Hybrid Non-Isolated and Non Inverting Nx Interleaved DC-DC Multilevel Boost Converter for Renewable Energy Applications

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Abstract– **In this paper hybrid non isolated/ non inverting Nx interleaved DC-DC multilevel Boost Converter for renewable energy applications is presented. The presented hybrid topology is derived from the conventional interleaved converter and the Nx Multilevel boost converter. In renewable energy applications, generated energy cannot be directly used at application end. In most of the cases it needs to be stepped up with DC-DC converter at operating voltage levels as per the requirement of the application. Though conventional boost converter can theoretically be used for this purpose, but obtaining such high gain implies that boost converter should operate at it its maximum duty cycle, which is not feasible due to the great variations in the output voltage caused by small variations in the duty cycle, leading the boost converter to instability and also increases the voltage stress across switches. The advantages of presenting topology of DC-DC converter are high voltage conversion, reduce ripple, low voltage stress, non inverting without utilizing the high duty and transformer. The main advantage of presented topology is more number of levels can be increased by adding capacitor and diode circuitry to increase the voltage gain without disturbing the main circuit. Moreover, the presented topology is compared with several recent high gain converters. The proposed topology is simulated in MATLAB/SIMULATION and results will verify the validity of the design and operation of the converter.**

Index Terms–**Non isolated; Interleaved; High Conversion; Multilevel Boost; Renewable Energy.**

I. Introduction

When current world energy scenario is analyzed, most of the generation is with exhaustible sources. Hence, for a cost effective power generation without these fossil fuel technologies is shifted to the power generation using renewable energy sources. There are so many ways to generate power using these sources like solar, wind, tidal, etc. From all these sources, solar energy is the most effective source which is abundant and constantly developing with advancement in photovoltaic cells which is leading to higher efficiency of the solar system. In this era, more and more renewable energy sources with low voltage output, such as fuel cell stacks, solar arrays are widely used for front-end DC/DC applications [1]-[4]. These non-conventional energy power generation systems need a high gain DC-DC converter for conversion of voltage required to connect it to a grid or an inverter.

The voltage generated from solar arrays is very low, and to connect it to end applications it needs to be stepped up. Boost converter is employed for such systems to fulfil application requirements [1]-[14]. The conventional Boost Converter is practically not applicable to high duty cycles because of the design constraints. To overcome this cascade boost converter is employed in [2]. But cascading of the converters leads to non-uniform voltage stresses across switches and also the efficiency of the converter is reduced with increasing the stages because of the insertion loss. To overcome this isolated boost converter is employed in [2]. But, in case of isolated converters with transformers there is problem of saturation of the transformer and the output is fluctuating from the desired value which points to ripples in output and also circuit becomes bulky. The most manageable and economical way to increase gain of the converter is application of voltage multipliers to enhance the output voltage of the system. Several non inverting as well as inverting boost converter topologies with voltage multiplier is proposed in the [14]. These multiplier boost converter topology provides a feasible solution to achieve a high conversion ratio. The proposed circuit avail cockraft-walton voltage multiplier which can be a very walkover solution for the gain intensification.

The values of passive elements employed in the converter and its operating frequency play a very vital role in the function-ability of the converter. Low values of the reactive components with high frequency switches give acceptable magnitude of the voltage at the output end, but at the same produce a noticeable amount of ripple [2]. To clarify the issue of current ripple across the inductor, the value of inductance can be increased which also increases cost and size of the converter and also increases its transient response time [14]. The interleaved structure is applied in high current applications to minimize the current ripple, reduce the size of the passive components. Basically interleaved structure is the same converter connected in parallel with the existing circuit. This reduces current rating of the components as well as

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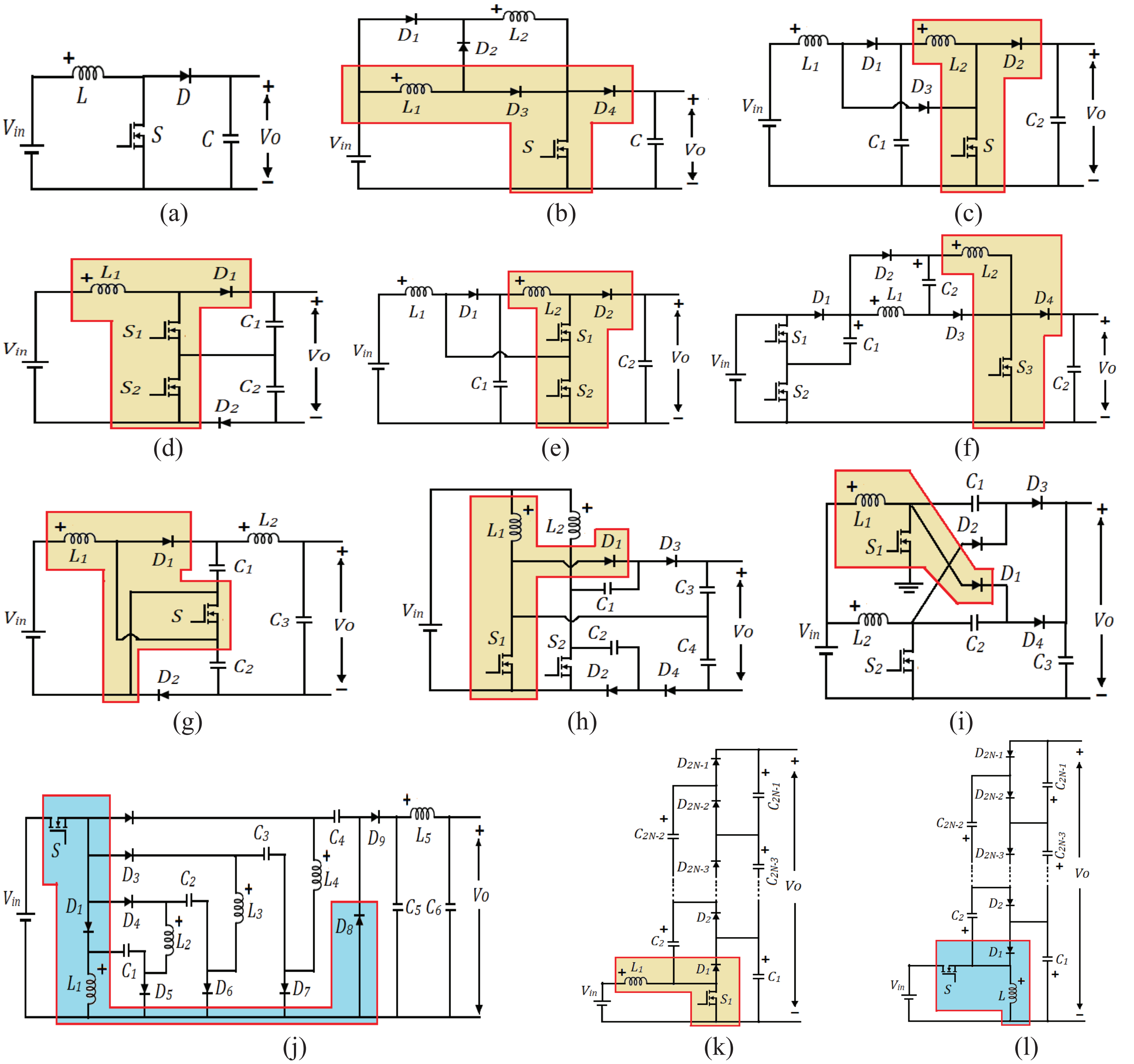


Fig.1(a) Conventional Boost Converter, (b) Switched Inductor (SI) Boost Converter[2] (c) Single switch Quadratic Boost Converter (QBC) [2],[4] (d) Conventional Three Level Boost Converter [2][6] (e) Quadratic Three Level Boost Converter [5] (f) Converters using bootstrap capacitors and boost inductors (g) Switched Capacitor Based Boost Converter [7] (h) Two-phase quadrupled interleaved boost converter [8] (i) High-voltage gain two-phase interleaved boost converter using one VMC [9] (j) Extra high voltage (HV) DC-DC converter [10]-[13] (k) Nx Multilevel Boost Converter (MBC) [14] (l) Nx Multilevel Buck Boost Converter (MBBC) [14].

reduces the output distortion. Several existing derived DC-DC converters to boost the output voltage are shown in Fig. 1(a) to Fig. 1(i) and the gain formulation of it is described in Table I. In this paper hybrid non isolated/ non inverting Nx interleaved boost converter is presented for renewable energy application.

This paper is organized as follows: The circuit description and operation modes of hybrid non isolated/ Non inverting Nx interleaved boost converter are provided in section-II. Analysis of the proposed converter with or without diode loss is discussed in the section III. In section-IV presented topology is compared with recent high step up converter. MATLAB simulation results of presenting topology are provided in V. Finally, a conclusion is provided in section VI.

II. Hybrid Non-Isolated and Non-Inverting Nx Interleaved DC-DC Boost Converter

A. Power Circuit Description

The power Circuit of hybrid non isolated/ non isolated Nx interleaved boost converter is depicted in the Fig. 2.

Converter Topology	Voltage Conversion Ratio, D= Duty Cycle
Conventional Boost Converter	$1/(1-D)$
Switched Inductor (SI) Boost Converter	$1+D/(1-D)$
Single switch Quadratic Boost Converter	$1/(1-D)^2$
Conventional Three Level Boost Converter	$2/(1-D)$
Quadratic Three Level Boost Converter	$1/(1-D)^2$
Converters using bootstrap capacitors and boost inductors	$3+D/1-D$
Switched Capacitor Based Boost Converter	$1+D/1-D$
Two-phase quadrupled interleaved boost converter	$4/(1-D)$
High-voltage gain two-phase interleaved boost converter using one VMC	$((VMC+1)/1-D)$
Extra high voltage (HV) DC-DC converter	$4/(1-D)$
Nx Multilevel Boost Converter (MBC)	$N/(1-D)$
Nx Multilevel Buck Boost Converter (MBBC)	$N/(1-D)$

Presented circuit is a hybrid configuration of interleaved converter and Nx Multilevel Boost Converter (Nx MBC).

Nx interleaved boost converter required 3N-2 capacitors, 4N-2 diodes along with 2 identical inductors and 2 switches. More number of levels can be increase by adding capacitor and diode circuitry in present topology to increase the voltage gain without disturbing the main circuit.

$$Vo = VC1 + VC2 + \ldots\ldots\ldots + VCN \quad (1)$$

B. *Operation modes*:

To elaborate the operation modes present topology 3x interleaved boost converter is assumed to assume ideal components and the capacitors are large enough, and the circuits operate in continuous conduction mode. The proposed converter can exercise in four modes of operations as given below:

1) Mode 1: When S1 and S2 are ON

When both the switches (S1 and S2) are conducting (ON) both the inductors L1 and L2 gets charged with source and the capacitors C1, C2 and C3 gets discharged through the load. The potential across the capacitors make diodes D21, D22, D41 and D42 forward biased and the load side capacitors C1,

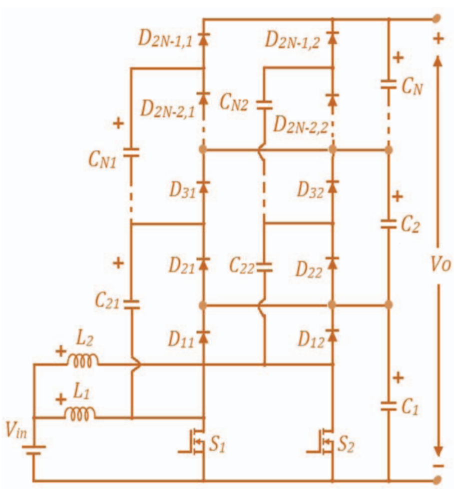


Fig. 2. Hybrid non isolated/ non isolated Nx interleaved boost converter

C2, C3 discharges through the path of diodes to charge capacitors C21, C22, C41 and C42. The Fig. 3(a) shows the equivalent circuit when both switches are conducting (ON). In this mode of operation, diode D11, D12, D31, D32, D51 and D52 are reversed biased.

$$VL1 = VL2 = Vin \quad (2)$$

$$VC21 = VC22 = VC1 \quad (3)$$

$$VC21+V31 = VC22+V32 = VC1+VC2 \quad (4)$$

$$Vo = VC1+VC2+VC3 \quad (5)$$

2) Mode 2: When S1 is ON and S2 is OFF

The equivalent circuit of the proposed converter when switch S1 is conducting (ON) and switch S2 is not conducting (OFF) is given in Fig. 3(b). The inductor L1 gets charged with source voltage and the capacitors C1, C2 and C3 charge and discharge within the ON time of the switch S1. When C1, C2 and C3 are discharged through load it also charges capacitors C21, C31 of the multiplier cell. In this mode diode D21, D41 D12, D32, and D52 are forward biased and diode D11, D31, D51, D22, D42 are reversed biased.

$$VL1=Vin \quad (6)$$

$$VC21=VC1 \quad (7)$$

$$VC21+VC31=VC1+VC2 \quad (8)$$

$$VC1=Vin-VL2 \quad (9)$$

$$VC2+VC1=Vin-VL2+VC22 \quad (10)$$

$$VC3+VC2+VC1=Vin-VL2+VC22+VC32 \quad (11)$$

3) Mode 3: When S1 and S2 are OFF

The equivalent circuit of the proposed converter when both switch S1 and S2 are not conducting (OFF) is given in Fig. 3(c). In this mode inductors L1 and L2 get discharged. Capacitors C1, C2 and C3 are charged by series combination Vin, L1 C21, C31 and the series combination of Vin, L2, C22 and C42. Diodes D11, D31, D51, D12, D32, D52 are forward biased and Diodes D21, D41, D22, D42 are reversed biased.

$$VC1=Vin-VL1=Vin-VL2 \quad (12)$$

$$VC2+VC1=Vin-VL1+VC21=Vin-VL2+VC22 \quad (13)$$

$$VC3+VC2+VC1=Vin-VL1+VC21+VC31 \quad (14)$$

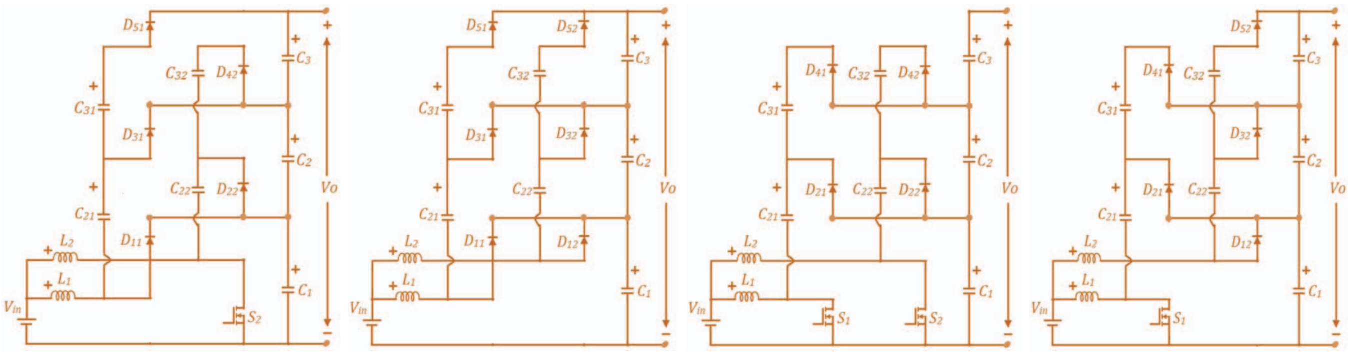
$$VC3+VC2+VC1=Vin-VL2+VC22+VC32 \quad (15)$$

4) Mode 4: When S1 is OFF and S2 is ON

The equivalent circuit of the proposed converter when switch S1 is not conducting (OFF) and switch S2 is conducting (ON) is given in Fig. 3(d). The inductor L2 gets charged with source voltage and the capacitors C1, C2, C3 charge and discharge within the ON time of the switch S2. When C1, C2 and C3 are discharged through load it also charges capacitors C22, C32 of the multiplier cell. In this mode diode D11, D31, D51, D22, D42 are forward biased and diode D21, D41, D12, D32, D52 are reversed biased.

TABLE I. COMPARISON OF VOLTAGE GAIN AT VARIOUS DUTY CYCLE.

Converter Type	Voltage Gain of Converter at Various Duty Cycle								
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Conventional Boost Converter	1.11	1.25	1.43	1.67	2.00	2.50	3.33	5.00	10.00
Switched Inductor (SI) Boost Converter	1.22	1.50	1.86	2.33	3.00	4.00	5.67	9.00	19.00
Single switch Quadratic Boost Converter	1.23	1.56	2.04	2.78	4.00	6.25	11.11	25.00	100.00
Conventional Three Level Boost Converter	2.22	2.50	2.86	3.33	4.00	5.00	6.67	10.00	20.00
Quadratic Three Level Boost Converter	1.23	1.56	2.04	2.78	4.00	6.25	11.11	25.00	100.00
Converters using bootstrap capacitors and boost inductors	3.44	4.00	4.71	5.67	7.00	9.00	12.33	19.00	39.00
Switched Capacitor Based Boost Converter	1.22	1.50	1.86	2.33	3.00	4.00	5.67	9.00	19.00
Two-phase quadrupled interleaved boost converter	4.44	5.00	5.71	6.67	8.00	10.00	13.33	20.00	40.00
High-voltage gain two-phase interleaved boost converter using one VMC	2.22	2.50	2.86	3.33	4.00	5.00	6.67	10.00	20.00
Extra high voltage (HV) DC-DC converter	4.44	5.00	5.71	6.67	8.00	10.00	13.33	20.00	40.00
4x Multilevel Boost Converter (MBC)	4.44	5.00	5.71	6.67	8.00	10.00	13.33	20.00	40.00
4x Multilevel Buck Boost Converter (MBBC)	3.44	4.00	4.71	5.67	7.00	9.00	12.33	19.00	39.00
4x interleaved boost converter	4.44	5.00	5.71	6.67	8.00	10.00	13.33	20.00	40.00



(a) (b) (c) (d)

Fig. 3. Equivalent Circuit Hybrid non isolated/ non isolated 3x interleaved boost converter (a) When both switches S_1 and S_2 are ON (b) When switch S_1 is ON and switch S_2 is OFF (c) When both switches S_1 and S_2 are OFF (d) When switch S_1 is OFF and switch S_2 is ON.

$$VL2=Vin \quad (16)$$

$$VC12=VC1 \quad (17)$$

$$VC12+VC32=VC1+VC2 \quad (18)$$

$$VC1=Vin-VL1 \quad (19)$$

$$VC2+VC1=Vin-VL1+VC21 \quad (20)$$

$$VC3+VC2+VC1=Vin-VL2+VC21+VC31 \quad (21)$$

III. COMPARISON OF INTERLEAVED BOOST DC-DC CONVERTER WITH EXISTING HIGH GAIN CONVERTERS

In Table I presented interleaved converter is compared with existing several non isolated DC-DC converter topologies and it is observed that the 4x interleaved converter have higher or equal gain than the existing non isolated DC-DC converter at given duty cycle. Fig. 4 shows graphs of voltage gain versus duty cycle for DC-DC discussed in this paper. Thus presented converter provides a feasible solution to increase the voltage with high conversion ratio for renewable energy application. In Table II voltage across the switch in DC-DC converter is compared to presenting interleaved converter. It is observed that the voltage across switch is very low in presenting interleaved DC-DC converter. Thus, low rating components provide a viable solution to design converter.

IV. NUMERICAL SIMULATION RESULTS AND DISCUSSION

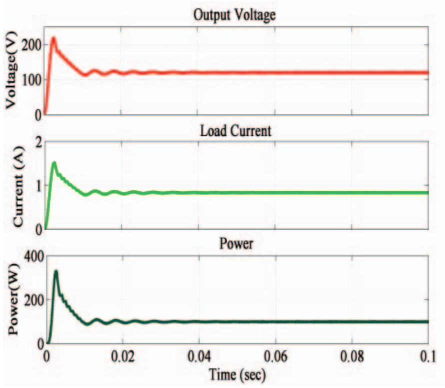
The interleaved converter for three levels (3x interleaved boost converter) is simulated in MATLAB with designing parameter given in the Table III. Output voltage, Load current and power are shown in Fig. 5(a).

It is observed that for a duty cycle of 0.75, the required output voltage 120V is obtained at the required output power 100W. The voltage at different output levels is shown in Fig. 5 (b). It is observed that each level provides equal voltage 40V.

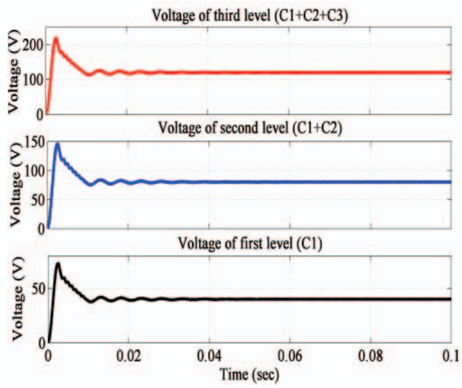
The voltage distribution across the all the multiplier capacitors shows that the converter performs satisfactorily. The voltage distribution across the capacitors is shown in Fig. 5(c). The voltage stress across a switch S1 and S2 is shown in Fig. 5(d). It is observed that the voltage stress of switches S1 and S2 is equal to Vo/3 i.e 40V. Output voltage ripple across load is shown in Fig. 5(f). It is observed that the voltage ripple is 0.3 V. Load current ripple across load is shown in Fig. 5(g). It is observed that the current ripple is 2.5mA. The proposed converter provides a low current ripple, highly desired in renewable energy generation systems.

V. CONCLUSIONS

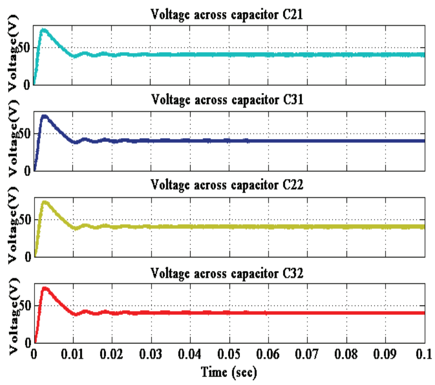
Hybrid non isolated/ non inverting Nx interleaved DC-DC multilevel Boost Converter is presented which provides a viable solution for renewable energy applications. Presented topology is a combination of interleaved converter and multilevel boost converter. The presented converter is compared with recent non isolated DC-DC Converter. The presented converter has a high conversion ratio and low voltage stress across switching devices compared to classical and recent derived non isolated converter for the same duty ratio. Reliability of the converter is higher compared with converters that have several synchronized switches. Number of output levels can be increase by adding capacitor and diode circuitry to increase the voltage gain without disturbing the main circuit. It is possible to conclude based on simulation result that it is a promising topology for renewable energy applications like automotive renewable appliances, electrical vehicles.



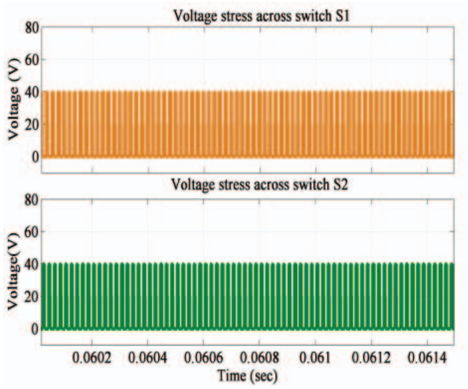
(a)



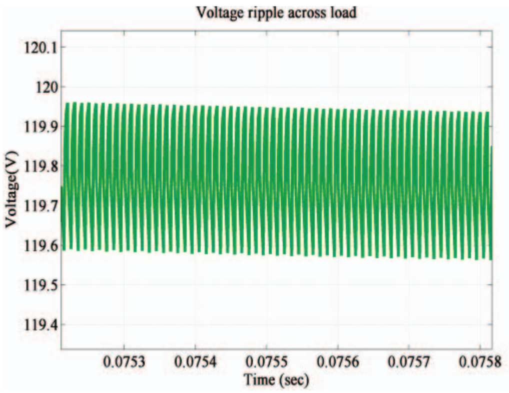
(b)



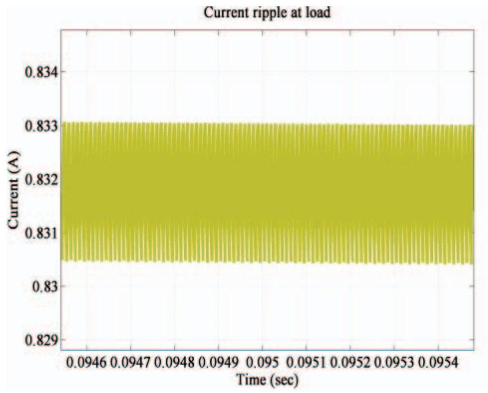
(c)



(d)



(e)



(f)

Fig. 5. Simulation Results by presented topology for input voltage 12V, power 100W,output voltage 120V, duty cycle 0.75, switching frequency 50kHz. 144ohm load (a) Output voltage, Load current and power (b) voltage at different output levels (c) voltage distribution across the capacitors (d) The voltage stress across a switch S_1 and S_2 (e) Output voltage ripple (f) Load current ripple.

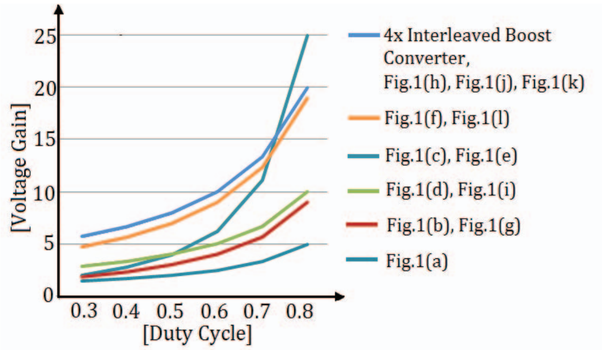


Fig. 4. Voltage gain versus duty cycle

TABLE II. TABULATION OF VOLTAGE STRESS ACROSS SWITCHES.

Converter Type	Voltage Stress
Conventional Boost Converter	Vo
Switched Inductor (SI) Boost Converter	Vo
Single switch Quadratic Boost Converter	Vo
Conventional Three Level Boost Converter	Vo/2
Quadratic Three Level Boost Converter	Vo(1-D), Vo-Vo(1-D)
Converters using bootstrap capacitors and boost inductors	Vo
Switched Capacitor Based Boost Converter	Vo/(1-D)
Two-phase quadrupler interleaved boost converter	Vo/4
High-voltage gain two-phase interleaved boost converter using one VMC	Vo/2
Extra high voltage (HV) DC-DC converter	Vo/4
4x Multilevel Boost Converter (MBC)	Vo/N or Vin/(1-D)
4x Multilevel Buck-Boost Converter (MBBC)	VinD/(1-D)
4x interleaved boost converter	Vo/N or Vin/(1-D)

TABLE III. MAIN PARAMETER OF NUMERICAL SIMULATION TEST.

Input Voltage	10 V
Output Voltage	120V
Power, Load	100W, 144ohm
Inductance, Capacitance	150uH, 75uF
Duty Cycle	0.75
Switching frequency	50kHz

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