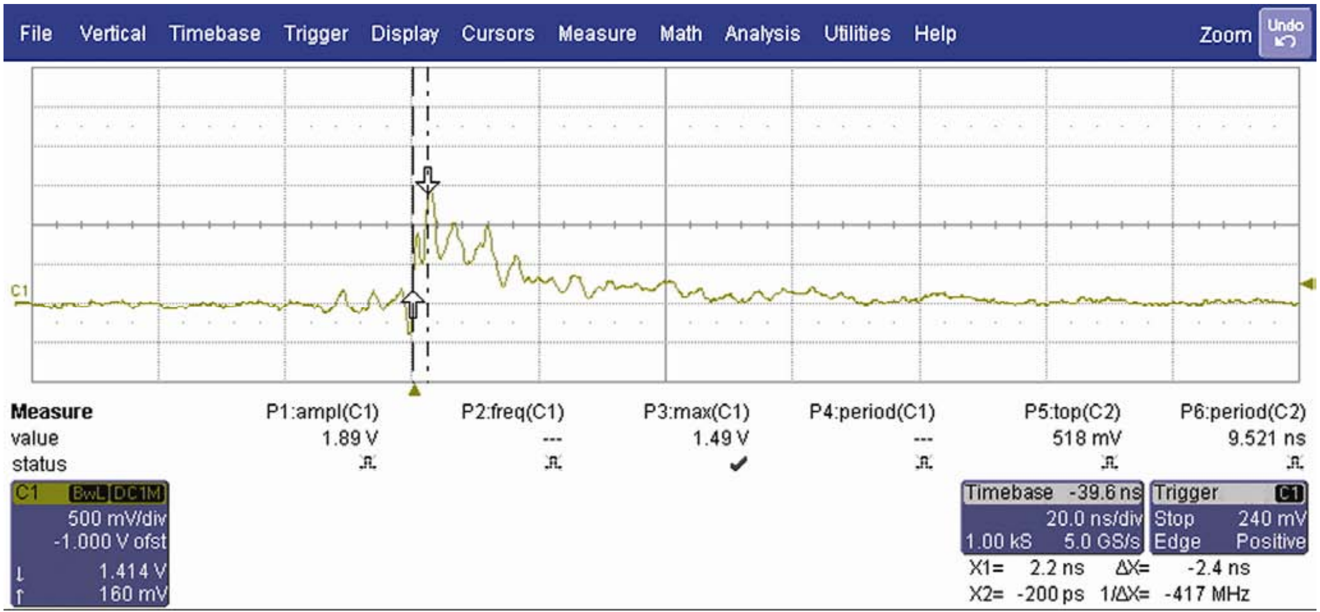

Fig. 16 — Rise time demonstration

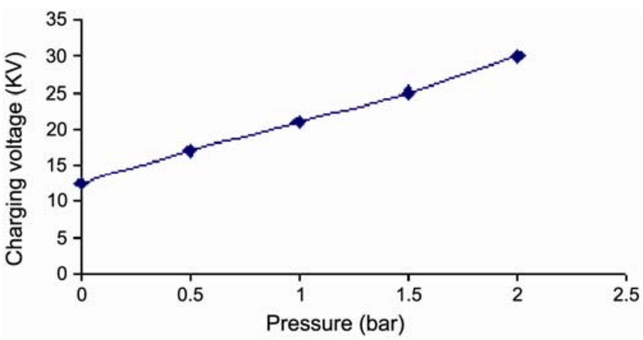

Fig. 17 — Charging voltage versus operating pressure

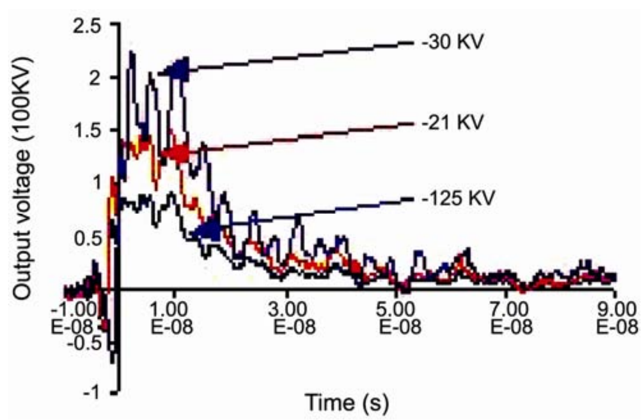

Fig. 19 — Output voltages at 100 Ω load

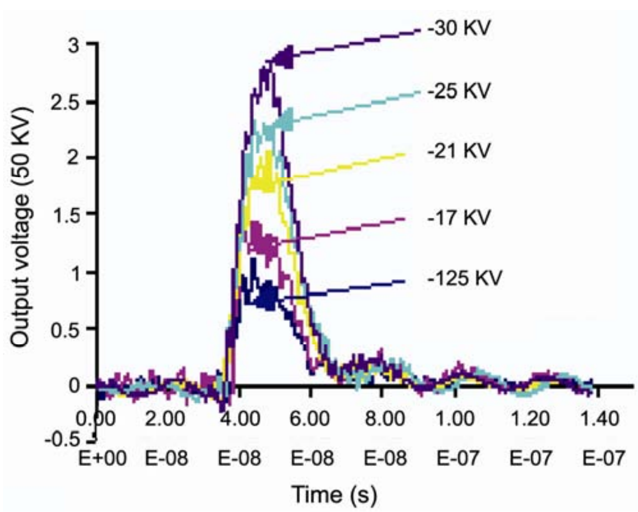

Fig. 18 — Output voltages at 50 Ω load

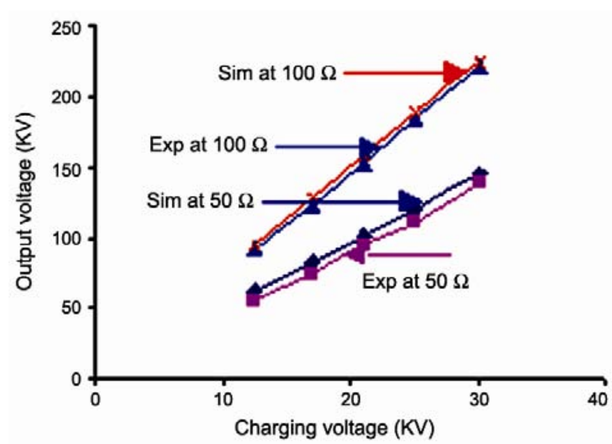

Fig. 20 — Experimental and simulated output voltages at 50 and 100 Ω

Table 2 — Simulation and experimental results of 50Ω load

Charging voltage (kV)	Simulated output load current (kA)	Simulated output load voltage (kV)	Experimental output load current (kA)	Experimental output load voltage (kV)
−12.5	1.22	62	1.1	55
−17	1.62	82	1.5	75
−21	2.04	102	1.9	95
−25	2.40	120	2.3	115
−30	2.9	145	2.8	140

Table 3 — Simulation and experimental results of 100Ω load

Charging voltage (kV)	Simulated output load current (kA)	Simulated output load voltage (kV)	Experimental output load current (kA)	Experimental output load voltage (kV)
−12.5	0.950	95	0.92	92
−17	1.28	128	1.24	124
−21	1.58	158	1.54	154
−25	1.9	190	1.85	185
−30	2.25	225	2.21	221

output pulse 2.4 ns is achieved (Fig. 16). The charging voltage corresponding to the operating pressure is shown in Fig. 17. The output voltage waveforms for the charging voltages of −12.5, −17, −21, −25 and −30 kV at 50 and 100 Ω loads are shown in Figs 18 and 19, respectively. The experimental output and the simulated output voltages at 50 and 100 Ω are shown in Fig. 20. The experimental results at 100 Ω load are exactly matching with simulation results. The minor changes in output voltage at 50 Ω load between the experimental and simulation results are shown in Fig. 20. The experimental output and the simulation output voltages are compared and given in Tables 2 and 3.

4 Conclusions

The 10 stage, 300 kV, 2.4 ns rise time, 20 ns pulse duration, 71 Ω source impedance and 4.2 J energy Marx generator is developed in our laboratory, which can deliver an output voltage pulse of 221 kV with 100 Ω load for the charge voltage of −30 kV. The erected voltage efficiency of 73% is achieved at 100 Ω load. By increasing the load resistance value the output load voltage can be increased.

Acknowledgement

The authors would like to thank all the members in Energetics and Electromagnetic Division of BARC for giving constant technical assistance and cooperation.

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