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Design and Implementation of 8 - Stage Marx Generator Used for Gas Lasers

Dr. Naseer Mahdi Hadi
Ministry of Science & Technology, Laser & Electro-Optics Research Center, Baghdad, Iraq.

Dr. Kadhim Abid Hubeatir
University of Technology, Laser & Optoelectronics Department, Baghdad, Iraq

Ghaidaa Hamza Khudair (M.Sc laser engineer)
Ministry of Science & Technology, Laser & Electro-Optics Research Center, Baghdad, Iraq.

Sarmad Fawzi Hamza
University of Technology, Laser & Optoelectronics Department, Baghdad, Iraq.

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Abstract
Marx generators have been designed, built and tested. A Marx generator with eight stages, which can be deliver 64 kV maximum output, is charged up to 2 kV and the high voltage output was 12 kV with pulse rise time of 666 ns, decay time 4 µs, inductance 11 µH and efficiency of 75%. Energy stored in Marx 75.2 mJ and erected capacitance $5.875*10^{-10}$ F, the Charging current is 1 mA. A Xenon flash lamp trigger circuit with high voltage output pulse (4.5 kV) and pulse width of 2µs, was used for triggering the Marx generator.

1. Marx Generator Power Supply:
1.1 Marx Generator
A Marx Generator is a clever way of charging a number of capacitors in parallel through resistance, then discharging them in series through spark caps. Originally it was described by Erwin Marx in 1924 [Young J. C.]. Marx generators offer a common way of generating high voltage impulses that are higher than the available supply charging voltage, as shown in figure (1).

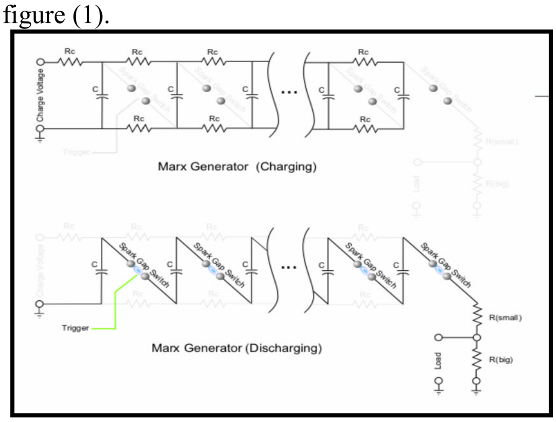


Fig. (1) Marx Generator (A) Charging (B) Discharging [Kuffel E. and Abdullah M.].

A typical circuit presented in figure (2) which shows the connections for a five-stage generator. The stage capacitors C charged in parallel through high-value charging resistors R. At the end of the charging period, the points A,B,…,E will be at the positive potential of the D.C sources, with respect to earth, and the points F,G,…,M will remain at the earth potential. The discharge of the generator initiated by the breakdown in the spark gap G_1, which followed by simultaneous breakdown of all the remaining gaps.

When the gap G_1 breaks down, the potential on the point A changes from +V to zero and that on point G swings from zero to -V owing to the charge on the condenser C. If for the time being the stray capacitance C` is neglected, the potential on B remains +V during the interval of the gap G_1 sparks over.

A voltage 2V, therefore, appears across the gap G_2 that immediately leads to its breakdown. This breakdown creates a potential difference of 3V across G_3 the breakdown process, therefore, continues and finally the potential on M attains a value of -5V [Kuffel E. and Abdullah M.] .

In effect, the low voltage plates of the stage capacitors are successively raised to -V, -2V…,-NV, if there are N stages. This arrangement gives an output with polarity opposite to that of the charging voltage.

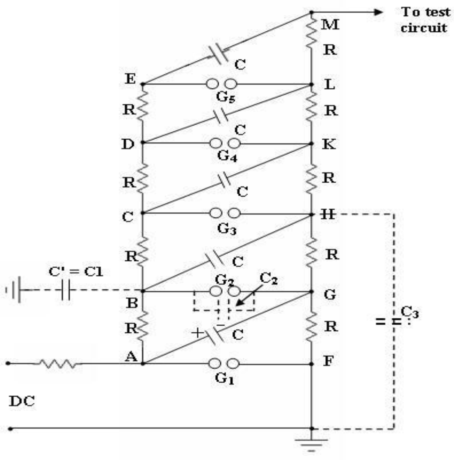


Fig. (2) Basic circuit of a five-stage impulse generator [Kuffel E. and Abdullah M.].

The above considerations suggested that a multistage impulse generator should operate consistently irrespective of the number of stages. In practice for a consistent operation it is essential to set the first gap (G_1) for breakdown only slightly below the second gap (G_2). A more complete analysis shows that voltage distribution across the second and higher gaps immediately after the breakdown of the lowest gap (G_1) is governed by the stray capacitances and gap capacitances shown in dotted lines in figure (2).

The effect of stray capacitances on voltage across G_2 immediately after breakdown of G_1 which may be estimated as follows:

Assume the resistors as open circuits and stray capacitances negligible in comparison with the stage capacitors. Let (A) in figure (2) be charged to (+V), after breakdown of G_1 the point G initially at earth will assume a potential –V, but the potential of B is fixed by the relative magnitudes of C_1 , C_2 and C_3 is given by [Zaengl W. S. and Kuffel E.]:

$$V_{BH} = V\left(\frac{C_1 + C_3}{C_1 + C_2 + C_3}\right) \ldots\ldots\ldots\ldots(1)$$

Hence the voltage across the gap G_2:

$$V_{G2} = V\left(1 + \frac{C_1 + C_3}{C_1 + C_2 + C_3}\right) \ldots\ldots\ldots (2)$$

If $C_2 = 0$, V_{G2} reaches its maximum value of 2V, but if C_1 and C_3 are zero, V_{G_2} will equal to V, i.e. its minimum value.

It is apparent, therefore, that the most favorable conditions for the operation of the generator occur when the gap capacitance C_2 is small and the stray capacitances C_1 and C_3 are large. The conditions set by the above expression are transient, as the stray capacitors start discharging. The practical stray capacitors are of low values, consequently the time constants are relatively short $\approx 10^{-1}$ µsec or less [Kuffel E. and Abdullah M.].

1.2 Spark Gaps

The spark gap is a conceptually simple device; it consists of two electrodes separated by an insulating material. The insulating material may be a gas, liquid, or solid, but a gas is the most commonly used material. So this research will consider only gas-filled spark gaps. A voltage is applied across the spark gap, lower than the breakdown voltage for the gas. Then a trigger pulse is applied and it's often consists simply of applying a momentary over voltage between the electrodes, then the gas breaks down and a current flows across the gap.

The required breakdown voltage depends on the nature of the gas, its pressure, the shape and separation of the electrodes. For plane spark gaps electrodes spaced one centimeter apart with gas pressure of one atmosphere, the breakdown voltage is 1.3 kV for neon, 3.4 kV for argon, 12 kV for hydrogen, 22.8 kV for nitrogen and 23 kV for air. These values are reduced for pointed electrodes [Simcik J. and Christensen C.].

1.3 Trigger Circuits

External triggering uses a high voltage trigger pulse to create a thin ionized streamer between the anode and cathode within the spark gap. Ionization starts when gas adjacent to the gap is excited by the voltage gradient induced by the high voltage pulse from the trigger device. The trigger pulse width is important because a finite amount of time is required for the ionized streamer to propagate down the space of the spark gap. The trigger rise time has a decisive effect on the commutation time of the tube; fast rising pulses of high peak amplitudes cause the device spark gap break down in a shorter time due to the over voltage function. Three major driver features will strongly affect the switching performance [Hadi N. M.]. They are (1) trigger jitter (2) trigger output delay time and (3) trigger rise time. Where; Delay time: is the time taken between the application of a trigger pulse and the commencement of conduction between the primary electrodes, while Jitter time: is the variation of time delay between shots which gives similar electrical stimulus [Ghaida' H.].

1.4 Charging of the Marx Generator

In N-stages Marx bank, the output voltage available at any instant is theoretically the sum of the individual stage voltages. Thus, there is an RC line in each, except for the first stage, all forcing functions are time and position dependent. Two solutions are conveniently available, one relationship according to Fitch as in figure (3) the charging time is:

$$T_{CH} = R_o C_o N^2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

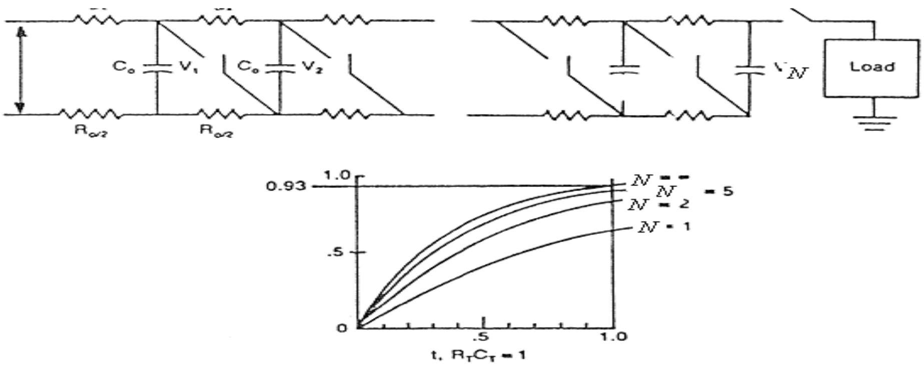


Fig. (3) Marx bank charging performance [Sarjeant W. J. and Dollinger R. E.].

The second relationship is shown in figure (3), presents a power series analysis that takes to the limit as N goes to infinity. In an LC circuit, recourse can be taken to the PFN and the characteristic time is given by:

$$\tau_{CH} = \sqrt{L_{MARX} C_{MARX}} \ldots\ldots\ldots\ldots\ldots (4)$$

The discharging into matched impedance requires a time 2τ . In mismatched cases, oscillations occur that extend this time. More commonly, some command charge system employed in which an external inductor, large with respect to the Marx inductors, is resonated against the total network capacitance. Charging usually accomplished in a half cycle of the resonant frequency, leading to [Sarjeant W. J. and Dollinger R. E.]:

$$\tau_{CH} = \pi \sqrt{L_{TOTAL} C_{MARX}} \ldots\ldots\ldots\ldots\ldots (5)$$

1.5 Discharging of the Marx Generator:

The inefficiencies of charging have a matching set of inefficiencies associated with the discharge. Figure (4) reveals that, in general, a stage capacitor is paralleled by two charging impedances, Z_o . In the resistive case, the self-time constant is just:

$$\tau_{DISCH} = \frac{R_o C_o}{2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

This time must be long compared to the output pulse for good efficiency. When inductances used as charging impedances, the behavior is similar except for the appearance of resonance in place of the simpler RC case. [Sarjeant W. J. and Dollinger R. E.]

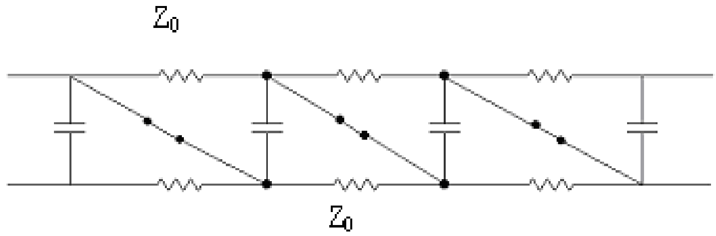


Fig. (4) Marx bank discharge relationships [Sarjeant W. J. and Dollinger R. E.].

2. Experimental Work

2.1 Variable High Voltage Supply

A homemade variable 4kV DC power supply is developed for charging the Marx capacitors as shown in figure(5), it is consist of a variac (0-220VAC, 5Amp), high voltage transformer (220V/4kV), current limiter resistor 330 Ω, high voltage diodes 6kVDC for rectification (it works as a half wave rectifier), capacitor (0.1µF-25kV) and 100kΩ charging resistor.

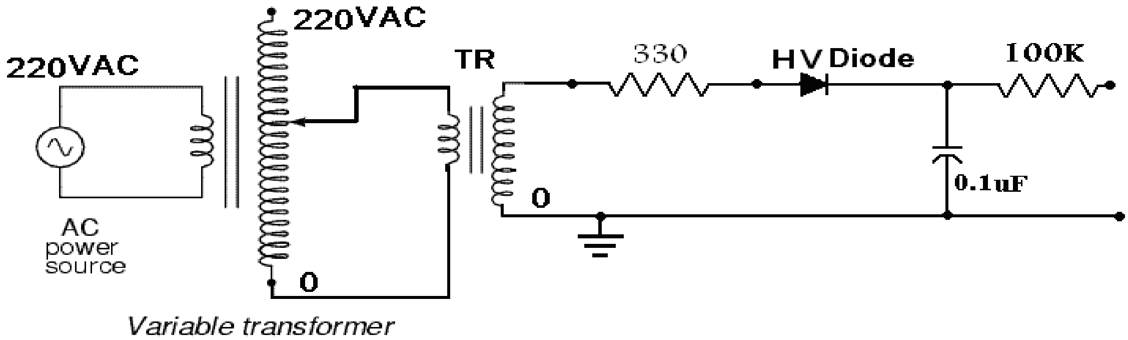


Fig. (5) A homemade high voltage power supply.

2.2 Flash Lamp Triggering Circuit

A small xenon camera liner flash lamp (300V max. applied voltage) with commercial trigger transformer (TR) with maximum input 200V and maximum output 20 kV. The resistor (R_t) and capacitor (C_t) are used to form the trigger generator circuit as shown in figure(6) and (7). The breakdown action in the xenon flash lamp occurs when the voltage across the lamp is 256 VDC. The (10nF) capacitor (C_t) is charged through (R_t) as the flash lamp breaks down discharging (C_t) into the primary coil of the trigger transformer to produce an output high voltage pulse on the secondary (~8 kV DC) which is used to trigger the first gap of the Marx generator (8-stage).

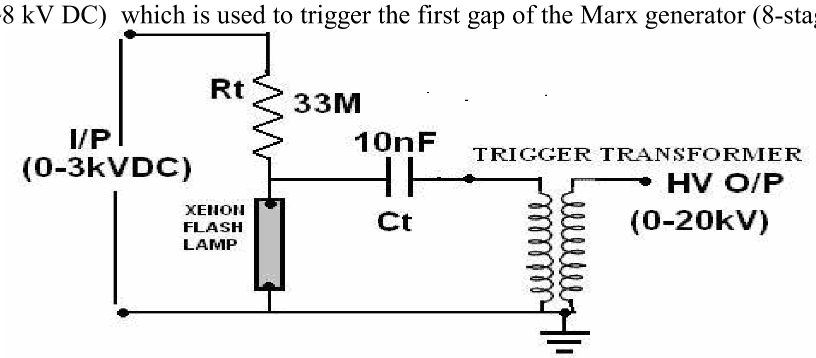


Fig. (6) Xenon flash lamp trigger circuit

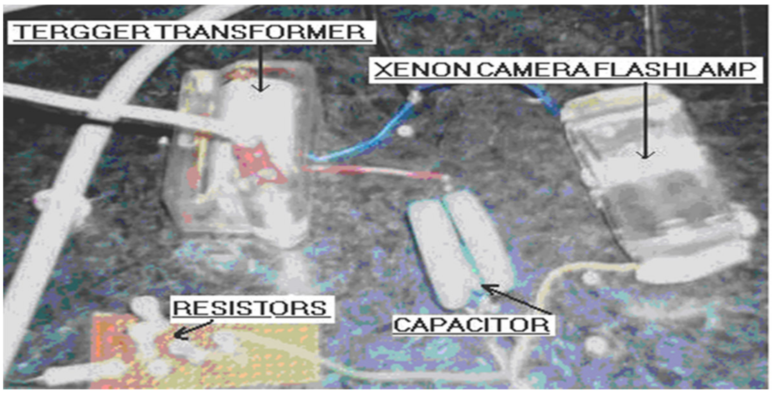


Fig. (7) Camera flash lamp triggers circuit.

2.3 Marx Generator (8 – Stage):

A compact repetitive Marx generator has been designed, built with dimensions shown in table (1) and tested as shown in fig(8). The generator of 8 stages is an R-C ring that consists of 8 capacitors (4.7 nF per capacitor) and 14 resistors (2 MΩ per resistor). The generator is charged quickly to 2kV within a charging time less than 0.52 second by a DC charging source. The trigger system is constructed for repetitively triggering the first discharging spark gap (There are 8 discharging spark gaps in the generator). Due to the limited capacity of the DC charging source the generator is tested at single pulse discharge with an output voltage about 12 kV (efficiency 75%).

Table (1)

Parameters	Diameters	Value	Unit
L_{Marx}	Marx length	38	cm
W_{Marx}	Marx width	5.5	cm
H_{Marx}	Marx height	4	cm

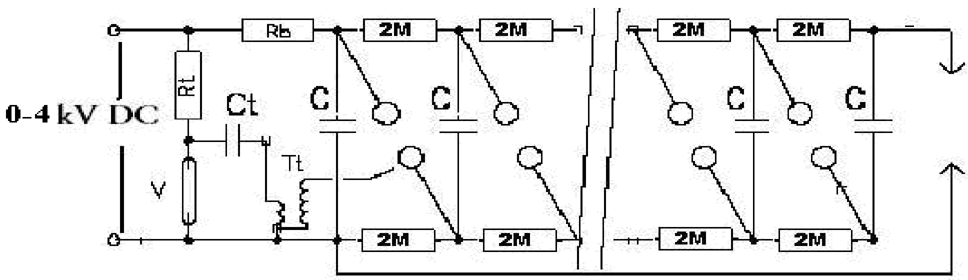


Fig. (8) Circuit diagram for Marx generator (8-stage).

The elements of Marx Generator are; C= 4.7 nF, R = 2MΩ and the input power supply voltage (0 - 4 kV DC), as shown in figure (9).

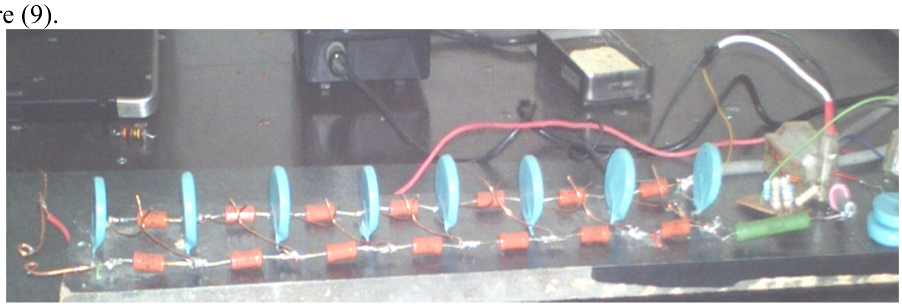


Fig. (9) Marx generator (8-stage).

The spark gap is formed with a tinned copper wire with a diameter of 1.5 mm and gaps should be initially set to about 1.5mm as shown in figure (10).

Fig. (10) Copper wire spark gap

The distance between the spark gaps depend on the input voltage and the number of stages. A high voltage probe is used to measure the output voltage pulse of Marx generator, also the trigger pulses and the current pulses were measured, and figure (11) shows the gaps glow discharge.

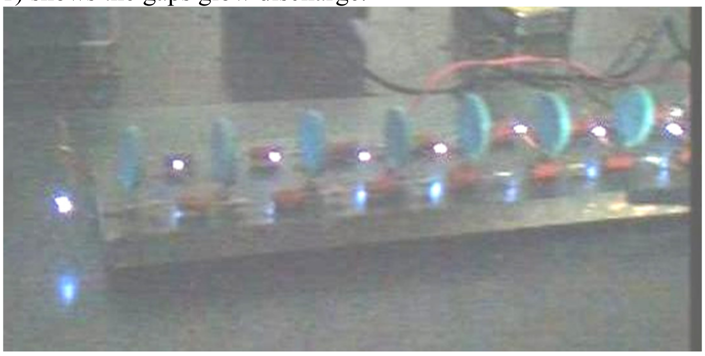


Fig. (11) Gaps glow discharge

3. Results and Discussion

3.1 Flash Lamp Trigger Circuit

Output voltage pulse from camera xenon flash lamp trigger circuit is measured by using high voltage probe (P6015, 1000X, 3pF, 100mega ohms DC, 20kV max. DC continuous, 40kV peak pulse, Tektronix Inc) and a 100 MHz oscilloscope (Oscillation Tektronix 2221A, 100 MHz Digital Storage Oscilloscope),as shown in figure (12) .

3.2 Current Pulse for Marx Generator

Marx generator current pulse was measured using current probe (Termination for P6021 AC Current Probe, Tektronix ® 011-0105-00, LP3db ≈ 450Hz, Tc ≈ 0.35ms). Figure (13) shows the current pulse.

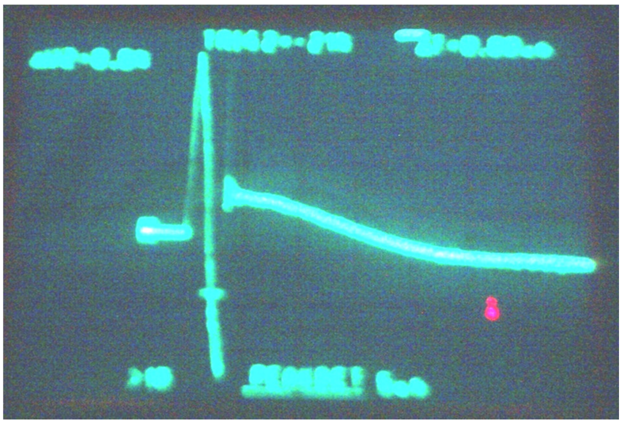


Fig. (12) Output voltage trigger pulse 4.5kV.
Scale (1V, 5µs)

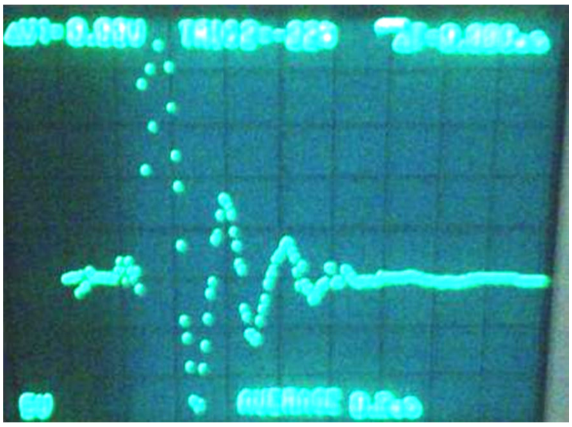


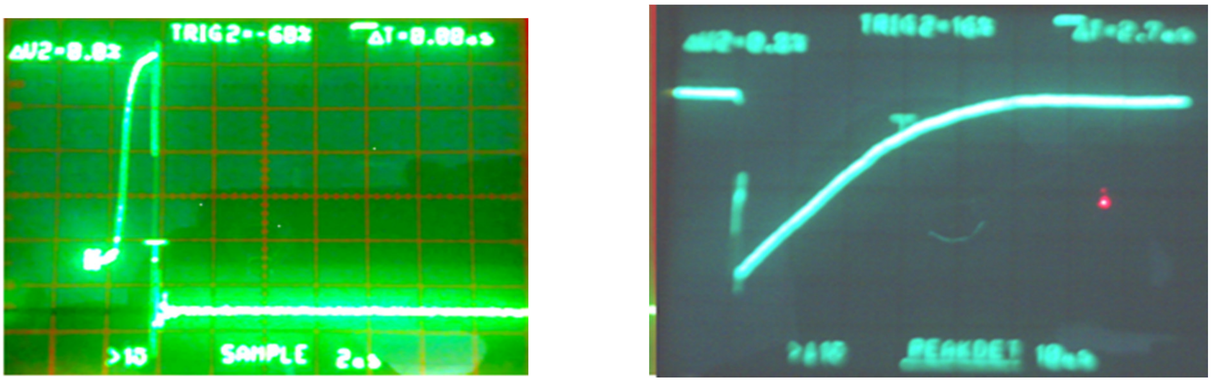
Fig. (13) Marx generator current pulse.
Scale (5V, 0.2 µs)

The Xenon trigger circuit shown in figure (6) was tested with different voltage from zero volts up to its maximum which is found to be ~ (256 volts).This voltage pulse has been used to trigger the first stage of Marx generator. Eight stages Marx generator current pulse is measured using current probe directly mounted to the output section of the generator, the current probe signals is shown in figure (13). The current calculations are:

- Maximum current pulse $I_{Max.} = 225$ mA
- Next peak current pulse $I_R = 140$ mA
- Minimum current pulse $I_{Min.} = 85$ mA
- The time period is, T = 300 ns

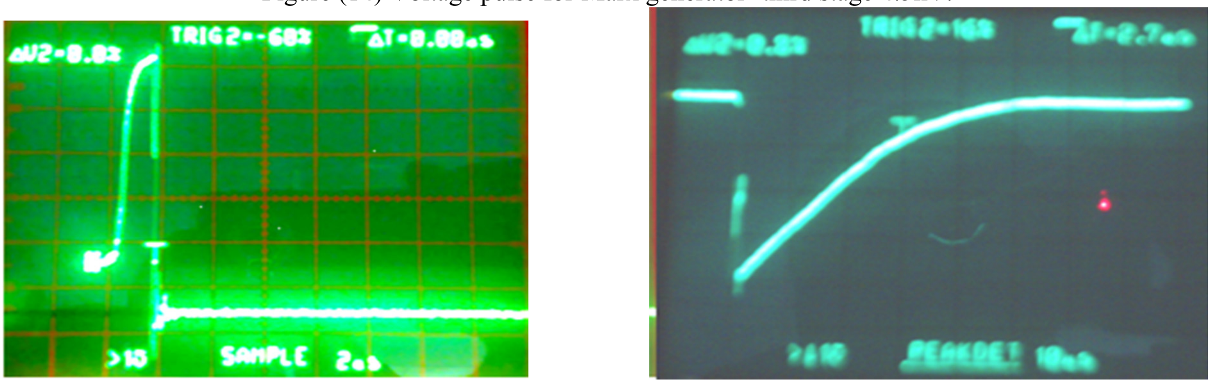
The Marx is charged up to (2 kV), the energy is: $E_{Marx} = 1/2\ C\ V^2 = 75.2$ mJ.

The output voltage pulses are shown in figures (14) and (15).



(a)Full voltage pulse, scale (1V, 2µs) (b)Selected voltage pulse (first stage), Scale (1V, 10 µs)

Figure (14) Voltage pulse for Marx generator- third stage 4.5kV.



(a) Full voltage pulse (fifth stage). Scale (1V, 10 µs) (b) Full voltage pulse (eight stages). Scale (2V, 10 µs)

$t_r \cong$ 666 ns , Pulse width $\cong$ 4.5µs

Figure (15) Voltage pulse for Marx generator stages

3.3 Marx Generator Output Pulse Calculation Method

For eight stages Marx generator the inductance measured from figure (15 (b)):

$f = (1 \backslash 2\pi)\ \ 1\backslash \sqrt{LC_T}$

$C_T = 8 * 4.7nF = 37.6nF$

$\Rightarrow$ Rise time $t_r \cong 6.66 \times 10^{-7}$s

$\Rightarrow\ f = \frac{1}{T} = 1.5 \times 10^6$ Hz.

$\Rightarrow L_{\text{Rise time}} = 2.99 \times 10^{-7}$ H.

$\Rightarrow$ Decay time $t_{de} \cong 4 \times 10^{-6}$ s

$\Rightarrow f = \frac{1}{T} = 2.5 \times 10^5$ Hz.

$\Rightarrow L_{\text{Decay time}} = 1.07897 \times 10^{-5}$ H.

$\Rightarrow$ Pulse width $\cong 4.5 \times 10^{-6}$s

$\Rightarrow f = \frac{1}{T} = 2.222 \times 10^5$ Hz

$\Rightarrow L = 1.3658 \times 10^{-5}$ H.

$\therefore L_{\text{Total}} = L_{\text{Rise Time}} + L_{\text{Decay Time}} = 11.0887$µH

3.4 Characteristic Marx Generator

The calculated results are listed in table (2) for the 8-stage Marx to show the all parameters which affected the Marx output pulse width. From table (2) the first important parameter is the output pulse rise which is 666 nsec; this result is far from the aim of the designed Marx which is around 10 nsec. The second parameter is the pulse repetition frequency which is 1.8996 Hz; this parameter was less than the expected which is about 10 Hz.

Table (2)

Parameter	Description	Value	Unit
V_{Open}	Open circuit voltage (typical)	64	kV
N	Number of stage	8	Stage
C_{Stage}	Stage capacitance, max. voltage 8kVDC	4.7	nF
$C_{eq.}$ or C_{Marx}	Erected capacitance	5.875	10^{-10}F
$V_{Max.Ch}$	Maximum charging voltage	8	kV
V_{Ch}	Real charging voltage	2	kV
L_{Marx} or $L_{eq.}$	Erected series inductance	11.0887	Hµ
L_{Stage}	Stage inductance	1.3860875	Hµ
Z_{Marx}	Marx impedance	137.38407	Ohm
P_{Peak}	Peak power	7.453	MW
E_{Marx}	Energy stored in Marx	75.2	mJ
T_{Ch}	Charging time	0.5264	S
f_{RR}	Maximum repetition rate	1.8996	Hz
t_r	Rise time	666	Ns
t_{de}	Decay time	4	sµ
$P_{ave.}$	Average power	0.1428	Watt
η	Efficiency into a load	75	%
I_{Charge}	Charging current	1	mA

4. Conclusions

From the present work, we can conclude the following:

1- The spark gap design imposes great effect on the discharge output pulse width and rise time. Spark gap also affected the Marx generator inductance and impedance because it adds an imaginary stray capacitance which causes increasing in the inductance of whole system.

2- The components of the Marx generator (capacitors, resistors and wiring connections type) play an important role in determining the impedance and inductance of the whole system. To design and build Marx generator with low inductance and fast rise time pulse, it must use low inductance capacitors and special resistors (e.g. silicon carbide type).

3- The trigger circuit is affecting the discharge properties for the first spark gap of the Marx, which will in parallel affect the whole gaps discharge too, so one must determine the trigger pulse properties such as; pulse width, rise time, fall time and peak power depending on the Marx generator spark gap design and properties.

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