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RESEARCH ARTICLE OPEN ACCESS

A Wide Voltage Gain Converter with Cockroft-Walton Voltage Multiplier Cells

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ABSTRACT
There has been increasing demand for the development of clean and pollution free energy. Fuel cell is one of the major leap in this field due to its high efficiency and non-pollution. In this a capacitor clamped H-type boost DC-DC converter with Cockroft-Walton voltage multiplier cell is presented. The input side of the converter is a capacitor clamped H-type structure which reduces the input current ripple and in the output side three units of Cockroft-Walton voltage multiplier cells are adopted to get high voltage gain. It has many advantages such as high voltage gain, low input current ripple and low stress on all power semiconductors and capacitors. The performance study of the converter is carried out with MATLAB/SIMULINK R2017a. The input voltage of the converter varies from 25 V to 70 V. From the simulation results it is observed that the efficiency is 77% at an input voltage of 70 V and 65.6 % at an input voltage of 25 V. The converter has wide voltage gain varying in the range 19 to 8.03 for an input voltage in the range of 25V to 70V. The converter can be used as a step up device in fuel cell vehicles to interface with the the fuel cell stack.

Keywords - Boost converter , Cockroft-Walton voltage multiplier cell, Wide voltage-gain range

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I. INTRODUCTION

The continuous use of fossil fuel resources are causing their fast depletion as well as increase in pollution. In such a scenario the development of clean energy systems is essential. Photovoltaic power generation, wind power generation and fuel cell power generation are important clean energy technologies which are in use nowadays. With regard to transport, clean-energy vehicles which include fuel cell vehicles, pure electric vehicles, and hybrid energy source vehicles can be considered as one of the most essential applications for clean energy.

In order to improve the reliability of the fuel cell stack and provide a constant output voltage for the load, we need to use a DC-DC converter with a wide voltage gain as a medium to connect to the high voltage DC bus. Due to the space constraints and reliability requirements for fuel cell vehicles, the step-up DC-DC converter should have the features like small size, high effciency and high reliability. Also the input current of the converter should be continuous and the current ripple must be low enough to avoid reducing the life of fuel cells. Several DC-DC converters based on isolated and non-isolated topologies have been presented in literatures to obtain the wide voltage-gain range. In isolated converters there is two-stage transformation of power, and these two stages are DC-AC-DC [6]. However, considering the limited cost and space in fuelcell vehicles, Non-isolated DCDC converters are more suitable to be interfaced to the fuel cell stack, with the advantage of low cost and high effciency. A capcitor clamped H-type boost converter with switched capacitor[1] was proposed, inspite of having voltage gain, the voltage stress across all switches and diodes are high. Even though the coupled inductor converters[2]-[4] provide very high voltage gain, for single-stage-single-phase coupled inductor converters, ripple in input current is very large. The leakage-inductor energy of the coupled inductor can be recycled, and the voltage stress on the active switch is reduced. Much higher voltage gain is achieved by using the coupled-inductor and voltage-lift techniques. However, the active switch will suffer high current stress during the switch on period. A switched inductor converter also provides better voltage gain but causes high voltage stress on diodes. Another common boost technique known as the switched capacitor structure[5] has been widely used as a step up solution. The use of different voltage multiplier units also increases the conversion ratio.

To overcome these difficulties a wide voltage gain boost converter with Cockroft-Walton voltage multiplier cells at the output side is proposed. The Cockcroft-Walton voltage multiplier is basically a device used for the generation of high DC voltage. It consists of networks of diodes and capacitors connected in form of a ladder network. Boost conveter with cockroft Walton Voltage multiplier cells at the output is presented in [6]-[8]. An input parellel output series capacitor boost converter was presented[9] series output capacitors increases voltage gain.

A nine stage CW voltage multiplier based stepup converter is introduced in [10]. Inspite of having high voltage gain the converter has certain short comings like overshoot that need to be addressed to make it robust and applicable for all the systems. These voltage multipliers are primarily used to develop high voltages where low voltage is present at the input side. The advantages of Cockcroft-Walton Multiplier circuit are that it is low in cost, small in size and can be easy to insulate the circuit. The use of voltage multiplier technique applied to the classical non-isolated dc-dc converters helps to obtain high step-up static gain, reduction of the maximum switch voltage.

II. OPERATING PRINCIPLES OF PROPOSED CONVERTER

2.1. Configuration of the Proposed Converter

The configuration of the proposed converter divides into two modules as shown in Fig. 2. Module 1 is a capacitor clamped H-type structure (L, S_1, D_1, D_2, C_1) and module 2 comprises of three units of Cockroft-Walton voltage multiplier cells cascaded. The capacitor clamped H-type structure is used to reduce input current ripple, the voltage multiplier cells at the output increases the voltage gain and also reduces the voltage stress across all power semiconductor devices and capacitors to less than the output voltage.

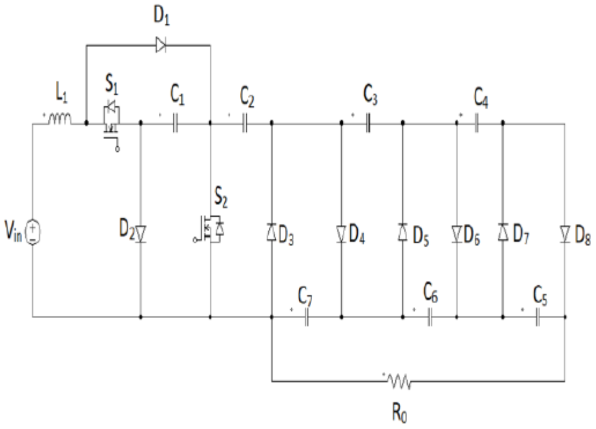


Fig.1. Configuration of Proposed Converter

The operating principles of the proposed converter are analyzed when the input current is continuous. In this case, suppose that d1 =d2 =d, where d1 and d2 are the duty cycle of S1 and S2 respectively, and the phase difference between the gates driving signals of two switches is 180. Module is a capacitor clamped H-type structure consisting of L, S_1,diodes D_1, D_2 capacitor C_1 , module 2 comprises of three units of Cockroft-Walton voltage multiplier cells which are cascaded.

The voltage multiplier cell consist of diodes D_3, D_4, D_5, D_6, D_7, D_8 and capacitors C_2, C_3, C_4, C_5, C_6 , C_7 and by using the capacitor clamped H-type structure and Cockroft- Walton voltage multiplier cells together the voltage gain is increased considerably.

2.2 . Mode 1 [t0-t1]

In this mode switch S1 is turned on and switch S2 is in off state. Diodes D_2, D_4, D_6, and D_8 are forward biased and all other diodes are reverse biased. Inductor L is charged from the input source with a linearly rising current iL. Capacitors C_3, C_6 and C_4, C_5 are connected in parellel. All the capaitors dischargeduring this mode. Capacitors C_7, C_6 and C_5 discharge to load. The output voltage decreases
linearly.

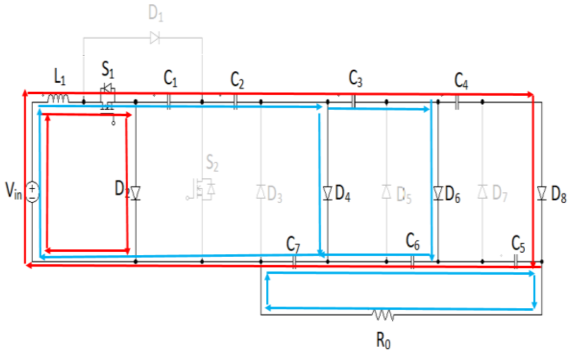


Fig. 2. Energy flow path in mode 1

2.3. Mode 2 [t1-t2]

During this mode both the switches S1 and S2 are turned on. Diodes D_1, D_2, D_4, D_6, and D_8 are forward biased and all other diodes are reverse biased. During this mode inductor discharges to capacitor C_1 and load. Capacitors C_6 and C_5 are charged from C_3 and C_4 respectively. Capacitors C_3 ,C_6 and C_4 , C_5 are connected in parellel. Capacitors C_7 , C_6 and C_5 discharge to load.The output voltage increases linearly.

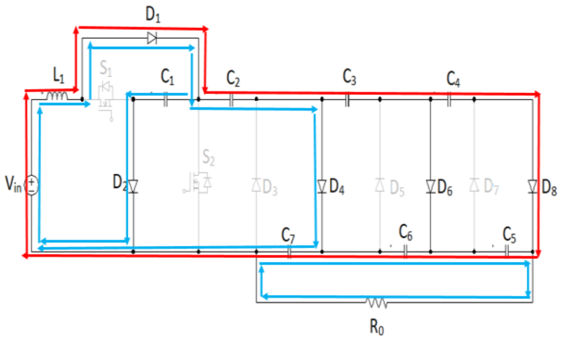


Fig. 3. Energy flow path in mode 2

2.4. Mode 3 [t2-T]

During this mode switch S2 is turned on and switch S1 is in off state. Inductor current rises linearly as it is charged from input source. Diodes D_1, D_3, D_5, D_7 are forward biased and all other diodes are reverse biased. The capacitor C_1 is neither charged nor discharged in this mode. Also Capacitors C_3 , C_7 and C_4, C_6 are connected in parellel. Capacitor C_6 charges C_4 and capcitor C_7 discharges to both C_3 and C_2. The load is supplied by output capacitor C_5.

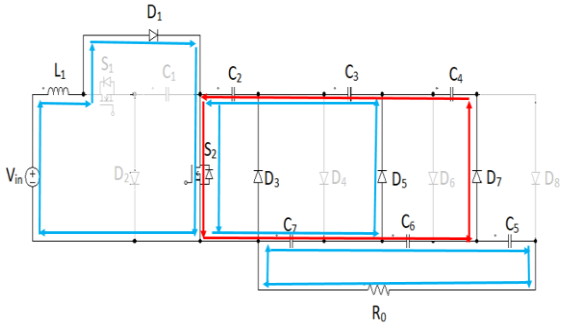


Fig. 4. Energy flow path in mode3

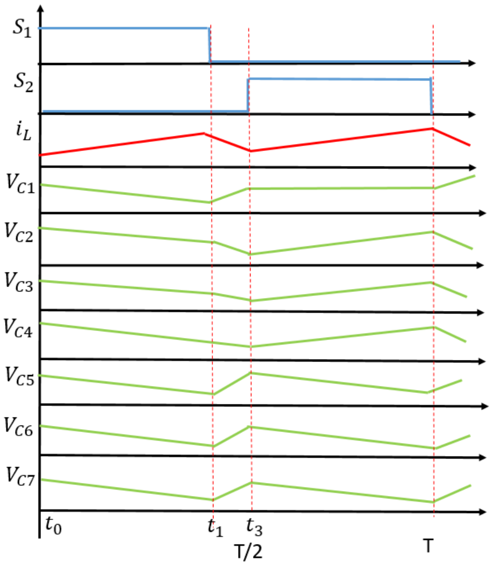


Fig.5. Theoretical Waveform

III. DESIGN CONSIDERATION OF MAIN COMPONENTS

The input voltage is taken as 25 V. The pulses are switched at the rate of 20 kHz with a duty ratio of 43.75% , Output Power P0=560.5 W. The output voltage is taken as V0= 475 V and the output current is I0=1.18 A with output power as 400 W. The voltage gain M is 16 for input voltage of 25 V and input current Iin =34.8 A. The voltage gain of the converter is given by

$$\frac{V_0}{V_{in}} = \frac{2}{1-2d} \qquad (1)$$

3.1 Design of Inductor L

At input voltage of 25 V with voltage gain 19 the inductance is,

$$L = \frac{d(1-2d)^2 * R}{4fr} \qquad (2)$$

For continuos current the an inductor with inductance of 120µH was selected.

3.2. Design of Capacitor C_1

The value of capacitor C1 is calculated as,

$$C_1 = \frac{(1+2d) * V_0}{f \Delta V_0 R} \qquad (3)$$

Leaving a certain margin, the selected capacitance value is 270 µF.

3.3. Design of Capacitors $C_{2,3,4,5,6,7}$

Inorder to facilitate later maintenance, capacitors of equall capacitance are selected for $C_{3\text{-}7}$

$$C_2 = \frac{I}{f * V_{C_2}} \left\{ \frac{2}{3} n^3 + \frac{n^2}{2 - \frac{n}{6}} \right\} \qquad (4)$$

Leaving a certain margin, the selected capacitance value is 270 µ F.

$$C_{3-7} = \frac{I}{f * V_{C_{3-7}}} \left\{ \frac{2}{3} n^3 + \frac{n^2}{2 - \frac{n}{6}} \right\} \qquad (5)$$

Inorder to avoid large output voltage ripple at heavy load of the converter, leaving a certain margin, the selected capacitance value is 25 µF.

IV. SIMULATION RESULTS

The performance study of the converter is carried out with MATLAB/SIMULINK R2017a.The values of the parameters used for simulation is given in Table .1. below.

Table.1. Simulation Parameters

Parameters	**Specifications**
Input Voltage (V_{in})	25 V
Output Voltage (V_0)	475 V
Switching Frequency (f_s)	20 kHz
Rated Output Power (P_0)	560 W
Output load Resistance(R_0)	400 Ω
Inductors (L)	120 μH
Capacitor (C_1)	270 μF
Capacitor (C_2)	50 μF
Capacitors (C_3 , C_4, C_5 , C_6 , C_7)	25 μF

The wide voltage gain boost converter with Cockroft-Walton voltage multiplier cell is simulated in MATLAB/SIMULINK by choosing the parameters listed in table. The simulation results of the wide voltage gain boost converter with CW cell are shown in the following figures.

It can be seen that the input voltage V_{in} is 25 V and the input current I_{in} is 34.8 A. The switching frequency is chosen to be 20 kHz and the duty ratios of S_1 and S_2 is equal to 0.4375. From figure the ripple in input current is 3.6 A. The voltage stress and current through switches S_1 and S_2 is shown in

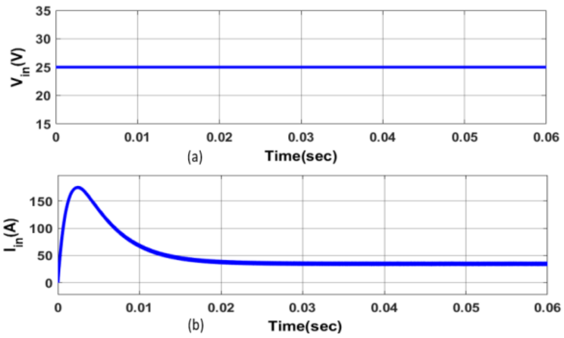


Fig. 6. (a) Input Voltage V_{in}, (b) Input current I_{in}.

Figure.7. It can be seen that by adding the voltage multiplier units to the converter, the switching stress across both the switches has reduced to 165.6 V, which is less than even half of the output voltage.

The input current of the converter shown I Figure.6. has a mean value of 34.8 A. The inductor current is same as that of the input current. From the simulation the ripple in the inductor current is 3.6 A, which is less than that of a conventional boost converter.

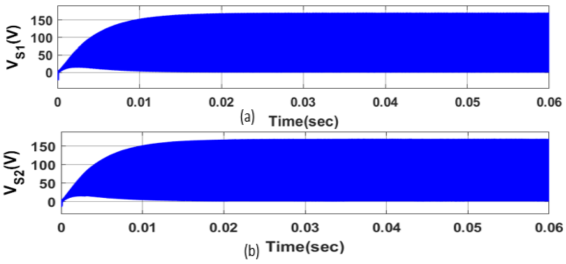


Fig. 7. Voltage stress across switches (a)V_{S1},(b)V_{S2}

The capacitor voltage values are obtained as V_{C1}=166.6 V, V_{C3}=159 V, V_{C4}=158 V, V_{C5}=160 V, V_{C6}=158 V, V_{C7}=157.4 V and the respective ripple values in the capacitor voltage are 0.4 V, 0.9 V, 0.55 V, 0.8V, 0.9 V, 0.4 V as per simulation. For an input voltage of 25 V the converter has an output voltage of 475 V and an output current of 1.18 A.

Also the gain of the converter is 19 for 25 V input voltage. From Figure.9. the mean value of output voltage is 475.5 V and mean value of output current is 1.188 A. The output voltage ripple is 2.7 V whereas the output current ripple is 0.006 A.

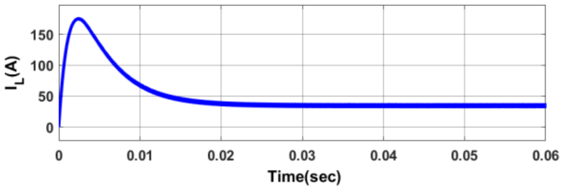


Fig.8. Inductor current

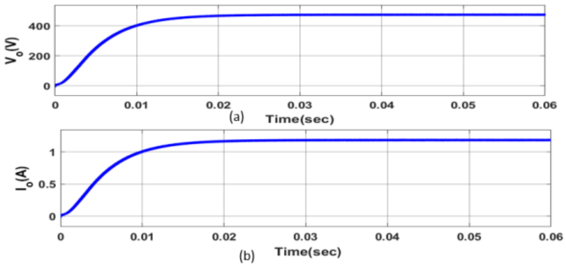
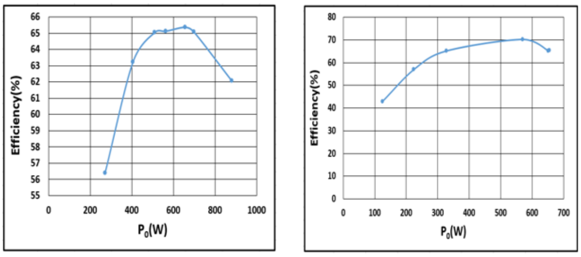


Fig. 9. (a) Output Voltage V_0, (b) Output current I_0

V. ANALYSIS FROM THE SIMULATION RESULTS

Based on the simulation results the analysis of the converter was performed to verify the operation of converter during different conditions.



(a)

(b)

Fig. 10. P_0 Vs Efficiency (a) R load, (b) RL load

Figure.10. shows the power output Vs Efficiency curve of the converter for R and RL load, for an input voltage of 25V. From the analysis it can be inferred that the converter has a maximum efficiency of 65.5% at an output power of 655.2 W, and for RL load the maximum efficiency is 70 % at an output power of 570.3 W.

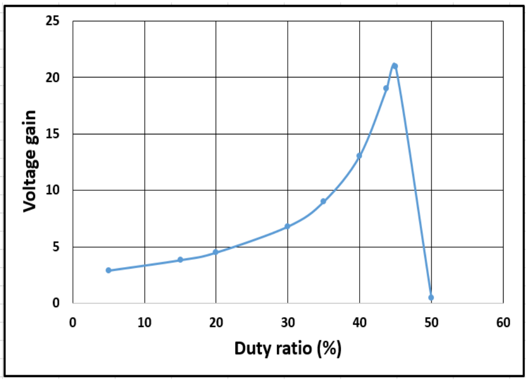


Fig. 11. Voltage gain Vs Duty ratio

The variation of voltage gain with duty ratio at a constant input voltage of 25 V is shown in Figure .11. As the duty ratio is varied from 5 to 45 % the voltage gain of the converter changes from 2.913 to 21 and it drops to .5 when the duty ratio is 50% . So by varying the control strategy the the gain of the converter has increased considerably. From the analysis of Output voltage ripple Vs duty ratio curve in Figure.12 it is clear that as the duty ratio is increased above the operating duty ratio of 43.75 % the ripple magnitude increases to higher values which is not desirable.

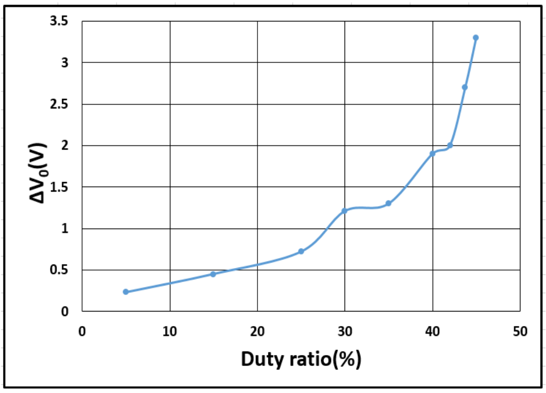


Fig. 12. Output voltage ripple Vs Duty ratio

From the analysis of various performance characteristics drawn based on the simulation results it can thus be concluded that the desirable duty ratio of the converter is always less that 50% otherwise it will lead to very low voltage gain and also increased voltage ripple.

VI. CONCLUSION

A wide voltage gain boost converter with Cockroft-Walton voltage multiplier cell was presented in this paper, which has the advantages of higher voltage gain, low voltage stress across all semiconductor devices and capacitors. For increasing voltage gain three units of voltage multiplier cell was added at the output side. The input voltage of the converter can be varied in the range 25-70 V and gain of the converter is 19 at input voltage of 25 V. The simulation of the converter was performed and analysis was done based on the simulation results. From the analysis it can be seen that the duty ratio of the converter should be below 50 %.

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