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고변압비와 고효율 특성을 가진 새로운 비절연형 벅부스트 컨버터

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A Novel Non-Isolated Buck Boost Converter with High Voltage Gain and High Efficiency Characteristics

Tran Manh Tuan[1], Saghir Amin[1], and Woojin Choi†

Abstract

The use of high-voltage gain converters is essential for distributed power generation systems with renewable energy sources, such as fuel and solar cells, due to their low-voltage characteristics. In this study, a novel high-voltage gain non-isolated buck boost converter topology is proposed to cope with the need of a high-voltage conversion ratio without the transformer for the renewable energy sources. Given that the proposed topology utilizes the cascode structure, the voltage gain and the efficiency are higher than those of other conventional non-isolated converters. To demonstrate the feasibility of the proposed topology, the operation principle is presented, and the steady-state characteristics are analyzed in detail. The validity of the proposed converter is verified by experiments with a 400 W prototype converter.

Key words: High voltage gain, High efficiency, NBB(Non-Isolated Buck-Boost) converter, Cascode structure

1. Introduction

Due to the energy crisis and the global warming the distributed power generation systems based on the renewable energy sources are drawing more and more attention. Since the outputs of renewable energy such as fuel cells and solar cells are DCs and low voltage, typically two stage power conversion is required to generate the AC output with suitable voltage level. Therefore the use of a high voltage gain dc-dc converter to step up the low voltage of the renewable source is essential to provide a suitable DC link voltage for the rear-end DC-AC inverter [1],[2]. For example, in a small single-phase power system with a two-stage structure, the DC link voltage required for the grid-connected inverter is as high as 380V DC if the line voltage is 220V AC. However, the output voltage of a photovoltaic module or a fuel cell stack with a small power rating(less than 300W) ranges from 25 to 45 V typically, which requires at least 1:10 voltage conversion ratio. One simply way to cope with this issue can be the use of an isolated dc-dc converter topology but it would not be a good option for the small power system of which volume and cost are critical factors.

As well known, the classical non-isolated dc-dc converter is often used for voltage step-up applications. However, as the voltage gain is increased, the duty cycle approaches to unity. Hence, the current ripple of the inductor and the turn-off current of the power device become large, which result in large conduction losses and switching losses leading to a lower efficiency [3],[4]. In order to solve this problem the coupled inductor (CI) is employed to provide a high voltage gain by selecting an appropriate turns-ratio[5]-[8]. However, the additional

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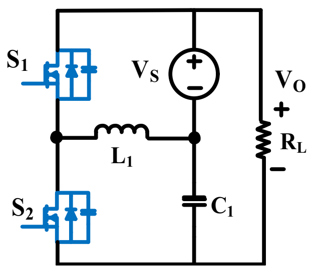


Fig. 1. Proposed non-isolated buck-boost converter.

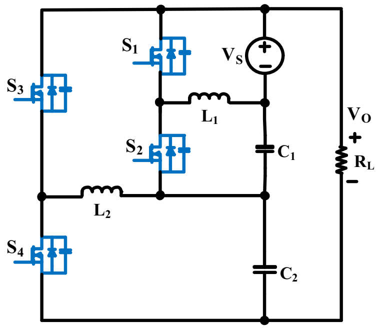
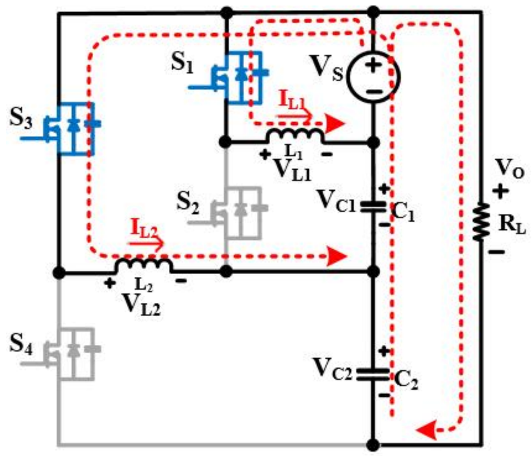


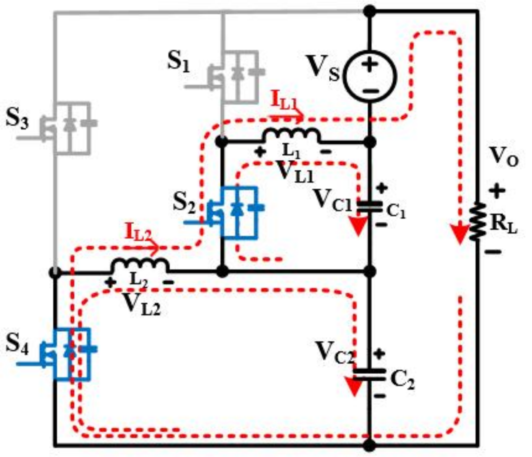
Fig. 2. Two stage expansion of the proposed non-isolated buck-boost converter.

snubber circuit is needed to absorb the energy stored in the leakage inductor which makes the circuit complex and expensive. Other methods to get the high voltage gain with no magnetic coupling include the converters utilizing the switched-capacitors (SCs)[9]-[11] and the voltage multipliers (VMs)[12]-[15]. However, it is disadvantageous in that the precise output regulation is not possible because the output varies by the multiple of a unit circuit voltage[15]. In response to this problem a hybrid structure including the CI, SCs and VMs techniques is proposed[16]. However, although the voltage gain can be easily obtained, the component counts of it is even higher than that of other topologies, which increases the circuit complexity and the cost of the system significantly.

In this paper a novel Non-isolated Buck Boost (NBB) converter is proposed as shown in Fig.1. This converter can be derived by connecting the input and output of the conventional Inverting Buck-Boost (IBB) converter in series to form a cascode structure[17]. Hence the output voltage of the proposed converter is the sum of input voltage and the output voltage of the conventional IBB converter, thereby achieving a higher voltage gain. It is also advantageous in that its power conversion efficiency is good since only a small portion of the power is converted by the switching.



(a) switching ON state



(b) Switching OFF state

Fig. 3. Operation mode of the proposed converter under CCM.

In order to achieve the even higher voltage gain the proposed converter can be easily expanded by stacking IBBs as shown in Fig.2. It should be noted that the circuit is inherently bidirectional. If the bidirectional switches are used for the rectification, then the proposed topology can be used for bidirectional applications.

2. Analysis of the Proposed Topology

In this section, the operation principle of the proposed converter is described in the continuous conduction mode with a two stage circuit and the voltage gain of it is derived based on the analysis. As shown in Fig. 3 one switching cycle is divided into two states based on the status of the main switches. In the proposed two stage converter the main switches and the synchronous rectifier switches

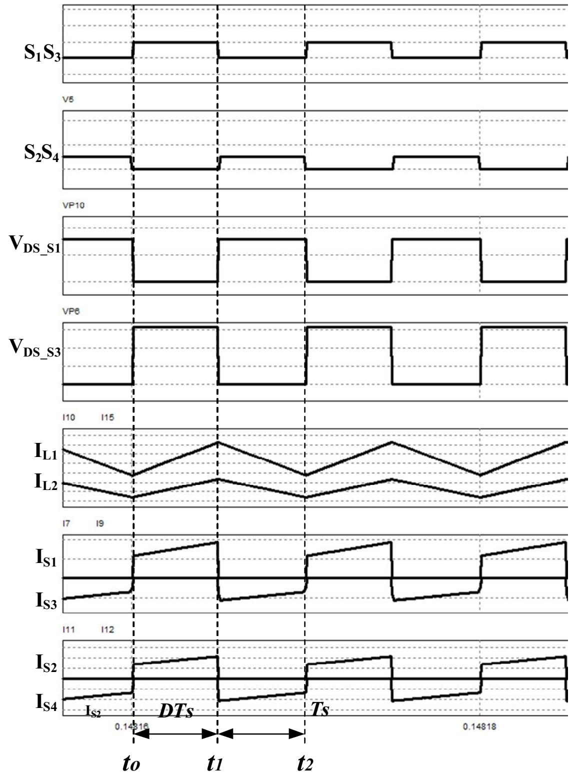


Fig. 4. Key waveforms of proposed converter for CCM operation With D = *0.5*.

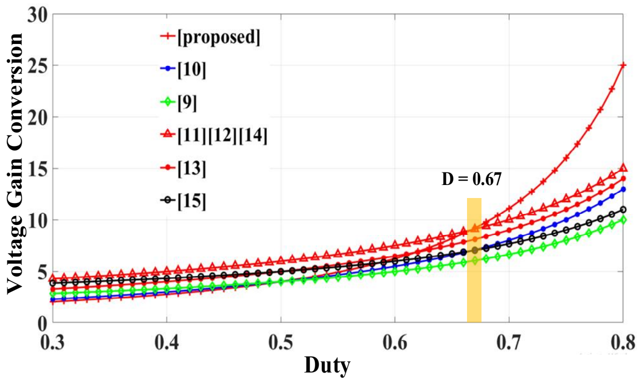


Fig. 5. Voltage gain vs. duty cycle of the high voltage gain converter.

are synchronized in operation. In order to describe the operation principle of the proposed converter, following assumptions need to be made.

1) The circuit is operating in the steady state and the inductor currents are continuous.
2) All the components are ideal and the parasitic components are neglected.
3) All the capacitors are large enough to maintain their voltages constant during a switch-off period.
4) A switching period is *Ts*; the switches are closed for time *DTs* and open for time (1-*D*)*Ts*.

2.1 Main switch on state (Fig. 3(a) t0 = 0, t1 = DTs)

As shown in Fig. 3(a), main switches of the two stage converter (S_1 and S_3) are turned on at the same time and the synchronous rectifier switches (S_2 and S_4) are turned off.

During the switch on state the voltage applied to the inductor L_1 and L_2 is V_S and V_S+V_{C1}, respectively and then inductor currents (I_{L1} *and* I_{L2}) are linearly increased. The load current is supplied by the input voltage source and the two output capacitors C_1, and C_2. Therefore, the following equations can be used to describe the circuit operation in this period.

$$V_{L1}=L_1\frac{di_{L1}}{dt}=V_S,\quad \triangle L_{1On}=\frac{V_S DT_S}{L_1} \tag{1}$$

$$V_{L2}=L_2\frac{di_{L2}}{dt}=V_S+V_{C1},\triangle L_{2On}=\frac{(V_S+V_{C1})DT_S}{L_1} \tag{2}$$

$$V_O=V_S+V_{C1}+V_{C2} \tag{3}$$

2.2 Main switch off state (t1 = DTs, t2 =Ts)

As shown in Fig. 3(b), all the main switches (S_1 and S_3) are turn off at t = DTs and the synchronous rectifier switches (S_2 and S_4) are turned on 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 and the following equations can be used to describe the circuit operation in this period.

$$-V_{L1}=-L_1\frac{di_{L1}}{dt}=V_{C1},\triangle L_{1\underline{Off}}=-\frac{V_{C1}(1-D)T_S}{L_1} \tag{4}$$

$$-V_{L2}=-L_2\frac{di_{L2}}{dt}=V_{C2},\triangle L_{2\underline{Off}}=-\frac{V_{C2}(1-D)T_S}{L_2} \tag{5}$$

2.3 Voltage gain derivation

In the steady state, the change in inductor currents during the switch on state and off state are the same. Therefore the voltage gain of the proposed two stage converter can be derived using (6)-(8).

$$\triangle L_{1On}+\triangle L_{1Off}=0,\ V_{C1}=\frac{DV_S}{1-D} \tag{6}$$

$$\triangle L_{2On}+\triangle L_{2Off}=0,\ V_{C2}=\frac{D(V_S+V_{C1})}{1-D} \tag{7}$$

TABLE I
COMPARISON BETWEEN THE PROPOSED CONVERTER AND THE OTHER CONVERTERS

Converters	Voltage gain	Switches	Diodes	Inductors	Capacitors	Total	Voltage stress (V_{stress} / Vo)
[9]	$\frac{2}{1-D}$	1	4	2	5	12	$1/2$
[10]	$\frac{1+2D}{1-D}$	1	4	2	4	11	N/A
[11]	$\frac{3}{1-D}$	1	5	1	5	12	$1/3$
[12]	$\frac{3}{1-D}$	1	5	2	5	13	N/A
[13]	$\frac{2+D}{1-D}$	1	6	2	7	16	N/A
[14]	$\frac{3}{1-D}$	2	6	1	5	14	N/A
[15]	$\frac{3-D}{1-D}$	1	4	1	4	10	$1/(3-D)$
[Proposed]	$1+\frac{2D}{1-D}+\frac{D^2}{(1-D)^2}$	2	2	2	2	8	$(1-D)$ for S_1, S_2 1 for S_3, S_4

By using equations (6), (7) and (3), the voltage gain of the proposed two stage converter can be derived as (8).

$$\frac{V_O}{V_S}=1+\frac{2D}{(1-D)}+\frac{D^2}{(1-D)^2} \tag{8}$$

Fig. 5 shows the voltage gain vs. duty cycle plots of the various kinds of high voltage gain non-isolated dc-dc converters. It can be found that the voltage gain of the proposed converter is higher than that of others when he duty cycle is larger than 0.67.

Table I shows the comparison of the various kinds of high voltage gain non-isolated converter topologies in terms of voltage gain component counts and switches voltage stress. It can be concluded from the Table I that the proposed converter is superior to others in term of voltage gain and component counts.

3. Design of the Proposed Converter

3.1 Inductor design

The inductors are designed to operate the proposed converter in CCM mode with 20% load. Then the inductor values L_1 and L_2 can be calculated as (9) and (10), respectively.

$$L_1=\frac{V_S D}{\triangle L_1 f_{sw}} \tag{9}$$

$$L_2=\frac{V_S D}{\triangle L_2 f_{sw}(1-D)} \tag{10}$$

3.2 Voltage stress on the switches design

According to operation principle, the voltage stress on the switches are given as (11) and (12)

$$V_{S1stress}=V_{S2stress}=\frac{V_S}{1-D} \tag{11}$$

$$V_{S3stress}=V_{S4stress}=1+\frac{2D}{(1-D)}+\frac{D^2}{(1-D)^2} \tag{12}$$

3.3 Output capacitor design

The output capacitors can be decided by using the maximum allowable output ripple voltage as (13) and (14)

$$C_{O1}\geq\frac{I_{01}D_{\max}}{\triangle V_{01}f_{sw}} \tag{13}$$

$$C_{O2}\geq\frac{I_{01}D_{\max}}{\triangle V_{01}f_{sw}} \tag{14}$$

TABLE II
SPECIFICATION OF THE PROPOSED TWO STAGE DC-DC CONVERTER

Parameter	Designator	Value
Input Voltage	V_s	40 V
Output voltage	V_O	380 V
Power	P_O	400 W
Switching frequency	f_{SW}	100 KHz

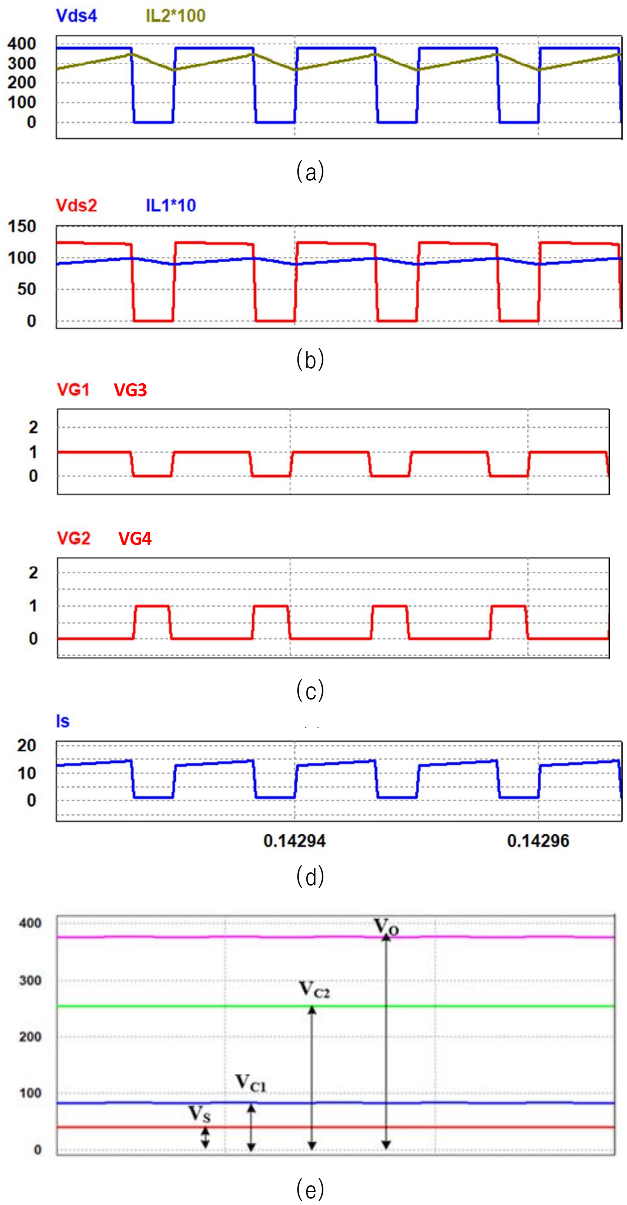


Fig. 6. Simulation results of the proposed two stage NBB converter. (a) drain to source voltage V_{DS3} of S_3, inductor current I_{L2} of inductor L_2, (b) the drain to source voltage V_{DS1} of S_1, inductor current I_{L1} of inductor L_1, (c) gate signal for the switches S_1, S_2, S_3 and S_4, (d) Input current I_S, (e) Input voltage V_S, Output voltage V_o, Output capacitor 1 voltage V_{C1}, Output capacitor 2 voltage V_{C2}.

TABLE III
SWITCHES AND PASSIVE COMPONENTS OF THE PROPOSED CONVERTER

Devices	Part #	Specifications
Si Mosfets (S_1 , S_2)	IPI110N20N	200 V, 80 A
SiC Mosfets (S_3 , S_4)	SCT3080AL	650 V, 30 A
Capacitor (C_{O1})	EPCOS/TDK	220uF/200 V
Capacitor (C_{O2})	EPCOS/TDK	100uF/400 V
Inductor (L_1)	CH400125	260 uH
Inductor (L_2)	CH400125	900 uH

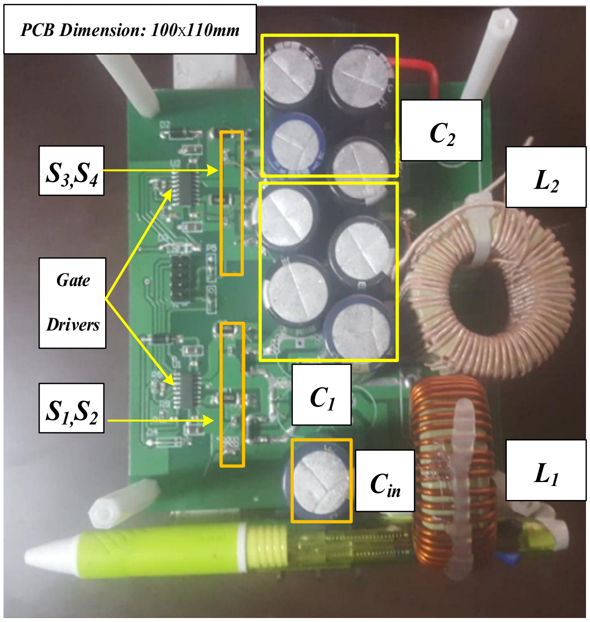


Fig. 7. Prototype of the proposed two stage NBB converter.

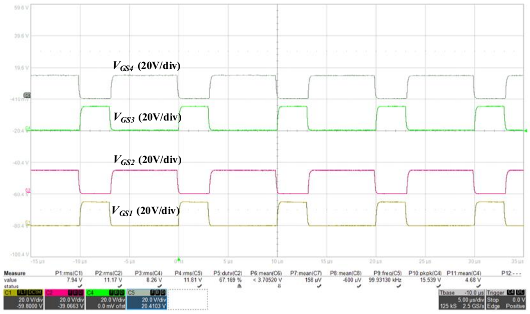
Where ΔV_{O1} and ΔV_{O2} is the maximum allowable output ripple voltage of C_{O1} and C_{O2}, respectively. D_{max} is the maximum duty cycle. I_{O1} and I_{O2} is the output current of first and second stage converter, respectively.

4. Simulation and Experiment Results

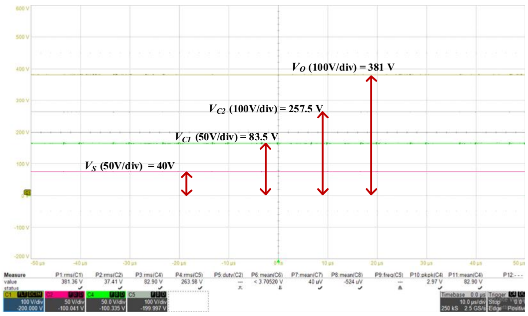
4.1 Simulation results

To confirm the operating principle of the proposed DC-DC converter, PSIM simulation was performed. A two stage DC-DC converter for 400W photovoltaic power generation module is designed and simulated. The specification of the converter can be found in Table II.

Fig. 6 shows the simulation results of the proposed converter. The parameters for the simulation are as

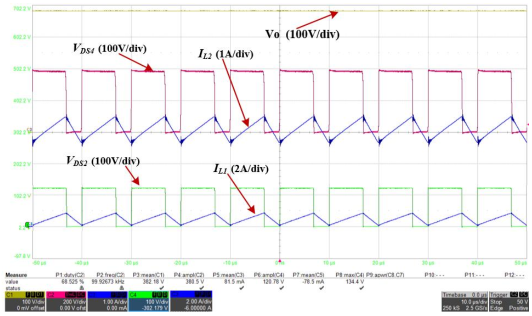


(a)

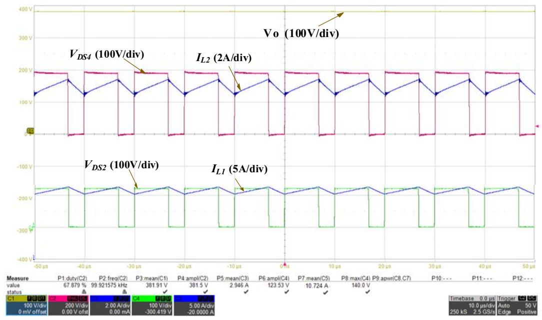


(b)

Fig. 8. Experimental waveforms of the prototype converter: (a) Gate signals of the switches V_{GS1}, V_{GS2}, V_{GS3}, and V_{GS4}, (b) Output voltage V_O, capacitor 2 voltage V_{C2}, capacitor 1 voltage V_{C1} and input voltage V_S.



(a)



(b)

Fig. 9. Experimental waveforms of the proposed converter under two different load conditions. (a) no-load, (b) Full-load (400W).

followings: input voltage Vs = 40 V, output voltage Vo = 380 V, output power Po = 380W, inductor L_1 = 260 uH, L_2 = 260 uH, and load resistor R_L=380 ohm.

As shown in Fig. 6, the output voltage of 380V is obtained with 40V input voltage and the input current I_S is continuous.

4.2 Experimental results

In order to verify the operation of the proposed converter a 400W prototype converter is built and tested. The information about the switches and passive components can be found in Table III and Fig. 7 shows the prototype of the proposed two stage NBB converter built.

In the experiments the gate signals (V_{GS1}, V_{GS2}, V_{GS3}, and V_{GS4}) are generated by a DSP TMS320F28335 as shown in Fig. 8 (a). As shown in Fig. 8 (b), it can be noticed that the output voltage is the sum of input voltage V_S, voltage across the capacitor C_1 (V_{C2}) and voltage across the capacitor C_2 (V_{C2}). Some key waveforms such as the drain-source voltages (V_{DS2} and V_{DS4}) of the synchronous rectifier switches, inductor currents (I_{L1} and I_{L2}) and the output voltage V_O are given in Fig. 9 under two different load conditions. As shown in Fig. 9, the output

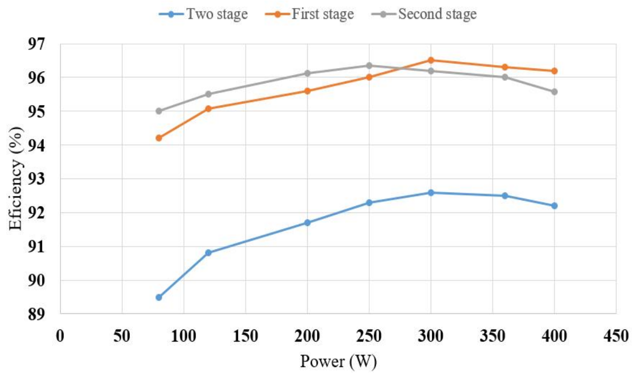


Fig. 10. Measured efficiency plot of the proposed stage NBB converter.

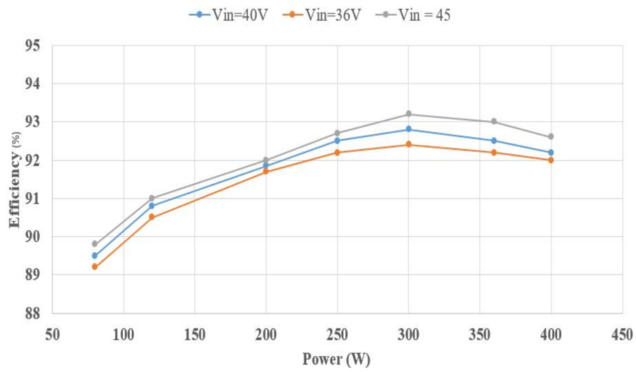


Fig. 11. Measured efficiency curve of proposed high step-up gain converter.

voltage is boosted from 40V to 381V with a duty cycle of 0.67.

Fig. 10 shows the measured efficiency plot of the proposed NBB converter when V_S = 40 V, V_O = 380V and f_{sw}=100 kHz. As shown in Fig. 10 the maximum efficiency of 92.7% is obtained at 300W.

Fig. 11 shows the efficiency plots of the proposed converter under various input voltage condition. The maximum efficiency of 93.3% is obtained at 300W when V_S = 45V, V_O = 380V and f_{sw}=100 kHz.

5. Conclusion

In this paper a novel non-isolated buck boost converter with high voltage gain and high efficiency characteristic is proposed and its validity and feasibility have been proved by the experiments. Since the proposed converter adopts a cascode structure, its voltage gain and efficiency are relatively higher than those of other topologies. In addition the components counts of the proposed converter is less than the other topologies. Throughout the experiments it has been verified that the proposed converter can achieve the theoretical voltage gain and the maximum efficiency of 93.3% was obtained. It can be concluded that the proposed converter is suitable for distributed power generation systems with renewable energy sources.

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