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INVESTIGATION ON VOLTAGE MULTIPLIER CELLS FOR HIGH STEP-UP CONVERSION

Anoop.K.J[1] and V. Rajini[2]
[1]Department of EEE, Saveetha School of Engineering, Chennai, Tamilnadu, India
[2]Department of EEE, SSN College of Engineering, Kalavakkam, Chennai, Tamilnadu, India
E-Mail: anoopkj7@gmail.com

ABSTRACT

The demand of high gain dc-dc converter is increasing as there is a need to utilize the power output from the low voltage sources such as PV, fuel cell. The high gain converters boost the low input voltage to high output voltage. In this paper a dc-dc converter with Cockcroft-Walton voltage multiplier cells is proposed to obtain high voltage gain. The voltage multiplier cells are made up of diodes and capacitors. They are used to develop a high static gain dc-dc converter with high efficiency.

Keywords: cockcroft-walton voltage multiplier cells (CWVM), dc-dc converter, high static gain.

INTRODUCTION

Several types of dc-dc converters are designed depending upon the applications. The dc-dc converters are used to boost the low input voltage to high voltage level. Such converters are used in audio amplifiers [1], uninterruptible power supplies (UPSs) [2], fuel cell powered systems [3] and forklift vehicles [4]. The dc-dc converters can be designed with transformer to increase the output voltage. This also provides isolation. But practically the transformer increases the weight and cost when it is used for high power applications [5-6].

The conventional boost converters are preferred where very high voltage gain conversion is not required. Such converter has a simple design and low losses [7]. The boost converters theoretically have infinite gain when duty cycle becomes unity. However, practically the gain is reduced by I^2R loss in the boost inductor [8]. There are many different topologies to boost low input voltage. One of the topology is switched capacitors. A high gain converter is obtained by integrating the switched capacitors to a boost converter [9]. However, it is applicable only to low power applications, this problem can be overcome by adding capacitors to increase the dc output voltage. The main drawback of this method is large number of components are required and cost is also increased.

Another method to develop a high gain converter is by using transformer. These converters can easily achieve the high voltage gain. But the major issue is the size of the transformer for high output power applications. The leakage inductance of the transformer also causes many problems such as high voltage stress, EMI generation and high switching losses. Such problem affects the efficiency of the boost converter and it can be avoided by providing active clamping techniques. By using this technique the voltage stress and EMI production can be limited. Isolated converters have limited use in the embedded applications because the size and weight of the transformer.

Many new non-isolated topologies were proposed to obtain high voltage gain and high efficiency converters [10-18]. The simplest and easiest way to produce a high step-up converter is by using voltage multiplier cells [19]. There are various topologies in voltage multiplier cells depending upon the arrangements of the capacitors and diodes. Cockcroft-Walton is one of the topology to obtain high gain converter. In this converter transformer is absent but low dc input voltage is boosted by using capacitors and diodes alone. In this paper a dc-dc converter with CW voltage multiplier is proposed and its performance is compared with Diode-capacitor voltage multiplier cells (DCVM).

System description

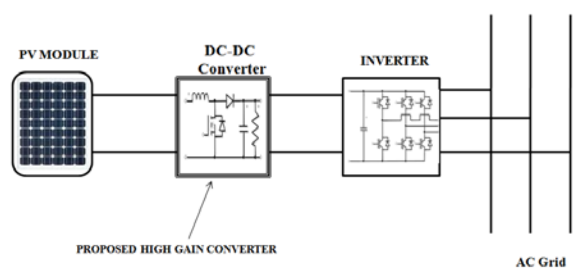

Figure-1. PV Module connected to AC grid.

The Figure-1 shows the application area of the proposed high gain converter. This converter can be used for fuel cell power system; solar PV system where the grid connected inverter needs to be fed.

Cockcroft walton voltage multiplier

Usually transformer is used to increase the low voltage. But the size and weight of the transformer is increased for high power applications. The alternative approach is voltage multiplier cells. This is a unique type of rectifier circuit used to convert AC input voltage to DC output voltage which is several times larger than its input voltage. It is used in cathode-ray tube field coils, microwave ovens, electrostatic and high voltage test equipment.

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The CW is a type of voltage multiplier circuit which converts a low input AC or pulsating DC voltage level to a higher DC voltage level. It is composed of capacitors and diodes to produce high voltages. Unlike transformers, it eradicates the need of heavy core and the bulk insulation. The voltage multiplier cells boost the low input voltage by using diodes and capacitors, so it is cheap and is light in weight.

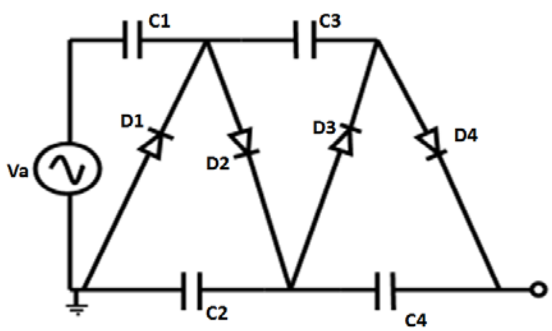


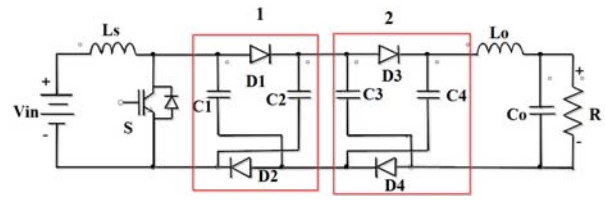
Figure-2. Two stages of fundamental Cockcroft-Walton circuit.

The operation of the CW voltage multiplier is quite simple. Figure-2 shows the two-stages of Cockcroft-Walton voltage multiplier cells, which is fed by ac source. During negative half cycle the leftmost diode D1 will conduct and first capacitor C1 will be charged. During positive half cycle the second diode D2 will conduct and second capacitor C2 is charged by both first capacitor and AC source. Thus the second capacitor is charged twice the first capacitor. The output voltage of the CW is twice the peak input voltage multiplied by number of stages when there is more than one stage. In the proposed circuit the AC source is suitably replaced by DC source with four switches to enable CW voltage multiplier to be used for DC applications.

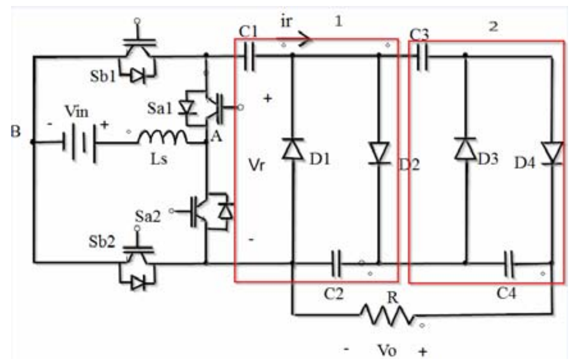
Voltage multiplier cells

The boost converter circuit with diode-capacitor voltage multiplier cells is shown in Figure-3 (a). It consist of input boost inductor Ls, switch S, output inductor Lo and two stages of voltage multiplier cells. The voltage multiplier cells consist of two diodes and two capacitors in each stage. The voltage gain of the converter can be increased easily by adding number of stages of voltage multiplier cells without modifying the main circuit. The main disadvantage of this circuit is that the voltage across the each capacitor increases when number of stages increases to achieve high voltage gain.

The CW voltage multiplier cells also consist of two diodes and two capacitors in each stage as shown in Figure-2(a). When voltage multiplier is designed for n-stages it requires 2n diodes and capacitors. The arrangement of capacitors and diodes are classified into odd and even group.



(a)



(b)

Figure-3. Converters with two different topologies of voltage multiplier cells. (a) Diode-capacitor voltage multiplier cells. (b) Cockcroft-Walton voltage multiplier cells.

The CW converter has the same number of devices as that of the first one in the multiplication stages. But in the first type circuit the capacitor stress progressively increase as the number of stages increase. So the proposed multiplier cell is capable of achieving higher voltage gain without high duty ratio.

Switching Pattern for CW cells

The different switching pattern of four switches is shown in Table-1. The given dc source is converted into ac by this switching pattern.

Table-1.

I				II			
Sa1	**Sa2**	**Sb1**	**Sb2**	**Sa1**	**Sa2**	**Sb1**	**Sb2**
0	1	0	1	0	1	1	1
0	1	1	0	0	1	1	0
1	0	0	1	1	0	0	1
1	0	1	0	1	0	1	1
-	-	-	-	1	1	1	1
-	-	-	-	1	1	1	1

Modes of operation

The CW dc-dc converter is supplied by a dc source. It is connected to one n-stage CW through boost inductor and four switches (Sb1, Sb2, Sa1 and Sa2). The four switches operate at two different frequencies fsa and fsb. The frequencies fsa and fsb can be referred to as alternating frequency and modulating frequency

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respectively. The switches Sa1 and Sa2 are operated at alternating frequency and switches Sb1 and Sb2 are operated at modulating frequency. In the present analysis, fsb is kept at high frequency whereas fsa has a low frequency. By using two different frequencies the ripples can be reduced in output voltage and increase in the efficiency of the dc-dc converter can be observed.

The different modes of operation of CW dc-dc converter as presented.

State 1

In state1 the switches Sb1, Sa1 are turned on and remaining switches are in off state. All the diodes in the CW are not conducting. The boost inductor in the CW dc-dc converter is charged by the input source. The capacitors C1 and C3 are floating. The load is supplied by the capacitors (C2 and C4) as shown in Figure-4(a).

State 2

The switches Sb2 and Sa1 are turned on in state2, where other switches are (Sb1 and Sa2) turned off. The positive current iγ is flowing in the circuit. The input source supplies the load through different even diodes of the CW voltage multiplier.

Figure-4(b) shows state2-A in which even diode D4 is conducting. The even capacitors C2 and C4 charged. The odd capacitors C1 and C3 are discharged.

State2-B is shown in the Figure-4(c). In this state diode D2 is conducting. The even capacitors C2 is charged and odd capacitor C1 is discharged. The load is supplied by capacitor C4 and capacitor C3 is floating.

State 3

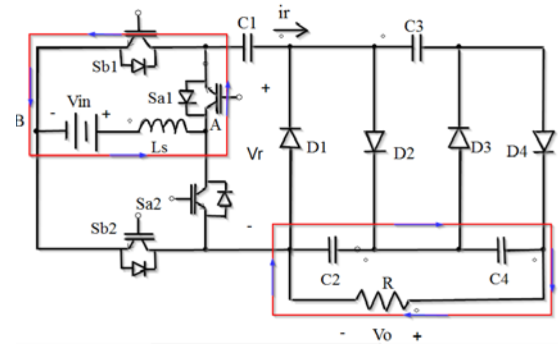
In this state the switches Sb2 and Sa2 are turned on. All the diodes in CW voltage multiplier are not conducting. The input source charges the boost inductor. The load is supplied by even capacitors (C2 and C4). The odd capacitors C1 and C3 are floating as shown in the Figure-4(d).

State 4

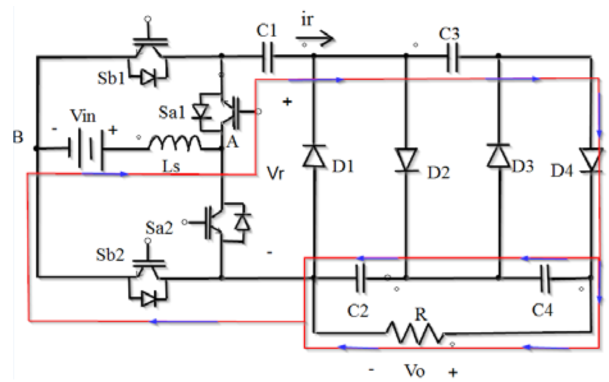
The switches Sb1 and Sa2 are turned on and the remaining switches Sb2 and Sa1 are turned off. The negative current is iγ flowing in the circuit. The boost inductor is discharged. The input DC source supplies the energy to the load through different odd diodes of CW.

Figure-4(e) shows the state4-A in which diode D3 is conducting. The capacitors C1 and C3 are charged and the capacitor C2 is discharged. The load is supplied by capacitor C4.

The state4-B is shown in Figure-4(f) in which odd diode D1 is conducting. The odd capacitor C1 is charged. All even capacitors C2 and C4 supplies load current and capacitors C3 is floating.



(a)



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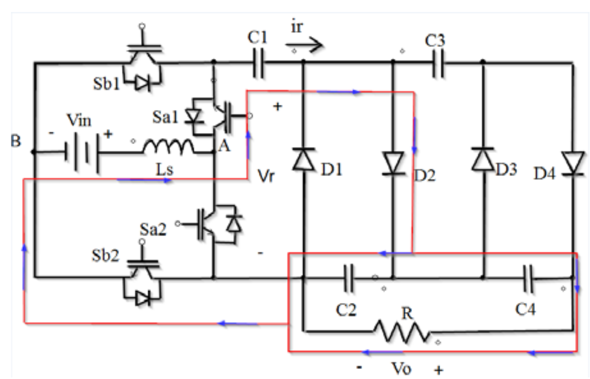
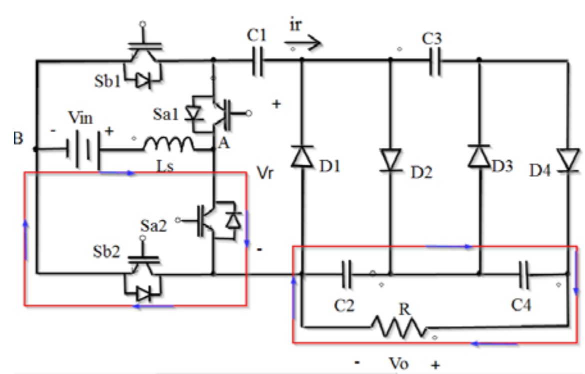


(c)



(d)

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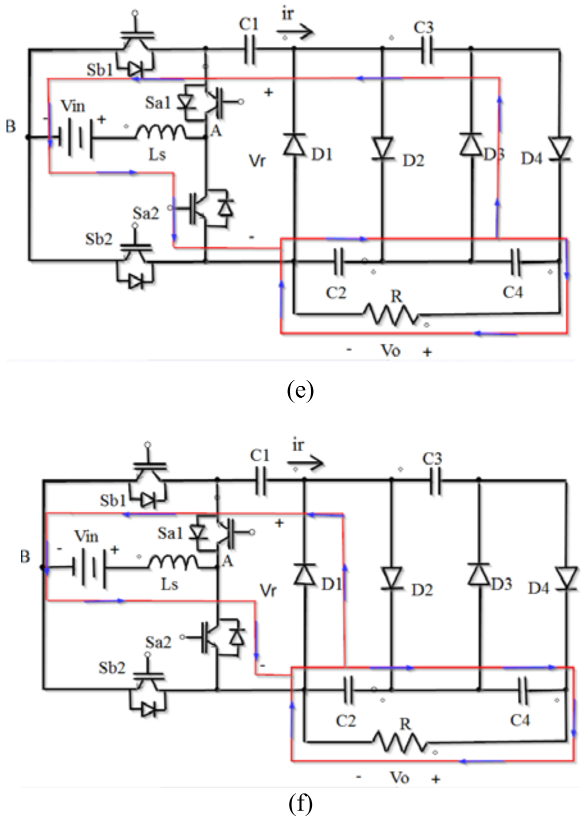

Figure-4. Modes of operation (a) State1. (b) State2-A (c) State2-B (d) State3 (e) State4-A (f) State4-B.

Analysis of CW converter

The voltage source is converted into current source for analysis purpose in CW converter as shown in Figure-5.

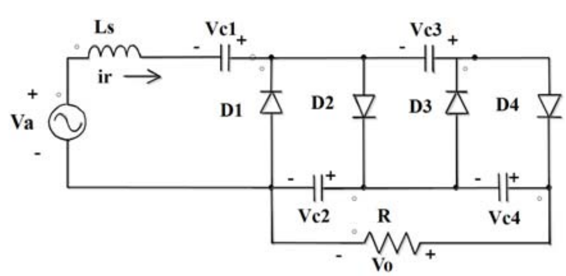

Figure-5. CW converter with current source.

The characteristics of the circuit are

a) In CW converter the energy flow to load takes place only through the diode when input voltage is greater than zero.
b) In both positive and negative half cycles the diodes will conduct from right side to left side in the circuit.
c) The conduction of the diode is determined by input voltage Va and capacitor voltages.

The conduction of the diode is denoted by term Ds

$$D_s = \max(K_x)\, for \begin{cases} V_a = 0, x = 0 \\ V_a \rangle 0, x = 2,4,...2n \\ V_a \langle 0, x = 1,3,...2n-1 \end{cases} \tag{1}$$

where *Kx* is

$$K_x = \begin{cases} x,\ forx \le 2 \\ x,\ forx \rangle 2 and V_{c(x-1)} \rangle V_c \\ 0,\ forx \rangle 2 and V_{c(x-1)} \le V_c \end{cases} \tag{2}$$

For analysis purpose the capacitors are classified into even and odd group capacitors. By using Ds we can identify the charging of even and odd capacitor.

$$EvenCapacitorC_{Ei} = \begin{cases} 0, D_s \langle i \\ 1, D_s \ge i, i = 2,4,...2n \end{cases} \tag{3}$$

$$OddCapacitorC_{oj} = \begin{cases} 0, D_s \langle j \\ 1, D_s \ge j, j = 1,3,..2n-1 \end{cases} \tag{4}$$

When C_{Ei} and C_{Oj} =0 means capacitor is located at right side of the conducting diode and C_{Ei} and C_{Oj} =1 means capacitor is located at left side of the conducting diode. The capacitor voltages are classified into four groups with the help of C_{Ei} and C_{Oj}.

$$v_{cel} = \sum_{i=2,4,..}^{2n} C_{Ei} v_{ci} \tag{5}$$

$$v_{col} = \sum_{j=1,3,..}^{2n-1} C_{oj} v_{cj} \tag{6}$$

$$v_{cer} = \sum_{i=2,4,..}^{2n} (1 - C_{Ei}) v_{ci} \tag{7}$$

$$v_{cor} = \sum_{j=1,3,...}^{2n-1} (1 - C_{oj}) v_{cj} \tag{8}$$

where v_{cel}(v_{col}) means series voltage of even (odd) capacitors on the left side of conducting diode and v_{cel}(v_{col}) means series voltage of even (odd) capacitors on the right side of conducting diode.

The input voltage of the CW converter can be determined by

$$v_{\Gamma} = v_{cel} - v_{col} \tag{9}$$

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$$v_o = v_{cel} + v_{cer} \quad (10)$$

The voltage gain equation for CW converter is

$$G = \frac{2n}{1-D} \quad (11)$$

where n is number of stages, D is duty cycle .

The boost inductor value at the input side can be calculated by

$$L_s = V_{in}\left(\frac{DT_{sb}}{K_c I_p}\right) \quad (12)$$

where Tsb=1/fsb, Ip is the maximum peak value of input current, Kc is expected percentage of the maximum peak to peak ripples in the inductor current.

The voltage across each capacitor for n-cascaded CW voltage multiplier is

$$V_{cx} = \begin{cases} \dfrac{V_o}{2n}, for x = 1 \\ \dfrac{V_o}{n}, for x = 2,3,..N \end{cases} \quad (13)$$

where Vo= nVc, Vc is the steady-state voltage of Vc2 to VcN.

RESULTS AND DISCUSSIONS

The Matlab simulation is done for two stages Cockcroft-Walton voltage multiplier. Figure-6 shows the gating pattern of the switches. The simulation parameters are given in Table-2.

Table-2. Parameters for simulation.

Components	Specifications
Capacitor	470µF
Inductor	1.5mH
Modulating frequency	60kHz
Alternating Frequency	1kHz
Load	1kΩ
Input Voltage	54V

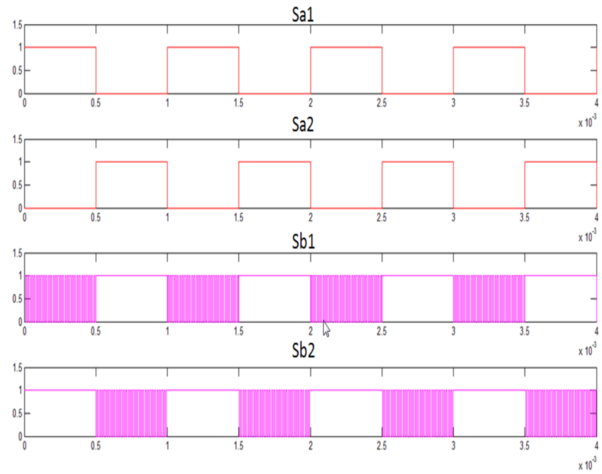

Figure-6. Gate pattern for switches.

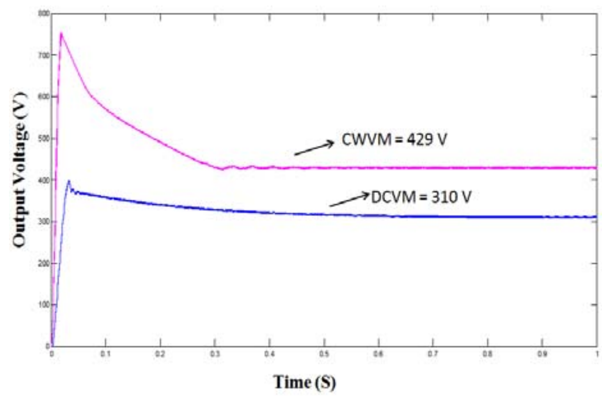

Figure-7. Load voltage for CWVM and DCVM.

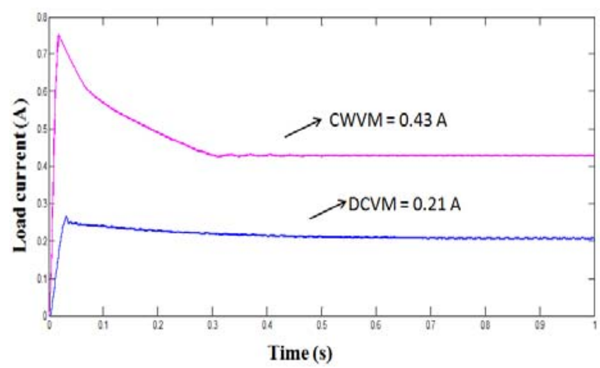

Figure-8. Load current for CWVM and DCVM.

The load voltage and current waveforms of both the circuits are shown in Figure-7 and Figure-8. From Figure-7 it may observe that the voltage gain of CWVM is higher than that of DCVM.

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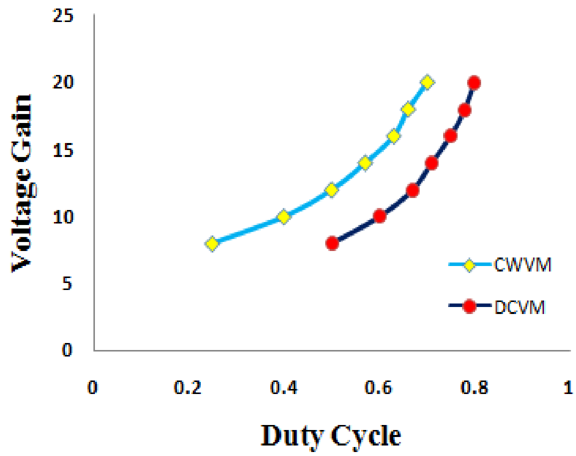

Figure-9. Duty cycle versus voltage gain.

The variation of voltage gain for different duty cycles of both Cockcroft Walton voltage multiplier and Diode-Capacitor voltage multiplier is shown in Figure-9. It shows that Cockcroft Walton has higher voltage gain for lower duty cycles.

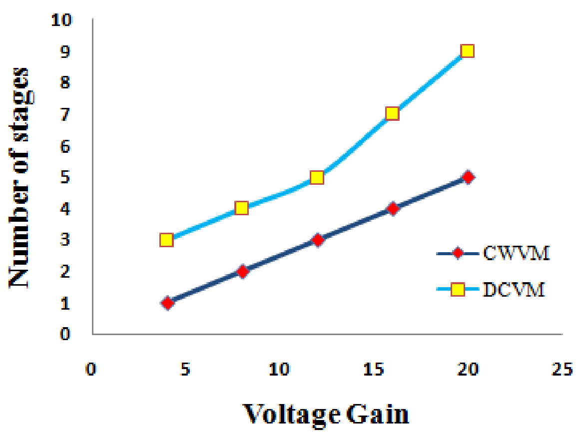

Figure-10. Voltage gain versus number of stages.

In Figure-10 shows the variant of voltage gain for number of stages for both Cockcroft Walton voltage multiplier and Diode-Capacitor voltage multiplier. It is clear that Cockcroft Walton has higher voltage gain for less number of stages. Thus the efficiency of proposed converter with Cockcroft Walton is higher with less number of stages.

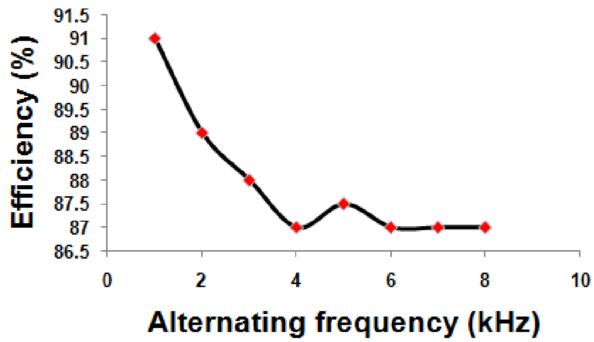

Figure-11. Alternating frequency versus efficiency.

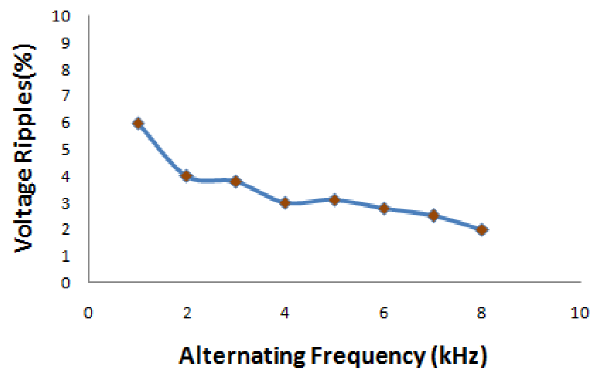

Figure-12. Alternating frequency versus voltage ripple.

Figures 11 and 12 justify the choice of lower frequency for switches Sa1 and Sa2. They show the efficiency and voltage ripple variation of the proposed converter for different alternating frequency. While the efficiency is maximum at lower frequencies the output voltage ripples would be less only at higher frequencies. As a tradeoff between efficiency and voltage ripple, the frequency is selected as 1 kHz, for switching Sa1 and Sa2.

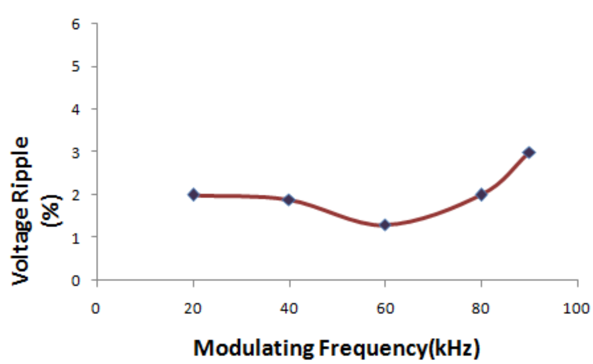

Figure-13. Modulating frequency versus voltage ripple.

The variation of voltage ripple for different modulating frequency is shown in Figure-13. Thus ripples

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in the output voltage are reduced at 60 kHz modulating frequency.

Experiments and Results

The hardware of DC-DC converter with Cockcroft-Walton voltage multiplier cell is shown in Figure-14.The hardware details of CW dc-dc converter is shown in Table-3.

Table-3.

Components	Specifications
Load	100Watts
Capacitor	1000µF/35V
Inductor	1.8 mH/1.2 A
Diode	IN5819
Voltage Controller IC	MAX232CPE
IGBT	FGA25N120
Microcontroller	PIC16F877A
Number of stages	3

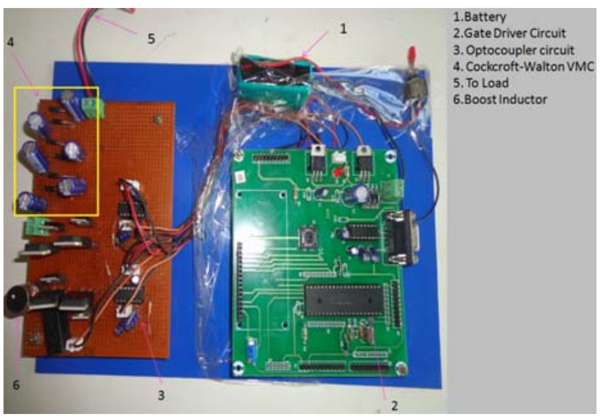

Figure-14. Hardware of DC-DC converter with Cockcroft-Walton.

The output voltage and input voltage of the DC-DC converter with CW is shown in Figure-15.

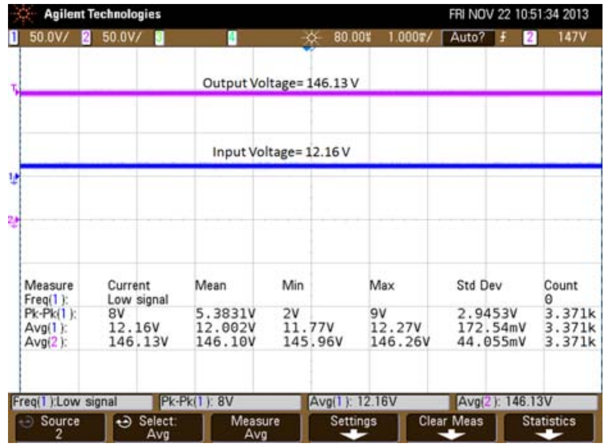

Figure-15. Input voltage and output voltage of the CW DC-DC converter.

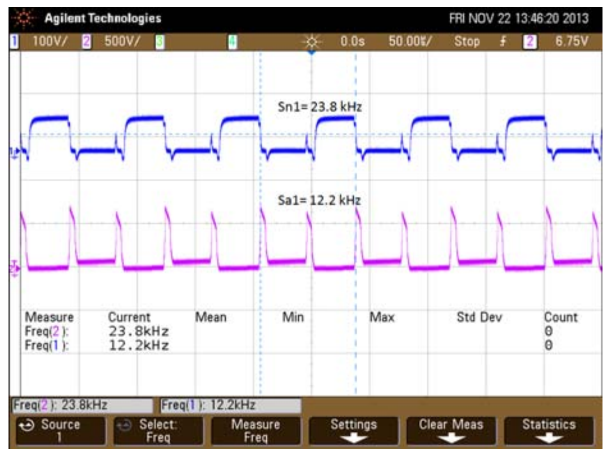

Figure-16. Gating pulse of two different switches.

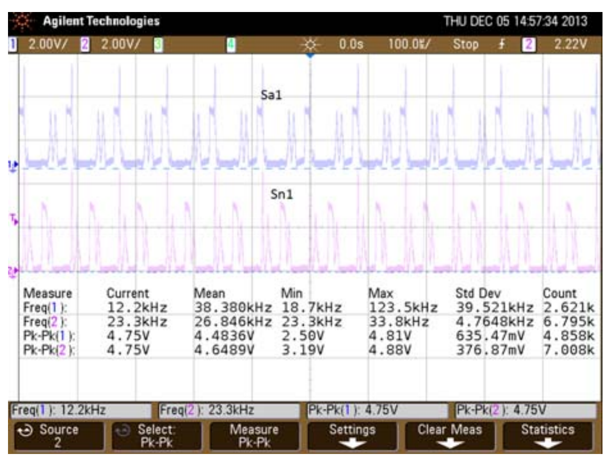

Figure-17. Voltage stress across the switches.

The gating pulse waveform of the switches and voltage stress across the switches is shown in Figure-16 and Figure-17.

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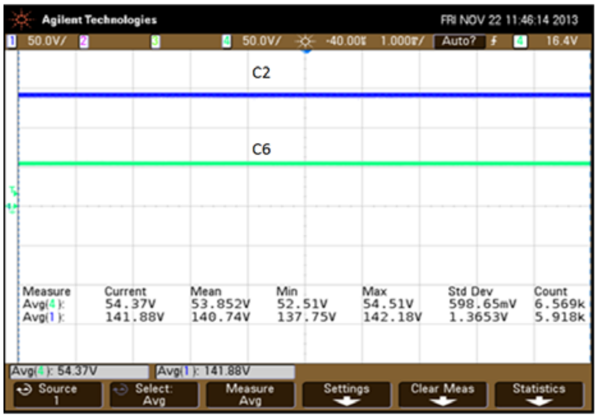

Figure-18. Voltage across the capacitors.

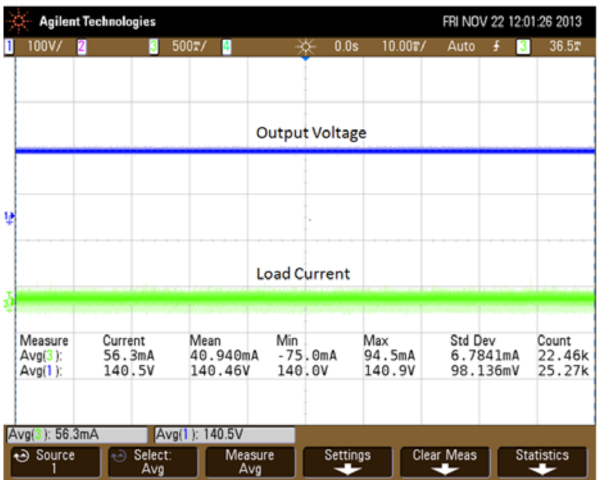

Figure-19. Output voltage and load current of the CW DC-DC converter.

Figure-18 shows the voltage across the capacitors and the load current and output voltage is shown in Figure-19. All these measurements were made using DSO Agilent Technologies.

CONCLUSIONS

Thus a high step-up dc-dc converter with CW voltage multiplier is proposed. This has got high voltage gain without high duty ratio. The voltage stress across switches and capacitors do not depend on the number of stages. So the devices can be selected with same voltage rating. The DC-DC boost converter with three-stage Cockcroft Walton voltage multiplier cells can be used for high gain requirements.

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