Practical Simulation and Modelling of Lightning Impulse Voltage Generator using Marx Circuit

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

Bachelor of Technology
in
Electrical Engineering
by

VIVEK KUMAR VERMA
Roll No. : 110EE0061
November 2014

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NATIONAL INSTITUTE OF TECHNOLOGY

Rourkela

CERTIFCATE

This is to certify that Mr. Vivek Kumar Verma has worked on the thesis entitled, "**Practical Simulation and Modelling of Lightning Impulse Voltage Generator using Marx Circuit"** in partial attainment of the requirements for the honour of Bachelor of Technology in Electrical Engineering at National Institute of Technology, Rourkela is a genuine work carried out by him under my mentor and guidance.

The candidate has fulfilled all the requirements prescribed.

To the best of my knowledge, the matter exhibited in the thesis is the record of authentic work carried out during the academic year (2014 – 2015).

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CONTENTS

ABSTRACT

Standard impulse waveform have similar characteristics as that of lightning strike and can be used for testing the strength of electrical equipment. For producing high voltage pulses Marx generator is the most popular and is most widely used method. This thesis describes the creation of a simulation circuit to match the output of a Marx Impulse Generator. In this project eight stages of standard Marx Impulse Voltage Generator were simulated and resulted impulse waves were recorded. The objective was to calculate the stray capacitance using standard formulas and embed that capacitance into the simulation circuit to adequately deliver a yield like that of the impulse generator. A genuine multi-staged impulse generator was utilized as the base. Eight distinctive levels of impulse voltage were tried, and the output waveforms were recorded. The simulation circuit was then subjected to a few cycles, conforming the capacitance qualities to achieve a yield as close as could be expected under the circumstances to that of the real generator. Finishes of the examination demonstrate that a successful simulation circuit could be made to give a yield that is near, yet not precisely that of, the genuine generator. In the exploration, a few zones of error were distinguished in the simulation that were not introduce in the simulation circuit. The entire simulations have been examined in the NI Multisim software. The simulation circuit could be utilized to figure out the front time, tail time, and peak voltage.

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

Symbols	Symbols Name
C_1, C_3, C_4, C_5	Charging Capacitors
C_2	Discharging capacitors/Test Object
R_1, R_2	Wave shaping resistors
$\boldsymbol{T_1}$	Rise Time
$\boldsymbol{T_2}$	Fall Time
$\boldsymbol{V_p}$	Peak output voltage
$\boldsymbol{V_o}$	Applied direct current voltage
n	Number of stage
α	Wave tail time constant
β	Wave rise time constant

CHAPTER 1

Introduction

Introduction

Introduction to NI Multisim

Practical Relevance

Objective

Organisation of thesis

INTRODUCTION

1.1 Introduction

Lightning and switching surges are transient overvoltage that cause disturbance of electric power transmission and distribution systems. The amplitudes of these voltages exceed the peak value of normal AC operating voltage. Hence, during the development stages of high voltage (HV) apparatus, testing against lightning and switching surges is necessary [1]. As per the origin of the transients, distinction between lightning and switching impulses are made in the relevant IEC standard (60060-1) [2-3]. Generation of these impulse voltages are necessary for testing purposes. Impulse testing has now expanded to a commercial field from an experimental field, and reliable means of calculating the test or discharge waves is desirable to facilitate experiments in this expending field [1].

Lightning overvoltage impulse wave can be characterised as double exponential waves given by the following equation -

$$V = V_o[e^{(-\alpha t)} - e^{(-\beta t)}] \quad (1)$$

This equation represents a unidirectional wave that quickly rises to peak value and slowly falls to zero value [3]. For specification of impulse waves their rise of front time, fall or tail time to 50% of peak value and peak value voltage are needed. Impulse waveforms can be produced in the laboratory by combination of series R-L-C circuit or by combination of R-C circuits [3]. The front time and tail time can be varied by varying the circuit parameters. Wave shape control is generally carried out by varying circuit resistance as generator capacitance and load capacitance are fixed for given generator and test object. If this method is used for generating impulse by single capacitor then the charging becomes too costly and there will be an increase in size of the equipment [2-8]. For producing high voltages a bank of capacitances are charged in parallel and then discharged in series. This idea was originally proposed by Marx. To save space and cost of the impulse generator setup, several modifications in the Marx circuit are employed.

1.2 Introduction to NI Multisim

National Instruments (NI) Multisim is an electronic schematic capture and in addition a simulation software used to simulate electronic circuits and Printed Circuit Boards. Alongside NI Ultiboard, it is a part of circuit scheme programs [9]. It is largely utilized within the scholarly world and industry for SPICE simulation, visual design and simulation of circuits.

This circuit configuration projects utilize the first Berkeley SPICE based programming simulation. Multisim was created by an organization named Electronics Workbench. It is now a part of National Instruments [9]. NI tools bring about spared printed circuit board (PCB) iterations and critical expense funds. Multisim simulation and circuit outline programming gives designs the advanced analysis and configuration abilities to enhance execution, reduce plan errors, and abbreviate time to model. Using the integrated platform of Multisim and Ultiboard, experts in modelling, engineers and researchers can shorten the time taken to prototype their design. Multisim software has a vast database of more than 26,000 components supported by renowned semiconductor manufacturers [9, 10]. The vast and elaborate library of Multisim containing up-to-date amplifiers, diodes, transistors and switch mode power supplies combined with advanced simulation makes is possible to implement design in short time.

1.3 Practical relevance

International Electrotechnical Commission (IEC) and American Society for Testing of Materials (ASTM) have set internationally accepted quality standards for testing of dielectric strength of materials used. The power equipment materials must be able to withstand normalised voltages with different waveforms, lightning and switching being the most common. The power equipment are designed not only to withstand normal operating voltages but also to withstand lightning and other disturbances [2-8]. Disturbances on power lines create a great hazard for the power apparatus, continuity of supply and the safety of staff. Research in this area is mainly concerned with the study of abnormal Impulse voltage waves, its production and characteristics as desired. Hence research in this area specifically the study of Impulse waves, its generation, its nature and characteristics is desired. Power lines and equipment are revealed to the atmosphere, hence lightning strike is a common phenomenon. The complication arises in low cost designing and construction of appropriate high voltage insulation systems. It is stated in (ASTM, 2004; IEC, 2001) that for dielectric testing impulse generators provide impulse voltages that are large enough to cause power disruption. The standard impulse voltage can be affected by the capacitance of the test material and it must be taken into account while monitoring and adjusting the voltage waveforms [5].

The main purpose of this thesis is:

- Development of Impulse Voltage Generator using Standard Marx Voltage Generator circuit using NI Multisim software.
- To build a Marx Generator practical circuit model and compare the results of the resulting waveform to that of the simulation circuit.

1.4 Organisation of thesis

This thesis has been classified into following set of chapters:

Chapter 1: The first chapter is devoted to the introductory part of the project. In this chapter a general information about the standard impulse voltages, its practical inference and importance of NI Multisim software are presented.

Chapter 2: This chapter presents the theoretical background of the standard impulse voltage waves. It mainly focuses on generation and characteristics of standard impulse waves.

Chapter 3: This chapter deals with the procedure applied for generating the impulse voltage wave which includes the calculation of circuit parameters which are front and tail resistors and charging and discharging capacitors.

Chapter 4: Results obtained from simulation are shown in this chapter including evaluation of front and tail time, error, energy and efficiency.

Chapter 5: This chapter deals with the experimental impulse voltage generator circuit and also the procedure followed while doing the experiment.

Chapter 6: This chapter presents the future research possibilities and concludes the thesis.

CHAPTER 2

History and Literature Review

Impulse Voltages

Standard Impulse Wave Shapes

Theoretical Background

HISTORY AND LITERATURE REVIEW

2.1 Impulse voltages

In systems which requires protection from lightning, surge arresters and other types of losses will damp and alter the travelling waves, and therefore lightning over-voltages having different wave shapes are present in the transmission system. The wave shapes are arbitrary, but mainly unidirectional. Lightening impulse voltage has a wave shape associated with it which can be given by the equation (1) where α and β are constants in the scale of microseconds and V_0 is the charging voltage.

Equation (1) signifies that lightning voltage can be represented by a doubly exponential curve that rises quickly to the peak and falls comparatively slowly to zero values with respect to time axis. For different waveforms, the value of α and β control the front and tail times of the wave respectively. Value of α is generally less than that of β [3]. The Impulse voltages in power systems are generally expressed in terms of rise time, fall time and the peak voltage. These parameters are different for different types of impulses. Determination of these parameters are crucial for producing the impulse voltage of exact same type and magnitude. In this thesis these parameters are determined with the mathematical analysis and also by assuming standard values of other circuit parameters.

2.2 Standard impulse wave shapes

As per IEC standards impulse voltage generators produces waves which can be impulse lightning and impulse switching, with 1.2-250µs standard front time and 50-2500µs for tail time.

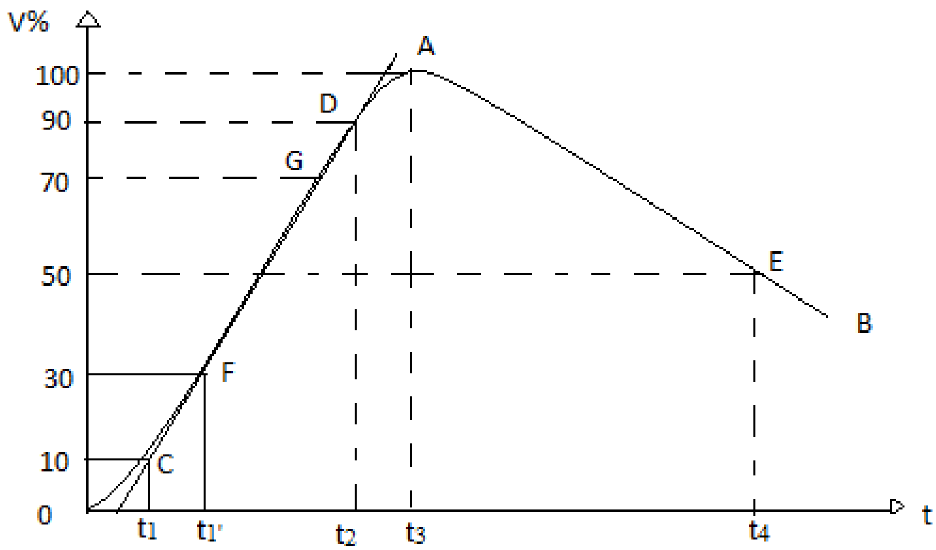

Figure 2.1 Standard Lightning Voltage Impulse wave and its specifications [2-4]

Front Time (T_1): 1.2 µs ± 30% Fall Time (T_2): 50 µs ± 20%

Time measurements for lightning wave

Referring to the wave shape in Figure 2.1, the fixed peak value A is mentioned as 100% value. Point D corresponds to 90% of the peak value and point C corresponds to 10% of the peak. These points are joined and then the line is then extended to cut the time axis at O_1. O_1 can now be treated as virtual origin. Front time is given by 1.67 multiplied by the interval between 30% and 90% of the peak value.

Standard tolerance allowed for front time is ±30% and that of tail time is ±20%. So, the front time the values should be between 0.84µs and 1.56µs. Similarly for the tail time the accepted values comes out between 40µs and 60µs [2].

2.3 Circuits for producing impulse waves

We can generate Impulse waves in a laboratory by combination of R-C circuits or by the combination of series R-C circuits with over damped conditions. Circuits for producing impulse waveforms are shown in Figure 2.2

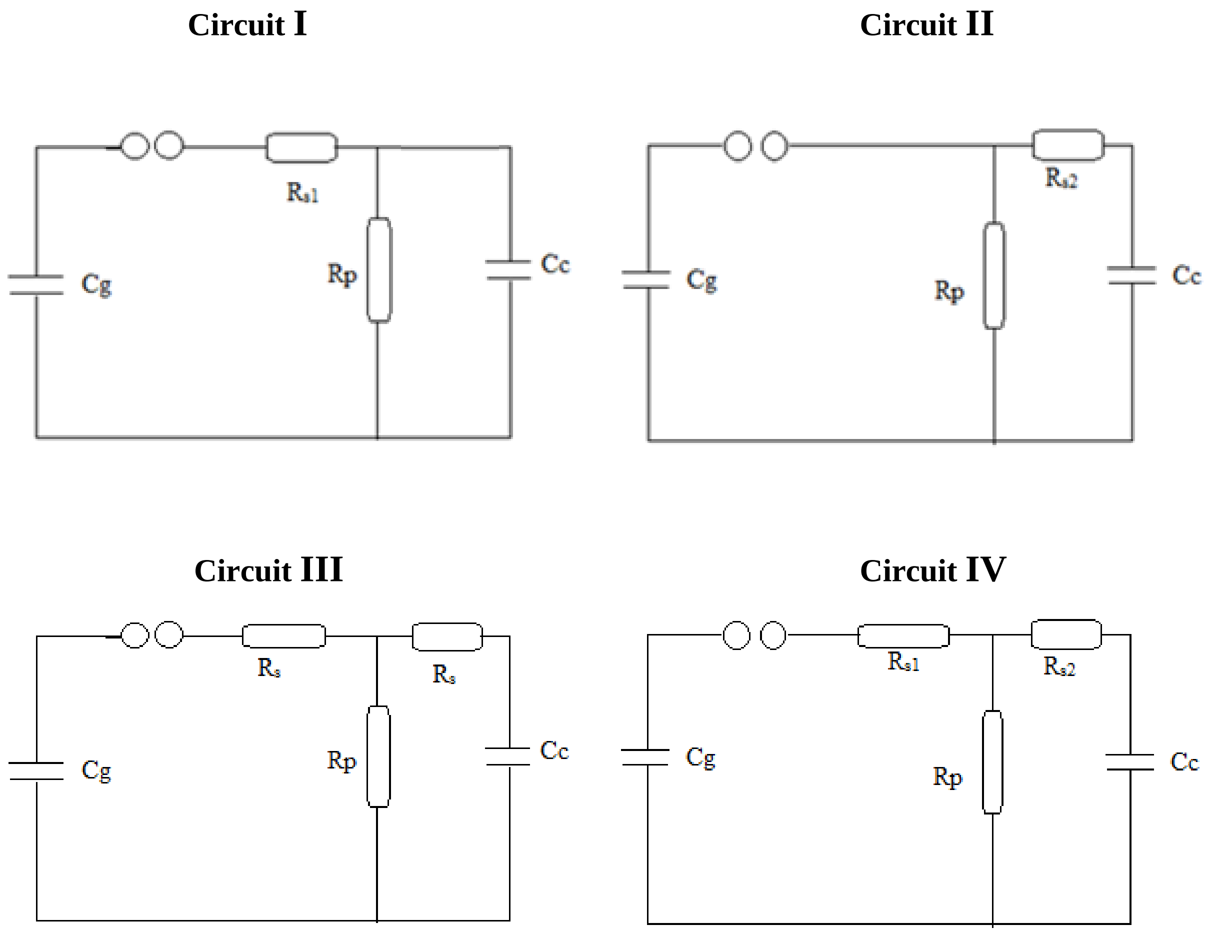

Figure 2.2 RC Circuits for Single Stage Impulse Voltage Generation [3]

Front or damping resistor: Rs1, Rs2, Rs.
Tail or discharge resistor: Rp
Discharge capacitor: Cg.
Charge capacitor: Cc.

Impulse voltages can be produced by either combinations of the above four circuits and other types of combinations are also possible. The mechanism behind the operation of all the circuits are same.

2.4 Standard Marx impulse voltage generator circuit

Circuits based on above discussions the generator capacitor is needed to be charged to a constant DC voltage level before discharging into the wave shaping circuits. Up to 200 kV, a single capacitor can be used for producing peak impulse voltages. Beyond this, a single capacitor and its charging element may become too costly and overheating is also likely to occur [3]. The size of the whole setup becomes bulky. Various difficulties are faced with the increase of peak impulse voltage like switching of the spark gap at a very high voltage, necessity of high DC voltage to charge the charging capacitors, increase in circuit element size and difficulties faced in suppression of corona discharge from the equipment during time period of charging. To overcome these problems, the single stage generator is expanded to multistage impulse generator. The size and cost of conventional impulse generators increases at the square or cube function of the peak impulse voltage rating [3]. For production of high impulse voltage, the capacitors are charged simultaneously in series and then made to discharge in series. The very idea of charging of the capacitors in series and discharging them in series was proposed by Marx. Improved versions of the Marx circuits are being developed and used nowadays.

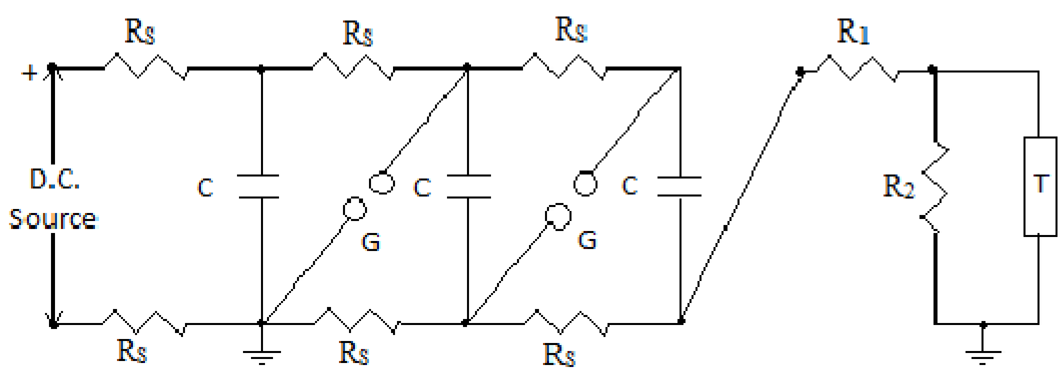

Figure 2.3 Schematic diagram of Marx impulse voltage generator circuit [7]

Figure 2.3 shows a schematic diagram of Marx circuit. Charging current is limited to about 50 to 100mA by the charging resistance. The generator capacitance is chosen to limit the product [3]. The gap spacing is selected in a way such that the breakdown voltage across the gap G should be greater than the charging voltage V. By this setup all the capacitors are connected in series and discharged into the capacitive load which is also the test object. Thus, the capacitors in series are charged to voltage V in about 1 minute. The charging time constant CRs will be large as compared to discharge constant CR_1/n (for n stages). As shown in figure the wave-shaping circuit is attached externally to the capacitor unit. Modified versions of Marx circuit are available to make it compact in design for commercial purposes. In a particular type of modified Marx circuit, wave-shaping resistors are divided so as to decrease the size. R_1 is divided into n parts having value R_1/n and put in series with gap G. Also R_2 is divided into n parts and connected in parallel to each capacitor unit after the gap G. By this setup the control resistors are smaller in size and efficiency $\frac{V_0}{nV}$ is high.

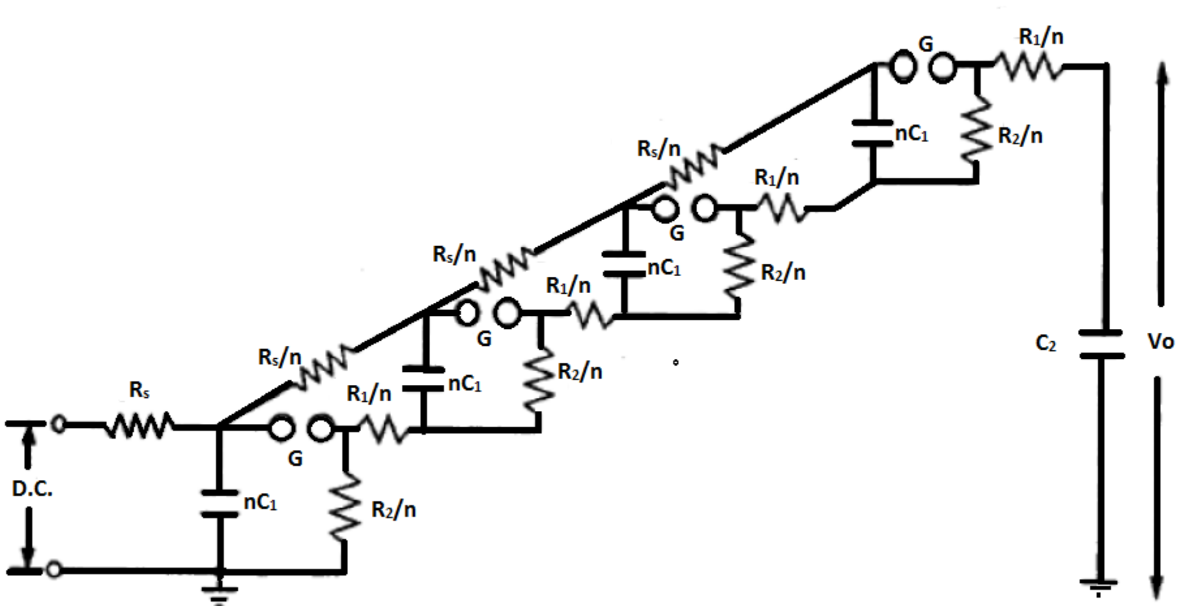

Figure 2.4 Modified impulse voltage generator incorporating the series and wave tail resistance within the generator [3]

The efficiency of each stage in terms of peak output voltage and applied DC voltage can be given as

$$\text{Efficiency} = \frac{Vp}{Vo} \qquad (2)$$

Where, V_p is the peak output voltage and V_o is the applied DC voltage. In terms of circuit parameters the above equation can also be represented as

$$\text{Efficiency} = \left(\frac{1}{1+(n\times C_2)C_2}\right) \times \left(\frac{1}{1+\left(\frac{R_1}{R_2}\right)}\right) \qquad (3)$$

Where, C_1 and C_2 are charging and discharging capacitors, R_1 and R_2 are front and tail resistors and n is the number of stages.

Energy stored in the capacitors during charging expressed in terms of applied DC voltage V_0, and charging capacitor, C_1 can be calculated using

$$W = \frac{((\frac{C1}{n})\times Vo\times Vo)}{2} \tag{4}$$

Where, n is the number of stages.

Existence of series resistance in the circuit causes capacitors to not charge at the same value. By simply increasing the number of stages desired output peak impulse voltage can be retrieved. But practically voltage obtainable is limited by the presence of series resistance and distant capacitors. Thus the solution is to increase the number of stages up to optimal levels for generation of high impulse voltages.

CHAPTER 3

Experimental Framework

Analysis of Circuit of One Stage Standard Marx Circuit

Determination of Circuit Elements

Simulation Calibration for NI Multisim

EXPERIMENTAL FRAMEWORK

3.1 Analysis of circuit of one stage Standard Marx circuit

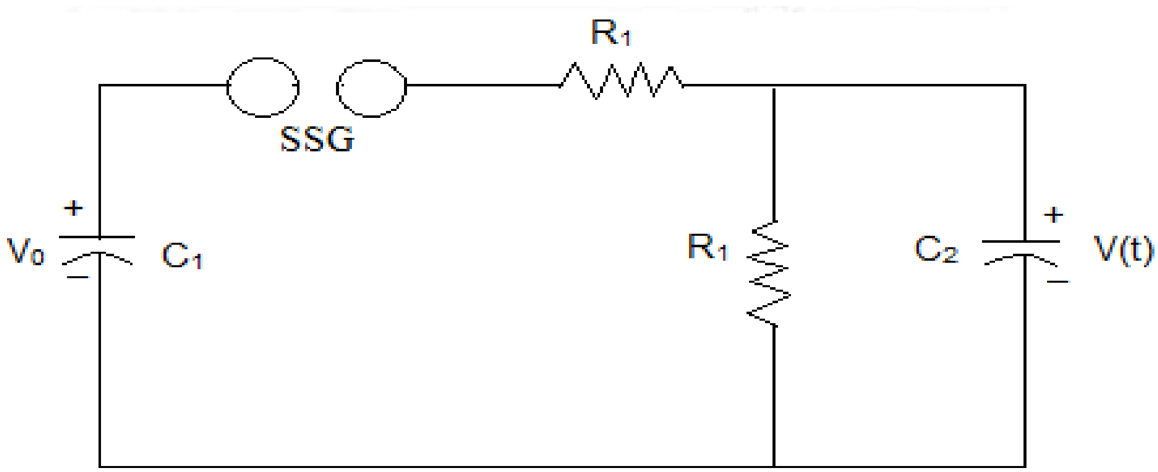

Figure 3.1 Circuit for impulse voltage generation

Fig. 3.1 shows one of the commonly used configurations for generating impulse voltages. The main advantage of these sort of circuit configuration is that the wave front and wave tail times can be separately controlled by separately changing either R_1 or R_2. Secondly, C_2 can be thought of as including the test object which is mainly capacitive.

For the configuration shown in Fig. 3.1, the output voltage across C_2 is given by,

$$v_0(t) = \frac{1}{C_2}\int_0^t i_2\, dt \qquad . \qquad (5)$$

Performing Laplace transformation,

$$\frac{1}{C_2(s)} I_2(s) = v_0(s) \qquad (6)$$

, where I_2 is the current flowing through C_2. Current through C_1 is I_1 and its transformed is $I_1(s)$,

$$I_2(s) = \left(\frac{R_2}{R_2+\frac{1}{C_2(s)}}\right)I_1(s) \tag{7}$$

and

$$I_1(s) = \frac{V}{s}\frac{1}{\frac{1}{C_1 s+R_1+\frac{R_1\cdot\frac{1}{C_1 s}}{R_2+\frac{1}{C_2(s)}}}} \tag{8}$$

Substitution of $I_1(s)$ gives $v_0(s)$ and simplifying and taking inverse transform of

$$v_0(t) = \frac{V}{R_1 C_2(\alpha-\beta)}[e^{-\alpha t} - e^{-\beta t}] \tag{9}$$

Here usually $\frac{1}{C_1 R_1}$ is much smaller compared to $\frac{1}{C_1 R_1}$

Hence, the roots may be approximated as

$$\alpha \approx \frac{1}{C_2 R_1}\ and\ \beta \approx \frac{1}{C_1 R_2}$$

It may be shown that the output waveform for the circuit configuration of Fig. 6.15c will be

$$v_0(t) = \frac{VCR_2\alpha\beta}{(\beta-\alpha)}[e^{-\alpha t} - e^{-\beta t}] \tag{10}$$

where α and β are the roots of the Eq. (6.19).

Analysis of circuit given in Figure 3.1 is performed for determining the circuit elements. For this analysis Laplace transformation is essential. The output voltage for the circuit given in Figure 3.1 can be written as

$$V(s) = \frac{V_0}{s} \times \frac{Z_2}{(Z_1+Z_2)} \tag{11}$$

Where Z_1 is given by $\left(\frac{1}{C1(s)}\right) + R_1$ and Z_2 is equivalent to $(\frac{R_2}{C_2(s)})/(R_2 + (\frac{1}{C_2(s)})$ and after substituting in the above equation (5) we get

$$V(s) = \left(\frac{V_0}{k}\right) \times \left(\frac{1}{s^2+as+b}\right) \quad (13)$$

Where $= \left(\frac{1}{R_1C_2}\right) + \left(\frac{1}{R_1C_2}\right) + \left(\frac{1}{R_2C_2}\right)$; $b = \left(\frac{1}{R_1R_2C_1C_2}\right)$ and $k = R_1C_2$.

From the transform table, time domain expression for this circuit is obtained and we obtain the following expression

$$V(t) = \left(\frac{V_o}{k}\right) \times \left(\frac{1}{\alpha_2-\alpha_1}\right) \times \left(e^{(-\alpha_1 t)} - e^{(-\alpha_2 t)}\right) \quad (14)$$

The roots of the equation, $s^2 + as + b = 0$, α_1 and α_2 is given by,

$$\alpha_1, \alpha_2 = \left(\frac{a}{2}\right) \mp \sqrt{\left(\left(\frac{a}{2}\right)^2 - b\right)} \quad (15)$$

3.2 Determination of circuit elements

The values of resistors R_1 and R_2 are to be found out, since C_2 and C_1 are generally known. In case of larger generators the values of discharge capacitors are provided. A certain range of values of C_2 are known which are dimensioned for better efficiency. The total load capacitance can be easily calculated, if load capacitance is not known in advance. The estimated resistance values for the circuit can then be calculated by the equation given below

$$R_1 = \left(\frac{1}{C_1}\right)\left[\left(\left(\frac{1}{\alpha_1}\right) + \left(\frac{1}{\alpha_2}\right)\right) - \sqrt{\left(\left(\frac{1}{\alpha_1}\right) + \left(\frac{1}{\alpha_2}\right)\right)^2 - \left(\frac{4(C_1+C_2)}{(\alpha_1\alpha_2C_2)}\right)}\right] \quad (16)$$

$$R_2 = \left(\frac{1}{2(C_1+C_2)}\right)\left[\left(\left(\frac{1}{\alpha_1}\right) + \left(\frac{1}{\alpha_2}\right)\right) - \sqrt{\left(\left(\frac{1}{\alpha_1}\right) + \left(\frac{1}{\alpha_2}\right)\right)^2 - \left(\frac{4(C_1+C_2)}{(\alpha_1\alpha_2C_2)}\right)}\right]. \quad (17)$$

In the above two equations there are the time constants $1/\alpha_1$ and $1/\alpha_2$, which depends on the wave shape. These time constants have no relationship between themselves. There are international standards for times T_1 and T_2. The relationship between time constants can be estimated by implementing the definitions to the mathematical expressions for $V(t)$. This involves numerical computation of the irrational relationship.

Result for some common selected wave shapes is shown in the table in the next page.

TABLE-I

RELATIONSHIP BETWEEN RISE TIME, FALL TIME AND TIME CONSTANTS [4]

T_1/T_2	$1/\alpha_1$	$1/\alpha_2$
1.2/5	3.480	0.800
1.2/50	68.20	0.405
1.2/200	284.0	0.381
250/2500	2877	104.0

The impulse wave of concern is 1.2/50 μs. From the table above, the time constants of 68.20 and 0.405 are to be used to determine circuit elements.

The wave front time T_1 and the wave tail time and T_2, can be calculated using following approximate analysis. Due to the large value of resistance R_2, charging time taken is approximately three times the time constant of the circuit.

$$T_1 = 3R_1C_e \tag{18}$$

Here C_e can be calculated by the formula given below

$$C_e = \frac{(C_1 \times C_2)}{(C_1 + C_2)} \tag{19}$$

Here, R_1C_e is the charging time constant (in μs). The time for 50% discharge i.e., discharging or tail time is given by.

$$T_2 = 0.7 \times (C_1 + C_2) \times (R_1 + R_2) \tag{20}$$

Estimation of wave front and wave tail resistances within the error limits can be there by using approximate formulae. Following equations are used for the calculation:

$$R_1 = \frac{T_1 \times (C_1 + C_2)}{(3 \times \left(\frac{C_1}{n}\right) C_2)} \tag{21}$$

$$R_2 = \left(\frac{T_1}{0.7 \times (C_1 + C_2)}\right) - R_1 \tag{22}$$

The C_1 / C_2 ratio were taken 40 and 20 respectively and for each stage and values of front and tail resistors for each stages were calculated by using equation (21) and (22). By using the procedure described, the resistor values used in each stage of impulse generator are given below in tabular form.

TABLE-II

PARAMETERS OF DESIGN FOR STANDARD MARX CIRCUIT FOR C_1: C_2 = 20, C_1 = 10 and C_2 = 0.5

Stage	Discharging Resistance $R_1(\Omega)$	Discharging Resistance $R_2(\Omega)$
1st	0.84	05.9600
2nd	0.88	012.107
3rd	0.92	17.7135
4th	0.96	22.8500
5th	1.00	27.5700
6th	1.04	31.9270
7th	1.08	35.9570
8th	1.12	39.6960

In practise, the standardised values of rise time and fall time cannot be achieved. This is because even if the value of C_1 is fixed, the load C_2 will vary and implementing the exact values for resistors R_1 and R_2 will not be available in general. For high rated voltage, these resistors which are used in generators should be expensive. So, the applicable tolerances are necessary for rise time and fall time and resistor values are changed by using these tolerances. The real output voltage V(t) is also to be recorded to testify the admissible impulse shape.

CHAPTER 4

Simulation Results Using Simulink

Marx Impulse Voltage Generator

Calculation of Front time, Tail time and Error

Calculation of Energy and Efficiency

SIMULATION RESULTS USING SIMULINK

4.1 Marx impulse voltage generator

Two stage Standard Marx impulse voltage generator

In figure 4.1, the basic circuit used for generation of impulse wave using two stage Marx Circuit is shown. The sphere gap in the circuit that is a voltage sensitive switch is represented by using toggle switches. For ease of simulation toggle switches are used in place of sphere gaps. To complete the requirement of discharging capacitors in series, toggle switches can be used. By the use of toggle switches, capacitors C_1 and C_2 can be discharged simultaneously. Such an approximation is feasible because of the very short duration of the breakdown of sphere gap. Large impulse voltage generator have the charging voltage in scale of megavolts. The components R_1, R_2 and C_3 combine together to form the wave-shaping network of the circuit. Resistor R_1 regulates the front time and acts as a damping resistor that damps the circuit. The discharging resistor is given my R_2 through which charging capacitors C_1 and C_2 will discharge. The equivalent capacitance of the load is represented by C_3. This includes capacitance of other elements which are in parallel with the load. After the break down of the sphere gap, charging capacitors C_1 and C_2 discharge in series into the wave shaping circuit which contains R_1, R_2 and C_3.

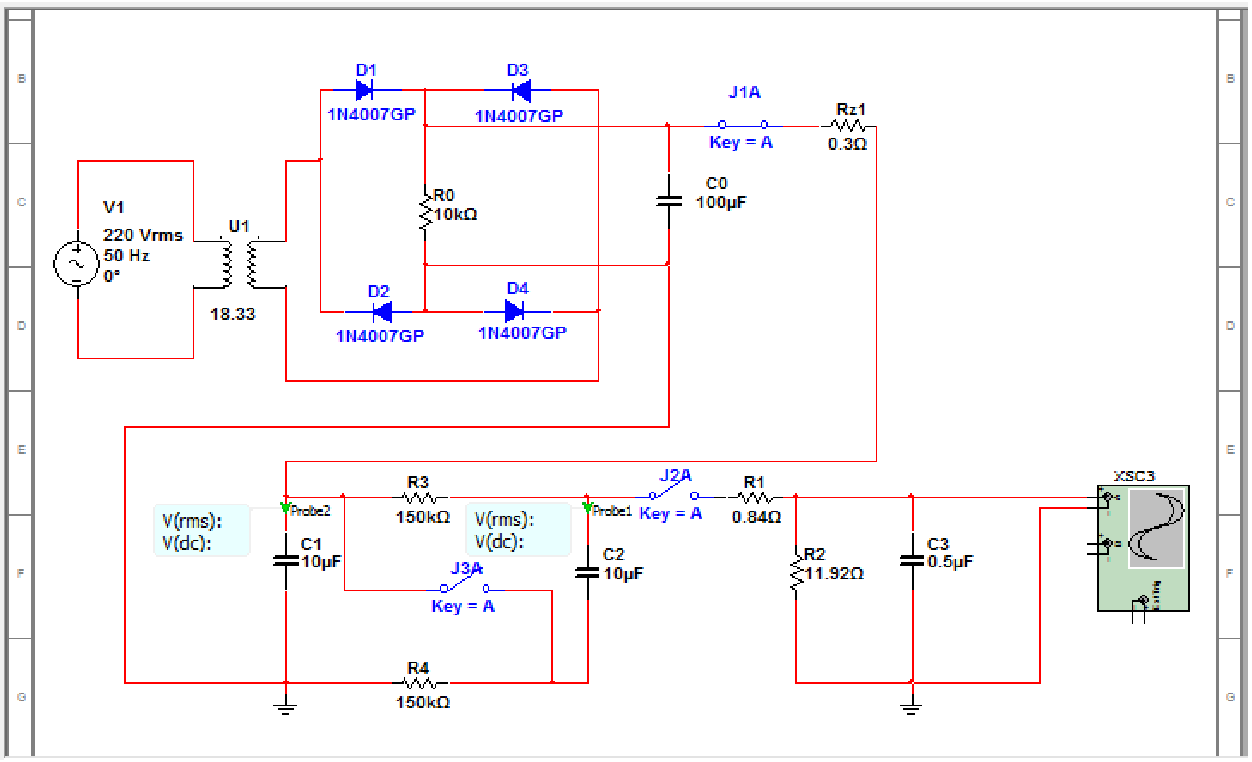

Figure 4.1 Schematic diagram of two stage Standard Marx impulse voltage generator in NI Multisim software.

The impulses can be generated according to need as fast impulses or slower impulses provided switching modifications are applied. For example, to generate a longer impulse an inductance can be added in series with R_1. Efficiency of impulse generator can also be changed by changing the circuit arrangement. Since our main aim is to charge capacitor to peak, the ripple effect is not of much concern. Sphere gap is represented by a switch. The voltage across it as well as the voltage across the capacitors builds up. Sphere gaps are made to fire naturally in practice and this is done for smooth operation. Controlled firing can also be done.

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Standard impulse wave for the two stage using the Standard Marx Impulse generator is shown below.

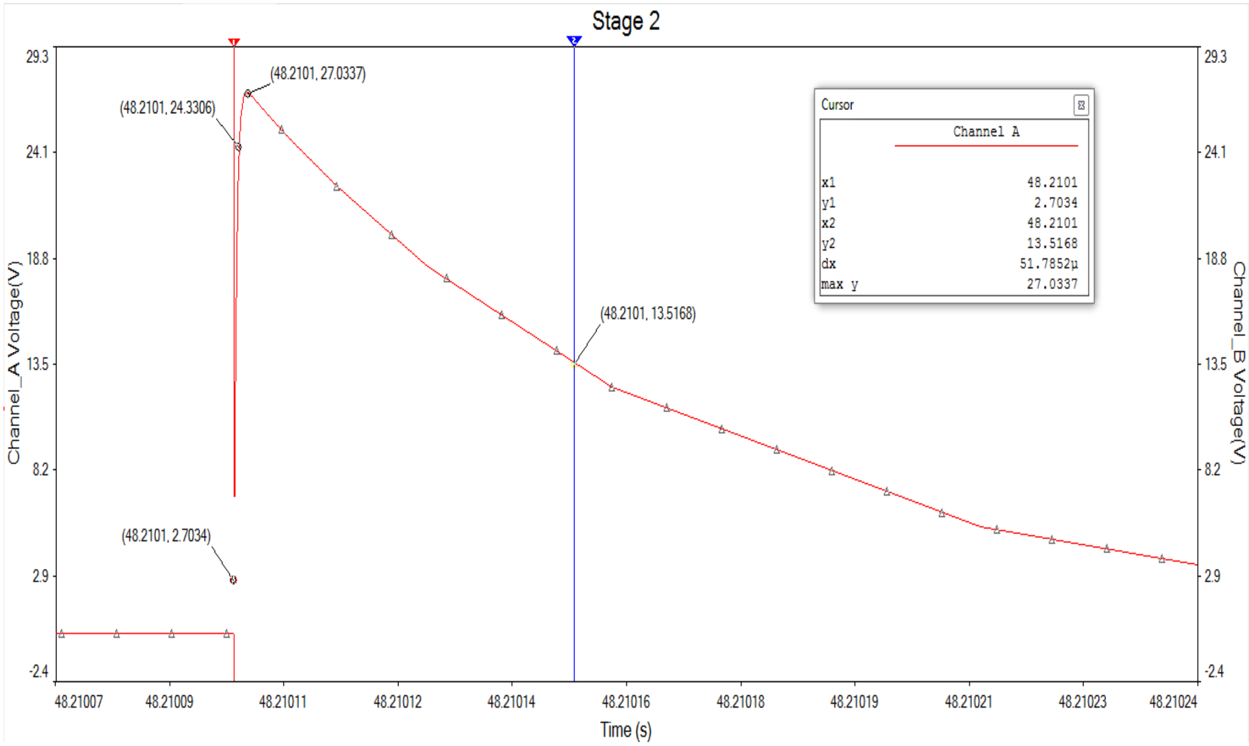

Figure 4.2 Output impulse voltage waveform generated using second stage standard Marx impulse voltage generator circuit

The dc voltage applied across the capacitors is around 15.5 V. This can be viewed by placing a measurement probe across the capacitor. The switch should be toggled only when the DC voltage across the capacitors in parallel is close to 15.5 V. The peak voltage is somewhat less than the total DC voltage across the capacitors. In the graph view in MULTISIM we can mark the cursor points at which the voltage is 10%, 50% and 90% of the peak value. The values required can represented as shown in a cursor box.

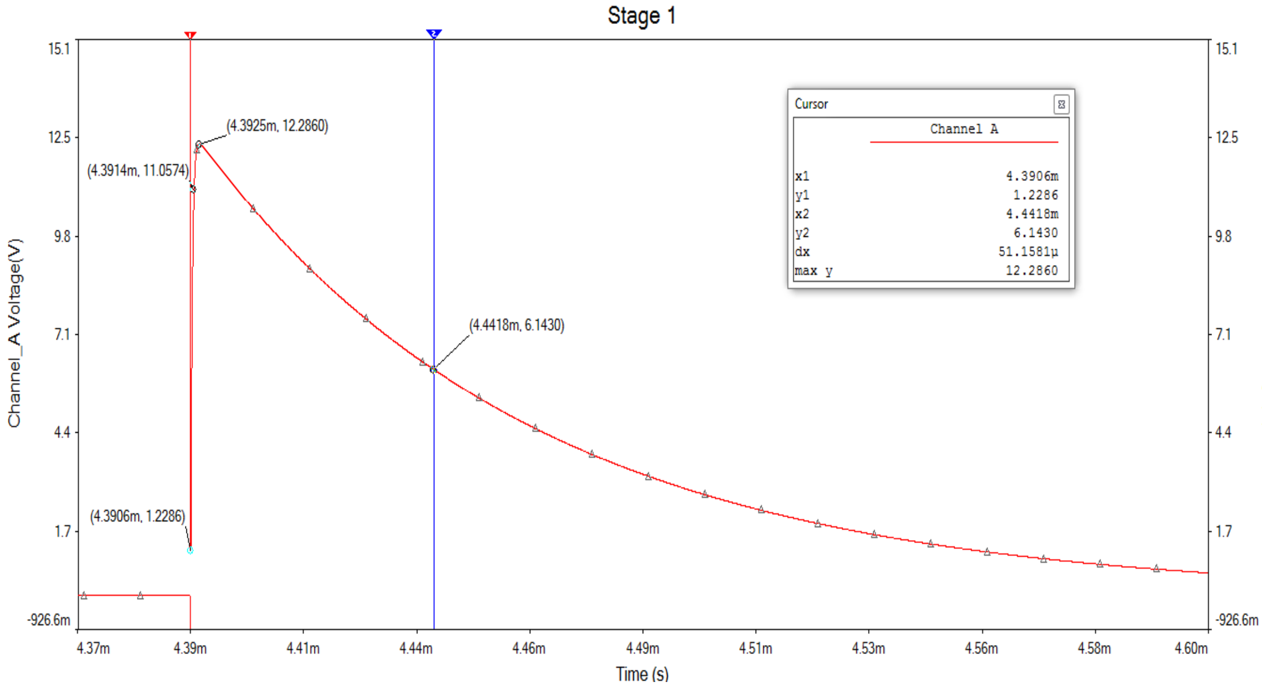

Figure 4.3 Output impulse voltage waveform generated using first stage Standard Marx impulse voltage generator circuit.

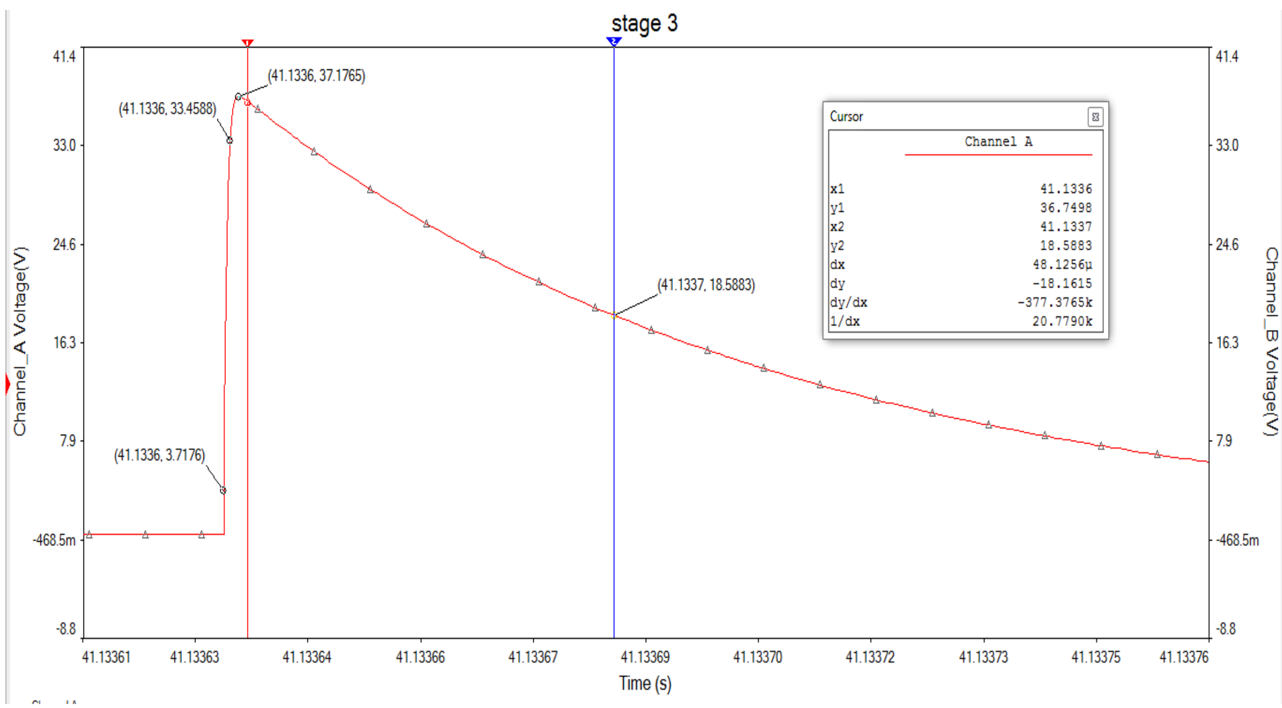

Figure 4.4 Output impulse voltage waveform generated using third stage Standard Marx impulse voltage generator circuit.

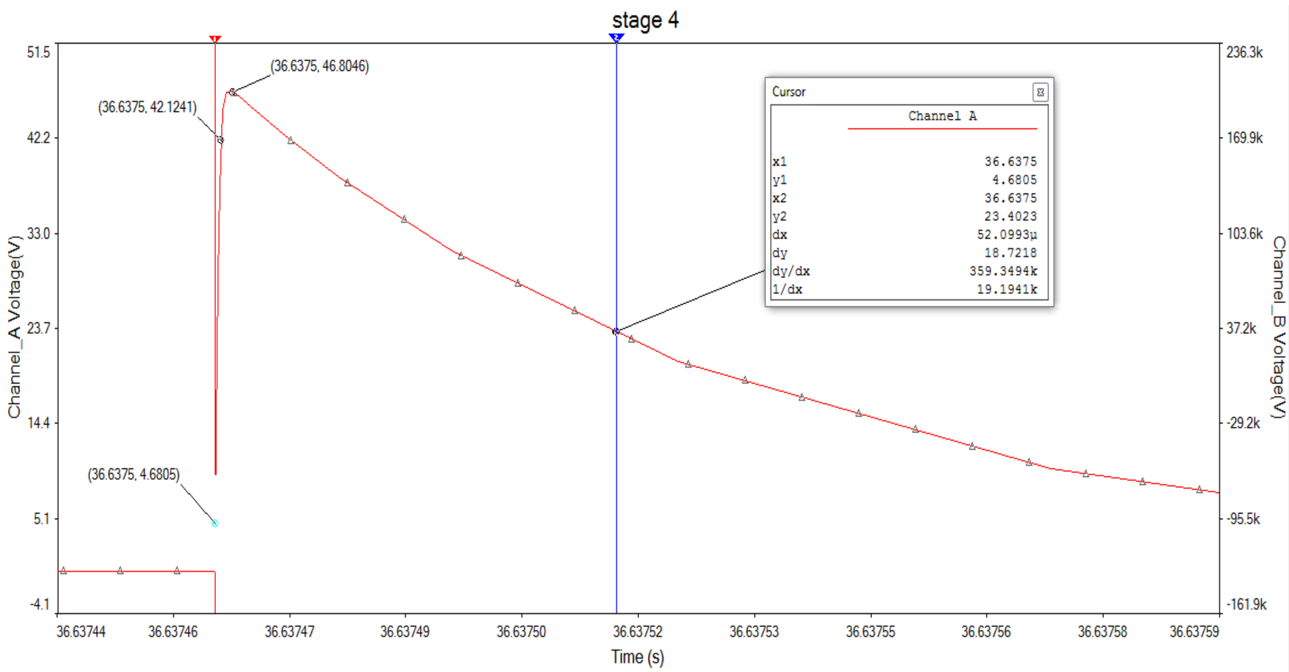

Figure 4.5 Output impulse voltage waveform generated using fourth stage Standard Marx impulse voltage generator circuit.

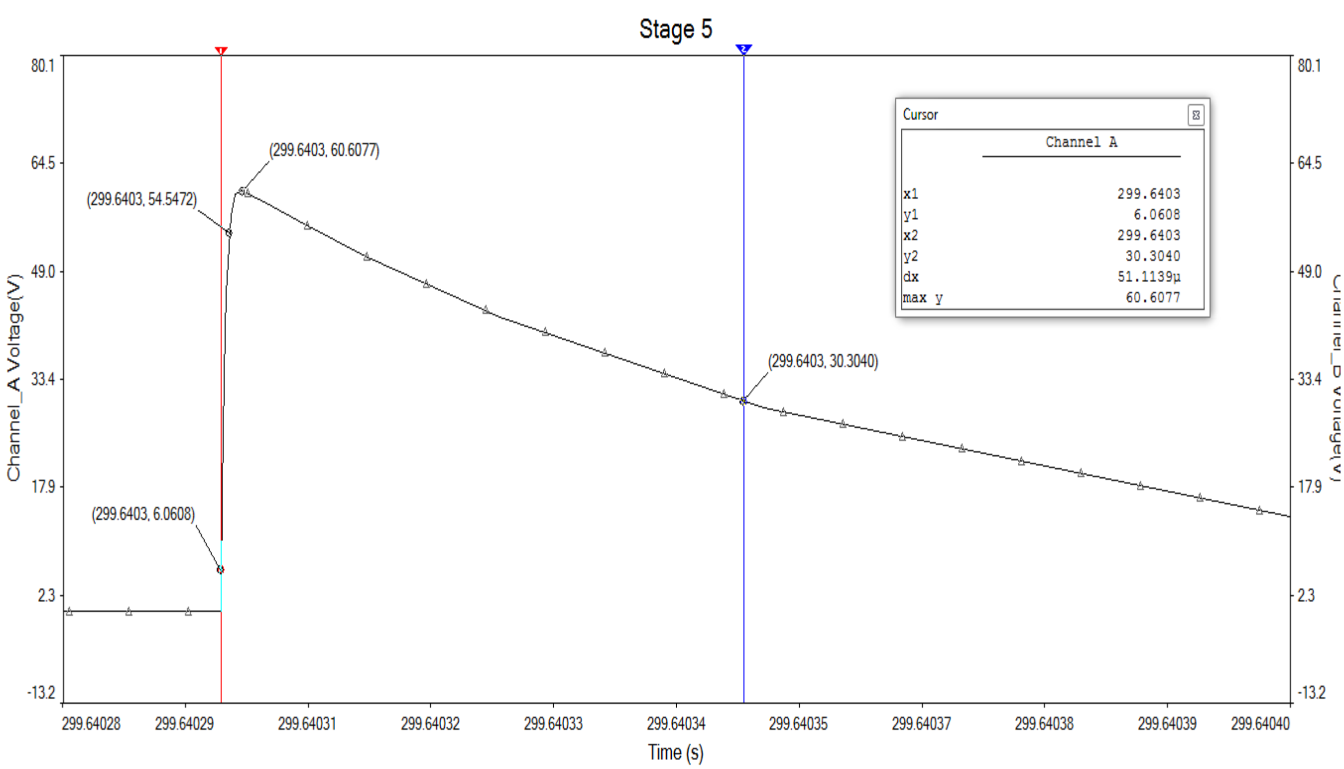

Figure 4.6: Output impulse voltage waveform generated using fifth stage Standard Marx impulse voltage generator circuit.

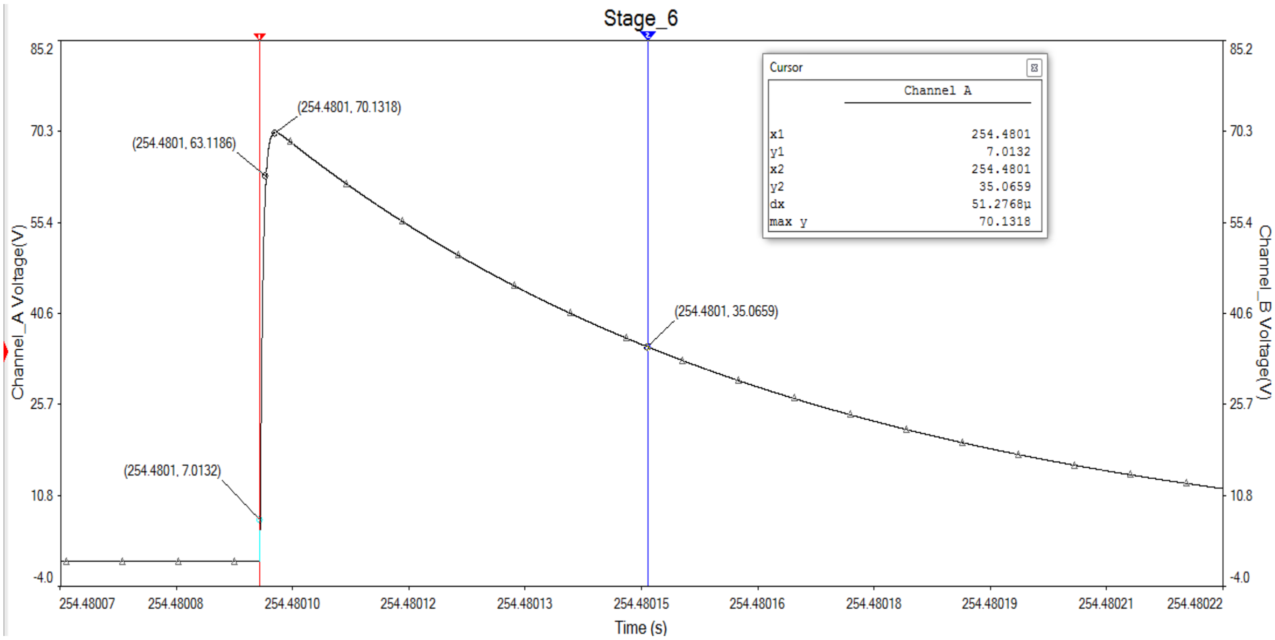

Figure 4.7 Output impulse voltage waveform generated using sixth stage Standard Marx impulse voltage generator circuit.

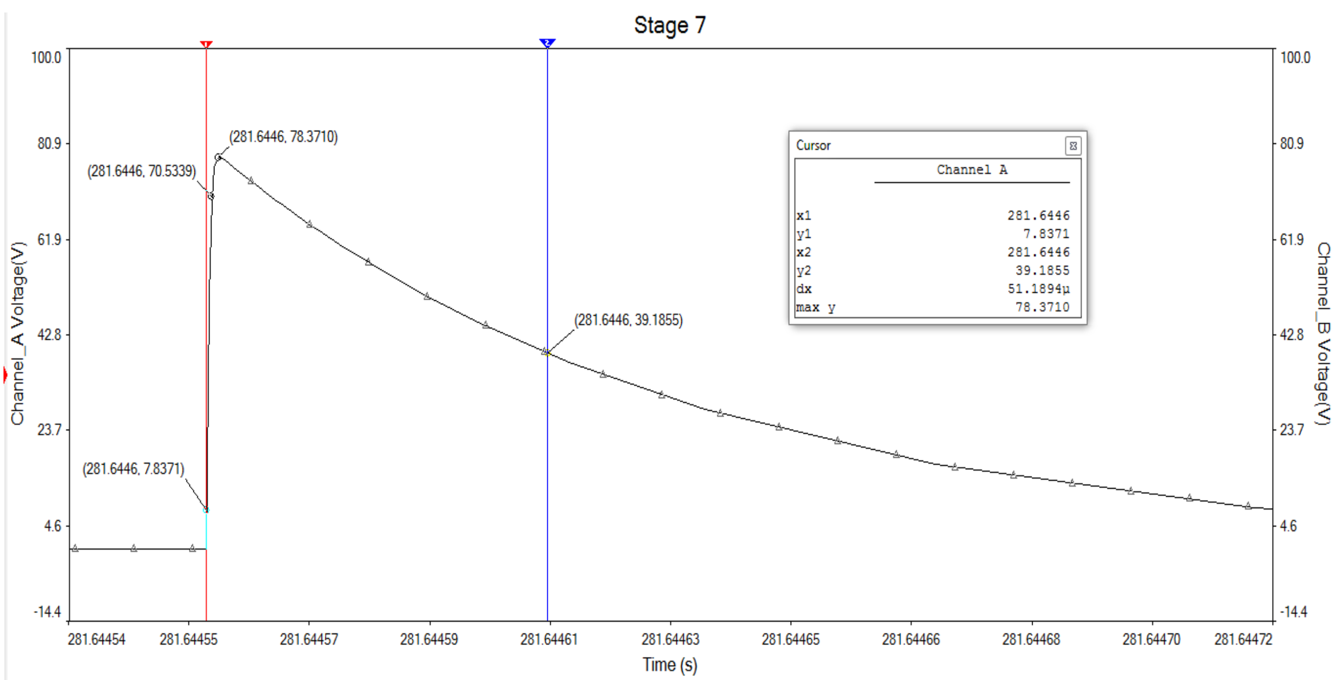

Figure 4.8 Output impulse voltage waveform generated using seventh stage Standard Marx impulse voltage generator circuit.

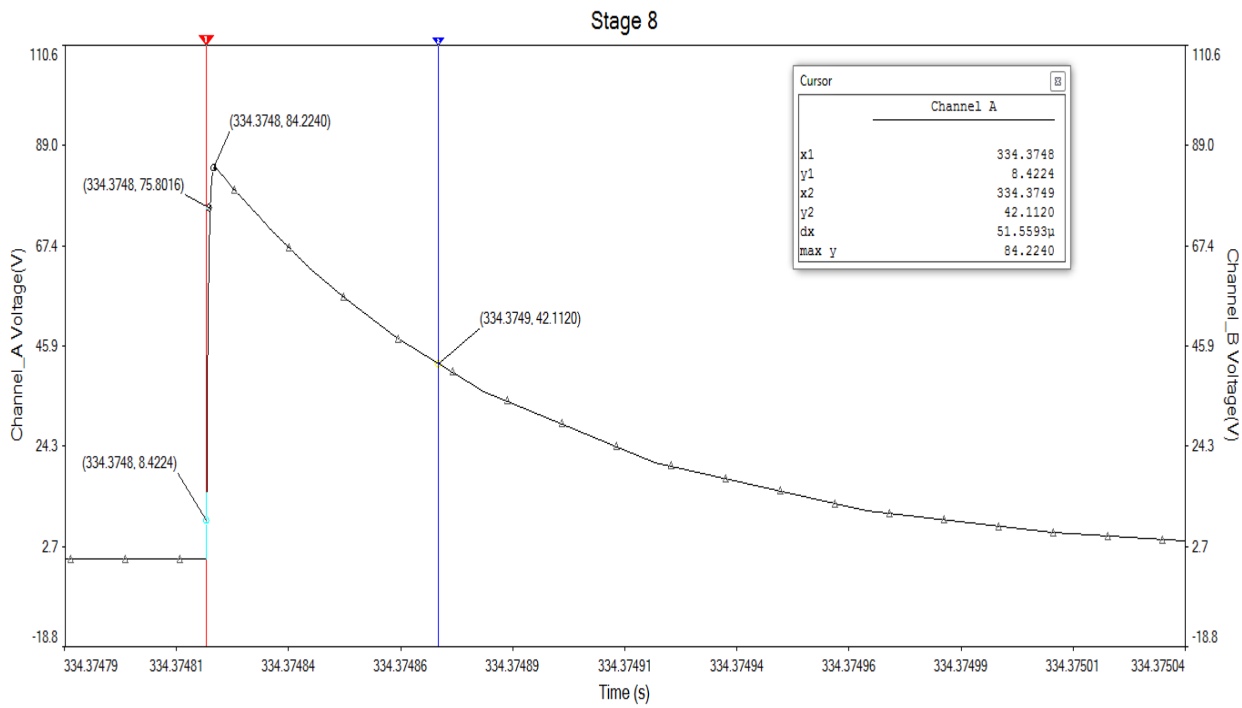

Figure 4.9 Output impulse voltage waveform generated using eighth stage Standard Marx impulse voltage generator circuit.

4.2 Calculation of front time, tail time and error

To get the front time and tail time the circuit is first scaled properly using Grapher window of the Multisim software. The scaling can be done either manually by mouse or by changing the range of the axis in the properties menu. After proper scaling the graph as shown in the fig. 4.1 to 4.8 is obtained. After that the cursor values are put to 90% and 10% of the peak value. This can be done by cursor menu present in the toolbar of the Grapher View window. The parameters to be selected for view in the cursor box can be selected by right clicking the cursor box. The difference obtained (dx) between the peak values are then multiplied by 1.25 to get the rise time. Similarly, tail time can be obtained by taking difference between time taken to reach 50% of the peak value and 10 % of the peak value.

The impulse voltage specifications for all the eight stages have been tabulated as shown in the table below. The allowable tolerances in the calculation of wave front time and fall time are 30% and 20% respectively. The errors obtained in the simulation results have been tabulated.

Standard Marx generator simulation results

Following the above procedure, the values of rise time, tail time and corresponding errors were calculated. The table below shows the results obtained from simulation circuit and calculations for a total of eight stages.

TABLE-III

CALCULATION OF FRONT TIME, TAIL TIME AND ERROR FOR STANDARD MARX IMPULSE VOLTAGE CIRCUIT

Stage	Rise Time (μ second)	Tail Time (μ second)	V_p (volt)	Rise time %error	Fall time %error
1st	0.87	51.15	12.29	16.66	2.6
2nd	0.91	51.78	25.93	16.66	2.6
3rd	0.94	51.26	37.18	16.66	2.6
4th	1.00	51.10	46.80	16.66	2.6
5th	0.93	51.11	60.61	27.08	2.6
6th	0.95	51.28	70.13	16.66	2.6
7th	0.94	51.19	78.37	16.66	2.6
8th	1.00	51.56	84.22	16.66	2.6

4.3 Calculation of energy and efficiency

Using equation (4), the nominal energy stored can be calculated

$$W = ((\frac{C_1}{n}) * V_o * V_o)/2$$

Here V_0 is the nominal maximum DC voltage applied, which is n times the charging voltage. C_1 is the charging capacitor and n is the number of stages. The number of stages, the nominal voltage and the gross energy stored are the most important parameters of Marx impulse voltage generators. The rating of the impulse generator is specified in terms of nominal total voltage, total energy stored and the number of stages.

We can derive the efficiency of Marx Impulse voltage generator by using equations (2) and (3) in terms of peak output voltage, V_p and applied DC voltage, V_o

$$\text{Efficiency} = \frac{Vp}{Vo} \qquad (23)$$

An alternate equation can be given as

$$\text{Efficiency} = \left(\frac{1}{(1+(C_2 \times n)C_1)}\right) \times \left(\frac{1}{(1+\left(\frac{R_1}{R_2}\right)}\right) \qquad (24)$$

Where, C_1, C_2 are the charging and discharging capacitors; R_1, R_2 are the front and tail resistors and n is the number of stages.

The efficiency value remains smaller than 100 percent. As the value of the ratio R_1/R_2 is dependent upon the wave shape, only the simple dependency from C_2/C_1 is lost. For 1.2/50μs impulse voltages and similar the increase in values of R_1/R_2 results in decreased efficiency for C_2/C_1 values less than 0.1. The efficiency has a optimum value at a particular C_2/C_1 value and efficiency decreases for higher C_2/C_1 ratio as well as for the lower values. There can be a failure in circuit if the value of the ratio is very small.

Standard Marx generator energy and efficiency calculations

The energy and efficiency of standard Marx Impulse voltage Generator were calculated by the above mentioned procedure. The peak voltage is obtained from the measurement cursor and the DC voltage is found using the measurement probe.

TABLE-IV

CALCULATION OF ENERGY AND EFFICIENCY FOR STANDARD MARX VOLTAGE GENERATOR CIRCUIT

Stage	V_p (Volt)	Energy (joules)	Efficiency (%)
1st	12.29	1.0728	79.29
2nd	25.93	0.6086	87.19
3rd	37.18	0.4693	82.62
4th	46.80	0.3209	76.67
5th	60.61	0.2414	80.00
6th	70.13	0.1906	77.92
7th	78.37	0.1522	74.64
8th	84.22	0.1240	70.18

CHAPTER 5

Practical Modelling of two Staged Standard Impulse Voltage Generator

Two stage Standard Marx Generator Practical Circuit Model

Analysis of Circuit and Comparison

PRACTICAL MODELLING FOR TWO STAGED STANDARD IMPULSE VOLTAGE GENERATOR

5.1 Two stage standard Marx impulse voltage generator practical circuit model

Practical model of II^{nd} stage standard Marx impulse voltage generator is shown in Figure 5.1. The transformer used for the circuit is a step down transformer of 230V/12V, 5mA. An AC supply of 230 V is provided to the circuit. The charging unit consists of circuit consists of charging capacitor C_1 and C_3 of value 20μF each. Charging circuit also consists of resistors R_3 and R_4 of values 150kΩ each. The discharging unit consists of capacitor C_2 of 0.5μF and wave shaping resistors R_1 of value 0.88 Ω and R_2 of value 12.107Ω.

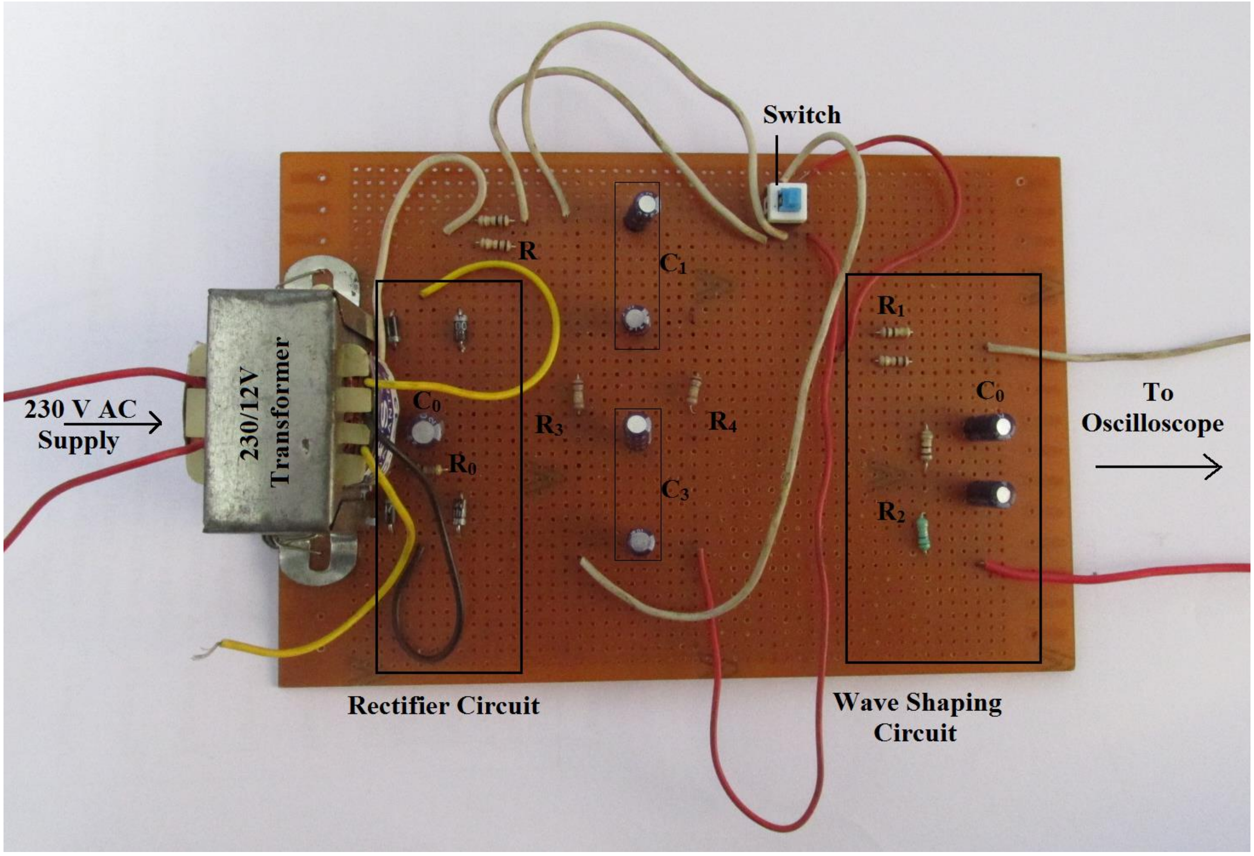

Figure 5.1 II^{nd} stage Marx Impulse voltage generator practical circuit model.

Two IN4007 diodes were used for a full wave rectifier circuit. The output form the full wave rectifier circuit is 19.2 V DC. This DC voltage obtained is then applied to charging capacitors connected in parallel. The sphere gap which is replaced by a six pin switch has two NO (Normal Open) and two NC (Normal Closed) contacts. During charging time the output of the rectifier is connected to the charging capacitors and resistor circuit through a NC contact, which is then toggled to NO to manually trigger the circuit.

By pressing the switch the NO contacts changes to NC contacts and vice versa. So, the capacitors connected in parallel were made to operate in series by pressing the switch. At the same time the DC voltage supply is taken out with the help of the same switch through toggling operation.

The output impulse is detected in the oscilloscope. The front time, tail time and the peak impulse voltage can be measured by setting the cursors. It can also be done by taking the data from the oscilloscope in a .CSV file and with the help of appropriate software the impulse specifications can be calculated. The software that are used normally are MATLAB, R and OriginPro. With the help of these software the graph obtained can be scaled as desired and the measurement can be taken easily on a PC.

5.2 Analysis of circuit and comparison

Two stage Marx generator circuit

The circuit arrangement shown in Figure 5.1 consists of an AC voltage source, a 230/12 V transformer, a full wave rectifier circuit and the charging and wave shaping circuit. The ac voltage supplied by the source is stepped down by transformer to required voltage range. The output obtained from transformer is given as input to the full wave rectifier circuit. The DC output of the rectifier circuit passes to the impulse generating circuit charging the capacitors in parallel and then discharging them in series. This results in voltage output that is several times more than the DC output voltage of the rectifier. Number of stages in the impulse circuit determines the increase of the peak of voltage. In the Figure 5.1, the charging capacitors are shown as C_1 & C_3. These capacitors are first keeping the switch closed. To discharge both the capacitors, the six pin switch is toggled. Series discharge of both the capacitor unit takes place through the wave shaping circuit due to which an impulse wave shape is generated.

Figure 5.2, shows the output waveform of impulse voltage across the capacitor. The output was observed in digital CRO. Then from the csv file saved from the oscilloscope, impulse voltage parameters were calculated.

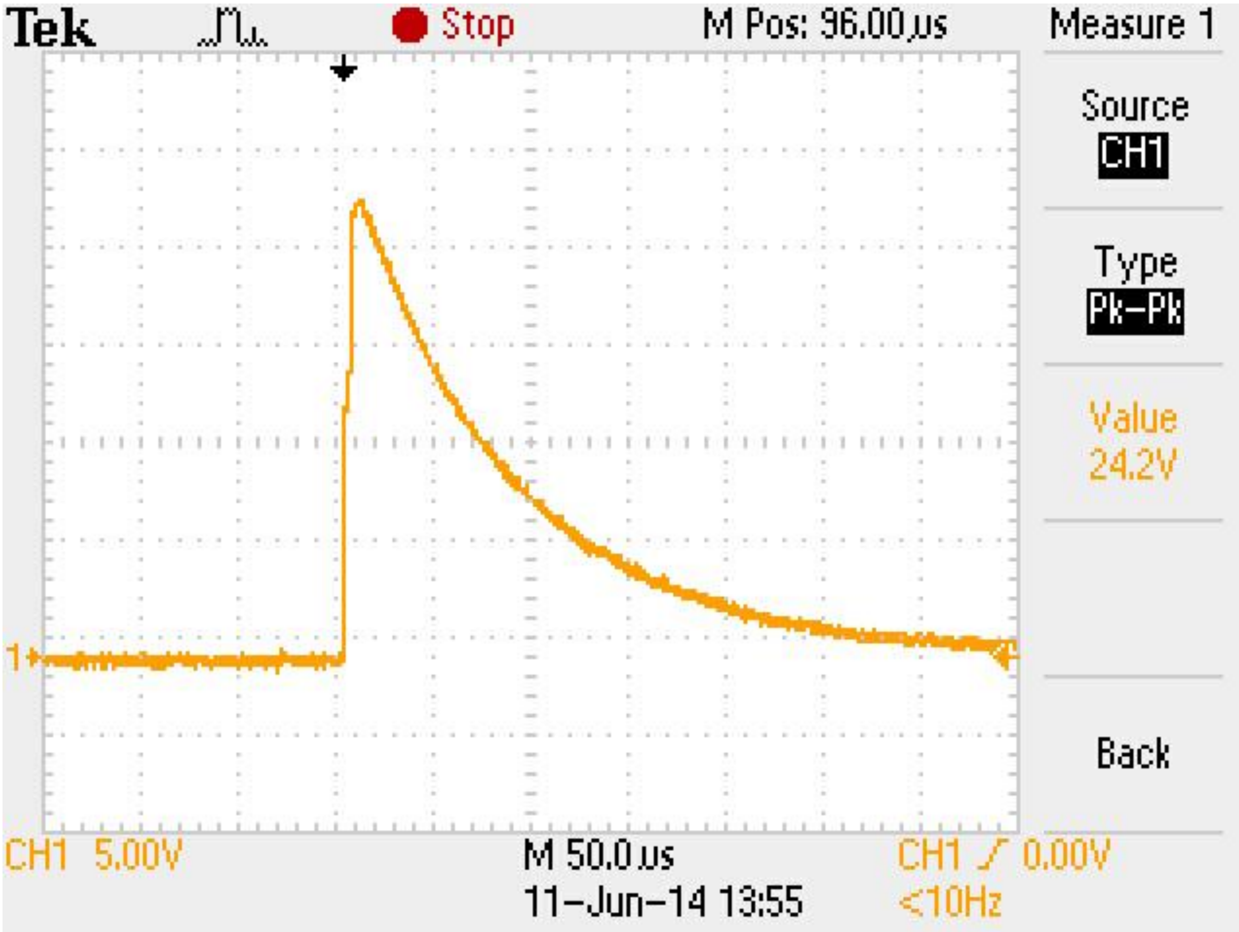

Figure 5.2: Output impulse waveform recorded from CRO for IInd stage Marx impulse voltage generator.

The charging capacitors were charged to about 19 V each and the peak impulse voltage obtained is less than the desired value. As shown in the Figure 5.2., the peak impulse voltage output of the second stage standard Marx impulse voltage generator circuit was found to be 24.2 V .

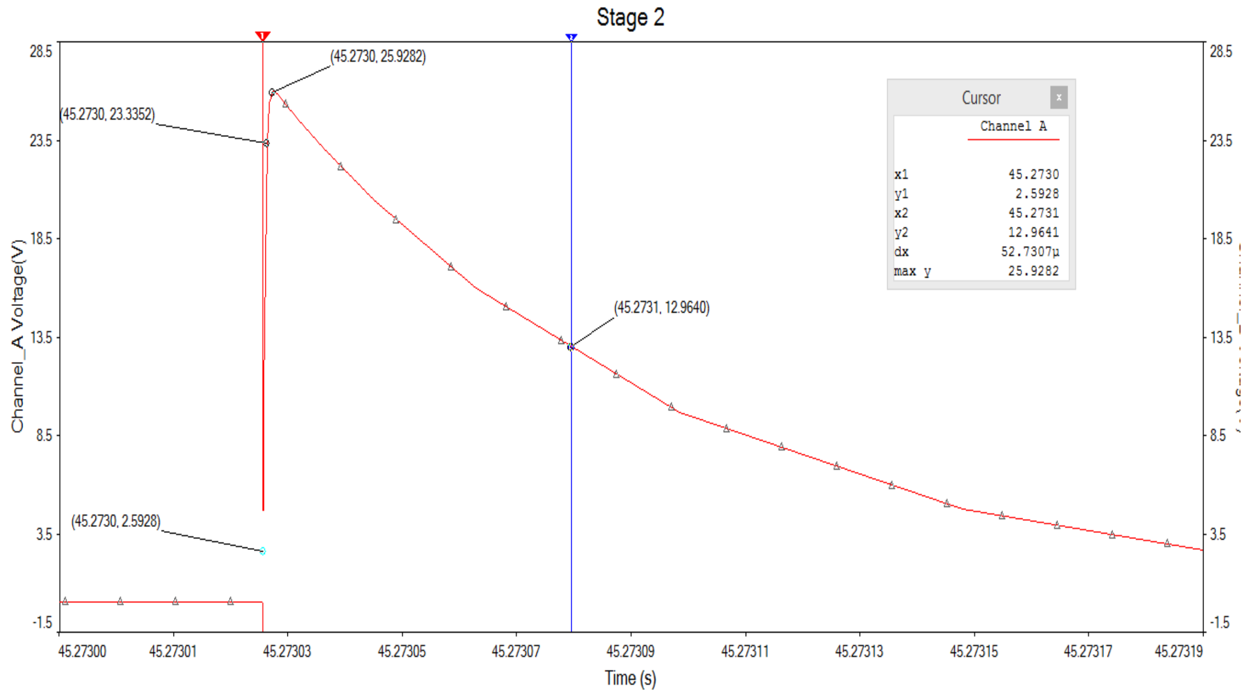

Figure 5.3: Output impulse waveform generated from Multisim for second stage Marx impulse voltage generator.

DC voltage applied in the second stage circuit of standard Marx impulse voltage generator circuit comes out to be 15.5 for each stage. The output peak impulse voltage of 25.9282V is obtained. This value is less than the desired value.

There is an error occurred in obtaining desired output voltage is because the capacitor was not fully charged and presence of the series resistance. The comparison of the results obtained from the practical as well as by the simulation are carried out. The errors in rise time, fall time, peak voltage are shown in Table V. The circuit parameters used in practical and simulation circuit are same. The results were compared so as to know the difference in the values obtained in the practical implementation of the circuit.

The table below compares the results obtained from simulated and practical Marx impulse voltage generator circuit.

TABLE-V

COMPARISON OF RESULTS OBTAINED FROM SIMULATED AND PRACTICAL MARX IMPULSE VOLTAGE GENERATOR CIRCUIT

	Results obtained from Simulated circuit					Results obtained from Practical circuit				
Stage	V_p (Volts)	Rise time(μs)	Fall time(μs)	Error in rise time %	Error in fall time %	V_p (Volts)	Rise time (μs)	Fall time (μs)	Error in rise time %	Error in fall time %
2nd	25.928	1	52.73	16.66	5.46	24.2	1.3	57	8.33	0.14

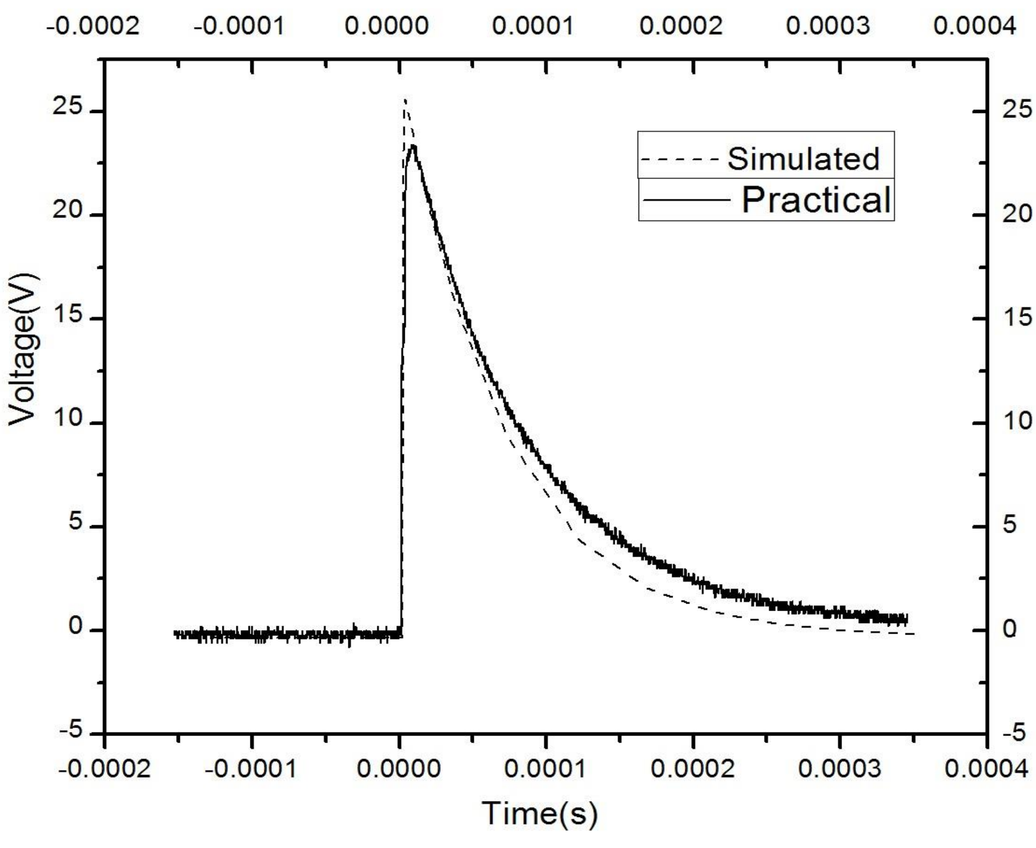

Figure 5.4 Graph comparison of results obtained from simulated and practical Impulse voltage generator circuit.

For both the cases, the information is gathered the plotted wave forms are shown in Figure 5.2 and Figure 5.3. The impulse voltage graphs acquired from the simulated circuit and practical circuit are distinctive because of the exact values of resistance and capacitance utilized. The tolerance characteristics of resistors which are utilized as a part of practical circuit are exactly not the same as those utilized as a part of Multisim and charging the capacitors to maximum voltages in both the practical circuit and the simulation circuit implementation are not the same. Additionally the association of resistors and capacitors in parallel and arrangement gives a rough estimation of what is precisely utilized as a part of simulation likewise adds to the lapses. Because of these parameters contrasts have brought about the two circuits. The ripples created in the rectifier circuit likewise add to the mismatch.

Due to the presence of series resistance in the practical circuit, all the capacitors are not charged to the same value. The output impulse voltage is always less than the gross nominal DC voltage applied. The voltage level can be increased by increasing the number of stages. But in practical applications the voltage obtainable is limited by the effect of series resistance. The effect of resistance can be viewed as the number of stages increase. The change in the peak of impulse voltage becomes lesser as the number of stages increases. This is shown in Figure 5.5, where the simulation results of 5 stages are plotted in a single graph.

Graph comparing different stages of Standard Marx Impulse Voltage Generator

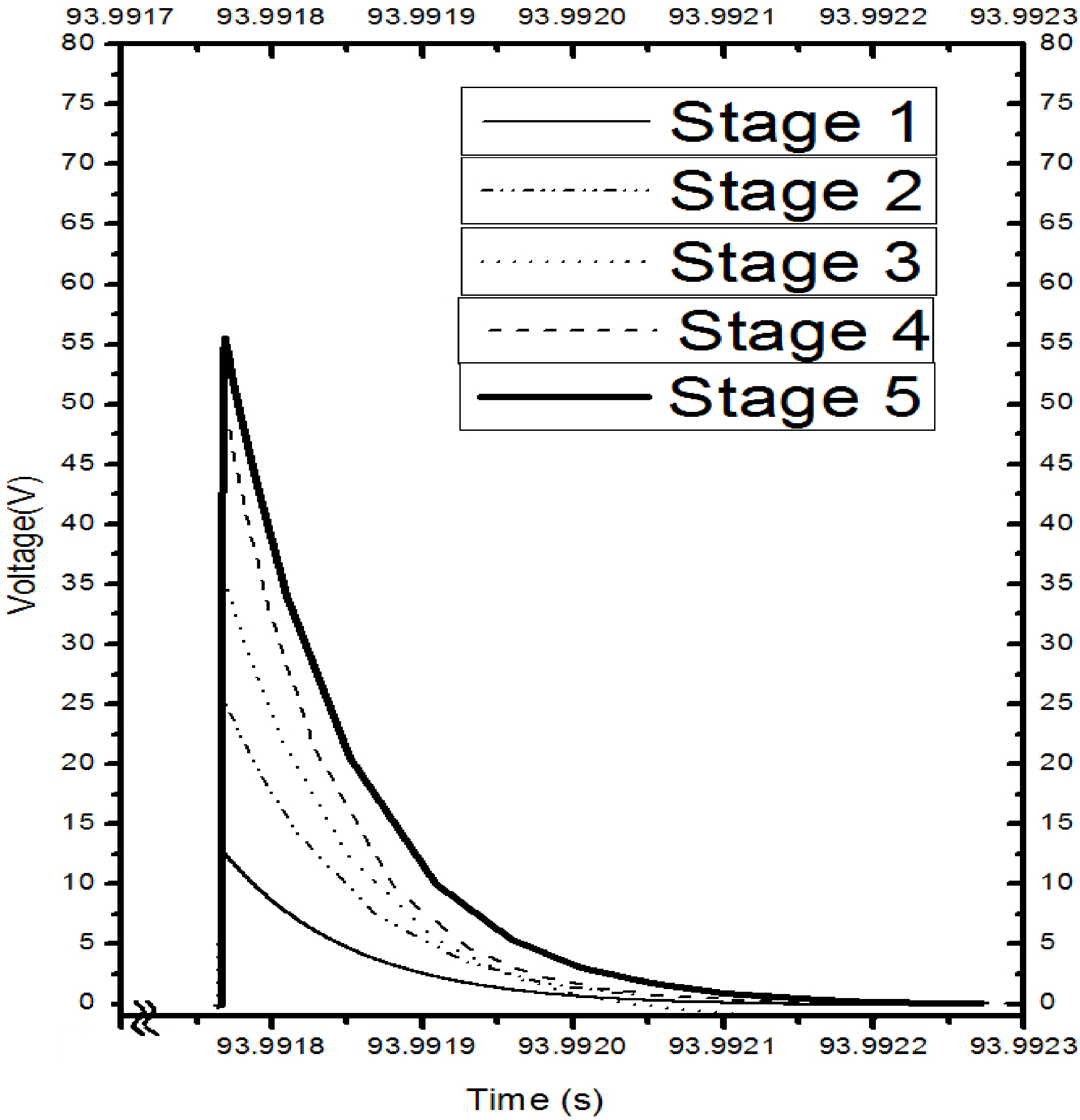

Figure 5.5 Graph comparing different stages of Marx impulse voltage generator circuit

Figure 5.5 shows the increase in the peak of impulse voltage due to increase in the number of stages. As shown in the figure, the peak voltage increased as the number of stages increase. The increase is more at the beginning stages of the impulse generator and as the number of stages increases the change in the peak voltage decreases.

CHAPTER 6

Conclusions

CONCLUSIONS

A prototype of high impulse voltage generator is performed and is based on the simulation results performed in NI Multisim software. The wave shape results are matched for up to eight stages. The practical implementation of two stage Marx impulse voltage generator is made. The simulated result and the practical circuit result are close to the IEC standard wave shape for lightning impulse testing. The ratio between C_1 and C_2 for each stage is taken as 40 and waveforms similar to standard impulse voltage are produced. By varying the values of front and tail resistance in accordance with the ratio. The errors come in the range of allowed standard tolerance levels. Acceptable assumption of replacing a sphere gap with a switch was made.

In this work, the entire circuit is simulated and modelled based on the circuit parameters which were methodically calculated. The calculated parameters and their effect on characteristics of the impulse wave was studied and it was found that by the proper assumptions and the method followed in the work, the standard impulse wave can be generated. The acquired data from the circuit model has also been studied in PC through data processing software origin.

This work can be further extended by making improvements in the circuit through modified Marx circuits which will not only make the design more compact and mobile but also the control over the wave shapes will increase as the resistances are more distributed throughout the circuit. The control of the switch in the circuit can also be done using a PC through proper hardware and software interfaces which will enable instantaneous observation of impulse voltage in a computer.

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