

# A High Step Up Dc-Dc Converter For Renewable Energy Applications Using Fuzzy Logic Technique

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**Abstract**—In this paper, a novel high step-up DC/DC converter is presented for Renewable Energy Applications. The suggested structure consists of a coupled inductor and two voltage multiplier cells in order to obtain high step-up voltage gain. In addition, two capacitors are charged during the switch-off period using the energy stored in the coupled inductor which increases the voltage transfer gain. The energy stored in the leakage inductance is recycled with the use of a passive clamp circuit. The voltage stress on the main power switch is also reduced in the proposed topology. Therefore, a main power switch with low resistance  $R_{DS(ON)}$  can be used to reduce the conduction losses. The operation principle and the steady-state analyses are discussed thoroughly. To verify the performance of the presented converter, a 300W laboratory prototype circuit is implemented. The results validate the theoretical analyses and the practicability of the presented high step-up converter.

**Index Terms**—Coupled inductor, DC/DC converters, high step-up, switched capacitor.

## I. INTRODUCTION

Demand for clean and sustainable energy sources has dramatically increased during the past few years with growing population and industrial development. For a long time, fossil fuels have been used as the major source of generating electrical energy. Environmental consequences of these resources have made it necessary to benefit from clean energy sources such as wind and solar. Therefore, distributed generation (DG) systems based on renewable energy sources have attracted the researchers' attention. The DG systems include photovoltaic (PV) cells, fuel cells and wind power [1]-[3]. However, the output voltages of these sources are not large enough for connecting to ac utility voltage. PV cells can be connected in series in order to obtain a large dc voltage. However, it is difficult to ignore the shadow effect in PV panels [4]-[6]. High step-up converters are a suitable solution for the aforementioned problem. Each PV panel can be connected to a particular high step-up converter. Therefore, each panel can be controlled independently. These converters boost the low input voltages (24-40 V) to a high voltage level

(300-400 V) [7]. The main features of high step-up converters are their large conversion ratio, high efficiency and small size [8]-[10].

Theoretically, conventional boost converters can achieve high voltage gain with an extremely high duty ratio [11]. However, the performance of the system will be deteriorated with a high duty cycle due to several problems such as low conversion efficiency, reverse-recovery and electromagnetic interference problems [12].

Some transformer-based converters like forward, push-pull or flyback converters can achieve high step-up voltage gain by adjusting the turn ratio of the transformer. However, the leakage inductor of the transformer will cause serious problems such as voltage spike on the main switch and high power dissipation [13]. In order to improve the conversion efficiency and obtain high step-up voltage gain, many converter structures have been presented [14]-[29]. Switched capacitor [14]-[16] and voltage lift [17]-[19] techniques have been used widely to achieve high step-up voltage gain. However, in these structures, high charging currents will flow through the main switch and increase the conduction losses.

Coupled-inductor based converters can also achieve high step-up voltage gain by adjusting the turn ratios [20], [21]. However, the energy stored in the leakage inductor causes a voltage spike on the main switch and deteriorates the conversion efficiency. To overcome this problem, coupled-inductor based converters with an active-clamp circuit have been presented in [22]. Some high step-up converters with two-switch [23]-[25] and single-switch [26]-[29] are introduced in the recent published literatures. However, the conversion ratio is not large enough.

This paper presents a novel high step-up DC/DC converter for renewable energy applications. The suggested structure consists of a coupled inductor and two voltage multiplier cells in order to obtain high step-up voltage gain. In addition, a capacitor is charged during the switch-off period using the energy stored in the coupled inductor which increases the voltage transfer gain. The energy stored in the leakage inductance is recycled with the use of a passive clamp circuit. The voltage stress on the main power switch is also reduced in the proposed topology. Therefore, a main power switch with low resistance  $R_{DS(ON)}$  can be used to reduce the conduction

losses. The operation principle and the steady-state analyses are discussed thoroughly. To verify the performance of the presented converter, a 300W laboratory prototype circuit is implemented. The results validate the theoretical analyses and the practicability of the presented high step-up converter.

## II. OPERATING PRINCIPLE OF THE PROPOSED CONVERTER

The circuit configuration of the proposed converter is shown in Fig. 1. The proposed converter comprises a DC input voltage ( $V_I$ ), active power switch (S), coupled inductor, four diodes and four capacitors. Capacitor  $C_1$  and diode  $D_1$  are employed as clamp circuit respectively. The capacitor  $C_3$  is employed as the capacitor of the extended voltage multiplier cell. The capacitor  $C_2$  and diode  $D_2$  are the circuit elements of the voltage multiplier which increase the voltage of clamping capacitor  $C_1$ . The coupled inductor is modeled as an ideal transformer with a turn ratio  $N$  ( $N_p/N_s$ ), a magnetizing inductor  $L_m$  and leakage inductor  $L_k$ .

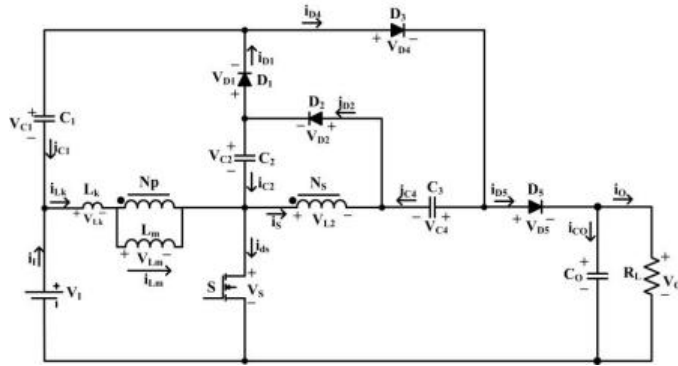


Fig. 1. Circuit configuration of the presented high step-up converter.

In order to simplify the circuit analysis of the converter, some assumptions are considered as follow:

- 1) All Capacitors are sufficiently large. Therefore  $V_{C1}$ ,  $V_{C2}$ ,  $V_{C3}$ , and  $V_O$  are considered to be constant during one switching period.
- 2) All components are ideal but the leakage inductance of the coupled inductor is considered.

According to the aforementioned assumptions, the CCM operation of the proposed converter includes five intervals in one switching period. The current-flow path of the proposed converter for each stage is depicted in Fig. 2. Some typical waveforms under continuous conduction mode (CCM) operation are illustrated in Fig. 3. The operating stages are explained as follows.

1) *Stage I* [ $t_0 < t < t_1$  see Fig. 2(a)]: In this stage, switch S is turned on. Also, diodes  $D_2$  and  $D_4$  are turned on and diodes  $D_1$ ,  $D_3$  are turned off. The DC source ( $V_I$ ) magnetizes  $L_m$  through S. The secondary-side of the coupled inductor is in parallel with capacitor  $C_2$  using diode  $D_2$ . As the current of the leakage inductor  $L_k$  increases linearly, the secondary-side current of the coupled inductor ( $i_s$ ) decreases linearly. The required energy of load ( $R_L$ ) is supplied by the output capacitor  $C_0$ . This interval ends when the secondary-side current of the coupled inductor becomes zero at  $t=t_1$ .

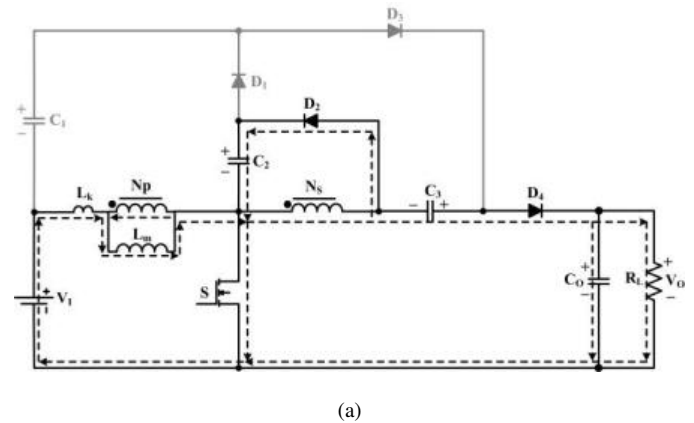
2) *Stage II* [ $t_1 < t < t_2$  see Fig. 2(b)]: In this stage, switch S and diode  $D_3$  are turned on and diodes  $D_1$ ,  $D_2$  and  $D_4$  are

turned off. The DC source  $V_I$  magnetizes  $L_m$  through switch S. So, the current of the leakage inductor  $L_k$  and magnetizing inductor  $L_m$  increase linearly. The capacitor  $C_3$  is charged by dc source  $V_I$ , clamp capacitor and the secondary-side of the coupled inductor. Output capacitor  $C_0$  supplies the demanded energy of the load  $R_L$ . This interval ends when switch (S) is turned off at  $t=t_2$ .

3) *Stage III* [ $t_2 < t < t_3$  see Fig. 2(c)]: In this stage, switch S is turned off. Diodes  $D_1$  and  $D_3$  are turned on and diodes  $D_2$  and  $D_4$  are turned off. The clamp capacitor  $C_1$  is charged by the stored energy in capacitor  $C_2$  and the energies of leakage inductor  $L_k$  and magnetizing inductor  $L_m$ . The currents of the secondary-side of the coupled inductor ( $i_s$ ) and the leakage inductor are increased and decreased respectively. The capacitor  $C_3$  is still charged through  $D_3$ . Output capacitor  $C_0$  supplies the energy to load  $R_L$ . This interval ends when  $i_{Lk}$  is equal to  $i_{Lm}$  at  $t=t_3$ .

4) *Stage IV* [ $t_3 < t < t_4$  see Fig. 2(d)]: In this stage, S is turned off. Diodes  $D_1$  and  $D_4$  are turned on and diodes  $D_2$  and  $D_3$  are turned off. The clamp capacitor  $C_1$  is charged by the capacitor  $C_2$  and the energies of leakage inductor  $L_k$  and magnetizing inductor  $L_m$ . The currents of the leakage inductor  $L_k$  and magnetizing inductor  $L_m$  decrease linearly. Also, a part of the energy stored in  $L_m$  is transferred to the secondary side of the coupled inductor. The dc source  $V_I$ , capacitor  $C_3$  and both sides of the coupled inductor charge output capacitor and provide energy to the load  $R_L$ . This interval ends when diode  $D_1$  is turned off at  $t=t_4$ .

5) *Stage V* [ $t_4 < t < t_5$  see Fig. 2(e)]: In this stage, S is turned off. Diodes  $D_2$  and  $D_4$  are turned on and diodes  $D_1$  and  $D_3$  are turned off. The currents of the leakage inductor  $L_k$  and magnetizing inductor  $L_m$  decrease linearly. Apart of stored energy in  $L_m$  is transferred to the secondary side of the coupled inductor in order to charge the capacitor  $C_2$  through diode  $D_2$ . In this interval the DC input voltage  $V_I$  and stored energy in the capacitor  $C_3$  and inductances of both sides of the coupled inductor charge the output capacitor  $C_0$  and provide the demand energy of the load  $R_L$ . This interval ends when switch S is turned on at  $t=t_5$ .



(a)

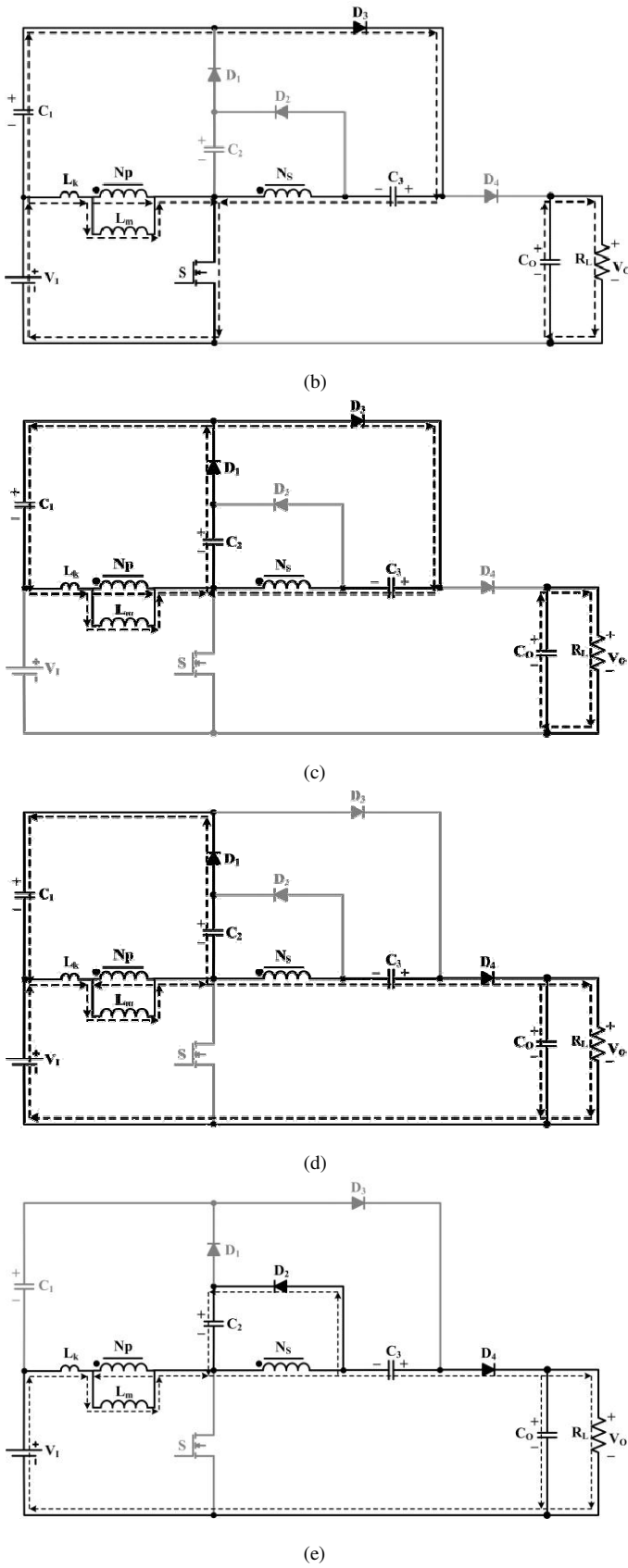


Fig. 2. Current-flow path of operating modes during one switching period at CCM operation. (a) Mode I. (b) Mode II. (c) Mode III. (d) Mode IV. (e) Mode V.

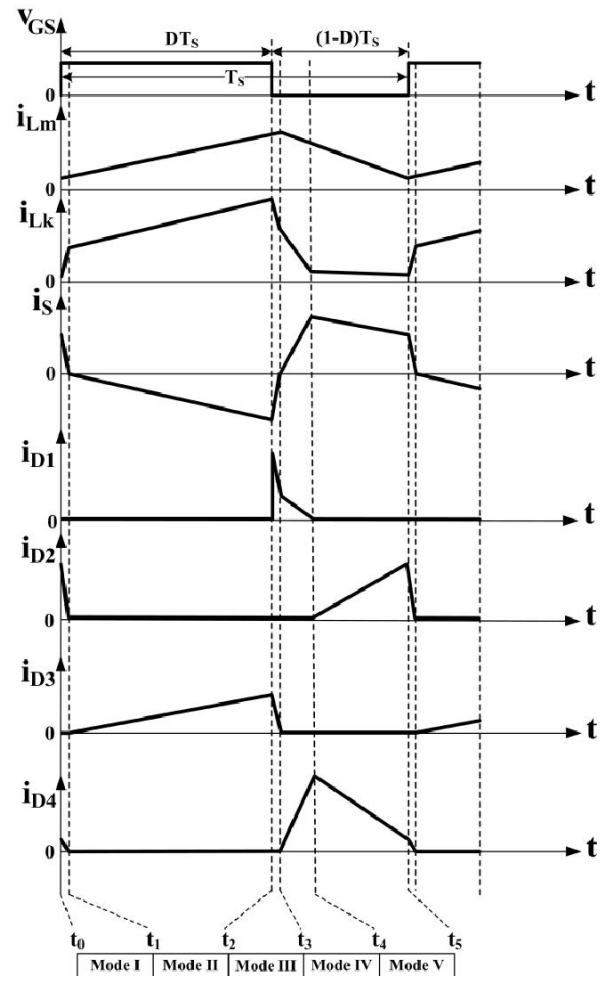


Fig. 3. Some typical waveforms of the proposed converter at CCM operation.

### III. STEADY-STATE ANALYSIS OF THE PROPOSED CONVERTER

#### A. CCM Operation

To simplify the steady-state analysis, only stages II, IV and V are considered since these stages are sufficiently large in comparison with stages I and III.

During stage II,  $L_k$  and  $L_m$  is charged by dc source  $V_I$ . Therefore, the following equation can be written according to Fig. 2(b):

$$V_{Lm} = kV_I \quad (1)$$

Where  $k$  is the coupling coefficient of coupled inductor which equals to  $L_m/(L_m+L_k)$ . Capacitor  $C_3$  is charged by clamp capacitor  $C_1$ , dc source ( $V_I$ ) and the secondary-side of the coupled inductor. The voltage across the capacitor  $C_3$  can be expressed by:

$$V_{C3} = V_{C1} + (kn + 1)V_I \quad (2)$$

Where  $n$  is the turn ratio of coupled inductor which is equal to  $N_S/N_P$ . As shown in Fig. 2(d), during stage IV,  $L_k$  and  $L_m$  demagnetize to the clamp capacitor  $C_1$  with the help of capacitor  $C_2$ . Hence, the voltage across  $L_m$  can be written as:

$$V_{Lm} = k(V_{C2} - V_{C1}) \quad (3)$$

Also, the output voltage can be formulated based on Fig.

Substituting (16) into (19) and for  $k=1$ ,  $t=DT$  and  $t_0=0$ , yielding:

$$i_{Lm} = \frac{L_m V_{in}}{L_m f_s} \quad (20)$$

According to Fig. 3 and applying the ampere-second balance principle on capacitors, the average current values of diodes are equal to  $I_O$ . Therefore, the peak values of diodes  $D_3$  and  $D_4$  can be obtained as:

$$i_{D3(peak)} = \frac{2I_O}{D} \quad (21)$$

$$i_{D4(peak)} = \frac{2I_O}{1-D} \quad (22)$$

$$i_{S(peak)} = i_{D1(peak)} = \frac{2+n+nD}{D(1-D)} i_O + \frac{DV_{in}}{L_m f_s} \quad (23)$$

Neglecting modes I and III, the time interval of modes IV and V are given as:

$$d_4 = \frac{2I_O}{I} = \frac{1-D}{n+1} \quad (24)$$

$$1-D-d_4 = d_5 \quad (25)$$

From equation (25), the peak value of diode  $D_2$  is obtained as:

$$i_{D2(peak)} = \frac{2(n+1)I_O}{n(1-D)} \quad (26)$$

#### B. Boundary Conduction mode (BCM) Operation

Similar to the analysis done in the former section, the voltage conversion ratio of the presented converter in discontinuous conduction mode (DCM) can be obtained as follows:

$$M_{DCM} = \frac{V_O}{V_I} = \frac{n+2 + \sqrt{(n+2)^2 + \frac{D^2}{\tau_{Lm}}}}{2} \quad (27)$$

If the proposed converter is operated in BCM, the voltage gain in the CCM will be equal to its voltage gain in the DCM operation. From (12) and (27), the boundary normalized magnetizing-inductor time constant  $\tau_{LmB}$  can be formulated as:

$$\tau_{Lm,B} = \frac{D(1-D)^2}{8(n^2(1+D) + n(3+D) + 1)} \quad (28)$$

The normalized magnetizing-inductor time constant  $\tau_{Lm}$  can be written as:

$$\tau_{Lm} = \frac{f_s L_m}{R_L} \quad (29)$$

Fig. 6 shows the curve of  $\tau_{LmB}$ . If  $\tau_{Lm}$  is larger than  $\tau_{LmB}$ , the proposed converter is operated under CCM. Fig. 7 shows the Comparison of  $\tau_{LmB}$  of the presented converter with converters in [28], [29] with respect to the duty cycle and the conversion ratio. As it is shown in Fig. 7, the CCM region of the presented converter is wider. Also, the CCM region of the

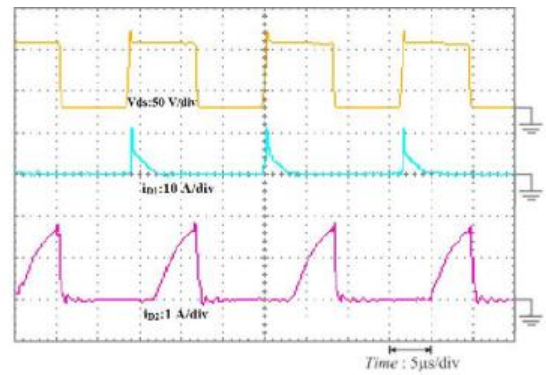
magnetizing inductance to assure the CCM operation of the converter.

The experimental results are shown in Fig. 8 under load 300W. The results verify the analysis of the steady state operation. The voltage on the switch ( $V_{DS}$ ) during the turn-off state is clamped to about 80V. Therefore, a low-voltage-rated switch can be used to improve the efficiency of the presented converter. Fig. 8(a) shows that the energy stored in the leakage inductance is recycled to capacitor  $C_1$  through diode  $D_1$ . Fig. 8(e), (f) depict the voltage stresses on the main switch and diodes. Also, Fig. 8(d) shows the voltages on capacitors  $C_1$ ,  $C_2$ ,  $C_3$  and  $C_O$  which are in consistency with (8)-(11). The current waveforms of the diodes, switches and the coupled inductor ( $i_{LK}$ ) shown in Fig. 8(a)-(c) validate the analysis and the feasibility of the proposed converter. The input current waveform with and without an input filter is also shown in Fig. 8(g). The input current ripple is as much as other proposed high step-up converters such as the converters in [27] - [29]. However, as it is shown in Fig. 8(g) ( $i_{Source}$ ), a low pass filter can be used to reduce the input current ripple.

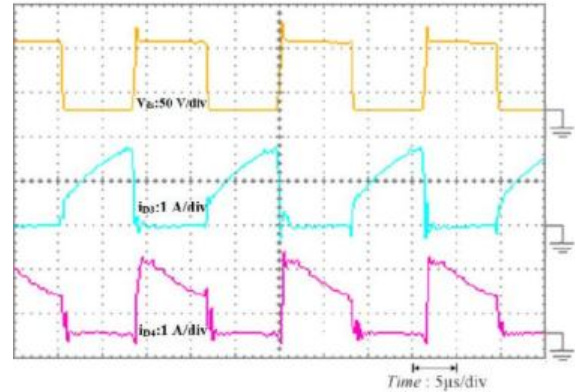
The experimental conversion efficiency of the presented converter is given in Fig. 9. The peak value of efficiency is 96.9% which is achieved at  $P_O=200W$ . The efficiency of the presented converter at full load  $P_O=300W$  is 96%. The results show the high conversion efficiency of the presented converter.

TABLE I  
SPECIFICATIONS OF THE IMPLEMENTED PROTOTYPE

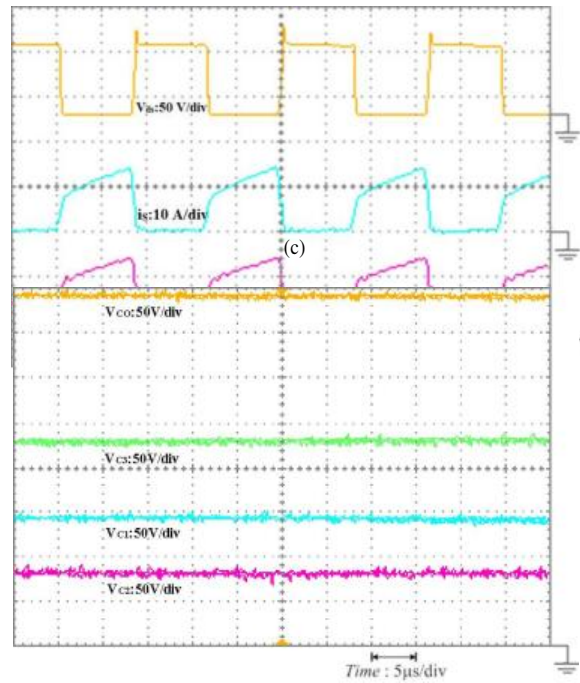
Specifications	Values
Input DC voltage	$V_{in}=40$ V
Output DC voltage	$V_{out}=400$ V
Switching frequency	$F=60$ kHz
Fast Diodes $D_1, D_2, D_3, D_4$	U1560
Coupled inductor	$L_K: 1 \mu H, L_m: 300 \mu H$
Capacitors $C_1, C_2, C_3, C_o$	47, 47, 100, 220 $\mu F$
Load	300 W
Power Switch (MOSFET)	IRFP260



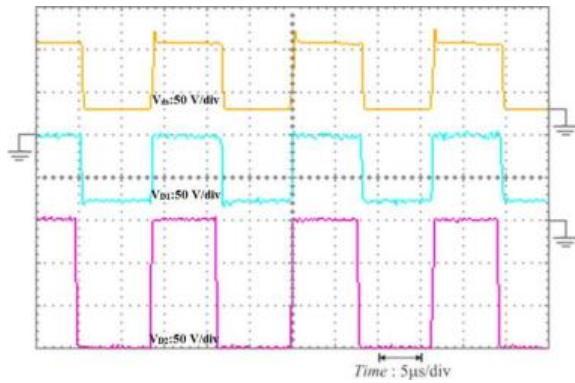
(a)



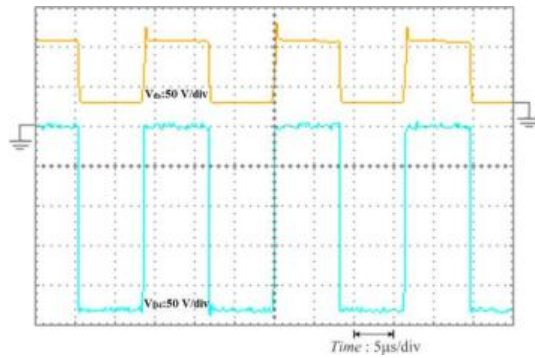
(b)



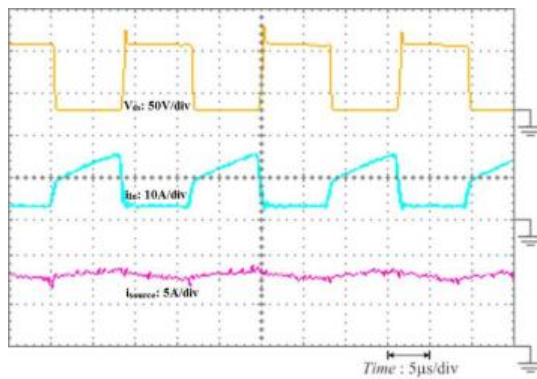
(d)



(e)



(f)



(g)

Fig. 8. Experimental results under load 300 W.

The experimental conversion efficiency of the presented converter is given in Fig. 9. The peak value of efficiency is 96.9% which is achieved at  $P_O=200\text{W}$ . The efficiency of the presented converter at full load  $P_O=300\text{W}$  is 96%. The results show the high conversion efficiency of the presented converter.

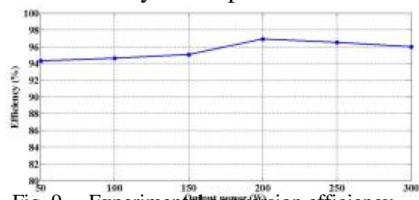


Fig. 9. Experimental conversion efficiency.

This paper presents a new high step-up DC/DC converter for Renewable Energy Applications. The suggested converter is suitable for DG systems based on renewable energy sources which require high step-up voltage transfer gain. The energy stored in the leakage inductance is recycled to improve the performance of the presented converter. Furthermore, voltage stress on the main power switch is reduced. Therefore, a switch with a low on-state resistance can be chosen. The steady-state operation of the converter has been analyzed in detail. Also, the boundary condition has been obtained. Finally, a hardware prototype is implemented which converts the 40-V input voltage into 400-V output voltage. The results prove the feasibility of the presented converter.

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