

# DESIGN, MODELING, AND SIMULATION OF MARX GENERATOR

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**Abstract** - : This project shows the development of a reliable and easy to carry compact 11 stages Marx Generator that can produce impulse voltage 11 times of input voltage with some minor losses. This project for generate high voltage DC form Charging and Discharging Capacitor Using MOSFET. This project consists of 11-stages and each stage is made of MOSFETS, diodes and capacitor. Diodes are used to charge the capacitor at each stage without power loss. A 555 timer generates pulses for the capacitors to charge in parallel during ON time. During OFF time of the pulses the capacitors are brought in series with the help of MOSFETS. Finally, number of capacitors used in series adds up the voltage to approximately 11 times the supply voltage. The highest output was above 4KV DC for which input was taken as the 400V for the experimental and simulated Marx generator circuit. This generator is useful in small-scale industries and academic institutions to demonstrate impulse voltages and to perform testing on insulators and transformers of lower rating in laboratory. In this work, the comparison in terms of magnitude of the experimental and simulated 11 stages Marx generator circuit has been carried out.

**Key Words:** High voltage generation, Marx generator, Over voltage trigger

## 1. NTRODUCTION

A Marx generator is a type of electrical circuit whose purpose is to generate a high-voltage pulse by a number of capacitors that are charged in parallel and then connected in series by spark gap switches.

### 1.1 Basics:

A Marx generator is a type of electrical circuit first described by Erwin Otto Marx in 1924 whose purpose is to generate a high-voltage pulse. It is extensively used for simulating the effects of lightning during high voltage and aviation equipment testing. A bank of 36 Marx generators is used by Sandia National Laboratories to generate X-Rays in their Z Machine. It can also be used as an ignition switch for thermonuclear devices.

### 1.2 Principle:

A number of capacitors are charged in parallel to a given voltage,  $V$ , and then connected in series by spark gap switches, ideally producing a voltage of  $V$  multiplied by the number,  $n$ , of capacitors (or stages). Due to various practical constraints, the output voltage is usually somewhat less than  $n \times V$ .

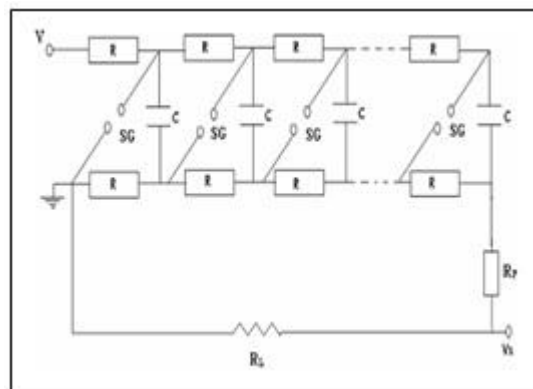


Figure 1. Circuit diagram of Marx Generator

R=Charging Resister

C=Capacitors

V= Input Voltage

$R_L$ =Resistive Load

SG= Spark Gaps

$V_x$ =Output Voltage

$R_F$ =Front Resistor

### 1.3 Optimization:

Proper performance depends upon selection of capacitor and the timing of the discharge. Switching times can be improved by doping of the electrodes with radioactive isotopes cesium 137 or nickel 63, and by orienting the spark gaps so that ultraviolet light from a firing spark gap switch illuminates the remaining open spark gaps. Insulation of the high voltages produced is often accomplished by immersing the Marx generator in transformer oil or a high-pressure electronegative gas such as Sulphur hexafluoride (SF6). Note that the less resistance there is between the capacitor and the charging power supply, the faster it will charge. Thus, in this design,

those closer to the power supply will charge quicker than those farther away. Marx generator diagrams Although the left capacitor has the greatest charge rate, the generator is typically allowed to charge for a long period of time, and all capacitors eventually reach the same charge voltage. If the generator is allowed to charge, long enough, all capacitors will attain the same voltage. In the ideal case, the closing of the switch closest to the charging power supply applies a voltage  $2V$  to the second switch. This switch will then close, applying a voltage  $3V$  to the third switch. This switch will then close, resulting in a cascade down the generator that produces  $nV$  at the generator output (again, only in the ideal case). The first switch may be allowed to spontaneously break down (sometimes called a self-break) during charging if the absolute timing of the output pulse is unimportant. However, it is usually intentionally triggered once all the capacitors in the Marx bank have reached full charge, either by reducing the gap distance, by pulsing an additional trigger electrode (such as a Tigerton), by ionizing the air in the gap using a pulsed laser, or by reducing the air pressure within the gap. The charging resistors,  $R_c$ , need to be properly sized for both charging and discharging. They are sometimes replaced with inductors for improved efficiency and faster charging. In many generators, the resistors are made from plastic or glass tubing filled with dilute copper sulphate solution. These liquid resistors overcome many of the problems experienced by more-conventional solid resistive materials, which have a tendency to lower their resistance over time under high voltage conditions.

## 2. Development of Marx Generator:

### 2.1 Conventional Marx Generator:

#### 2.1.1 Introduction:

The generator capacitance  $C$  is to be first charged and then discharged into the wave shaping circuits. A single capacitor  $C$  may be used for voltages up to 200 kV. For producing very high voltages, a bank of capacitor is charged in parallel and then discharged in series. The arrangement for charging the capacitors in parallel and then connecting them in series for discharging was originally proposed by Erwin Otto Marx in 1923 as shown in Figure 4 Usually the charging resistance is chosen to limit the charging current to about 50 to 100 mA, and the

generator capacitance  $C$  is chosen such that the product CRs is about 10s to 1 min. The gap spacing is chosen such that the breakdown voltage of the gap  $G$  is greater than the charging voltage  $V$ . Thus, all the capacitances are charged to the voltage  $V$  in about 1 minute. When the impulse generator is to be discharged, the gaps  $G$  are made to spark over simultaneously by some external means. Thus, all the capacitors  $C$  get connected in series and discharge into the load capacitance or the test object. The discharge time constant (for  $n$  stages) will be very small compared to charging time constant. Which will be few be very small compared to charging time constant which will be few seconds.

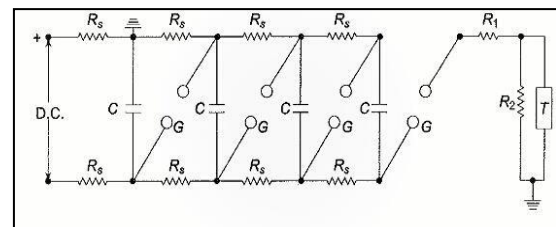


Figure 2. Conventional Marx Generator

#### 2.1.2 Demerits of the conventional Marx circuit as follows:

- Long charging time because the charging current flows through the charging resistors.
- Low efficiency because of the same reason mentioned above.
- Low repetition rate because of the same reason.
- Few output voltage appearances in charging period because the charging current flows through the charging resistors and a load.
- Turn-off is impossible because of using the spark gap switches.
- Short lifetime of the spark gap switches. In order to solve these problems, some new Marx circuits are proposed.

These new improved circuits use semiconductor switches such as MOSFETs or IGBTs.

## 2.2 Modern Marx Generator:

### 2.2.1 Introduction:

With the development of solid-state electronics, solid-state devices are becoming more and more suitable for pulsed power application. They could provide the pulsed power systems with compactness, reliability, high repetition rate and long lifetime. The rising of pulsed power generators using solid-state devices eliminates limitations of conventional components, and promises pulsed power technology to be widely used in commercial applications. However, Solid-state switching devices such as Metal Oxide Semiconductor Field Effect Transistor (MOSFET) available now are only rated up to a few kilo Volts. Previously, it employed spark gaps as switches, which are replaced, by electronic switches such as (MOSFETs) and resistors as isolator is replaced by diodes. Therefore, Convention Marx generator had drawbacks such as low repetition rate, short lifetime; modern Marx generator as shown in below Figure eliminates inefficiency.

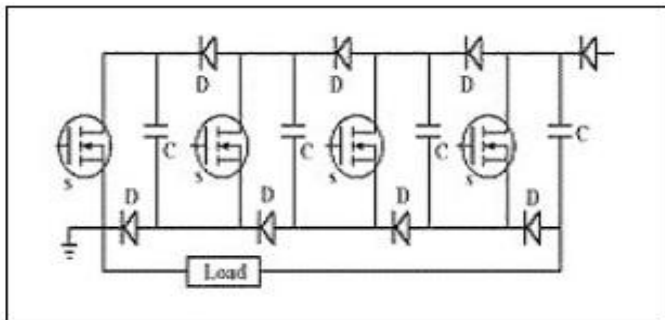


Figure 3. Contemporary Structure of Marx Generator

### 2.2.1 Block Diagram:

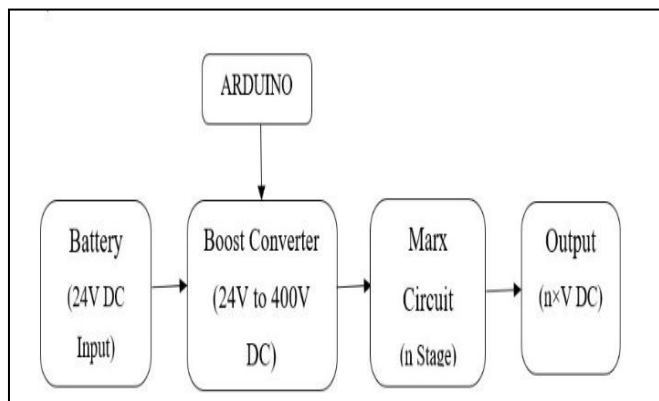


Figure 4. Block Diagram of Marx Generator

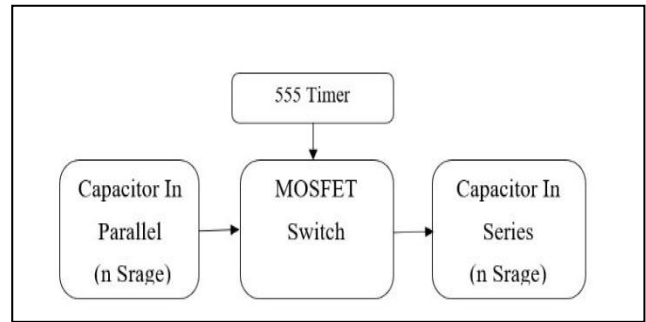


Figure 5. Block Diagram of Marx Circuit

In this project the battery is used as DC input of Boost Converter. The boost converter is boosting the voltage from 24V to 400V by providing Signals from Arduino Then the 400V voltage is input of n-stage Marx Circuit. This project consists of n-stages and each stage is made of MOSFETS, diodes and capacitor. diodes are used to charge the capacitor at each stage without power loss. A 555 timer generates pulses for the capacitors to charge in parallel during ON time. During OFF time of the pulses the capacitors are brought in series with the help of Power Electronics switches. Finally, number of capacitors used in series adds up the voltage to approximately n times the supply voltage.

### 2.2.2 Charge Mode:

In this mode, MOSFETs are at off-state., the high frequency transformer T passes the energy to the secondary winds from a generator of high repetition rates sine voltage. Via the large inductor L and diodes D, the capacitors C in parallel are charged by the high voltage (HV) and high frequency rectify bridge. The large inductor acts as a current limiter and cause boost of the voltage of capacitors.

### 2.2.3 Discharge Mode:

In this mode, MOSFETs turn on simultaneously. Then they are at on-state and, consequently, the capacitors are linked in series. Thus, the load could acquire a negative high voltage which is the sum of the voltage of capacitors. Via MOSFETIGBTs, the capacitors discharge their energy to the load. Diodes take place of resistors as the isolator in conventional Marx generator. Capacitors C, inductor L and diode D compose of another discharge loop. In this mode, the inductor L isolates high output voltage apart from the rectify bridge.

**2.2.4 Demerits of conventional Marx circuit are improved as follows:**

- a) Relatively short charging time because the charging current flows through the diodes instead of the charging resistors.
- b) Relatively high efficiency because of the same reason mentioned above.
- c) n Relatively high repetition rate because of the same reason.
- d) Turn-off is possible because of using the semiconductor switches instead of the spark gap switches.
- e) Long lifetime of the switches.

**3. Design of Marx Generator:**

**3.1 Boost Converter:**

It is the design for given Input Voltage in 11-stage Marx Generator.

**3.1.1 Mathematical Model Calculation:**

$$\text{Basic formula, } \frac{V_o}{V_i} = \frac{1}{(1-D)} \quad (4.1)$$

Where,  $V_o$  = output voltage

$V_i$  = input voltage

D = Duty cycle

Solving for  $V_i = 24$  V and  $V_o = 390$  V

We get D = 94 %

**3.1.2 Specification:**

Necessary boost voltage, the values of component are as under:

Inductor (L) = 120 mH

Capacitor (C) = 12  $\mu$ F

Resistor (R) = 10 K $\Omega$

Duty cycle (D) = 94 %

**3.1.3 Arduino Program:**

```
void setup() {
// initialize digital pin=9 as an output.
pinMode(9, OUTPUT);
}
```

```
void loop() {
digitalWrite(9, HIGH);
delay(940);
digitalWrite(9, LOW);
delay(60);
}
```

**3.2 11-Stage Marx Circuit:**

**3.2.1 Mathematical Model Calculation:**

Basic formula,  $C_{eq} = V_R^0 L \times \Delta \Delta V^T$

Where,  $V_o$  = output voltage

$V_i$  = input voltage

Solving for

$V_i = 400$  V

$V_o = 4400$  V

$\Delta V = 10$  % of  $V_o = 40$  V

$\Delta T = 0.5$  ms

$R_L = 1$  K $\Omega$  put value

in eq. (4.2)

$$V_o \times \Delta V$$

$$C_{eq} = R_L \times \Delta V$$

$$4400 \times 0.5 \times 10^{-3}$$

$$C_{eq} = 1 \times 10^3 \times 440$$

$$C_{eq} = 5 \mu F$$

Basic formula,  $C_i = n \times C_{eq}$ . (4.3)

Where,  $n$  = Number of stage

$C_e$  = Equivalent Capacitance

$C_i$  = Individual Capacitance in each Stage put value in eq.(4.3),

$$C_i = 11 \times 5$$

$$C_i = 55 \mu F$$

### 3.2.2 Specification:

The values of component are as under:

Capacitor (C) = 55  $\mu$ F

Resistor (R) = 1 K $\Omega$

MOSFET = IRFZ44

Diode = 1N4007

This Mathematic Design for Simulation

### 3.2.3 Five Stage Marx Generator:

#### 3.2.3.1 Mathematical Model Calculation:

- Basic formula,  $C_{eq} = V_R^0 L \times \Delta V^T$

Where,  $V_o$  = output voltage

$V_i$  = input voltage

Solving for

$V_i = 12$  V

$V_o = 60$  V

$\Delta V = 10\%$  of  $V_o = 6$  V

$\Delta T = 0.5$  ms

$R_L = 1$  Kohm

Put value in eq. (4.4),

$C_{eq} = VROL \times \Delta VT$

$C_{eq} = 601 \times 0.105 \times 310 \times 6^{-3}$

$C_{eq} = 5 \mu F$

- Basic formula,  $C_i = n \times C_{eq}$

Where,  $n$  = Number of stage

$C_{eq}$  = Equivalent Capacitance

$C_i$  = Individual Capacitance in each Stage Put all value in equation

$C_i = 5 \times 5$

$C_i = 25 \mu F$

#### 3.2.3.2 Specification:

The values of component are as under:

- Capacitor (C) = 25  $\mu$ F
- Resistor (R) = 1 K $\Omega$
- MOSFET = IRFZ44

#### 3.2.3.3 Arduino Program:

```
void setup () {
  pinMode(13, OUTPUT);
  pinMode(10, OUTPUT);
  pinMode(9, OUTPUT);
  pinMode(8, OUTPUT);
  pinMode(7, OUTPUT);
}

void loop () {
  digitalWrite(13, HIGH);
  digitalWrite(10, HIGH);
  digitalWrite(9, HIGH);
  digitalWrite(8, HIGH);
  digitalWrite(7, HIGH);
  delay (2000);
  digitalWrite(13, LOW);
  digitalWrite(10, LOW);
  digitalWrite(9, LOW);
  digitalWrite(8, LOW);
  digitalWrite(7, LOW);
  delay (200);
}
```

This Mathematic Design For Simulation and Prototype Hardware Model.

### 3.3 Simulation of Marx generator:

#### 3.3.1 Boost Converter:

A boost converter (step-up converter) is DC to DC voltage converter that step-up voltage from it input to it output. It is a class of switched mode power have at least two semiconductors, A diode and A MOSFET and contain either Capacitor or inductor else combination of both to store Energy. To reduce voltage ripple, filter made of



capacitor in combination with inductor is used in Boost Converter.

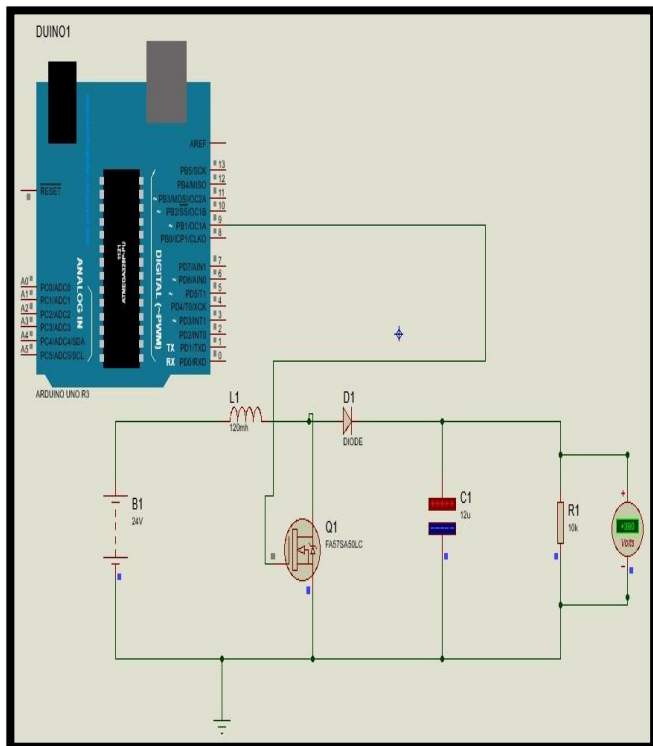


Figure 6. Simulation of Boost Converter

Simulation of boost converter in Proteus, simulation with 24 V DC battery as a input and the Duty cycle of MOSFET is 94 % then the Output voltage is 390 V DC.

### 3.3.2 Timer Circuit:

An Astable Circuit has no stable state - hence the name "Astable". The output continually switches state between high and low without any intervention from the user, called a 'square' wave. This type of circuit could be used to give a mechanism intermittent motion by switching a motor on and off at regular intervals. It can also be used to flash lamps and LEDs, and is useful as a 'clock' pulse for other digital ICs and circuits.

A 555 timer is used Astable mode, i.e., pin 2 and 6 are shorted. 12V input given in pin 8 and output is connected to all MOSFETS.

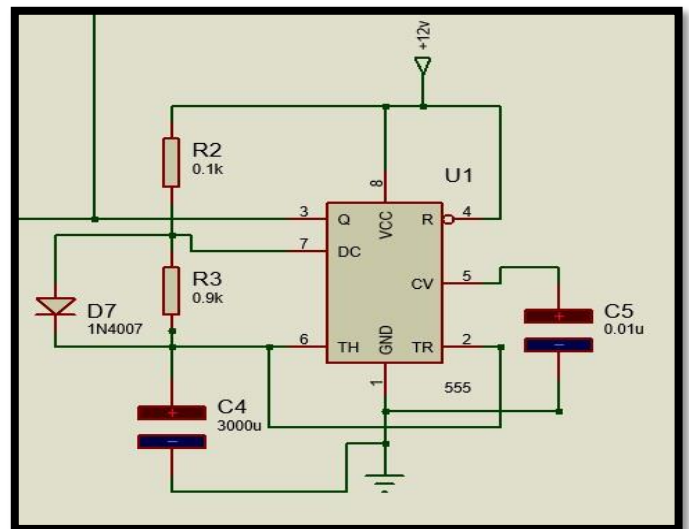


Figure 7. Simulation of 555 Timer Circuit

### 3.4 Marx generator (11 Stage):

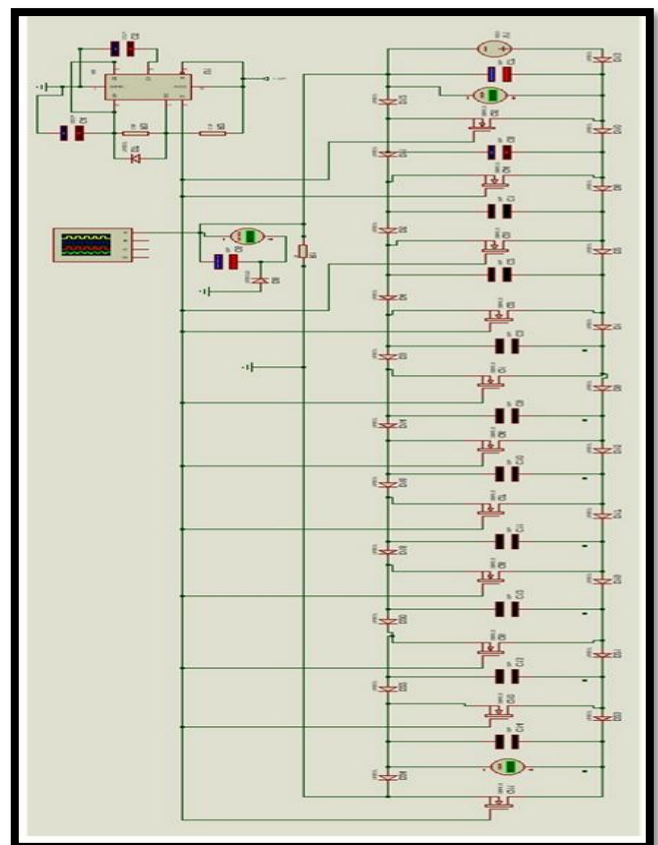
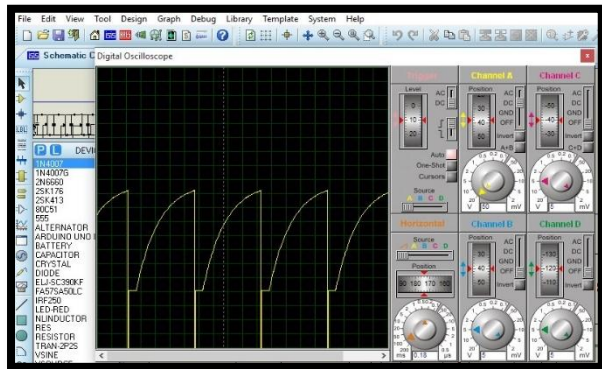


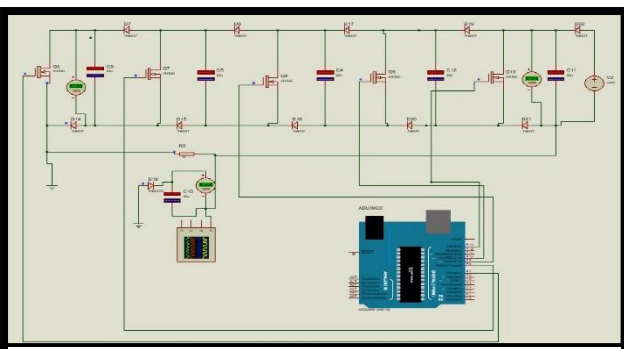
Figure 8. Simulation of 555 Timer circuit

**Simulation Result:**



**Figure 9. Waveform of 11 stage Marx Generator**

The circuit diagram is made by combining all the required circuits that are fixed voltage circuit (390V), 555-timer circuit and MOSFET based 11- stage Marx Generator circuit. This circuit is then simulated on Proteus.

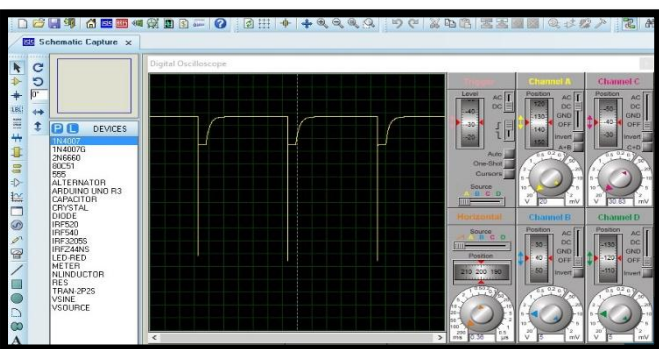


**Figure 10. 5-Stage Marx Generator**

**4. Marx Generator (5 Stage):**

**4.1 Simulation Result of 5 stage Marx Generator:**

The designed circuit diagram is made by combining all the required circuits that are fixed voltage circuit (45V), Arduino Based Pulse Driven Circuit and MOSFET based 11- stage Marx Generator circuit. This circuit is then simulated on Proteus 8 Professional simulation tool, which



**Figure 11. Waveform of 5-stage Marx generator**

is shown in figure 5 Stage Marx generator.

**5. Hardware Design:**

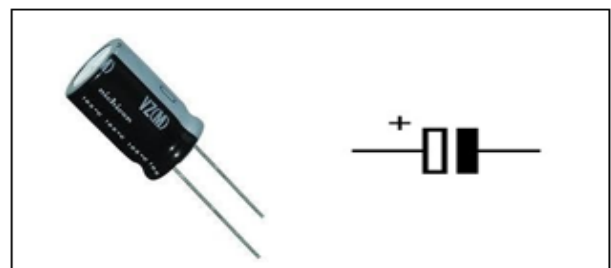
i. List of Component

- a) DC Voltage Source
- b) Capacitor
- c) Diodes
- d) Resister (Load)
- e) MOSFET
- f) 555 Timer
- g) ARDUINO
- h) Resister (Load)

**a) DC Voltage Source:**

In this simulation 24V DC voltage battery used for input voltage and 12V given to 555 timer.

**b) Capacitor:**



**Figure 12. (22µF, 2200µF, 0.01µF)**

capacitor is a device that stores electrical energy in an electric field. It is a passive electronic component with two terminals.

The circuit generates the high voltage pulse by connecting the capacitors in parallel and connecting in the series of capacitors in the circuit. Normally 'N' number of capacitors are charged in parallel to the voltage connected in series. In this operation, the circuit acts as an open circuit when all the capacitors are charged.

**c) Diode (1N4007):**

A diode is a device which allows current flow through only one direction. That is the current should always flow from the Anode to cathode. The cathode terminal can be identified by using a grey bar as shown in the picture above. For 1N4007 Diode, the maximum current carrying capacity is 1A it withstands peaks up to 30A. Hence, we can use this in circuits that are designed for less than 1A. The reverse current is 5uA, which is negligible. The power dissipation of this diode is 3W.

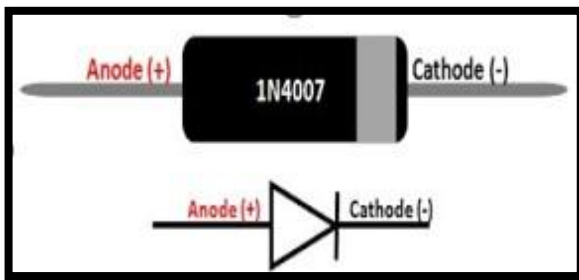


Figure 13. IN4007 Diode

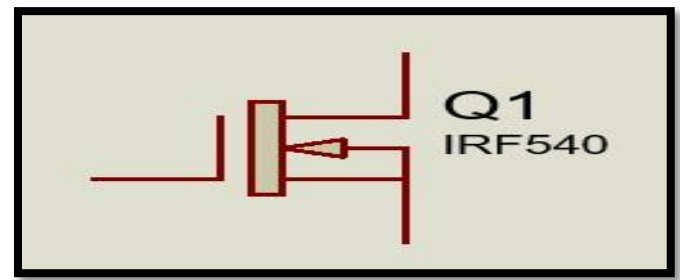


Figure 15. IRF540 MOSFET

Applications of Diode:

- a) Can be used to prevent reverse polarity problem
- b) Half Wave and Full Wave rectifiers
- c) Used as a protection device
- d) Current flow regulators.

**e) MOSFET:**

A metal-oxide-semiconductor field-effect transistor (MOSFET, MOS-FET, or MOS FET) is a field-effect transistor (FET with an insulated gate) where the voltage determines the conductivity of the device. It is used for switching or amplifying signals. The ability to change conductivity with the amount of applied voltage can be used for amplifying or switching electronic signals.

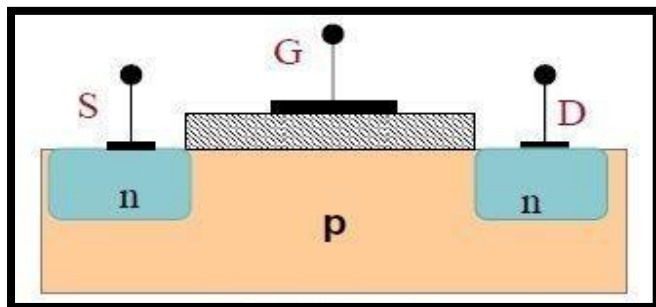


Figure 14. MOSFET Structure

In this project, MOSFET 2N660 and Power MOSFET FA57SA50LC is used.

**IRF540 MOSFET:**

IRF540 is an N-Channel powered MOSFET used for very fast switching operations as well as for amplification processes. It operates in enhancement mode. It has many applications in daily life for example, switching regulators, relay drivers, switching converters, motor drivers, high-speed power switching drivers etc.

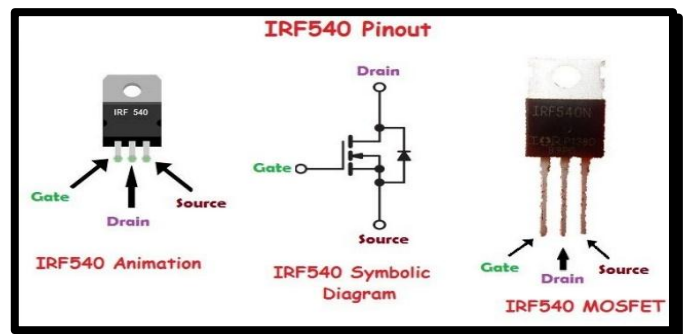


Figure 16. IRF540 MOSFET PINOUT

**f) 555 Timer:**

The 555 timer IC is an integral part of electronics projects. Be it a simple project involving a single 8-bit micro-controller and some peripherals or a complex one involving system on chips (SoCs), 555 timer working is involved. These provide time delays, as an oscillator and as a flip-flop element among other applications.

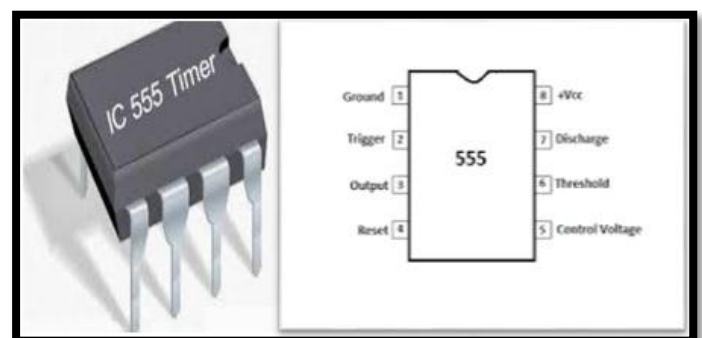


Figure 17. IC555

The standard 555 timer package includes 25 transistors, 2 diodes and 15 resistors on a silicon chip installed in an 8-pin mini dual-in-line package (DIP-8). Variants consist of combining multiple chips on one board.



**Important features of the 555 timer:**

- a. It operates from a wide range of power ranging from +5 Volts to +18 Volts supply voltage.
- b. The external components should be selected properly so that the timing intervals can be made into several minutes along with the frequencies exceeding several hundred kilohertz.
- c. The duty cycle of the timer is adjustable.

**Pin Description:**

Pin	Name	Purpose
1	GND	Ground reference voltage, low level (0 V)
2	TRIG	The OUT pin goes high and a timing interval starts when this input falls below 1/2 of CTRL voltage (which is typically 1/3 V <sub>CC</sub> , CTRL being 2/3 V <sub>CC</sub> by default if CTRL is left open). In other words, OUT is high as long as the trigger low. Output of the timer totally depends upon the amplitude of the external trigger voltage applied to this pin.
3	OUT	This output is driven to approximately 1.7 V below +V <sub>CC</sub> , or to GND.
4	RESET	A timing interval may be reset by driving this input to GND, but the timing does not begin again until RESET rises above approximately 0.7 volts. Overrides TRIG which overrides threshold.
5	CTRL	Provides "control" access to the internal voltage divider (by default, 2/3 V <sub>CC</sub> ).
6	THR	The timing (OUT high) interval ends when the voltage at threshold is greater than that at CTRL (2/3 V <sub>CC</sub> if CTRL is open).
7	DIS	Open collector output which may discharge a capacitor between intervals. In phase with output.
8	V <sub>CC</sub>	Positive supply voltage, which is usually between 3 and 15 V depending on the variation.

**Figure 18. Pin Description of 555 Timer**

**555 timers working:**

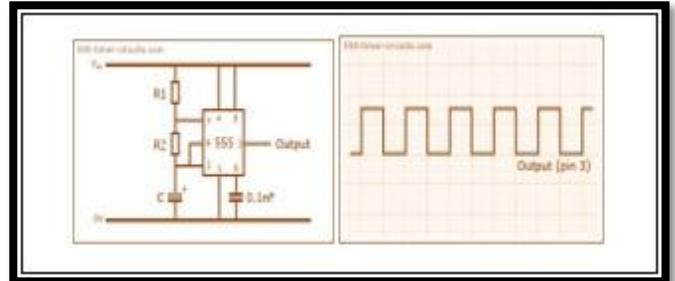
The 555 generally operates in 3 modes:

- a. A-stable
- b. Mono-stable
- c. Bi-stable modes

**a)Astable**

An Astable Circuit has no stable state - hence the name "astable". The output continually switches state between high and low without any intervention from the user, called a 'square' wave. This type of circuit could be used

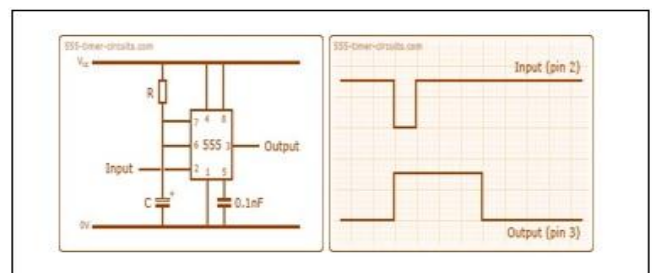
to give a mechanism intermittent motion by switching a motor on and off at regular intervals. It can also be used to flash lamps and LEDs, and is useful as a 'clock' pulse for other digital ICs and circuits.



**Figure 19. Circuit Diagram and Waveform of Astable Mode**

**B. Monostable**

A Monostable Circuit produces one pulse of a set length in response to a trigger input such as a push button. The output of the circuit stays in the low state until there is a trigger input, hence the name "monostable" meaning "one stable state". This type of circuit is ideal for use in a "push to operate" system for a model displayed at exhibitions. A visitor can push a button to start a model's mechanism moving, and the mechanism will automatically switch off after a set time.



**Figure 20. Circuit Diagram and Waveform of Monostable Mode**

**C. Bistable (or Schmitt Trigger)**

A Bistable Mode or what is sometimes called a Schmitt Trigger, has two stable states, high and low. Taking the Trigger input low makes the output of the circuit go into the high state. Taking the Reset input low makes the output of the circuit go into the low state. This type of circuit is ideal for use in an automated model railway system where the train is required to run back and forth

over the same piece of track. A push button (or reed switch with a magnet on the underside of the train) would be placed at each end of the track so that when one is hit by the train, it will either trigger or reset the bistable. The output of the 555 would control a DPDT relay which would be wired as a reversing switch to reverse the direction of current to the track, thereby reversing the direction of the train.

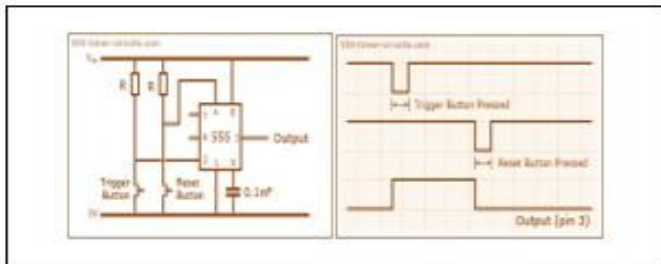


Figure 21 Circuit Diagram and waveform of Bistable Mode

## 6. Arduino

Arduino Uno is a microcontroller board based on 8-bit ATmega328P microcontroller. Along with ATmega328P, it consists other components such as crystal oscillator, serial communication, voltage regulator, etc. to support the microcontroller. Arduino Uno has 14 digital input/output pins (out of which 6 can be used as PWM outputs), 6 analog input pins, a USB connection, A Power barrel jack, an ICSP header and a reset button.

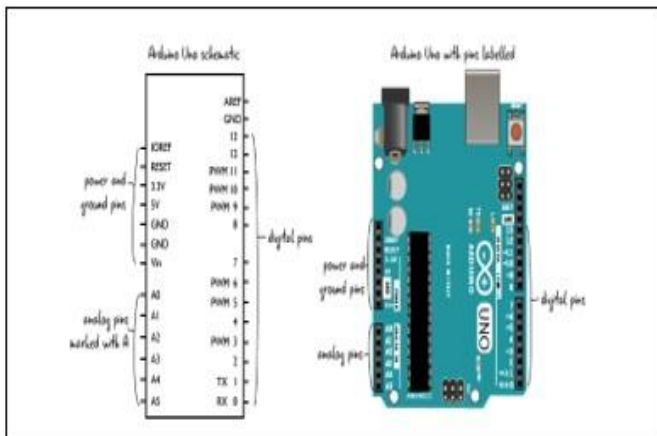


Figure 22. Arduino uno (With Pin Diagram)

### 6.1 Applications

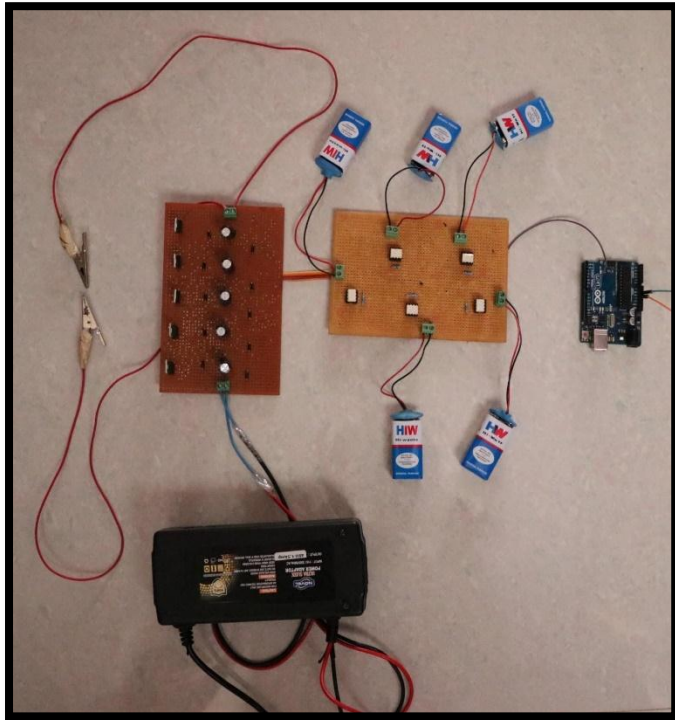
- Prototyping of Electronics Products and Systems Multiple DIY Projects.
- Easy to use for beginner level DIYers and makers.
- Projects requiring Multiple I/O interfaces and communications.

### 6.2 Pin Description

Pin Category	Pin Name	Details
Power	Vin, 3.3V, 5V, GND	Vin: Input voltage to Arduino when using an external power source. 5V: Regulated power supply used to power microcontroller and other components on the board. 3.3V: 3.3V supply generated by on-board voltage pain regulator. Maximum current draw is 50mA. GND: ground pins.
Reset	Reset	Resets the microcontroller.
Analog Pins	A0- A5	Used to provide analog input in the range of 0-5V
Input/output Pins	Digital Pins 0 - 13	Can be used as input or output pins.
Serial	0(Rx), 1(Tx)	Used to receive and transmit TTL serial data.
External Interrupts	2, 3	To trigger an interrupt.
PWM	3, 5, 6, 9, 11	Provides 8-bit PWM output.
SPI	10 (SS), 11(MOSI), 12 (MISO) and 13 (SCK)	Used for SPI communication.

Figure 23. Pin Description of Arduino

## 7. Prototype Hardware



**Figure 24. Prototype Hardware of Marx Generator**

In Shown figure 24 is the prototype hardware of MOSFET based 5 stage Marx Generator 48V

Input Voltage Given by SMPS module and the MOSFET Pulse Given By Arduino through MOSFET Drive Circuit. The output of 5-stage Marx Generator is the form of Spark between Spark gape.

### Conclusion:

Solid state Marx generator is more compact and offers simplicity in controlling the pulse width as compared to conventional spark gap switch. In this type of Marx generator, we have change traditional resistor and spark gap circuit into diode and MOSFET circuit so, by using this diode and MOSFET we can reduce the operation time of Marx generator and also the efficiency of the generator will increase. And on the input side of solid state Marx generator we have placed the boost converter to convert input voltage of 24 volt in to 400 volt so, by that we can also able to reduce the stages of the Marx generator so, the cost of the generator will reduced and also in future if any fault happen then we can easily find the location of it.

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