

Interleaved quadratic boost converter integrated with Dickson voltage multiplier with energy storage for high power photovoltaic applications

D. Amudhavalli¹, Nalin Kant Mohanty², Ashwin Kumar Sahoo³

^{1,2}Department of Electrical and Electronics Engineering, Sri Venkateswara College of Engineering, Tamil Nadu, India

³Department of Electrical and Electronics Engineering, C. V. Raman Global University, Bhubaneswar, Odisha, India

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ABSTRACT

In this paper interleaved quadratic boost converter with Dickson voltage multiplier is proposed. Photovoltaic system is connected to high power load through the proposed converter. Structure of this high gain interleaved converter comprised of two stages: interleaved quadratic boost converter stage and Dickson voltage multiplier stage. Interleaved quadratic boost converter is a parallel combination of two quadratic boost converter. The interleaving increases frequency of converter that could be filtered using small capacitors, making input current smoother than the current of conventional quadratic boost converter. Thus, interleaved circuit minimizes current ripple present in input current, cascading of voltage multiplier cell increases the gain voltage ratio of converter making it suitable for high power, high voltage gain photovoltaic applications. Stress voltage of the switches and reverse recovery problems gets reduced, thereby reducing EMI problems. 300W prototype capable of increasing 24V input voltage to 400V output voltage is designed and results tested using MATLAB/Simulink software. Hardware prototype is also implemented to verify simulation results. Also, application of this converter in integrated energy storage is demonstrated.

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Corresponding Author:

D. Amudhavalli

Departement of Electrical and Electronics Engineering

Sri Venkateswara College of Engineering

Sriperumbudur, Tamil Nadu, India

Email: amudhavalli@svce.ac.in

1. INTRODUCTION

Demand for electricity is consistently increasing throughout the globe year by year [1], [2]. The choice for supplying electricity produced from fossil fuel would not be a good option, because of their adverse effects like, continuous change in climatic conditions as a threat created by increasing emission of greenhouse gasses, by burning of fossil fuels [3]. Hence the entire world is turning towards generation of electricity using RES like wind, fuels cell and photovoltaic. Among them photovoltaic power is analyzed as promising electrical power generation systems, as sunshine required to generate electricity is available throughout the year and also it is available globally.

Recently Nano-grid concepts are introduced to utilize photovoltaic power and supplement the existing main grid efficiently, especially at remote rural areas [4], [5]. They are becoming a solution for providing electricity because of their advantages like (i) easy construction of renewable energy systems, (ii) ability to operate in both grid-connected and standalone mode and (iii) providing excess power generated either to grid

or battery swapping stations [6]. In this model generally motor loads are supplied by using inverter and the DC loads like DC fan, DC lights and electric vehicles are supplied directly from solar panel. Photovoltaic power available at low voltage levels has to be increased in level to satisfy the load voltages, especially when supplying 230V AC, where DC power has to be converted to AC by the inclusion of inverter [7], DC power available in photovoltaic panel has to be increased from 24V to 400V, for this DC converter plays a vital role. Challenging task is that the design should involve converters with large stepping up ratio and more efficiency. Boost converter used conventionally produces higher voltages only at higher duty ratios, leading to increased losses and decreased efficiency; moreover, it also leads to reverse recovery losses and requires use of large inductors to maintain continuous conduction stage leading to the accommodation of bulky magnetics. Hence two boost converters were connected in series, named cascaded converters, to obtain higher voltages at low duty ratios. This model involves provision of gate pulse to two separate switches; increasing complexity of the system operation especially when converter is operated in closed loop. To overcome this disadvantage single switch cascaded converters were introduced and were named Quadratic boost converter that is capable of increasing the input voltage to larger value [8], [9].

Many converters were designed to obtain high voltage gain by incorporating switched inductors or transformers [10], [11]. These topologies increase voltage gain by increasing turns ratio of the converter, but this leads to issues like, voltage spikes across switching devices urging to inclusion of Active clamping circuits [12]. It also reduces power density of converter and increases weight. Since the technological improvements made in semiconductor materials are faster than improvements made in magnetic materials, any suggestion to increase the power density of the converter by increasing its switching frequency increases losses occurring in magnetic materials, introducing them as severe culprits. A step-up DC-DC converter composed of resonant voltage doubler and active clamp circuit is proposed [13]. The active clamp circuit reduces the voltage stress of the switch to a maximum of input voltage and resonant voltage doubler aids to zero current switching turn-off of diodes reducing losses occurring due to reverse recovery of diode.

With switched capacitor (SC), the voltage gain is increased by charging in parallel and discharging in series [14]-[16]. Generalized fundamental limit theory in SC sets voltage gain ratio for k-flying capacitors in SCs were given [17]. This limit was acceptable for positive voltage-gain ratio, it was also discussed for negative voltage-gain ratio and multiple input and multiple output system. Efficiency of capacitor charging/discharging RC circuit was discussed [18], complete evaluation of overall efficiency was made and design rules were suggested for developing high efficiency SC. But as the voltage gain is increased, the numbers of SCs were increased making the converter complex and also flowing of high charging current through the switch is considered to be a drawback that increases conduction loss.

Two-stage converter consisting of interleaved boost converter with bifold Dickson Voltage multiplier for interfacing renewable energy sources to high voltage applications. It offers high voltage gain with low voltage stress on switches and passive components. Inductor currents are said to be equal regardless of number of VMCs. This equal sharing of current reduces conduction losses in active switches, improving overall efficiency, as the conduction power is a quadratic function [19]. Interleaved converter that is capable of drawing power from either a single source or two independent sources. Further voltage multiplier uses low voltage rating capacitors that leads to size reduction [20]. Very high voltage gains interleaved converter that uses two coupled inductors and voltage multiplier cell. This converter also holds all advantages of interleaved boost converter with voltage multiplier cell. Further reverse recovery problem is mitigated and the leakage energy is recycled and also implementing low voltage rated MOSFETs with a small ON-resistance, conduction losses is reduced, improving efficiency of converter [21], [22]. Three winding coupled inductors, voltage multiplier cell and a clamp circuit is proposed. Step-up voltage gain is increased owing to voltage-stack and voltage lift techniques using voltage multiplier cells. Leakage inductor energy is recycled by the clamp circuit to avoid the voltage surge on power switch. Moreover, this converter also holds the advantages of interleaved converters [23], [24].

Due to the advantages of interleaved converters and voltage multiplier cells a high voltage gain converter is proposed in this paper. High voltage gain is obtained by connecting Dickson Voltage Multiplier in series with interleaved quadratic boost converter. Proposed converter comprises of two stages: first stage is interleaved boost stage and second is the voltage multiplier stage. Interleaving shares input current equally in parallel connected converters, reducing input ripple occurring in source, making converter input current magnitude more suitable for maximum power point algorithms [25]-[28] and second stage increases overall voltage gain of converter [29]-[31]. Hence the converter includes the advantages of both interleaving and Voltage Multiplier Cell. The paper is organized in the following way. Section 2 elaborates modes of operation and steady state equations of converter. Section 3 displays the simulation results; Section 4 describes hardware results and Section 5 concludes the paper suggesting an application of the proposed converter.

2. OPERATION OF CIRCUIT

Interleaved quadratic boost converter with Dickson Voltage multiplier cell is shown in Figure 1(a). The converter proposed consists of two capacitors and inductors, with four diodes and nVMC cells. Single VMC cell consist of two diode and two capacitors.

To simplify the operation principle and steady state analysis, only two VMC are considered. Rearranged circuit is shown in Figure 1 (b). Switching pattern for the converter proposed is shown in Figure 1 (c). Gate driving is given. Mode 1 shown in Figure 2 (a), switch S_1 and S_2 are ON, hence diode D_1 and D_3 becomes ON and diodes D_2 and D_4 becomes OFF. Inductors L_1 and L_3 are charged by source voltage and inductors L_2 and L_4 are charged by charge stored in capacitor C_1 and C_2 . Since the two quadratic converters are shorted by switches S_1, S_2 no current is passed from source to load. Current in load is supplied by charge stored in capacitor V_{C2A} and V_{C2B} .

$$V_{L1} = V_{dc} \tag{1}$$

$$V_{L2} = V_{C1} \tag{2}$$

$$V_{L3} = V_{dc} \tag{3}$$

$$V_{L4} = V_{C2} \tag{4}$$

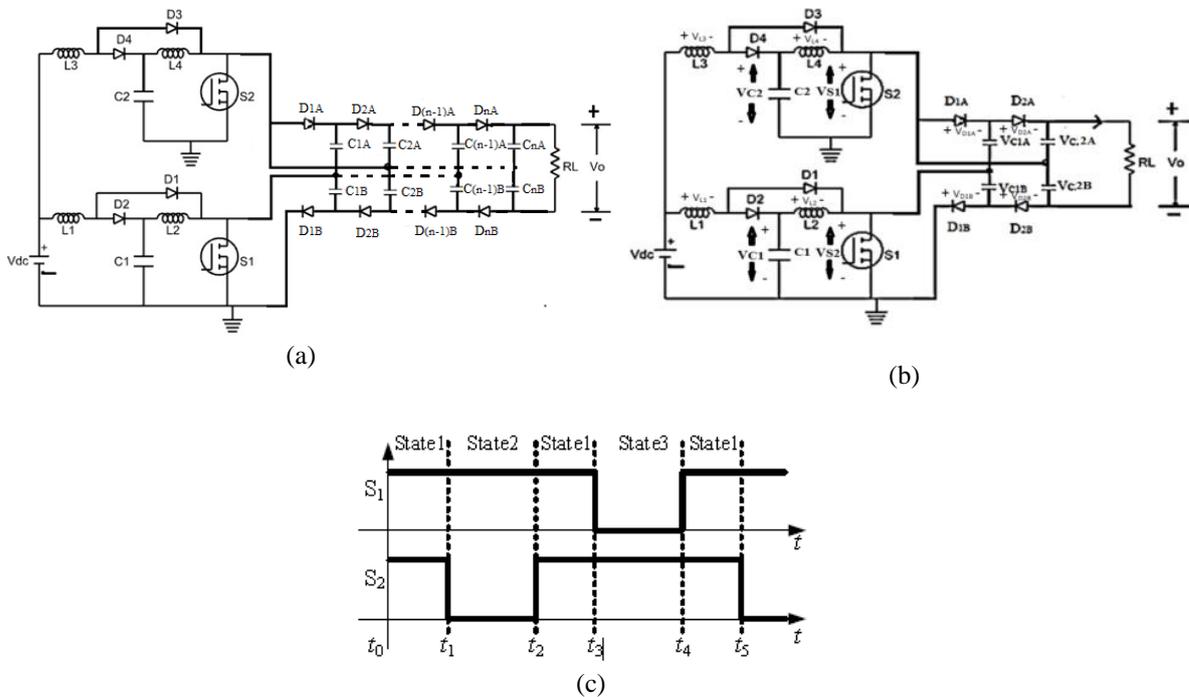


Figure 1. (a) interleaved quadratic boost converter with Dickson voltage multiplier cell, (b) with two Dickson voltage multiplier cell, and (c) Switching pulse for the interleaved quadratic boost converter with VMC

Mode 2 shown in Figure 2 (b), among the two switches, S_2 is made ON and S_1 is made OFF, hence diode D_3 becomes ON and D_4 becomes OFF by capacitor voltage V_{C2} , by this inductor L_3 gets charged with input voltage V_{dc} , L_4 comes in parallel with capacitor C_2 and it gets charged by energy present in C_2 . However, switch S_1 is made OFF, D_1 gets reverse biased making D_2 is forward biased, now current from source flows through L_1, D_2, L_2 through VMC and one portion through S_2 .

$$V_{L1} = V_{dc} - V_{C1} \tag{5}$$

$$V_{L2} = V_{C1} - (V_{C2A} - V_{C1A}) \tag{6}$$

$$V_{L3} = V_{dc} \tag{7}$$

$$V_{L4} = V_{C2} \quad (8)$$

Mode 3 shown in Figure 2(c), among the two switches S_1 is made ON and S_2 is made OFF, hence D_1 becomes ON and D_2 becomes OFF by capacitor voltage V_{C1} , by this inductor L_1 gets charged by input voltage V_{dc} , L_2 comes in parallel with capacitor C_1 gets charged by energy present in capacitor C_1 . However, switch S_2 is made OFF, D_3 is reversed biased and D_4 is forward biased; now current from source flow in inductor L_3 , diode D_4 , inductor L_4 through VMC completes its path through switch S_1 . Voltage equations of inductors L_1 , L_2 , L_3 and L_4 are

$$V_{L1} = V_{dc} \quad (9)$$

$$V_{L2} = V_{C1} \quad (10)$$

$$V_{L3} = V_{dc} - V_{C2} \quad (11)$$

$$V_{L4} = V_{C2} - V_{C1A} \quad (12)$$

Applying Volt-balance equation to the inductance

$$\int_{t_0}^{t_1} V_{dc} dt + \int_{t_1}^{t_2} (V_{dc} - V_{C1}) dt + \int_{t_2}^{t_3} V_{dc} dt + \int_{t_3}^{t_4} V_{dc} dt = 0 \quad (13)$$

$$\int_{t_0}^{t_1} V_{dc} dt + \int_{t_1}^{t_2} V_{dc} dt + \int_{t_2}^{t_3} V_{dc} dt + \int_{t_3}^{t_4} (V_{dc} - V_{C2}) dt = 0 \quad (14)$$

$$\int_{t_0}^{t_1} V_{C1} dt + \int_{t_1}^{t_2} (V_{C1} - (V_{C2A} - V_{C1A})) dt + \int_{t_2}^{t_3} V_{C1} dt + \int_{t_3}^{t_4} V_{C1} dt = 0 \quad (15)$$

$$\int_{t_0}^{t_1} V_{C2} dt + \int_{t_1}^{t_2} V_{C2} dt + \int_{t_2}^{t_3} V_{C2} dt + \int_{t_3}^{t_4} (V_{C2} - V_{C1A}) dt = 0 \quad (16)$$

By solving above equation voltage across capacitor is

$$V_{C1A} = V_{C1B} = \frac{V_{dc}}{(1-D)^2}; V_{C2A} = V_{C2B} = \frac{2V_{dc}}{(1-D)^2} \quad (17); (18)$$

Hence

$$V_0 = \frac{4V_{dc}}{(1-D)^2} \quad (19)$$

Now, voltage gain ratio for inclusion of two VMCs is calculated from (19) and is given below

$$\frac{V_0}{V_{dc}} = \frac{4}{(1-D)^2} \quad (20)$$

Voltage gain of nVMCs is given by

$$V_0 = \frac{4nV_{dc}}{(1-D)^2} \quad (21)$$

and the capacitor voltages are

$$V_{C1A} = V_{C1B} = \frac{nV_{dc}}{(1-D)^2}; V_{C2A} = V_{C2B} = \frac{2V_{dc}}{(1-D)^2} \quad (22); (23)$$

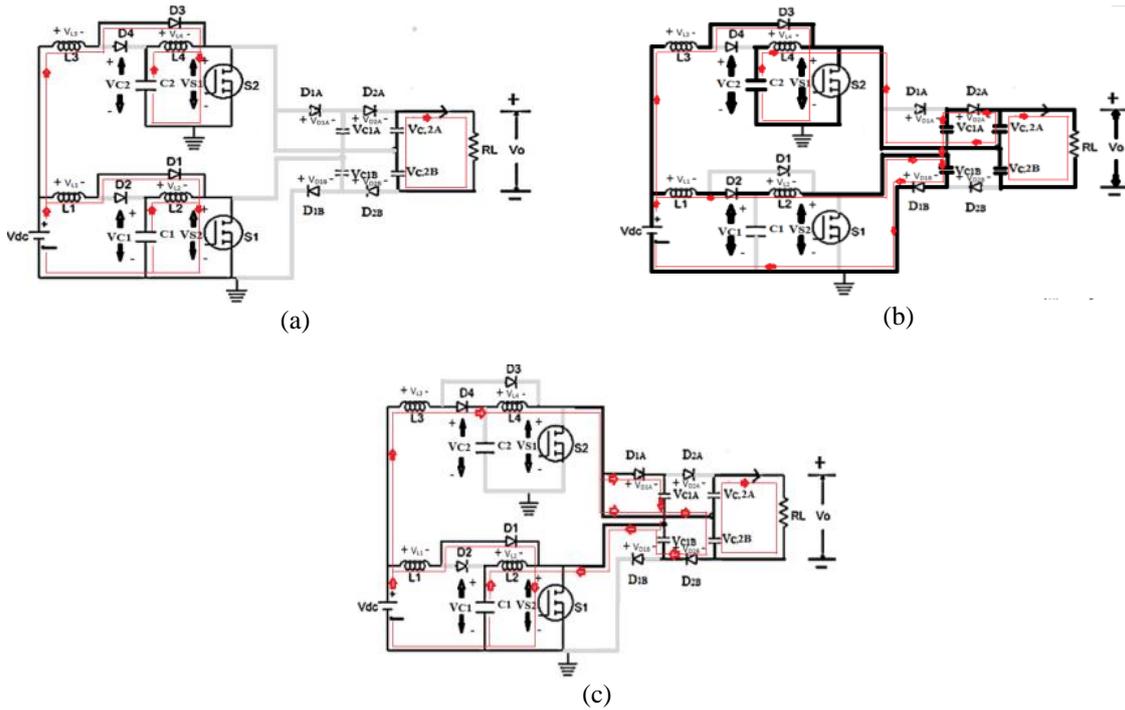


Figure 2. (a) mode 1 operation, (b) mode 2 operation, and (c) mode 3 operation of the circuit

2.1. Selection of inductor

Average value of inductor current depends upon the load current and number of VMCs. Equation for average current is given by

$$I_{in} = \frac{2nI_o}{(1-D)^2} \tag{24}$$

Input current is shared with inductors of two interleaved QBC is calculated as

$$I_{L1\ avg} = I_{L2\ avg} = \frac{I_{in}}{2} = \frac{nI_o}{1-D} \tag{25}$$

As inductor current ripple decides the value of inductor. Equations of L₁ and L₂ are

$$L_1 = \frac{V_{in}}{\Delta i_{L1} f_s} ; L_3 = \frac{V_{in}}{\Delta i_{L3} f_s} ; L_2 = \frac{V_{c1} D}{\Delta i_{L2} f_s} ; L_4 = \frac{V_{c2} D}{\Delta i_{L4} f_s} \tag{26}; (27); (28); (29)$$

2.2. Efficiency analysis

Power loss occurring in DC resistance of inductor is

$$P_L = \sum_{i=1}^{\phi} I_{Li(odd)rms}^2 \times DCR_{i(odd)} \tag{30}$$

Switching and conduction loss in MOSFET is

$$P_{Q1sw} = P_{Q2sw} = \frac{fV_{in}}{2(1-d)^2} \{ [nI_o(T_r + T_f)] + \cos V_{in} \}; \tag{31}$$

$$P_{Q1cond} + P_{Q2cond} = I_{Q1rms} R_{ON1} + I_{Q2rms} R_{ON2} \tag{32}$$

Power loss of in diode and capacitor is

$$P_D = \sum_{i=1}^N I_{Davg} X V_F + \sum_{i=1}^N I_{Drms} X V_F ; P_C = I_{Crms}^2 \times ESR \tag{33}; (34)$$

The total power loss is

$$P_{Loss} = P_{L\ tot} + \sum_{i=1}^{\infty} P_{Qi,sw} + \sum_{i=1}^{\infty} P_{Qi,cond} + \sum_{N=1}^{2n} P_{DN} + \sum_{N=1}^{2n} P_{CN} \quad (35)$$

Efficiency of the converter is

$$\% \eta = \frac{P_O}{P_O + P_{Loss}} \times 100 \quad (36)$$

Efficiency graph is plotted by considering the datasheet of MOSFET, diode, inductor and capacitor. The proposed converter produced maximum efficiency of 97.6%. Figure 3 shows efficiency graph for various loads. It could be observed that for load power of 200 W, efficiency of converter is maximum and for all other powers its value is much lesser.

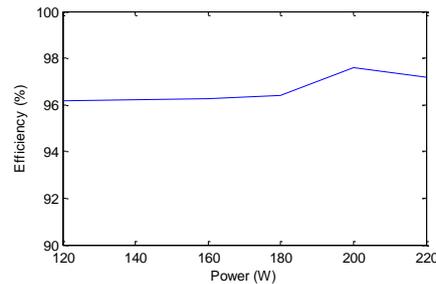


Figure 3. Efficiency of the converter with variable load

3. SIMULATION OF CIRCUIT

Circuit is simulated in MATLAB/Simulink software. This high ratio gain converter is designed for power rating of 300W with input voltage of 24V and output voltage of 400V having voltage gain ratio of 16 times. It comprises of two quadratic converters connected in parallel, combination gets connected in series with Dickson Voltage Multiplier. Inductors L_1 , L_2 , L_3 and L_4 with values of $140\mu\text{H}$, $280\mu\text{H}$, $140\mu\text{H}$ and $280\mu\text{H}$ are used in quadratic converter. Design parameters for the simulation system is detailed in Table 1. Inductor current of magnitude 6 A flows through inductor L_1 and L_2 , 2.8 A flows through L_3 and L_4 as shown in Figure 4 (a). Two switches are selected as high frequency MOSFET switches; they are triggered at the rate of 20kHz. When duty ratio is fifty one percent, for input voltage of 24V, the output voltage obtained is 400V as shown in Figure 4 (b). Output current of 0.49A flows in load resistance of 800Ω . Magnitude of voltage is obtained as 400V providing gain ratio of converter as 16. For this nature this converter can be made suitable for photovoltaic applications.

Table 1. Design parameters for simulation system

Component	Value
Supply voltage, V_s	24V
Output voltage, V_o	400V
Input current, I_s	12A
Output current, I_o	0.49A
Switching frequency, f_s	20kHz
Inductor, L_1, L_2	$140\mu\text{H}$
Inductor, L_3, L_4	$280\mu\text{H}$
Capacitors	$100\mu\text{F}$
Resistive load R_L	800Ω

Figure 5 (a) shows voltage across first stage capacitor of Dickson voltage multiplier cell, that is around 100V and Figure 5 (b) shows voltage across second stage capacitor, which is around 200V from this it could be observed that voltage stress across capacitors is much lesser than output voltage. This necessitates choosing a capacitor of much lower voltage rating compared to output voltage. Figure 6 (a) illustrates current flowing in first stage capacitors. Figure 6 (b) shows the voltage stress of switches. Magnitude of switch voltage is obtained as 100V that is four times lower than output voltage. When this situation is compared with any other boost or quadratic boost design, presence of voltage multiplier cell makes the designer to

select a switch that has very low voltage rating compared to output voltage; thereby switch voltage stress is much lower in proposed converter of this paper. Figure 9 depicts current waveform of inductor. It could be proved interleaving of converter has made presence of low current ripple in input photovoltaic side, that favors for accurate maximum power point design. Figure 7 (a) and Figure 7 (b) depicts voltage measured across diodes of voltage multiplier cell.

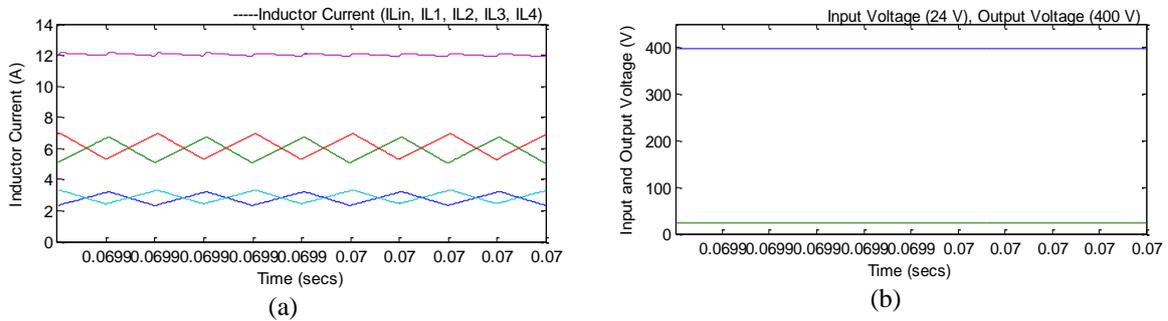


Figure 4. Simulation waveforms (a) inductor currents and input current and (b) input and output voltage

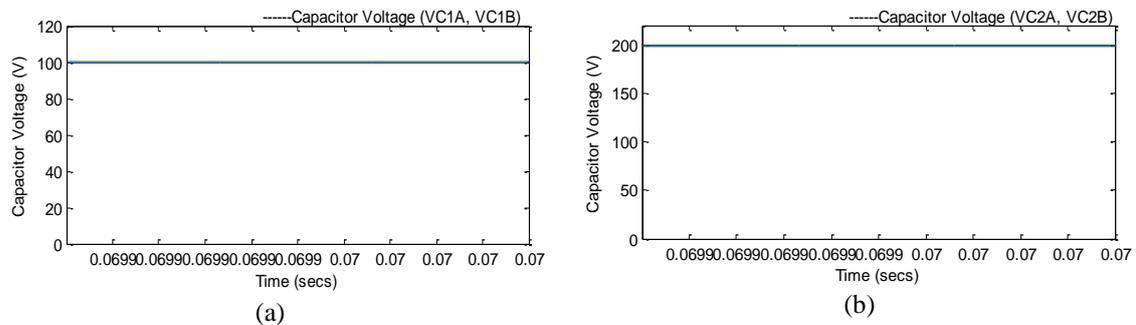


Figure 5. Simulation waveforms (a) voltage across first stage capacitor and (b) voltage across second stage capacitor of Dickson multiplier cell

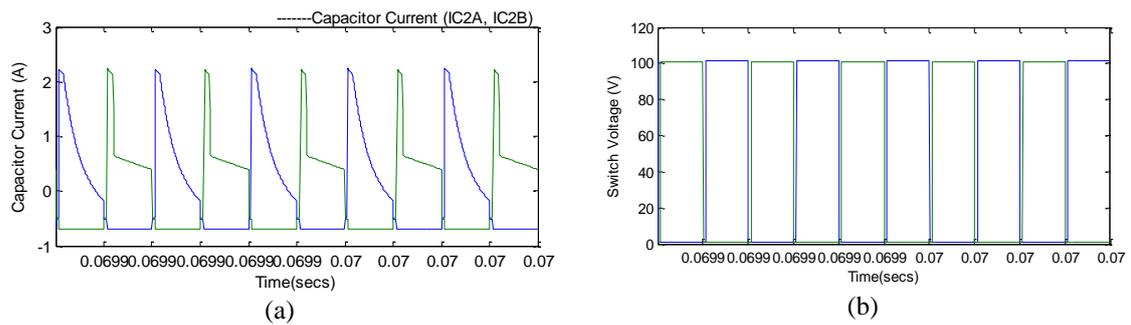


Figure 6. Simulation waveforms (a) capacitor currents of second stage and (b) Voltage stress across switches SW1 and SW2

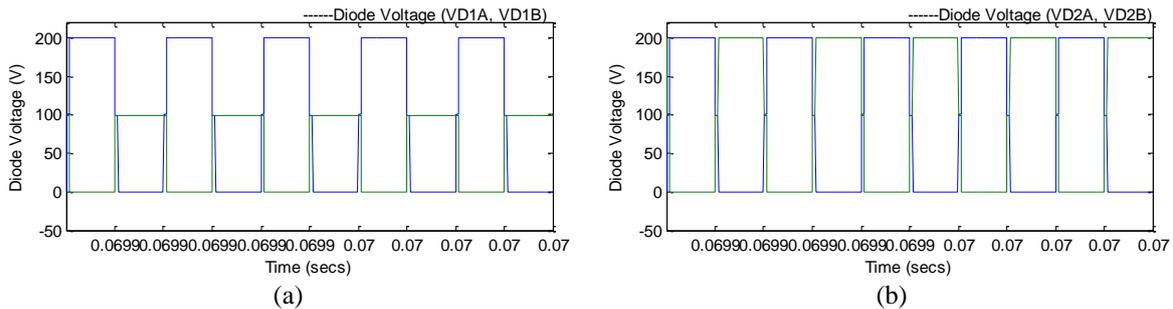


Figure 7. Simulation waveforms (a) voltage across first stage diode and (b) voltage across second stage diode of Dickson multiplier cell

4. HARDWARE IMPLEMENTATION

The proposed circuit is implemented in hardware to validate the design. A prototype of 300W interleaved quadratic boost converter and series connection of Dickson Voltage Multiplier is made. For an input voltage of 24V it produces load voltage of 400V. This property makes converter suitable for photovoltaic applications. PIC16F877A microcontroller was used to produce gate pulse to interleaved quadratic boost converter. Figure 8 (a) shows first stage and second stage capacitor voltage of Dickson Voltage Multiplier Cell. Voltage across first stage capacitor is measured to be 100V and second stage capacitor is measured to be 199.5V.

Figure 8 (b) shows voltage across first stage diodes of Dickson Voltage Multiplier Cell, it is said to be equal to 100V. Figure 9 (a) shows voltage across second stage diodes of Dickson Voltage Multiplier Cell, it is said to be equal to 200V. Figure 9 (b) measures input current and output current of the proposed converter, input current is measured to be 11.35 A and output current is measured to be 0.64 A. As it is said interleaved circuit has reduced input current ripple that reduced value of inductor used in quadratic boost converter circuit. Hence a high-voltage gain which could handle high power is designed. Low value of ripple current of 0.29A from photovoltaic panel, ensures constant current drawn from photovoltaic panel and also enables the use of MPPT technique when required. The use of high value of capacitor produces almost no ripple in output voltage.

Moreover, this converter can be exclusively used for stepping up voltage obtained from photovoltaic panels to input voltage of inverter that converts DC power to AC power and runs single phase induction motors that are used for water pumping, especially in isolated OFF grid photovoltaic powered residential homes. The design is proposed to be an innovative design; because integrated energy storage can be included that eliminates the disadvantage of intermittent power generation of solar panel. Connection of energy storage across capacitor whose voltage is always twice that of input voltage also increases capacity of battery that is used. Depending on power obtained from photo-voltaic panel, three modes of operation occur as given in the Table 2.

As given in Table 2, three different situations are due to the stochastic fluctuation of the photovoltaic power with variation in insolation, here depending upon the power difference happening between the source and load power, the behaviour of the discharge and charge mode of the integrated energy storage, the operation of the circuit is classified into three different cases, where in the first case photo-voltaic power is lesser than the load demand, battery is in discharging state, in the second case photo-voltaic power is greater than load demand, battery is in charging state and in last state photo-voltaic power becomes equal to the load demand battery is in floating state.

Simulation made in MATLAB/Simulink is shown in Figure 10 and the inductor currents during three different power levels between the photovoltaic panel power, battery power and load power is illustrated in Figure 11. Focussing made on magnitude of input current, and inductor currents, justifies the above said concept. In the simulation waveform, from time zero seconds to 0.3 second, photovoltaic power is maintained greater than load power. From 0.3 second to 0.5 second photovoltaic power is reduced such that its magnitude becomes lesser than load power. Now, when transition is made at 0.3 second, the input current transits from higher value to lower value, hence inductor currents i_{L1} and i_{L3} also transits from highest value to lower value as they are located before battery. But inductor currents i_{L2} and i_{L4} is maintained constant instead of reducing, this proves that, excess current to these inductors is supplied from battery. Therefore, batteries connected in parallel to capacitors C_1 and C_2 , maintain constant current in inductors i_{L2} and i_{L4} and thereby maintain constant current in load, irrespective of Photovoltaic power variation.

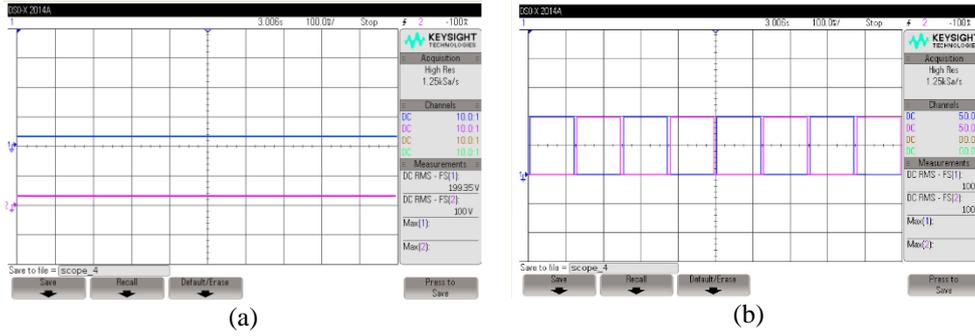


Figure 8. (a) first stage and second stage capacitor voltages and (b) voltage across the first stage diodes

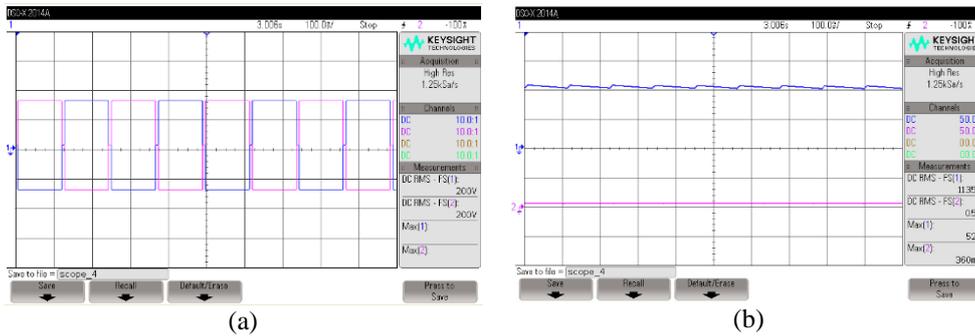


Figure 9. (a) voltage across second stage diodes and (b) input current and output current of proposed converter

Table 2. Relationship between P_{in} , P_o and P_{bat}

Input and Output power relationship	Battery Power
$P_{in} < P_o$	$P_{bat} > 0$, Discharging state
$P_{in} > P_o$	$P_{bat} < 0$, Charging state
$P_{in} = P_o$	$P_{bat} = 0$, Floating state

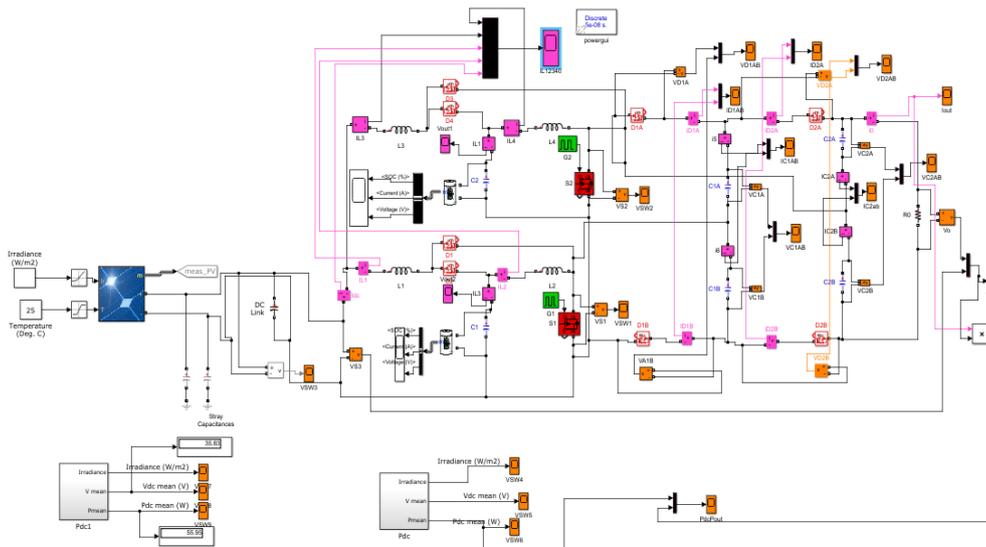


Figure. 10 Simulation of the proposed converter circuit

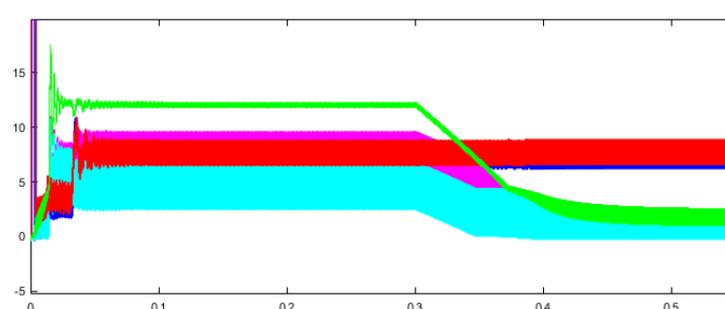


Figure 11. Simulation waveforms: first inductor current, i_{L1} (light blue), i_{L3} (magenta), second inductor current, i_{L2} (red), i_{L4} (dark blue) input current (green colour)

5. CONCLUSION

Paper proposed interleaved quadratic boost converter with Dickson voltage multiplier cell. Converter holds the advantage of lesser current ripple in input photovoltaic panel and lesser voltage ripple in output load. Moreover, interleaving had made converter to operate with high photovoltaic power, making them a suitable choice for high power low input side voltage applications. Cascading voltage multiplier cell with interleaved converter produces high gain ratio voltage, which makes converter to be incorporated in power electronic circuits used in interfacing with high voltage applications like grid connected photovoltaic, electric vehicle charging station and battery swapping stations. A 300W circuit with input voltage of 24V and output voltage of 400V is designed, analyzed and simulated in this paper. Prototype is also made to verify simulation results. At the end application of this converter to integrated energy storage is discussed.

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