A HIGH VOLTAGE GAIN INTERLEAVED CONVERTER WITH A VOLTAGE MULTIPLIER FOR ELECTRIC VEHICLE POWER MANAGEMENT APPLICATIONS

Preetha.M[1], Karthik.V[2], Kirankumar.R[3], Lokeshwaran.R[4]

Assisant professor, Dept. of EEE, Prathyusha Engineering College, Chennai ,TamilNadu ,India[1]

UG students, Department of EEE ,Prathyusha Engineering College, Chennai , TamilNadu ,India[2,3,4]

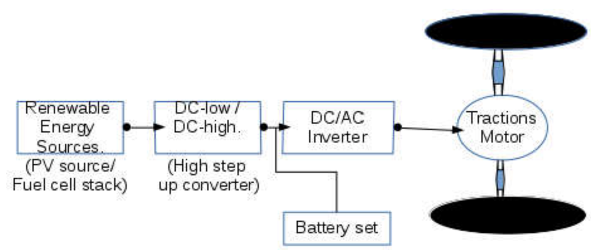
Abstract-This paper proposes a high-step-up interleaved converter with a voltage multiplier, which is suitable for electric vehicle power management applications. High-step-up interleaved converters play an important role in renewable energy sources such as fuel energy systems, DC-back up energy system for UPS, high intensity discharge lamp and auto mobile applications. Renewable energy sources such as photo voltaic energy are available in both clean and economical due to new advancement in technology and use of good and efficient cells. The proposed converter resembles a two-phase interleaved boost converter on its input side while having a Modified Dickson charge-pump-based voltage multiplier (VM) on its output side. DC power can be converted into AC power at desired output voltage and frequency by using an inverter. The low voltage stress enables the use of low-voltage-rated metal–oxide–semiconductor field-effect transistors (MOSFETs) for reductions of conduction losses and cost. Also, the proposed converter is capable of drawing power from either a single source or two independent sources. The VM used offers low voltage ratings for capacitors that potentially leads to size reduction. The converter design and component selection have been discussed in detail with supporting simulation results.

Keywords- High-voltage-gain dc–dc converter, Modified Dickson charge pump, voltage multiplier (VM).

I. INTRODUCTION

In present scenario renewable energy is progressively more valued and employed worldwide because of energy shortage,cleanliness,sustainability and environmental contamination. The output voltage obtained from the renewable energy systems is very low. So, for many renewable energy applications like photo-voltaic systems, fuel cells, wind power generation high step-up dc/dc converters have been used. Such systems transform the low voltage energy from the renewable resources into high voltage via a step-up converter. Renewable energy sources such as photo voltaic energy are available in both clean and economical due to new advancement in technology and use of good and efficient cells. Solar energy is advantageous compared to any other renewable energy sources available. The efficient and fast growth in the field of solar energy result in Photo voltaic (PV) system design for various application with reliable operation and application for more reliable and efficient operation.

Fig. 1. Block diagram of a typical electric vehicle



power management system.

Referring to Fig. 1, the high step-up interleaved converters serving as DC/DC power converters are capable of converting the low levels of input voltage from pv/fuel cell stack into high levels of output voltage, which are then fed into a battery set or a DC/AC inverter for supplying a tractions motor with an AC load. Hence, high efficiency,high step-up DC/DC converters play an important role in this kind of power management system.Currently, telecom centers, data centers, commercial buildings, residential buildings, and micro grids are among the emerging examples of dc distribution systems.

TABLE I

HIGH VOLTAGE GAIN CONVERTERS USING BOOST STAGE AND VM CIRCUITS

Topology	[8]	[9]	[10]	[11]
No. of switches	1	1	2	2
No. of inductors	1	1	2	2
No. of capacitors	4	3	3	3
No. of diodes	4	3	3	4
V_{out}/V_{in}	$\frac{3-d}{1-d}$	$\frac{2}{1-d}$	$\frac{3+d}{1-d}$	$\frac{1}{d(1-d)}$
V_{Switch}/V_{out}	$\frac{1}{3-d}$	$\frac{1}{2}$	$\frac{1}{3+d}$	$(1-d), d$
Input current	Discontinuous	Continuous	Discontinuous	Continuous

Table-I summarizes the converters based on their individual component count, voltage gain, and voltage stress on their switches. The second-order hybrid boosting converter proposed in [8] offers relatively low voltage gain in comparison to its VM component count. It also has a very large input current ripple in proportion to its average current. The multiple-inductor-energy-storage-cell-based switched capacitor based high-voltage converters [9]offer a relatively low voltage gain in proportion to their component count. The switched-capacitor-based active-network converter proposed in [10] has a discontinuous input current ripple due to the series and parallel connection of the inductors in its two modes of operation. The transformer-less high-gain boost converter proposed in [11] offers continuous input current but the switches experience a high voltage stress—more than two thirds of its output voltage.

High-voltage-gain dc–dc converters using coupled inductors and high-frequency transformers have been proposed for the integration of solar panels to 400-V dc bus [12]–[18]. In such converters, the design of high-frequency transformers and coupled inductors is complicated as the leakage inductance increases when higher voltage gains are intended. As a result, the converter switches experience large voltage spikes and, therefore, would require clamping circuitry to reduce the voltage stress on the switches. These clamping circuits have a negative effect on the converter voltage gains.

A family of non isolated high-voltage gain dc–dc converters that makes use of VM cells derived from the Dickson charge pump (see Fig. 1) has been proposed in [19]. The voltage rating of each VM cell capacitor is twice that of its previous VM cell. Also,

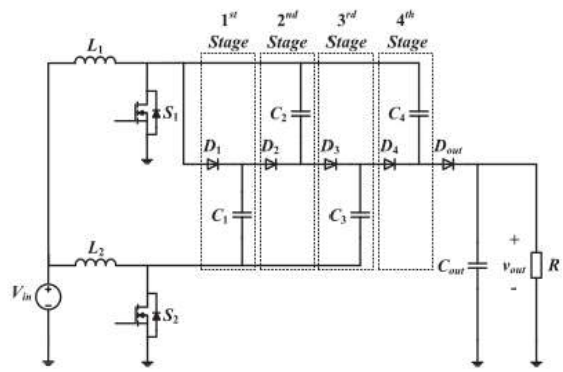


Fig. 1.High-voltage-gain dc–dc converter proposed in [19].

the inductors (L 1 , L 2) and switches (S 1 , S 2) experience different current stresses whenever even number of VM cells are used. A high-voltage-gain dc–dc converter based on the modified Dickson charge pump VM circuit is introduced in this paper. The proposed converter offers continuous input current and low voltage stress (one-fourth of its output voltage) on its switches. This converter can draw power from a single source or two independent sources while having continuous input currents, which makes it suitable for applications like solar panels. Compared to the topology presented in [19], the proposed converter requires lower voltage rating capacitors for its VM circuit and also one less diode. The inductors and switches experience identical current stresses, making the component selection process for the converter simpler.

In Section II, the modified Dickson charge pump VM circuit has been discussed. Section III introduces modes of operations. The voltage gain of the proposed converter has been derived in Section IV. Section V analyzes the component stress and provides supporting simulation results. Section VI discusses the experimental results obtained using the hardware prototype. A comparative analysis of the proposed converter and the high-voltage-gain converter shown in Fig. 1 has been discussed in Section VII. Finally, Section VIII concludes the paper.

II. MODIFIED DICKSON CHARGE PUMP VM

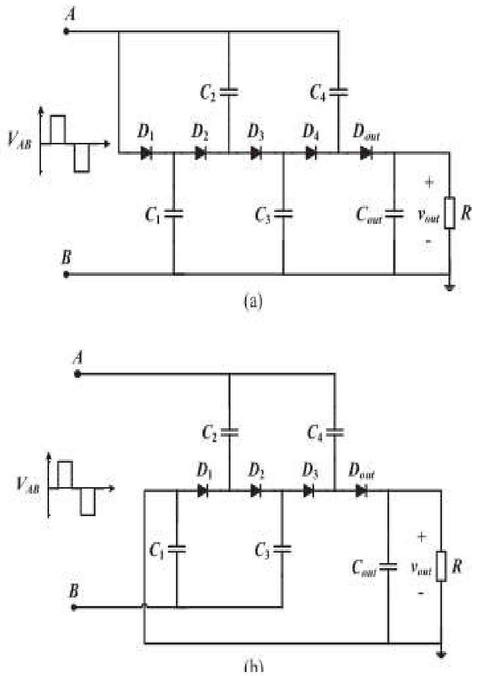


Fig. 2. Conventional and modified Dickson charge pump VM circuits: (a) Dickson charge pump and (b) modified Dickson charge pump.

The Dickson charge pump VM circuit [20], shown in Fig. 2(a), offers a boosted dc output voltage by charging and discharging its capacitors. The input voltage V_{AB} is a modified square wave (MSW) voltage. The voltages of the capacitors in the Dickson charge pump double at each stage as one traverses from the input-side capacitor C_1 to the load-side capacitor C_4 . For an output voltage of Vout = 400 V, the voltages of capacitors C_1 , C_2 , C_3, and $_{C4are}$ 80, 160, 240, and 320 V, respectively. The authors propose to make a slight modification to the Dickson charge pump circuit, as shown in Fig. 2(b). For a same output voltage, the voltages of all the capacitors in the modified Dickson charge pump are smaller than the voltage of capacitor C_2 in the Dickson charge pump. For an output voltage of V out= 400 V, the voltages of capacitors C_1 , C_2 , C_3 , and $_{C4are}$ only 150, 50, 50, and 150 V, respectively. Therefore, the volume of the capacitors used in the proposed modified Dickson charge pump VM circuit is potentially less compared to the Dickson charge pump.

III. TOPOLOGY AND MODES OF OPERATION

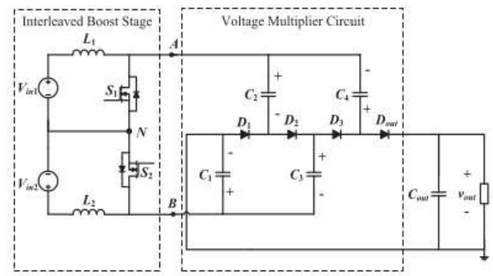


Fig. 3. Proposed high-voltage-gain dc–dc converter.

The proposed converter provides a high voltage gain using the modified Dickson charge pump VM circuit (seeFig.3). It can be seen that the converter is made up of two stages. The first stage is a two-phase interleaved boost converter. The second stage is the modified Dickson charge pump voltage multiplier circuit that boosts voltage to provide a higher dc output voltage. The gating signals of the two interleaved boost stage switches S1 and S2 are shown in Fig. 4. For the proposed converter to operate normally, both switches S1 and S2 must have an overlap time where both are ON and also one of the switches must be ON at any point of time. This can be achieved by using duty ratios of greater than 50% for both the switches and having them operate at 180° out of phase from each other. As can be seen from Fig. 4, such gate signals lead to three different modes of operation, which are explained as follows.

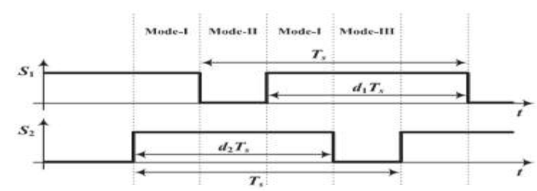


Fig. 4. Input boost converter switching signals for the proposed converter.

Mode I

In this mode, both switches S1 and S2 of the two-phase interleaved boost converter are ON (see Fig. 5). Input sources Vin1 and Vin2 charge inductors L1 and L2, respectively. Inductor currents iL1 and iL2 both increase linearly. All the diodes of the VM circuit are reverse-biased and hence OFF. The voltages of the multiplier capacitors remain same and the output diode D_{out} is reverse biased. Therefore, the load is supplied by the output capacitor.

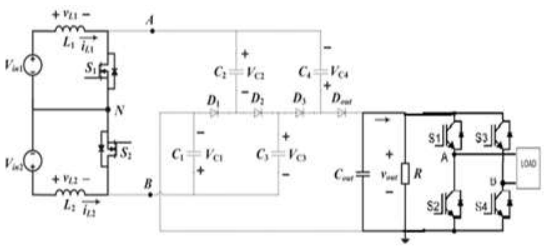


Fig.5. Proposed converter operation in mode I

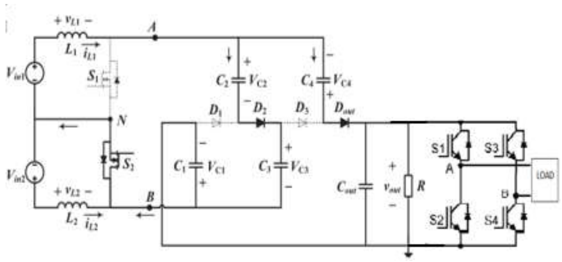


Fig.6. Proposed converter operation in mode II

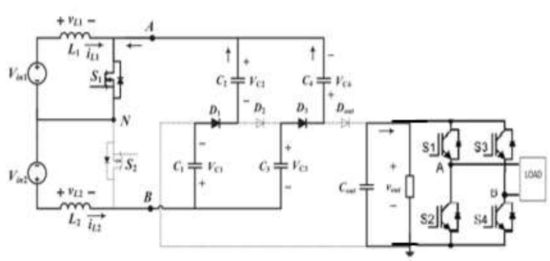


Fig.7. Proposed converter operation in mode III

Mode II

In this mode, switch S1 is OFF and switch S2 is ON. Diodes D1 and D3 are OFF as they are reverse biased, while diodes D2 and Dout are ON as they are forward biased (see Fig. 6). A part of inductor current iL1 flows through capacitors C2 and C3, there by charging them. There maintaining current flows through the capacitorsC4and C1,discharging them to charge the output capacitor Cout and supply the load.

Mode III

In this mode, switch S1 is ON and switch S2 is OFF (see Fig. 7). Diodes D1 and D3 are ON as they are forward biased, while diodes D2 and Dout are OFF as they are reverse biased. Inductor current iL2 flows through diode–capacitor VM cell capacitors C1,C2,C3, and C4. Capacitors C1 and C4 are charged while discharging capacitors C2 and C3.In this mode, the output capacitor supplies the load.

IV. VOLTAGE GAIN OF THE CONVERTER

In the propose dc inverter, the input power is transferred to the output by charging and discharging the VM circuit capacitors. For an ideal converter shown in Fig. 3, the voltage gain of the converter can be derived as described later. For inductors L1 and L2, the average voltage across the inductors according to volt–second balance can be written as

$$VL1=VL2=0\ . \quad (1)$$

From Fig. 6, based on the volt–second balance of inductor L1, one can write

$$V_{AN}=V_{C2}+V_{C3}=V_{out}-V_{C1}-V_{C4}=V_{in1}/(1-d_1). \quad (2)$$

where d1 is the duty cycle of switch S1. From Fig. 3, based on the volt–second balance of the inductor L2, one can write

$$V_{BN}=V_{C1}-V_{C2}=V_{C4}-V_{C3}=V_{in2}/(1-d_2). \quad (3)$$

Assuming capacitors C2 and C3 are identical, the voltage across them would be equal and can be written as

$$V_{C2}=VC3=1/\ 2\times V_{in1}/(1-d1). \quad (4)$$

By substituting(4)into(3),One can derive capacitor voltages V_{C1} and V_{C4} to be

$$V_C=V_{C4}=1/2\times(\ V_{in1})/(1-d1)+((Vin2)\ /(1-d2). \quad (5)$$

Finally, the output voltage is derived by substituting (5) into (2), which yields

$$V_{out}=2\times V_{in1}/(1-d)+\ 2\times\ V_{in2}/(1-d2). \quad (6)$$

The proposed converter can be supplied from two inputs (see Fig. 3) as well as using only one input source. When a single input is used for the proposed converter, switches S1 and S2 have the same switching duty cycle d and are 180° out of phase from each other. The proposed converter with single source is shown in Fig. 8. The multiplier circuit capacitor voltages and the output voltage are simplified as follows:

$$V_{c2}=V_{c3}=1/\ 2\times V_{in}/(\ 1-d) \quad (7)$$

$$V_{c1}=V_{c4}=3/2\times V_{in}/(1-d) \quad (8)$$

$$V_{out}=4\times Vin/(\ 1-d). \quad (9)$$

A 20-V input source at 80% switching duty cycle will generate an output voltage of 400 V using the proposed converter. Capacitors C1 and C4 are charged to 150 V, and capacitors C2 and C3 are charged to 50 V.`

V. SIMULATION RESULTS

A simulation model of the proposed converter has been built in MATLAB software. The parameters used in the simulation are given in Table II.

TABLE II
SIMULATION PARAMETERS

Parameter	Value
Input Voltage	20 V
Output Voltage	400 V
Load Resistance	800 Ω
Duty cycle of switches S_1 and S_2	80%
Switching frequency f_{sw}	100 kHz
Boost inductors L_1 and L_2	100 µH
VM capacitors	60 µF
Output capacitor	22 µF

SIMULATION DIAGRAM

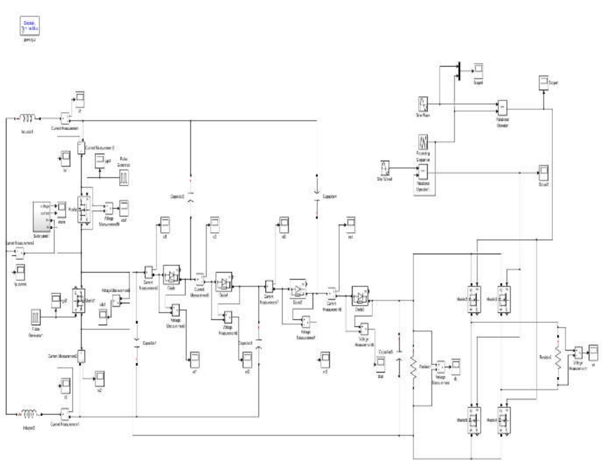


Fig.8.simulink model.

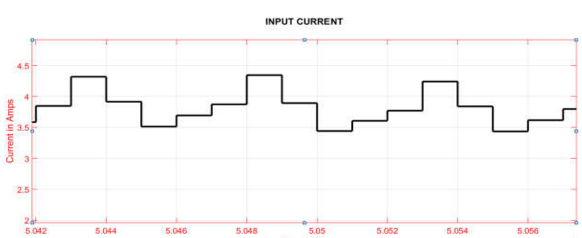
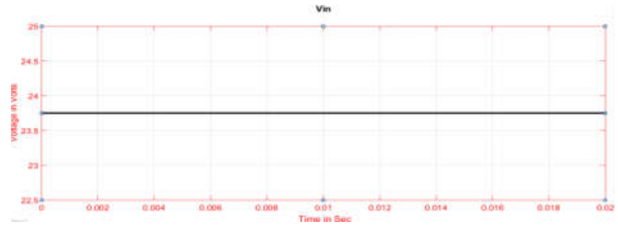


Fig.9. Input current from source



.Fig.10. Input voltage from source

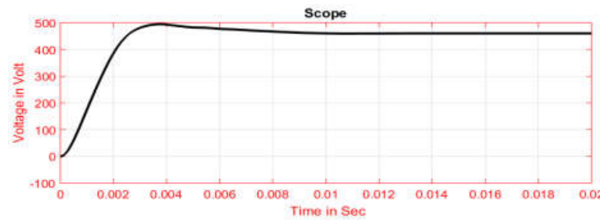


Fig.11.DC Output voltage of PWM technique

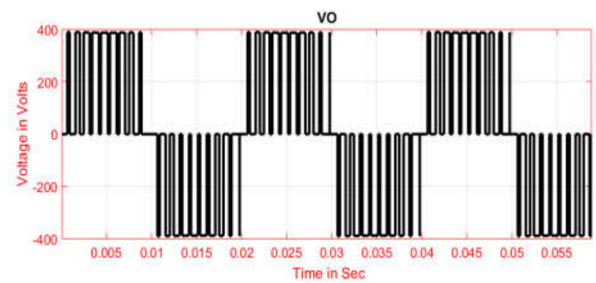


Fig.13.Final AC output voltage.

VI. EXPERIMENTAL RESULTS

A hardware prototype of the proposed converter was built to test and validate the proposed converter operation. The specifications of the components used for building the hardware prototype are given in Table III.

TABLE III
COMPONENT SPECIFICATIONS OF THE HARDWARE PROTOTYPE

Component	Name	Rating	Part No.
Inductor	L_1, L_2	100 µH, DCR = 11 mΩ	CTX100-10-52LP
MOSFET	S_1, S_2	150 V, 43 A, $R_{ds(on)}$ = 7.5 mΩ	IPA075N15N3G
Diode	D_1, D_2, D_3, D_{out}	250 V, 40 A, V_F = 0.97 V	MBR40250T
VM capacitors	C_1, C_2, C_3, C_4	60 µF, 250 V, ESR = 2.6 mΩ	C4ATDBW5600A3OJ
Output capacitor	C_{out}	22 µF, 450 V, ESR = 6.2 mΩ	B32774D4226

VII. PROPOSED CONVERTER VERSUS HIGH VOLTAGE GAIN CONVERTERS USING BOOST STAGE AND VM CIRCUITS

In this section, the proposed converter is compared to other high-voltage-gain converters using boost stage and VM circuits.

TABLE IV

COMPARISON OF THE PROPOSED CONVERTER TO OTHER HIGH VOLTAGE GAIN CONVERTERS

Topology		[8]	[9]	[10]	[11]	Proposed Converter
V_{out}/V_{in}	C_{out}	$\frac{3-d}{1-d}$	$\frac{2}{1-d}$	$\frac{3+d}{1-d}$	$\frac{1}{d(1-d)}$	$\frac{4}{1-d}$
V_{Switch}/V_{out}	S_1	$\frac{1}{3-d}$	$\frac{1}{2}$	$\frac{1}{3+d}$	$1-d$	$\frac{1}{4}$
	S_2	-	-	$\frac{1}{3+d}$	d	$\frac{1}{4}$
V_{diode}/V_{out}	D_1	$\frac{1}{3-d}$	$\frac{1}{2}$	$\frac{2}{3+d}$	$1-d$	$\frac{1}{2}$
	D_2	$\frac{1}{3-d}$	$\frac{1}{2}$	$\frac{2}{3+d}$	d	$\frac{1}{2}$
	D_3	$\frac{1}{3-d}$	-	-	d	$\frac{1}{2}$
	D_4	$\frac{1}{3-d}$	-	-	-	-
	D_o	-	$\frac{1}{2}$	$\frac{2}{3+d}$	-	$\frac{1}{2}$
V_{cap}/V_{out}	C_1	$\frac{1-d}{3-d}$	$\frac{1}{2}$	$\frac{1+d}{3+d}$	$1-d$	$\frac{3}{8}$
	C_2	$\frac{1}{3-d}$	$\frac{1}{2}$	$\frac{2}{3+d}$	d	$\frac{1}{8}$
	C_3	$\frac{1}{3-d}$	-	$\frac{2}{3+d}$	d	$\frac{1}{8}$
	C_4	$\frac{1}{3-d}$	–	–	–	$\frac{3}{8}$

TABLE V

COMPARISON OFTHE PROPOSED CONVERTER TO THE REFERENCE CONCONVERTER

Component	Parameter	Reference Converter [19]	Proposed Converter
Input	Current	Continuous	Continuous
Inductor	Current	$i_{L_1} = 6\,A, i_{L_2} = 4\,A$	$i_{L_1} = 5\,A, i_{L_2} = 5\,A$
Switches	Voltage	$V_{S_1} = 80\,V$, $V_{S_2} = 80\,V$	$V_{S_1} = 100\,V$, $V_{S_2} = 100\,V$
	Duty Cycle	$D_1 = D_2 = 75\%$	$D_1 = D_2 = 80\%$
	Current	$I_{S_1} = 6\,A, I_{S_2} = 4\,A$	$I_{S_1} = 5\,A, I_{S_2} = 5\,A$
VM Capacitors	Capacitance for 1% voltage ripple	$C_1 = 12.5\,\mu F$, $C_2 = 6.25\,\mu F$, $C_3 = 4.17\,\mu F$, $C_4 = 3.125\,\mu F$	$C_1 = C_4 = 6.66\,\mu F$, $C_2 = C_3 = 20\,\mu F$
	Voltage	$V_{C_1} = 80\,V$, $V_{C_2} = 160\,V$, $V_{C_3} = 240\,V$, and $V_{C_4} = 320\,V$	$V_{C_1} = V_{C_4} = 150\,V$, $V_{C_2} = V_{C_3} = 50\,V$
Diodes	Voltage	$V_{D_1} = 160\,V$, $V_{D_2} = 160\,V$, $V_{D_3} = 160\,V$, $V_{D_4} = 160\,V$, and $V_{D_{out}} = 80\,V$	$V_{D_1} = 200\,V$, $V_{D_2} = 200\,V$, $V_{D_3} = 200\,V$, and $V_{D_{out}} = 200\,V$
Output Capacitor	Capacitance for 1 V ripple	$C_{out} = 1.875\,\mu F$	$C_{out} = 1.875\,\mu F$
	Voltage	$V_{C_{out}} = 400\,V$	$V_{C_{out}} = 400\,V$

VIII. CONCLUSION

In this paper, a high-voltage-gain dc–dc converter is introduced that can offer a voltage gain of 20, i.e., to step up a 20 V input to 400 V output. The proposed converter is based on a two-phase interleaved boost and the modified Dickson charge pump VM circuit. It can draw power from a single source as well as from two independent sources while offering continuous input current in both cases, making the converter well suited for renewable applications like solar. The proposed converter is symmetric, i.e., the semiconductor components experience the same voltage and current stresses, reducing the effort and time spent in the component selection during the system design. The proposed converter has smaller VM capacitors compared to a reference converter based on Dickson charge pump VM cells; hence, it is smaller in size. The converter finds its application in integration of individual solar panels onto the 400 V distribution bus in data centers, telecom centers, dc buildings, micro grids and household applications .

CONVERTER FEATURES

High step-up conversion, high circuit efficiency, a low input-current ripple, increased lifetime of the input renewable energy source, and it is suitable for electric vehicle power management applications. In addition, the built-in transformer and voltage-multiplier circuit extend the voltage gain and lower the voltage stresses. As a result, low-voltage-rated semiconductor devices (such as power MOSFETs and diodes) can be adopted in the presented converter. The key characteristics of the proposed converter are listed as follows:

(1) Lowering the input-current ripple and reducing the conduction losses results in an increased lifetime of the renewable energy sources.

(2) The converter easily obtains a high step-up gain.

(3) By recycling the leakage energy, the voltage stresses of the clamp diodes are alleviated and the circuit efficiency is improved.

(4) The voltage stresses on the semiconductor components are substantially lower than the output voltage.

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