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Characterization of a compact low cost 6.5kV Cockcroft voltage multiplier

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ABSTRACT

Generation of high voltages is often necessary in industrial, medical, civilian and defense applications. One of the popular methods of generation of high voltage DC is using a Cockcroft voltage multiplier generator. Knowledge on characterization of the voltage multiplier circuit helps the designer to study the effect of various input parameters on output, saves lot of time and money. In this paper various methods of generation of high voltages, advantages and disadvantages of each method are discussed. Design of five stage voltage multiplier circuit, fabrication and characterization of the 6.5kV voltage multiplier generator are presented. Simulation was carried using PSPICE software under different load conditions. Effect on the output voltage, ripple voltage with different values of load, frequency was studied. Experiments were carried out on the proposed prototype model and validated by comparing the values obtained from experimentation with the simulation and theoretical values.

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1. INTRODUCTION

The Cockcroft Walton type generators find applications in particle accelerators, X-ray machines, micro-ovens, Industrial, Radio frequency energy harvesting, non thermal food processing equipment, used to drive photomultiplier tube. Also used in defense applications like radar, transmitter which functions with the help of high voltage. There are many topologies based on these voltage multipliers using step-up DC-DC converter, High boost converter with high conversion ratio, Transformer less AC-DC converters, obtaining high voltage gain using step up converter and with coupled inductor, raising the voltage using boost converter [1]-[3]. A three-stage conventional Cockcroft Walton type generator was modified to improve the response speed, the output voltage can be applied to underwater shock waves. For gas lasers instead of using a conventional Cockcroft voltage multiplier, a bipolar Cockcroft voltage multiplier was implemented, the output voltage obtained is more compared to the symmetrical multiplier circuit. This method also reduces the effect of odd harmonics especially fundamental and higher order harmonics. For certain applications where the DC voltage gain is the main criteria, there voltage multiplier in conjunction with a magnetically coupled boost converter is preferred [4]. To boost up the voltage by a factor of 2 to 4, topology with cells get connected in matrix form are used to generate high voltages [5]. Applications involving high voltage DC power supply need voltage multiplier circuit [6]. Also, these multipliers are used in pulsed power generation circuits which are often used for liquid food and solid food treatment [7]-[13].

Commonly used method of generation of high voltage in a laboratory is using a step-up transformer with a half wave rectifier. To reduce the ripple a capacitor is used across the load. Even though the ripple can be improved by using Full wave rectifier, still half wave rectifier is used in practice because providing a center tap is difficult in high voltage transformer. For generation of still higher voltages the transformer size increases and cost also increases.

- Literature review

High voltage transformer used to step up the voltage which generally has high turns ratio. The size of transformer becomes bulky for generating high voltages on secondary side which is a disadvantage where application include compact circuit for generating high voltage DC. There is a limitation of high turn ratio transformer as it offers high reactance because of the high voltage winding and parasitic capacitance posed [14], [15]. Therefore, alternatively high voltages can be produced with less turns ratio using the voltage doubler circuit, Cockcroft Walton voltage multiplier circuit and Kathaus Fischer cascade voltage doubler circuit. Mohsen Ruzbehani has presented a mathematical model of Cockcroft voltage multiplier circuit, simulation was performed on different symmetrical voltage multipliers and comparison was made between them. Experiments were conducted on low voltage multiplier circuit [16]. Another method of generating high voltage is using resonant converter, fast operating switches in addition to capacitor diode voltage multiplier. In this method both wide as well as narrow pulses can be generated which are used in food treatment [17]. From the available literature Cockcroft Walton type generator is developed for different applications with different rating. Information related to complete design and characterization of Cockcroft Walton type generator is very limited. Therefore, in this paper importance was given for complete design of 6.5kV generator, simulation using PSPICE and characterization of this generator is presented.

2. METHOD

To reduce the rating of step-up transformer used in high voltage generation circuits, voltage doubler circuit is popularly used in high voltage circuits [18]. In negative cycle B is positive and Diode D_1 conducts charging the capacitor to Maximum voltage Vmax as shown in Figure 1. In Positive cycle A is positive and supply voltage V_s are at V_{max}, this gets added to the C_1 voltage and the total voltage at D_2 becomes $2V_{max}$ and Diode D_2 conducts and charges the capacitor C_2 to $2V_{max}$. Therefore, the voltage across the load, i.e., C_2 will be $2V_{max}$. Second method of generating high voltages is by connecting each stage voltage doubler circuit in parallel. Hence this is also called as Parallel voltage multiplier [16]. Another method of generating high voltages is by connecting the voltage doubler circuits in series connection as shown in Figure 2. This is the most common method of increasing the voltage using a voltage multiplier circuit.

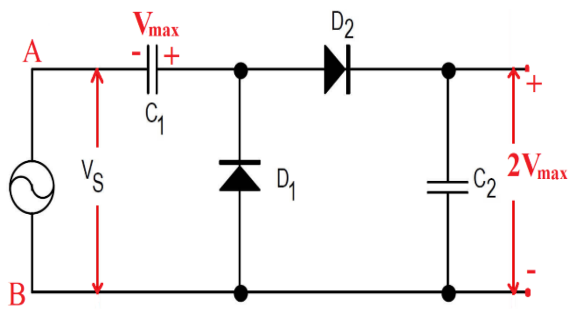

Figure 1. Voltage doubler circuit

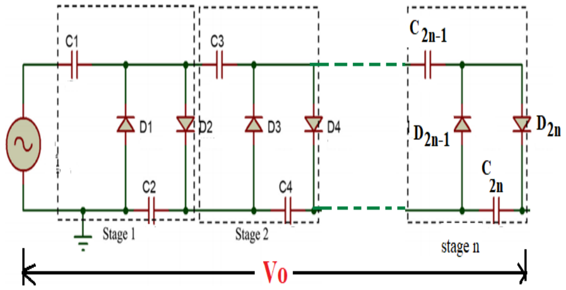

Figure 2. Voltage multiplier circuit

This circuit is originally developed by Cockcroft Walton in 1932. In this circuit, voltage doubler circuits are connected in series in Cockcroft voltage circuit [19]. This method is widely used to generate high voltages in the order of a few kilo volts to Mega Volts. This method is widely used to test the high voltage equipment, added advantage is we can tap the output voltage from any stage based on the voltage to be applied for testing equipment. Input voltage is fed to the primary of step-up transformer and on secondary side the capacitors and diodes are connected as shown in the Figure 2, this arrangement isolates the multiplier circuit from the switching surge voltages as it is isolated from the main line. The charging of capacitors happens similar to the operation of the voltage doubler circuit. Except C_1 all the capacitors get charged to $2V_{max}$. The voltage across Capacitors C_3, C_5, … C_{2n-1} keeps on Oscillating hence this is also called Oscillating column. The voltage across capacitors C_2, C_4, … C_{2n} remains constant, hence this column is also called smoothening column. In one half cycle the capacitors in the oscillating column get charged through D_1, D_3, D_5, … D_{2n-1} respectively. Similarly, all the capacitors in Smoothening column, i.e., C_2, C_4, … C_{2n} get charged through D_2,

D_4, … D_{2n} respectively. Output voltage with respect to ground at stage-1, stage-2 and stage-n will be $2V_{max}$, 4 V_{max} and 2n V_{max} respectively. This is the voltage that will be available during no load condition. When the circuit is connected to the load there will be voltage drop ΔV in the circuit and the output voltage waveform consists of ripples and magnitude is proportional to the load current.

2.1 Design of 6.5 kV Cockcroft voltage generator

It is intended to design a five-stage generator to deliver a load of 350µA. The available range of capacitors of rating 0.47µF was selected. Two capacitors are connected in parallel and the equivalent capacitance is 0.94µF, this is the capacitance of each capacitor in oscillating and smoothening column. The input source is 115V, 400Hz variable frequency drive and this supply is fed to a single-phase step-up transformer with rating 115V/470V, 50mA. 470V is a rms voltage and maximum voltage is given by:

$$V_{max} = \sqrt{2} * V_{rms} = \sqrt{2} * 470 = 664.68V \quad (1)$$

Ideal output voltage is given by

$$V_o = 2nV_{max} = 2 * 5 * 664.68 = 6646.8V \quad (2)$$

Load resistance for obtaining a load current of 350µA is given by

$$R_L = \frac{V_o}{I} = \frac{6646.8}{350*10^{-6}} = 19\ M\Omega \quad (3)$$

Therefore, to obtain load of 19MΩ, five non inductive resistors each of 100 Mega ohms are considered and are connected in parallel to form a load resistance. The equivalent load resistance formed is 20 MΩ. The voltage drop and ripple voltage [19] are given by:

$$\Delta V = \frac{I}{fc}\left[\frac{2}{3}n^3 + \frac{n^2}{2} - \frac{n}{6}\right] \quad (4)$$

$$\delta V = \frac{I}{2fc}\left[\frac{n(n+1)}{2}\right] \quad (5)$$

Where I is the load current in amperes, f is the frequency of the input supply in Hertz's, C is the capacitance of each capacitor in farads and n is the number of stages. Voltagedrop increases as the number of stages increases [20], hence there is limitation on the number of stages, by deciding the optimum number of stages, maximum output voltage can be obtained. Optimum number of stages and output voltage is given by:

$$n_{opt} = \sqrt{\frac{V_{max}*I}{fc}} \quad (6)$$

$$V_o = 2nV_{max} - \Delta V \quad (7)$$

2.2 Simulation of 6.5 kV Cockcroft voltage generator

To save the time, cost and make the design perfect it is always recommended to perform simulation until we get desired results. Simulation is performed under no load and different load conditions using PSPICE software. Simulation gives better idea about the effect of various parameters on output voltage. The Simulation circuit developed in PSPICE is shown in Figure 3. The output at each stage under load of 20MΩ is shown in Figure 4. The output voltage at each stage, load current, ripple voltage and voltage drop for different load values are calculated using (4) and (5) and is tabulated in Table 1.

Table 1. Simulation results under different load values

	No Load	20MΩ	25 MΩ	33.33 MΩ	50 MΩ
Output voltage at 1st stage (V)	1298	1293	1294	1295	1295
Output voltage at 2nd Stage (V)	2595	2579	2580	2583	2586
Output voltage at 3rd Stage (V)	3892	3858	3862	3867	3874
Output voltage at 4th Stage (V)	5189	5134	5141	5149	5159
Output voltage at 5th Stage (V)	6486	6407	6417	6429	6445
Current (µA)	---	320.3	256.75	192.91	128.91
Ripple voltage, δV (V)	---	12.77	10.242	7.695	5.14
Voltage drop, ΔV (V)	---	80.92	64.87	48.74	32.57

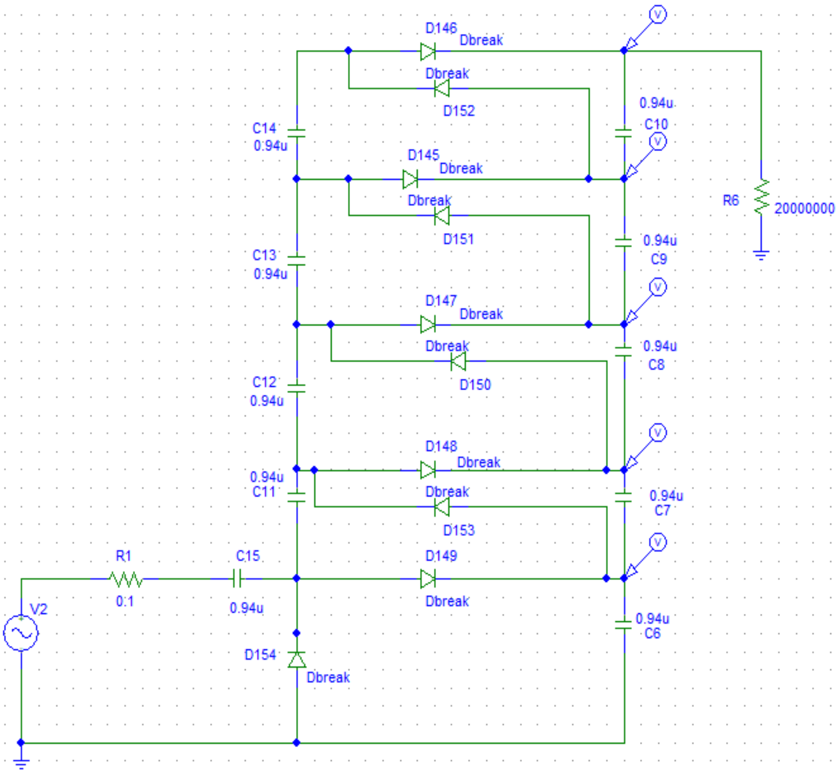

Figure 3. Simulation circuit of a five-stage generator

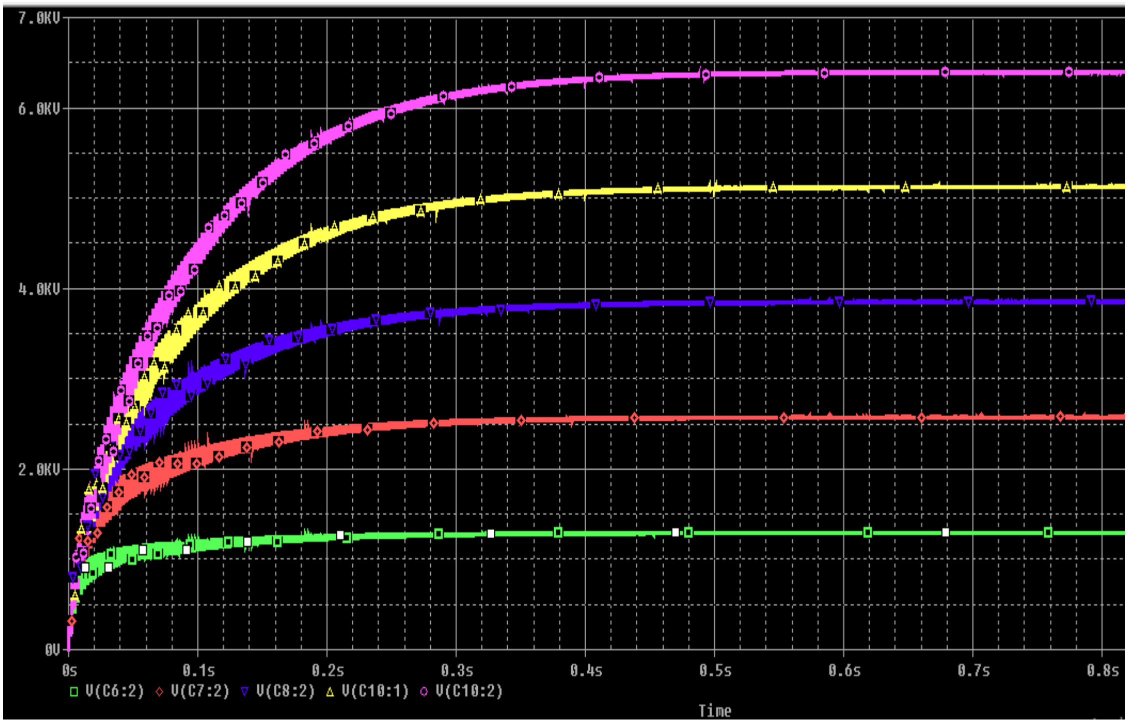

Figure 4. Stage voltages with 20MΩ load

From the voltage drop and ripple voltage in (4) and (5), it is very much clear that these are depending on Load current, frequency, capacitance and number of stages. There will not be any control over the capacitance and number of stages [19]. Also, the load current depends on the load. Hence, by controlling the frequency, the voltage drop and ripple can be reduced. Hence, in most of the applications the supply frequency will be more than 50 Hz. Capacitors used in normal 50 Hz applications will be in the range of 1 microfarad to few tens of micro farads, whereas for high frequency applications it will be in the range of 0.02 microfarad to 0.06 microfarads. Also, the voltage rating has to be decided properly, since each capacitor in the multiplier circuit will get charged to $2V_{max}$. In general, the peak inverse voltage rating of each capacitor is double the input voltage rating and mainly depends on application of usage. Therefore, capacitor voltage rating of each capacitor used in this generator is rated for $4V_{max}$. The diodes used in the circuit will experience reverse voltage of double the maximum voltage. Therefore, each diode should be rated for $2V_{max}$ [20], [21]. Therefore, there is a need to analyze the effect of change in frequency on voltage drop and ripple voltage. Table 2 shows the simulation results Frequency versus ripple voltage for a 20 Mega ohm load. Figure 5 shows the frequency versus the ripple voltage and voltage drop. Table 3 shows the effect of change of capacitance on ripple voltage and voltage drop and Figure 6 shows a graph capacitance versus the ripple voltage and voltage drop.The curve is non-linear due to the capacitance effect of all the capacitors in each stage of generator.

Table 2. Frequency versus ripple voltage for a 20M ohm load

S.no	Frequency (Hz)	Ripple voltage, δV (Volts)	Voltage drop (volts) ΔV
1	50	102.22	647.41
2	100	51.11	323.7
3	200	25.55	161.85
4	300	17.03	107.9
5	400	12.77	80.92
6	500	10.22	64.74
7	1000	5.11	32.37

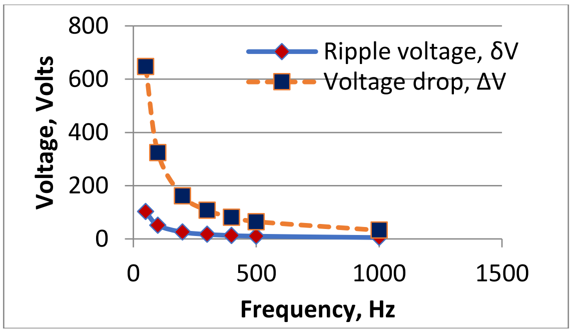

Figure 5. frequency vs ripple voltage &voltage drop

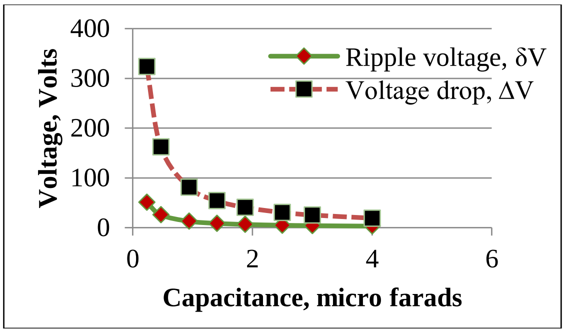

Figure 6. capacitance vs ripple voltage & voltage drop

Table 3. Capacitance versus ripple voltage for a 20M ohm load

s.no	Capacitance, μF	Ripple voltage, δV, volts	Voltage drop ΔV, volts
1	0.235	51.11	323.7
2	0.47	25.55	161.85
3	0.94	12.77	80.92
4	1.41	8.51	53.95
5	1.88	6.38	40.46
6	2.5	4.8	30.42
7	3.0	4	25.35
8	4.0	3	19.01

3. METHOD TO DEVELOP EXPLORATORY MODEL

Main components used are frequency converter of 400 Hz, single phase step up transformer of 115V/470V, 50 mA rating, diodes IN4007 model which has peak inverse voltage of 1000V, in each branch two diodes are connected in series thereby making to withstand peak inverse voltage of 2000V. Each capacitor of rating 0.47μF, 1500V are used in the circuit. The whole assembly is placed on Teflon sheet, and is shown in Figure 7. Whole setup connected to frequency converter on input side and output connected to digital storage oscilloscope (DSO) is shown in Figure 8. The experimental output waveform is shown in Figure 9. For measuring the high voltage commonly used technologies are by using a RC potential divider and Capacitive divider, to prevent the reflection of wave coaxial cable has to be terminated with the impedance equal to source impedance [22]-[25]. Capacitive dividers are not suitable for measuring high transients only in the narrow frequency band and in certain applications dividers filled with copper sulphate solution will be used to measure high voltages [26]. In the present work, high voltage probe of 1:1000 ratio is used, one end of the high voltage probe connected to output of generator and other end is connected to Digital storage oscilloscope.

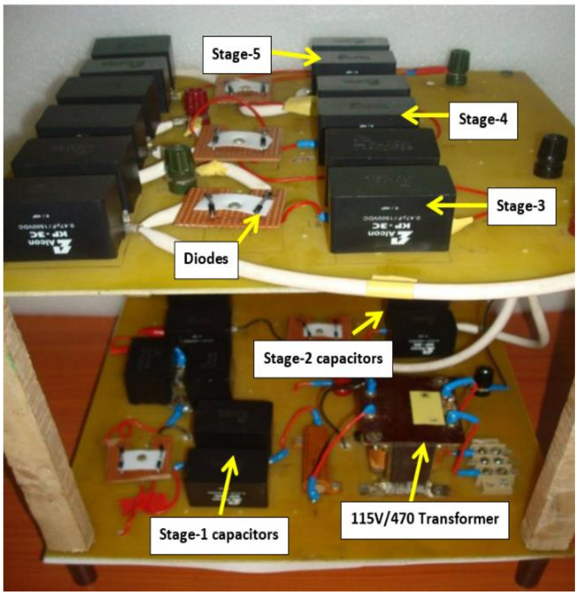

Figure 7. Whole circuit assembly

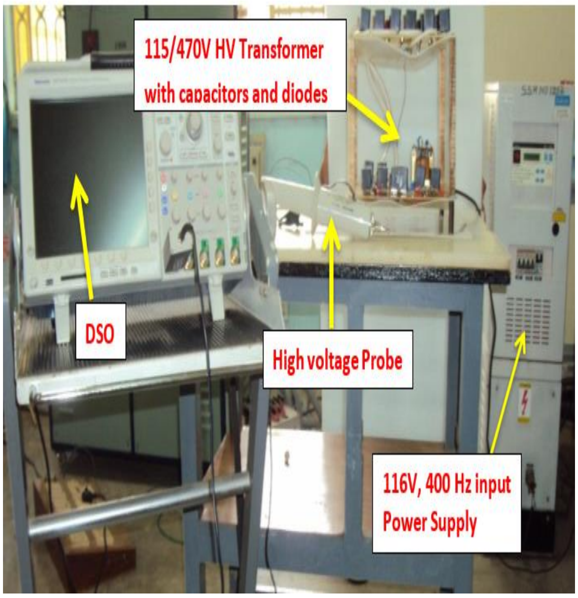

Figure 8. Circuit connected to DSO

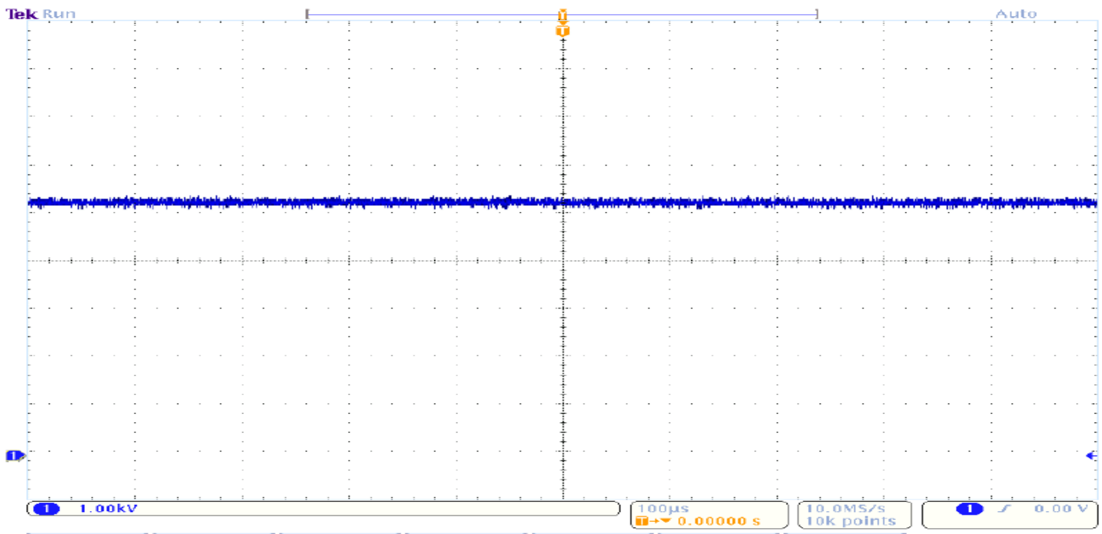

Figure 9. Experimental output voltage waveform

4. RESULTS AND DISCUSSION

The output voltage at each stage, load current, ripple voltage and voltage drop were obtained by conducting the experiment on the prototype model for different load resistance values and the results are tabulated in Table 4. It is ascertained that during no load the total output voltage is 6100V and when loaded with 20MΩ, the output voltage is fallen to 5200V. The ripple voltage is 10.77 and voltage drop is 68.2V. As the load current decreases the ripple voltage and voltage drop decreases.

Table 4. Experimental results under different load conditions

Practical Values	No Load	20 MΩ	25 MΩ	33.33 MΩ	50 MΩ
Output voltage at 1st stage (V)	1300	1100	1150	1200	1250
Output voltage at 2nd Stage(V)	2600	2200	2250	2300	2400
Output voltage at 3rd Stage (V)	3800	3200	3300	3400	3600
Output voltage at 4th Stage (V)	5000	4200	4400	4500	4600
Output voltage at 5th Stage (V)	6100	5200	5500	5600	5800
Current (μA)	---	270	220	170	130
Ripple voltage, δV,(V)	--	10.77	8.77	6.78	5.18
Voltage drop, ΔV, (V)	---	68.2	55.58	42.95	32.84

Table 5 shows the data related to Load versus load current, ripple voltage and voltage drop. In general, the load on the generator changes depending on load, hence it is necessary to study the effect of load on the output voltage. In this work, the load is chosen based upon the available load resistors. By series and parallel combination of these resistors a load of 20, 25, 33.33 and 50 MΩ resistance is obtained. It is observed that as the load resistance increases, the load current decreases, for higher value of load current the difference in simulation and experimental values is about 15% and for lower values of load current it is around 0.8% and the same holds good for voltage drop and ripple voltage, which proves that the developed model is giving accurate results. The graphs with simulation and experimental data are plotted load versus load current, ripple voltage and voltage drop and are shown in Figure 10, Figure 11 and Figure 12 respectively.

Table 5. Load versus load current, ripple voltage and voltage drop

S. No	Load (MΩ)	Load current (μA)		Ripple voltage (V)		Voltage drop (V)	
		Sim	*Exp*	*Sim*	*Exp*	*Sim*	*Exp*
1	20	320.3	270	12.77	10.77	80.92	68.2
2	25	256.7	220	10.24	8.77	64.87	55.58
3	33.33	192.9	170	7.69	6.78	42.95	42.95
4	50	128.9	130	5.14	5.18	32.94	32.94

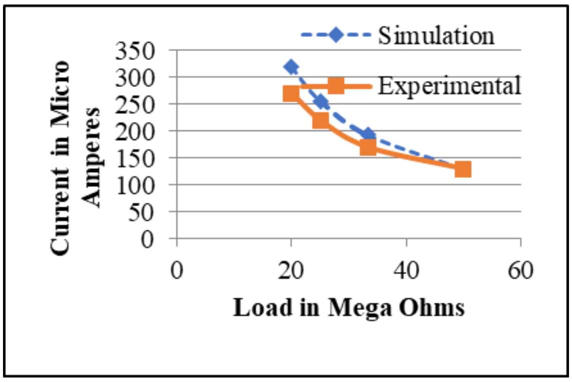

Figure 10. Load versus load current

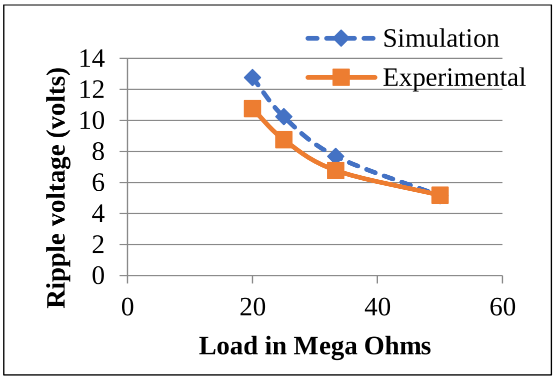

Figure 11. Load versus Ripple voltage

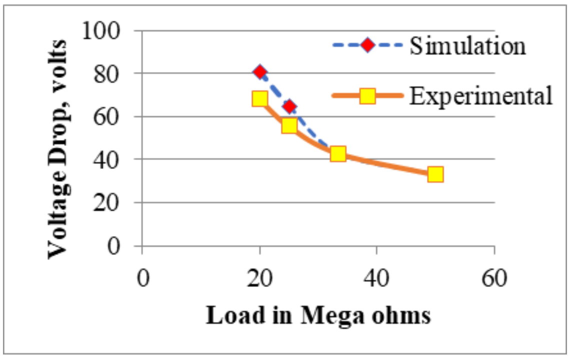

Figure 12. Load versus voltage drop

The proposed voltage generator is best suitable for applications which has load current of 130 to 170 micro amperes. Beyond these values, increase in load current, increases the ripple voltage and voltage drop. For higher load current, difference in simulation and experimental results increase. The non linearity is due to same capacitance value of each capacitor in the circuit. The voltage drop and ripple voltage can be reduced by replacing the bottom stage capacitors with higher capacitance values. This model is best suited for demo purpose in academic institutions to show the effect of various input parameters on output voltage.

5. CONCLUSION

A compact prototype model was developed with five stages which gives an output voltage of 6100V on no load and gives an output voltage of 5200V when delivering a load current of 350µA. The results obtained by theoretically, simulation and experiment were compared and they are well within the limits which validates the model. This generator can be used to test high voltage equipment which needs a test voltage of up to 5kV. Also, this can be used in universities, academic institutions to demonstrate the effect of load current, capacitance and frequency on ripple voltage and voltage drop. Better results with more accuracy can be obtained at higher values of load current by selecting the capacitors of high value, frequency converter with still high frequencies, designing the model with optimum number of stages and using square wave instead of sine wave as input.

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