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Zeta Converter with Improved Voltage Conversion Gain

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***Abstract*—Demand for electricity is increasing day by day. However, due to the shortage of fossil fuels as well as their huge burden of environmental pollution, the proliferation of renewable energy systems is increasing. DC-DC converters are very popular and important because of the need for step up of the low output voltage of most of these renewable energy systems. The traditional Zeta converter among other DC-DC converters has many benefits like low output voltage ripple and can be used to step up as well as step down the input voltage. It is difficult to apply the traditional Zeta converter in renewable energy systems as the voltage step up capacity of the traditional converter is limited at high duty cycle due to the negative influence of parasitic parameters from the components. A single switch zeta converter with improved voltage conversion ratio is used to address the issue. The converter not only achieves high voltage gain based on our requirement but also has considerably lower voltage stress across the switch. The voltage multiplier circuit is composed of passive components which ensures a continuous output current like the traditional Zeta converter. The drive and control circuits are simple and remain the same as the converter has only one active switch. The performance study is carried out with MATLAB/SIMULINK and simulation results are obtained.**

Keywords—Zeta converter, switched capacitor, improved voltage conversion gain, DC-DC converter

I. INTRODUCTION

The use of electricity is increasing day by day with an ever-increasing population. This energy demand will be co-accelerated by the rapid industrial growth. This energy crisis, depletion of fossil fuels, an alarmingly rising level of environmental pollution and ever-increasing population are the primary reasons for stressing to switch over to renewable energy sources [1]. About 75% of the total CO_2 emissions in the world is contributed by the power systems energy production sector. Thus, the UN is urging all nations to go green [2]. The non-conventional energy resources like photovoltaic (PV) modules, small wind turbines and fuel cells generate low dc voltage and need to be stepped up to the grid requirement voltage.

A DC-DC converter is an electronic circuit that converts a source of DC from one voltage to another voltage. There are different types of traditional DC-DC converters like buck, boost, buck-boost, Cuk, SEPIC and Zeta converters. These are widely used for application in both industrial and commercial sectors. The increase in the use of renewable energy sources has increased the demand for high gain DC-DC power converters that do not compromise efficiency [3].

Zeta converter is a fourth-order DC-DC converter that works as a buck-boost converter with a non-inverted output. It is also known as an inverting SEPIC converter which is made up of two inductors and two capacitors capable of operating in either step-up or step-down mode. However, unlike the buck-boost converter, it does not give an inverted output and has the same polarity as the input. The benefits of the Zeta converter over the SEPIC converter includes low output voltage ripple as well as easier compensation [3].

In ideal conditions, by adjusting the duty cycle of the switch, any voltage conversion gain can be achieved. However, in actual working conditions, the boost capacity of these traditional converters is greatly limited by parasitic elements of the circuit and voltage drops across the switch and diodes. The conduction losses across the switch increase with higher duty

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cycles. This makes the application of the converters difficult in situations where a large voltage conversion ratio is required, especially in renewable energy systems. To achieve a high voltage conversion ratio, a family of generalized passive voltage multiplier circuits termed coat circuits are employed [4]. These circuits are termed coat circuits for DC-DC converters because such circuits surround the DC-DC converters like a coat. In addition to increasing voltage gain, these coat circuits also reduce the voltage stress across the switch comparatively [8].

A higher voltage gain can be achieved by employing a switched capacitor circuit in the traditional zeta converter. This switched capacitor is formed by splitting the energy transfer capacitor in the traditional zeta converter into two capacitors [5]. The advantage of this topology is that there is only one active switch [6]. The voltage boosting techniques presented in [6]-[7] either use transformers or coupled inductors which increase the losses in the converter.

II. PROPOSED CONVERTER

The proposed zeta converter is shown in Figure 1. The converter consists of a single switch S_1, four diodes D_c, D_1, D_{11}, D_{12}, four inductors L_1, L_2, L_{11}, L_{21}, seven capacitors C_1, C_c, C_{11}, C_{21}, C_2, C_{12} and output capacitor C_{22}. Capacitors C_1 and

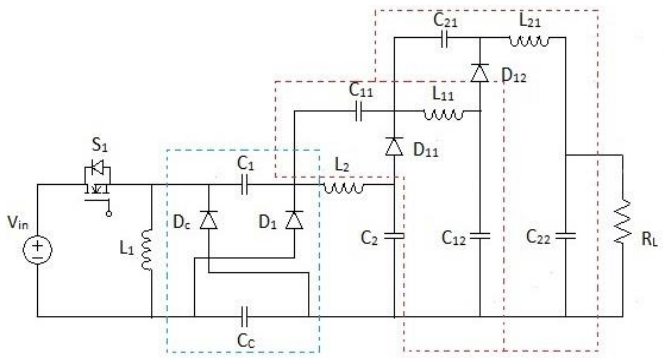

Fig. 1. Proposed converter

C_c and diodes D_1 and D_c together constitute a switched capacitor combination. Capacitors C_{11} and C_{12}, inductor L_{11} together with diode D_{11} constitute a single unit of the voltage multiplier circuit. To perform analysis of the converter, a converter with two units of the voltage multiplier circuit is considered.

Some assumptions are considered during the analysis of the converter. They are as follows:

1) The capacitances of all capacitors are assumed to be large enough that the effects of voltage ripple across them are negligible.

2) All devices are assumed to be ideal, i.e , the influence of parasitic parameters is negligible

III. MODES OF OPERATION

Since the proposed converter has only one active switch, there are only two operating modes in continuous conduction mode. These modes of operation are shown in Figure 2. Mode 1 is between the time interval ($t_0 < t < t_1$).

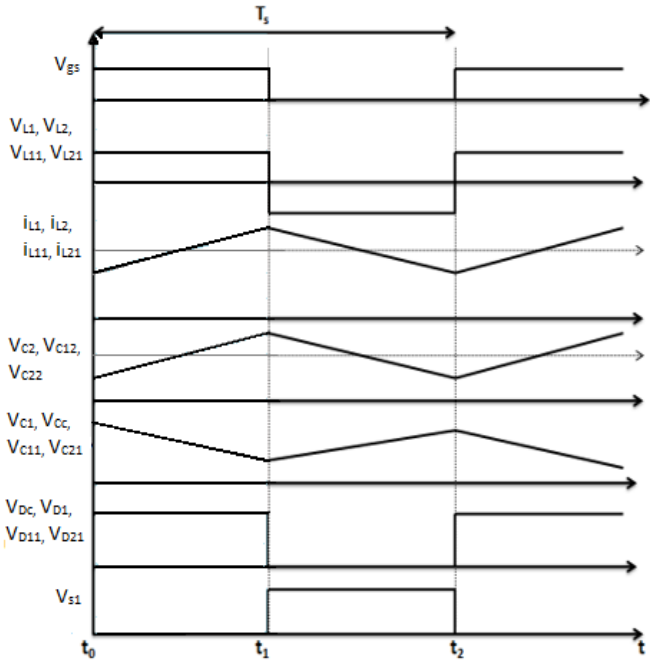

Fig. 2. Theoretical Waveforms

Mode 2 is between the time interval ($t_1 < t < t_2$). The modes of operation are as follows:

Mode 1:

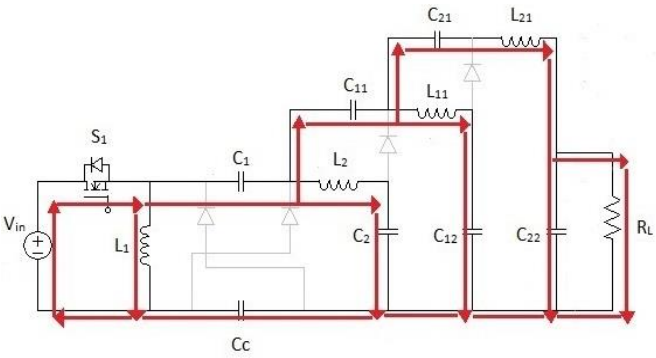

Fig. 3. Equivalent circuit of converter in Mode 1

In this mode, switch S1 is turned ON and all diodes work in the OFF state. During this stage, the input voltage source charges the inductor L_1. The capacitor C_1 and C_c discharge into the inductor L_2 and the capacitor C_2. The capacitor C_{11} and C_1 discharge into the inductor L_{11} and the capacitor C_{12}. Similarly, the capacitor C_{21}, C_{11} and C_1 discharge into the inductor L_{21} and the capacitor C_{22}. Therefore, all inductor currents are found to increase linearly. In this interval, C_2, C_{12} and C_{22} are charging while, C_1, C_C, C_{11} and C_{21} are discharging. The equivalent circuit of Mode 1 is presented in Figure 3.

The equations of Mode 1 are as follows:

$$V_{L1} = V_{in} \quad (1)$$

$$V_{L2} = V_{in} + V_{C1} + V_{Cc} - V_{C2} \quad (2)$$

$$V_{L11} = V_{in} + V_{C11} + V_{Cc} - V_{C12} \quad (3)$$

$$V_{L21} = V_{in} + V_{C21} + V_{Cc} - V_{C22} \quad (4)$$

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Mode 2:

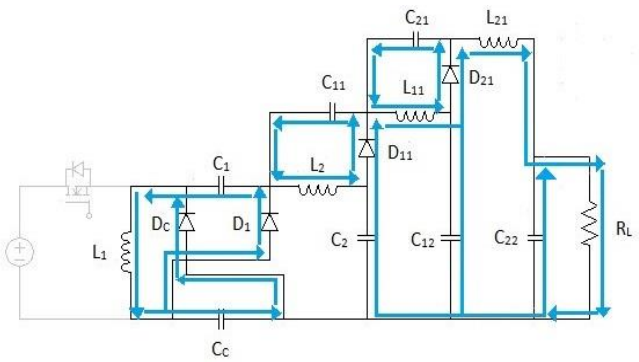

Fig. 4. Equivalent circuit of converter in Mode 2

In this mode, switch S_1 is turned OFF and all diodes work in the ON state. During this stage, the inductor L_1 discharges into capacitor C_1 and C_c. The inductors L_2 and L_{11} discharge into capacitors C_{11} and C_{21} through D_{11} and D_{21} respectively. The inductor L_{21} discharges through the output stage (C_{22}/R_L). In this interval, C_1, C_c, C_{11} and C_{21} are charging while C_2, C_{21} and C_{22} are discharging. The equivalent circuit of Mode 2 is presented in Figure 4.

The equations of Mode 2 are as follows:

$$V_{L1} = -V_{C1} = -V_{Cc} \quad (6)$$

$$V_{L2} = -V_{C11} = -V_{C2} - V_{Cc} \quad (7)$$

$$V_{L11} = -V_{C21} = V_{C11} - V_{C12} = V_{C2} + V_{Cc} - V_{C12} \quad (8)$$

$$V_{L21} = V_{C21} - V_{C22} = V_{C12} - V_{C11} - V_{C22} \quad (9)$$

$$V_{L21} = V_{C12} - V_{C2} - V_{Cc} - V_{C22} \quad (10)$$

On applying the volt-second balance principle on the inductors L_1, L_2, L_{11} and L_{21} and considering the above analysis of the operation of the converter, we get the following equations.

$$V_{in}\, D = V_{C1}(1\text{-}D) = V_{Cc}(1\text{-}D) \quad (11)$$

$$(V_{in} - V_{C2} + V_{C1} + V_{Cc})\, D = V_{C11}(1\text{-}D) \quad (12)$$

$$(V_{in} - V_{C2} + V_{C1} + V_{Cc})\, D = (V_{C2} + V_{Cc})(1\text{-}D) \quad (13)$$

$$(V_{in} + V_{C11} + V_{Cc} - V_{C12})\, D = V_{C21}(1\text{-}D) \quad (14)$$

$$(V_{in} + V_{C11} + V_{Cc} - V_{C12})\, D = (V_{C12} - V_{C11})(1\text{-}D) \quad (15)$$

$$(V_{in} + V_{C11} + V_{Cc} - V_{C12})\, D = (V_{C12} - V_{C2} - V_{Cc})(1\text{-}D) \quad (16)$$

$$(V_{in} + V_{C21} + V_{Cc} - V_{C22})\, D = (V_{C22} - V_{C21})(1\text{-}D) \quad (17)$$

$$(V_{in} + V_{C21} + V_{Cc} - V_{C22})\, D = (V_{C22} + V_{C11} - V_{C12})(1\text{-}D) \quad (18)$$

$$(V_{in} + V_{C21} + V_{Cc} - V_{C22})\, D = (V_{C22} + V_{Cc} + V_{C2} - V_{C12})(1\text{-}D) \quad (19)$$

The voltage conversion gain can be obtained from the above equations. It is shown in equation (20)

$$M = V_o/V_{in} = 4{\cdot}D/(1\text{-}D) \quad (20)$$

This converter can be generalized to contain n basic units of the voltage multiplier circuit. The generalized equation is as follows.

$$M = V_o/V_{in} = (n+2){\cdot}D/(1\text{-}D) \quad (21)$$

From equation (21) it is evident that the converter can be designed as per the voltage requirement.

IV. Design Considerations

The input voltage is taken as 48V. The pulses are switched at a frequency of 100 kHz. The output power is taken to be 350W.

Voltage conversion gain, $M = V_o/V_{in} = 4D/(1\text{-}D)$

where D is the duty ratio of the switch S_1. D is taken to be 0.74.

A. Inductor Design

The ripple current for the inductor L_1,

$$\Delta I_{L1} < 204\% \text{ of } I_o = 1.35 \text{ A}$$

Similarly, the ripple currents of the inductors L_2, L_{11}, L_{21}

$$\Delta I_{L2} = \Delta I_{L11} = \Delta I_{L21} < 52\% \text{ of } I_o = 0.35 \text{ A}$$

$$L_1 = V_{in}{\cdot}D{\cdot}T/\Delta I_{L1} \geq 263.11\ \mu\text{H} \quad (22)$$

$$L_{2,11,21} = V_{in}{\cdot}D{\cdot}T/\Delta I_{L2,11,21} \geq 896.96\ \mu\text{H} \quad (23)$$

To keep the ripple currents well within range, the value of the inductors is taken as $L_1 = 300\ \mu$H and $L_{2,11,21} = 950\ \mu$H.

B. Capacitor Design

The voltage ripple for the capacitors C_1, C_c, C_2, C_{11}, C_{21}

$$\Delta V_{C1,Cc,C2,C11,C21} < 5\% \text{ of } V_{C1,Cc,C2,C11,C21} = 6.83 \text{ V}$$

The voltage ripple for the capacitor C_{12}

$$\Delta V_{C12} < 5\ \% \text{ of } V_{C12} = 20.49 \text{ V}$$

The voltage ripple for the output capacitor C_{22}

$$\Delta V_{C12} < 0.5\ \% \text{ of } V_{C12} = 2.645 \text{ V}$$

$$C_1 = C_c = 3{\cdot}I_o{\cdot}D{\cdot}T/\Delta V_{C1,Cc} \geq 2.157\ \mu\text{F} \quad (24)$$

$$C_{11} = 2{\cdot}I_o{\cdot}D{\cdot}T/\Delta V_{C11} \geq 1.483\ \mu\text{F} \quad (25)$$

$$C_2 = C_{21} = I_o{\cdot}D{\cdot}T/\Delta V_{C2,C21} \geq 0.719\ \mu\text{F} \quad (26)$$

$$C_{12} = I_o{\cdot}D{\cdot}T/\Delta V_{C12} \geq 0.283\ \mu\text{F} \quad (27)$$

$$C_{12} = I_o{\cdot}D{\cdot}T/\Delta V_{C22} \geq 1.849\ \mu\text{F} \quad (28)$$

Considering the uniformity of devices and to keep the voltage ripples well within limits, the value of the capacitors.

$$C_1 = C_2 = C_c = C_{11} = C_{12} = C_{21} = C_{22} = 4\ \mu\text{F}$$

V. Simulation Results

TABLE I. SIMULATION PARAMETERS

Parameters	Specification
Input voltage V_{in}	48 V
Switching frequency f_s	100 kHz
Output voltage V_o	529 V
Inductor L_1	300 µH
Inductors L_2, L_{11}, L_{21}	950 µH
Capacitors C_c,C_1,C_2,C_{11},C_{12},C_{21},C_{22}	4 µF
Load resistance R_L	800 Ω

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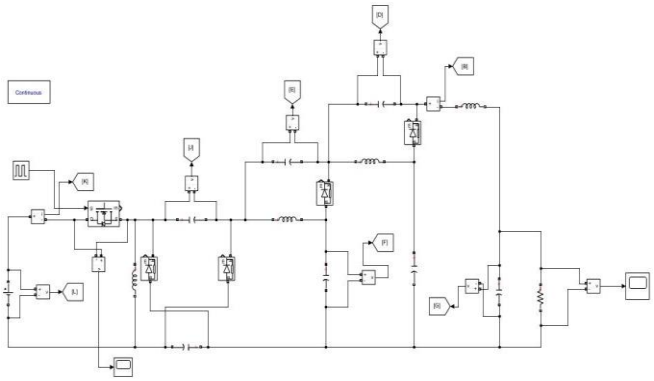

Fig. 5. Simulink Model

The simulation parameters of the converter are shown in Table 1. A converter with two basic units of the voltage multiplier circuit is simulated. An input voltage V_{in} of 48 V gives an output voltage V_o of 529 V for an output power P_o of 350W. The pulses are switched at a frequency of 100 kHz . The duty ratio is taken as 0.74. The converter is simulated in MATLAB/SIMULINK by using the mentioned parameters. The Simulink model is shown in Figure 5.

The simulation results of the converter are shown in the following figures. It can be seen from Figure 6. (a) and 6. (b) that the input voltage V_{in} = 48V and the output voltage is about 529 V. The output voltage has a ripple of 0.017% which is very low and one of the characteristics of the zeta converter.

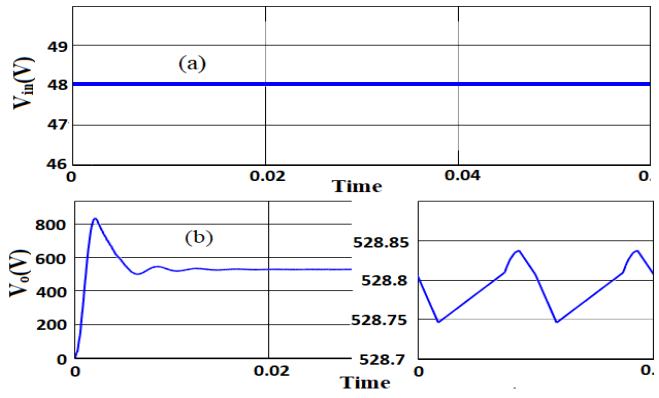

Fig. 6. (a) Input voltage V_{in} (b) Output voltage V_o

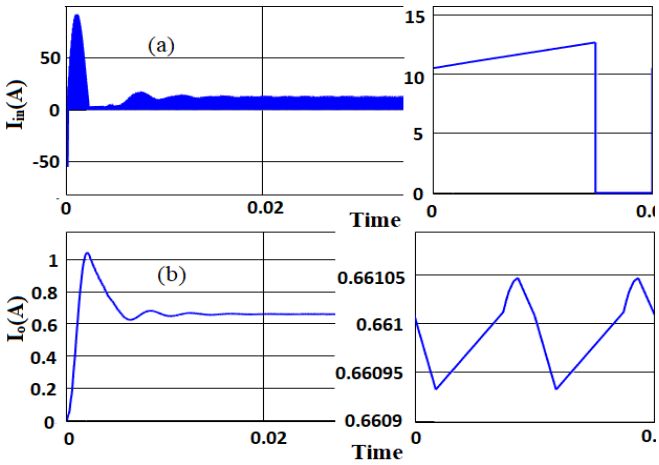

Fig. 7. (a) Input current I_{in} (b) Output current I_o

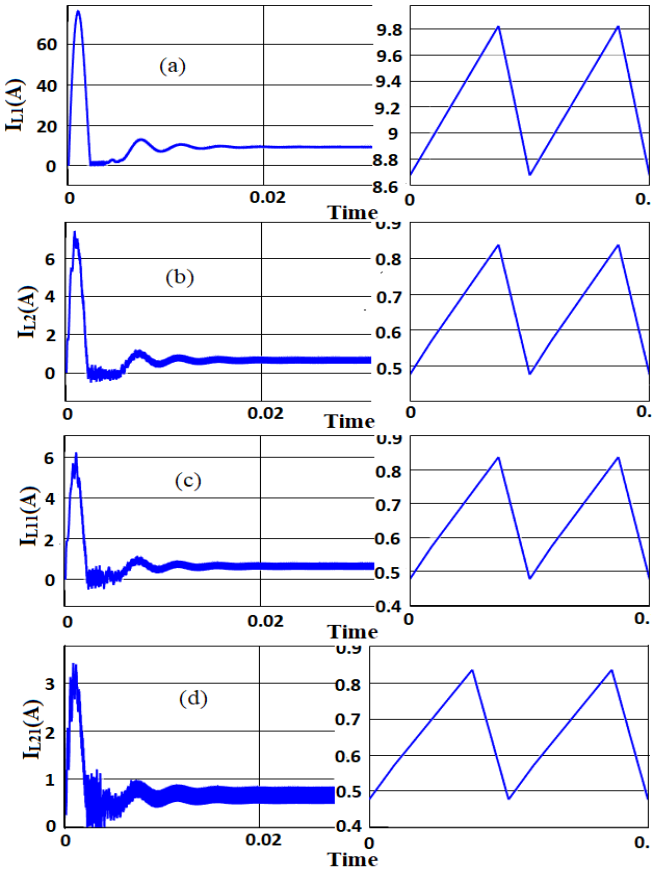

Fig. 8. Inductor currents (a) I_{L1} (b) I_{L2} (c) I_{L11} (d) I_{L21}

Figures 7. (a) and 7. (b) represent the input and output current waveforms. The peak input current passing through the switch is equal to 12.67 A and the peak output current is equal to 0.661 A. Figures 8. (a), 8. (b), 8. (c) and 8. (d) are the inductor current waveforms. It can be observed that the current ripples are well within the designed limits. The voltage waveforms of the capacitors C_2, C_{12} and C_{22} are shown in Figure 9.

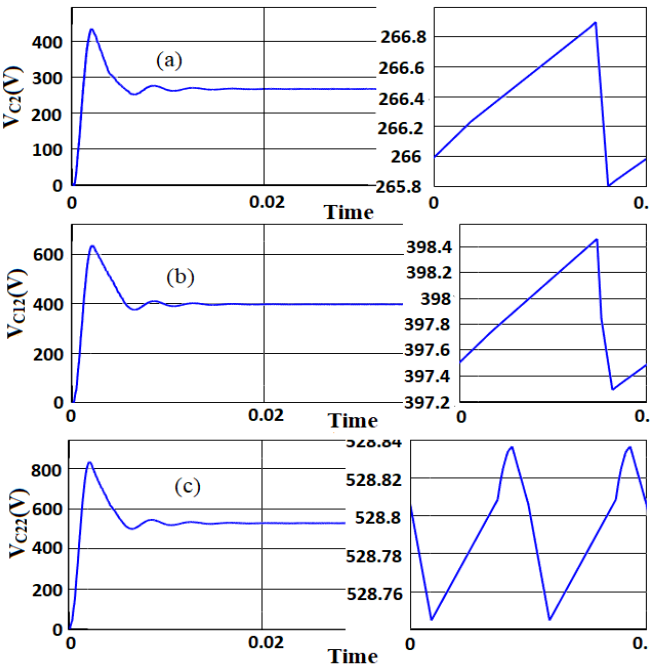

Fig. 9. Capacitor voltages (a) V_{C2} (b) V_{C12} (c) V_{C22}

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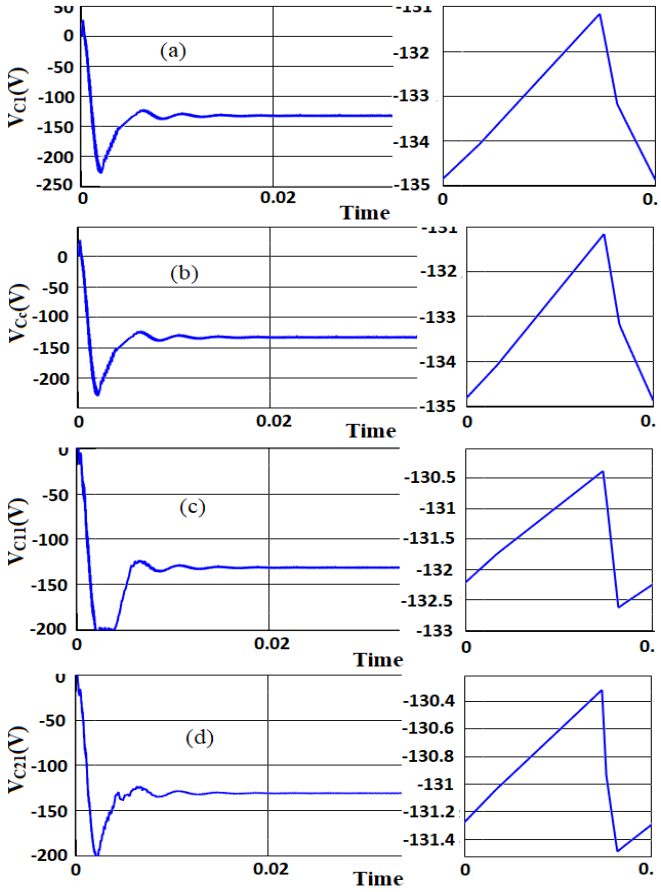

Fig. 10. Capacitor voltages (a) V_{C1} (b) V_{Cc} (c) V_{C11} (d) V_{C21}

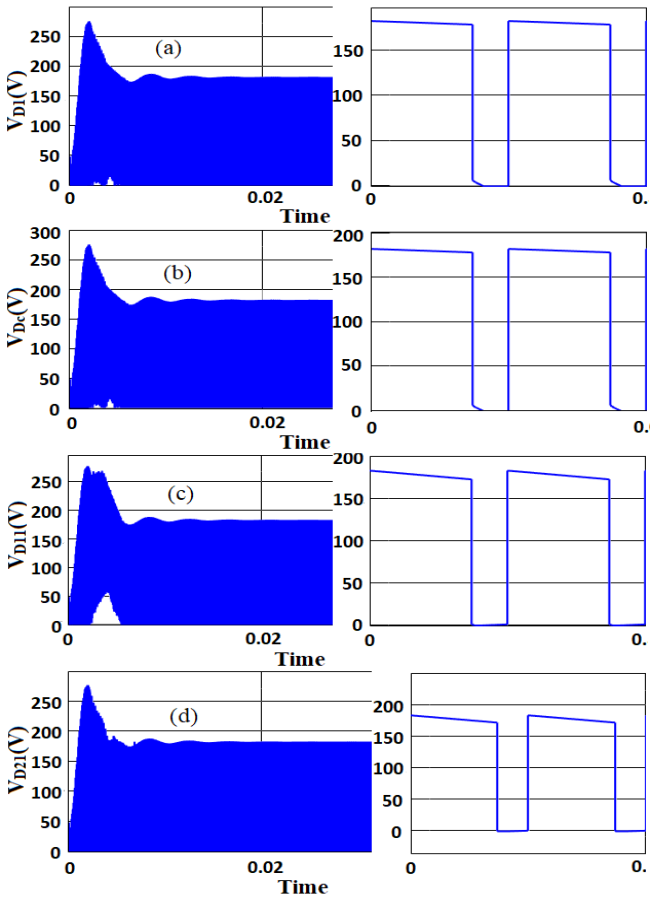

Fig. 12. Diode voltages (a) V_{D1} (b) V_{Dc} (c) V_{D11} (d) V_{D21}

The voltages across capacitors C_1, C_c, C_{11} and C_{21} are -131.6 V, -131.6 V, -130.38 V and -130.32 V respectively and are shown in Figure 10. It can be observed that the voltage ripples of the capacitors are well within the designed limits.

The voltage across the switch S_1 is equal to 183.68 V and is shown in Figure 11. (a). This voltage stress across the switch is low considering the large increase in output voltage. Figure. 11. (b) shows waveform of the switching pulses.

Figure 12. shows the voltages across the diodes D_1, D_c, D_{11} and D_{21}. They are 181.8 V, 181.8 V, 182.9 V and 182.7 V respectively.

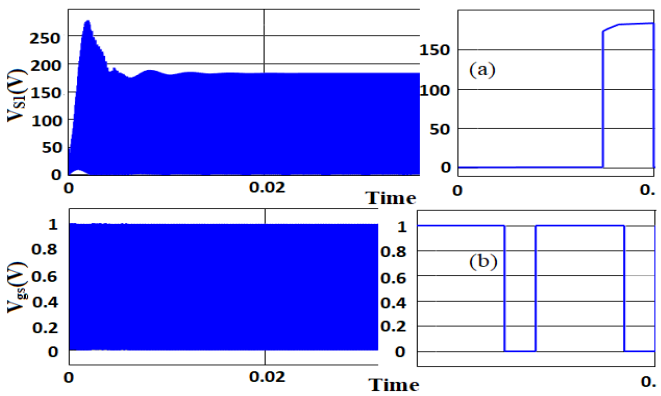

Fig. 11. (a)Voltage across switch V_{S1} (b) Switching pulse V_{gs}

VI. ANALYSIS

The analysis of the proposed converter is performed by considering various parameters like efficiency, duty ratio and output voltage ripple.

From the plot of efficiency vs output power, the converter is found to have a maximum efficiency of 88.5% at a power of 864 W.

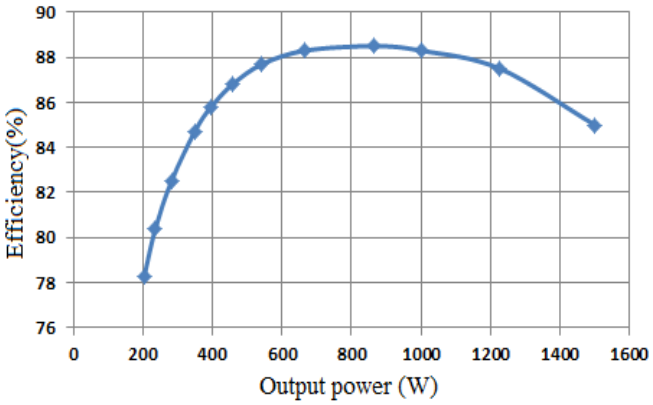

Fig. 13. Efficiency Vs Output Power

On performing the analysis of voltage gain vs duty ratio, the plot in Figure 14 is obtained. The voltage gain is found to

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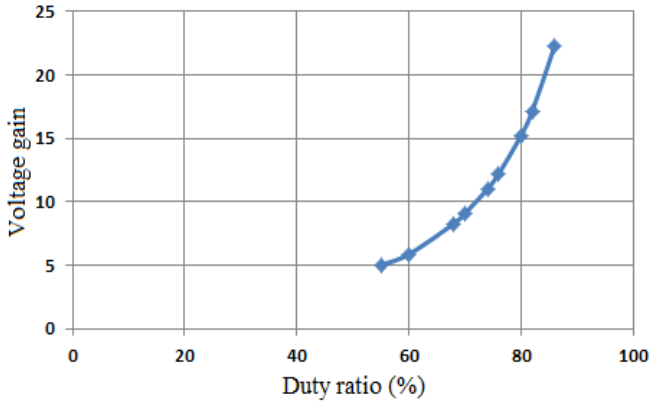

Fig. 14. Voltage gain Vs Duty ratio

increase with increase in duty ratio. However large duty ratios can result in larger conduction losses, thus reducing the efficiency of the converter. Therefore, large duty ratios are avoided.

From Figure 15, it is observed that the output voltage ripple decreases with increase in the duty ratio. However, increasing the duty ratio to very high values is not practical as conduction losses increase.

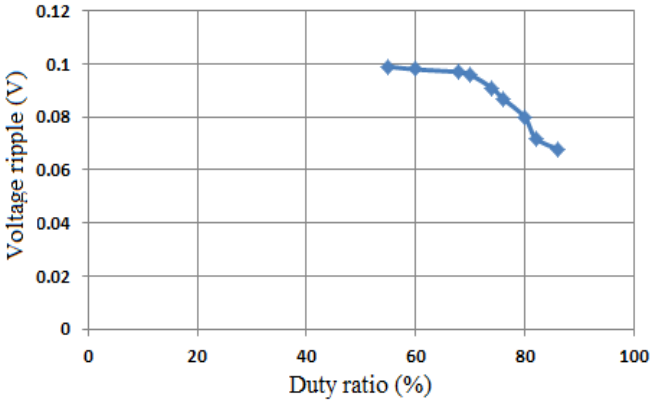

Fig. 15. Voltage ripple vs Duty ratio

Based on these and other parameters, the proposed converter is compared to the traditional zeta converter as well as the zeta converter with only voltage multiplier circuits. The comparison is given in Table II.

TABLE II. COMPARISON

Parameters	Conventional	Coat circuit	Proposed
Efficiency	82.9 %	85.15 %	88.5 %
Output voltage ripple	0.22 (0.165%)	0.1 (0.025%)	0.09 (0.017%)
Gain	2.77	8.33	11.02
Input current	11.604 A	11.825 A	8.592 A
Voltage stress of switch	184 V	184 V	183 V

VII. CONCLUSION

The proposed converter offers improved voltage conversion gain and low output voltage ripple. This is achieved by the addition of a switched capacitor circuit as well as voltage multiplier circuits. On analysis and simulation, the proposed converter is found to have high voltage conversion gain. The number of basic cells of the voltage multiplier circuit can be adjusted based on different applications. Since the proposed converter has only a single active switch, the driver and control circuit are uncomplicated to design and cost-effective to implement. The converter helps avoid extreme duty cycles. These characteristics show that the converter is suitable for applications where a wide voltage conversion ratio is required.

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