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High Step-Up Converter Based On Cockcroft-Walton Voltage Multiplier with Different Capacitor Configuration

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Abstract— Demand for electrical energy and concern about green energy evoke research in the renewable energy sources for electrical power production. Since the output of major renewable energy sources like solar and fuel cell is a low voltage DC, a step-up DC-DC converter plays a major role in renewable energy applications. Transformer less step-up converter based on Cockcroft-Walton voltage multiplier, proposed by Chung-Ming Young et. al, dealt with the computation of gain with capacitors all are equal. Objective of this paper is to analyse different capacitor combination in the step-up converter with Cockcroft-Walton voltage multiplier topology. A seven stage converter of 1kW rating is designed for different capacitor configurations. For validation, simulation is carried out for both equal capacitors and different capacitors configurations. From low-input-level renewable energy sources, the proposed converter provides a high DC voltage at relatively low cost. This converter is suitable for various applications to boost the DC voltage in a cost effective manner.

Keywords— High gain step-up converter, Cockcroft-Walton voltage multiplier, Transformer-less boost converter, Voltage ripple reduction, Low voltage stress, Various capacitor configuration of CWVM, Low current ripple.

I. INTRODUCTION

ELECTRIC power is an issue that touches almost every person on the planet and the demand for electrical energy increases day-by-day. Renewable energy sources especially fuel cell and solar cell attract the researchers and the government all over the world. Because of low level voltage generation, a high gain dc-dc converter is required in the power conversion systems corresponding to these two sources.

A. Boost Converter

Conventional boost converters provide a high voltage gain at the cost of extremely high duty cycle. Many boost converters with isolated transformers or coupled inductors have been proposed to obtain high gain without high duty cycle. Main drawback is the requirement of high rating switches to withstand high voltage spikes during turn off instant. Current-fed converters are generally superior to the voltage-fed type because of low input current ripple and high voltage ratio. Modified current-fed converters integrated step-up transformers or coupled inductors associated with soft-switching or energy-regeneration techniques were presented recently. The design of magnetic components is complex in these topologies. By cascading diode-capacitor or diode-inductor modules, step-up converters provide high voltage gain with simple and robust structures. Voltage stress on each individual switch and passive element depends on the number of stages. A transformer-less boost converter based on Cockcroft-Walton voltage multiplier was proposed by Chung-Ming Young et. al. Since it is operating in continuous conduction mode(CCM), the switching losses , the stress on the switches, and EMI noise can be reduced.

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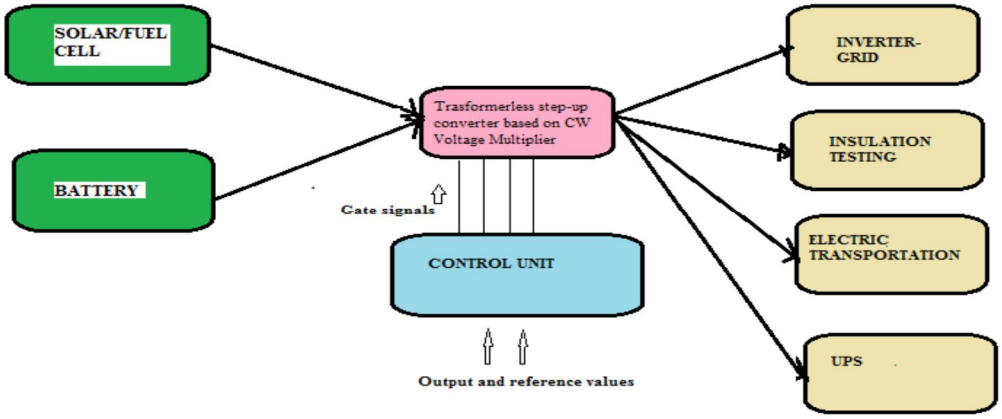


Fig. 1. Block diagram

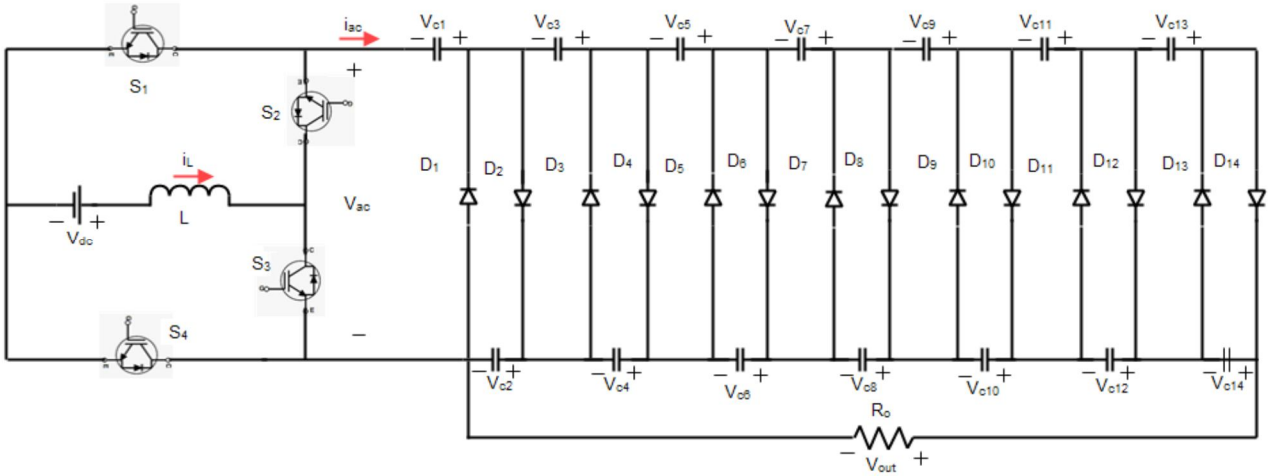


Fig. 2. CW voltage multiplier based stepup converter.

B. General Applications

Step-up converter based on CWVM is suitable for various applications especially where high voltage gains are desired. It can be directly applied for numerous applications; some of them are listed below.

Equipments in telecom sector uses a 48V bus distributed power system which has a backup of 48V dc battery plant. The information industry uses uninterruptable power supplies, but the backup time provided by them is not enough; a better choice for providing longer reverse time is to use the 48V telecom power supply and to boost it to 380-V intermediate dc bus.

Most of the industrial electrical equipments and commercial power systems are operating in 50 Hz AC. So use of an AC source for insulation testing seems to be the logical choice. Since insulation systems are extremely capacitive and AC test equipments are bulky, DC test equipment is considered to be more suitable than AC. For testing a cable of one-mile length at 50 kV AC would require an equipment of 500 kVA capacity . A DC test at 50 kV would require an equipment of 50 W capacity.

In fuel cell vehicle, step-up converter is employed to provide an input to the inverter which in turn supplies the AC loads. Output from the boost converter of n stage can be utilized for all AC applications by connecting a suitable inverter of n+1 level. Thus application of step-up converter has been spreading in every corner of residential, electric transportation, electrical testing, space and utility systems. A block diagram showing some of the applications is depicted in fig.1

C. Organisation

Chapter II discuss with operation Cockcroft-Walton voltage multiplier based step-up converter.

Chapter III deals with the design of the seven stage converter.

Chapter IV provides analysis of simulation under different configuration of capacitors.

In chapter V, a brief summary of workdone is presented.

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In chapter VI, future works to be done in this area is discussed.

II. CIRCUIT DESCRIPTION

Proposed converter is an integration of a conventional boost converter and voltage multiplier as shown in the fig.2

A. Circuit Components

Supply: A low-level dc source, such as battery, PV array or fuel cell sources
One boost inductor L, four MOSFET switches (S1,S2, S3 and S4)
One n-stage Cockcroft-Walton voltage multiplier.
The input voltage and current are represented by V_{dc} and I_L respectively ; the output voltage is denoted by V_{out}, and the output resistor is represented by R_o.

1) Source: Supply is obtained from a DC source of 40V which can be obtained from renewable energy soures or battery.

2) Switches: S1(S2) and S4(S3) operate in complementary mode, and the operating frequencies of S1 and S2 are termed as f_{mod} and f_{alt} respectively. f_{mod} is the modulation frequency and f_{alt} is the alternating frequency; f_{mod} is set much higher than f_{alt}. High frequencies are selected so that smaller inductor and capacitors can be used. Regulation of output voltage is done by controlling the duty cycle of S1 and S4, while the output voltage ripple can be adjusted by f_{alt}.

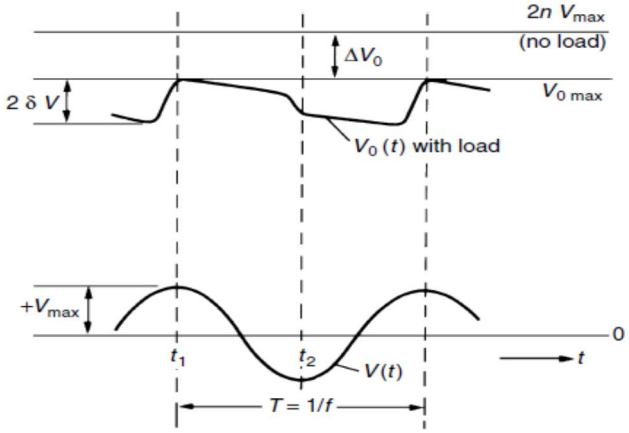


Fig. 3. Output voltage of CW voltage multiplier circuit

3) Cockcroft-Walton Voltage Multiplier: In the circuit shown in the fig.2, the subsequent stage is a Cockcroft-Walton Voltage Multiplier. One of the cheapest and popular ways of generating high voltages at low currents is the multistage diode-capacitor voltage multiplier also known as Cockcroft- Walton multiplier.(Proposed by James Douglas Cockcroft and Ernest Thomas Sinton Walton). Merit of such circuit is that the voltage across each stage is only equal to twice the peak input. Thus size and cost of the components can be reduced to a great extent. Output can be tapped from any stage like a multi-tapped transformer. In CW voltage multiplier, each stage has two capacitors and two diodes. In Cockcroft-Walton voltage multiplier of n-stage , the number of diodes and capacitors will be of 2n. For no load, the output voltage will be of 2n times of input. The output voltage and ripple of a Cockcroft-Walton voltage multiplier is shown in the fig.3.

B. Assumptions

In the fig.2, V_{ac} represents terminal voltage and i_{ac} represents the current of the cascade Cockcroft-Walton voltage multiplier circuit. The reference direction is indicated in the fig.2. The capacitors and diodes are denoted by C_i and D_i respectively.
For the simplification of analysis, it is assumed that
The converter in fig.2 is operating in steady state and continuous conduction mode.
All the components are ideal and thus the circuit has 100% efficiency
All capacitors are sized to have a relatively small voltage ripple at reasonable load.
Boost inductor is sized in-order to reduce the input current ripple.

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C. Circuit Operation

By using the switches S1, S2, S3 and S4, the input DC voltage is converted into alternating waveform. Moreover the boost inductor, L boosts the input voltage of the CCW voltage multiplier circuit. The forward biasing of diode depends upon the charge of the capacitors to which the particular diode is connected. Only one of the diodes in the CW circuit will conduct when $I_{CW} > 0$. Sequence of conducting diode is from right to left with even diodes conducting in positive half cycle and odd diodes conducting in negative half cycle. The condition for the conduction of each diode is determined by the terminal current I_{CW} and capacitor voltages Vc_1 to Vc_{14}. The boosted dc voltage is available across the load which is connected across the even capacitors.

D. Modes Of Operation

During positive half cycle of the alternating waveform, only one of the even diodes conducts with the sequence D14, D12, D10, D8, D6, D4 and D2 and that the even (odd) capacitors gets charged (discharged) through the conducting diodes. The characteristic behavior of each mode in the positive half cycle is explained by using the fig.4 to fig.11.

*1) MODE-1:*During the first mode, S1 and S2 turn on whereas S3, S4 and all diodes are in off condition. Energy stored in the inductor increases. Even group capacitors C14, C12, C10, C8, C6, C4, and C2 supply the load. Odd-group capacitors C13, C11, C9, C7, C5, C3, and C1 are floating.

2) MODE II: During the second mode, S2 and S4 turn on whereas S1, S3 and all diodes except D14 are in off condition. Thus, in this stage, even group capacitors C2i for every i ϵ [1,7] fed the load. while the input voltage V_{dc} , inductor and the odd group capacitors C2i-1 for every i ϵ [1,7] charge the even group capacitors.

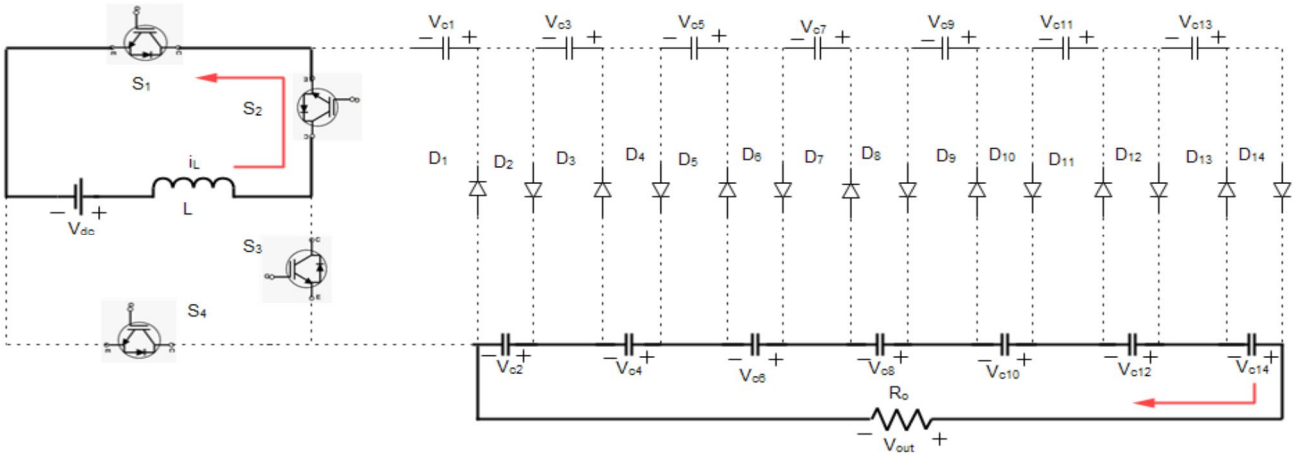


Fig. 4. I Mode of operation

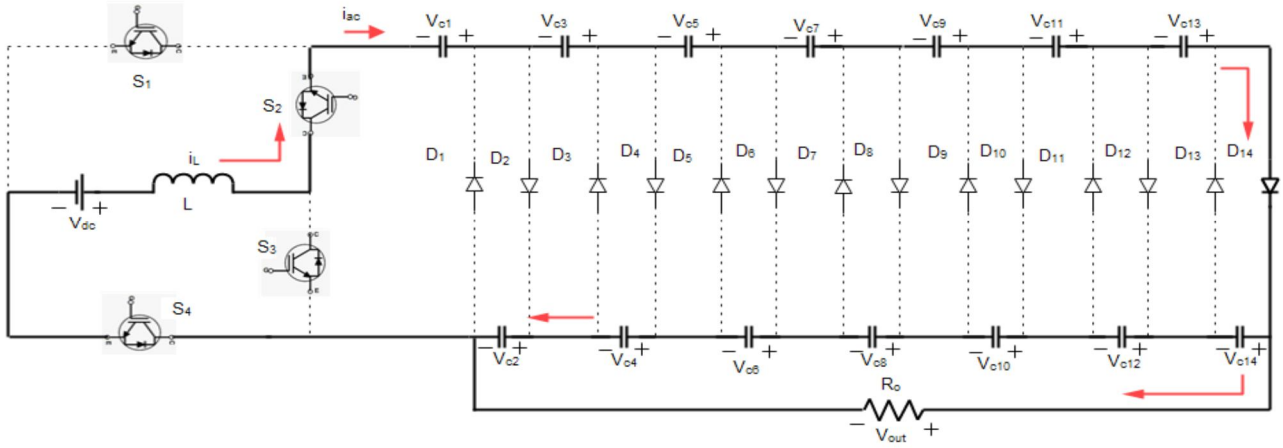


Fig. 5. II Mode of operation

3) MODE-III: During the third mode, S2 and S4 turn on whereas S1, S3 remain open. All diodes except D12 are in off condition as shown in the fig.6. Thus, in this stage, even group capacitors C2i for every i ϵ [1,7] fed the load, while the input

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voltage V_{dc} , inductor and odd group capacitors C2i-1 for every i ϵ [1,6] charge the even group capacitors.

4) MODE-IV TO VIII: Switches S1, S2, S3 and S4 remain in the same state. Diode conduction is shown in the fig.7 to 11. Thus at the end of eighth mode, energy gets transfered from supply side to load. Behavior of the circuit is similar during the negative half cycle of the alternating waveform. The odd diodes are conducting with the sequence D13, D11, D9, D7, D5, D3, and D1. Moreover the odd capacitors are charged and even capacitors are discharged. The behavior of the CW circuit during the positive and negative half cycle can be obtained through eight modes of operation each. Inductor gets charged when S3 & S4 are closed and discharges while S1 and S3 are conducting.

III. DESIGN CONSIDERATIONS

A. Design

The analysis was carried out for three stage step-up converter in [3]. Design of inductance, capacitance and resistance are based on expressions in [3].

Gain of the converter depends on number of stages and duty ratio of the modulating switches.

$$G = \frac{2n}{1-D} \quad (1)$$

Voltage stress across the first capacitor is half the stress across other capacitors.

$$Vc1 = \frac{Vout}{2n} \quad (2)$$

$$Vci = \frac{Vout}{n} \quad \text{for i = 2; 3... 2n} \quad (3)$$

Maximum current stress across the switches and diodes are equal to the peak value of the inductor current.

Ipk

Maximum voltage stress across the switches and diodes depends on output voltage and number of stages.

$$\frac{Vout}{2n}$$

Design of input Inductance is based on input current, ripple current and operating frequency of the modulating switches.

$$Vdc = \frac{Ls*diLs}{dt} \quad (4)$$

$$Ls = \frac{Vdc*DTsm}{KIpk} \quad (5)$$

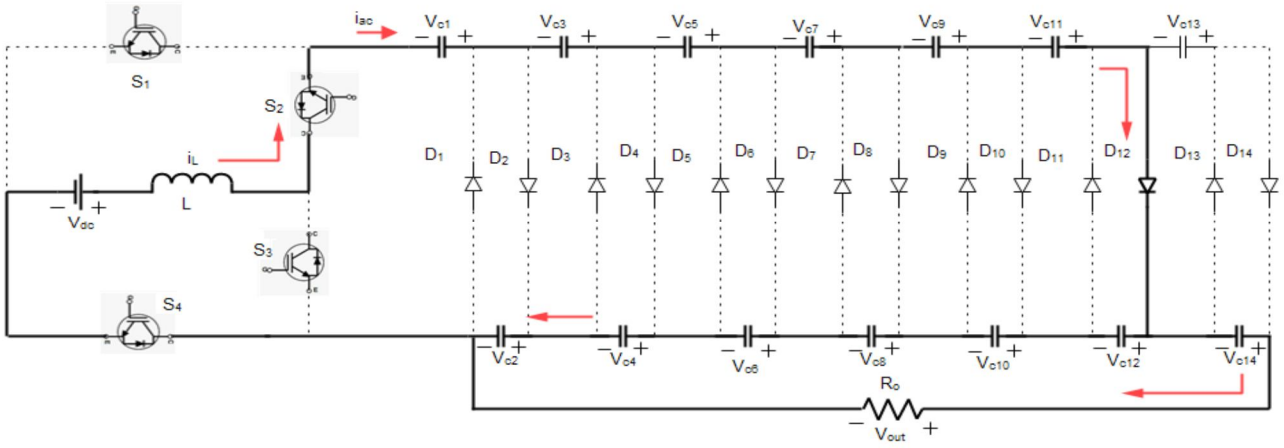


Fig. 6. III Mode of operation

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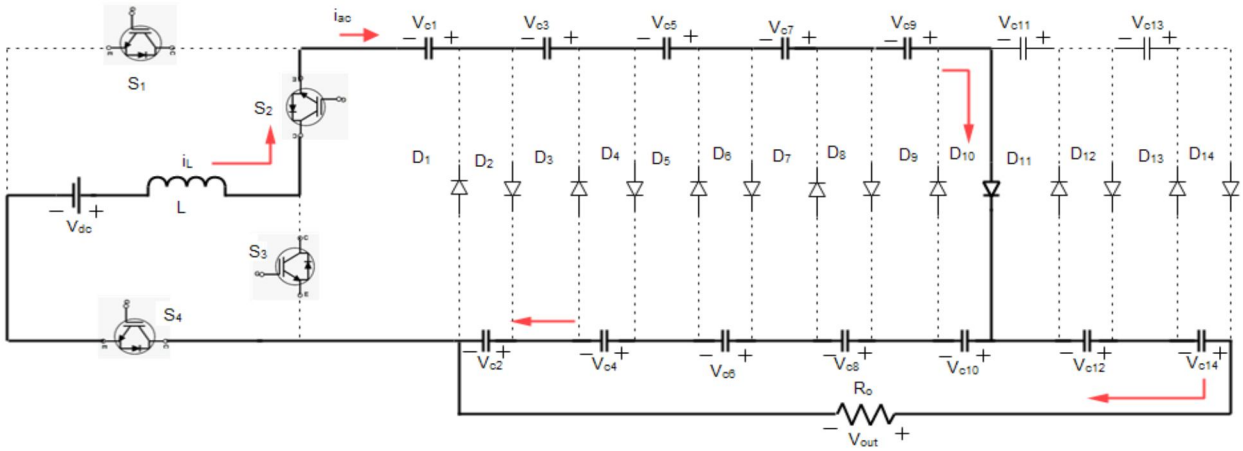


Fig. 7. IV Mode of operation

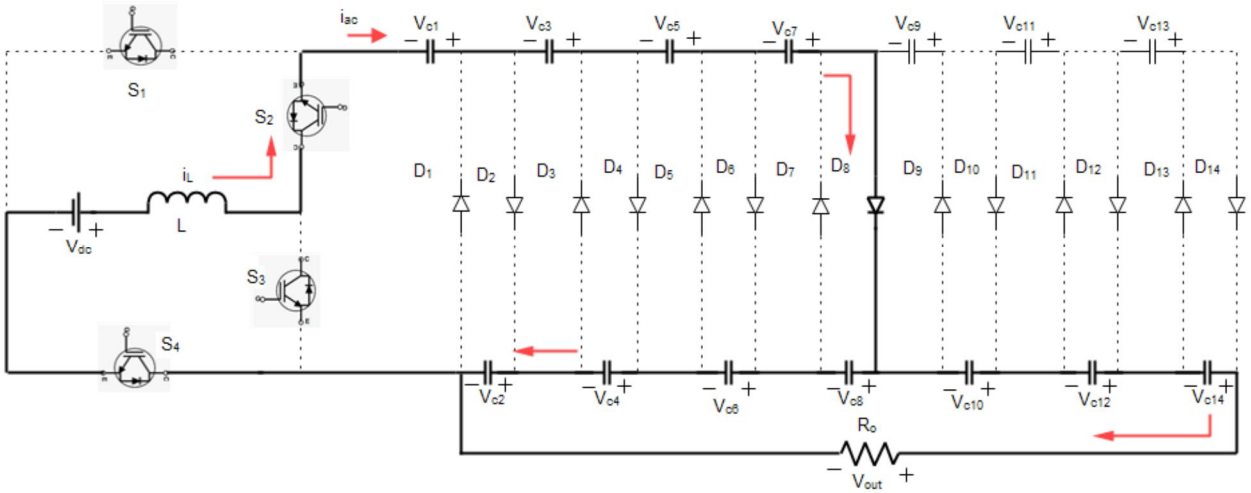


Fig. 8. V Mode of operation

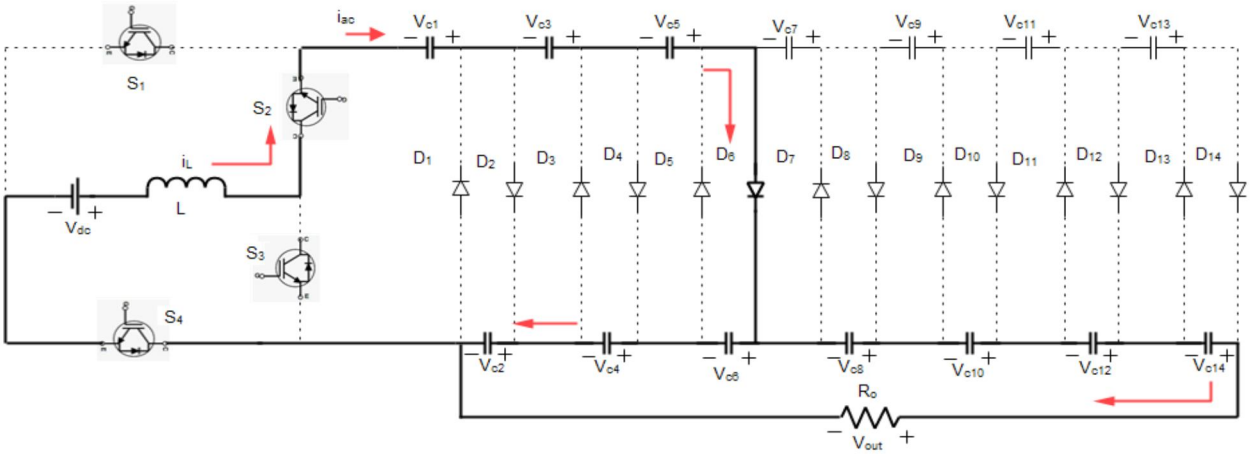


Fig. 9. VI Mode of operation

Load resistance

$$Ro = \frac{Vout^2}{Po} \quad (6)$$

Capacitance: Design of capacitor depends on the operating frequency of alternating switches, voltage ripple, number of stages and time of conduction of diode.

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$$\delta Vci = \frac{Io(2n-i+1)}{fsc*C} \quad (7)$$

Output voltage ripple is equal to the sum of all even capacitor voltage ripples;

$$\delta Vout = Io\frac{n^2}{2Cfsc} \quad (8)$$

Where,

V_{dc} Input voltage

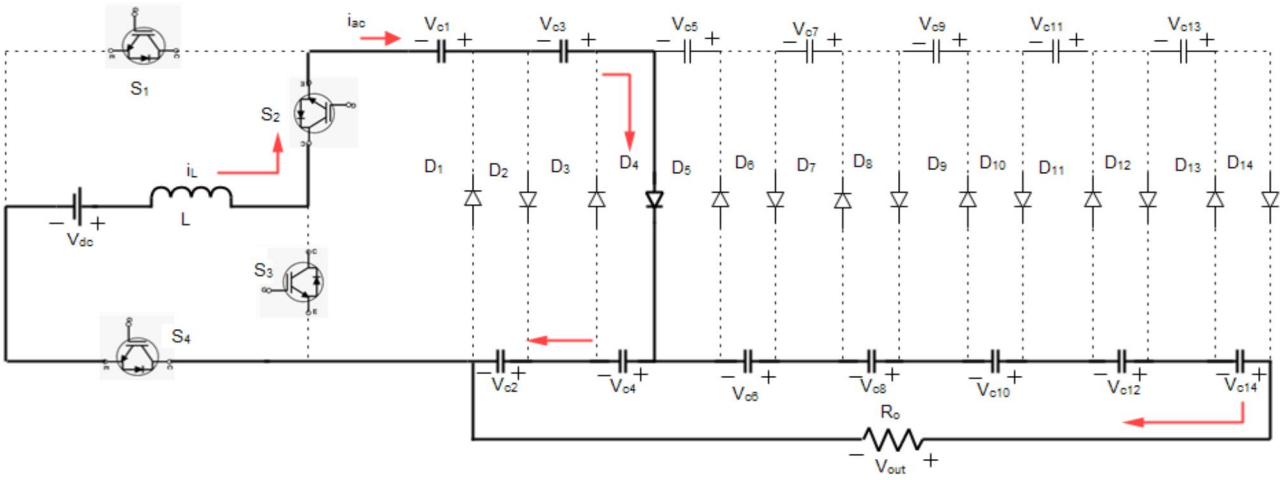


Fig. 10. VII Mode of operation

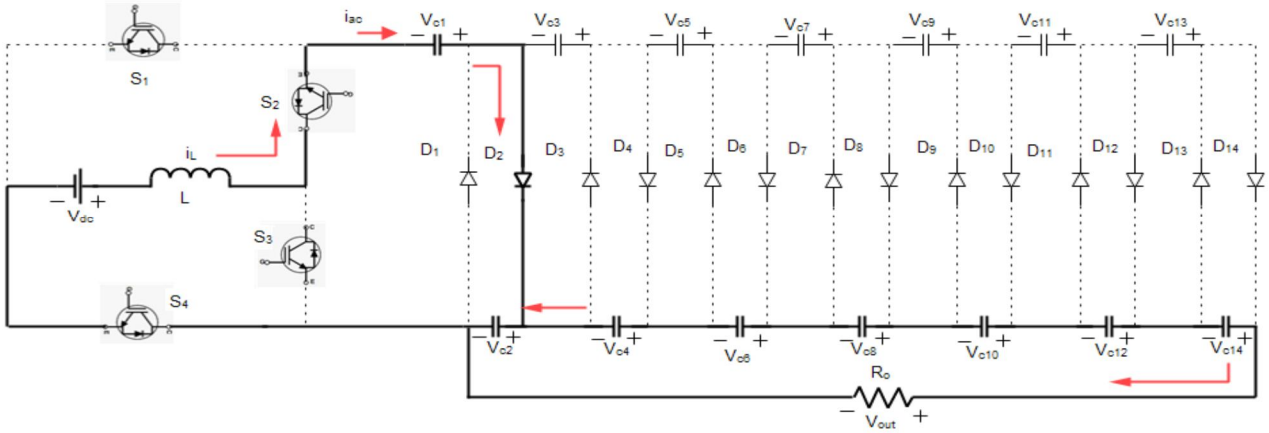


Fig. 11. VIII Mode of operation

V_{out}	Output voltage
n	Number of multiplier stages
D	Duty ratio of switch sm1
K	Percentage of the peak-peak ripple current
V_{ck}	Steady state voltage of the k^{th} capacitor.
Po	Output power
δV_{out}	Output voltage ripple
f_{sc}	Operating frequency of switches sci
T_{sm}	Switching period of switches smi

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TABLE I
CIRCUIT PARAMETERS

Parameters	Values
Vin	40 V
Vout	1200 V
n	7
Po	1 kW
fsc	7 kHz
fsm	70 kHz
Ro	1.4 kΩ
K	0.05 %
Ls	2.1 mH
C	47 µF

. *B.Circuit specification*

In this work, a seven stage converter is considered and the input voltage of 40 V is boosted to 1200 V. Selected parameters and the designed component values are tabulated in Table.I

IV.SIMULATION ANALYSIS

The impact of different combinations of capacitors are determined by conducting simulation studies on the seven stage converter using MATLAB/SIMULINK software. Simulation diagram is shown in the Fig.12. The simulation is done for three different configuration of capacitors.

A. Case-i:C2i=Ci=C

In this case, all the capacitors of Cockcroft-Walton voltage multiplier are of same value. Designed value of base capacitance is 47µF. The output voltage ripple is around 66 V (i.e.) 5.5 % of voltage ripple is present in the output voltage of 1200 V. The inductor current has a ripple of around 350 mA. The gain of the converter is around 28.75

B. Case-ii: $C_{2i}=C_i=C$ & C1=2C

In this case, the first capacitance is considered to be twice than that of others. Here C1 = 94 µF and Ci = 47 µF for every i = 2,3..2n. The output voltage ripple is around 64 V (i.e.) 5.33 % of voltage ripple is present in the output voltage. The inductor current has a ripple of around 350 mA. The gain of the converter is around 29.7.

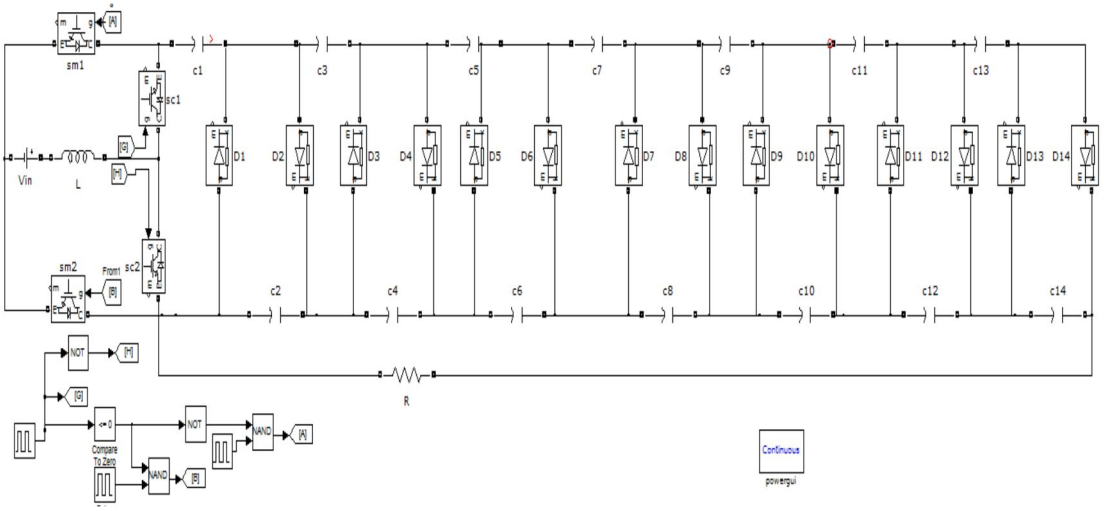


Fig. 12. Simulation circuit

C. Case-iii: C2i=Ci=(n-i+1)C

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Here, the capacitance of each stage differs from other stages. Here the value of capacitor depends on that particular stage number.

C1 = C2 = 329 µF
C3 = C4 = 282 µF
C5 = C6 = 235 µF
C7 = C8 = 188 µF
C9 = C10 = 141 µF
C11 = C12 = 94 µF
C13 = C14 = 47 µF

The output voltage ripple is around 16 V (i.e.) 1.33 % of voltage ripple is present in the output voltage. The inductor current has a ripple of around 180 mA. The gain of the converter is around 30.375.

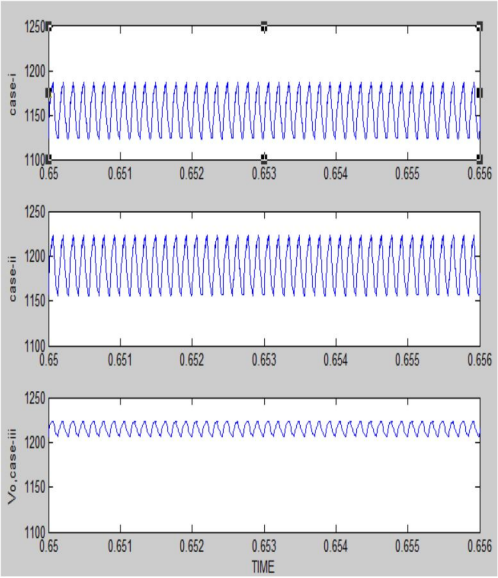


Fig. 13. Output voltage

D. Comparison Of Different Capacitor Configuratons

From the fig.13, it is observed that the voltage ripple in caseiii is lesser than that of case-i and ii. Moreover the ripple content in input current is also reduced as shown in the fig.14. It is also observed that different capacitor combination has impact in gain of the converter. Thus overall performance of the converter is improved while using different capacitors(C2i=Ci=(ni+1)C) at different stages of the multiplier section.

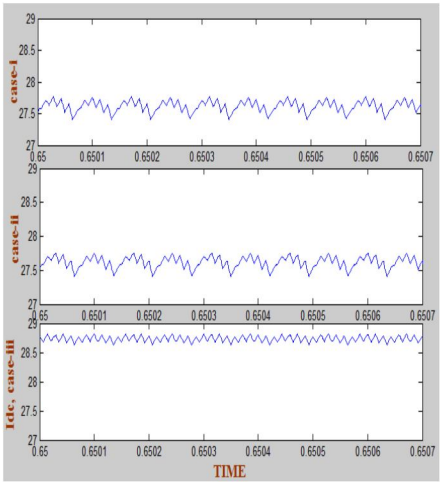


Fig. 14. Output current

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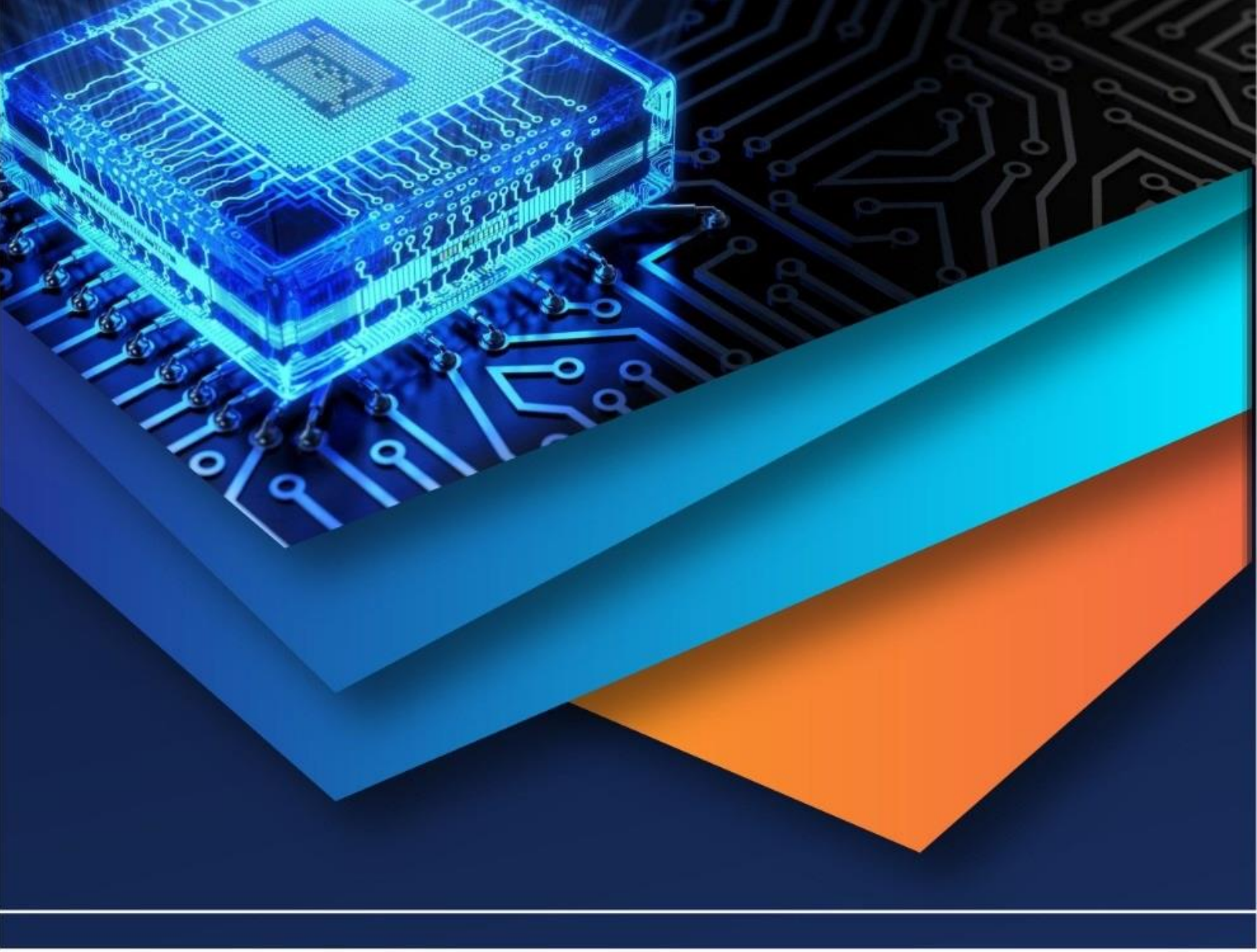
V. CONCLUSION

A step-up converter based on seven stage Cockcroft-Walton voltage multiplier is analysed. Converter with three different capacitor combinations are designed and simulated. The impact of different capacitor configuration on output voltage ripple, input current ripple and gain of the converter is analysed. Impact of different capacitor combination is more pronounced as the number of multiplier stages increases. Thus converter performance has been improved by using different capacitor combination. Thus voltage multiplier based step-up converter provides a cost effective solution for high voltage requirements. The proposed configuration has a few short comings like overshoot that need to be addressed to make it robust and applicable for all the systems.

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