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Faculty of Engineering

Electrical-Electronics Engineering Department

EEE 471 – High Voltage Engineering

Marx Generator: Structure, Operation and Simplified Simulation

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1. Introduction

Lightning or switching overvoltages in high-voltage systems can lead to severe equipment destruction. Impulse generators are utilized to simulate and safely analyze such transient phenomena. Among the most common and effective impulse generators is the Marx generator. It enables the generation of high-voltage pulses from relatively low-voltage DC sources, making it extremely useful for insulation testing as well as other pulsed power applications (Eljugmani, 2015).

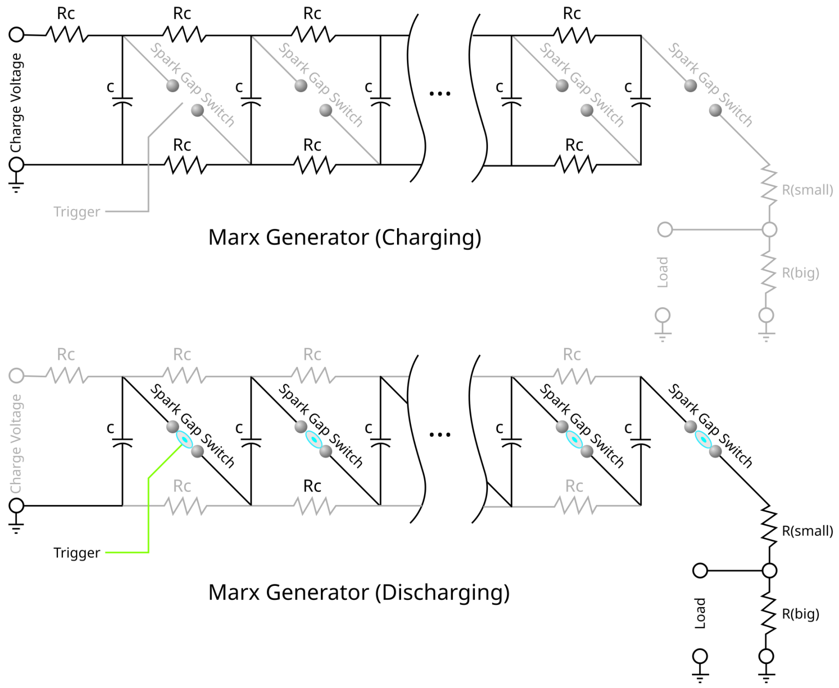

Figure 1.1 Typical Marx Generator Circuit: Charging and Discharging States. Source: Wikipedia contributors (n.d.).

2. Background

The Marx generator principle was originally presented by Erwin Otto Marx in 1924 to produce high-voltage pulses through parallel charging and sequential discharging of capacitors. This method circumvents real-world voltage limits of one-stage circuits. The impulse voltage waveform produced by a Marx generator is especially useful in determining the insulation coordination of electrical systems, as stated by Kuffel (2000).

Initially developed to simulate atmospheric overvoltages like lightning strikes, Marx generators became widely used in laboratory and industry testing environments. Over time, their use further diversified into other broader pulsed power engineering applications where high peak voltage and rapid energy discharge are essential. Marx generators' modularity and scalability have also made them versatile in terms of their power range from small-scale academic research setups to large national laboratory dimensions (Dholariya et al., 2020).

Improvements of the modern era brought with them the application of pulse-forming networks (PFNs) and semiconductor switches, which allow for the shaping of the pulse with precision and increased efficiency (Li et al., 2008). However, despite technological improvements, the essence of the overall process remains staged energy accumulation followed by rapid discharge. Carey and Mayes (2002) noted that the evolution of Marx generators also brought with it improvement in trigger synchronization and component protection, thus making them more reliable and have varying points of application.

3. Structure and Working Principle of the Marx Generator

3.1 Stage Design and Key Components

A typical Marx generator consists of multiple stages, each with a capacitor, charge resistor, and spark gap. The capacitors are charged in parallel in the charging process through high-resistors. Upon charging, triggering of the initial spark gap results in a series breakdown through all stages, connecting the capacitors in series and producing a high-voltage pulse across the load (Dholariya et al., 2020).

The capacitors are the main energy storage components of the Marx generator. They are carefully selected by their values based on the desired current and output voltage. The charging resistors are used for current limiting charging and also for insulation between stages during operation. The spark gaps are the switches that transition from a high-resistance state to a low-resistance state when reaching the breakdown voltage, creating a fast and synchronized path for discharge.

Kuffel (2000) indicates the importance of the gap distance and synchronization in achieving proper spark gap operation. Spark gaps are built with spaced intervals of increasing gaps to enable sequential triggering. Other devices such as front and tail resistors are also used to condition the waveform to generate standard waveforms such as 1.2/50 μs lightning impulses.

3.2 Advanced Configurations

In more advanced configurations, the Marx generator can use triggered spark gaps or even solid-state switches for better control of the pulse shape and timing. Li et al. (2008) continue on to explain designs that incorporate pulse-forming networks (PFNs) to create rectangular pulses, which are better suited to some applications like radar and EMP systems.

The Marx generator output is typically attached to the test object by a coupling resistor or capacitor, depending on the waveform fidelity required. The entire system must be properly insulated and shielded in order to avoid corona discharge, flashovers, or radiated unwanted emissions especially when the output exceeds several hundred kilovolts.

3.3 Theoretical Calculations

At a theoretical level of operation, several basic equations can be used for the analysis of Marx generator operation. Theoretical output voltage could be calculated as the product of the number of stages (n) and the charging voltage (Vcharge), i.e., $V_{out} = n \times V_{charge}$. The total energy stored in each capacitor is expressed by the equation $E = (1/2) \times C \times V^2$, where the capacitance of each stage is expressed as C and the voltage to which the capacitor is charged expressed as V. Thus, the total amount of energy stored in the entire generator becomes $E_{total} = n \times (1/2) \times C \times V^2$. Besides, the charging time constant for each stage is given by $\tau = R_{charge} \times C$, where Rcharge is equal to the charging resistance in each stage. Such equations play a crucial role in the voltage multiplication prediction, stored energy, and dynamic response of the Marx generator when in use.

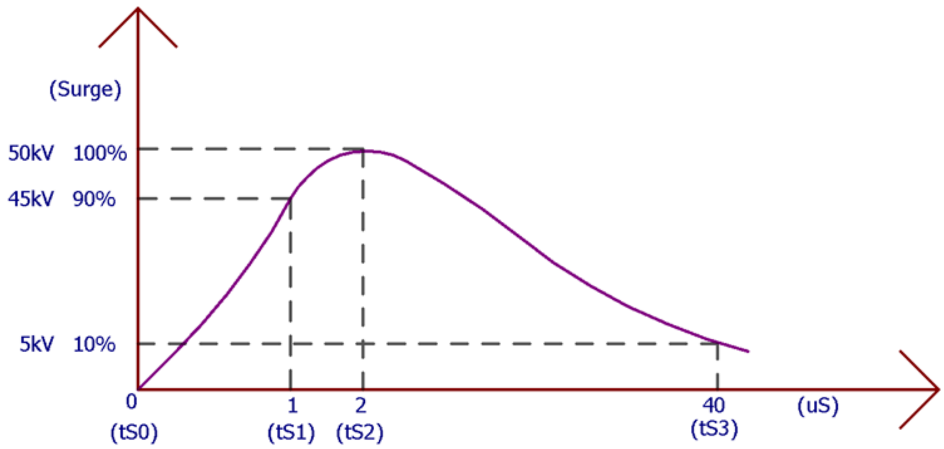

Figure 3.1. Characteristic Waveform of Standard Impulse Voltage (1.2/50 µs).
Source: Circuit Digest (n.d.).

4. Applications of Marx Generators

Marx generators are employed to take center stage in high-voltage engineering applications:

Insulation Testing: As explained by Naidu and Kamaraju (2013), impulse testing plays a critical role to verify the insulation capacity of transformers, circuit breakers, and surge arresters. These tests simulate lightning or switching-induced overvoltages such that insulation is able to withstand transient stresses without breakdown. The Marx generator allows repeatable, controlled impulses required by international test specifications (e.g., IEC 60060) to be generated.

Pulsed Power Systems: Marx generators are employed to supply high-voltage pulses for particle accelerators and electromagnetic launch systems (Li et al., 2008). In particle accelerators, these pulses are used to drive acceleration structures, which achieve strong electric fields necessary for the acceleration of particles. In electromagnetic launch devices such as railguns or coilguns, Marx pulses are employed to supply the vast transient current necessary to propel projectiles at high velocity.

UWB and EMP Systems: Small Marx circuits are able to produce ultra-short pulses utilized in radar systems and EMP generators (Li et al., 2008). Ultra-wideband (UWB) radar systems are improved upon by Marx circuit-synthesized nanosecond-scale pulse widths for resolution and penetration. Similarly, electromagnetic pulse (EMP) generators employ Marx topologies to generate short-duration, high-intensity electromagnetic energy bursts for military testing or for testing shielding.

Triggering Large Systems: Small Marx circuits are able to trigger larger systems using synchronized pulses (Carey & Mayes, 2002). These trigger functions encompass operating plasma switches, discharging laser flashlamps, or regulating other pulsed high-energy power modules. The precise timing and amplitude-controllable properties of pulses that are generated by Marx make them perfectly suited for operating complex multi-stage pulsed systems.

5. Simplified Simulation of the Marx Generator

To demonstrate the operation principle, a Marx generator was implemented in a simplified form with low-voltage components as described in the student presentation.

5.1 Experimental Setup

In our prototype experiment, we constructed a minimized Marx generator circuit with six 1 nF, 4 kV capacitors as the charging path and ten 1.5 MΩ resistors. A single 10 MΩ resistor was added in series to limit the peak discharge current and for added safety. The capacitors were energized by a high-voltage boost module (shock voltage generator), powered through a buck converter reducing 9 V to 3.3 V, drawing power from a 9 V battery. Breakdown was observed across the air gap with visible spark discharges when the voltage across the capacitor bank was about 3.5–4.0 kV per stage. Theoretically, under ideal conditions, the maximum output voltage was computed around 800V-1200V with this setup.

5.2 Observations and Results

The experiment was successful in demonstrating the basic principle of parallel charging and series discharging of capacitors. It also allowed observation in practice of the effect of capacitor rating, charging voltage, and spark gap distance on the resultant impulse discharge.

This experiment setup is a teaching model of the energy storage and its sudden release to produce a spark. The capacitors in the circuit are first charged by the DC boost module, and the spark is observed when the voltage across the discharge gap exceeds the dielectric strength of air. This is a simulation of the sequential breakdown of a real Marx generator but in a single-stage or simplified two-stage setup.

While this prototype lacks the full stage-by-stage series discharge and insulation complexity of high-voltage models, it remains useful for conceptual understanding. As Eljugmani (2015) observes, such simplified models are needed for undergraduate and early-stage researchers to understand impulse generation dynamics without safety risks of high-energy systems.

5.3 Limitations and Possible Improvements

Under test, various capacitor values and charge voltages were tried to observe the effect on spark size and consistency. Setup limitations were component heating, the need for triggered control, and the lack of convenience in repeatable discharge timing. Despite these limitations, the demo worked very well to demonstrate how energy conversion and fast discharge phenomena occur in the Marx generator topology.

Furthermore, refinements such as the addition of a multi-stage configuration, addition of manual or electronic trigger circuits, or use of enhanced isolation techniques can render the model closer to practical applications. Such enhancements can facilitate voltage waveform measurement and better adherence to standard impulse test waveforms detailed in Kuffel (2000).

6. Conclusion

The Marx generator remains a simple yet versatile device in high-voltage engineering. The ability to generate controlled high-voltage pulses makes it a must for insulation testing, pulsed power studies, and various industrial and military applications. The straightforward concept of charging parallel capacitors and discharging series capacitors enables the achievement of extremely high voltages in a compact and modular form.

As inferred from the literature and experiments covered in this report, traditional spark-gap-type systems and modern PFN-coupled variants continue to be fundamental to power system tests as well as pulse generation. As demonstrated with the miniaturized prototype, even scaled-down implementations of the Marx generator can well convey its operating principles and applications.

Future research would include the creation of multi-stage laboratory models, refinement of synchronization and timing accuracy, and incorporation of digital triggering systems. With increasing applications for high-speed and high-reliability generation of high-voltage pulses, the Marx generator continues to be an area of interest and innovation within electrical engineering research and practice.

7. References

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