INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH & DEVELOPMENT

ISSN 2278 – 0211 (Online)

DC-DC Converter Based on Cockcroft-Walton for High Voltage Gain

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Abstract:
This paper proposes a high step-up DC-DC converter based on Cockcroft-Walton (CW) voltage multiplier without using step up transformer. The low input DC voltage is boost up by boost inductor (Ls) in DC-DC converter and the proposed circuit performs the inverter operation. The n-stage CW-voltage multiplier is applying low input AC voltage to high output DC voltage. It provides continuous input current with low ripple, high voltage gain, reduced switching losses, low voltage stress on the switches, diodes and capacitors and also improving efficiency of the converter. The power switches having two independent frequencies fsm and fsc. The fsm operates at higher frequency of the output voltage and it is regulated by controlling the duty cycle of Sm1 and Sm2, while the fsc operates at lower frequency of the desired output voltage ripple and it can be adjusted by Sc1 and Sc2. Finally the proposed converter is validated by MATLAB simulation.

Key words*: Cockcroft-Walton Voltage Multiplier, High Voltage Ratio, Multilevel Inverter, Step-Up DC-DC Converter*

1. Introduction

The extensive use of electrical equipment has imposed severe demands for electrical energy and this trend is constantly growing. The conventional boost DC-DC converter can provide a very high voltage gain by using an extreme high duty cycle. The step-up dc-dc converters have been proposed to obtain high voltage ratios without extreme high duty cycle by using isolated transformers or coupled inductors. The current fed converters are providing a low input current ripple and high voltage ratio. The design of the high-frequency transformers, coupled inductors or resonant components for these converters are relatively complex compared with the conventional boost DC-DC converter. The step-up DC-DC converters without step-up transformers and coupled inductors were presented. By cascading diode-capacitor or diode-inductor modules, these kinds of DC-DC converters provide not only high voltage gain but also simple and robust structures. The conventional Cockcroft-Walton voltage multiplier is very popular among high voltage DC applications. Replacing the step-up transformer with the boost type structure, the proposed converter provides a higher voltage ratio than that of the conventional CW voltage multiplier. The proposed converter operates in continuous conduction mode, so that switch stresses, the switching loss, and EMI noise can be reduced.

2 Steady State Analysis of Proposed Converter

The proposed converter is supplied by a low-level dc source, such as battery, PV module or fuel cell sources. The proposed converter consists of one boost inductor L_s, four switches (S_{m1}, S_{m2}, S_{c1}, and S_{c2}), and one n-stage CW voltage multiplier. S_{m1} (S_{c1}) and S_{m2} (S_{c2}) operate in complementary mode, and the operating frequencies of S_{m1} and S_{c1} are defined as f_{sm} and f_{sc}, respectively. For convenience, f_{sm} is denoted as modulation frequency and f_{sc} is denoted as alternating frequency. In this paper, f_{sm} is set much higher than f_{sc}, and the output voltage is regulated by controlling the duty cycle of S_{m1} and S_{m2}, while the output voltage ripple can be adjusted by f_{sc}. As shown in figure 1, in an n-stage CW voltage multiplier, there are N (=2n) capacitors and N diodes.

2.1. Circuit Operating Principle

As shown in figure 1, the proposed converter is an integration of a boost converter with a CW voltage multiplier. The proposed converter is supplied by a low-level DC source such as a battery. The proposed converter consists of one boost inductor (L_s), four switches (S_{m1}, S_{m2}, S_{c1}, and S_{c2}), and one n-stage CW voltage multiplier. S_{m1} (S_{c1}) and S_{m2} (S_{c2}) operate in complementary mode, and the operating frequencies of S_{m1} and S_{c1} are defined as f_{sm} and f_{sc}, respectively. For convenience, f_{sm} is denoted as modulation frequency and f_{sc} is denoted as alternating frequency.

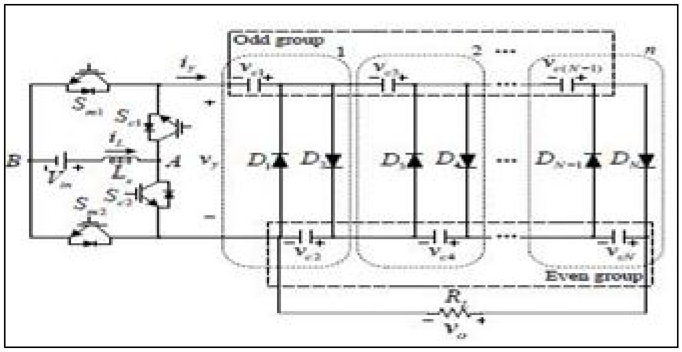
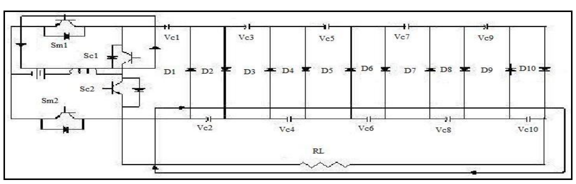


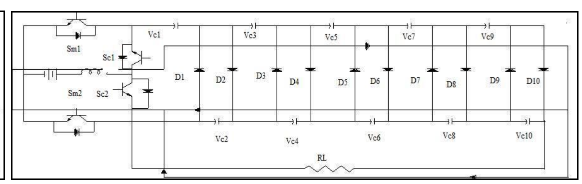
Figure 1: Proposed Converter With N-Stage CW Voltage Multiplier

These two frequencies should be as high as possible, so that smaller inductor and capacitors can be used in this circuit. The frequency f_{sm} is set much higher than f_{sc}, and the output voltage is regulated by controlling the duty cycle of S_{m1} and S_{m2}, while the output voltage ripple can be adjusted by f_{sc}. The circuit operation principle of the proposed converter and the characteristic behavior of each mode in both positive and negative-half cycles are presented as follows:

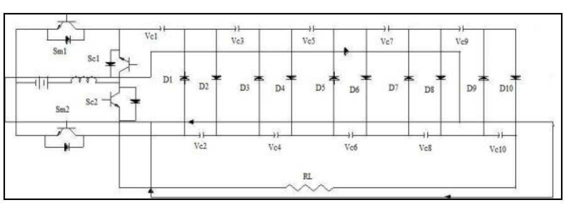
- **Mode-1:** S_{m1}, S_{c1} are turned on, and S_{m2}, S_{c2}, and all CW diodes are not conducting. The boost inductor is charged by the input DC source, the odd-group of capacitors C_1, C_3, C_5, C_7, C_9 are Floating, and the even-group of capacitors C_2, C_4, C_6, C_8, C_{10} and are Supply the load as shown in figure 2.
- **Mode-2:** D_8 is conducting and D_1 to D_9 are not conducting, thus, the even-group capacitors C_2, C_4, C_6, C_8, C_{10} Charged and the odd-group capacitorsC_1, C_3, C_5, C_7, C_9, and C_9 are discharged by i_γ.
- **Mode-3:** D_8 is conducting, thus, C_2, C_4, C_6, C_8, C_{10} is charged while C_1, C_3, C_5, C_7, C_9 are discharged by i_γ.
- **Mode-4:** D_{10} is conducting, thus, C_2, C_4, C_6, C_8 and C_{10} are charged while C_1, C_3, C_5, C_7& C_9 are discharged by i_γ.



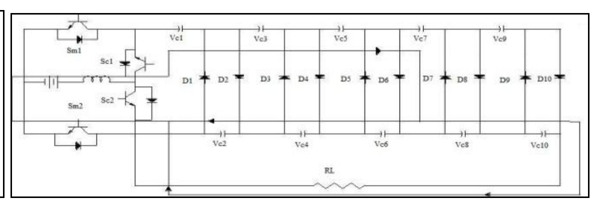
Mode-1



Mode-2

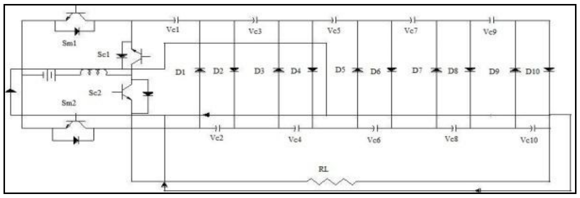


Mode-3

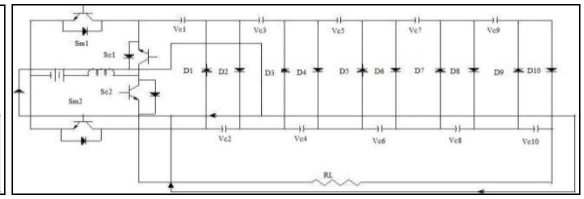


Mode-4

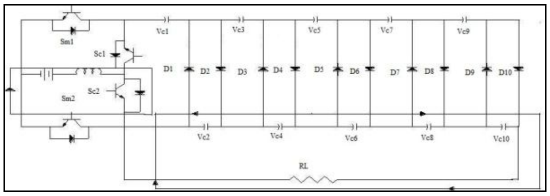
- **Mode-5:** D_8 is conducting, thus, C_2, C_4, C_6 and C_8 are charged whileC_1, C_3, C_5 and C_7 are discharged by i_γ.
- **Mode-6:** D_6 is conducting, thus, C_2, C_4 and C_6 are charged while C_1, C_3 and C_5 are discharged by i_γ.
- **Mode-7:** D_4 is conducting, thus, C2 and C_4 are charged whileC_1 and C_3 are discharged by i_γ.
- **Mode-8:** D_2 is conducting, thus, C_2 is charged while C_1 is discharged by i_γ.
- **Mode-9:** S_{m2} and Sc_2 are turned on, S_{m1}, Sc_1 and all CW diodes (D_1 to D_{10}) are not conducting. The boost inductor is charged by the input DC source, the even-group capacitors C_2, C_4, C_6, C_8 and C_{10} are supplying the load, and the odd-group capacitors C_1, C_3, C_5, C_7 and C_9 are floating.



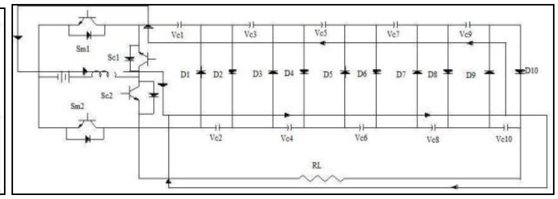
Mode-5



Mode-6

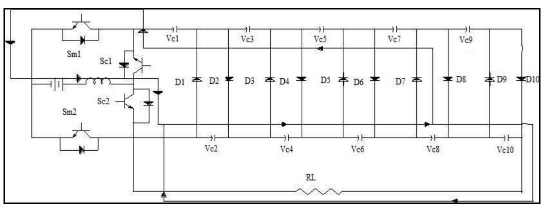


Mode-7

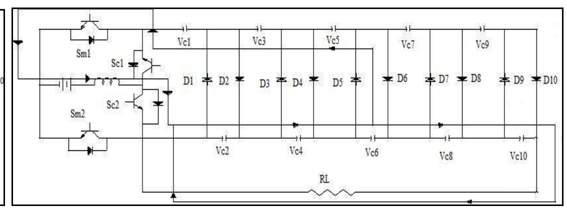


Mode-8

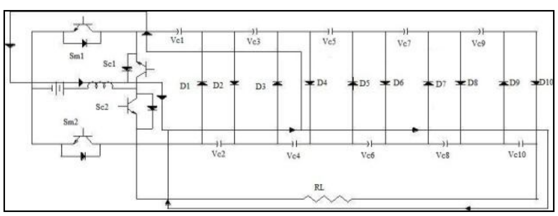
- **Mode-8:** D_9 is conducting, thus, the even-group capacitors C_2, C_4, C_6, C_8 and C_{10} are discharged and the odd-group capacitors C_1, C_3, C_5, C_7, and C9 are charged by i_γ as shown in figure 2.
- **Mode-9:** D10 is conducting, thus, C_2, C_4, C_6, C_8, C_{10} and C_{12} are discharged and C_1, C_3, C_5, C_7 and C_9 are charged by i_γ, C_{14} is supply load current and C_{13} is floating as shown in figure 2.
- **Mode-10:** D_9 is conducting, thus, C_1, C_3, C_5, C_7 and C_9 are charged by i_γ, while all even capacitors C_2, C_4, C_6, C_8 and C_{10} are discharged.



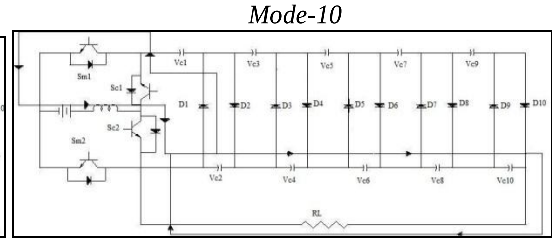
Mode-9



Mode-10



Mode-11



Mode-12

- **Mode-11:** D_7 is conducting, thus, C_2, C_4, C_6 and C_8 are discharged and C_1, C_3, C_5 and C_7 are charged by i_γ, C_{10} are supply load current and C_9 are floating.
- **Mode-12:** D_5 is conducting, thus, C_1, C_3 and C_5 are charged by i_γ, while all even capacitors C_2, C_4 and C_6 are Discharge, C_8, C_{10} are supply load current, and C_7, C_9 are floating.

2.2. Cockcroft Walton Voltage Multiplier

The Cockcroft Walton (CW) voltage multiplier is constructed by a cascade of n-stage with each stage containing two capacitors and two diodes. The CW-voltage multiplier having both capacitors and diodes are divided into odd group and even group according to their suffixes.

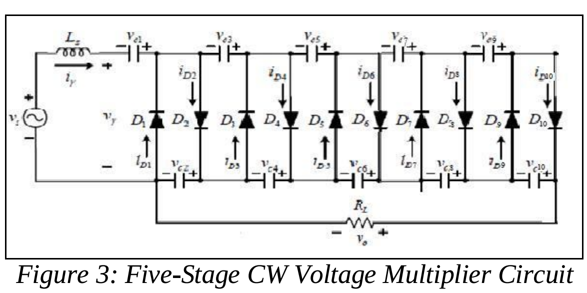


Figure 3: Five-Stage CW Voltage Multiplier Circuit

According to the polarity of the current is i_γ, the operation of the proposed converter can be divided into two parts: positive conducting interval for $i_\gamma>0$ and negative conducting interval for $i_\gamma<0$. During the positive conducting interval, only one of the even diodes can conduct with the sequence D_{10}-D_8-D_6-D_4-D_2, during negative conducting interval, only one of the odd diodes can conduct with the sequence D_9-D_7-D_5-D_3-D_1. Moreover, during positive conducting interval, there are four modes of operations. In mode-1, S_{m1} turns on, thus the energy stored in the inductor increases. The switching pulse waveforms are shown in figure 4. In modes-2, 3, 4, 5, 6, 7 and 8, S_{m2} turns on, and the inductor transfers energy to the CW circuit through D_{10}, D_8, D_6, D_4, and D_2 respectively.

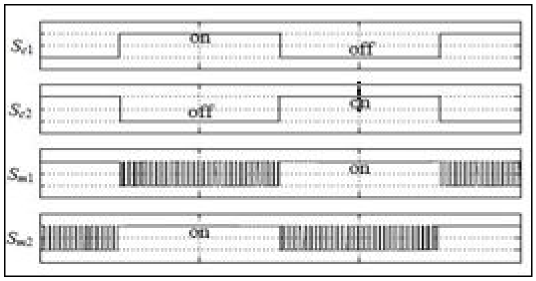


Figure 4: Switching Pulse Waveforms

3. Simulation Circuit

The simulation circuit is separated into two parts; they are DC-DC boost converter with inverter and five stages of Cockcroft Walton voltage multiplier circuit. The proposed converter is supplied by a low-level DC source such as the battery. The simulation circuit of the proposed converter with five-stage CW voltage multiplier is shown in figure5. For convenience, fsm is denoted as modulation frequency and fsc is denoted as alternating frequency these two frequencies should be as high as possible, so that smaller inductor and capacitors can be used in this circuit.

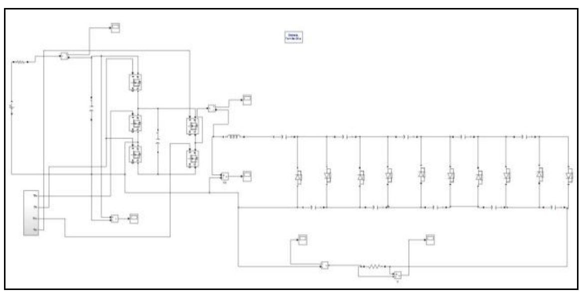


Figure 5: Simulation Circuit of Proposed Converter with Five-Stage CW Voltage Multiplier

The frequency fsm (60 kHz) is set much higher than fsc (1 kHz), and the output voltage is regulated by controlling the duty cycle of Sm1 and Sm2, while the output voltage ripple can be adjusted by fsc in Sc1 and Sc2. The system specification of the prototype designs is shown in table I.

4. Design Considerations of Proposed Converter

In this section, the voltage and current stresses on each capacitor, switch, and diode will be considered. Moreover, the values of inductor and capacitors will be discussed as well.

4.1. Capacitor Voltage Stress

In steady-state condition, assuming that all capacitors are large enough, then each capacitor in an n-stage CW voltage multiplier, theoretically it has the same voltage except the first one, which has one half of the others. It can be seen that the capacitor voltage of the proposed converter only depends on the input voltage and duty cycle, while the capacitor voltages of the others are dependent on the number of the cascade stages, thus the determination of the capacitor rating is easier for the proposed converter.

4.2. Capacitance of CW-Voltage Multiplier

In steady-state condition, assuming that all capacitors are large enough, then each capacitor in an n-stage CW voltage multiplier, theoretically it has the same voltage except the first one, which has one half of the others. For comparison, the voltage stress on each capacitor corresponding to the high step-up converters. It can be seen that the capacitor voltage of the proposed converter only depends on the input voltage and duty cycle, while the capacitor voltages of the others are dependent on the number of the cascade stages, thus the determination of the capacitor rating is easier for the proposed converter.

4.3. Formula and Mathematical Representation

The individual stages are:

C1=C'1=C2=C'2=Cn=C'n

$$\Delta V_n = \left(\frac{q}{c}\right) n$$

$$\Delta V_{n-1} = \left(\frac{q}{C}\right) [2n + (n-1)]$$

By summation and with q=I/f

$$\Delta V_0 = \frac{1}{fc}\left(\frac{2n^3}{3} + \frac{n^2}{2} - \frac{n}{6}\right)$$

- V out = 2n*V ac.
    - n = Number of Stags.
    - V ac = Peak input AC voltage.
- V out = 2(5)*11.95.
- V out = 119.5v.

5. Simulation Results and Waveform Analysis

The system specifications and the waveform explain in detail the operation of proposed DC-DC boost converter with five-stage Cockcroft Walton voltage multiplier. Components of the prototype are summarized in table I and table II, respectively. Moreover, Matlab/Simulink is applied to simulate the mathematic model and control strategy of the proposed converter. Some selected waveforms of the proposed converter at *Vin*=12V and *Vo*=119V for both simulation and experiment. The upper part of the switching signals having four switches, in which *Sc1* and *Sc2* are operated at *fsc*, and *Sm1* and *Sm2* are operated at *fsm*. Moreover, the simulation results of the output voltage *vo*, the input current *iL*, the terminal voltage *vγ* and current *iγ* of the CW voltage multiplier are shown in the lower part. The experimental waveforms of the switching signals, *vo*, *iL*, *vγ*, and i*γ*. Obviously, the simulation results well agree with experimental results.

Parameters	Ratings
Input DC voltage, Vin	12V
Output Voltage, Vo	119V
Modulation frequency, fsm	52KHZ
Alternating frequency, fsc	1KHZ
Resistive load, RL	1KW
Stage numbers, n	5
Capacitors, C1 - C2	470µF

Table 1: System Specification of the Prototype

Components Description	Symbol	Value/Part no.
Control IC	-	PIC16F788A
CPLD	-	LC4256V
Boost Inductor	Ls	1.5mH
Power Switches	Sm1, Sm2,Sc1,Sc2	IRF640
Capacitors	C1-C2	470µF
Diodes	D1-D2	SF20L60U
Gate driver	-	HCPL-3120

Table 2: Component List for the Prototype

5.1. Simulation and Experimental Results

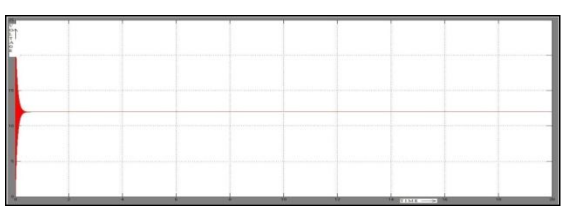


Figure 6: Simulation of Boost Converter of DC Input Voltage Waveform

The output waveform of the boost converter of DC input voltage is shown in figure 6.Some selected waveforms of the proposed converter Vin=12V, and Vout=119V for both simulation and experiment. The upper part of the switching signals of simulation for the four switches, which Sc1and Sc2 are operated at fsc, and Sm1 and Sm2 are operated at fsm.

Figure 7: Simulation of Gate Switching Pulse Waveforms

The simulation of switching pulse waveforms in DC-DC boost converter is shown in figure7.Obviously, the simulation results well agree with experimental results. In theoretical analysis, the input current ripple frequency (fsc) is ignored due to that the capacitors are assumed large enough to obtain stable capacitor voltages with no voltage ripple in the CW voltage multiplier. The simulation of output voltage waveform is shown in figure 8. The results also influence the terminal voltage Vγ and current iγ of the CW voltage multiplier.

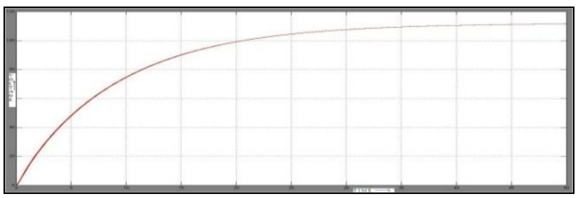


Figure 8; Simulation of Output Voltage Waveform

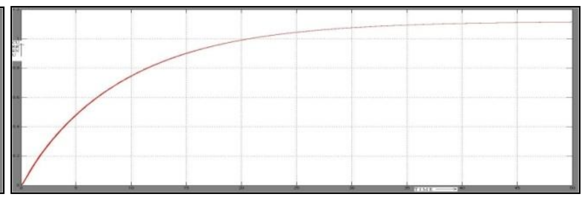


Figure 9: Simulation of Output Current Waveform

The results represent that the proposed converter has lower efficiency at lower input because of higher conducting loss accompanied by higher input current. The results represent that the proposed converter has lower efficiency at lower input because of higher conducting loss accompanied by higher input current. Thus the simulation of the DC-DC boost converter using Cockcroft Walton voltage multiplier was successfully carried out using MATLAB Simulink software and the output waveforms were observed.

6. Conclusion

In this paper, a high step-up DC-DC converter based on CW voltage multiplier without a line or high-frequency step-up transformer was presented to obtain a high voltage gain. The proposed control strategy employs two independent frequencies, one of which operates at high frequency to minimize the size of the inductor, while the other one operates at relatively low frequency according to the desired output voltage ripple. Finally, the simulation and experimental results proved the validity of theoretical analysis and the feasibility of the proposed converter. In future work, the influence of loading on the output voltage of the proposed converter will be derived for completing the steady-state analysis. Thus the design, simulation and analysis of proposed DC-DC boost converter with five-stage Cockcroft Walton voltage multiplier was done.

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