A new high step-up soft switching converter for photovoltaic system

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Abstract: In this paper, a new DC-DC boost converter with ZCS condition is presented. The ZCS condition of the proposed converter is established without adding any auxiliary switches and with minimum auxiliary elements, so the converter efficiency is high. The converter is controlled by pulse width modulation for which the design and implementation of the control circuit for the converter is very simple. The proposed converter has low current and voltage stress on the switch and the other advantage of the converter is high voltage gain due to existence of coupled inductors and voltage lifting in output, therefore the proposed converter is very suitable for photovoltaic systems. The experimental results verify the theoretical analysis and the converter efficiency at full load is approximately 96%.

Keywords: DC-DC converter; soft switching; zero voltage switching; ZVS; zero current switching; photovoltaic systems.

Reference to this paper should be made as follows: Vesali, M., Delshad, M. and Naeini, A.K. (2022) 'A new high step-up soft switching converter for photovoltaic system', *Int. J. Power Electronics*, Vol. 15, No. 1, pp.131–140.

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1 Introduction

Nowadays, the DC-DC converters have a special place in the power electronics, in the meantime, boost converters are used in photovoltaic systems because of need to have high level of voltage (Boumaaraf et al., 2018; Han et al., 2004; Sri Revathi, 2018). In solar power station to connect the DC power generated to the grid, voltage level should be raised up to acceptable amount, since the boost converters are large performance in this regarded. Figure 1 shows a simple single phase photovoltaic systems, which shows the importance of the existence of such converters.

These converters are divided to isolated (Mantovanelli and Barbi, 1996) and non-isolated (Li and He, 2011). If two sides of the circuit cannot be connected to a common ground, must be used isolated type, but if isolation is not required, the non-isolated type is used which structure is simpler and more comfortable design, also non-isolated type has higher efficiency and lower volume.

The conventional step up converter which used in the photovoltaic systems is hard switching converter. The main disadvantages of these converters are switching losses, high voltage stress and limits on increases switching frequency and increase EMI noise. Therefore, soft switching technique is used to reduce switching losses and EMI noise and increase the switching frequency to reduce the size of magnetic elements.

The soft switching techniques can be divided to resonant and quasi-resonant (Burkhart et al., 2012; Shamsi and Fahimi, 2013; Momeneh et al., 2018; Shang et al., 2015) and pulse width modulation converters (PWM) (Siddhartha and Hote, 2018; Adib and Farzanehfard; 2010; Mantovanelli and Barbi, 1996). In the resonant converters, a resonant circuit includes an inductor and capacitor are added to the main circuit. This resonant circuit causes fluctuations in the voltage and current, which by controlling switching frequency, it is switched when voltage or current zero. But in these converters because of the nature of resonance voltage and current, stress in the switches is high, and due to the variable switching frequency, the design of magnetic elements are not optimum. For this reason, soft switching PWM converters are more considered.

Some of the PWM converters are presented by the active clamp (Choi et al., 2010), which by using one or more additional switches and passive elements, zero voltage switching (ZVS) condition is provided for all switches. But these converters have duty cycle losses and the current stresses are high.

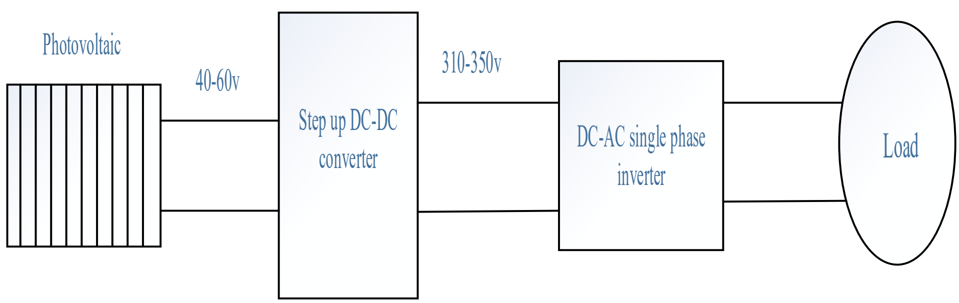
Some of the auxiliary circuits provide ZVS (Luo et al., 2014), zero current switching (Rezvanyvardom et al., 2011), or zero voltage and zero current switching (Chen et al., 2012) for switches, so the losses decreased and efficiency increased. In these circuits by one or more auxiliary switches the soft switching conditions is provided. Therefore, design and implementation of control circuit of these converters is complicated, moreover auxiliary elements added to these converters cause conductive losses in converters which decreases efficiency.

In recent years, the use of solar systems has led to the increasing use of high step up converters. Due to the high voltage level difference in such applications, the problems of low voltage gain and high voltage stress on the elements are more important. Therefore, high efficiency converters and low voltage stresses are very important.

In this paper a zero current switching DC-DC non-isolated high step up converter without auxiliary switch and switch voltage stress is introduced. By minimum auxiliary elements the soft switching condition is provided, which increases efficiency. Another advantage of this converter can be noted that controlled by PWM and only has one switch, which design and implementation of control circuit is simple. Therefore, the proposed high step up converter is suitable for photovoltaic systems.

The proposed converter is analysed and operation of circuit is described in Section 2. The design procedure is presented in Section 3, the experimental results of the proposed converter are presented in Section 4, and conclusion of this paper is introduced.

Figure 1 A simple photovoltaic system (see online version for colours)



2 Description and operation principle of the circuit

Figure 2 shows the circuit structure of the proposed converter. The converter composed of two main parts which both are operating with one switch. First part is a boost converter with a coupled inductance technique. It consists of a switch *S*, coupled inductances L_1 and L_2, output diode and capacitor D_2 and output capacitor C_1, and also clamp diode and capacitor D_1 and C_4. Moreover, leakage inductance L_4 provides soft switching condition for switch. Second part is a flyback circuit with voltage lifting technique. The proposed flyback circuit consist of coupled inductances L_3 and L_1, diodes D_3 and D_4 and, capacitors C_2 and C_3.

As shown in Figure 3, there are five operation modes for the proposed converter.

Mode 1 [t_0-t_1]: This mode starts when *S* turns on under zero current condition because of leakage inductance L_1. L_4 current starts to increase linearly as expressed in equation (1) until it reaches L_1 current. During this interval L_2 and L_3 current decrease linearly and reach zero at t_1. At the end of this mode D_2 and D3 turn off under ZCS.

$$\alpha = \frac{V_{in}\left(V_{C1} - V_{C4} - V_{in}\right)/N}{L_4} \tag{1}$$

Mode 2 [t_1-t_2]: At t_1, switch is on and leakage inductance current increases which describes as equation (2). Also, D_4 turns on because of L_1 reflective voltage effect on L_3. Moreover, L_3 current starts to increase by slop of $1/M$ to L_1.

$$\alpha = \frac{V_{in} - V_{L1}}{L_4} \tag{2}$$

Figure 2 Circuit structure of the proposed converter

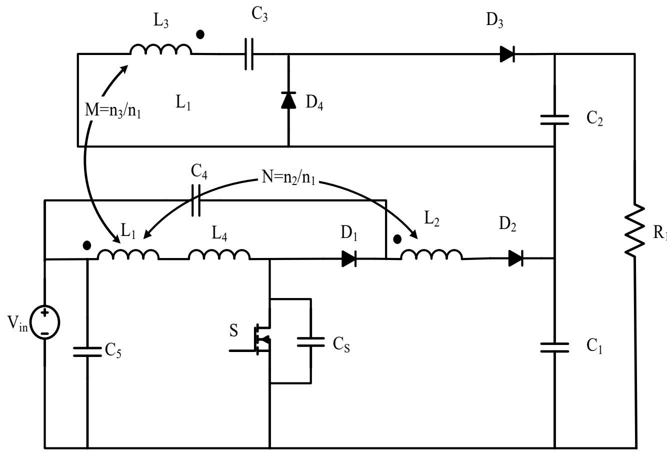
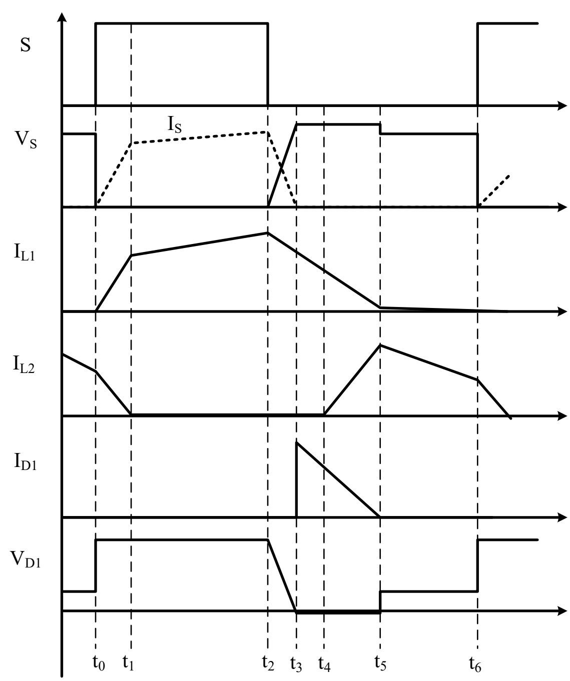


Figure 3 The key waveform of proposed converter



Mode 3 [t_2-t_3]: This mode starts with switch turns off and the switch parasitic capacitor voltage starts to increase due to magnetising current. At this time L_1 and L_3 current starts to decrease linearly.

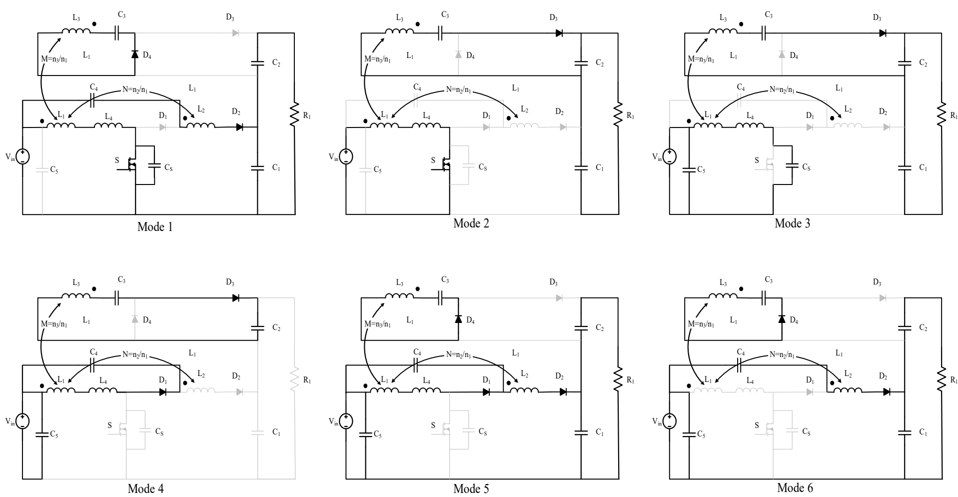
Mode 4 [t_3-t_4]: At the beginning of this mode the switch parasitic capacitor charge is as much as $V_{in} + V_{c4}$ and D_1 turns on. This mode ends when inductance current reaches zero.

Mode 5 [t_4-t_5]: At this interval C_4 and L_4 starts to resonant and L_4 current starts to decrease; on the other hand, L_2 and L_3 currents start to decrease. As a result, D_2 conducts under ZCS condition. When D_2 and D3 currents reach I_1 this mode ends.

Mode 6 [t_5-t_6]: At this interval, the converter operates like a conventional boost converter, and energy transferred to the output through D_2.

The equivalent of these modes are shown in Figure 4.

Figure 4 The equivalents of six modes in the proposed converter



2.1 *Design procedure*

In order to simplify the converter's voltage gain analysis, M and N are described as followed in equations (4) and (5). Also since L_4<< L_1 leakage inductance L_4 is neglected.

$$M = n_3 / n_1$$

$$N = n_2 / n_1$$

Volt-sec balance for L_1 written as:

$$V_{in} DT - V_{c4}(1 - D)T = 0 \quad (3)$$

and

$$V_{in} D = \left(\frac{V_{c1} - V_{in}}{N + 1} \right)(1 - D) \quad (4)$$

$$V_{in}D=\left(N+1\right)=\left(V_{c1}-V_{in}\right)\left(1-D\right) \tag{5}$$

As a result:

$$V_{c1}=\left(\frac{ND+1}{1-D}\right)V_{in} \tag{6}$$

Also volt-sec balance for L_1 could be written as:

$$V_{in}DT-\left(\frac{V_{c3}}{M}\right)\left(1-D\right)T=0 \tag{7}$$

And

$$V_{c3}=V_{c2}-MV_{in} \tag{8}$$

$$V_{in}DT-\left(\frac{V_{c2}-MV_{in}}{M}\right)\left(1-D\right)T=0 \tag{9}$$

As a result:

$$V_{c2}=\frac{MV_{in}}{1-D} \tag{10}$$

So that

$$V_0=V_{c1}+V_{c2} \tag{11}$$

$$\frac{V_0}{V_{in}}=\frac{M+ND+1}{1-D} \tag{12}$$

Moreover, the clamp capacitor C_4 voltage is given by:

$$V_{c1}=V_{in}+(N+1)V_{c4} \tag{13}$$

$$V_{c4}=\frac{D}{1-D}V_{in} \tag{14}$$

Between t_3-t_5 maximum voltage applies to switch.

The voltage expression is derived as

$$V_{DS}=V_{c4}+V_{in} \tag{15}$$

$$V_{DS}=V_{in}+\frac{D}{1-D}V_{in} \tag{16}$$

The provided circuit consists of inductance L_1, L_2, L_3 and, L_4 also coupled inductance L_1 and L_2. L_4 provides ZCS condition for S at turning on. L_4 can be determined based on equation (1).

$$L_4>L_{4\min}=\frac{V_{sw}t_r}{I_{sw}} \tag{17}$$

where t_r is current rise up time before it is turn-off and V_{sw} is switch's voltage after it is turn-off. In order to grantee soft switching condition it is assumed that $L_4 >> L_4$min.

3 Experimental results of the proposed converter

To verify the theoretical analysis of the proposed converter, a 100 W prototype with the input voltage of 60 V, output voltage of 320 V and switching frequency of 100 kHz has been built and tested. The value of elements that used to make the proposed converter has been shown in Table 1.

Table 1 Value of the component in experimental prototype

Component	*Value*
Input inductance (L_1)	150 μH
Leakage inductance (L_4)	2 μH
Output inductance (L_2)	1600 μH
Flyback inductance (L_3)	800 μH
Switch (S)	IRF640
All diodes (D_1, D_2, D_3, D_4)	MUR860
Clamp capacitor (C_4)	2 μF
Output capacitors (C_1, C_2, C_5)	22 μF

The experimental results of the proposed converter are presented in Figure 5.

As can be seen from the figure, because of the current slope in turning on instance, ZCS condition is provided for switch and all diodes, therefore reverse recover problem in diodes are solved. Also as shown, there is a resonant in the switch voltage that it is due to resonance between leakage inductance and parasitic capacitance of the switch.

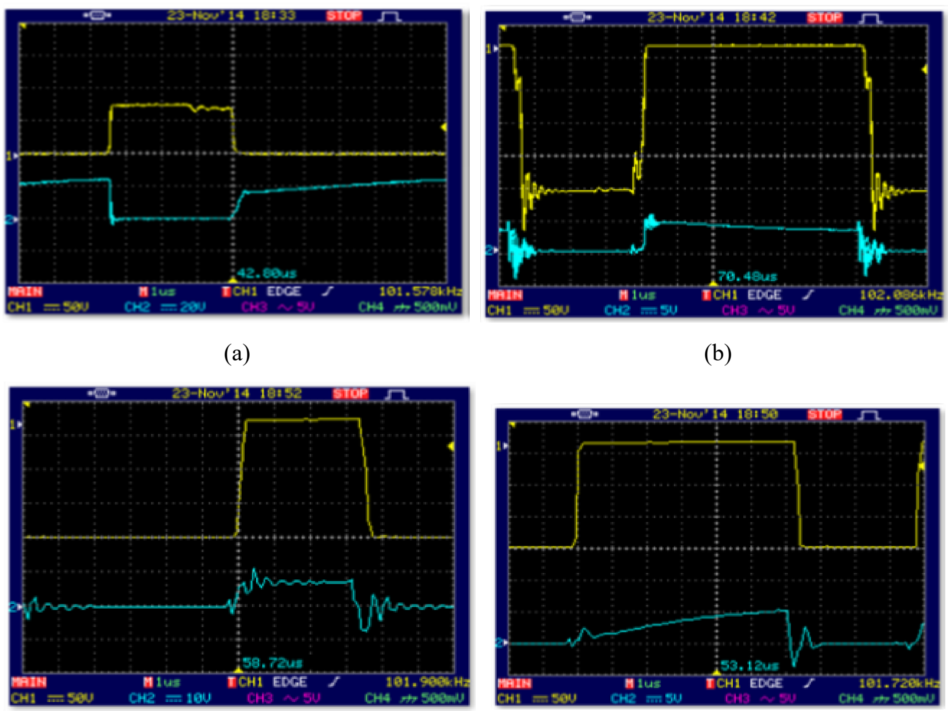
Figure 6 shows the comparison between efficiency of the proposed converter and hard switching step up converter. These results are obtained by PSPICE simulation at the same condition and output power in the converters. As shown in this figure, the efficiency of the converter is higher than conventional one. Also these simulation results are verified by experimental results.

The other advantage of the proposed converter is low stress voltage on the switch and diodes which control with ratio of M and N. Figure 7 shows these relationships that is drawn from analysis equation with constant value of $N(N = 1)$. As can be observed from this figure stress voltage of the switch is reduced with increasing M.

Table 2 shows comparison between the proposed converters with two other soft switching converters. These results are achieved at same condition and output power. This table shows that the switch voltage stress of the proposed converter is lower than two other converters. The proposed converter has one switch but the converter in Rezvanyvardom et al. (2011) has three switch. Also the current stress in proposed converter is lower than Wu et al. (2005) and Rezvanyvardom et al. (2011).

The technique used in the proposed converter has the advantage of not using the extra switch compared to other techniques. In most high step up techniques with soft switching, the use of auxiliary switch complicates the circuit.

Figure 5 Experimental result of the proposed converter, (a) current (down) and voltage (top) of switch (vertical scale 200 volt/div or 0.5 A/div and horizontal scale 1 μs/div) (b) current (down) and voltage (top) of D_2 (vertical scale 80 volt/div or 0.5 A/div and horizontal scale 1 μs/div) (c) current (down) and voltage (top) of D3 (vertical scale 100 volt/div or 0.5 A/div and horizontal scale 1 μs/div) (d) current (down) and voltage (top) of D_4 (vertical scale 100 volt/div or 0.5 A/div and horizontal scale 1 μs/div) (see online version for colours)



(a) (b)

(c) (d)

Figure 6 Comparison between efficiency of the proposed converter with conventional ones (see online version for colours)

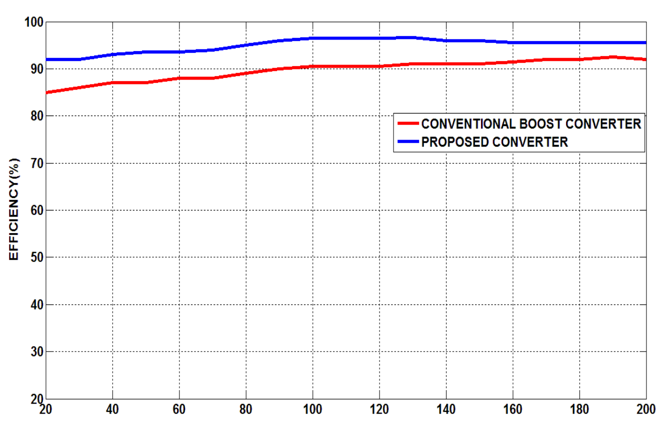


Figure 7 Relationship between M and voltage of the switch and diodes (see online version for colours)

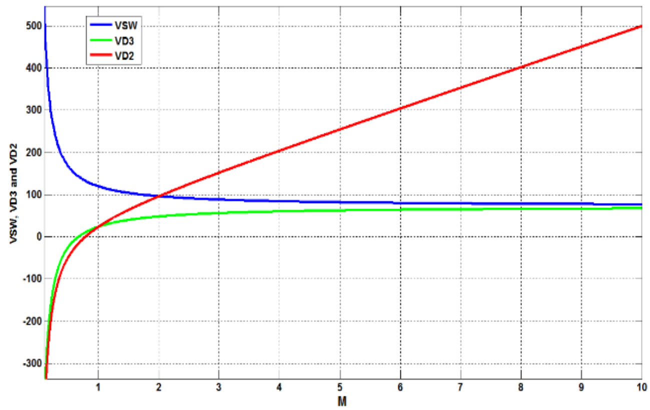


Table 2 Comparison between proposed converter with two other soft switching converter

Converter parameter	*Proposed converter*	*Converter in Wu et al. (2005)*	*Converter in Rezvanyvardom et al. (2011)*
Efficiency	96%	92%	94.5%
Switch current stress	I_{in}	$I_{in} + \frac{1}{2}\Delta I_L$	$\frac{P_O}{2V_{in}} + \frac{\Delta_{IL}}{2}$
Number of switch	1	2	3
Switch voltage stress	$V_{in} + \frac{V_O}{N}\left(1 + \frac{1}{M}\right)$	$V_{in}\left(1 + \frac{D}{1-D}\right)$	V_O
Voltage gain	$\frac{M + ND + 1}{1-D}$	$\frac{ND + 1}{1-D}$	$\frac{2D}{1-D}$

4 Conclusions

In this paper, a new high step up converter with ZCS condition is introduced. The soft switching condition is established without any extra switch and with minimum auxiliary elements, which cause to high efficiency. The current and voltage stress on the switch is low, which by use of low voltage switch in the converter, the conductive losses is decreased. Also the proposed converter has high voltage gain. The control of the proposed converter is simple because of PWM control circuit and one switch in the proposed converter. The proposed converter is analysed and to verify this analysed the experimental results are presented.

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