Chapter 6

Marx Generators for High Voltage and High Current Pulse Generation

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This article discusses about the principle of operation, various types, triggering mechanism of Marx generator. A design approach of Marx generator with aid of formulae is given. Different types of Marx generator like conventional Marx topology, coaxial Marx generator, PFN based Marx generator and repetitive Marx generator is discussed. An improved triggering method for Marx generator for increasing the triggering range is included in this chapter. Design of individual components of Marx generator is considered. Different kind of Marx generator developed in the division is listed.

6.1. Basics of Marx Generator

The simplest and most widely used high voltage impulse generator is Marx generator established as back as 1925. Basically, in Marx generator number of capacitors are charged in parallel and discharged in series, hence produce high voltage. Earlier days, Marx generators were used for testing of high voltage insulator and as a simulator for lightning surges and switching surges. The scope of Marx generator has now extended to production of high power pulsed electrons, ions, and lasers. Concisely, it is being used for driving high power microwave and Flash X ray systems. A typical Marx generator schematic is shown in Figure 6.1. It consists of charging resistor, energy storage capacitor and high voltage spark gap (SG) as a switch. Figure 6.1. is four stage Marx generator. The capacitors *C1* to *C4* are the Marx stage capacitors, resistors *R1, R3, R5* and *R7* are the charging resistors, resistors *R2, R4, R6* and *R8* are the ground resistors. C_a, C_b and C_c are the coupling capacitors which helps in triggering the succeeding stage's SGs .

SG is the high voltage switch; it turns on when the voltage across it exceeds the breakdown voltage of the switch. High voltage power supply is applied to the HV (V_{charge}) point to charge all the capacitors in parallel and each switch holds the same voltage. The switch's gap is kept in such a way that it holds the applied voltage V_{charge}. When the external trigger is applied, the first switch closes and ideally $V_{charge}/\ (N\text{-}1)$ over voltage voltage is developed across the all the remaining switches. Due to the over-volting of spark gap *SG2*, it closes; in this way all the remaining spark gap have the over-volting of $2V_{charge}/N\text{-}2$. The over-volting increases as the switches close. It automatically erects the full Marx after applying the externally triggering. Although this explains the ideal case of Marx generator operation, in practical case some stray parameters change the operation scenario.

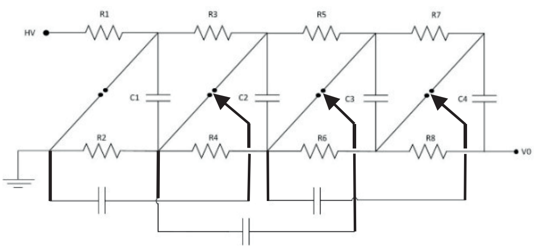

Figure 6.1. Schematic of Marx generator.

6.1.1. Effect of Stray capacitance in operation of Marx generator

In the presence of stray capacitance, the over voltage on spark gaps are reduced and affects the ideal operation of Marx. When the SG_1 closes, the voltage loop GND-SG_1-C_1-SG_2-C_2-Cs_1-Cs_2-GND is formed. Cs_1 and Cs_2 are the stray capacitance formed between the stage metal plate and outer cylinder. In ideal case full voltage V_{charge} / (N-1) is developed across the SG_2 once SG_1 breakdowns, but practically the voltage is divided across stray capacitances and $SG2$ capacitance. The voltage across SG_2 is

$$V_{SG2} = \frac{C_S * 2Vcharge}{C_s + C_{SG2}} \tag{6.1}$$

If $C_s >> C_{SG2}$, the ideal voltage is achieved. For voltage build up of the Marx generator, stray capacitance needs to be as high as possible, to make sure the over voltage appears across SG_2, the structure needs to be near to the stage capacitor's plate. However, the voltage build up on the stages dictates the closeness of the chamber, this leads to reduce the possibility of very high capacitance. So, the voltage across $SG_2 < V_{charge} + V_{charge}/(N\text{-}1)$, this reduces the over-volting and reduces the chance of breakdown. The detailed discussion is given in [1].

6.2. Design of Marx Generator

Input parameters: Output voltage V_{out}, Output current I_{out}, full width half maxima duration t (FWHM).

From energy equation,

$$\frac{1}{2} nCV_{ch}^{2} = V_{out} I_{out} t \tag{6.2}$$

C: Per stage capacitance

V_{ch}: charging voltage

n: Number of Marx stages

Commercially, capacitors are available with maximum voltage rating of 50 kV. Open circuit voltage is nV_{ch}. As to reduce the stress on the capacitor, it is operated at 80% of rated voltage. The number of stages can be calculated for the open circuit voltage. The voltage on the matched load is 70.3% of the open circuit voltage. Once the number of stages known, per stage capacitance can be calculated from Eq. (6.2). Once per stage capacitance is known, total erected capacitance can be found out. Given FWHM, the total inductance of the critically damped system can be estimated from Eqs. (6.3) and (6.4).

$$T = 0.7\pi\sqrt{L_{Total} C_{Erected}} \tag{6.3}$$

$$Z = 2\sqrt{\frac{L_{Total}}{C_{Erected}}} \tag{6.4}$$

Here, Z is the impedance of the Marx generator. L_{total} is the total inductance contributed by three major parameters, (1) Inductance of capacitor, (2) Inductance of spark gap and (3) Inductance of lead connectors. Once the parameters are known, circuit simulation can be done to visualize the output voltage, output current and pulse duration on different load.

Circuit simulation gives the ideal result, but to accommodate the stray parameters, CST microwave studio solved in a high frequency time domain analysis is performed to verify the result. The Marx module and enclosure has been modeled as close as possible to the actual components used. The capacitors can be realized as per the physical dimension and permittivity is chosen of selected capacitor. Discrete ports were placed across the spark gaps. These ports are programmed in such a way that, all the spark gaps hold the high voltage and then all the spark gaps will discharge simultaneously to simulate the output voltage pulse. The load is connected to the last plate. This simulation does not include processes involved in spark gap switching mechanism such as formative time, statistical time etc. Simulation was carried out to validate the structure inductance and stray capacitance.

6.3. Component selection

This section talks about the features of the various components used in the Marx generator.

6.3.1. DC Power supply or Capacitor Charging Power Supply

If number of stages to achieve the output voltage is high then per stage charging voltage is less and vice versa. If stage charging voltage is low then, no of stages increases with more number of spark gaps and larger physical dimension, resulting in higher inductance and stray parameters. It deteriorates the pulse shape and reduces the efficiency of the Marx generator. On the other hand, if stage charging voltage is higher, increases the possibility of dielectric breakdown. Higher charging voltage reduces the reliability of the system as probability of pre-firing is more. So, there is a trade-off between the number of stages and the charging voltage. DC power supply is made up of 3 phase mains rectified by diodes and series resistors are connected to limit the current. These power supplies are used to charge the single shot pulse power system. Moreover 50% energy is lost in the resistor, which implies less efficient system. To charge the Marx generator fast, capacitor charging power supply (CCPS) is used. Mostly the current is maintained constant in CCPS, which charges the Marx capacitors quickly, hence used for reprate Marx generator.

6.3.2. Marx charging Resistors and inductors

A. Resistors

The significance of Marx resistors are to prevent the Marx capacitor from getting short circuited when spark gap breakdowns. The resistors needs to be non-inductive as to prevent the unnecessary oscillation when Marx erects. The resistors are used to charge the high voltage capacitors, so it needs to have proper insulation to prevent any surface breakdown. The non-inductive resistors are made with ceramic material and epoxy casted such a way that it gives insulation while charging to high voltage. Marx resistor's end connections are very crucial, when Marx erects, the upper stages' resistors becomes transient high voltage points.

B. Inductors

The inductor is ideal choice for rep-rate Marx generator as it is not lossy and fast charging is possible. The inductors are made with copper winding on a Perspex former. The inductor value may be chosen in a manner that the energy drawn by the inductor is less than 1%.

6.3.3. Spark gaps (SGs)

SGs are used as high voltage, high current and fast switches in Marx generators. The electrode shape, size, gap and insulating material are the physical parameters of the SGs. If the applied voltage of the SG is higher than the breakdown voltage of it, then SG closes and very low resistance is offered by it. When the external triggering is applied to the first stage, the SG's electric field is enhanced and it can breakdown with lesser charging voltage. Ultra violet light helps to trigger the SG. SGs are used in two different fashions, one has been used in the insulator housing, where the SG is pressurized and it is kept in oil insulation medium. Such SGs has the capability of higher coulomb transfer. On the other hand, system with low energy have SGs in the gas medium without housing, they are physically small in dimension.

6.4. Triggering Mechanism

The first stage's SG is externally triggered to initiate the erection of Marx generator. The trigger generator is made up of IGBT switch and high voltage pulse transformer. When low voltage pulse of 15 V is applied to the gate of the IGBT, it gets triggered and the pulse voltage of 300 V is step up to 30 kV, 150 ns. Usually two types of triggered SGs are used. First one is trigatron type and second one is field enhancement type. It is advantageous to trigger the all the SGs of Marx generator to increase the triggering range of the Marx generator [2].

6.5. Different types of Marx generator recently developed at BARC

6.5.1. Marx generator of KALI 30 GW

KALI-30 GW system has three stages: (1) Bipolar MARX generator, (2) Blumlein pulse-forming line, and (3) Relativistic electron beam diode. MARX generator consists of 15-stage bipolar configuration of 0.2 μF, 50 kV low-inductance capacitors. Charging resistors (2.2 kΩ) and ground resistors (20 kΩ) are used. The whole assembly is kept under transformer oil. The capacitors are mounted on the Perspex sheets of thickness 30 mm, the inter stage connections are made with the SS rod. The resistors are made up with the Nichrome wire, wound on the Perspex cylinder. Corona guards made of SS is provided at both the end connections. Marx generator charges blumlein pulse forming line with 1 MV [3]. Figure 6.2 shows the schematic of Bipolar Marx generator. Figure 6.3 shows the photograph of Bipolar Marx generator of KALI 30 GW.

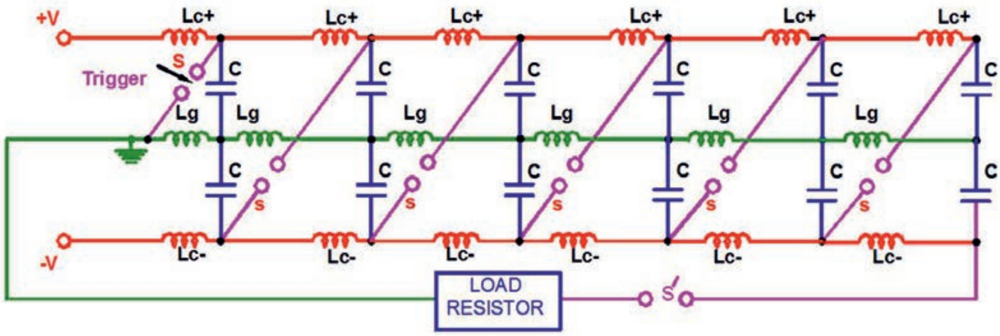

Figure 6.2. Schematic of bipolar Marx generator.

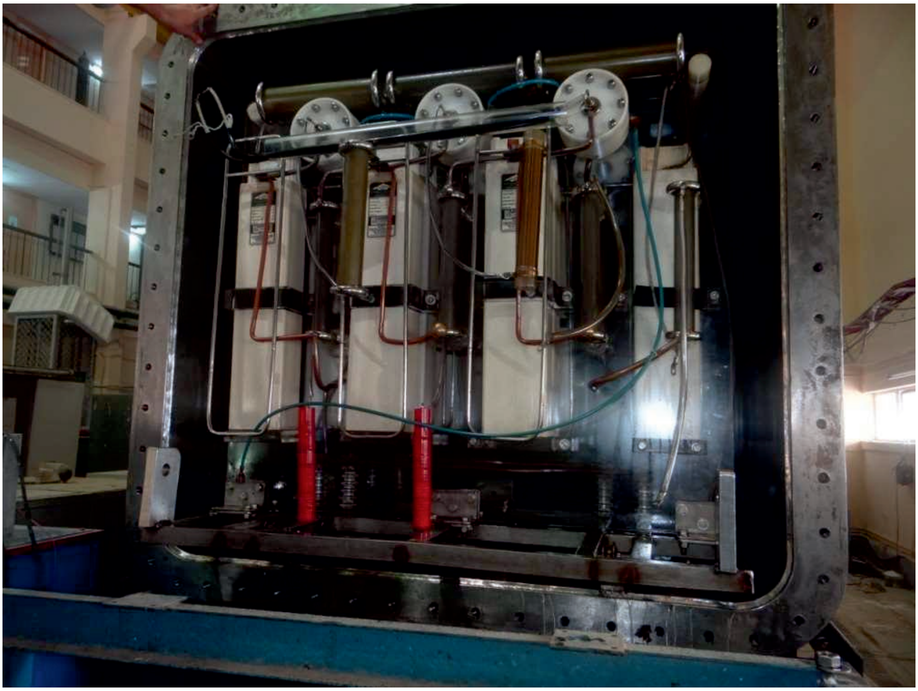

Figure 6.3. Photograph of Bipolar Marx generator.

6.5.2. Reprate 1kJ Marx generator

The rating of this system is output voltage 300 kV, output current 12 kA, FWHM 300 ns and repetition rate is maximum 10 Hz. Figure 6.4 shows photograph of 1kJ Marx generator.

Figure 6.4. Photograph of 1kJ Marx generator.

Marx generator is housed in a SS chamber of 600 mm diameter and 2 m length. The Marx generator is bipolar having 6 stages and each stage has 150 nF capacitor. The chamber can be pressurized with HP N_2 up to 4 kg/cm^2 to vary the output voltage from 150 kV to 300 kV. This is inductive charging system as the system is repetitive. Marx generator is charged with 50 kJ/s capacitor charging power supply. The output of this system is connected to various narrowband microwave generator devices [4, 5].

6.5.3. Zig-Zag Marx generator

This type of Marx generator has zig-zag discharging path due to placement of SGs. The SGs are placed in such a way to make use of assistance of ultraviolet rays emitting from preceding SG breakdown. The system developed at BARC has outputs 400 kV output voltage, 4 kA output current and 100 ns full width half maxima. Marx generator has 23 stages with each stage has 20 nF capacitor [6]. Figure 6.5 shows the 3D model of the Marx generator showing capacitor arrangement and spark gaps.

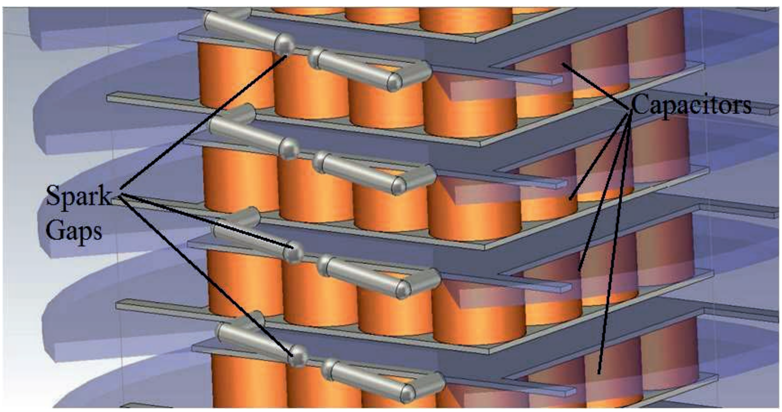

Figure 6.5. 3D model of the Marx generator capacitor arrangement and spark gaps.

6.5.4. Coaxial Marx generator

All the SGs are placed in the axis of the Marx stage assembly which is coaxial with the outer chamber. This type of Marx generator offers lowest possible inductance. A 600 kV, 10 kA, 60 ns FWHM Marx generator has been developed for X-band backward wave oscillator (BWO) system and 1 GW peak power was achieved. This Marx generator has twenty stages of 20 nF capacitance per stage. The total inductance of the system is 550 nH. The Marx generator is housed in the SS chamber of 600mm diameter and 1400 mm length. The chamber is pressurized with 4 kg/cm^2 pressure of high purity Nitrogen to get the high voltage output. A cable fed FXR system with 550 kV, 10 kA, 40 ns Marx generator and FXR diode is developed at APPD, BARC. This system has 20 stages of 14 nF capacitance /stage. The total inductance of the system is 430 nH. The system is housed in the SS chamber of 500 mm diameter and 1200 mm length. The chamber is pressurized with high purity nitrogen gas with 4 kg/cm^2 pressure. The X-ray parameters like dose at 65 mR at 1 m, X-ray peak energy 500 keV, penetration depth of steel at 2.5 m is 32 mm and cone angle is 30° are achieved [7]. Figure 6.6 shows the photograph of Coaxial Marx generator.

6.5.5. Pulse Forming network (PFN) based Marx generator

The PFN based Marx generator is used to produce flattop pulse. Two different types of PFN Marx generators are developed. First one is the Marx generator which uses special kind of folded pulse forming line (FPFL) capacitor. The voltage of each FPFL is 35 kV and there are 15 such stages in PFN based Marx. Each stage charged to 30 kV to get 225 kV on 40 Ω load. The FWHM and rise time of 120 ns and 40 ns are achieved respectively. This system is used for Flash X-ray generation. A stage of second type bipolar PFN Marx generator is assembled using lumped capacitors and inductors. Each bipolar stage has total 40 nF capacitance and 94 nH inductance. Such 18 stages are stacked to form bipolar PFN based Marx generator. The output parameters are 650 kV, 8 kA and 150 ns Flattop. This system is a pulser for S-band BWO system. Figure 6.7 shows the photograph of Erected bipolar PFN Marx generator.

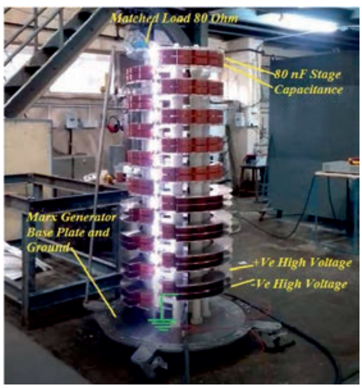

Figure 6.6. (left) Photograph of coaxial Marx generator and (right) photograph of Erected Bipolar PFN Marx generator.

6.6. Conclusion

Various types of Marx generators have been developed in APPD, BARC. The Higher energy Marx generator to compact Marx generator has been developed. The peak power ratings of the Marx generator varies from 1.6 GW to 30 GW, voltage varies from 400 kV to 1 MV, current ranging from varies from 4 kA to 25 kA, FWHM varies from 40 ns to 300 ns. Modifications in the configurations are done to improve the output parameters. Marx generators are used to drive relativistic electron beams, which ultimately used to drive Flash X-ray source and narrow band microwave sources.

References

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