A Novel Hybrid High Gain DC-DC Converter for Renewable Energy Applications

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Abstract- Power electronics plays a key role in the renewable energy systems as an intermediate stage. To remove the transformer at the AC side, high gain converter is an essential part which helps in boosting up the voltage to higher level. Numerous converters are proposed so far, however it requires more number of components to achieve higher gain. Higher components counts are required to achieve appropriate gain. In order to overcome this issue, a novel hybrid high gain DC-DC converter with reduced voltage stress is proposed in this ace research. The operational details along with the equivalent circuits under CCM and DCM conditions are described in this paper. The mathematical analysis of the converter is presented and moreover, the comparative performance of the proposed converter with existing converters has been reported. Finally, the simulation and laboratory experimentation were carried out to analyse the performance of the proposed converter respectively..

Keywords Globalized MPPT, solar PV, renewable energy, partial shading, PSCAD/EMDTC.

1. Introduction

Due to energy crises and increasing power demand day by day, many countries seeking an alternative solution as renewable energy generation to meet the power demand [1]. Due to technology growth, the solar photovoltaic based generation is becoming a popular and cost per kW is also gets reduced since last few years. In India, 150 GW of renewable energy generation would be installed across the nation as per the MNRE report [2-3]. To achieve this target, government of India is planning to install solar rooftop system across the country. Generally, the solar PV system can be operated under on-gird mode and off-grid mode. In both the modes of operation intermediate stages are required to operate smooth power transfer in both on-grid and off-grid mode. It consists of DC-DC converter, DC-AC converter and transformer section to operate the load. However, the size and cost of on-grid and off-grid structure is higher due to this presence of bulky transformer [4-5]. The generalized structure of renewable based micro grid structure is shown in Fig. 1.

Classic boost type converters are often used in the solar PV system to achieve higher voltage at DC-link voltage side. However, due to practical considerations, the duty ratio is limited to 0.8 and beyond this, the inductor core may get attain saturation level. Therefore, where the voltage gain requirement is beyond five, this classic type converter fails to satisfy the voltage level [6]. Thereby, authors focus about derived topologies of dc-dc converters. To achieve higher gain, isolated converters are suitable option and many articles are being published in flyback, forward, half and full bridge and push pull converter based configurations [7-10]. By adjusting the turn's ratio of coupling transformer, the voltage gain can be achieved. However, for low and medium power range applications, the converter dimensions are too high and bulky, which increases the complexity and cost of the system. Especially, voltage spikes often cause damage the switching devices [11]. Apart these, it creates leakage inductance and more power dissipation. To attain higher gain, an alternative solution of coupled inductor approach is focused in many papers. In [12], coupled inductor type high gain converter is proposed. But, the EMI, leakages inductance is difficult to suppress in the converter. To overcome this, non-dissipative snubbed circuitry and clamping circuit has been introduced [13] in the converter. However, it increases the bulkiness and higher cost involvement. Compared to all these isolated and coupled inductors, non-isolated converters are more promising converter to achieve higher efficiency [14, 15].

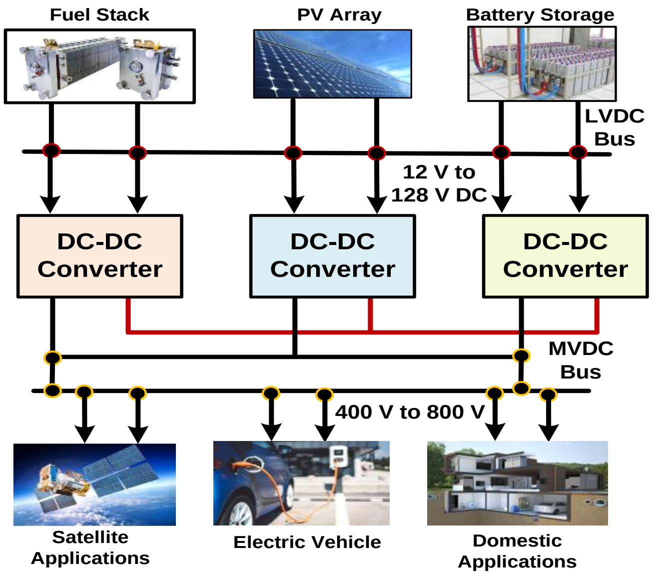


Fig. 1 Generalized renewable energy based microgrid structure

Many researchers have been proposed with variety of derived dc-dc converter to achieve higher gain in the past studies [16]. In [17], the switched inductor approach is familiarized to yield higher gain. A novel switched capacitor network based high gain converter is proposed in [18], but the device stress is almost equal to output voltage and deteriorates the efficiency. To reduce the device stress, the combination of switched inductor and switched capacitor based high converter is proposed in [19]. But, it requires more number of components count, which also reduces the efficiency and higher in cost. In [20], hybrid converter is proposed with minimum number of components, however, the higher voltage gain can be achieved after 50% of the duty cycle ranges, and therefore it degrades the performance of the converter [21]. Recently, authors are arrived with active network based approach to attain higher gain with smaller duty ratio itself. But, the components involvement is a common problem these approaches and losses are more [22-27]. In [23] and [24], the switched capacitor and switched inductor network based transformerless converter is proposed to enhance the gain using hybrid structure. Due to presence of more passive elements, the efficiency enhancement get fails. Because of the advantage of higher gain in dc-dc converter, it is more suitable for renewable energy applications and a modified SEPIC converter is presented in [25] to achieve higher gain for renewable applications. The voltage multiplier and coupled inductors are most promising solution approach to boosting up the voltage gain to very higher level. Therefore, the performances of very high step up converters are compared and analysed in [26] and [27]. From all these literature, it is clearly stated that, certain investigation is required on the derived topologies of high gain converter. By keeping this goal as aim, this paper proposes a novel configuration of high gain converter based on hybrid network approach. The switched inductor and switched capacitors are arranges in such a way that the proposed converter can yield higher gain when compared to other recently derived topologies. In addition, the number of components involved in the circuitry is lesser than the conventional approach. It is notable that the higher gain can be achieved with single switch. And also, the stress across the device is very less; therefore switching losses are drastically reduced. The detailed operational waveforms with mathematical analysis were presented in this paper. The detailed investigation on the past studies were conducted and summarized in this paper.

To analyze and validate the proposed high gain converter, the simulation model has been developed in PSCAD/EMDTC software and measured results are presented in this appear. Finally, to verify the operational behaviour, the experimental set up of proposed hybrid high gain converter has been developed and experimental results are observed and reported in this paper.

2. Proposed Hybrid High Gain DC-DC Converter

The circuit diagram of proposed high gain converter is illustrated in Fig. 2. It consists of two inductors, three capacitors and five diodes along with single switch. The double boosted type configuration is merged with quadratic converter to attain higher gain with minimum components count.

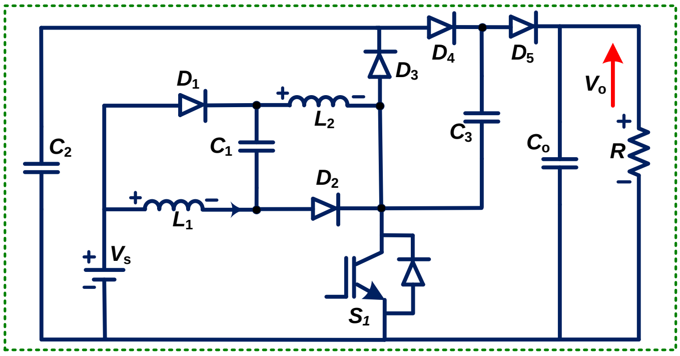


Fig. 2 Circuit diagram of proposed hybrid high gain DC-DC converter

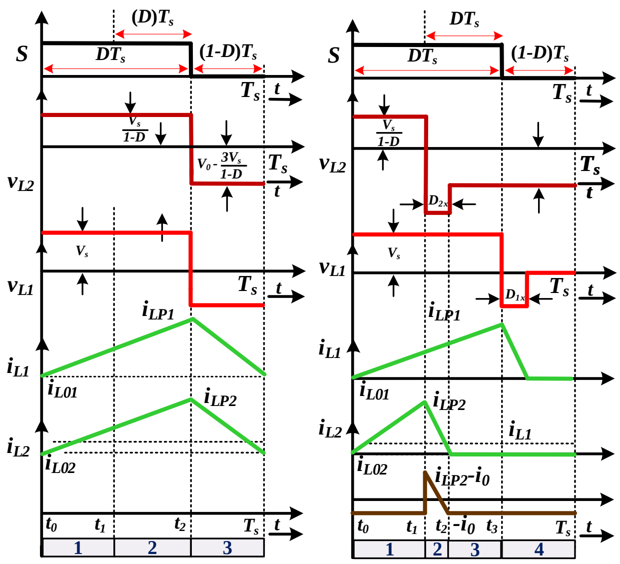


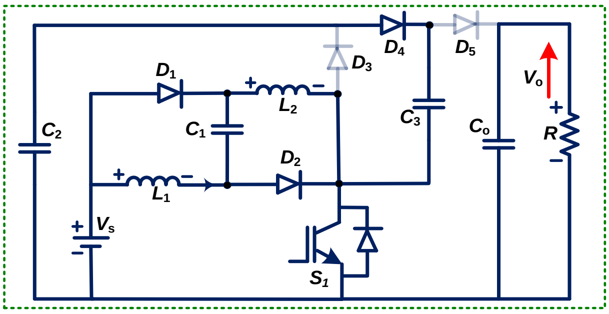
Fig. 3 Operational waveform of the proposed hybrid high gain DC-DC converter

The modes of operation can be identified based on and off state of the switches. The operating waveform of the converter under CCM and DCM conditions is clearly illustrated in Fig. 3.

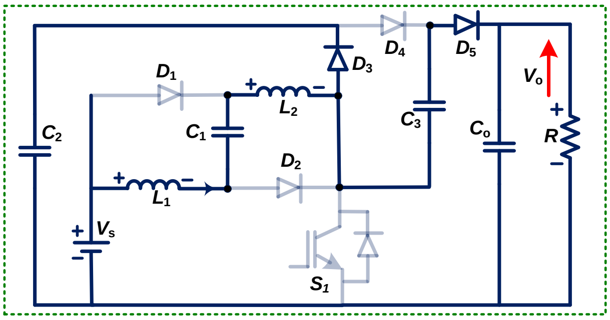
2.1. Continuous current conduction mode (CCM)

There are two modes in CCM operation. The equivalent circuit of proposed converter is also clearly depicted in Fig. 4. Based on the on and off states of switch, the operating waveforms are plotted for CCM and DCM condition. Due to ON and OFF states of the switch, the inductor and capacitor voltage across the devices and current through these elements are clearly indicated. Therefore, it is easier to analyze the mathematical relation between voltage and current of these elements.

Mode 1: When switch is ON condition, the inductor L_1 and L_2 are gets charged simultaneously. At the same time, the C_2 energy is released to C3 through the switch. Therefore, the previous cycle energy is also fed back to C_3 and voltage across C_3 is starts increases to maximum level. At this time, the output gets energy from C_O. Under this state of operation, the equivalent circuit is clearly depicted in Fig. 4 (a).



(a)



(b)

Fig. 4 Equivalent circuit of proposed hybrid high gain DC-DC converter in (a) Mode 1 (b) Mode 2

During on state of the switch, the voltage relation between the inductor and capacitor can be expressed as,

$$\begin{aligned} V_{L1} &= V_{L2} = V_s \\ V_{C1} &= V_s \\ V_{C3} &= V_{C2} \end{aligned} \quad (1)$$

Mode 2: When the switch S_2 is off state, the energy stored in the inductor L_1 and L_2, and capacitor C_1 and C_3 are discharged to the load and as well C_O gets charged to deliver the energy during on state of switch. Simultaneously, the capacitor C_2 is gets charged at the level of Vs, V_{L1}, V_{C1} and V_{L2}. The equivalent circuit under mode 2 is clearly depicted in Fig. 4(b). The mathematical relations can be written as,

$$V_{L1} + V_{L2} = V_s + V_{C1} + V_{C3} - V_o \quad (2)$$

The output voltage relation with respect to inductor voltage can be written as,

$$V_{L1} = \frac{2V_s + V_{C3} - V_o}{2} \quad (3)$$

Using (2) and (3), the expression can be altered as,

$$V_{L1} + V_{L2} = V + V_{C1} - V_{C2} \quad (4)$$

By considering the voltage balance equation across the inductor is zero, the expression can be written as,

$$dV_s + \left(V_s - \frac{V_{C2}}{2}\right)(1-d) = 0 \quad (5)$$

The voltage across the capacitor C2 during switch off state can be written as,

$$V_{C2} = \frac{2V_s}{1-d} \quad (6)$$

By considering the voltage balance equation across the inductor is zero, the expression can be written as,

$$dV_s + \left(\frac{2V_s + V_{C3} - V_o}{2}\right)(1-d) = 0 \quad (7)$$

The output voltage relations can be written as,

$$V_o = \frac{2V_s}{1-d} + V_{C2} \quad (8)$$

After simplifying, the output voltage and load current (Io) relationship can be written as,

$$V_o = \frac{4V_s}{(1-d)} \quad (9)$$

$$I_o = \frac{(1-d)}{4} I_s \quad (10)$$

After solving the gain ratio can be written as,

$$G = \frac{V_o}{V_s} = \frac{4}{(1-d)} \tag{11}$$

2.2. Discontinuous current conduction mode (DCM)

Due to smaller value of inductor, the current reaches to zero before complete the cycle of operation, therefore again inductor charged to extreme level, therefore more voltages develops across the load. The output voltage yield at extreme level but, performance of the converter gets degraded. The value of inductor must be chosen at right value to obtain such an operation. The operational waveform under this mode of operation is clearly depicted in Fig. 3. The inductor voltage and current relations during ON and OFF states of the switch can be written. Similar to the CCM analysis, after careful derived all of these mathematical relations, the load current expression can be found as,

$$\frac{(dV_s)^2 T_s}{(2V_s - V_{C2} - V_o)L} = \frac{V_o}{R} \tag{12}$$

In DCM condition, after simplifying the gain ratio can be written as,

$$G_{dcm} = \frac{d}{1-d} + d\sqrt{\frac{d}{(1-d)^2} + \frac{1}{\tau_L}} \tag{13}$$

Where, the time constant of inductor is determined as,

$$\tau_L = \frac{d^2(1-d)^2}{4-2d} \tag{14}$$

Various Converter Configuration	L	C	Switch (S)	Diodes (D)	Components count	Gain (M)	Voltage Stress on Device	Current Stress on Device	Efficiency
[21]	1	1	1	1	4	$\frac{1}{1-d}$	1	I_{in}	-
[22]	1	3	1	3	8	$\frac{2}{1-d}$	0.5	$I_{in}+I_{C1}$	94.6% at 100W
[23]	2	2	2	4	10	$\frac{1+d}{d(1-d)}$	$\frac{1}{(1-d)M}$	$\frac{2I_{in}}{1+d}$	-
[25]	2	1	1	4	8	$\frac{1+d}{1-d}$	1	I_{in}	95.2% at 50W
[26]	2	1	2	1	6	$\frac{1+d}{1-d}$	$\frac{1+M}{M}$	$\frac{2I_{in}}{1+d}$	92.7% at 100W
[27]	2	3	1	2	8	$\frac{1+d}{1-d}$	$\frac{1+M}{2M}$	I_{in}	92.2% at 100W
[17]	3	4	1	4	12	$\frac{3+d}{1-d}$	$\frac{M}{3+d}$	$I_{in}+I_{C1}$	94.4% at 250W
[18]	3	3	1	3	10	$\frac{d}{(1-d)^2}$	1	$I_{in}+I_{C1}+I_C$	91.4% at 100W
[28]	3	3	1	5	12	$\frac{1-d}{(1-d)^2}$	$\frac{1}{(1-d)}$	$I_{in}+I_{C1}$	94.8 at 30 W
Proposed Hybrid	2	4	2	4	12	$\frac{4}{1-d}$	0.5, 0.5	$\frac{I_{in}}{2}, \frac{I_{in}}{2}$	96.5% at 500W

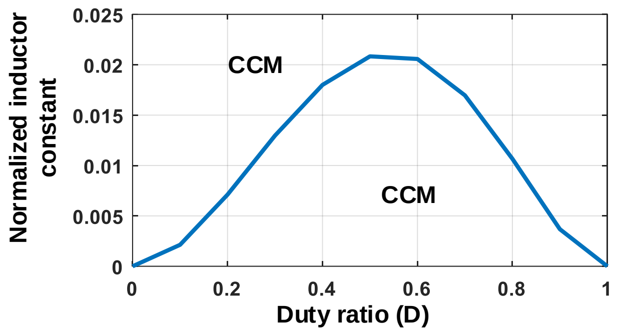


Fig. 5 Boundary region of CCM and DCM with respect to duty ratio.

Using (14), the boundary condition of proposed converter can be identified by plotting the graphical representation. The normalized inductor constant has been identified derived from (13) and also, it varies with respect to d. The boundary regions can be identified from the following plot. The boundary region of CCM and DCM operation is shown in Fig. 5. The designers have to choose suitable value of inductor for the given voltage rating to operate the converter in CCM mode.

3. Comparative Analysis of the Proposed Hybrid High Gain DC-DC Converter

The performances of the proposed converter can be analyzed by comparing the merits with existing converters reports in the literature. In [22] presents the multilevel boost converter, it has higher range of gain than classic type. However, the voltage lifting is not as much, therefore [23] is proposed higher voltage lifting technique. But the voltage components are higher, therefore, switched inductor and capacitor approach is proposed in [25]. From this switched inductor approach, some more modification done to enhance the performances and reported in [26, 27] and [17] to [18].

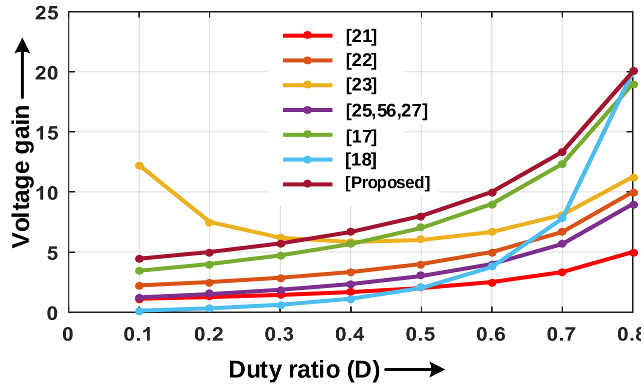
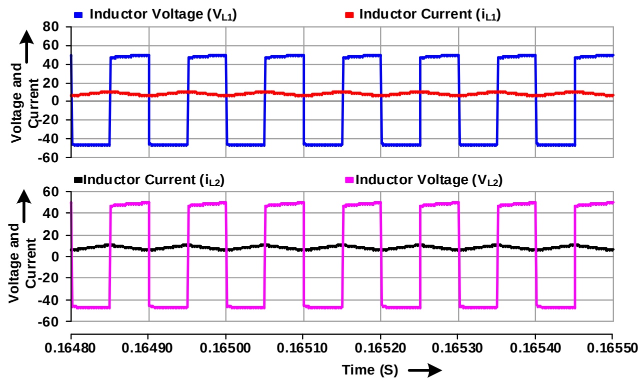


Fig. 6 Comparative gain plat with various duty cycles

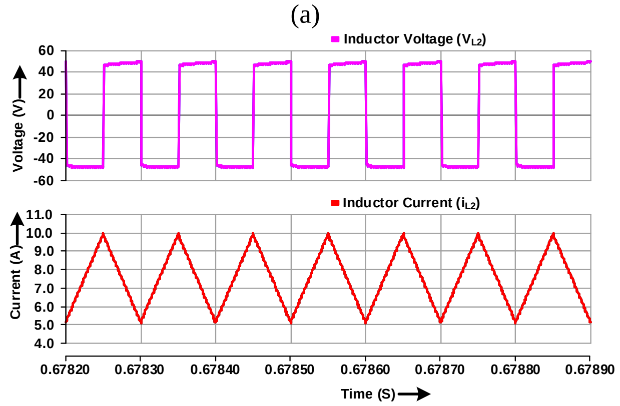
The merits of proposed converter has been compared with these entire recently reported converter and summarized in Table 1, therefore it provides higher efficiency under wide range of duty ratios. For better view, the gain value of proposed converter under various duty ranges along with existing converters are plotted as shown in Fig. 6. From this plot, it can clearly understand that the proposed converter has higher voltage lifting capacity than other converters. Therefore, the required duty cycle range is much lower than the all other converter. And also, from table, it can be seen that, the voltage stress and current stress on the devices are very less compared to other converters.

4. Simulation Results

To validate the operation and performance of proposed hybrid high gain dc-dc converter, the simulation model has been developed in PSCAD/EMDTC platform and simulation studies were conducted and presented in this section. The inductor current and voltage across the inductor is validated in Fig. 7 (a) and (b). It is seen from here that the current getting charge and discharged in proportion to the duty ranges and corresponding inductor voltage polarity is gets changed.



(a)



(b)

Fig. 7 Simulation results (a) Inductor voltage and current (b) Zoomed view of inductor voltage and current

The current flow inductor and capacitor is actually responsible to yield higher voltage at output side. The simulation results of output voltage and inductor and capacitor currents are shown in Figs. 8-10.

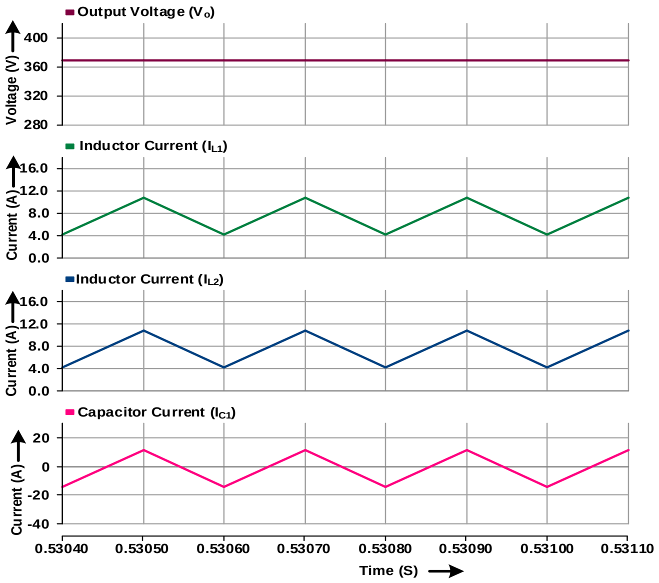


Fig. 8 Simulation results of output voltage and passive elements current

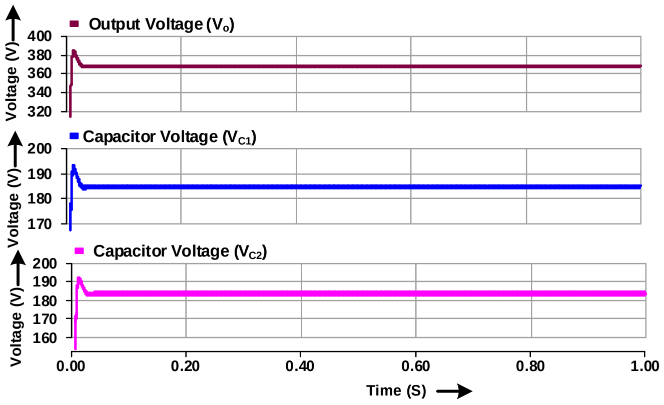


Fig. 9 simulation results of voltage across C_1 and C_2 with output voltage

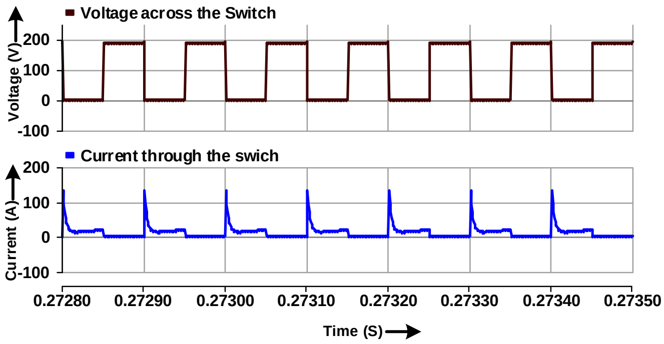


Fig. 10 Voltage and current stress on the device

5. Simulation Results

To verify the operation feasibility of proposed converter, the experimental results are also observed from the converter. The voltage across the passive elements are observed through experimental setup and presented in Fig. 11. It has very good matched with theoretical waveform. The experimental set up paramters are listed in Table II.

Table II Experimental set up parameters

Parameter	Values
Input Voltage	20 to 32 V DC
Inductance L_1 and L_2	1 mH
Capacitance C_1, C_2 and C_3	100 µF 100 µF 200 µF
Switching Frequency	25 kHz
Resistive load (R)	120 [Ω]
MOSFET Switch	IRFP260 N

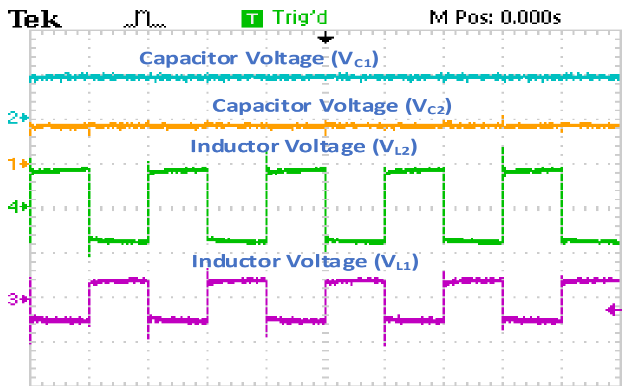


Fig. 11 Experimental results of Voltage across the passive elements

These passive elements are responsible to build the voltage to higher level. As per the analytical waveform and mathematical relationship, the output voltage is summation of voltage across 2 V_{L1} and V_{C1} and V_{C3}. In order to verify this experimentally, the results are captured and presented in Fig. 12.

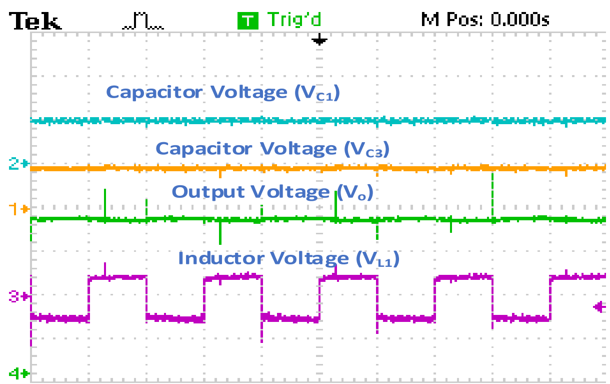


Fig. 12 Experimental results of output voltage and voltage across inductor and capacitor voltage

And also, to verify the characteristics and other operating waveforms, the measured results are taken for inductor current and output voltage as shown in Fig, 13. Moreover, to verify the operation of proposed converter operates under DCM mode, the experimental results are observed, as shown in Fig. 14. It can be seen here that, the inductor current reaches to zero before off state of the device completed. It means the time constant is less; therefore the gain is also high. This experimental is exactly aligned with theoretical waveform. The simulation and experimental results are having very good correlation with theoretical study.

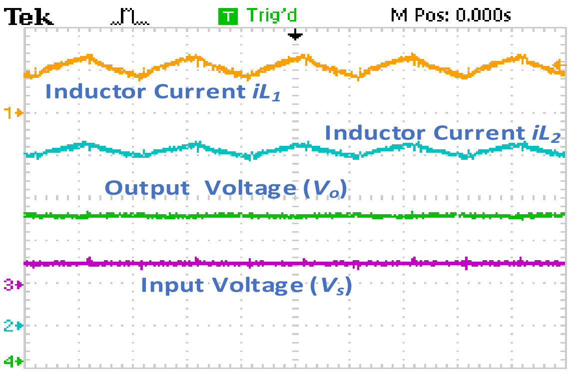


Fig. 13 Experimental results of Inductor current and Inductor voltage

The loss breakdown analysis was made for each components of proposed converter to estimate the losses of the system. Thereafter, the efficiency has been determined under various ranges of power, as shown in Fig. 15. It has been investigated under various ranges of input voltages.

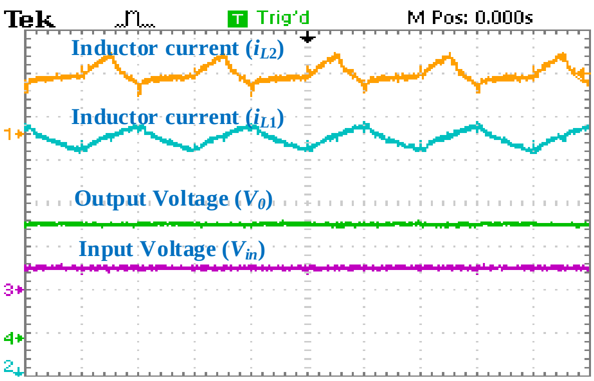


Fig. 14 Experimental results of inductor current and output voltage under DCM

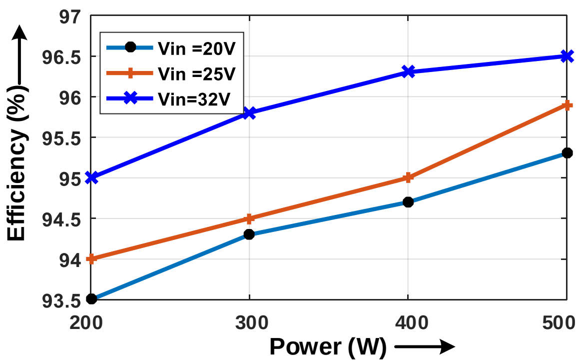


Fig. 15 Efficiency graph with respect to load power at different input ranges

6. Discussion

Compared to the conventional converters presented in the litaruture, the proposed converter can improves the gain values with minimum number of components utilization. And also, the device stress is lesser, therefore lower compoents rating is enough to produce higher voltage gain. Thereby, the overall efficiency of the converter gets improved than the reported converters.

7. Conclusions

In renewable energy system applications, the high gain converter is the important stage of conversion medium to boosting up the voltage to desired level. The research gap has been identified from the recent literature to enhance the performance of high gain converter with minimum components count. By keeping this target, this paper proposes a novel hybrid high gain converter to achieve higher voltage gain with minimum number of components count. It has the merits of the lower voltage and current stress on the devices compared to recently derived converters. The detailed operating waveforms under CCM and DCM conditions are described along with boundary conditions are denoted in this paper. In order to validate the performance analysis in all aspects, the comparative merits of proposed converter is summarized in Table I. Finally, the operational details have been verified through simulation studies and confirmed the same through experimental results. Form these results, it is concluded that the measured results have very good correlation with theoretical study.

Conflicts of Interest

"The authors declare no conflict of interest."

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