Chapter 1

Gigawatt Pulsed Power Systems at APPD

—Dr. Amitava Roy

The pulsed power work at BARC in India started in the early 60s. The research on Exploding Wire Phenomenon (EWP) started in 1964 and energy storage capacitor banks, Marx generators, pulsed voltage and current measurement techniques were developed alongside. In the seventies, considerable work was done on the development of Flash X-ray (FXR) systems as well as magnetic flux compression techniques for application in High Energy Rate Forming (HERF). BARC's early involvement in pulsed power gave the necessary impetus to indigenous development of energy storage capacitors, pulsed voltage current measurement techniques and innovative insulation designs for the development of high magnetic field coils possessing high electrical and mechanical strengths. Pulse power systems store energy over long time scale (in milliseconds to few seconds) and release it in very short time scale of few nanoseconds. Several pulse power systems have been developed having voltage rating from 100 kV to 1000 kV with current rating 4 kA to 30 kA and pulse duration 1 ns to 500 ns. Most significant among those systems were the KALI series of pulsars of different ratings built over four decades. Depending on the applications both single shot and repetitive systems were developed and tested to its designed ratings. All the KALI systems were single shot systems, however, 1 kJ Marx Generator was developed at 10 Hz repetitive rate and LIA-200 systems was developed and tested at 100 Hz pulse repetition frequency.

1.1. Kilo Ampere Linear Injectors (KALI)

Pulse power systems for supplying kilo ampere relativistic electron beam current were developed. These systems in the chronological order are listed below [1, 2].

1.1.1. KALI-60 System

KALI-60 system was developed in the 1970. It was based on Marx generator configuration. This was rated at 60 J energy. KALI-60 has been delivered to TBRL (Terminal Ballistic Research Lab), Chandigarh, for their Flash X-ray systems development and applications.

1.1.2. KALI-75 System

KALI-75 was delivered to Dept. of Electrical Engineering, I.I.T., Madras, for research in insulation material studies. It was also based on Marx generator configuration. It was developed in 1980. It was rated at 75 Joule energy.

1.1.3. KALI-200 System

KALI-200 system is rated at 300 kV, 20 kA and has pulse duration of 50 ns. Energy in the electrical pulse is 200 J. It was delivered to MTRDC/ LRDE, Bangalore for High Power Microwave (HPM) generation related applications. KALI-200 system is a Tesla Transformer and oil Pulse Forming Line (PFL) based system and has been used for several experiments on Intense Relativistic Electron Beam (IREB) generation and HPM generation studies. The pulse power generator KALI-200 is a capacitive energy storage system consisting of series capacitors, tesla transformers, oil filled PFL and spark gap switches. The power supply will charge the capacitors and the energy is transferred to the tesla transformer through a sparkgap switch. The Tesla transformer builds up a voltage up to 600 kV and feeds the PFL. The PFL reduces the voltage output to 300 kV, 80 ns.This system operates in a single mode.

This system is connected to a diode chamber, which in turn connected to a high vacuum system with properly arranged interlocks. The diode chamber contains a graphite field emission cathode of 25 mm radius, and an anode made up of copper mesh of 50 mm radius at a gap of 8 mm. This diode produces about 10 kA, 80 ns relativistic electron beam.

1.1.4. KALI-1000 System

This system was developed for applications requiring very low load impedance like HPM generation using vircator and Flash X-ray diodes [3]. This system has a rating of 300 kV, 20 kA with 100 ns pulse duration [4]. The photograph of the KALI-1000 pulse power system is displayed in Figure 1.1. It consists of a Tesla transformer charging water PFL as shown in Figure 1.2. Radial tesla transformer charges the water PFL up to -600 kV peak voltage in 4 microseconds. At this instance SF_6 spark gap is fired due to over voltage and voltage of -300 kV is achieved at the graphite cathode.

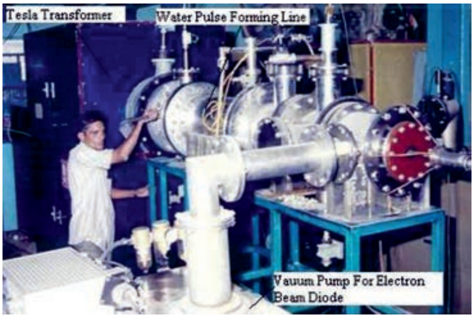

Figure 1.1. KALI-1000 pulse power system.

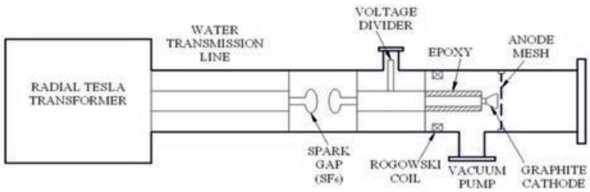

Figure 1.2. Schematic of KALI-1000 pulse power system.

KALI-1000 system is used for Intentional Electro-Magnetic Interference (IEMI) generation using Vircators and Flash X-ray generation owing to its low impedance.

1.1.5. KALI-5000 and KALI-30 GW System

KALI-5000 pulse power system had a rating of 1 MV, 40 kA with pulse duration of 100 ns. A picture of the KALI-5000 system is displayed in Figure 1.3. It consisted of a bipolar Marx generator which had 15 stages with 0.7 μF capacitance in each stage. This Marx generator charges the bulmlein pulse forming line in 500 ns to a voltage of 1.4 MV. At 500 ns SF_6 spark gap is fired due to overvoltage as shown in Figure 1.3. Transformer oil is used for insulation in the Marx generator and Castor oil is used for insulation in Blumlein pulse forming line. For the KALI-5000 system with the 1.4 MV peak Marx Generator voltage, 1.0 MV is achievable on the load [5]. The residual voltage is reflected back to the Marx generator. This leads to voltage breakdown in the Pulse forming line at higher voltage. To rectify this issue complete KALI-5000 system is redesigned and modified for reflection minimization. The modified system is renamed as KALI-30 GW due to modifications in the system parameters.

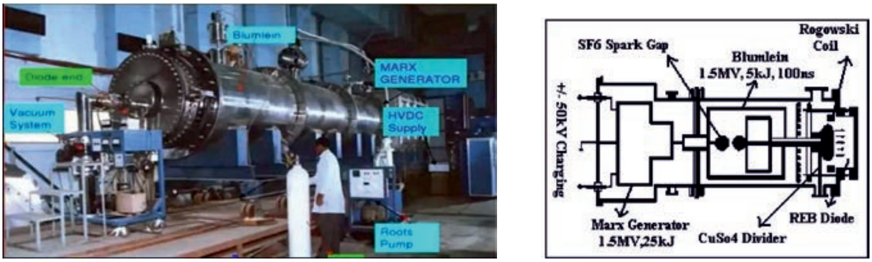

Figure 1.3. Photograph of the KALI-5000 system and schematic of KALI-5000 system.

KALI-30 GW system is capable of supplying 1 MV peak voltage, and 30 kA peak current electrical pulses for 80 ns pulse duration [6]. It is a single shot system. Blumlein [7] based pulse power system which is used as a test bench for various HPM devices [8] and FXR diodes [9]. The number of stages in KALI-30 GW system has been reduced to 14.5. Per stage capacitance of the Marx generator also reduced to 0.2 µF. The capacitors used were indigenously designed and developed 50 kV capacitors. The KALI-30 GW system is shown in Figure 1.4.

Figure 1.4. Photograph of the KALI-30 GW system.

The transformer oil is used for insulation in the KALI-30 GW pulse power system in both Marx generator and Blumlein PFL. The Marx generator is discharged on the Blumlein PFL load. Peak voltage is achieved after 1.0 µs. At this instance the Blumlein is discharged and total voltage is transferred at the load. Length of the Blumlein including pre-pulse switch [10] is 7.0 m.

The typical KALI-30 GW electron beam diode voltage and beam current waveform are shown in Figure 1.5. In X-ray mode maximum of 1.2 R dose is achieved at 1 m distance from source and in High Power Microwave generation maximum of 1.1 GW power generation in S-band frequency [11].

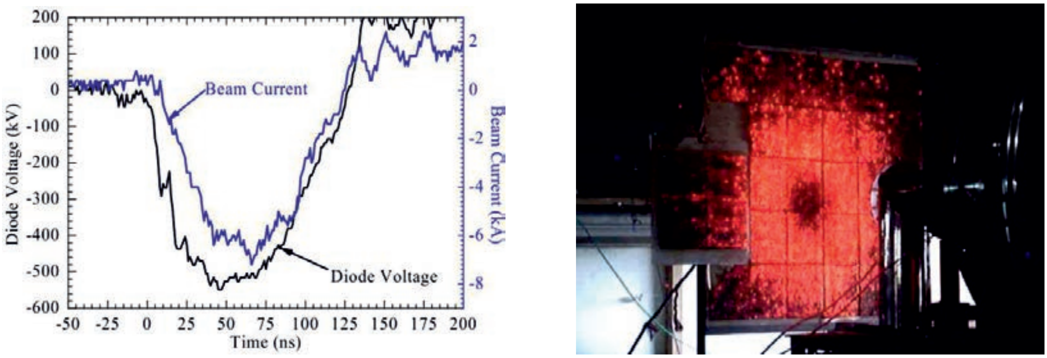

Figure 1.5. The electron beam voltage and current waveforms from KALI-30 GW system and imprint of radiated microwave signal on Neon Array for HPM applications.

The overall dimensions of this system are 10 m length and 1.0 m radius. Thus this system is used as a test bench for testing of IEMI sources and Flash X-ray sources.

1.2. Linear Induction Adder Pulse Power Systems

All the systems mentioned in the previous sections are basically single shot pulse power systems and have spark gap switches. Use of spark gap switches limits the rep-rate operation of the pulse power systems. The pulse repetition frequency is limited up to 10 Hz with spark gaps. Even with 10 Hz pulse repetition frequency, operating voltage keeps dipping in the subsequent pulses [12]. Hence magnetic pulse compression technique [13] and voltage adder techniques [14] have been employed.

The pulse compression technique is used for temporal compression of electrical voltage pulses. It works on the principle of saturable inductance. In this scheme a voltage pulse is used to charge a capacitor through a saturable inductor. This inductor has a magnetic core which is magnetized to the point marked as P_1 in Figure 1.10 of the *B*-*H* loop. When the voltage pulse is applied on this curve in the opposite direction of saturation, voltage at the capacitor C_2 starts increasing and inductance of the saturable inductor L_s keeps increasing. L_s acts as the charging inductor of capacitor C_3 and high inductance of it does not let voltage increase across C_3. This instant of time is depicted P_2 in the Figure 1.10. Once the voltage V_{C2} becomes sufficient enough and current I_{Ls} in the loop saturates the inductor again. This instant of time is depicted as P_3 in the Figure 1.10. At this instant of time inductance of saturable inductor drops very sharply and C_3 starts charging very rapidly. The voltage waveform across C_3, depicted by V_{C3} is shown in Figure 1.10. This pulse again gets discharged in the capacitors in subsequent stages.

Induction voltage adder (IVA) is used for voltage multiplication in the LIA systems. Voltage adders also known as induction cavities are the pulse transformers in which primary windings are in parallel and secondary winding are in series with each other. If there are n number of inductive voltage adders in any circuit, nV voltage is achieved in the output.

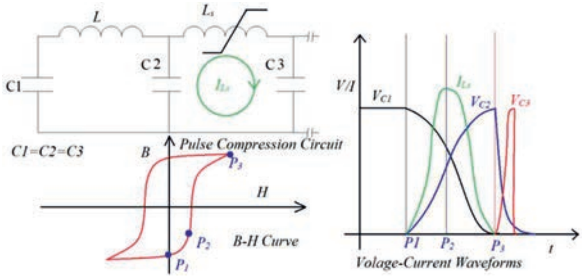

Figure 1.10. Circuitry of a magnetic pulse compression stage, *B-H* curve and output parameters at various stages.

1.2.1. LIA-200

LIA-200 system has a rating of 200 kV, 5 kA with pulse duration of 100 ns. It can operate in pulse repetition frequency of 10 to 100 Hz depending on the output voltage-current parameters and application [15]. This system was commissioned in 2008. Actual photograph of this pulse power system is shown in Figure 1.11.

Figure 1.11. Photograph of the LIA-200 pulse power system.

This system consists of two transformers and four numbers of magnetic pulse compression switches (MPC) or saturable inductors. The schematic of the pulse power system is displayed in Figure 1.12. Power modulator is used to charge 80 µF capacitor through an inductor. The charging voltage profile was ramp and the ramp frequency determines the output pulse repetition frequency. The LC circuit discharge in to primary of the first transformer is enhanced from 2.5 kV to 20 kV in first transformer. The pulse duration of the output from the secondary of the first transformer is having 20 µs pulse duration and this pulse charges 1.2 µF capacitor.

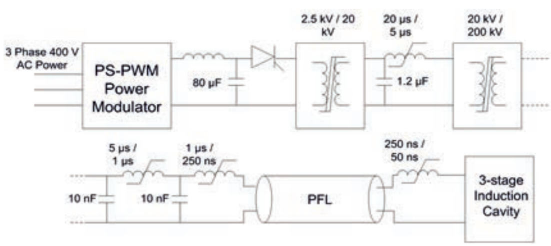

Figure 1.12. Schematic of the LIA-200 pulse power system.

The MPC switch again compresses the electrical voltage pulse to 5 μs. The 20 kV voltage then becomes 200 kV by the transformer. The 200 kV pulse is stored in water capacitors of 10 nF and is further compressed to 1 μs and then 250 ns by two MPC stages. The 250 ns pulse charges the water PFL and voltage of the pulse reduces to 70 kV. Three cable carrying 70 kV voltage supply primary voltage pulse to the three stage inductive voltage adder and 200 kV, 100 ns voltage pulse is achieved in the output. The output voltage pulse waveform at various stages is shown in Figure 1.13.

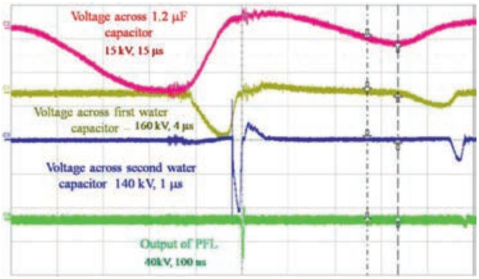

Figure 1.13. Output voltage pulse at various levels in the LIA 200 System.

This system is utilized for narrow band IEMI generation using virtual cathode oscillators and has been tested for intense electron beam generation.

1.2.2. LIA-400

LIA-400 system has electrical rating of 400 kV peak voltage, 4 kA peak current with 100 ns pulse duration. The pulse repetition frequencies up to 300 Hz are possible depending on the output power and requirement. At full rating of 400 kV this system operates at 8 Hz pulse repetition frequency. The actual photograph of this system is displayed in Figure 1.14.

Figure 1.14. Photograph of the LIA400 pulse power system

Linear induction accelerator (LIA-400) is an integral unit consists of the following components.

1) A 700 mm diameter housing stainless steel chamber on MS trolley.
2) A 70 kW capacitor charging power supply (CCPS) for charging at 1–300 Hz.

3) A 1:30 amorphous Permalloy (NP50) magnetic core-based toroidal saturable pulse transformer.
4) MPC is used in three stages. First stage does 60–10 μs, second stage does 10–3 μs and third stage does 3–1 μs pulse compression.
5) 14-stage Induction Voltage Adder (IVA) assembly is wrapped in a strip forming line. Pulse compression of 1 μs to 250 ns was done using strip line.
6) Reset choke and electron-gun assembly in a vacuum chamber. The welded trolley framework houses all parts of the CCPS and LIA 400 system. The power supply is connected to the input of the pulse transformer through low inductance copper strips [16].

The complete system has been integrated and characterized with $CuSO_4$ dummy load.

1.3. Marx Generators

All the systems discussed above have some kind of pulse forming for square waveform generation in the output. It is possible to generate nanosecond duration electrical pulses with low inductance high capacitors. With the development of door knob type ceramic capacitors which have parallel plate configuration and inherently very low inductances, pulse power systems based on the Marx generator alone became feasible. To study the discharge behavior of Marx generator analytical methodologies using Laplace transform are preferred. During erection, Marx generator acts as series and parallel combination of lumped and stray capacitances and inductances. Depending of the operating range and frequency, effect of certain stray components can be ignored judiciously. For pulse rise time of 0.1 µs to 10 µs, Marx generator can comfortably modeled using linear second order differential equation model. While charging capacitive load, output voltage equation of Marx generator can be defined as

$$V_o = \frac{V}{C_L R_S(\beta-\alpha)}\left[e^{-\alpha t} - e^{-\beta t}\right] \tag{1.1}$$

Where, α and β are roots of equation

$$p^2 + \left[\frac{1}{C_M R_p} + \frac{1}{C_M R_s} + \frac{1}{C_L R_s}\right] p + \frac{1}{C_M R_p C_L R_s} = 0 \tag{1.2}$$

Here CM is the erected capacitance of Marx generator, CL is the load resistance, RP is the resistance parallel to Marx generator which is equivalent resistance of charging resistor, ground resistor, resistive divider etc and Rs is equivalent resistance in series with load which is equivalent resistance of sparkgap resistance, capacitor equivalent series resistance (ESR) and contact resistances.

While discharged into matched resistive load directly, output voltage follows the equation

$$V_o = \frac{Vt}{\tau} e^{-\alpha\frac{t}{\tau}} \tag{1.3}$$

Where, τ depends on MARX generator components i.e. capacitors and inductors. This waveform is of critically damped capacitor discharge waveform and can deliver maximum of

0.7V voltage across matched load. Pulse width of this pulse can be calculated approximately as $0.8\pi\sqrt{LC}$.

However, as soon as rise time of the MARX generator reduces below 10 ns and pulse width smaller than 100 ns, stray parameters dominate the equivalent circuit significantly. Thus it becomes difficult to model the circuit as second order differential equation and requires higher order complicated differential equations to model it. Thus mostly, for such a fast Marx generator design use of software like CST microwave studio etc. are more prevalent. In APPD, BARC two classes of systems based on Marx generator have been developed.

1.3.1. Compact Marx Generators

In the Marx generator based systems without a PFL, the output voltage pulse duration and rise time depends on the capacitance of the Marx stages and inductance of capacitors, spark gap and discharge circuitry. Thus for obtaining very small pulses inductance of the capacitors is minimized. With the development of door knob type ceramic capacitors the inductance minimization of capacitors was achieved. The film capacitors can still be used in the Marx generators having 250 ns or larger pulse duration. The typical bipolar circuit diagram of a Marx generator is shown in Figure 1.15.

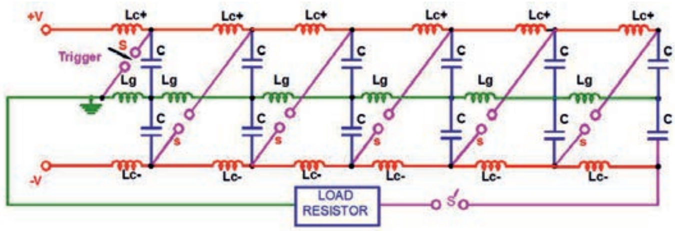

Figure 1.15. Circuit diagram of the Marx generator.

Here all the capacitor stages are charged in parallel to a peak voltage level of V. Once the capacitor stages are charged up to V voltage, spark gaps are fired due to over voltage or triggering generating nV in the output voltage waveform on an infinite load. The inductance and capacitance of the stages constitute the impedance of the Marx generator. If the load impedance matches with the Marx impedance then $0.7nV$ is achieved in the output voltage. The systems developed under this category in detail are given below.

A. 1 kJ Repetitive System

The 1 kJ Marx is a 6 stage bipolar Marx generator which can generate 300 kV, 12 kA, 300 ns pulses at 10 Hz repetition rate [17]. The 1 kJ repetitive system with reflex triode vircator load is shown in Figure 1.16.

Each stage of the 1 kJ Marx is charged up to 35 kV through charging inductor and then all the stages are discharged in series to attain 300 kV, 12 kA pulse in the output. It uses 0.15 μF, 50 kV film type capacitors. The capacitors have intrinsic inductance of 20 nH. Thus to improve rise time of the voltage pulse a peaking gap has been added after all the capacitor stages. Inductive charging of the capacitors allows the 10 Hz pulse repetition operation of 1 kJ pulse power system. The output voltage pulse in repetitive pulse mode with reflex triode is shown in Figure 1.16 (b). Reflex triode geometry generated 18 kV/m electric field narrow band IEMI with 2.2 GHz frequency at 1.75 m distance from source.

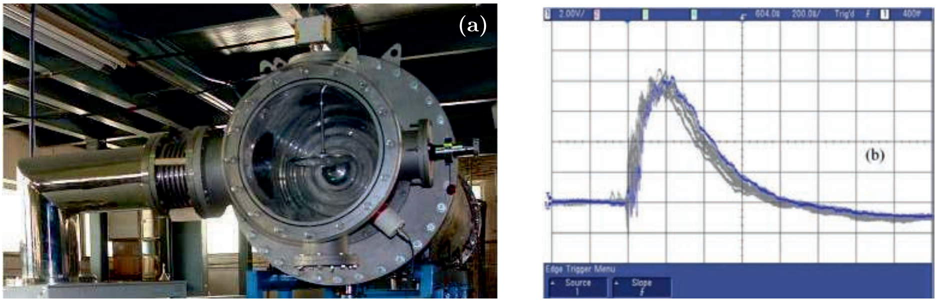

Figure 1.16(a) Photograph of 1 kJ pulse power system and (b) output voltage current waveform from 1 kJ pulse power system at 10 Hz pulse repetition frequency.

B. Compact Marx Generators for Flash X-ray Generation

Four Marx Generators for FXR Generation are developed indigenously, which can generate four time spaced (user controlled 1 μs to 1 s) X-ray pulses of less than 50 ns pulse width. Dose available in each pulse is measured to be 25 mR at 1 m distance in the bore sight. This system is being used for hydrodynamic studies at Pyro lab (SOG) in VSSC, Thiruvananthapuram for measurement of flare velocity during explosive firing.

Figure 1.17. Marx generators with four channels of Flash X-ray sources designed for hydrodynamic studies.

This product is an import substitute. Many explosive research laboratories in India use this type of system to radiograph hydrodynamic experiments. Till date all such systems are used to be imported. Indigenous capability to develop similar system will reduce foreign import of products and services. There are very few international manufacturers of similar systems; hence this development opens the opportunity to export the product as our manufacturing cost is much low.

1.3.2. Pulse Forming Network (PFN) type Marx generators

As discussed in the previous section, output pulse of a MARX generator generates a critically damped exponential voltage curve, while discharges into a resistive load. However, many physics experiments and industrial applications demand flat top output voltage across the load. Historically such a pulse is generated using a pulse forming line and the pulse forming line is charged using MARX generator. We will discuss here two types of pulse forming network (PFN) based Marx generator topologies generally used for square voltage pulse generation.

A. Flat top pulse generating Marx generator

With advancement of pulse power technologies, innovative efforts are reported for generation of flat top pulse directly from MARX generator without using pulse forming line. To generate such a pulse, capacitors and inductors are chosen selectively so as to generate higher order odd harmonics i.e. 3^{rd}, 5^{th} etc simultaneously while discharging. It can be shown mathematically, that addition of all n^{th} harmonics with amplitude of 1/n will make a perfect square pulse. Thus introduction of 3^{rd} and 5^{th} harmonic improves the pulse shape significantly. However, due to practical limitations it is extremely difficult to generate lot of higher harmonics of different values of high voltage pulses simultaneously and discharge into load. Hence, such an effort is usually limited to 3^{rd} or 5^{th} harmonics only for all practical purposes. Use of pulse forming network in each stage also helps in getting square pulse output. Details of PFN based Marx generator scheme will be discussed in detail in section 6.5.5 of chapter 6.

B. Guilleman PFN type MARX generator

A special type of PFN based Marx generator known as Guilleman PFN type Marx generator shown in Figure 1.18 [18]. In this Marx generator, energy storage capacitors are used in combination with inductors in every stage. Based on the arrangements of inductors and capacitors in each stage, Guilleman PFN networks can be classified in three categories i.e. type A, type B and type C. Advantage of this modified Marx generator is that it is capable of generating long duration high voltage pulses with improved flatness. These generators are capable of generating 200-300 kV, 100-150 kA and 2-5 μs high power pulses into matched

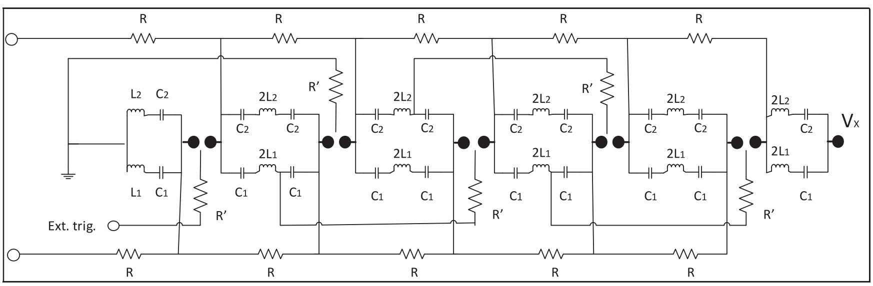

Figure 1.18. Type C Guilleman type MARX generator

load. In this configuration, shown in Figure 1.18, only the first spark gap is externally triggered. Remaining spark gaps are triggered by resistive coupling of overvoltage produced in previous other stages. L_1, L_2, C_1 and C_2 can be chosen judiciously to meet the pulse requirements like pulse width, flatness, impedance etc.

1.4. Conclusion & Future Research

The pulsed power activity started in India at BARC and several systems both single as well as multiple shot systems have been developed. The biggest of these systems is the KALI-30 GW, located at BARC, Mumbai and provided 1 MeV of electron beam energy at 30 kA beam current for 80 ns. Also various compact pulsed power systems have been developed at BARC, Mumbai for the application of FXR and HPM. Research and development of the subsystems of the Pulsed Power applications is in a very mature state and as the application demands any modern pulsed power systems can be designed and developed at India.

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