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A Novel Non-Isolated DC-DC Converter with High Efficiency and High Step-Up Voltage Gain

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Abstract - This paper proposes a novel high step-up non-isolated DC-DC converter, suitable for regulating dc bus in various inherent low voltage micro sources especially for photovoltaic (PV) and fuel cell sources. This novel high voltage Non-isolated Boost DC-DC converter topology is best replacement, where high voltage conversion ratio is required without the transformer and also need continuous input current. Since the proposed topology utilizes the stack-based structure, the voltage gain, and the efficiency are higher than other conventional non-isolated converters. Switches in this topology is easier to control since its control signal is grounding reference. Also, there is no need of extra gate driver and extra power supply for driver circuit, which reduces the cost and size of system. In order to show the feasibility and practicality of the proposed topology principle operation, steady state analysis and simulation result is presented and analyzed in detail. To verify the performance of proposed converter and theoretical analysis 360W laboratory prototype is implemented.

Key words: High step up voltage, High efficiency, Non-isolated converter, Stacked-Based structure.

1. INTRODUCTION

Due to the increase in demand of high voltage gain dc– dc converters for numerous applications supplied low dc output voltage power sources. The high voltage gain dc–dc converters are used in several applications, such as low power wind turbines, photovoltaic (PV) systems, fuel cells (FC), dc distribution networks, energy storage systems, hybrid electric vehicles, and uninterruptable power supplies.

The output dc voltage of the renewable energy sources such as PVs and FCs is low. Therefore, high step-up dc–dc converters should be used to boost and regulate the voltage level in these systems. Also, in order to achieve maximum power point tracking for PV panels, the input current of the converter should be continuous with low ripple. Accordingly, to use a dc–dc converter in renewable energy sources, it should have a high voltage transfer gain and continuous input current.

Recently, many research works have been done in dc–dc converters to achieve high voltage gain. The usual solution for a high step-up gain is the use of isolated dc–dc converters [1]. The transformer turns ratio allows to increase the converter voltage gain. However, the transformer increases the total volume and weight. Moreover, in these converters the leakage inductance of the transformer causes voltage spikes across the switches during the turn-off process. Therefore, clamping circuits are necessary to limit the switch voltage and recycle the energy, which increases the cost and complexity and reduces the converter efficiency .

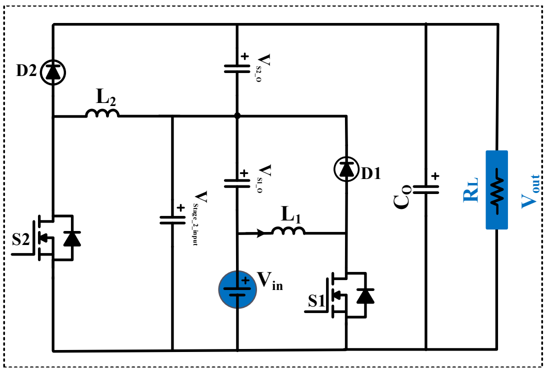


Fig. 1 Proposed Non-isolated high Boost converter

Recently, the non-isolated high step-up dc–dc converters are becoming more popular, because of their simplicity, compact size, lower cost, and better efficiency in comparison with isolated topologies [2]. High step-up non-isolated dc–dc converters can be categorized as noncoupled inductor and coupled inductor converters. The high voltage gain for the coupled inductor converters can be achieved by the increase of the coupled inductor turns ratio. Nevertheless, in these topologies like isolated converters, the coupled inductor leakage inductance can produce voltage spikes across the switches during the turn-off process. Thus, additional clamping circuit is needed to clamp or recycle the energy and improve the efficiency [3].

The non-coupled inductor dc–dc converters are based on the classical boost converter with an additional modified techniques. The main converter techniques are cascaded converters, voltage multipliers, switched-inductor and switched capacitor cells and combinations of these techniques. These types of converters are able to provide high static step-up gain without using any coupled inductors and isolated transformers. However, the large number of components, especially when several voltage multiplier stages are added, can be reduce the efficiency and increase the complexity.

This paper proposes a novel high step-up non-isolated DC-DC converter, suitable for regulating dc bus in various inherent low voltage micro sources especially for PV and FC sources. This converter can be derived by connecting the input and output of the conventional Buck-Boost converter in series to form a stack-based structure. Hence the output voltage of the proposed converter is the sum of input and the output voltage, thereby achieving a higher voltage gain. In order to achieve the even more higher voltage gain, the proposed converter can be easily expanded by stacking the more stages. Moreover, one more advantage of proposed converter is that its input current is continuous on the other hand conventional buck-boost have discontinuous input current. Switches in this topology is easier to control since its control signal is grounding reference. Also, there is no need of extra gate driver and extra power supply for driver circuit, which reduces the cost and size of system

2. PROPOSED STRUCTURE

The proposed converter structure is shown in Fig. 1. As can be seen, two power switches, two inductors, two diodes, and two capacitors are used. The operation of switches is controlled by the PWM technique and both have same signal. To simplify the analysis, the following assumptions are considered a) Converter is in a steady state, so V_o is constant b) C_1 and C_2 are large enough, and therefore, their voltage in each switching period remains unchanged c) All switches, and diodes are ideal. Other observations are that the average inductor voltages are zero and the average capacitor currents are zero for the steady stateoperation. In the following, equation of the voltage and

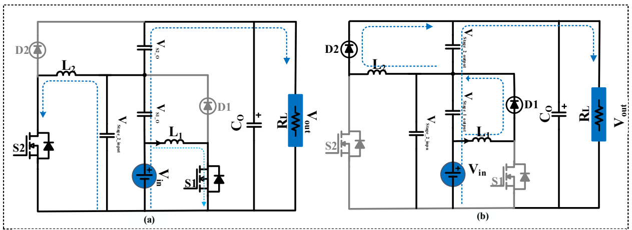


Fig.2 Operation mode of the proposed converter under DCM (a) T_{on} ($0 < t < DTs$) (b) T_{off} ($DTs < t < Ts$)

current in CCM and DCM are discussed.

A. Analysis of Proposed Converter in CCM Mode

Switch on state T_{on} ($0 < t < DT_s$) As shown in Fig 2(a), main switches of the two-stage converter (S_1 and S_2) are turned on at the same time and Diodes (D_1 and D_2) are turned off, L_1 is directly connected to V_{in} and L_2 is output of first stage ($V_{in}+V_{S1\_O}$). So, the inductor current of I_{L1} and I_{L2} is linearly increased from its minimum value to its maximum value. The load current is supplied by the input voltage source and the two output capacitors C_1, and C_2. Therefore, Applying *KVL* at T_{on} the following equations of the circuit can be found;

$$V_{L2} = L_2 \frac{di_{L2}}{dt} = V_{in} + \mathrm{V}_{S1\_O},\ \Delta L_{2\_on} = \frac{(V_{in} + \mathrm{V}_{S1\_O})DT_s}{L_2} \quad (1)$$

$$V_O = V_S + \mathrm{V}_{S1\_O} + \mathrm{V}_{S2\_O} \quad (2)$$

Switch off State T_{off} ($DTs < t < Ts$) as shown in Fig 2 (b), all the main switches (S_1 and S_2) are turn off at $t = DTs$ and diodes (D_1 and D_2) are forward biased during this period. The energy stored at the inductors (L_1 and L_2) is released to supply the current to the capacitors (C_1 and C_2) and the load, respectively. The inductor currents (I_{L1} *and* I_{L2}) are linearly decreased from maximum value to minimum. Inductor voltage can be express as;

$$-V_{L1} = -L_1 \frac{di_{L1}}{dt} = \mathrm{V}_{S1\_O},\ \Delta L_{1\_off} = -\frac{\mathrm{V}_{S1\_O}(1-D)T_s}{L_1} \quad (3)$$

$$-V_{L2} = -L_2 \frac{di_{L2}}{dt} = \mathrm{V}_{S2\_O},\ \Delta L_{2\_off} = -\frac{\mathrm{V}_{S2\_O}(1-D)T_s}{L_2} \quad (4)$$

In the steady state, the change in inductor currents during the switch on state and off state are the same. Therefore, applying the voltage-balancing rule and defining duty cycle (D = Ton /Ts) the voltage gain of the proposed two stage converter in the CCM mode can be derived using (5) and (6).

$$\Delta L_{1\_on} + \Delta L_{1\_off} = 0,\ \mathrm{V}_{S1\_O} = \frac{D}{1-D} V_{in} \quad (5)$$

$$\Delta L_{2\_on} + \Delta L_{2\_off} = 0,\ \mathrm{V}_{S2\_O} = \frac{D}{1-D}(V_{in} + \mathrm{V}_{S1\_O}) \quad (6)$$

By using equations (5), (6) and (2), the CCM voltage gain of

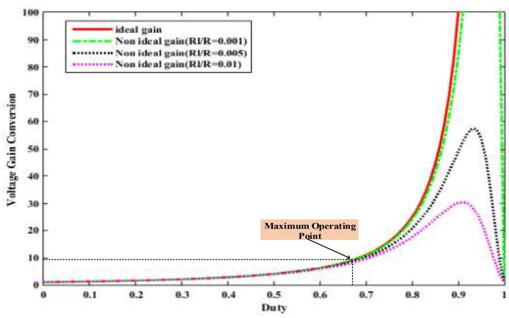


Fig. 3. Ideal and Non-ideal Voltage gain vs. duty cycle of the high voltage gain converters

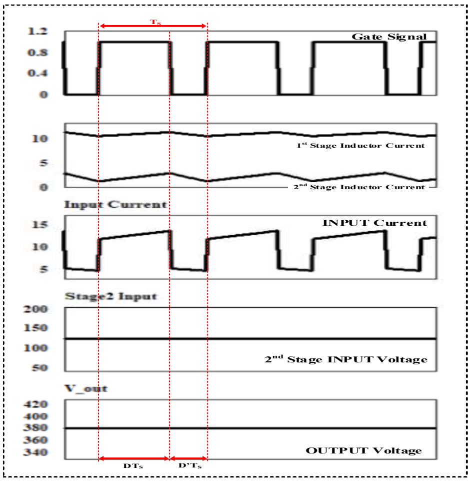


Fig 4. Key waveforms of proposed converter for CCM operation

the proposed two stage converter can be derived as (7).

$$\frac{V_O}{V_{in}} = 1 + \frac{2 \times D}{(1-D)} + \frac{D^2}{(1-D)^2} \quad (7)$$

Fig. 5 shows the voltage gain vs. duty cycle plots with ideal and Non-ideal condition considering the different *Rl/R* ratios. And also shows the desire operating point of the proposed converter.

B. Analysis of Proposed Converter in DCM Mode

The proposed converter will operate in DCM if the current i_D reduces to zero during the switching-off interval. Therefore, the proposed converter operation can be divided into three modes under DCM operation as shown in Fig.5a Mode 1 (D_1T_s) and mode 2 (D_2T_s) are the same as those of CCM operation, and in mode 3 (D_3T_s), the switches S_1,S_2 and the diodes D_1 and D_2 are turned OFF and also the voltage across the inductors L_1 , L_2 , is approximately zero. The key waveforms under DCM operation and the current flow in mode 3 are shown in Fig.5(b)

Applying *KVL* at all three modes the following equations of the circuit can be found;

$$V_{L1} = L_1 \frac{di_{L1}}{dt} = V_{in},\ \Delta L_{1\_on} = \frac{V_{in} D_1 T_s}{L_1} \quad (8)$$

$$-V_{L1} = -L_1 \frac{di_{L1}}{dt} = \mathrm{V}_{S1\_O},\ \Delta L_{1\_off\_1} = -\frac{\mathrm{V}_{S1\_O} D_2 T_s}{L_1}, \Delta L_{1\_off\_2} = 0$$

$$\Delta L_{1\_on} + \Delta L_{1\_off\_1} + \Delta L_{1\_off\_2} = 0,\ \mathrm{G}_1 = \frac{\mathrm{V}_{S1\_O}}{V_{in}} = \frac{D_1}{D_2} \quad (9)$$

From Charge balance principle considering the $\langle i_c \rangle = 0$ the Current through Diode is;

$$i_D = \frac{V_O}{R} \quad (10)$$

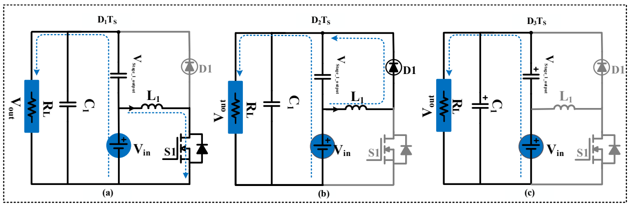
By considering the Peak values of Diode Current from Fig 4(b) can be written as;

$$\langle i_D \rangle_{pk} = \frac{D_1 D_2 T_s V_{in}}{2L} \quad (11)$$

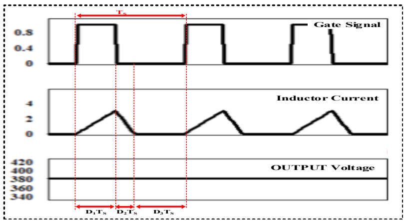
Compare (10) and (11) we got

$$\frac{V_O}{R} = \frac{D_1 D_2 T_s V_{in}}{2L} \rightarrow \frac{2L}{RT_s} = \frac{D_1 D_{2s} V_{in}}{V_O} \rightarrow K = \frac{D_1 D_2}{G}$$

Where $G = \frac{V_O}{V_{in}}$ $K = \frac{2L}{RT_s}$ Now using (9) and (11) and



(a)



(b)

Fig 5(a). Operation mode of the proposed converter under DCM (b) Key waveforms of proposed converter for DCM operation

rearranging and solve the equation, we got gain equation in DCM;

$$G^2 - G - \frac{D_1^2}{K} = 0 \quad ;G = \frac{1+\sqrt{1+4(\frac{D_1^2}{K})}}{2}$$

3. *DESIGN OF THE PROPOSED CONVERTER*

A. Inductor design.

The inductors are designed in that way, the proposed converter operate in CCM mode with 20% load. Then the inductor values L_1 and L_2 can be calculated as (10).

$$L_1 = \frac{V_S D}{\Delta L_1 f_{SW}}; L_2 = \frac{V_S D}{\Delta L_2 f_{SW}(1-D)} \tag{12}$$

B. Voltage stress of the Switches

According to Fig.4 and the operation principles, the voltage stress of the switch can be represented as (13) and (14).

$$V_{S1\_stress} = V_{D1\_stress} = \frac{V_{in}}{1-D} \tag{13}$$

$$V_{S2\_stress} = V_{D2\_stress} = V_S(1+\frac{2D}{1-D}+\frac{D^2}{(1-D)^2}) \tag{14}$$

C. Output capacitor design

The output capacitors can be decided by using the maximum allowable output ripple voltage as (15).

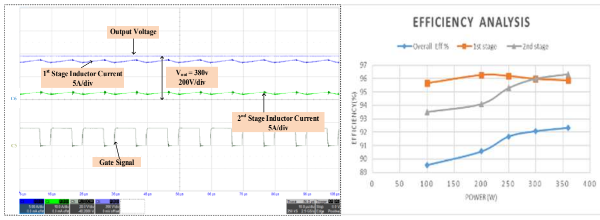
$$C_{O1} \geq \frac{I_{O1}D_{\max}}{f_{SW}\times\Delta V_{O1}} \quad ;C_{O2} \geq \frac{I_{O2}D_{\max}}{f_{SW}\times\Delta V_{O2}} \tag{15}$$

Where ΔV_{O1} and ΔV_{O2} is the maximum allowable output ripple voltage of C_{O1} and C_{O2}, respectively. D_{max} is the maximum duty cycle. I_{O1} and I_{O2} is the output current of first and second stage converter, respectively.

4. EXPERIMENTAL RESULT

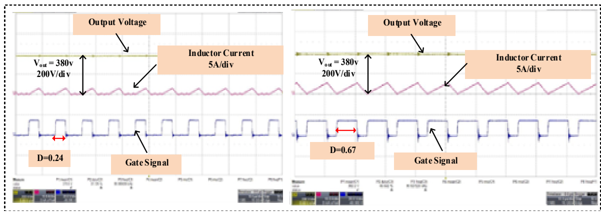
In order to examine the feasibility and effectiveness of proposed high boost dc-dc converter 360w protype is built and hardware test is performed. The main parameters of the circuit are as followings: V_{in}=40V,V_o=380V, P_o=360w, f_s=100kHz, C_0=220uF, inductor L_1=260uH and L_2=900uH and for DCM mode L_2=150uH.

Fig.6 shows the experimental result results of the proposed converter when the input voltage V_{in}= 40 V, output voltage V_o = 380 V, output power P_o= 360W and duty cycle is 0.67. it can be noticed that the output voltage is the sum of input voltage V_S, voltage across the capacitor C_1 (V_{S1_O}) and voltage across the capacitor C_2 (V_{S2_O}). As shown in Fig. 6(a), the output voltage is boosted from 40V to 380V with 67% duty cycle. Figure also shows that both stages inductor current waveform I_{L1} and I_{L2} which clearly indicate that the converter works in CCM.



(a) (b)

Fig. 6(a)Experimental result of the Output voltage(V) inductor current I_{L1} and I_{L2} and Gate signal V_g in CCM mode (b)Efficiency



(a) (b)

Fig. 7 Experimental result of the Output voltage(Vo),inductor current IL and Gate signal V_g in DCM mode (a)50W (b) 360W

Fig.7 shows the hardware result of single stage with discontinuous conduction mode. For that second stage is selected as DCM mode so this way we can reduce the size of inductor from 900uH to 150uH and also reduce the switching losses by getting the soft switching at the second stage switch. Fig6(a) and (b)shows the result of inductor current, gate signal and output voltage which is 380v at light load 50w and full load 360w with duty cycle 0.24 and 0.67 respectively. Inductor current clearly indicate that this stage is working in DCM mode.

Fig. 6(b) shows the measured efficiency plot of the proposed novel high boost converter when V_S = 40v, V_O = 380V and f_{sw}=100 kHz at different load condition. As shown in Figure the maximum efficiency of 92.7% is obtained at 360W.

5. CONCLUSION

Novel topology of non-isolated high boost converter with high voltage gain and high efficiency characteristic is proposed for renewable sources. Input current of converter is continuous so current stress on source was reduced. To produce a higher gain input and output voltage are added in series and also further gain can be increased by increasing more stages. In addition, the components counts of the proposed converter is less than the other topologies. CCM and DCM analysis is also provided along with experimental prototype, it has been verified that the proposed converter can achieve the theoretical voltage gain and the maximum efficiency of 92.7% was obtained.

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