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DESIGN AND IMPLEMENTATION OF A HIGH VOLTAGE MARX GENERATOR IN A COAXIAL STRUCTURE

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Halid Furkan AYDOĞAN

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The thesis study titled "DESIGN AND IMPLEMENTATION OF A HIGH VOLTAGE MARX GENERATOR IN A COAXIAL STRUCTURE” is submitted by Halid Furkan AYDOĞAN in partial fulfillment of the requirements for the degree of Master of Science in the Department of Electrical Electronics Engineering, Gazi University by the following committee.

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ETHICAL STATEMENT

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DESIGN AND IMPLEMENTATION OF A HIGH VOLTAGE MARX GENERATOR IN A COAXIAL STRUCTURE

(M. Sc. Thesis)

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ABSTRACT

In this study, a high voltage Marx generator is produced in coaxial structure. A literature review is performed and previous studies are examined before production. The structure of the Marx generators developed in these studies, the output voltage amplitude, rise time etc. parameters are examined. Then the production of the generator is started and the output voltage of the generator, capacitor number, stage number and sphere size of the spark gap etc. are identified. Later, the production studies of the generator are started, capacitors are soldered for each stage and sphere electrodes are mounted. Eight stages are produced and these stages are connected with each other. Then the return conductors of the Marx generator are manufactured and connected. After that, power supply of the generator is designed and produced. The connection between the power generator and the Marx generator, the earth connection of the generator are made. Following the completion of the production studies, experimental studies are started. The generator is operated at various voltages and the charging voltage is measured. As a result, some modifications are made for power supply. The charge voltage is determined for the safe operating range and sphere gaps are optimized according to this voltage amplitude. Following the observation of the correct operation of the Marx generator, the measurement system is produced and the output voltage of the generator was measured through a capacitive voltage divider. The amplitude of the output voltage, rise time and fall time are recorded in the oscilloscope. Various load combinations were created with various front resistors and tail resistors, and the measured signals were recorded. In these signals, the effect of resistance change on the output of the Marx generator output was observed.

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KOAKSİYEL YAPIDAKİ BİR YÜKSEK GERİLİM MARX ÜRETECİNİN TASARIMI VE GERÇEKLEMESİ

(Yüksek Lisans Tezi)

Halid Furkan AYDOĞAN

GAZİ ÜNİVERSİTESİ
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ÖZET

Bu çalışmada koaksiyel yapıda bir yüksek gerilim Marx üreteci üretilmiştir. Üretim öncesinde literatür taraması yapılmış, daha önceki çalışmalar incelenmiştir. Bu çalışmalarda geliştirilen Marx üreteçlerinin yapısı, çıkış gerilim genliği, yükselme zamanı vb. parametreleri incelenmiştir. Ardından üretecin üretim çalısmalarına başlanmış ve üretecin çıkış gerilimi, kapasitör sayısı, kat sayısı, kıvılcım aralığı küre boyutu vb. belirlenmiştir. Sonrasında üretecin üretim çalışmalarına geçilmiş, her bir kat için kapasitörler lehimlenmiş ve küre elektrotlar monte edilmiştir. Sekiz adet kat üretilmiş ve bu katlar birbirine direncler ile bağlanmıştır. Sonrasında Marx üretecinin dönüş iletkenleri üretilmiş ve bağlantısı yapılmıştır. Ardından üretecin güç kaynağı tasarlanmış ve üretilmiştir. Güç kaynağı ile Marx üreteci bağlantısı ve üretecin toprak bağlantısı yapılmıştır. Üretim çalışmalarının tamamlanmasının ardından deneysel çalışmalara geçilmiştir. Üreteç çeşitli gerilimlerde çalıştırılmış ve şarj gerilimi ölçülmüştür. Bunların sonucunda güç kaynağında birtakım değişiklikler yapılmıştır. Şarj gerilimi güvenli çalışma aralığı için belirlenmiş ve bu gerilim genliğine göre küre aralıkları optimize edilmiştir. Marx üretecinin sorunsuz çalıştığının gözlenmesinin ardından ölçüm sistemi bağlantısı yapılmış ve üretecin çıkış gerilimi bir kapasitif gerilim bölücü aracılığıyla ölçülmeye çalışılmıştır. Çıkış geriliminin genliği, yükselme zamanı, düşme zamanı parametreleri osiloskopta gözlenerek kaydedilmiştir. Çeşitli cephe direnci ve kuyruk dirençleriyle farklı yük kombinasyonları olusturulmus ve ölçülen sinyaller kaydedilmiştir. Bu sinyallerde, direnc değişimlerinin Marx üreteci çıkış gerilimine etkisi gözlenmiştir.

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LIST OF SYMBOLS AND ABBREVIATIONS

The symbols and abbreviations used in this thesis are presented in below with explanations.

Symbols	**Explanations**
k	Kilo
M	Mega
Ω	Ohm
He	Helium
N_2	Nitrogen
SF_6:	Sulfur hexafluoride
T	Oscillation period
F	Farad
µ	Micro (10^{-6})
n	Nano (10^{-9})
etc.	Etcetera
V	Volt
s	second
$CuSO_4$	Copper Sulphate
AC	Alternating current
DC	Direct current
Hz	Hertz
SiC	Silicon carbide

Abbreviations	**Explanations**
HPM	High power microwave
IEMI	Intentional electromagnetic interference
KVL	Kirchhoff's voltage law
MOSFET	Metal oxide semiconductor field effect transistors
PVC	Polyvinyl chloride
UV	Ultraviolet

1. INTRODUCTION

Since invention of the electricity, amount of usage and applications have been increased. Besides the alternating current (AC) and direct current (DC), impulse current and voltage have been needed with time. Scientists, researchers and students have shown interest to impulse voltage and current technology increasingly. Table 1.1 shows the some impulse voltage applications [1].

Table 1.1. Some impulse voltage applications.

Application subject	Applicaton areas
X-ray	Lithography, Microscope, Laser, Material treatment Light source, Medical use, Micro-machine
High Eenrgy Density Plasma	Radiography, Reactor material test, Crystal analysis, Medical use
Nuclear Fusion	Power plant
Electron Beam	Plasma heating, Accelerator, Laser, Radar, Energy transmission, Atmosphere ionization, Sterilization
Ion Beam	Plasma Nuclear fusion, Material development
Discharge	Excitation and chemical reaction, Laser, Pollution control, Film formation, Ozonizer, Light source
High electromagnetic field	Military applications, intentional electromagnetic interference (IEMI),
High voltage	Lightning surge test, Insulation test, high power microwave (HPM) device sources

Impulse voltage levels have increased with developing technology. Then, impulse voltage have been used to research effects of the lightning pulse to electrical equipments such as energy transmission lines, transformers, circuit breakers. Therefore some protection methods and precautions could have been developed. Thus high voltage impulse sources have been prominent in impulse voltage technology.

Some circuit topologies that generate high voltage impulse have been created in the early 1900s. Main idea of these circuits based on storing electrical energy and discharging suddenly. Even if there were a lot of developments in storing devices i.e. capacitors and very fast switches, many high voltage impulse devices are based on the Marx generator that is one of the impulse voltage sources [2].

Marx generators are high voltage impulse sources that have simplicity, reliability, and versatility [3]. Traditional uses of the Marx generators are energy storage and delivery systems, such as charging capacitor banks or pulse forming lines. When the compactness of the Marx generators combined with voltage pulses have low rise time, several gigawatts peak power, ability to be supplied by battery technology, these generators becomes a common impulse source for both civil and military applications.

Moreover, Marx generators are able to provide high power electric field by delivering of stored electric energy to a load. High power electric field is considered the source of strongly ionizing cold plasma, electron beams, portable X-ray sources, electromagnetic shock waves, jamming systems, etc. There are also some civil applications of pulsed power energy such as cleaning up, bacteria extermination [4, 5].

In recent years, there is an interest in HPM systems for using them for military applications. Some of these systems are based upon pulse power sources [3]. HPM applications generate a prominent threat against targets equipped with modern digital electronic devices that are more susceptible to electromagnetic radiation. The aim of an HPM weapon system is composing an interference with electronic devices. HPM sources generates short high-power electromagnetic pulses able to hinder or damage electrical and electronic systems such as computers, communication systems, electronics of a car, etc. HPM sources could be used in electronic warfare since create software and hardware failures on enemy threat risks [6, 7].

Marx generators are used as a source of HPM systems such as virtual cathode oscillator [8, 9] magnetically insulated line oscillator [10]. These devices are could be used researches about high power electromagnetic field and its effects. Furthermore Marx generators are could be used driving some antennas to create intentional electromagnetic interference high with power electromagnetic field [7].

2. THEORY

Marx generator is a device that utilized for voltage-multiplying introduced by Erwin Otto Marx in 1925. It is a high voltage impulse generator which simple and most common used. The Marx generator consists of a number of capacitors. Capacitors are charged in a parallel configuration by dint of the high impedances. Then they are discharged in a series configuration. Thus, voltage is increase incrementally i.e. multiplied since the discharge process [11].

"Erection of the Marx generator" can be defined as the transaction of turning into from parallel configuration to series configuration [11]. "Stage" consists of an energy storage capacitor that is one or more capacitors and a switch that is usually sparked gaps and resistors. Spark gaps comprise of an arrangement two vis-à-vis sphere electrodes that separated by a gap. The gap between the spheres is filled with a gas such as air, Helium (He), Nitrogen (N_2), Sulfur hexafluoride (SF_6) and a mixture of them [12].

Figure 2.1 illustrates the fundamental Marx generator circuit diagram where C_0 is the capacitance value charged with voltage V_0 through charging resistors R. In this diagram, stray capacitances are neglected. The charged capacitors are discharged in series configuration via the spark gap switches. V_{oc} is the open-circuit voltage generated by multiplying charging voltage (V_0) and the stage number as stated Eq. (2.1) [11].

$$V_{oc} = V_0.N \tag{2.1}$$

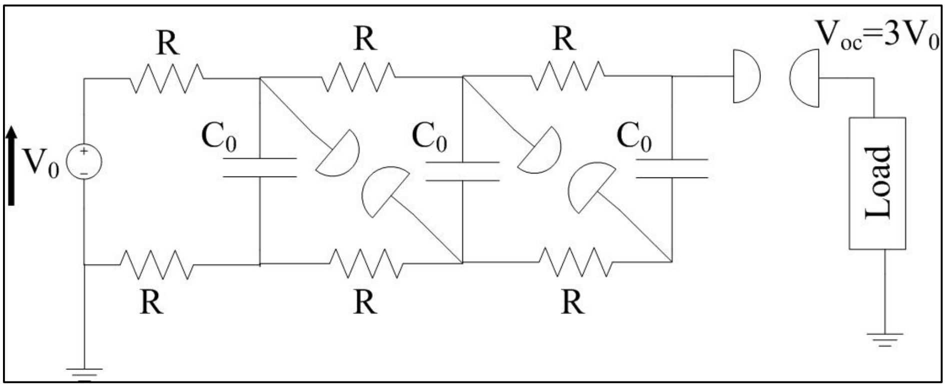

Figure 2.1. Typical Marx generator circuit diagram

Charging resistors are located in both upside and downside of the circuit and provide a path to ground potential. In the discharge phase, resistors assure a high-impedance route, pushing the current flowing by dint of the spark gap switches [11]. They serve as isolating component between every stage to defend the capacitors from getting short circuit [13]. These resistors are selected high enough (~few kΩ to few ~MΩ) to restrict the current through them [11]. In some applications [14], inductors could be used rather than resistors. Inductors provide a faster charge of the Marx generator, further pulse repetition frequency and decrease electrical stress on the insulation oil medium [15].

Impedance of the Marx generator is critical effect on the performance. If the impedance is decreased, attained power is will be higher. Because of the impedance rise with stage number, increasing the power of the Marx generator to terawatt grade is very difficult [16].

The inductance of the Marx generator significantly influences the rise time of the output pulse. For this reason, the inductance should be quite low to obtain fast pulses [17]. Enhancement of the enclosure diameter boosts the leakage inductance of the Marx generator that results in heightening the rise time [18].

Besides the inductance, small design could affect the rise time. The small design of the Marx generator provides reducing the inductance result in allows the electrons to increase rapidly from the spark gap and thus accelerating the generator waveform i.e. rise time is reduced [19].

Wave erection Marx generators are characterized by efficiency, compactness, light weight, stability and low cost. They have been applied in many fields such as driving wideband antennas, flash X-ray sources and generating electromagnetic pulses [13]. Thanks to wave erection, conventional Marx generators could generate voltage impulses have short rise times that means quick erection [3]. This type Marx generators are used in the case that the energy of the Marx generator is small [11]. On the contrary the slow Marx generators that have long rise time are able to store more energy and transfer the charge.

There are a few differences between traditional Marx generator and wave erection Marx generator:

1. The coaxial structure contribute to decreasing total inductance of the Marx generator simplicity of the construction [13, 19]. The coaxial structure restrict the loop inductance. The returning current flow to ground through an external return conductor that ensure the coaxial structure. However the space between the return conductors result in increased inductance [20].
2. The stray capacitance that composed between electrodes and ground is used for attaining overvoltage before each spark gap switch closes. This utilization provides good discharge process. This means a high voltage output pulse. Appropriate stray capacitances are critical for achieving good wave erection process [13]. Stray capacitance is studied in next chapters.

Spark gaps are in ascending order from the first spark to the last one. This is due to all spark gap switches could fire successively. Generally, the first few stages of a Marx generator is triggered by the self-breakdown sequence. It is essential for non-triggered Marx operation [4, 21].

In some Marx generator designs, owing to the spark gap switches are introduced into a pressurized gas vessel, the output voltage of the Marx generator could be adjusted [11]. Breakdown voltage of the spark gaps is related with gas kind and gas pressure Gas medium could be occurred from a single gas or a gas mixture [22]. Another function of the gas is insulating the compact Marx generators from high voltage risk due to small distances in the generator. However, generally gas applications are experimental laboratory studies. Gas systems require complex control systems, gas recirculation instalments. Because gas medium incur electrical breakdown constantly and ionize so gas medium must be refreshed continuously [23].

2.1. Circuit Analysis

The circuit analysis of the Marx generator is analyzed at three sections as Marx charge cycle, Marx erection phase, and Marx discharge cycle.

2.1.1. Marx charge cycle

A Marx generator that a number of stages is N, the capacitance of each stage is C_0, charged to the voltage V_0 through charging resistors R, is examined for a charge cycle. Charging cycle equivalent circuit that according to typical Marx generator circuit diagram (see in Figure 2.1) is given in Figure 2.2.

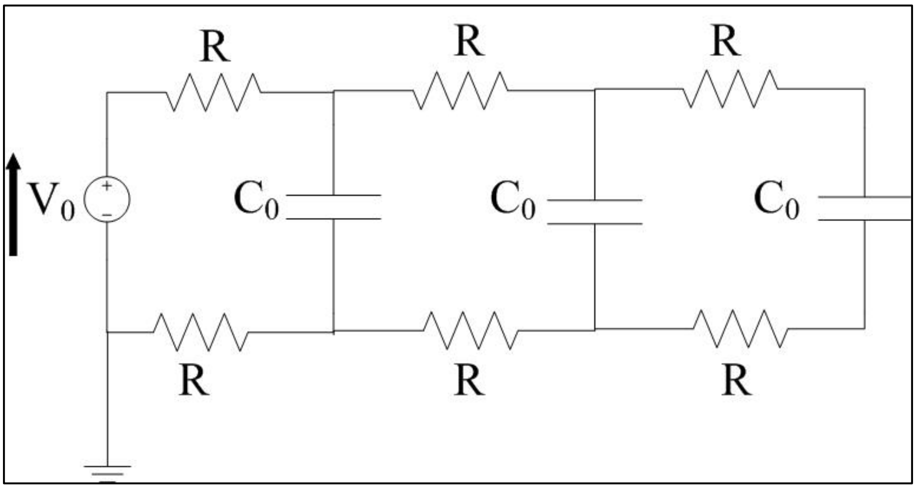

Figure 2.2. Marx generator charging cycle equivalent circuit

The capacitors are not charged immediately, they are charged at distinct rates and consecutively. The approximate time constant that determine charging time at the *nth* stage (τ_n) is stated as follows in Eq. (2.2) [16,24].

$$\tau_n = n^2 R C_0 \qquad 1 \leq n \leq N \tag{2.2}$$

According to Eq. (2.2), higher stage capacitances necessitate longer charge times. Charging period of the Marx generator (T_{MG}) is interrelated with the difference between the last (*Nth*) stage charge voltage and the first stage charge voltage. Eq. (2.3) states this correlation [25].

$$\frac{V_{c,N} - V_{c,1}}{V_c} = \frac{N^2 R C_0}{T_{MG}} \tag{2.3}$$

where $V_{c,N}$ is charging voltage of the last stage, $V_{c,1}$ is charging voltage of the first stage. For repetitive operation, voltage difference between the first and last stage could restrict the pulse repetition frequency.

If enough time is given, the last stage of the Marx generator is able to charge full charging voltage V_0. Nevertheless, the longer charge time, the longer electrical stress on the Marx generator. Therefore, longer charge time might cause some irreversible failures. Thus, minimizing T_{MG} rises the reliability of Marx generator design [11].

There are energy losses in the charging resistors on each side of the Marx generator. Due to this energy dissipation, each capacitor in the Marx generator is charged at different voltage value. This unwanted losses mean inefficiency for the Marx generator. For high efficiency, the discharge time of the Marx generator should be short. High efficiency provides extraction of the stored energy with the maximum ratio.

The stored energy formula in the Marx generator is Eq. (2.4) [11]:

$$E_{Marx} = \frac{1}{2}(NC_0)V_0^{\,2} \tag{2.4}$$

T_{MG} is proportional with $\sqrt{\frac{E_{Marx}}{V_{Marx}}}$ where V_{Marx} is output voltage of the Marx generator.

NC_0 represent the equivalent capacitance of the Marx generator due to the parallel linkage. This energy value should be considered ideal. Because there are decreased charging voltage in the upward stages and non-negligible energy losses in the charging resistors [11].

Charging type can be both unipolar and bipolar for the Marx generator. Unipolar charging means (see in Figure 2.2) each stage is charged with the same polarity voltage. The lumped circuit topology of unipolar charging is illustrated in Figure 2.3.

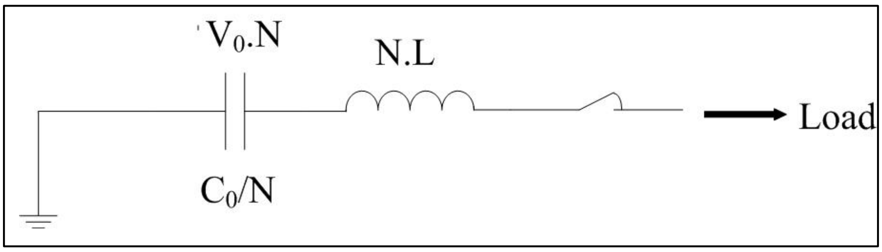

Figure 2.3. The lumped circuit topology of the unipolar charged Marx generator

In Figure 2.3, *N* is the stage number, *NL* is the total inductance of the spark gap switches, C_0/N is the equivalent capacitance of the Marx generator and $V_0.N$ is the open circuit voltage. Eq. (2.4) is valid for stored energy in a unipolar charged Marx generator.

In bipolar charging, there are two capacitors whose charging voltage has same magnitude but opposite polarity. This charging type is used especially in generators that can store very high energy. According to bipolar charging Marx generator topology in Figure 2.4, the number of switches is half of the unipolar charging topology [11, 16].

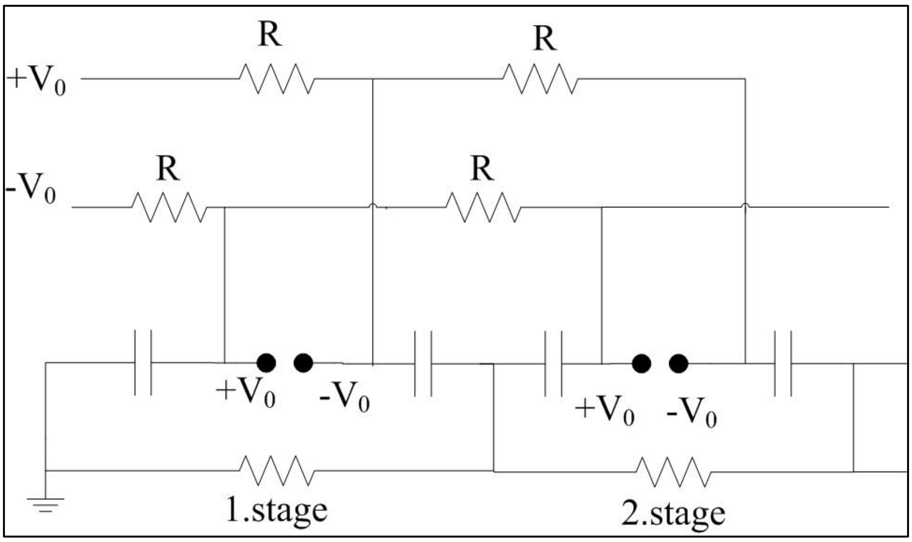

Figure 2.4. Circuit topology the bipolar charged Marx generator

Figure 2.5 illustrates the lumped circuit model of the bipolar charged Marx generator. In this model, *NL* is the total inductance derived from spark gap switches (see in Figure 2.3) [16].

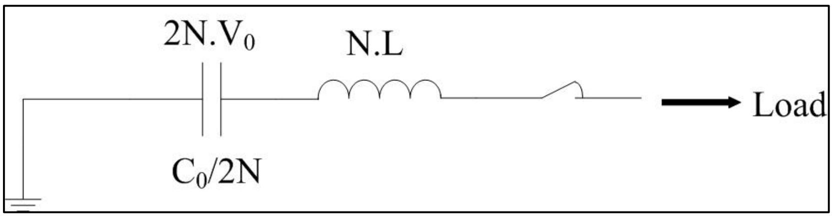

Figure 2.5. The lumped circuit topology of the bipolar charged Marx generator

In Figure 2.5, *NL* is the total inductance of the spark gap switches, $C_0/2N$ is the equivalent capacitance of the Marx generator and $2N.V_0$ is the open circuit voltage. Because of the spark gap switches in bipolar charging is twice of the unipolar charging, erected capacitance of the bipolar charging is half of the unipolar charging.

Total inductance of the bipolar charged Marx generator is given in Eq. (2.5).

$$L_{Marx} = N.L_{switch} + 2N.L_{cap} \tag{2.5}$$

where L_{switch} is the inductance of a spark gap switch, L_{cap} is the inductance of a capacitor.

Impedance for a bipolar charged Marx generator as shown in Eq. (2.6) [18, 21].

$$Z_{Marx} = \sqrt{\frac{L_{Marx}}{C_{Marx}}} \tag{2.6}$$

C_{Marx} means equivalent capacitance and given in above (see in. Figure 2.3 and Figure 2.5) for both unipolar and bipolar charging.

Stored energy in a bipolar charged Marx generator is stated in Eq. (2.7).

$$E_{Marx} = \frac{1}{2}(2NC_0)\,\mathrm{V}_0{}^2 = NC_0\,\mathrm{V}_0{}^2 \tag{2.7}$$

2.1.2. Marx erection phase

Erection phase is defined as the consecutive closing of the spark gaps to transform the capacitors from the parallel configuration to the series configuration. This process is started in the event of a spark gap switch fires concluded a growing voltage across the residual stages. The essential time for Marx erection is in the order of a microsecond [16]. The voltage across between the electrodes of the spark gap exceed its self-breakdown value, the spark gap is “be overvolted”. These overvoltage values are important for the reliability of the Marx generator [11].

Erection phase could be initiated by any spark gap switch in the Marx generator. However, the maximum output voltage can be obtained if only the first spark gap launches the discharge and fires each consecutive stages. Simultaneity in the firing of spark gaps provides increasing output voltage amplitude and smooth waveform [11].

For the simultaneity, triggering technique is used in the some Marx generators’. Triggerable three electrode spark gaps (trigatron) are used in the first stage. Triggering is acquired with implementing firing pulse signal to trigger electrode of the trigatron switch. In the later spark gaps, switching is achieved by self-breaking [16].

During erection phase, as each stage is switched, stored energy in that stage discharges with the time constant (τ_{disch}) by dint of the charging resistors of the generator. τ_{disch} is stated in Eq. (2.8). [11].

$$\tau_{disch} = \frac{RC_0}{2} \tag{2.8}$$

If the Marx generator is discharged into a load, τ_{disch} depends on the load impedance and must be short than $\frac{RC_0}{2}$ if most of the stored energy is to be transferred to the load [16].

Each spark gap conducts delay time and “jitter” to the erection time of the Marx generator. Jitter means statistical standard deviation at the switching time [16]. There should be high overvoltages on each stage during the discharge cycle for reliable operation. High overvoltage on the stages, helps reducing switch jitter, but stray capacitance might hold in the stage overvoltage [11].

A common way to obtaining low jitter in Marx generators, benefit from ultraviolet (UV) radiation. The UV light is generated with firing of the first spark gap and ionizes the next spark gap. Thus it is a trigger for the next stage. The firing of each next stage generate UV light and helps the erection of the Marx generator in a cascade manner. Figure 2.6 shows the regulated version of the circuit diagram (see in Figure 2.1) according to UV radiation. Switches are collocated in line-of-sight. Solid line symbolize a cylindrical vessel for the spark gap switches and resistors may be placed around the cylinder [11].

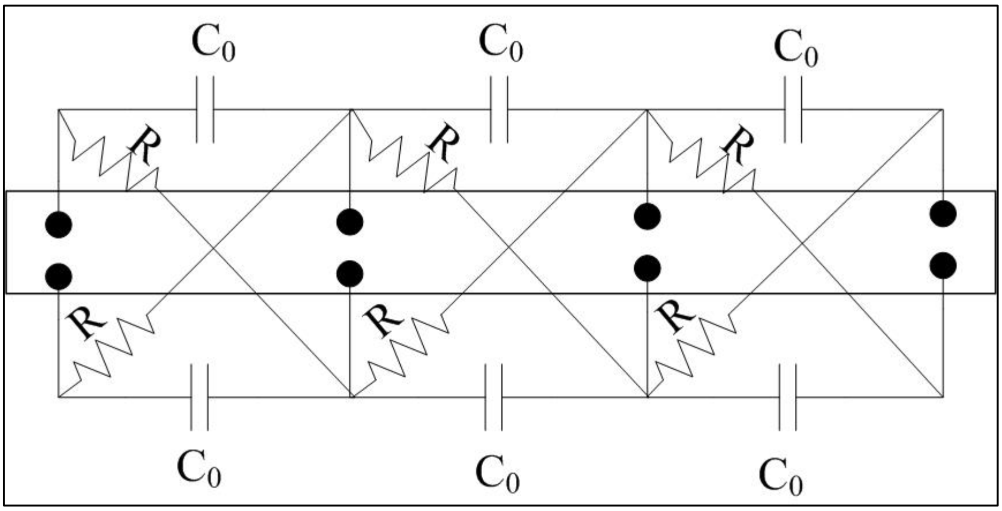

Figure 2.6. Marx circuit diagram with a line-of-sight configuration of switches

To consider spark gap switch overvoltages during the erection phase, the Marx generator must be taken into account having nearly infinitely large resistors, thus there is no drawing current. Each stage consists of a capacitor that charged to V_0 with C_0 capacitance value. Voltages across the spark gap switch electrodes symbolized with V_g. Erection order illustrates provide overvoltage of the spark gaps (Figure 2.7) [11].

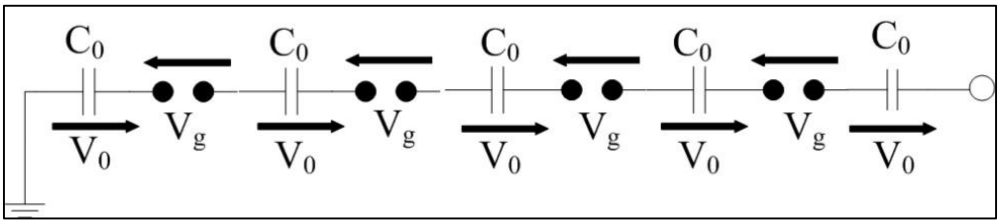

Figure 2.7. Equivalent circuit schematic that illustrates overvoltage of the spark gaps

Because of the unfired Marx generator do not draw any current so V_{oc}=0. If Kirchhoff's voltage law (KVL) is implemented to each stage, Eq. (2.9) and Eq. (2.10) is attained.

$$V_{oc} = 0 = \sum_{n=1}^{N} V_0 - \sum_{n=1}^{N-1} V_g = NV_0 - (\mathrm{N}-1)\,\mathrm{V_g} \tag{2.9}$$

$$V_g = \frac{N}{N-1} V_0 \tag{2.10}$$

It can be made an inference from Eq. (2.9) that as each spark gap switch fires, the voltage across each spark gap switch rises up to exact open-circuit voltage is obtained across the last spark gap switch. Therefore the Marx generator is fully erected. Inadequate overvoltage could induce late firing or non-firing of some stages. In the practice designs, there are extra losses in resistors, stray capacitance influence considerably the grade of overvoltage [11].

2.1.3. Marx discharge cycle

Discharge cycle of the Marx generator can be investigated in two cases. The first one is the discharge that last (final) spark gap switch does not fire. The second one is the last (final) spark gap of the Marx generator discharge into a load [11].

The equivalent circuit of the no fire status case is illustrated in Figure 2.8. The stored energy is not discharged with a spark gap fire. However, energy is dissipated via two charging resistors in parallel [11].

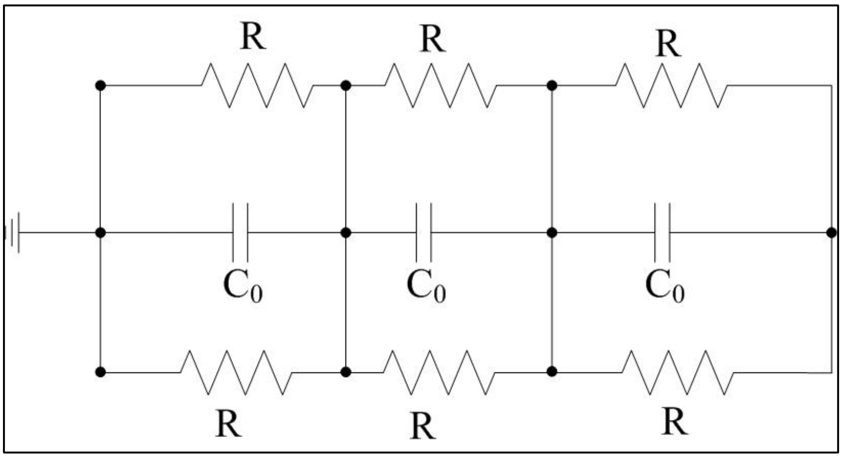

Figure 2.8. The equivalent circuit of no fire status of the Marx generator

In the second case, the last (final) spark gap switch of the Marx generator fires. The Marx generator, in this case the whole Marx generator is represented by a capacitor that discharges into a load (see in Figure 2.3). There is the inductance that derived from inductance of the spark gap switches, stage capacitors, and connectors C_0/N is the equivalent capacitance of the Marx generator [11].

Marx erected impedance is can be calculated from $Z_{Marx} = \sqrt{\frac{L_{Marx}}{C_{Marx}}}$ (see in Eq. (2.6)).

Eq. (2.11) states inherent discharge time of the Marx generator [21]:

$$T_{Marx} = \sqrt{L_{Marx} C_{Marx}} \tag{2.11}$$

Undamped resonance frequency (ω) of the Marx generator is Eq. (2.12) [5]:

$$\omega = \frac{1}{\sqrt{L_{Marx} C_{Marx}}} \tag{2.12}$$

The maximum output voltage with varied load circumstances is different from the open-circuit voltage V_{OC} that equals to $V_0.N$. The discharge phase significantly depends on the load characteristics. Furthermore, charging voltage is decreased towards to last stage and due to the stray capacitance of the spark gap switches voltage multiplication is less than theoretical value [22].

2.2. Load Effects on the Marx Operation

A fully charged Marx generator could be considered a capacitor due to it consists of the stage capacitors. Therefore, output voltage depends on both parameters of the Marx generator and the load characteristics. Usually, the load of the Marx generator is a capacitor or a resistor. In this thesis, both of them is analyzed [11].

2.2.1. Capacitive load

In this load type, the Marx generator charges a capacitor. It is the basis of the devices that build upon pulsed power technology. In these devices, the energy of the charged capacitor is transferred to a load (capacitor) [11].

The Marx generator equivalent circuit for a capacitive load is figured in Figure 2.9 C_{Marx} and L_{Marx} represent the capacitance that stores the whole energy of the Marx generator and the inner inductance of the Marx generator, respectively. When the spark gap is switched, the whole stored energy of the Marx generator is discharged via the inductor and charge the load capacitor (C_2) [11].

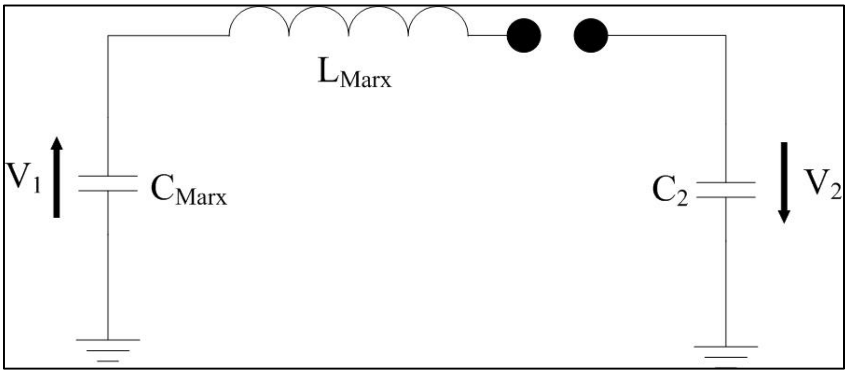

Figure 2.9. Marx generator equivalent circuit for a capacitive load

There are the voltage equations for two capacitors in Eq. (2.13) and Eq. (2.14)

$$V_1(t) = V_M - \frac{V_M C_2}{(C_{Marx} + C_2)}(1 - \cos \omega t) \tag{2.13}$$

$$V_2(t) = \frac{V_M C_{Marx}}{(C_{Marx} + C_2)}(1 - \cos \omega t) \tag{2.14}$$

where V_M is the initial charging voltage of the C_{Marx}.

Capacitive ringing gain is a parameter of the Marx generator related to Eq. (2.14) and be determined as V_2/V_M. If the $\cos\omega t = -1$, capacitive ringing gain has the maximum value [11].

Eq. (2.14) expresses that if a Marx generator discharges to a capacitive load via an inductor, charging waveform can be stated with $(1 - \cos \omega t)$ equation [11].

The capacitive load has two special cases as follows: the first one is, Marx capacitance is nearly tantamount to load capacitance ($C_{Marx} \sim C_2$) and the second one is, Marx capacitance has a higher value than the load capacitance ($C_{Marx} >> C_2$) [11].

C_{Marx}~ C_2 case case is the fundamental of the pulsed power technology devices due to transferring of Marx generator energy to load to a large extent. When the spark gap switch is overvoltaged i.e. switched, the energy transferred between C_{Marx} and C_2. There are the voltage equations for two capacitors in Eq. (2.15) and Eq. (2.16).

$$V_1(t = \frac{\pi}{\omega}) = 0 \tag{2.15}$$

$$V_2(t = \frac{\pi}{\omega}) = \frac{V_M C_{Marx}}{(C_{Marx} + C_2)} \tag{2.16}$$

Due to C_{Marx}~ C_2 and V_2~V_M, the energy stored in the Marx capacitor could be transferred to load efficiently [11].

When it comes to C_{Marx}>> C_2 case, it is named as a peaking circuit. When (1-cosωt) in equals to 2 in Eq. (2.14), energy transfer happens. There are the voltage equations for two capacitors in Eq. (2.17) and Eq. (2.18).

$$V_1(t = \frac{\pi}{\omega}) \approx V_M \tag{2.17}$$

$$V_2(t = \frac{\pi}{\omega}) \approx 2V_M \tag{2.18}$$

The peaking circuits could be used to decrease the rise time of the Marx generator (Figure 2.10).

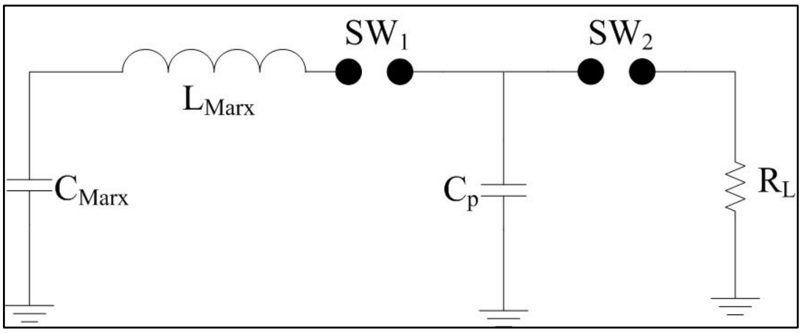

Figure 2.10. A peaking capacitor utilized to decrease rise time of the Marx generator

In Figure 2.10, C_p (C_2) illustrates the peaking capacitor, R_L means load resistance of the Marx generator. SW_1 and SW_2 are called last spark gap switch of the Marx generator and peaking switch, respectively.

V_2 (t) is approximately double of the V_M, but V_1 (t) stay almost equal. Energy transfer is inefficient. For an efficient energy transfer, C_{Marx} should be a minimum of 10 times of C_2 [11].

2.2.2. Resistive load

When a Marx generator whose capacitance is C_{Marx} charges a resistor (R_L), voltage across on the load is stated in Eq. (2.19):

$$V_L = V_M e^{-t/R_L C_{Marx}} \tag{2.19}$$

Eq. (2.19) states that when the spark gap switch fires at t=0, the load voltage rises immediately to the V_M and decline with R_L C_{marx} (ideal case). But in practice, there is a substantial inductance in the Marx generator. There is the equivalent circuit of the Marx generator that has a resistive load and series inductance in Figure 2.11.

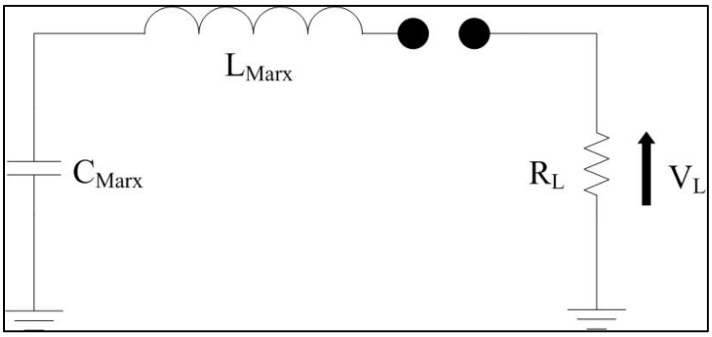

Figure 2.11. The equivalent circuit of the Marx generator that has a resistive load and series inductance

L_{Marx} , have a key role in the performance of the Marx generator since inductance enhances the rise time and reduced the output peak current [11].

2.3. Stray Capacitance Effect

The Marx generator concept nearly has no change since the invention of it. Because it has a simple operation principle: the spark gaps are triggered due to breakdown from switching prior stages. Each spark gap switch has a share in delay of the Marx generator erection time. As a result of the studies focused on pulsed power applications, the Marx generator working principle and manufacturing processes was the center of interest. This interest covers increasing the voltage, energy amplitude and power capability of the Marx generators. Consequently, the stage number and physical dimensions of the Marx generators' are increased [11].

These variable necessities brought escalated stray capacitance that anymore must be considered. Stray capacitance cause rise of the erection time by setting transient voltage divider, limit the grade of overvoltage in spark gap switches. Hereby, the stray capacitance value affects the performance of the Marx generators [11].

Stray capacitance which composed of between metallic molds of the Marx generator and ground enclosure have a significant influence on output voltage amplitude and rise time. If the diameter of the enclosure rise, the stray capacitance of the Marx generator decreases [18].

Stray capacitance must be higher than capacitance composed between the spark gap switch to obtain a consecutive breakdown. However, overmuch values could induce a decrease in the output voltage amplitude of the Marx generator [18].

Stray capacitance could be analyzed in three sections. The first one is, stray capacitance is rooted in spark gap switches. Before the closing, the spark gap switch consists of two electrodes and an insulating medium (gap) between them. This gap defined a capacitance. Therefore, before the discharging cycle, the spark gaps could be illustrated as a capacitor (C_g) in the circuit diagram in Figure 2.12 The second one is, the conducting links of each stage what insulated ground potential result in stray capacitance (C_s). The last one, there is stray capacitance between contiguous stages of the Marx generator. Because the lead of the stage capacitors has a little gap between contiguous stages that induce coupling via capacitance (C_c) [11].

There is the Marx generator circuit diagram during the charge cycle that illustrates some stray capacitances in Figure 2.12.

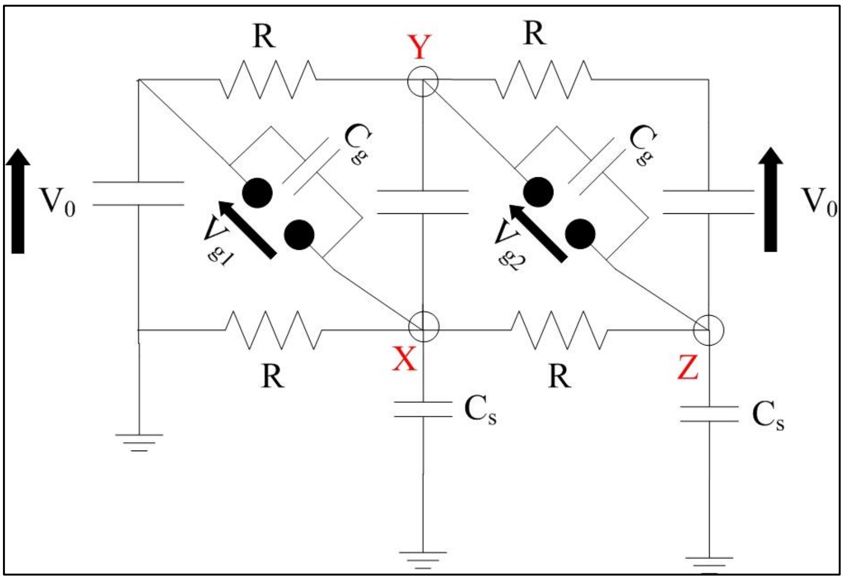

Figure 2.12. Some stray capacitances of the Marx generator during the charge cycle

This circuit diagram shows stray capacitances that derived from spark gap switches (C_g) and between conductors and ground (C_s).

When the first spark gap triggered, V_x (voltage at terminal X) equals to V_0 due to one lead of the first-stage capacitor is linked to ground potential. Vy (voltage at terminal Y)

V_y-V_0=V_x where recalling V_x=V_0

$$V_y=2V_0 \tag{2.20}$$

V_z (voltage at terminal z) equals the voltage across the stray capacitance (C_s) i.e. V_z=V_s

The voltage across the second spark gap is V_{g2}=V_y-V_z

$$V_s = 2V_0 - V_{g2} \tag{2.21}$$

Stray capacitances C_s and C_g set up a voltage divider as following:

$$V_s = V_y \frac{C_g}{C_s + C_g} \quad = 2V_0 \frac{C_g}{C_s + C_g} \tag{2.22}$$

$$V_{g2} = 2V_0 \frac{C_s}{(C_g + C_s)} \tag{2.23}$$

Eq. (2.23) states that overvoltage on second spark gap switch is maximum if C_g<<C_s. Spark gap overvoltages could be risen by triggering a few spark gaps in a Marx generator. Overvoltages of a spark gap is a transient phenomenon. If the voltage across stray capacitances which conductor to ground increases, overvoltage on the spark gap reduces (see in Eq. (2.21). Quick erection time provides high overvoltages at spark gap switches result in low jitter [11].

Stray capacitance is associated with the geometry of the enclosure of the Marx generator. Conical structure assists in decreasing the stray capacitance [18]. Compact design helps to attain an appropriate stray capacitance of the spark gap electrode with respect to the ground in each stage of the Marx generator [13].

2.4. Impulse Generators

Impulse generators are the most common application of the Marx generators. Impulse generators are used for high voltage testing of power and high voltage equipments, simulate the effects of the lightning impulse on the electrical devices. For specific testing, waveform of the impulse voltage could be adjusted with tail and front resistor. Figure 2.13 shows the N stage Marx generator equivalent circuit with tail and front resistor.

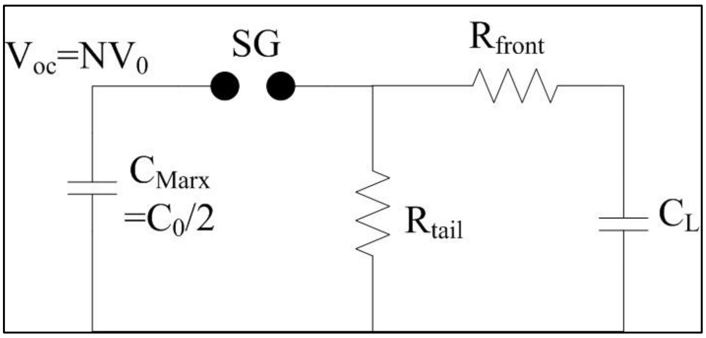

Figure 2.13. N stage Marx generator equivalent circuit

R_{front} basically damps the output voltage and regulates the front time (similar to rise time) and R_{tail} discharge the C_{Marx} and therefore essentially control the tail time (similar to fall time) of the impulse voltage. C_L represents the capacitance of the load itself and capacitance of other elements parallel with the load [26, 27].

3. LITERATURE SURVEY

In this chapter, there are some featured studies in open literature. Some parameters of the Marx generators that developed in these studies are written. These parameters are Marx generator output voltage, rise time, capacitor type, stage number, structural details etc.

M.M.Kekez developed a coaxial structure Marx generator that has 200 kV output voltage amplitude on 100 Ω load with 50 ps rise time. Each stage consisted of a storage capacitor, serial inductance, a closing switch and a peaking capacitor. The output voltage of the Marx generator was simulated with Spectrumsoft microcomputer analysis program [28]. Furthermore, it was stated that PSPICE program would be promising in future studies. 2.7 nF, 40 kV capacitors were used in experimental studies. Spheres were made of brass. There was a gap of 6 cm between the consecutive sphere intervals. The generator was enclosed in a plexiglass structure. The generator was able to produce a square or double exponential signal according to the load [19].

B. Cadilhon *et al.* developed a repetitive, high voltage, nano-second rise time Marx generator. In this study, a low-stray inductance structure was used to improve the rise time of a Marx generator. Developed Marx generator comprised four stages that each of them consist of 1.7 nF/50 kV capacitors and connected to one another through 82 kΩ carbon resistors. Therefore 200 kV output voltage whose rise time 2.15 ns was obtained with a few tens Hertz pulse repetition rate. The vessel of Marx generator was designed coaxial shape to prevent any stray inductance and pressurized with different gas mixtures. [4]

L.Pecastaing *et al.* developed a coaxial Marx generator whose last stage is integrated into a pulse forming device (a peaking stage and a crowbar switch). Marx generator has 500pf/100 kV DC capacitors and 33 kΩ axial charging resistors. Output voltage pulses of the Marx generator delivered in the range of 250 kV/1.5 J and sub-nanosecond rise time with 350 Hz pulse repetition frequency. The primer charging source of the Marx generator was a DC/DC converter 300V/60 kV [6].

Egorov and Stepanov produced a prototype Marx generator was developed for energizing cryogenic track spark chamber. In the generator, there were two independent evacuated volumes that were filled with gasses in order to avoid violating the operation of the surrounding low-current equipment. For fast discharge, a neon-helium mixture was used due to its cheapness and easy accessibility. The generator consisted of non-inductive 2.2 nF, 20 kV capacitors having a dielectric made of barium titanate. The generator had a 300 kV amplitude output pulse and 20 ns pulse duration with 15kV charging voltage per stage [29].

Dragt and Elizondo designed and produced a compact, movable, battery powered 20-stage Marx generator. According to gas pressure and gas kind, the output voltage of the Marx generator could reach to 400 kV with nearly 20 ns rise time on the 100 Ω load. On each stage two pieces series linked 10 kV, 22 nF rated surface mount chip capacitors whose current limit was 10 kA were used. Spark gaps were insulated with SF_6 and aligned with a line of sight order for UV coupling. It is decided to choose ½ watt solid carbon composition resistor because they were capable of accomplishing very high voltages pulses for short durations. The power supply of Marx generator composes of two 30 W, 25 kV DC-DC converter [5].

Veron and Brion developed a 13 stage Marx generator whose output voltage gave 350 kV on a 50 Ω load with 15 ns rise time in a 50%-50% SF_6-air mixture. Moreover, the charging voltage of the Marx generator and pulse repetition frequency were 40 kV and 115 Hz, respectively [14]. The power supply unit parameters are 6 kJ/s. Non-triggered gas switches of the Marx generator work in a dry air/SF_6 mixture whose pressure 3 atm. The Marx generator is included in a metal cylinder housing that made of light alloy. In the designing of the Marx generator, they used charging inductors rather than resistors in order to minimize the load time. Inductance values are chosen enough large so as not to change the waveform of the output voltage pulse at the Marx generators' output [14].

J.Gao *et al.* produced a repetitive ten-stage wave erection Marx generator that developed as a source for electron beam accelerators. Each stage comprised 3 nf, 50 kV rated voltage capacitors whose internal inductance was relatively low. Spark gaps switches were brass except for the first pair whose material was stainless steel. The generator was operated in an environment filling with N_2 and SF_6 gas mixture. Experimental results presented that with a 30 kV charging voltage, the Marx generator could work at an 8.5 Hz pulse repetition frequency without gas blow-off, generating 150 kV output pulse amplitude, ~ 40 ns pulse width, <20 ns rise time [13].

Bischoff *et al.* upgraded the ISL Marx generator, designed before this study, for repetitive operation. They designed the generator with a modular coaxial type due to compactness. Ceramic type capacitors which successfully tested up to 70 kV were mounted in a parallel configuration. Hand-made charging inductors were used instead of charging resistors to fast charging. Components were mounted in a special fiberglass housing so as to maintain electrical strength between the stages and from the stages to ground. With 50 kV charging voltage, 165 kV generator output voltage -means 82.5% efficiency- was obtained with 100 Hz pulse repetition frequency [12].

L.M. Redondo *et al.* developed a prototype Marx generator based on Silicon carbide (SiC) metal oxide semiconductor field effect transistors (MOSFETs) were manufactured to substitute a system containing pulse forming line and thyratron in CERN. SiC MOSFETs were used due to their advantages such as low inductance, low on-state voltage drop, high current switch on and switch off capability and very fast switching. MOSFETs were triggered by a pulse transformer. Two pieces 30 μF, 800 V metalized polypropylene film capacitors were used on each stage of the Marx generator. 3.2 kV output voltage pulse, 3 μs pulse width and 53 ns rise time were observed. Figure 3.1 and Figure 3.2 shows the designing of the Marx generator and proposed circuit diagram, respectively [20].

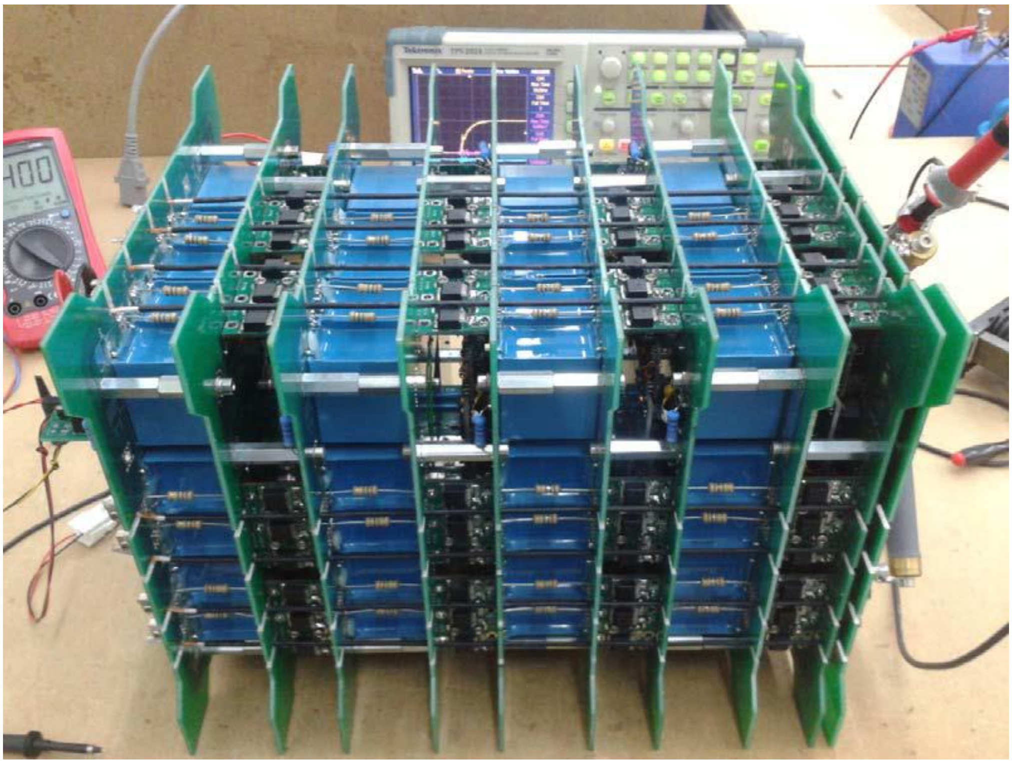

Figure 3.1. Assembled four-stage Marx generator

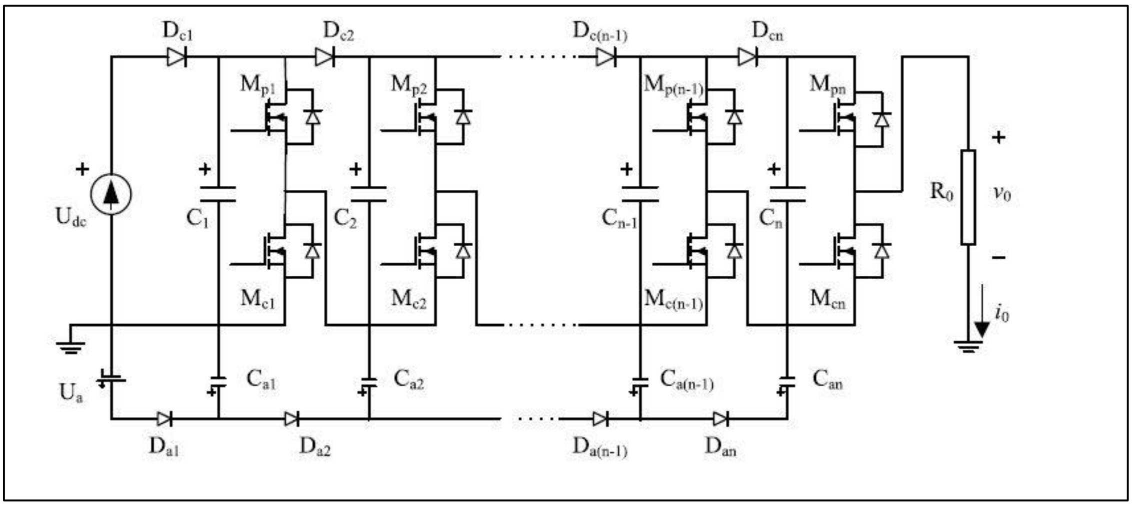

Figure 3.2. Suggested Marx generator circuit diagram

C. Nunnally *et al.* studied with APELC's SM3C model Marx generator. APELC is a company has focused on the research and development of compact deployable Marx generators. SM3C model has 15 stages that each of them comprises of capacitors which durable to high pulse repetition frequency. Charge voltage of the Marx generator circuit is 40 kV and capable of delivering 1.7 GW at 200 Hz PRF. Figure 3.3 and Figure 3.4 illustrates APELC SM3C model Marx generator and the output waveform of the Marx generator on a 50 Ω, respectively [30].

Figure 3.3. APELC SM3C model Marx generator [30]

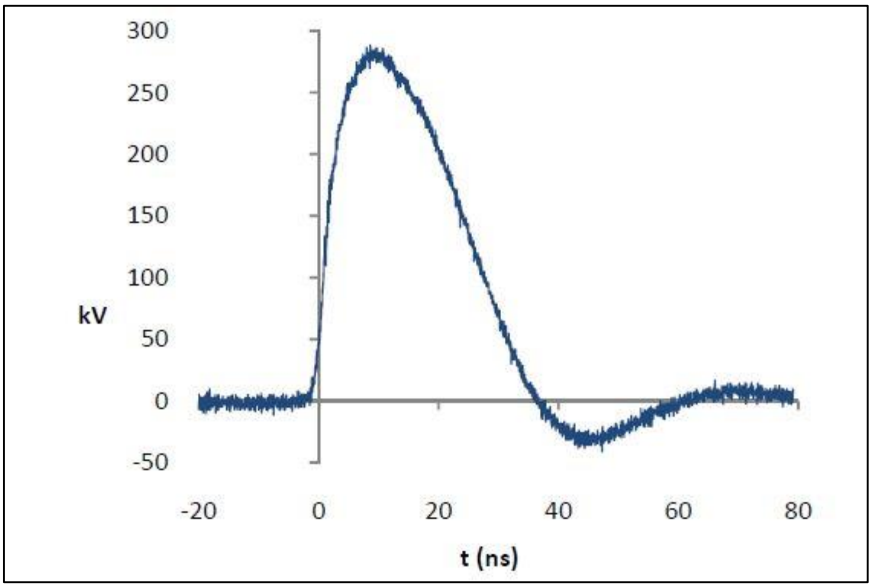

Figure 3.4. Marx generator output voltage on a 50 Ω load [30]

H.Heo *et al.* developed a compact Marx generator for repetitive applications. The Marx generator included 25 stages that each of them contains 4 pieces ceramic doorknob capacitors. It was able to operate 10 Hz pulse repetition frequency. The spark gap distances were 7 mm and spheres were made of 10 mm diameter brass sphere. For insulation, the Marx generator was immersed in a tank filled with high pressurized SF_6 and N_2 gas. For reliable triggering of the Marx generator, spark gap switches were located line-of-sight configuration. Therefore, UV aids self-breakdown of the consecutive spark gaps. The Marx generator gave an output peak voltage of 238 kV with 10 kV charging voltage. There were typical output voltage waveform on 25 Ω load and developed the Marx generator in Figure 3.5 and Figure 3.6, respectively [22].

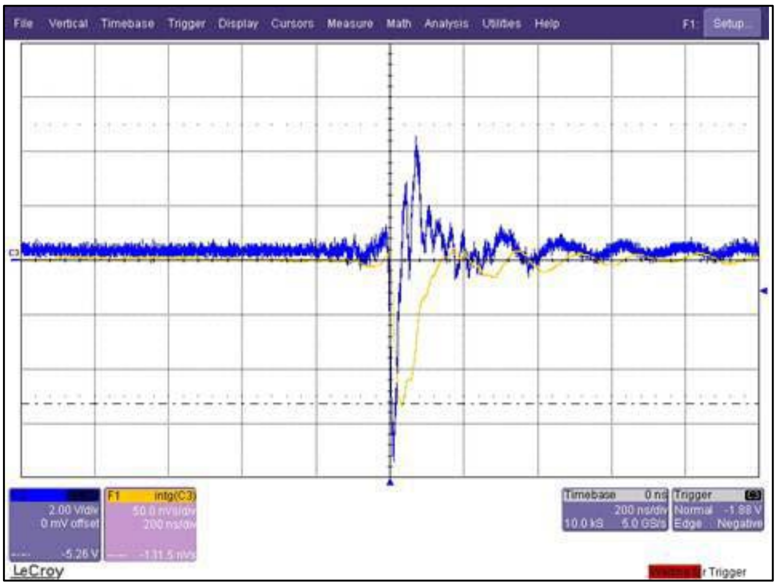

Figure 3.5. Typical output voltage waveform on 25 Ω load [22]

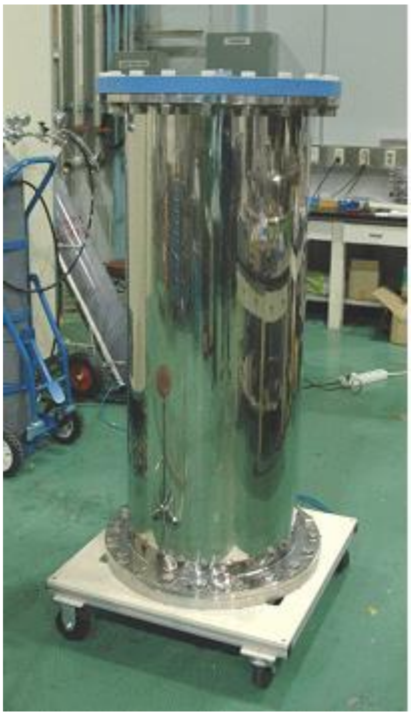

Figure 3.6. Developed Marx generator [22]

S. Mitra *et al.* developed a 22 stage Marx generator that each stage had 15 capacitor equals to 6 nF capacitance value and charged to 40 kV. It was surrounded in a stainless steel vessel that had a cylinder shape. Simulation of the design was performed on CST Microwave Studio. According to output voltage amplitude, radiuses of the enclosure were optimized. Wire wound resistors were used as charging and ground resistors. The whole system was operated with pressured N_2 gas. Simulation and experimental studies showed that conical enclosure gives higher output voltage amplitude and rise time than cylindrical structure. ~460 kV and ~50 ns rise time and ~220 kV and ~30 ns rise were are attained for conical and cylindrical enclosure structures, respectively [18].

H. Bhosale *et al.* developed a 50 stage Marx generator that had IGBT switches. In this study, it was stated that spark gap switches have some disadvantages such as short life, low switching frequency, broad dimensions etc. However, IBGT switches make possible producing pulses with high pulse repetition frequency and they can be controlled by altering magnitude and pulse width of the output voltage by inspecting the gate signal of the switches. Nevertheless, providing the synchronization of gate signals, the same sharing of the voltage between the IBGTs and necessity of complicated protection methods were considered as some difficulties. The designed Marx generator gave ~50 kV output voltage with 18 ns rise time. The pulse width was 6.4 μs and pulse repetition frequency is 10 Hz [17].

3.1. Measurement of the Marx generator parameters

In order to measure the Marx generator, there are two critical parameters that give the characteristics of the output voltage: rise time and amplitude. However, classical measurement techniques do not provide a measurement of both the rise time of the waveform and voltage amplitude at the same time. That is why home-manufactured probe was realized [6].

Measurement probes must have a large bandwidth to capture fast pulses, on the other hand, a sufficient attenuation ratio that constant on the bandwidth. Attenuation ratio must be adequate to not damage measurement device. Otherwise destructive voltages on the measurement devices lead irreversible damages [4,6].

Cadilhon et. al developed a home-manufactured coaxial probe based on capacitive divider. The probe consisted of two capacitors made by two concentric cylindrical coaxial lines. This probe was fitted on the Marx generator’s output. The frequency analysis of this probe was done by a network analyzer. The analysis indicated that this probe could measure rise-times as short as ~ 500 ps [4].

Dragt and Elizondo could measure typical voltage and current waveforms via a 10 kΩ Carborundum type load resistor. It was observed that altering the load resistance to 100 Ω provided reducing rise time to nearly 20 ns. When measurements were examined in expanded time base, some ringings emerged that probably arisen from the inter-stage inductance of all stages. In order to estimate the total inductance, a current viewing resistor was used and the ringing period was measured [5].

In another study, a copper sulfate ($CuSO_4$) solution resistor column was connected to a low inductance shunt device. This device allows the measurement of pulses has a few nanosecond rise time. J.Gao et al. developed a capacitive divider to measure the output pulse of the Marx generator. A water resistor load of different resistances was used to calculate the impedance of the Marx generator then the internal inductance was estimated. Furthermore a metal film resistor load was used for eliminating the reflections on the load i.e. more accurate measurements. $CuSO_4$ solution resistor and water resistor are quick solutions for measurement. However, they are not precise and stable. [13].

Redondo et al. used a resistive load and output voltages were measured with 200 MHz, 2GS/s oscilloscope. A high-voltage probe named that have 100:1 voltage division ratio, 400 MHz bandwidth [20].

4. PRODUCTION AND EXPERIMENTAL STUDIES

4.1. Production Studies

Before the beginning of production studies, components and materials were supplied. Capacitors, resistors, sphere balls for spark gap switches, carcass material of the Marx generator etc. is purchased.

Polyvinyl chloride (PVC) foam (dakota) is chosen as the material for the carcass of the Marx generator. Dakota is a derivative of rigid PVC sheet. However, the density of PVC foam is reduced by mixing some chemicals homogenously to the powdered raw-materials of the PVC. Dakota is lightened to easy machining, carriage, and stacking. Because of the reduced density, it is economical according to rigid PVC. The surface of the dakota is smoother than these alternates. Table 4.1 contains some technical features belonging to dakota material [31].

Table 4.1. Some technical features of the dakota material

Technical Feature	Unit	Value	Standard
Density	g/cm^3	0,50-0.70	DIN EN ISO 1183
Impact Strength	kj/m^2	17,2	ISO 179/1 Eu
Tensile strength	Mpa	19,5	ISO 527(50mm/min)
Stretch Resistance	Mpa	32,9	ISO 178 (2mm/min)
Edge strength	D	44-47	ISO 868
Surface tension	ROE (ohm)	2,00E + 14	DIN IEC 60 167
Sound Resistance	ROE (ohm)	1,86E + 14	EIN IEC 60 093
Dieelectric constant	E_r	1,8-2,1	DIN 53 483
Expansion Coefficient	100000/K	6x0,00001	DIN 53 752
Heat deflection temperature	C	57	ISO 75-2 (1,8 Mpa)
Water absorpation	%	0,9	ISO 62
Sound insulation	Db	24-28	DIN ISO 717-1
Thermal conductivity	W/m2k	3-3,7	DIN 52 612

Due to mentioned superiorities, dakota is chosen for carcass material of the Marx generator. It is implied with the carcass material that base plate of Marx generator stages. The dakota layer ensures a pedestal for capacitors in each stage and provides the insulation between the stages.

The thickness of the layer is selected as 10 mm. More thickness results longer and heavier Marx generator. Thinner layers might fail at carrying capacitors. Therefore 10 mm thickness could be considered the best choice.

Dakota layer is cut off in a CNC milling machine. The 2-D model drawing of a layer prepared at dwg format. Dimensions of the layer are calculated in compliance with the sizes of the capacitors. The pattern of the layer is determined according to the placement of the capacitors. Figure 4.1 shows the capacitor layout on the dakota layer from top view.

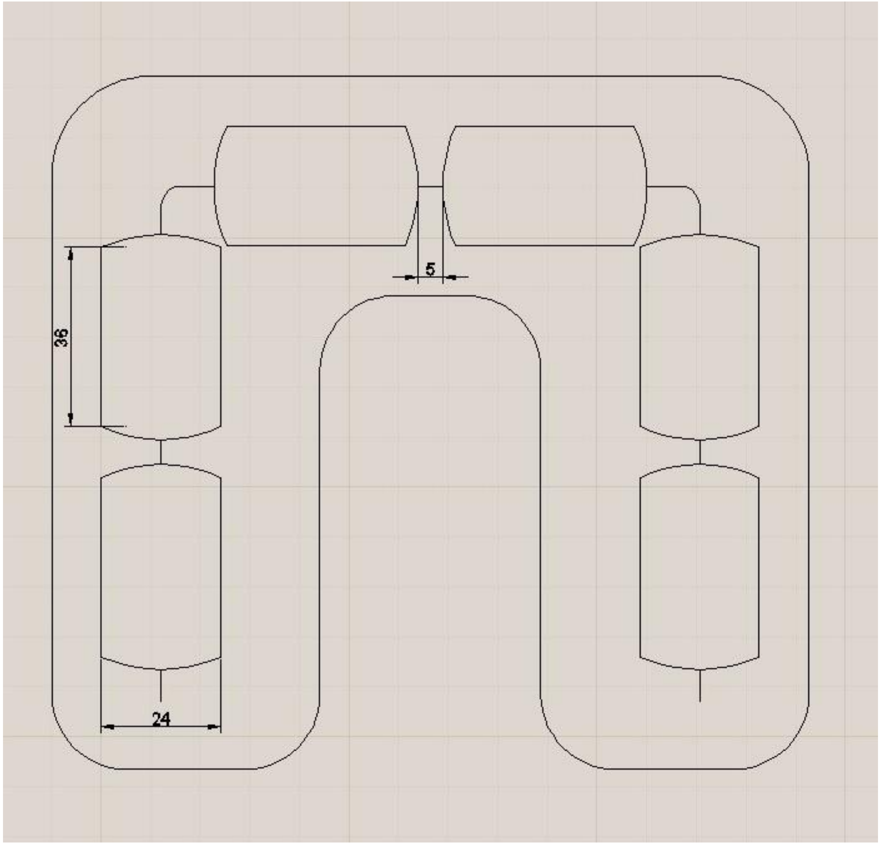

Figure 4.1. Capacitor layout on the dakota layer

After the 2D drawing, *dwg* file format transformed into *bmp* format (Figure 4.2). Later, the *bmp* file is recorded as *16-bit gif* format via MS Paint. Then *gif* file converted into format of the CNC milling machine via CNC's software.

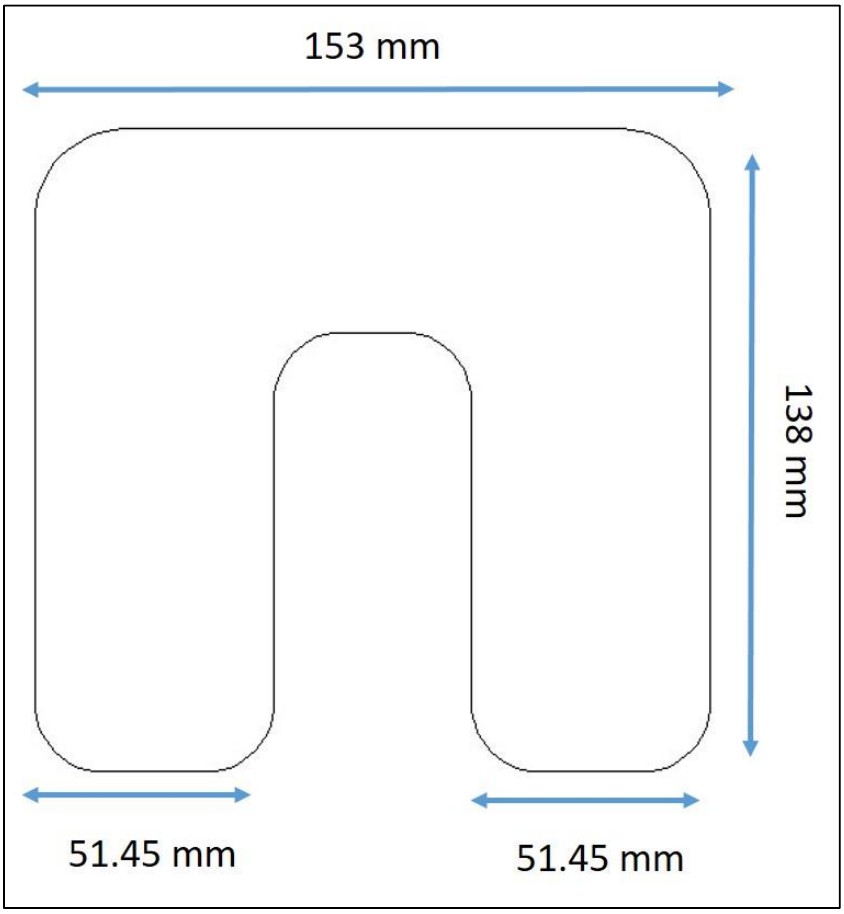

Figure 4.2. Converted bmp file

After the file conversion process, CNC milling cutting program is implemented. 10 pieces dakota layer is cut off. In Figure 4.3, there is cutting-off processes that illustrate CNC milling machine follow the cutting route according to dimensions of the 2-D model of dakota layer.

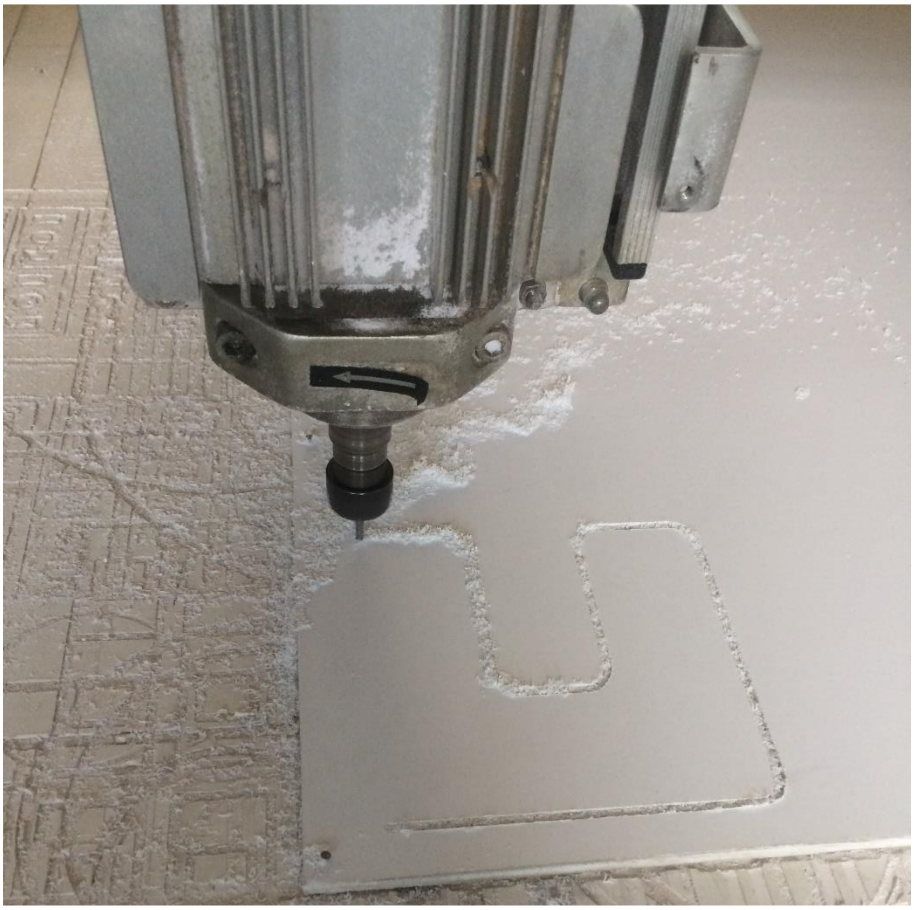

Figure 4.3. CNC milling machine is cutting the dakota layer

After the cutting process, the dakota layers are burred with sandpaper. Then, the corners of them are rounded with a band sander machine. Subsequently, the dakota layers of the Marx generator are obtained smoothly.

Stage capacitors of the Marx generator are determined according to the design. The Marx generator is designed as 8 stages that each of them capable of 15 kV. Therefore, the Marx generator will be able to produce approximately 120 kV. Moreover, capacitors are chosen suitable for high pulse applications. ES Electronics MKT 211 model capacitors are selected after market research is conducted. MKT 211 is metalized polyester film type capacitor that rated voltage is 2500 V and capacitance is 220 nF. It is constructed for applications with DC voltage basically and has non-inductive construction, cylindrical shape, and self-healing ability. Leads of the capacitor are tinned copper wire. Surface coating by polyester film tape wrapped, epoxy resin sealed [32].

Generally, high voltage capacitors have small capacitance values. Because the stored energy formula of a capacitor directly proportional with the square of the charge voltage. Since the charging voltage is in the range of kV's, the amount of stored energy is very high due to the square of the voltage. This high voltage might cause insulation problems. Therefore, the capacitance values of high voltage capacitors are in the order of nF and μF so as to prevent isolation problems.

Due to each stage is capable of produce 15 kV, 6 pieces capacitors were used on each floor. Totally 8×6=48 capacitors are utilized. Some replacement capacitors are provided for the possible faults.

There is the stage capacitor layout in Figure 4.4 according to design.

Figure 4.4. Stage capacitor layout plan

Stage capacitors are soldered to each other. Leads of the capacitors are curled after soldering. Then, small dakota pieces where placed between the stages of the Marx generator are prepared. Thanks to these dakota pieces that function as a spacer, each stage layer do not contact to the next stage capacitors. Dakota pieces are bonded with adhesive.

Later, spark gap switches are produced. 12 mm diameter stainless steel balls are used as sphere gap electrodes. Spark gaps are designed as changeable. Firstly, M5 30 mm set screws and balls are sanded on band sander machine to ease soldering. Balls are soldered to lead of the set screws. Then, brass stick whose shape is hollow cylinder is chased in power lathe. After the chasing process, soldered balls are passed through the brass sticks (Figure 4.5).

Figure 4.5. Soldered balls with brass sticks

A brass plate is cutted and formed for each soldered balls to be a pedestal. Brass plate is sawed off and side parts are twisted. Therefore, brass sticks could have been placed between side parts.

Balls are soldered to brass plate. Thank to these steps, soldered balls could have been pasted to each layers of the Marx generator and sphere gaps could have been adjusted with allen wrench. Figure 4.6 shows one of the stage of the Marx generator with capacitors and sphere gap.

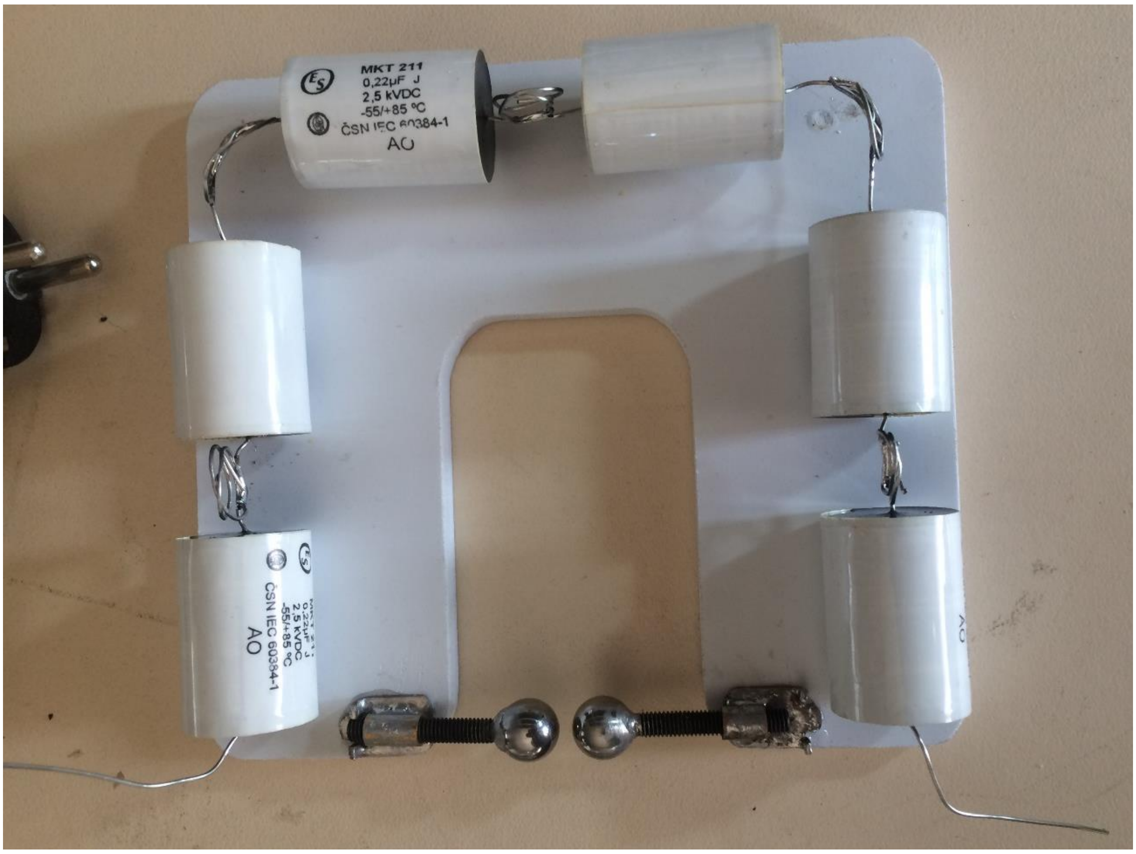

Figure 4.6. One of the stage of the Marx generator

Six pieces capacitors soldered and a sphere gap is adhered to dakota layer for each stage of the Marx generator. Then all stages are glued to each other with spacers. After the stages are joined, main structure of the Marx generator is attained.

2 kΩ (two pieces series 1kΩ) charging resistors are soldered between the stages of the Marx generator and each stage is connected to next stage with 1.5 mm^2 H07V-K cable (Figure 4.7). Charging resistors are selected 5W 1 kΩ wire wound cement type resistor. This resistor is made by winding the resistance wires on the alkaliless ceramic cores, then coated with noncorrosive, heat-proof and humidity-proof material (special flameproof cement).

Figure 4.7. Charging resistors connections at each side of the Marx generator

Sharp leads of the resistors are rounded to prevent any jumping of sparks. Each of the two leads of the resistors are soldered to adjacent stage capacitors mean resistors are placed each stage. Leads of the stage capacitor block are soldered to joins of the resistors and a macaron tube is installed to this joint (Figure 4.8).

Figure 4.8. Macaron tube on the charging resistor junction

An aluminum plate whose dimensions are 35 cm ×24 cm × 4 mm is used for a ground plane. Sharp corners of the plate are rounded in band sander machine so as to prevent jumping high voltage from the Marx generator. Sides of the plate are filed with a rasp. Then, four holes are drilled on each corner of the aluminum plate with an upright drilling machine

An 8 mm diameter brass stick is segmented to four-part as dimensions of each part is 42 cm. These sticks function as a return conductor. The Marx generator current returns to ground through these conductors. The lead of the brass sticks is rubbed with band sander machine. Therefore they are deburred and smooth surface is obtained. Later, gears are threaded on the leads of the brass stick with a diestock. Brass sticks are clamped at a vice when threading.

The brass sticks that M10 nuts are mounted are passed through the aluminum plate holes. Then, the aluminum plate was fixated by mounting acorn nuts to leads of the brass sticks. Thus, the upside of the ground plate of the Marx generator was prepared.

Another aluminum plate that identical with the upside of the ground plane was processed with the same operations to function as bottom side. In other words; firstly, sharp corners of the plate were rounded in band sander machine. Then four holes were drilled on each corner of the plate. Later, M10 nuts are mounted to passed through the aluminum plate holes and the aluminum plate was fixated by mounting acorn nuts to leads of the brass sticks. Therefore, the ground plane of the Marx generator was completed (Figure 4.9).

The Marx generator is putted onto the ground plane. There is an approximately 10 cm space between the last spark and the ground plane. In this space, there will be terminating resistance for discharging whole Marx generator energy. The space must be far enough to prevent insulation problems. There are two dakota blocks between first dakota layer and upside part of the ground plane.

Figure 4.9. The Marx generator with the ground plane

After the ground planes are prepared, terminating (tail) resistor is connected to between output of the Marx generator and upper side ground plane. Nine pieces 10 Ω (totally 90 Ω) is soldered to each other. Resistors are chosen cement fixed wire wound type. They have flame and moisture durability. Table 4.2 contains some technical parameters of the terminating resistor [33].

Table 4.2. Some technical parameters of the terminating resistor.

Manufacturer	Royalohm
Mounting Type	THT
Pin Type	Axial
Composition	Wire Wound
Special Feature	Standard Product
Watt	5 W
Resistance	10 Ω
Tolerance	±5%
Dimensions (mm) Dxlxh	9.00x22.00x35.00
Temperature Coefficient	±400 ppm/°C
Working Voltage	500 V

Nine pieces resistors are connected in series configuration. This connection is divided three part that each of them is 30 Ω to ease soldering. Resistors are soldered to one another with a circular shape that contains no sharp edges to prevent jumping arcs.

Two holes are drilled on the upside of the ground plane to set an end for terminating resistor connection. 1.5 mm^2 H07V-K multi-wire cable is grazed and soldered to combine wires. Wire lead is rounded, wrapped around a M6×20 mm screw and pinched between two M6 nuts (Figure 4.10).

Figure 4.10. Cable connection to ground plane for terminating resistor

Nine pieces 10 Ω resistors are soldered with to each other and finally linked to cable lead. Helical shape is moulded to prevent jumping arcs from capacitors to terminating resistor (Figure 4.11).

Figure 4.11. Terminating resistor connection

4.1.1. Power supply theory and operating principle

A power supply system is designed to charge the Marx generator. This system consist of a AC variac i.e. autotransformer, an ignition transformer and a half wave voltage doubler circuit. The flowchart of the power supply system is illustrated in Figure 4.12.

Figure 4.12. Flowchart of the power supply

Operating principle of the power supply and function of the each component is explained as follows.

The variac is powered by mains voltage 220 VAC. Variac sets the mains voltage as 0-220 VAC at its' output. Variac is an autotransformer. In the autotransformer, a primary voltage is connected from the bottom to a certain winding known as a "tap," and a secondary voltage is connected from the bottom to a distinct winding. Each winding stands for a distinct voltage level. There is a positioner in the variac which alter the winding number in the secondary side. As winding number increases, secondary voltage increases. The secondary voltage is increased or reduced, depending on the location of the variac positioner. There is the circuit model of an autotransformer in Figure 4.13.

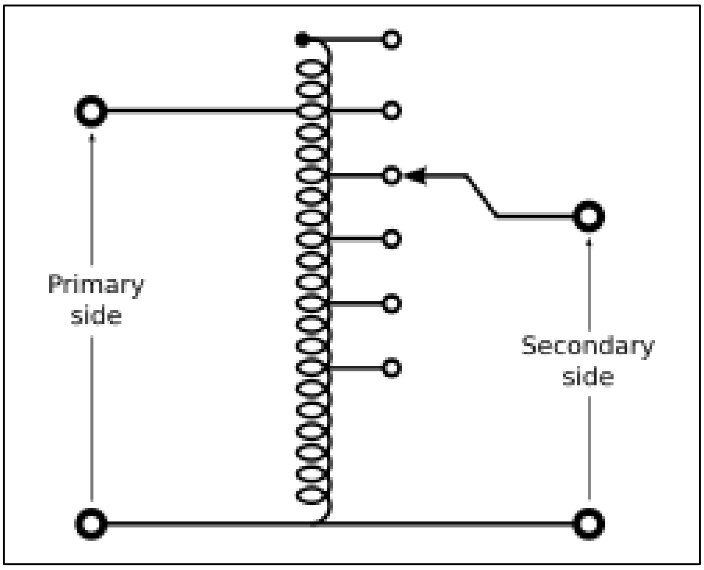

Figure 4.13. Circuit model of an autotransformer [31]

1 kVA, 4.5 A variac is used in the power supply of the Marx generator. The primary voltage of the variac is 220 VAC. Seconder voltage is 0-220 VAC [34].

Output of the variac is connected to the ignition transformer. Ignition transformers are used in fuel burners to produce flame through suitable automats and thermostats. It is a unit that provides combustion circulation in heating plants which work both with fuel-oil and gas. The intensity and length of the arc between the electrodes is proportional to the voltage and current occurring in the secondary windings of the transformers.

The ignition coil is a center-tapped transformer. Center tapped transformer is a transformer with a voltage tap in the middle of the secondary winding. Therefore we can have two secondary voltages. There is the ignition transformer in Figure 4.14

Figure 4.14. The ignition transformer

Primary voltage of the ignition transformer that supplied from secondary voltage of the variac is 220 VAC 50 Hz. Seconder voltage is 2×5000 VAC. output contacts can be seen in Fig. In the middle of these contacts, there is a tap point that is connected to body.

Each stage of the Marx generator consist of 6 pieces 2500 kV capacitors so capable of 15 kV. Therefore power supply of the Marx generator should ensure ~15 kV. Due to seconder voltage of the ignition transformer is 2×5000 VAC, an isolation transformer is needed to obtain 2×5000 VAC=10 kV in the output. However, due to low volume and less complexity, a half wave voltage doubler circuit is developed and one of the windings of ignition transformer is not used. Therefore, 5000 VAC is rectified and doubled through the half wave voltage doubler circuit.

The diagram of voltage doubler circuit and whole power supply system is illustrated in Figure 4.15 and Figure 4.16, respectively.

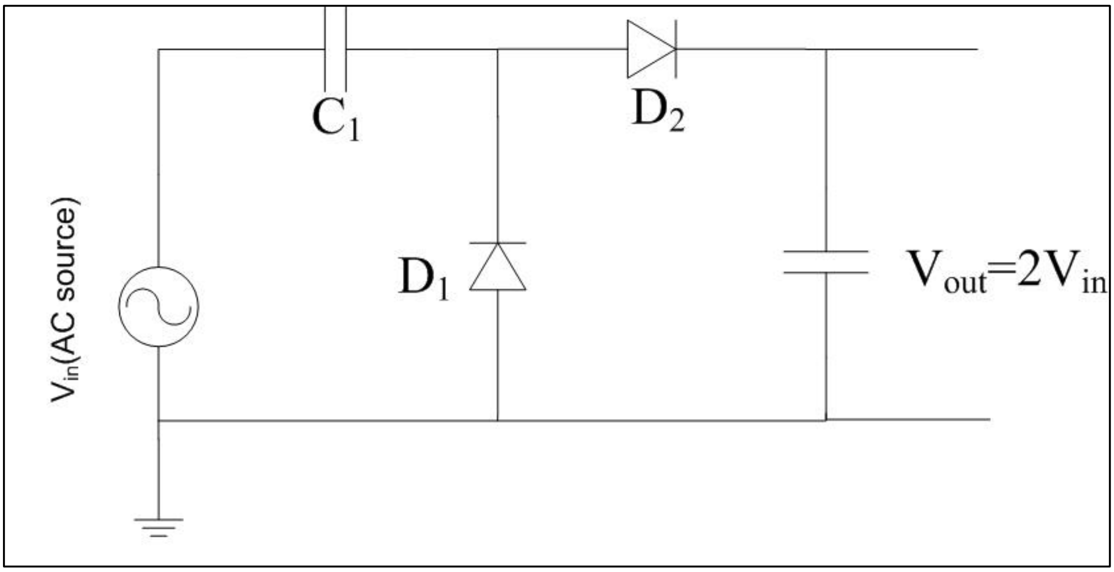

Figure 4.15. Voltage doubler circuit diagram

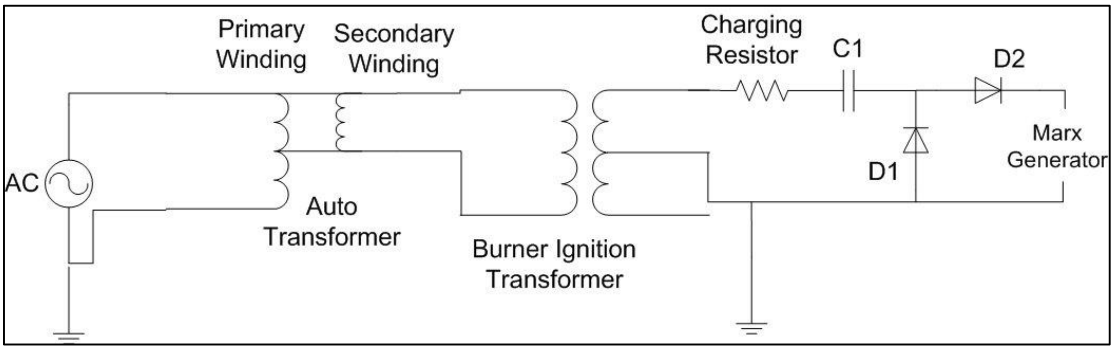

Figure 4.16. Diagram of whole power supply system

The half wave voltage doubler is consists of two diode (D_1 and D_2) and a capacitor. In Figure 4.15, C_2 attributed to the first stage of the Marx generator so doubled voltage charges the Marx generator.

For the production of the power supply system, firstly a board is produced for the variac (auto transformer). The variac is mounted into a polyester board and output pins are connected to a C10 class circuit breaker with cables via terminal block. Circuit breaker will be used to open and close the power supply. A cable with a male pin is contacted to input pin of the variac via the terminal block pins. This supply cable feeds the variac from mains voltage. A scale plaque is installed onto frontend of the board. A digital voltmeter is used in the board to measure the secondary voltage i.e. output voltage of the variac. Furthermore, a signal lamp is mounted to point out presence of the voltage for safety. In a few words, variac could be switched, secondary voltage could be measured with voltmeter and it can be seen whether there is voltage or not in the output through signal lamp. Therefore, mains voltage could be adjusted 0-220 VAC so input voltage of the ignition transformer could be changed. This alteration enables the adjustment of the charging voltage of the Marx generator. Thus, output voltage of the Marx generator could be increased and decreased.

There are variac, signal lamp, circuit breaker, voltmeter and their connections in the inside of the variac board. Scale plaque, voltmeter, signal lamp and circuit breaker is seen on the front face. On the side part, there is supply cable and inlet to variac board. Figure 4.17 shows the front face and inside of the variac board.

Figure 4.17. Front face and inside of the variac board.

After this step, downside of the ignition transformer is rubbed and bonded with adhesive to a dakota block. Later, high voltage spark plug cable (red) whose length 50 cm is inserted to the one of the output pin of the ignition transformer. A dakota piece is bonded to transformer to prevent any spark jumping from open pin to surround. Input cable of the transformer is (black) is clipsed to body (Figure 4.18). Then transformer input cable is connected to output pins of the variac.

Figure 4.18. High voltage spark plug cable connection of the ignition transformer

For the half wave voltage doubler circuit of the power supply, two high voltage diodes D_1 and D_2 that can withstand to 15 kV are manufactured. 15 pieces 1N5408 diode connected and soldered in a series configuration. There are some technical parameters of the 1N5408 diode in Table 4.3 [35]

Table 4.3. Some technical parameters of the 1N5408 diode

Characteristic	Unit	Value
Peak Repetitive Reverse Voltage	V	1000
Working Peak Reverse Voltage	V	1000
DC Blocking Voltage	V	1000
Average Rectified Output Current	A	3
Typical Total Capacitance	pF	25
Forward Voltage @ I_F= 3.0A	V	1.0

When a resistor is linked in series with a capacitor there is an RC circuit. The capacitor will charge up by stages through the resistor up to the voltage across the capacitor arrives the supply voltage value. The duration needed for the capacitor to fully charge is equals to about 5 time constants or 5τ. This transient response time (τ), is stated in Eq. (4.1).

$$\tau = R \times C \tag{4.1}$$

where R is the resistor value in ohms and C is capacitor value in Farads and τ is in seconds. Capacitor charging graphic is shown in Figure 4.19.

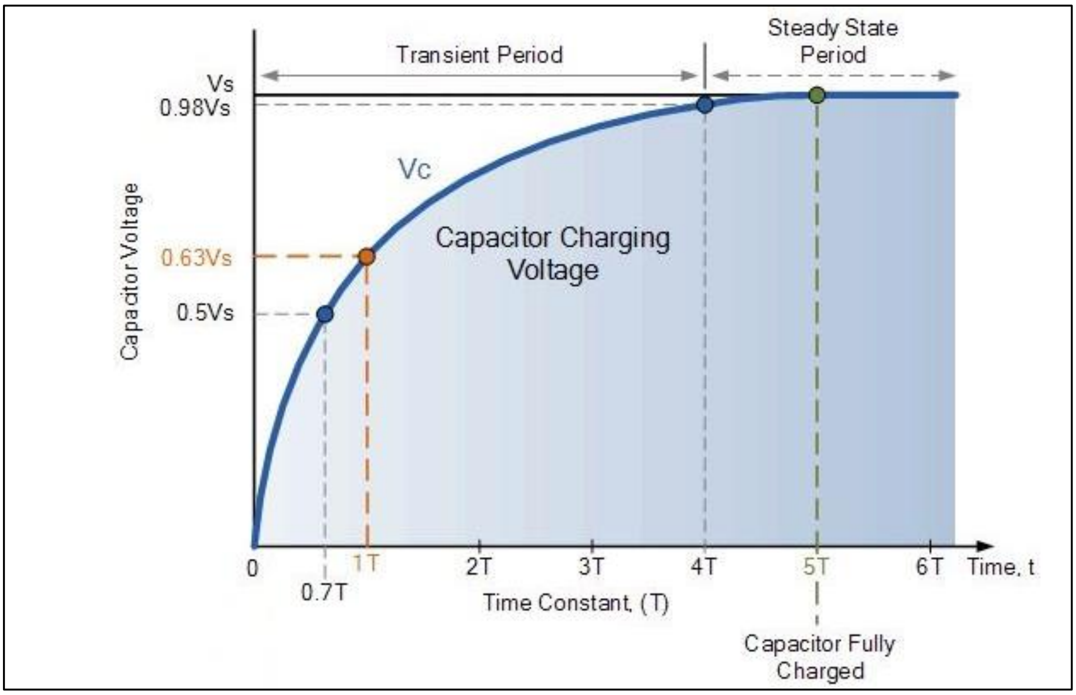

Figure 4.19. Capacitor charging graphic [36]

In Eq. 4.1, R refers to charging resistor of the Marx generator, C refers to Marx generator erected equivalent capacitance (C_{Marx}).

$$C_{Marx} = \frac{220 \times 10^{-9}}{8 \times 6} \quad = 4{,}58 \text{ nF}$$

where 8 is the stage number and 6 is the number of capacitors in each stage

τ is selected 0.3 second to calculate Marx charging resistor value. τ =0.3 second means whole Marx generator could be charged in 0.3 second.

$R_{charging}$ is derived from Eq. (4.1), by apply τ and C_{Marx} values.

$$R = \frac{0.3}{5 \times 4.58 * 10^{-9}} = 14.4 \times 10^{6} \approx 15 M\Omega$$

15 pieces 1 MΩ 2W metal oxide resistors are connected and soldered to each other in series configuration. Dakota layers that have 20 mm thickness are prepared to place diodes and resistor. Sharp corners of the dakota layers are rounded in band sander machine.

Figure 4.20 and Figure 4.21 shows each dakota layers that resistors and capacitors placed and taped for fixing, respectively. Moreover, two H07-V-K 1,5 mm2 multiwire cable is soldered to two terminals of the components.

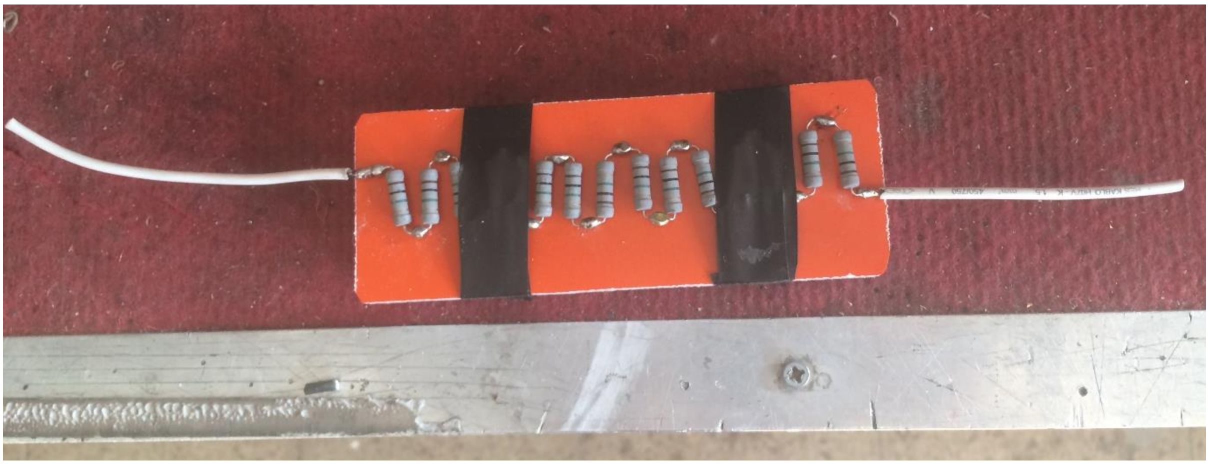

Figure 4.20. Resistor connections and fixing

Figure 4.21. Diode connections and fixing

Totally, two diode chains and a resistor chain are prepared for power supply of the Marx generator.

In Figure 4.22, C_1 is consists of four pieces series connected MKT 211 2.5 kV capacitors that used in the stages of the Marx generator. Four pieces capacitors means 10 kV rated voltage so C_1 could withstand the output voltage of the ignition transformer.

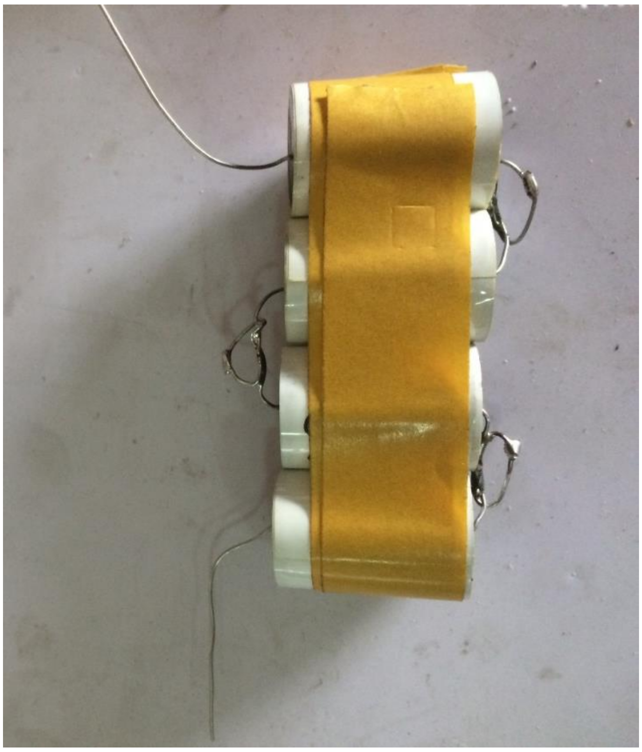

Figure 4.22. Connection of the C_1 capacitor

All component of the half wave doubler circuit are placed on a dakota layer and soldered to each other according to circuit diagram illustrated in Figure 4.16. Dakota blocks are used on the purpose of stabilizing and supporting. Connection between output of the ignition transformer and charging resistor is illusrated in Figure 4.23.

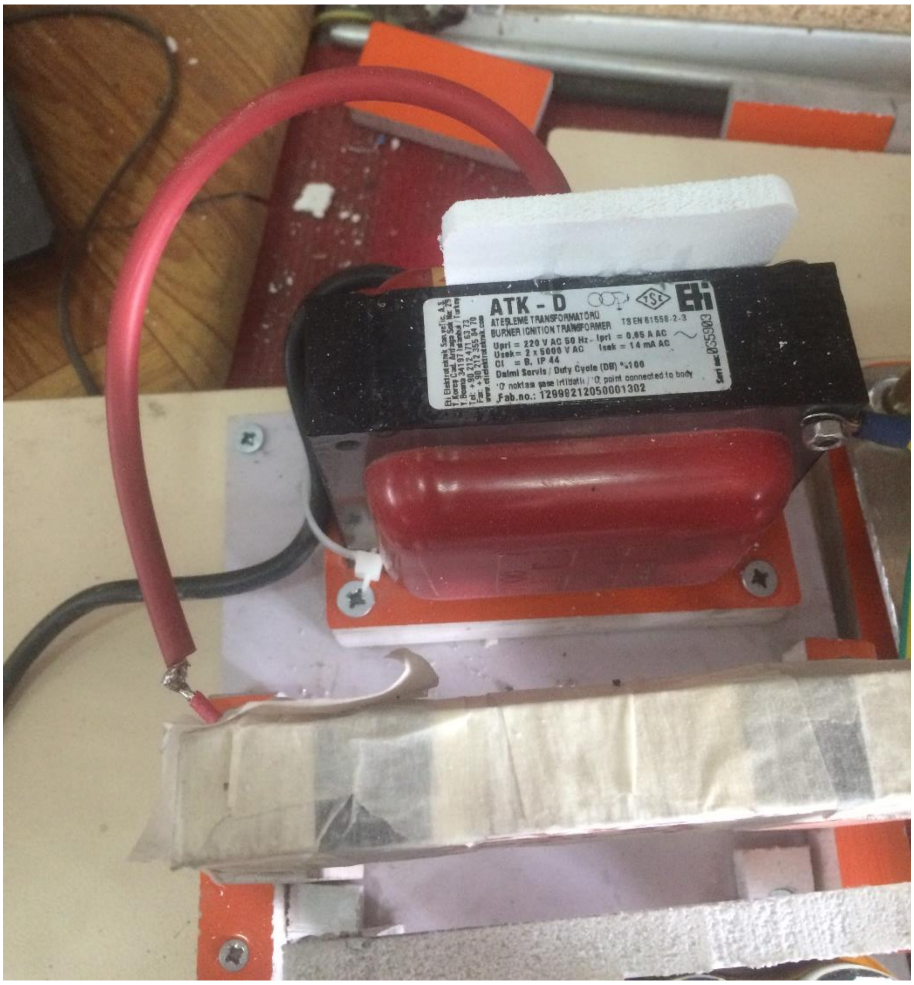

Figure 4.23. Connection of the ignition transformer and charging resistor

Capacitors are bonded to a dakota layer and placed a vertical shape to decrease footprint (Figure 4.24). D_1 and D_2 are connected to each other. Diodes are in front of the ignition transformer, 15 MΩ charging resistor and capacitor (C_1) (Figure 4.25).

Figure 4.24. Capacitor of the power supply system

Figure 4.25. D_1 , D_2 diodes and its connections

The body of the ignition transformer is grounded. 1.5 mm2 H07V-K cable (yellow-greeen) is mounted to transformer and other lead of the cable is connected the ground plane (Figure 4.26). A hole is drilled and M4 screw is mounted to ground plane for connection.

Anode lead of the D_1 and ground terminal of the Marx generator is connected to ground plane. Cables are overlapped to M4 screw. A spark plug cable is soldered to cathode lead of the D_2 and first stage of the Marx generator to charging generator with the high voltage. The spark plug cable is passed through a dakota piece to set in the midst between generator and return conductor. Otherwise, there may be some sparks due to high voltage. Figure 4.26 shows the ground and high voltage connections.

Figure 4.26. Ground and high voltage connections

A resistive high voltage divider is produced to measure the charging voltage of the Marx generator. 20 pieces series 1 MΩ (i.e. 20 MΩ) and 2 pieces series 10 kΩ (i.e. 20 kΩ) resistors are used in high voltage divider (Figure 4.27). Voltage division ratio is 1000.

Figure 4.27. Resistors that are used in high voltage divider

High voltage divider is placed output of the D_2 (see in Figure 4.16), before the first stage of the Marx generator (Figure 4.28). Voltage across 20 kΩ is measured via a cable with multimeter.

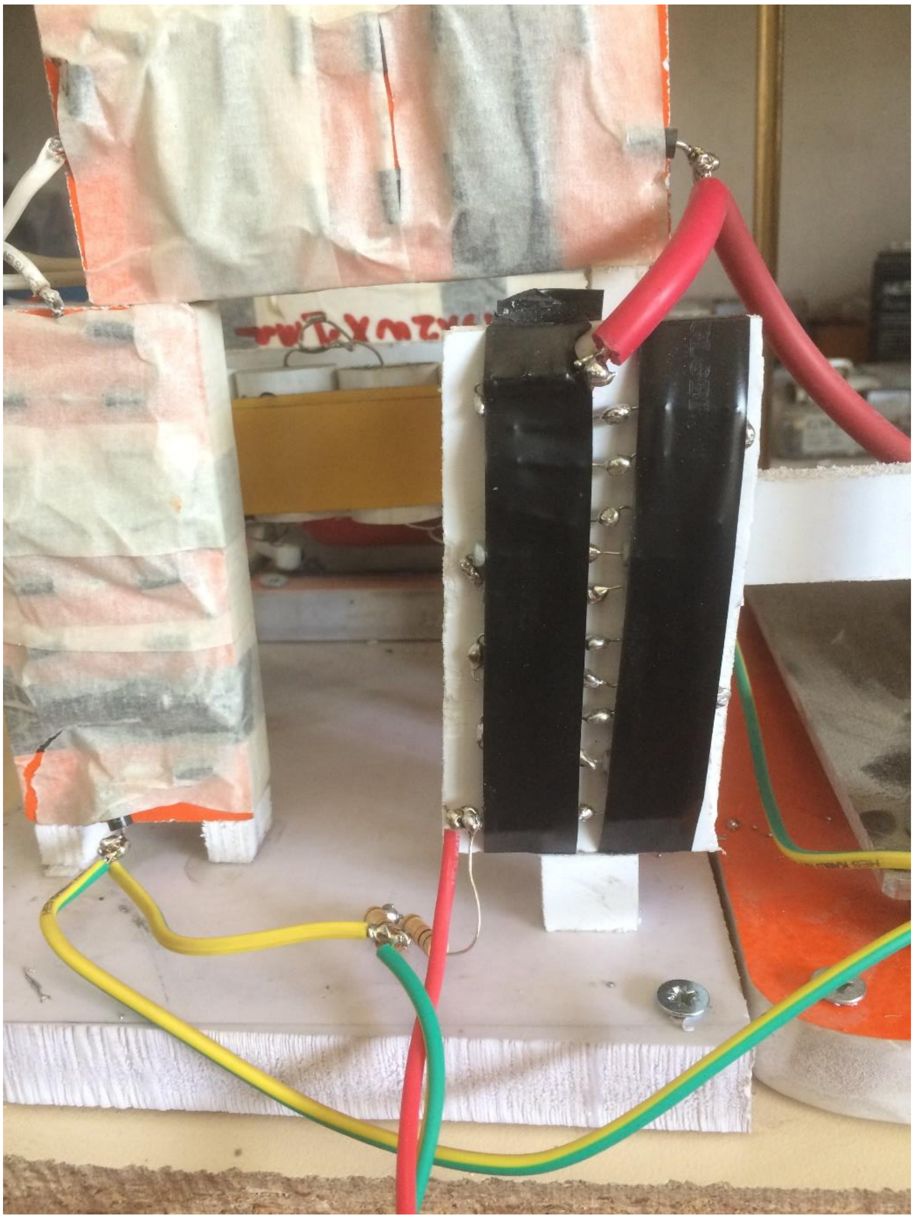

Figure 4.28. Voltage divider positioning

For safety working, a grounding rod is prepared. 1.5 mm^2 copper wire is curved and attached to a plastic rod (Figure 4.29). A cable is connected with rod and ground potential. Therefore, while operation of the Marx generator, stored energy in the stage capacitors could be discharged. This grounding provide safety operation.

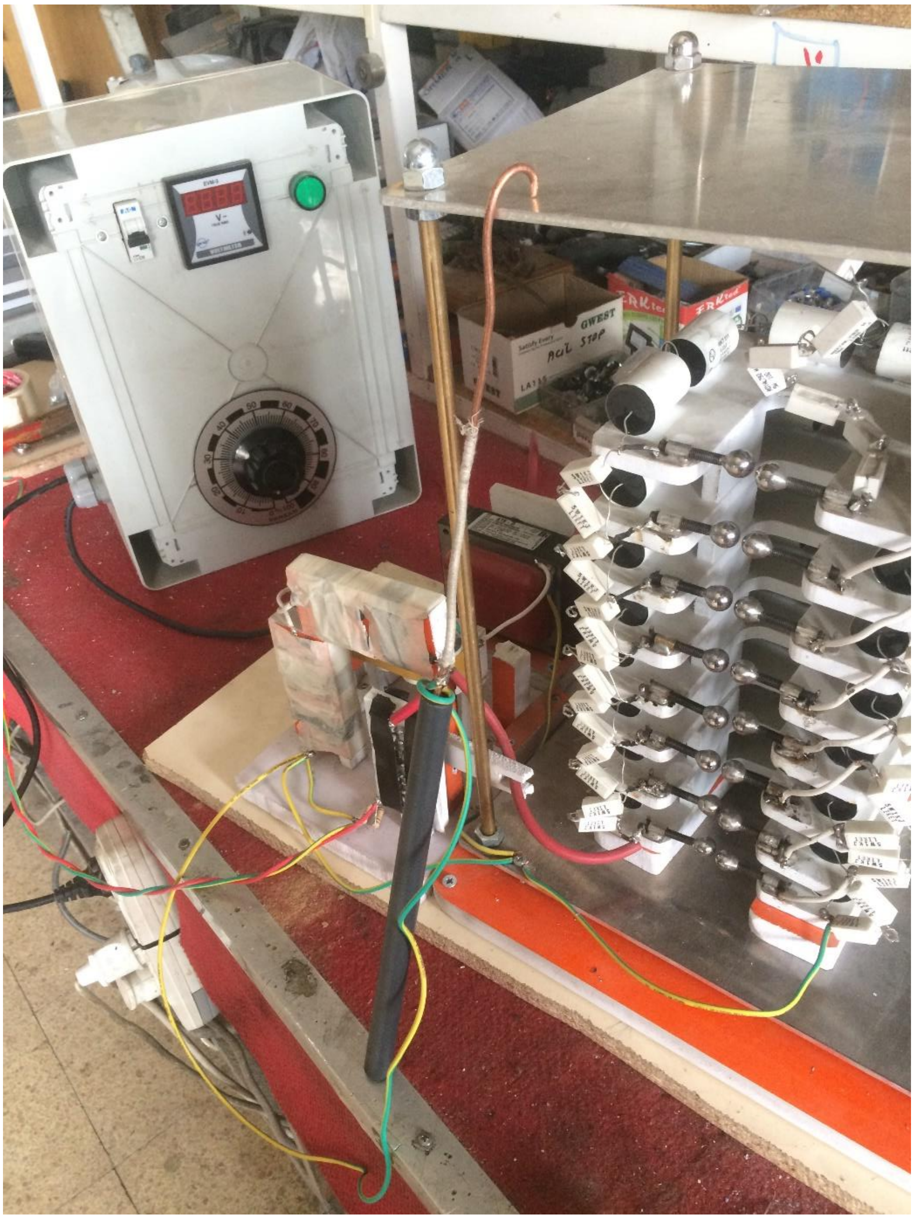

Figure 4.29. Grounding rod

4.2. Experimental studies

After the production studies, the Marx generator is powered with power supply system. Autotransformer (variac) switch is positioned to “on” state and turned voltage adjuster. Therefore, 0-220 VAC is supplied to power supply system. Variac voltage is increased up to breakdown of the spark gaps and voltage levels both on the voltmeter of the variac board and multimeter connected to resistive voltage divider are saved.

Spark gaps must be optimized for a proper operation of the Marx generator. When air between the spheres of the spark gap switch stressed by a sufficiently high voltage (an electric field of about 3 x 10^6V/m or 3 kV/mm), air can begin to break down, becoming partially conductive.

For spark gap optimization, spark gaps are adjusted to 2.4 mm except the first and second spark gaps. The first one and second one are adjusted to 2.0 and 2.1 mm, respectively. Later, the Marx generator is run. Some regulations are done up to synchronous trigger of the spark gaps.

After the spark gap optimization, the Marx generator is operated up to observe sparks. When sparks are observed, variac voltage level is increased up to full voltage (220 VAC). Therefore maximum charging voltage is obtained. However, 4V value is read on the multimeter that is connected to resistive voltage divider. This means 4 kV charging voltage due to resistive divider division ratio is 1/1000.

It is thought that there are losses due to the charging resistor (15MΩ) and resistive voltage divider. Voltage across the charging resistor may cause the losses. Resistive voltage divider may draw much current so it is planned that reducing the charging voltage and increasing the resistance of the divider to limit the drawn current by divider.

Charging resistor is set to 800 kΩ that consist of 47 kΩ and 33 kΩ resistors. Resistances of the voltage divider are adjusted to 94 MΩ (20×4.7 MΩ) and 54 kΩ (3×18 kΩ) so division ratio is 1/1740. Figure 4.30 and Figure 4.31 shows the new modified resistive voltage divider and charging resistor, respectively.

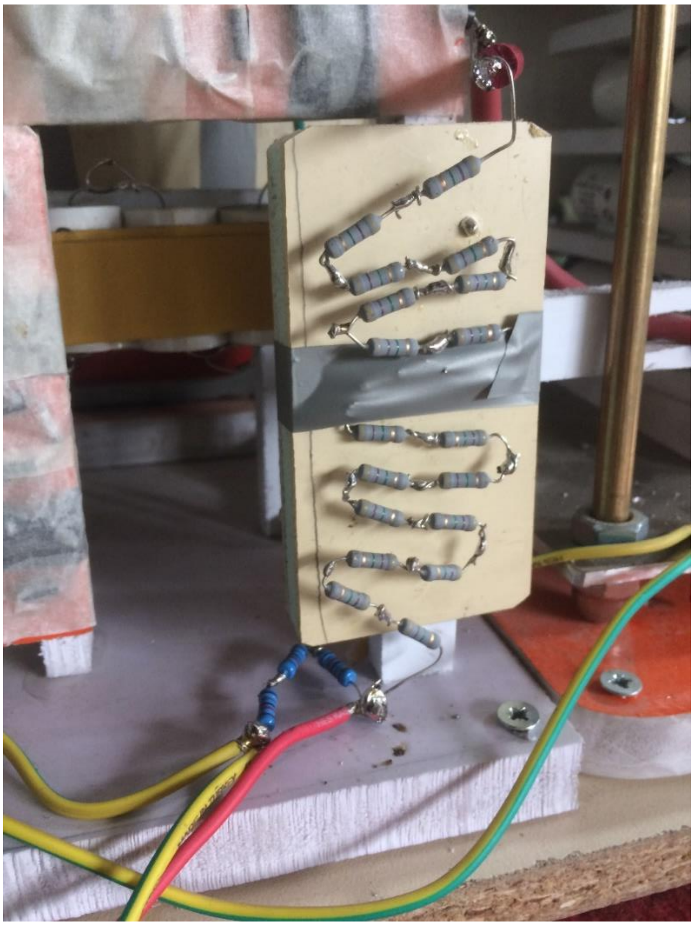

Figure 4.30. Modified resistive voltage divider

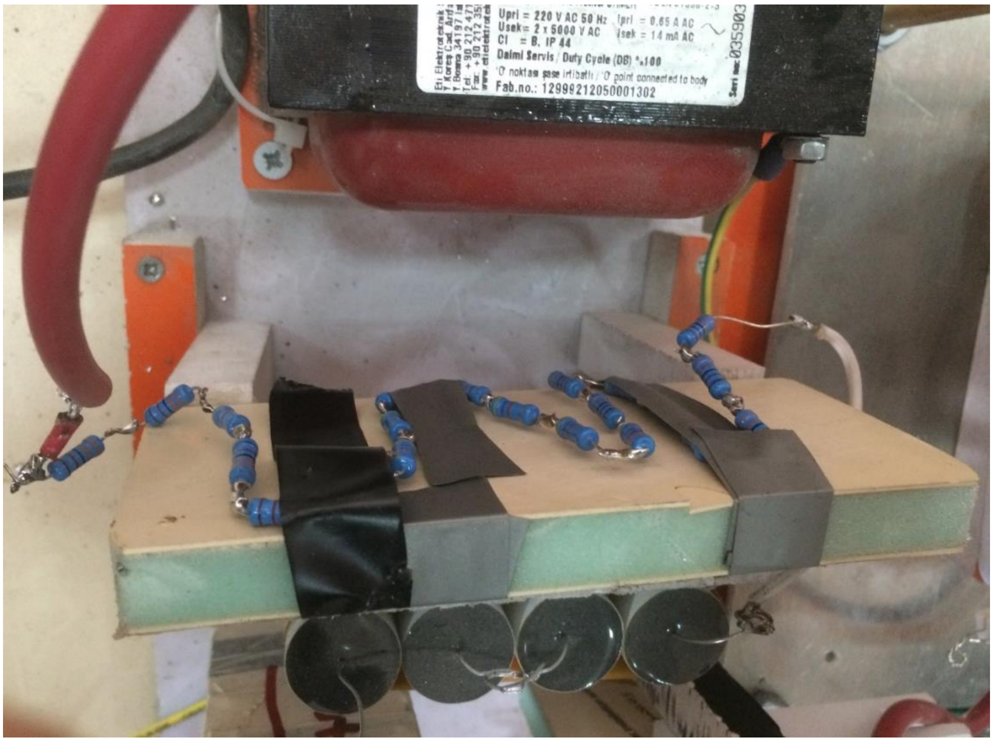

Figure 4.31. Modified charging resistor

After these regulations, the Marx generator is fired at variac output voltage is 122.6 V and measured voltage from voltage divider is 3.1 V. Therefore charging voltage is 3.1 V× 1740 (division ratio)= 5.4 kV. Marx output voltage is expected as 5.4×8≈ 43 kV due to stage number is eight. However, there may be losses due to charging resistors on each stage.

Then, a 2.5 m length coaxial cable is stripped and a BNC connector is mounted to one lead of the cable for measurement. A capacitive voltage divider whose measurement limit is 50 kV is used for measurement of the output voltage (Figure 4.32).

Figure 4.32. Capacitive voltage divider

Capacitive dividers are consist of two series capacitor (C_1 and C_2) that determine the voltage division ratio (4.2).

$$k = \frac{C_1 + C_2}{C_1} \tag{4.2}$$

C_1 is the capacitance that inside of the cylinder (see in Figure 4.32) and its value is 0.215 nF that is measured with capacitance meter. C_2 is the two pieces orange color parallel capacitors whose equivalent capacitance is 112 nF. According to Eq. (4.2), voltage division ratio (k) is calculate as 521.

A tablet oscilloscope is used for observing waveform. Other lead of the coaxial cable is stripped and a probe is attached to it. Therefore, waveform from obtained across the capacitive divider is transmitted via coaxial cable, measured from the lead of the coaxial cable and observed on the oscilloscope screen. Trigger mode is used on the oscilloscope to capture the waveform then saved screen shots.

In measurement, tail and front resistors (see in Figure 2.17) are altered and changes on the waveform are observed. Front resistors are chosen 600 Ω, 1.2 kΩ and no resistance. Tail resistors are 90 Ω, 130 Ω and 180 Ω.

There are measured waveforms in below for various front and tail resistors. Waveforms are measured from capacitive voltage divider resistors and saved on oscilloscope. Measurement function of the oscilloscope is activated for the peak to peak voltage, rise time, fall time and period.

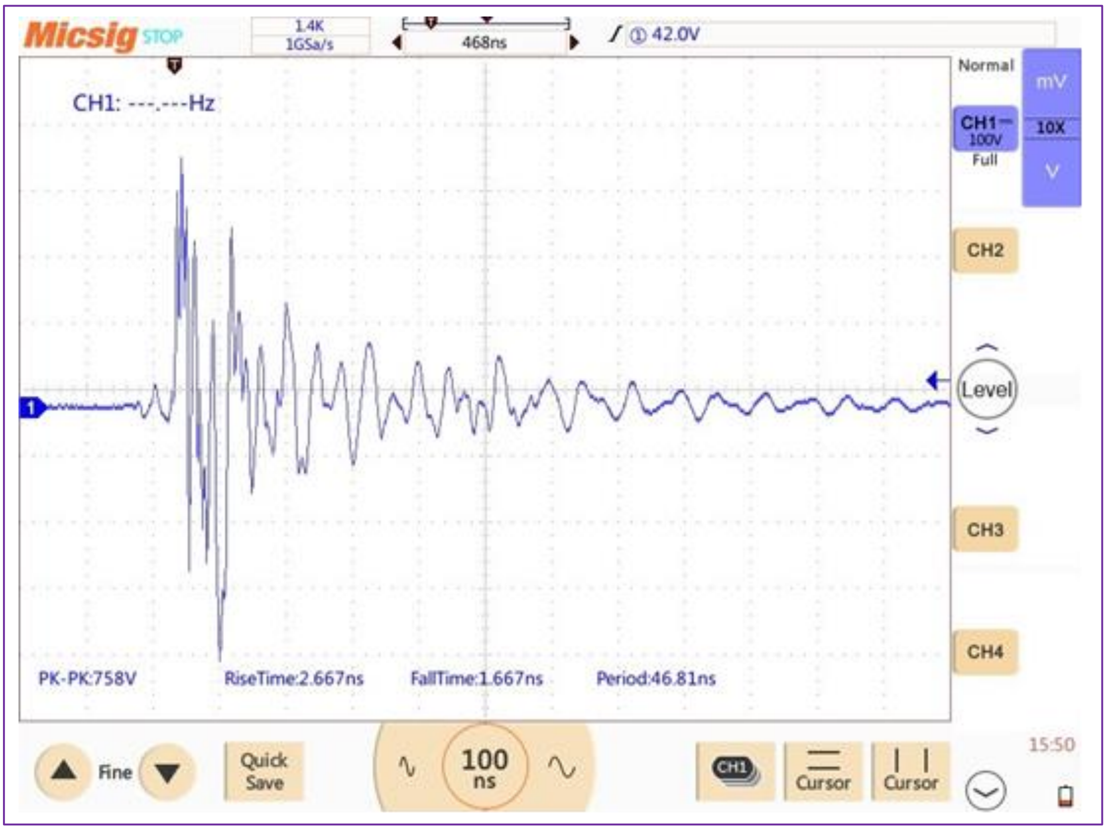

Figure 4.33. Output voltage for front resistor= 0 Ω and tail resistor= 90 Ω

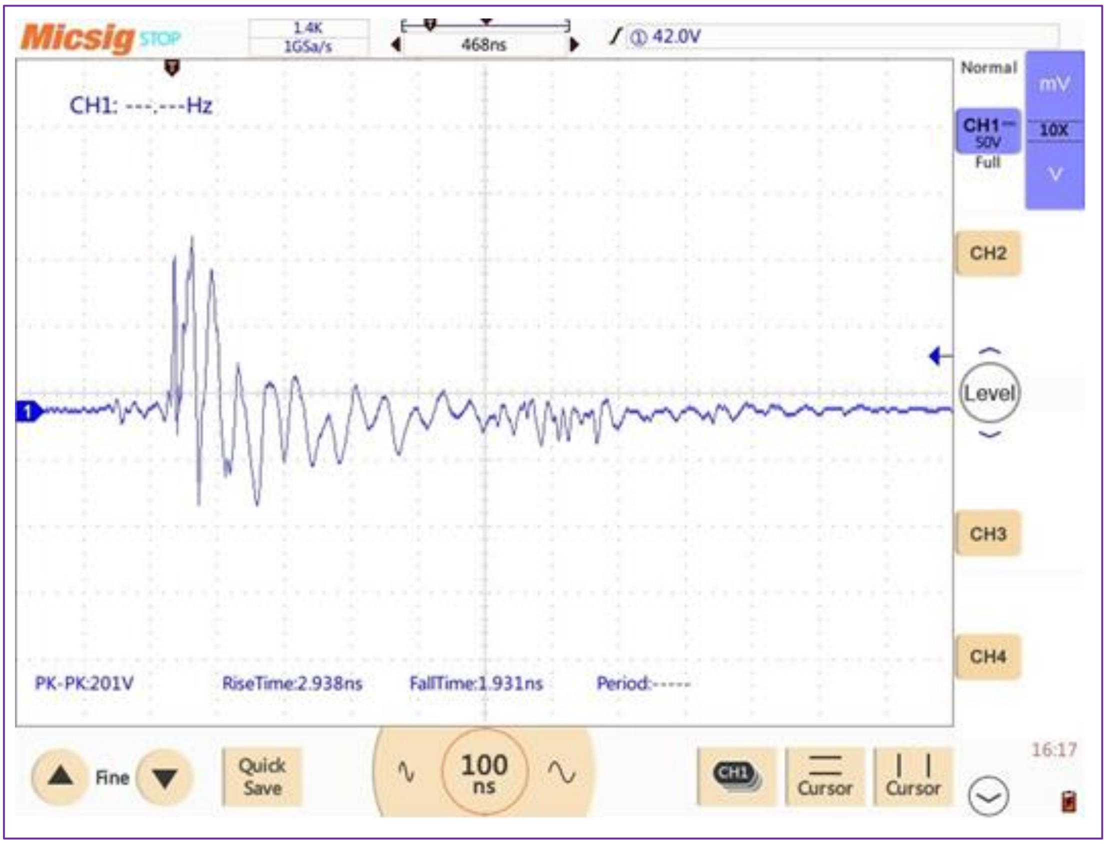

Figure 4.34. Output voltage for front resistor= 1.2 kΩ and tail resistor= 90 Ω

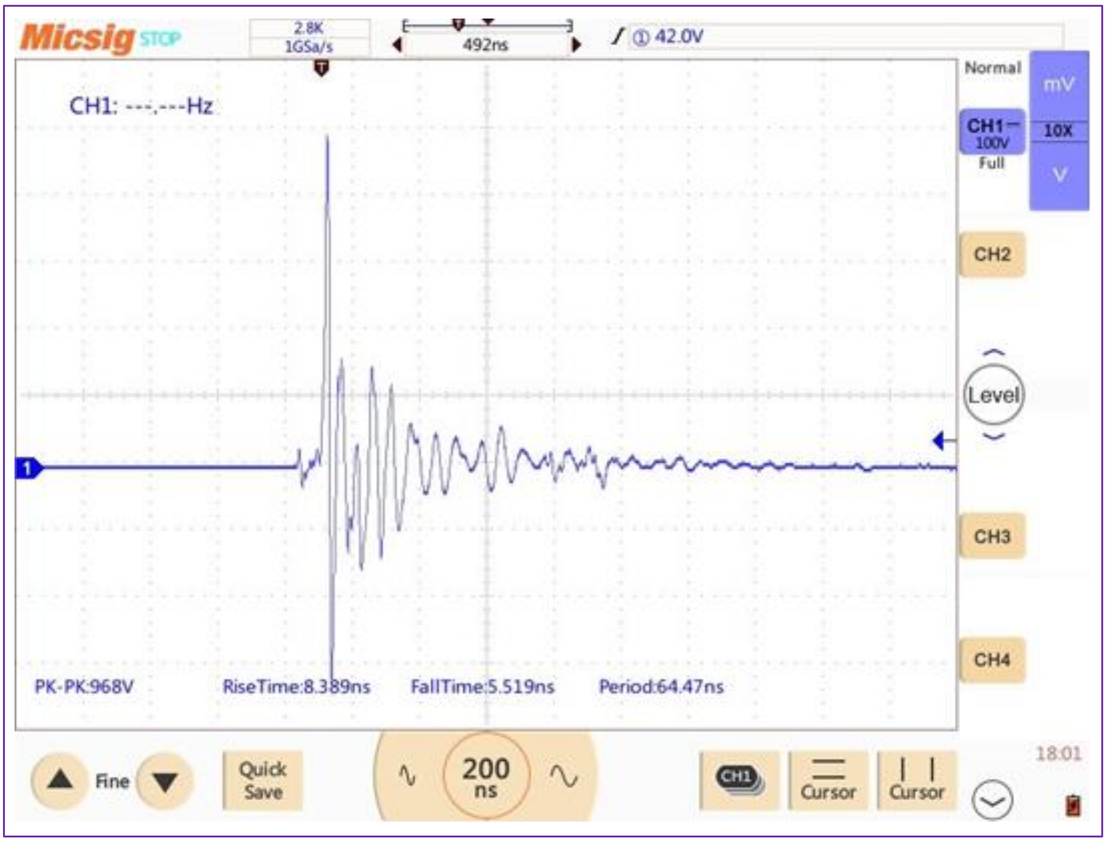

Figure 4.35. Output voltage for front resistor= 600 Ω and tail resistor= 130 Ω

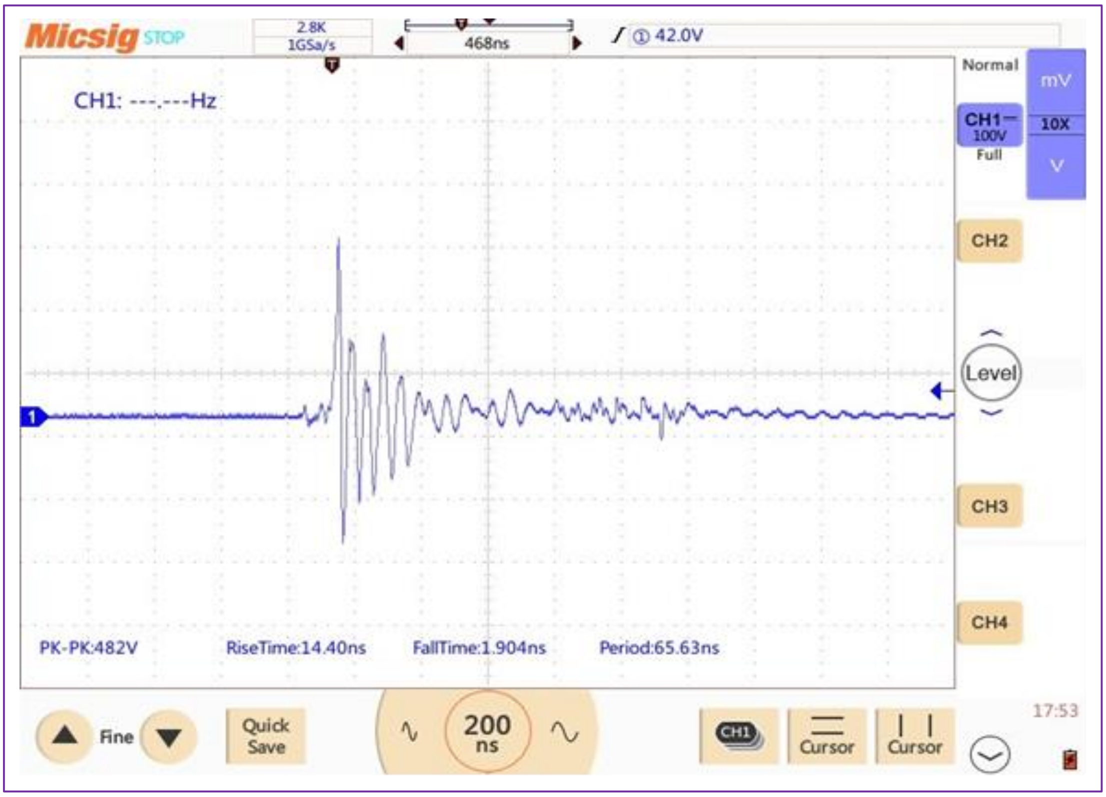

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Figure 4.36. Output voltage for front resistor= 1.2 kΩ and tail resistor= 130 Ω

There are always damped oscillation on waveforms. Because Marx generator equivalent circuit is a RLC circuit including stage capacitance, stray capacitance, inductance that originated from resistors and capacitors and resistance originated from charging resistors, front resistor and tail resistor.

Figure 4.33 and Figure 4.34 shows when front resistor is increased, peak to peak voltage amplitude decreases from 758 V to 201 V. Alike; in Figure 4.35 and Figure 4.36, front resistor is increased from 600 Ω to 1.2 kΩ and peak to peak voltage amplitude decreased 968 V to 482 V. This is front resistor effect to peak peak to voltage amplitude.

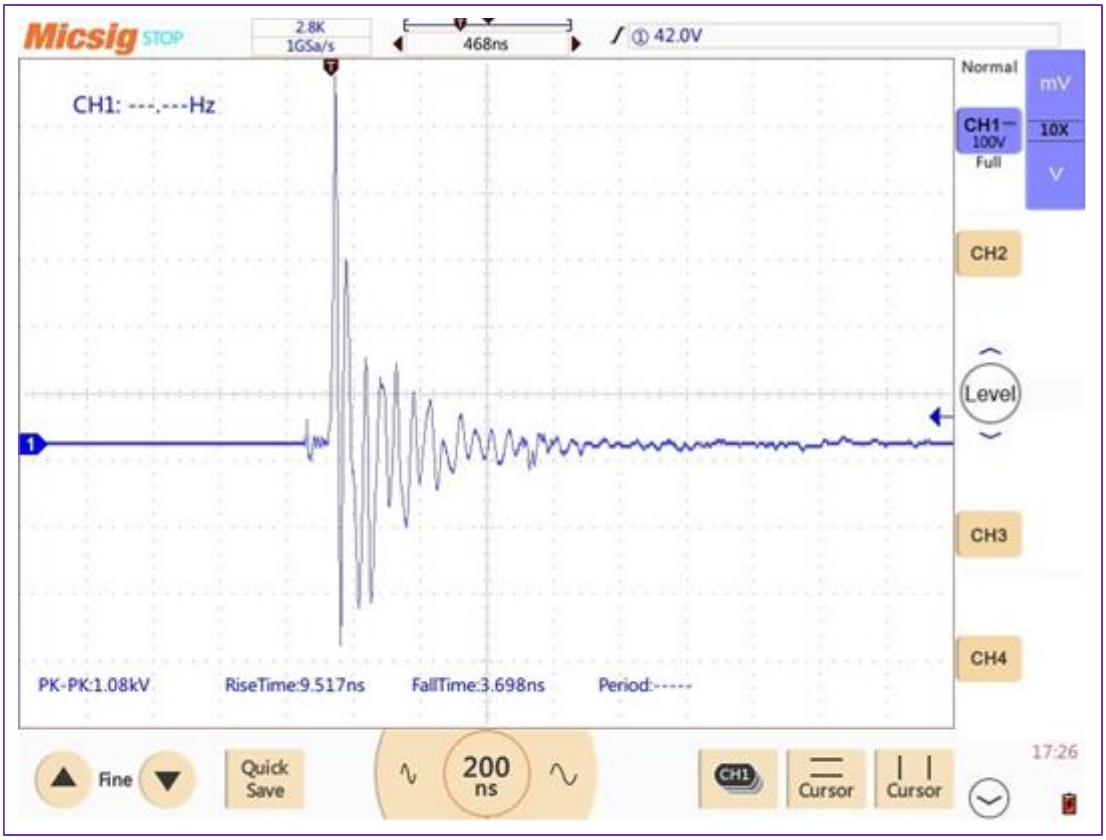

Figure 4.37. Output voltage for front resistor= 0 Ω and tail resistor= 180 Ω

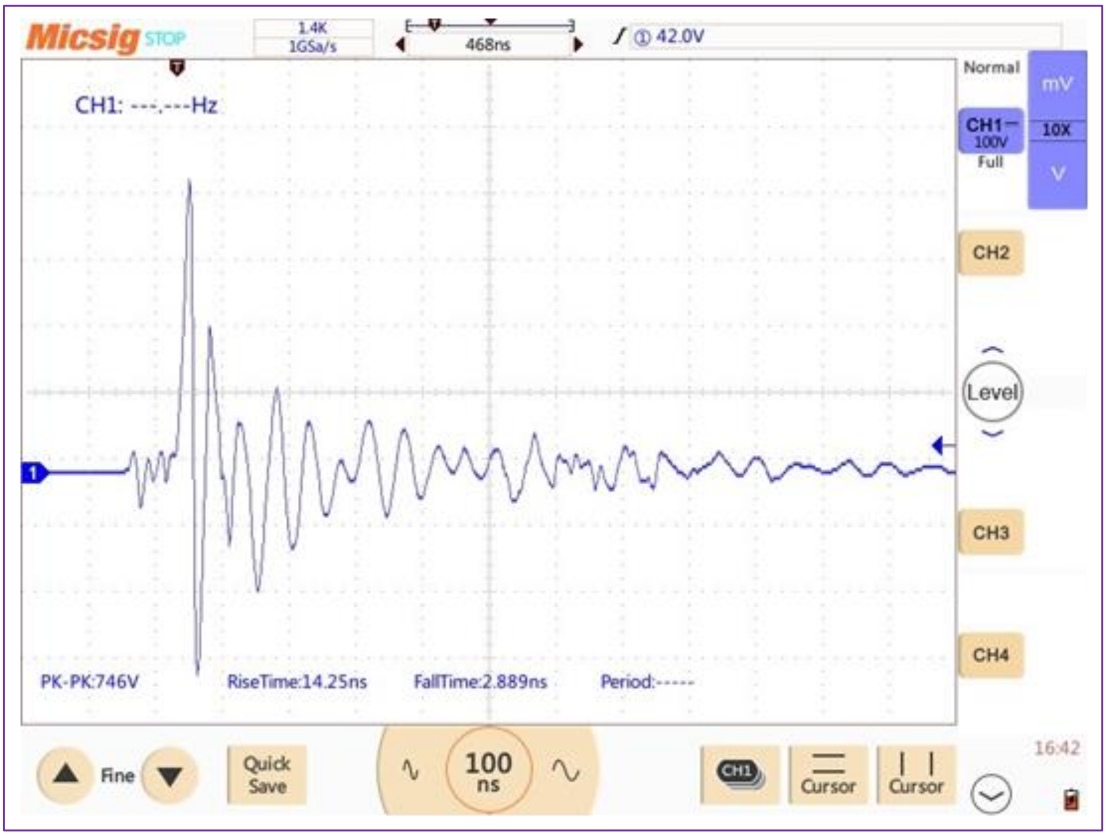

Figure 4.38. Output voltage for front resistor= 600 Ω and tail resistor= 90 Ω

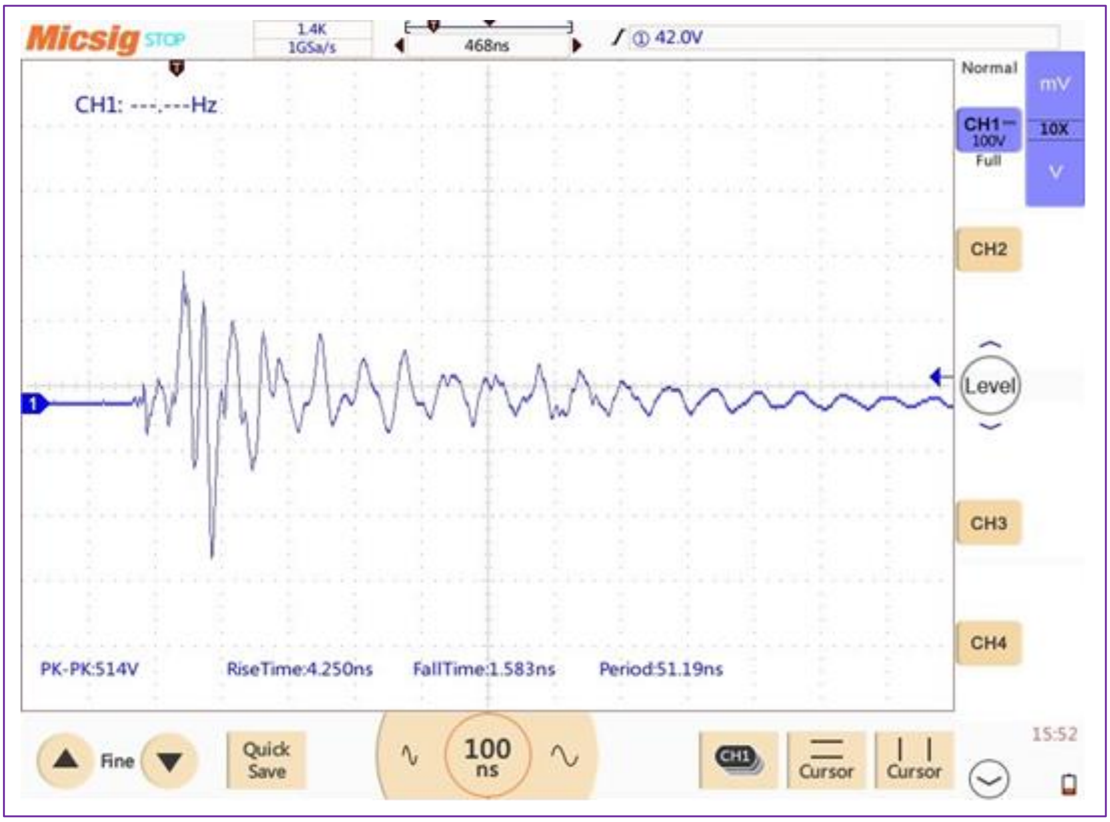

Figure 4.39. Output voltage for front resistor= 0 Ω and tail resistor=90 Ω

Figure 4.35 and Figure 4.38 shows that when tail resistor is increased (from 90 Ω to 130 Ω), fall time changes from 5.51 ns to 2.88 ns.

When tail resistor is raised from 90 Ω to 180 Ω, fall time increased from 1.58 ns to 3.69 ns (see in Figure 4.37 and Figure 4.39)

5. CONCLUSION

This thesis examines design of a high voltage Marx generator with coaxial structure. Operating principle and circuit analysis of the Marx generators are studied. Then various Marx generator designs on the open literature are investigated. Then, designs parameters of the Marx generators are determined. Unipolar charged topology is selected. Output voltage capacity, stage number, capacitor number on each stage, capacitor voltage rating etc. parameters are determined. On the production studies, for Marx generator stages and spheres of the spark gap switches, suitable materials are selected after research. During the production of the Marx generator, some precautions are taken against high voltage.

Spark gap switches are designed and produced in such a way that space between the spheres of the spark gap switches could be changed. Therefore, output voltage could be adjustable. A different method is implemented in this thesis about charging power supply of the Marx generator. Generally, off the shelf DC power supplies are used to charge Marx generator However, in this study, a power supply system whose output voltage amplitude is variable is designed and produced.

After the power supply system production, the Marx generator is run. According to performance some modifications are made on the power supply system. Spark gaps are optimized for sequential firing of all stages.

For a safety operation, the Marx generator is not forced to high charging voltage. Because, the charging resistors could have been damaged.

Later these studies, experimental studies are performed. Output voltage of the Marx generator is measured with capacitive voltage divider method. The measurement setup is prepared with a voltage divider, a coaxial cable and an oscilloscope. Measurements are performed various tail and front resistors have different values. Therefore, effect of these resistors to output voltage amplitude and waveform is observed.

In future work, Marx generators that have more output voltage and shorter rise time may be designed if suitable components are supplied. The design may developed more stable and more compact. Measurement technique may be improved and stabilized.

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