Design and Experimental Analysis of a Cascaded Voltage Multiplier for High Voltage Testing

Goru Radhika[1]*, Dr. M. Suryakalavathi[2], D. Rohith kumar[3]

[1]*Senior Assistant Professor, Dept. of EEE, VNR VJIET, Hyderabad, India*
[2]*Professor, Dept. of EEE, JNTU Hyderabad, India*
[3]*Engineer. Mindtree, Hyderabad, India*
*Corresponding author E-mail:radhika_g@vnrvjiet.in

Abstract

This paper highlights the details of the Voltage Multiplier circuit and expresses the technical aspects of the circuit in detail. This circuit has the capability to produce a 12kV High Voltage DC output from a conventional 230-volt AC supply. This circuit is essentially a Cascaded Voltage Multiplier, designed to multiply the output by 8 times the input voltage from the power supply in series with a step-up transformer. The circuit can generate energy in the range of kilo joules which can be used for the testing of high voltage equipment.

Keywords: *Capacitor Bank; High Voltage Diodes; Neon Sign Transformer; Resistor Bank; Spark Gap*.

1. Introduction

The voltage multiplier circuit is essentially known as Cockcroft–Walton (CW) generator or multiplier. It can generate a high DC voltage from a low voltage AC input. This generator was named after physicists John Douglas Cockcroft and Ernest Thomas Sinton Walton. In 1932, this circuit design was used to power their particle accelerator, performing the first artificial nuclear disintegration in history and for most of their research. They won the Nobel Prize in Physics in 1951 for their design and demonstration about transmutation of nuclei and sub atomic particles and this was later known as splitting the atom.

Cockcroft-Walton generators find applications in particle accelerators and high voltage equipment like x-ray machines, television sets and photocopiers [8], [9]. They also find applications in low rating equipment like oscilloscopes in laboratories, cathode ray tubes, as amplifier circuits in displays. They find use in in military as night vision and missile guidance systems. This wide range of applications open possibilities into testing high voltage equipment like insulators for dielectric strength and transmission line cables for their leakage reactance. The current paper details the mathematical model and suitability of the circuit for testing high voltage equipment.

2. Circuit description and operation

A voltage multiplier circuit works on the principle of rectification and is an extension of a voltage doubler circuit. For the current setup a series of 4 stages are connected to complete the circuit and hence the name "cascaded".
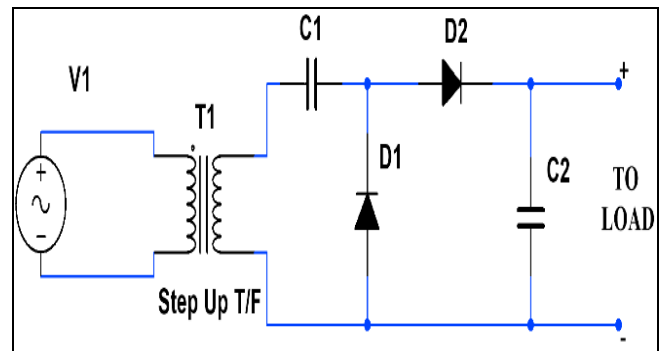

Fig. 1: Voltage Doubler Circuit

During a negative half cycle the condenser C_1 is charged through rectifier D_1 to a voltage of V_{1max}. As the voltage of the transformer rises to V_{1max} during the positive half cycle, the potential of the other capacitor C_2 rises to a voltage of V_{1max}. Thus, the condenser C_2 in turn is charged through D_2 and the available potential across the terminals is $2V_{1max}$ [1].

The available output voltage on load will generally be less than $2V_{1max}$ due to the time constant of the circuit depending on load resistance. The rectified output is stored in the capacitor in one half cycle and in the next half cycle, an output double of the input potential appears across the single stage. The input when taken across multiple stages of the circuit produces huge output which is a multiple of the AC input Value. For higher output potential of $2n$ times the input voltage V_1, the circuit is repeated with a cascaded connection. Thus, a condenser C_{2n} at a nth stage will charge to a potential of $2nV_{1max}$ above ground [1], [5].
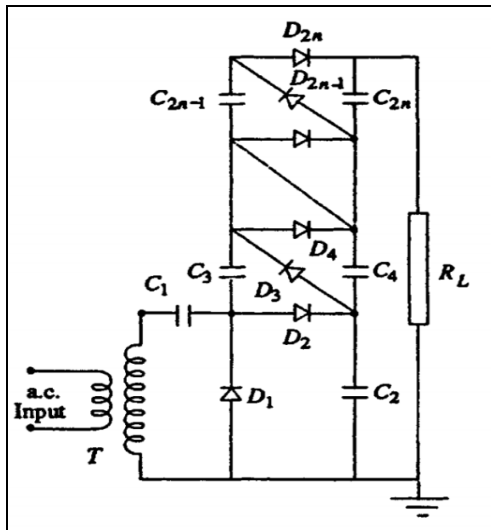
Fig. 2: Cascaded Voltage Multiplier Circuit

3. Design and construction

3.1. Neon sign transformer

Neon sign transformer has a high step-up ratio. The secondary has a significant impedance due to neon gas, because it takes a high voltage to get the gas ionized and after that the transformer operates with a fixed current at a much lower voltage. They do not allow the flow of reverse current in case of any short circuit. This makes it very suitable for use in Voltage Multiplier circuit. The transformer rating used for the current setup is a 450VA, 7.5-0-7.5kV at 60mA rated current for center tapped configuration.

Fig. 3: Neon sign transformer

3.2. Diodes

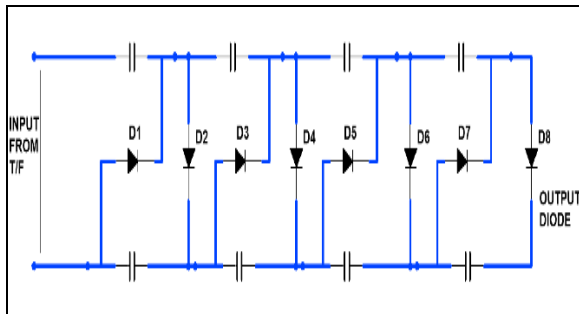The chosen diodes are of model ESJA53-16, PIV of 16kV diodes with a peak forward current rating of 500mA [7].

Fig. 4: Arrangement of diodes in the circuit

The diodes aid in the charging of the capacitors and prevent charge loss in the capacitor charge cycles. The reverse blocking capability of the diode is important, and the diodes are chosen such that their Peak Inverse Rating (PIV) is always greater than or equal to twice the input voltage from the transformer. [1], [3].

3.3. High voltage probe

A high voltage probe is used to measure very high voltages by reducing the input voltage to a safe, measurable level with a precision voltage divider circuit within the probe. This probe can then be connected to an ordinary voltmeter for measurement. In order to measure the output of the voltage multiplier circuit, this probe is used to step down the voltage to a measurable value. The probe has a step-down ratio of 1000:1

Fig. 5: High Voltage Probe

3.4. Voltage divider

The values of the resistor are designed like that of the high voltage probe detailed in section 3.4, for obtaining a measurable output across CRO.
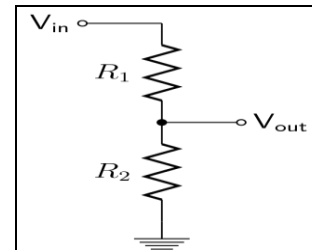

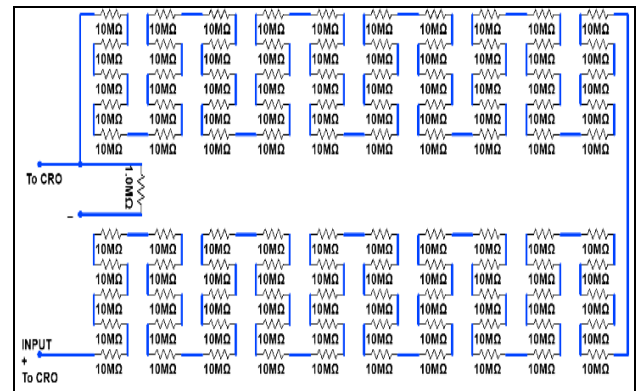**Fig. 6:** Illustration of a voltage divider

Fig. 7: Design of a resistive voltage divider

In Fig 6. The current in both resistors is same, hence,

$$\frac{V_{in}}{R_1 + R_2} = \frac{V_{out}}{R_2} \tag{1}$$

Therefore, the output Voltage across the second resistor is

$$V_{out} = V_{in} \cdot \frac{R_2}{R_1 + R_2} \tag{2}$$

In Fig 7. The voltage divider is designed such that,

$$R_1 = 988M\Omega, R_2 = 1M\Omega \tag{3}$$

$$R_1 + R_2 = 989 \ M\Omega \tag{4}$$

If the theoretical Input Voltage from the circuit to the resistor bank is V_{in}= 12kV then the corresponding output voltage would be V_{out}= 12.133V.

3.5. Spark gap

A spark gap is an arrangement of two conducting electrodes separated by a gap which is filled with a gas such as air in the current setup and is designed to allow an electric spark to pass between the electrodes when the voltage difference between the electrodes exceeds the breakdown voltage of the gas.

Fig. 8: Spark gap

The amount of charge held in the circuit is very high during the functioning of the circuit. To prevent damage to the circuit by directly discharging through ground wire, a spark gap is connected to the circuit across the last stage and ground. In this way, the entire charge is discharged through the gap in the form a spark without affecting the circuit components.

3.6. Current limiting resistor

The charge held in the circuit corresponds to a voltage of 12kV. When discharge takes place through the resistor bank during measurement, the current is about 12µA, when the circuit is discharged through spark gap the resistance offered is almost zero. Assuming a 1kΩ resistance offered by the spark gap the current through the terminals of the circuit rises instantaneously to I = V/R = 12kV/1kΩ = 12A. This huge current rise will instantaneously damage the diodes connected in the circuit.

Fig. 9: Spark gap with resistor to limit current in the circuit

For this reason, a resistance of 10MΩ is placed in series with the spark gap as shown in Fig 9. This acts as a current limiting resistor and the resistance offered by the circuit when grounded with a wire is quite higher than 10MΩ and the circuit takes a very long time to discharge completely. This current limiting resistor of rating 10MΩ/2W protects the diodes from any damage.

3.7. Capacitor bank

Film capacitors of rating 2µF, 2kV, are used to create a bank of 4 capacitors of rating 2µF, 4kV, with an instantaneous rating of 500V/µsec [6]. This comprises of one half of the first stage. Similar units are arranged on the circuit to create the required 4 stage circuit. The capacitance of each stage of the capacitor bank is verified with an LCR Meter and the appropriate values are fed into the simulation for obtaining the output. The voltage rating of the capacitor is a very important factor in the design of the circuit and chosen such that it is charged up to 80% of its rated voltage [10].

This implies that a 4kV capacitor bank can be charged to an optimum voltage of 3.2kV and therefore the input supply will be fixed at a maximum of 1.6kV to obtain a $2V_{max}$ output.

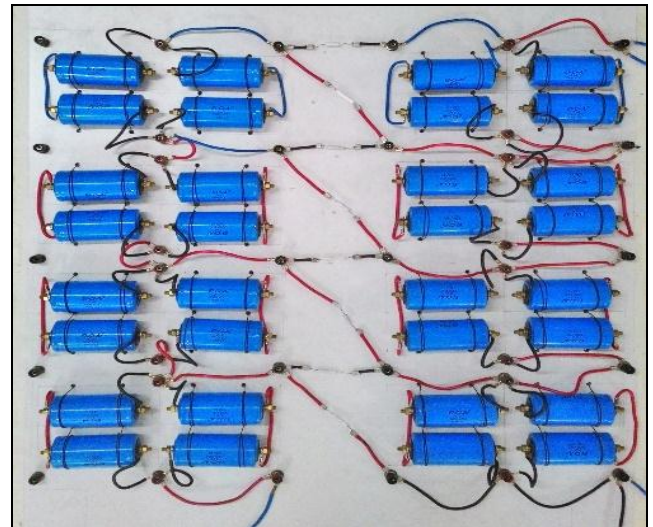**Fig. 10:** Capacitor Bank- four stage setup for 4µF, 4kV

4. Modes of operation

Mode 1- Power Frequency operation

This is normal power frequency level of 50Hz ac supply input. The voltage regulation of the circuit is quite poor, and the output voltage drops rapidly and maintains a steady state after this drop.

Mode 2- High Frequency operation

This mode of operation is at a very high frequency of about 250 kHz. The voltage regulation of the circuit in this mode is good and the average output voltage is very close to the theoretically estimated value. The circuit supports this high level of frequency as the capacitors have a maximum rate of rise of voltage limit of 500V/µsec. With an input of 1.6kV at a high frequency of about 250 kHz, implies the rate of rise of voltage value is at 400V/µsec [6]. Hence, for optimum functioning of the circuit the input voltage can be between 1kV to 1.6kV with high frequency from 1 kHz to 250 kHz.

5. Mathematical modelling

The circuit is currently tested at power frequency level with a planned testing at high frequency from 1 kHz to 250 kHz at the same rated input of 1.6kV.
Theoretical input voltage to the circuit 1.6kV= V_{max}
So, the single stage output is $2V_{max}$ = 3.2kV.
Therefore, For a 4 Stage circuit,

The output voltage = $2nV_{max}$ (5)
$$= 2*4*1.6kV = 12.8kV$$

Ripple Calculation:

The Maximum load current from the circuit is I = $\frac{V_{in}}{R}$ (6)
$$= \frac{12.8\,kv}{989M\Omega} = 12.942µA$$

The Ripple voltage δV from each stage is δV = $\frac{I}{fC}$ (7)

Where, f = Frequency of input supply = 50 Hz
C = Capacitance of arrangement measured from the LCR meter

= 1.9µF

$$= \frac{12.942\mu}{50 \cdot (1.9\mu)} = 0.136V$$

Ripple voltage for the four stage circuit [2]

$$\delta V_{total} = \frac{n\,(n+1)}{2}(\delta V) = 1.362V \qquad (8)$$

The Voltage drop across the output of the circuit

$$\Delta V = \delta V\,[(2/3).\,n^3 + n^2/2 - n/6] = 0.136 * 50 \qquad (9)$$
$$= 6.8V$$

The available total output voltage is $2nV_{max}$ - ΔV = 12.79kV.
The theoretical maximum energy output for one minute

$$E_{max} = 2.n.\,V_{max}.I_{max}.t \qquad (10)$$
$$= 12.79kV.\,30mA.\,60secs = 23kJoules$$

I_{max} = Maximum loadable current from the NST in mid-point configuration = 30mA.

6. Simulation and calculations

The Simulation is done in Powersim 9 software. Circuit is developed in Multisim 12 and the practical circuit is verified for waveform comparison. The output voltage from the circuit is taken across the oscilloscope and the reading is reduced by a factor of 1/989 from (3) and (4). This reduced value is obtained in the oscilloscope in the range of mV to Volts.
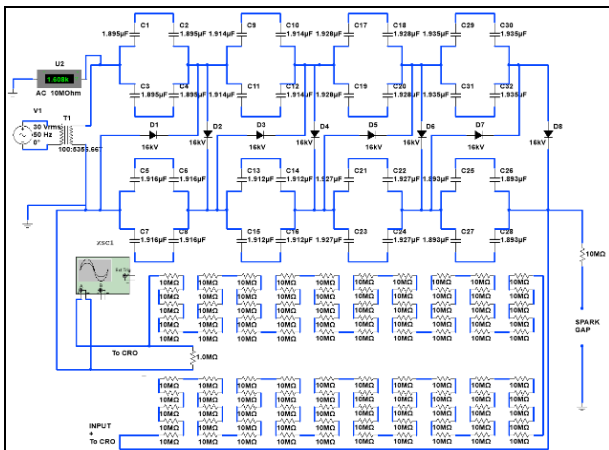

Fig. 11: Simulation Circuit of the four-stage setup in lab

The actual output from the circuit can be obtained as discussed earlier in resistive voltage divider circuit.
Where,

$$V_{in} \text{ or } V_{actual} = V_{out} \text{ or } V_{meas} * \frac{R_1}{R_1+R_2} \qquad (11)$$
$$= V_{out} * \frac{1M\Omega}{988M\Omega + 1M\Omega}$$

V_{out} = Voltage across the oscilloscope
V_{in} = Voltage available at the circuit.

6.1. Waveforms and observations
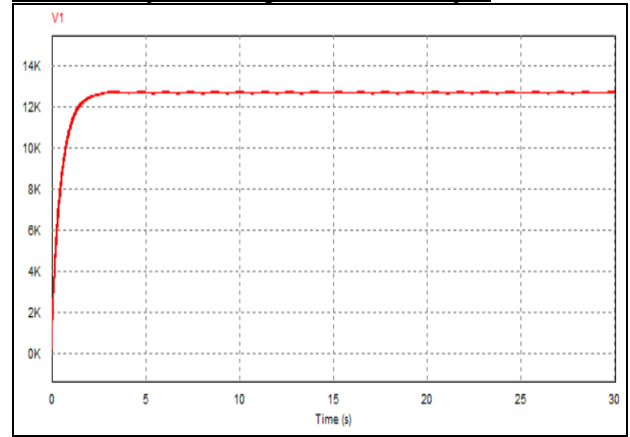
Simulated output- four stage at 1.6kV rated input:

Fig. 12: Simulation output- four stage output
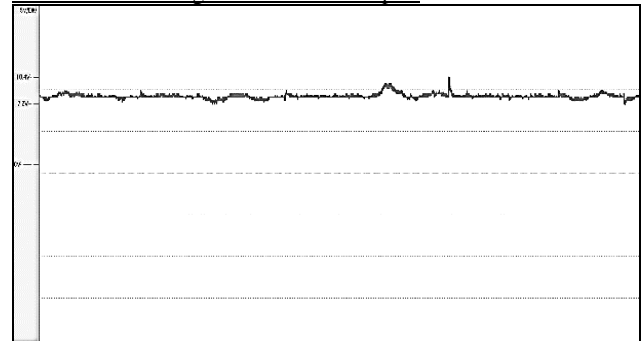
Practical- Four Stage at 1.6kV rated input:

Fig. 13: Conventional Output - Four stage

The obtained output is a pulsating DC wave with output range varying from 8.4kV to 10.28kV. Simulation shows a similar output V1 taken for the four stage which varies between 12.65kV to 12.7kV.

Output Calculations:
$$R_1 = 988M\Omega,\ R_2 = 1M\Omega \qquad \text{from (4)}$$

$V_{meas} = 10.4$volts
$$V_{in} = V_{meas} * \frac{R_1+R_2}{R_1}$$
$$= 10.4 * \frac{989M\Omega}{1M\Omega} = 10.285kV$$
Theoretical Projected Value = 1.6kV X 8 = 12.8kV
= Voltage at No-Load condition
Measured Value = 10.285kV = Voltage at loaded condition
The voltage regulation =

$$\frac{\text{No Load Voltage} - \text{Voltage on Load}}{\text{No Load Voltage}} \text{ X } 100 \qquad (12)$$
$$= \frac{12.8kV - 10.285kV}{12.8kV} \text{ X } 100 = 19.648\%$$

6.2. Measured output at oscilloscope

Table 1: Output values in oscilloscope

Input Voltage	Output voltage from Oscilloscope
Single Stage-1.47kV	2.88V
Two Stage- 1.47kV	4.88V
Three Stage- 1.47kV	7.6V
Four Stage	
400V	2V
800V	4.32V
1.2kV	7V
1.6kV	10.4V

6.3. Measured output at oscilloscope

Table 2: Voltage Regulation Calculation

Input Voltage	Measured Voltage (Load Voltage)	Theoretical Voltage (No Load Voltage)	Voltage Regulation
Single Stage			
1.47kV	2.769kV	2.8kV	1.1%
Two Stage			
1.47kV	4.826kV	5.6kV	13.82%
Three Stage			
1.47kV	4.430kV	8.4kV	10.5%
Four Stage			
400V	1.978kV	3.2kV	38.1%
800V	4.272kV	6.4kV	33.25%
1.2kV	6.923kV	9.6kV	27.88%
1.6kV	10.285kV	12.8kV	19.648%

6.4. Measured output at oscilloscope

The four-stage tolerance of the circuit at an input of 1.6kV varies between 9.6% at 11.4kV to 28% at 9.4kV.
The simulation output = 12.75kV
The theoretical output from the circuit = 12.8kV
The practical measured output potential = 10.285kV

$$\text{The tolerance of the circuit} = \frac{\text{Simulation} - \text{Theoretical}}{\text{Theoretical}} \qquad (13)$$

The tolerance of the circuit = -0.39%
Tolerance with respect to obtained output =

$$\frac{\text{Practical} - \text{Theoretical}}{\text{Theoretical}} \qquad (14)$$

= -19.6%

Below table shows best tolerance values obtained at highest output from the four-stage setup.

Table 3: Tolerance of four stage circuit at 1.6kV

Time (S)	Test Output (kV)	Simulation (kV)	Tolerance %
11.184	11.4724	12.69135	9.60
11.185	11.4724	12.71713	9.79
11.186	11.4724	12.71520	9.77
11.187	11.4724	12.71597	9.78
11.188	11.4724	12.71654	9.78
11.189	11.4724	12.71678	9.79
11.191	11.4724	12.71612	9.78

This gives the 4-stage setup an average tolerance level of ±10%

This difference between expected and calculated output is due to the presence of considerable reactance from the capacitors at power frequency. This results in conduction losses which are greatly reduced by increasing input supply frequency.
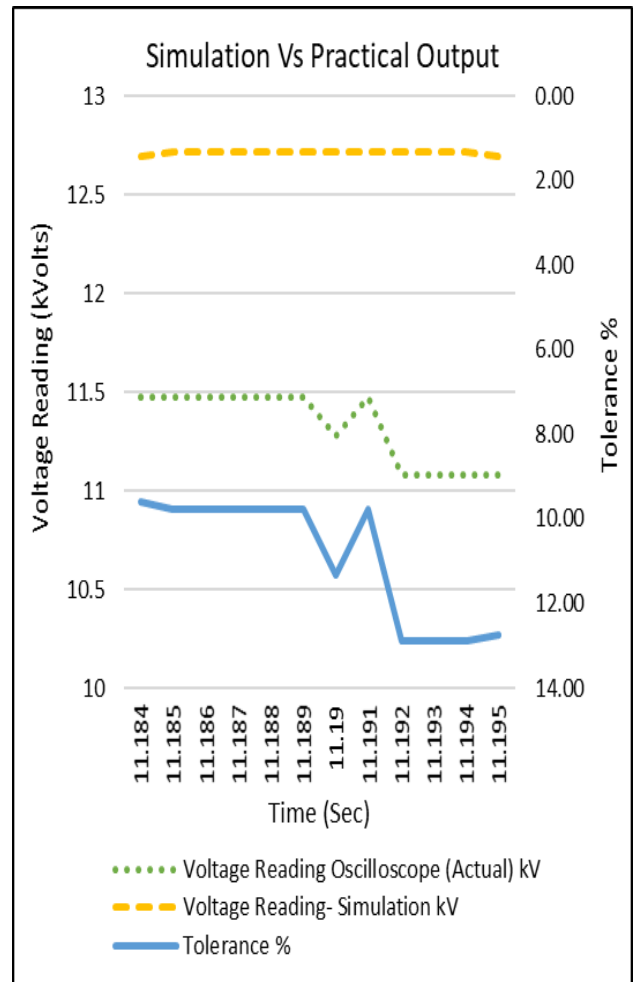
7. Future Scope

Mode 1- Power Frequency:
- This circuit can be used as the main power supply for Gas Emitted Helium-Neon Laser at power frequency [4].
- The circuit can be coupled with a wave shaping inductor of appropriate rating and used to generate an impulse voltage from each stage of the circuit from 3kV to 12kV.

Mode 2- High Frequency:
- An extension of the circuit can be made to generate voltages as high as 25kV to 50kV and can be used to test DC type insulators for testing their dielectric withstand capability
- The circuit can be used as an input source to calculate leakage reactance of Single phase transmission lines and insulators of high power rating when stressed under high voltage.

Fig. 14: Tolerance chart of four stage circuit at 1.6kV

8. Future Scope

This paper has proposed the design of a high voltage generator which offers a smooth DC output at high operating voltages. The circuit offers less ripple and good voltage regulation with two modes of operation i.e., at power frequency and high frequency of 250 kHz. The highest measured output is at 11.4kV for 4 stages which can be extended to generate voltages up to 50kV. This offers good possibilities of testing high voltage devices to study their insulating characteristics.

Acknowledgement

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