Research paper

A New Low-Stress Boost Converter with Soft-Switching and Using Coupled-Inductor Active Auxiliary Circuit

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Abstract

Background and Objectives: Many applications use boost converters as front-end circuits, including power factor correction (PFC), solar power generation, fuel cell power conversion, battery chargers, and uninterruptible power supply. In addition, boost converters have a simple structure with low component counts, which makes them a convenient choice.

Methods: This article proposes a coupled-inductor active auxiliary circuit to create a new low-stress boost converter with soft-switching. The proposed auxiliary circuit supplies the main switch and diode with soft-switching ZVC turn-on and ZCS turn-off states. The main switch and diode are not deal with any extra stress of voltage or current. Furthermore, the soft switching condition is also provided for auxiliary circuit components.

Results: The proposed auxiliary circuit also has a simple structure, low circulating current losses, low cost, and simplicity in control. The operation state and performance of the proposed soft-switching boost converter are examined, and the design procedure is presented. Finally, a 200W prototype is implemented and tested to validate the theoretical results. The offered experimental data verified the theoretical analysis.

Conclusion: This paper provides a new low-stress soft-switching boost converter using a simple coupled-inductor in the auxiliary circuit. Moreover, the auxiliary part consists of two diodes, one switch, one resonance capacitor, and a coupled inductor. The suggested auxiliary circuit provides soft switching condition for the main switch, which provides ZVS in the turn-on transient and ZCS in the turn-off transient, while in this situation, the soft-switching condition is provided for the auxiliary switch, which turns on under ZCS and also turns off with practically ZVS conditions. The auxiliary circuit does not impose additional voltage or current stress on the main switch. A 200 W prototype is implemented to validate the performance of this snubber cell. The experimental data reported here support the theoretical analysis. The best point of efficiency is 95.9% which is occurred at maximum load, and is 6.3% greater than the traditional counterparts.

Introduction

Many applications use boost converters as front-end circuits, including power factor correction (PFC), solar power generation, uninterruptible power supply (UPS), fuel cell power conversion, battery chargers, and car high-intensity discharge (HID) headlamps [1]-[7]. Regarding
boost, converters have a simple structure with low component counts, straightforward to implement, design, and control [8]-[10]. However, the main switch of a boost converter is hard switched, and switching losses and reverse recovery problems of the diode limit the efficiency, power density, and switching frequency. Furthermore, hard switching intensifies electromagnetic interferences (EMI) [11]-[13]. On the other hand, by introducing and developing soft-switching techniques which remove switching losses, these converters can operate at high switching frequencies. The significant advantages of a soft-switching converter are small size, lightweight, low EMI, and high-power density [14]-[15]. Meanwhile, soft-switching PWM converters, like PWM hard-switching converters, use a simple control circuit to design and experiment. Recently, many passive and active auxiliary circuits have been proposed for the boost converter [16]-[30]. Although passive auxiliary circuits do not need any auxiliary switches and have a simple control method, their construction is typically complex and causes extra voltage and also current stress over the switch and diode of the converter [16]-[19]. Furthermore, this solution can only provide a turn-on ZCS condition and cannot recover capacitive turn-on losses. On the other hand, the active auxiliary circuits are proposed in [20]-[21] provide soft switching conditions for both the main switch and the main diode, although they operate with additional current stress on the main switch. The converter proposed in [22] provides the ZCS condition for the main switch. The primary switch voltage stress is increased in [23]-[24] by the series inductor that is used in the power path. In [25], the soft switching condition is achieved by way of having two auxiliary switches and increasing the converter’s cost. [26]-[29] suggest an auxiliary circuit with a large number of components to decrease the current and voltage stress on the primary switch, however this increases cost and lowers efficiency and reliability. Higher conduction losses are caused by [20]-[22] and [25]-[29]’s significant circulation current losses and current stress through the auxiliary switches. The auxiliary switch in [30] also functions when being stressed by high voltage.

In this research, a novel coupled-inductor auxiliary circuit-based low stress soft-switching boost converter is suggested. The recommended auxiliary circuit corrects the issues listed above. The recommended auxiliary circuit turns on and off the main switch and main diode in ZVS and ZCS scenarios. Additionally, when ZCS requirements are met, the auxiliary switch activates, and when switching losses are minimal, it deactivates. The primary switch or main diode are not subjected to any additional current or voltage stress from the suggested auxiliary circuit. The recommended auxiliary circuit also features a straightforward design, little circulating current, and low losses.

**Operating Statuses and Performance Analysis**

Fig. 1 depicts the schematic of the proposed converter. Generally, this converter is divided into two sections: a) the boost converter and b) the auxiliary circuit. The input inductor \( L_1 \), the main switch \( S \), the output capacitor \( C_o \), and the main diode \( D_m \) comprise the boost converter.

![Fig. 1: The schematic of the proposed converter.](image)

The auxiliary circuit is made up of the following components: the auxiliary input diode \( D_{a1} \), the auxiliary capacitor \( C_s \), the auxiliary switch \( S_a \), the coupled inductors \( T_1 \), and the auxiliary output diode \( D_{a2} \). \( T_1 \) is modeled by an ideal transformer with the turns ratio \( n_1 \) and magnetic inductance \( L_m \), as shown in Fig. 1. Furthermore, \( C_{ds} \) is the drain-source parasitic capacitance of the primary switch \( S \). The following assumptions simplify the analysis of the proposed circuit:

- The suggested converter works in a steady-state mode.
- Because the output capacitor \( C_o \) and the input inductor \( L_1 \) are both large enough, the output capacitor voltage and the input inductor current will be constant over a switching cycle.
- It was supposed that all components of this converter operate without losses, with the exception of the drain-source capacitance of the main switch.

During each switching cycle, seven operating states are identified to illustrate the operating principle of the suggested boost converter. Fig. 2 depicts the corresponding sub-intervals of the proposed structure. The key waveforms of the operational states are also illustrated in Fig. 3. The voltage is expected to be the same as the output voltage \( V_o \) before the initial status.

**Operating Statuses**

**Status 1 \([t_0, t_1]\):** Previous to this status, \( D_o \) is conducting and \( S \) is turned off. This mode is initiated by applying the gate signal to the auxiliary switch \( S_a \), and it is turned on under ZCS conditions. When the output voltage is applied across the magnetizing inductor of the \( L_m \), the current \( i_{m} \) increases linearly to \( I_{b} \), and the current \( I_{do} \) falls linearly to
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Fig. 2: The equivalent configurations of the proposed converter at operating subintervals (a) Status1, (b) Status2, (c) Status3, (d) Status4, (e) Status5, (f) Status6, (g) Status7.

zero. Under ZCS conditions, the output diode \( D_o \) turns off, and the following status begins. The corresponding configuration of this status is depicted in Fig. 2a. The equations of this mode are derived as:

\[
i_m = i_w = \frac{V_o}{L_m} (t - t_n) \quad (1)
\]

\[
v_o = V_o \quad (2)
\]

\( L_m \) represents the magnetizing inductance of \( T_1 \), and \( V_o \) is the output voltage.

This is how the duration of this mode is expressed:

\[
\Delta t_1 = \frac{I_o L_m}{V_o} \quad (3)
\]

Status 2 (\( t_1, t_2 \)): When the output diode turns off, this subinterval starts. The magnetizing inductor \( L_m \) and the resonant capacitor \( C_s \) combine to create a resonant circuit. In a resonance, as depicted in Fig. 3, the voltage of the capacitor \( C_s \) starts to fall from the output voltage to zero. When the voltage of the resonant capacitor is fully depleted, this status is finished. The corresponding configuration of this state is depicted in Fig. 2b. The voltage of the capacitor \( C_s \) and the current passes through the auxiliary switch \( S_a \) are calculated using the following equations.

\[
v_c = V_o \cos(\omega_2(t - t_1)) \quad (4)
\]

\[
i_m = i_m = I_o + V_o \sqrt{\frac{C_s}{L_m}} \sin(\omega_2(t - t_1)) \quad (5)
\]

where \( \omega_2 \) is the status 2 auxiliary circuit resonance frequency.

The duration of this status can be obtained as follows:

\[
\Delta t_2 = \pi \sqrt{\frac{C_s L_m}{L_o}} \quad (6)
\]
The appropriate equivalent circuit of this status is shown in Fig. 2d. At the end of this status, the auxiliary diode \( D_{a2} \) turns off and the energy stored in the magnetizing inductor \( L_m \) is fully discharged. The voltages across the windings \( n_1 \) and \( n_2 \) and the currents flowing through the winding \( n_2 \) and the output auxiliary diode \( D_{a2} \) are stated as follows:

\[
i_{n_2} = i_{D_{a2}} = \frac{n_1}{n_2 - n_1} I_b \tag{7}
\]

\[
v_{a1} = \frac{n_1}{n_1 - n_2} V_o \tag{8}
\]

\[
v_{a2} = -\frac{n_2}{n_1 - n_2} V_o \tag{9}
\]

where \( n_1 \) is the primary and \( n_2 \) is the secondary winding of the coupled inductor \( T_1 \).

Following is the description of timeframe for this status:

\[
\Delta t_4 = \left( \frac{n_2 - n_1}{n_1} \right) L_m I_b \tag{10}
\]

**Status 5** \([t4, t5]\): In this state, the primary switch \( S \) is conducting, the output diode of the boost converter is off, and the magnetizing inductances of coupled inductors are fully discharged in this state. The corresponding configuration of this state is shown in Fig. 2e. This condition is comparable to the typical boost converter.

**Status 6** \([t5, t6]\): The main switch \( S \) does not conduct at the start of this condition. The input current \( i_1 \) parallels the parasitic drain-source capacitance \( C_{ds} \) of the main switch by passing via the resonant capacitors \( C_r \). As a result, under ZVS conditions, the voltage of the primary switch rises linearly, and the switch turns off. The output diode turns on under ZVS when the voltage of the main switch reaches the output voltage. The voltage of the resonant capacitor and the voltage of the main switch are thereby constrained to the output voltage. The equivalent configuration of this state is shown in Fig. 2f. Following is the equation for this status:

\[
v_c = v_{ds} = v_{dsi} = \frac{I_b}{C_r} (t - t_i) \tag{11}
\]

which the period of this mode is derived as follows:

\[
\Delta t_6 = \frac{C_r}{I_b} \frac{V_o}{I_b} \tag{12}
\]

**Status 7** \([t6, t7]\): The input inductor is being discharged at the start of this condition, and the output diode \( D_o \) becomes forward-biased. The suggested converter functions similarly to a standard boost converter in this state. The corresponding configuration of this state is shown in Fig. 2g.

**Simulation Results**

To verify the performance of the proposed active...
snubber cell and compare the experimental results with simulation results, the waveforms of the proposed converter are extracted. The gate commands of switches and the voltage of the resonance capacitor and main switches are shown in Fig. 4(a), and it can be seen the main switch turns on just after its voltage reaches zero by resonance occurring between the resonance and body capacitor of the main switch and magnetizing inductance.

The voltage and current waveforms of the main switch are shown in Fig. 4(b).

Moreover, to monitor the performance of the auxiliary switch, its current and voltage waveform are illustrated in Fig. 4(c), and the input and output current of the coupled inductor are depicted in Fig. 4(d) by measuring the current of the auxiliary switch $S_a$ and current of the auxiliary diode $D_{a2}$.

Fig. 4: A 200 W simulation result of the suggested active snubber cell, (a) the gate commands of switches and resonance and main switch voltage, (b) the main switch’s voltage and current, (c) the auxiliary switch’s voltage and current, (d) measured current of coupled inductors which passed the auxiliary snubber switch and the auxiliary output diode.

**Stresses Analysis of the Proposed Converter**

At the end of status 6, the peak voltage across the switches $S, S_a$, and can be calculated as follows:

$$v_S = V_o$$

$$v_{sa} = \left( \frac{n_1}{n_2 - n_1} \right) V_o$$

The voltage stress across $S_a$ is equal to $V_o$ and the peak current passes through the main switch $S$ can be determined as follow:

$$i_S = \frac{P_{out} + \Delta I}{V_o}$$

Where $\Delta I$ is the current ripple of the input inductor $I_b$.

Also, the peak current which passes through the auxiliary switch is obtained from mode 2:

$$i_{sa} = I_b + V_o \sqrt{\frac{C}{L_{in}}}$$

The voltage and current stresses of the main diode $D_o$ is calculated as follows:

$$v_{D_o} = V_o$$

$$i_{D_o} = \frac{P_{out} + \Delta I}{V_o}$$

The voltage stress and the current peak of the input and output auxiliary diodes $D_{a1}, D_{a2}$ are calculated using:

$$v_{D_{a1}} = \frac{n_2}{n_1} V_o$$

$$v_{D_{a2}} = 0$$

$$i_{D_{a1}} = I_b + V_o \sqrt{\frac{C}{L_{in}}}$$

$$i_{D_{a2}} = \frac{n_1}{n_2 - n_1} I_b$$
Design Method

When the input current $I_b$ at the end of status 1 exceeds the current flowing through magnetizing inductance of the coupled inductor $T_2$, the main switch $S$ is in the soft-switching condition. As a result, as long as the following equation is established, the main switch works under soft-switching conditions:

$$I_b < i_m(t_1) = \frac{V_m}{L_m} \Delta t_1$$

(23)

Where the $\Delta t_1$ is obtained from (3).

By considering $i_m(t_1)$ 15% higher than $I_b$, the following relation is obtained:

$$1.15 I_b = \frac{V_m}{L_m} \Delta t_1$$

(24)

Additionally, compared to the main switching cycle, the operating time of the auxiliary circuit must be insignificant. This duration is therefore chosen to be ten times shorter than the switching period.

$$\Delta t_1 + \Delta t_2 + \Delta t_4 + \Delta t_6 = \frac{T_{\text{switching}}}{10}$$

(25)

Where $\Delta t_i, i = 1, 2, 4, 6$ are the time duration of statuses 1, 2, 4, and 6 and are given from (3), (6), (10), and (12) and $T_{\text{switching}}$ is the switching cycle of the proposed converter.

From (24), the inductance $L_m$ is calculated by taking into consideration a specific value for the time duration. The ratio of the peak current of the auxiliary switch and the main switch is used to determine the value of the resonant capacitor $C_s$.

$$\left(\frac{I_m}{I_b}\right)_{\text{peak}} = \frac{1 + \frac{V_m}{I_b} \frac{C_s}{L_m}}{\lambda}$$

(26)

The longer the time period for $\lambda$ is obtained, the larger the value for $\Delta t_2$ is. The turn ratio of the primary winding of the coupled inductor depends on the value of the inductance $L_m$. The minimum voltage stress on the auxiliary components $S_a$ and $D_a$ is used to calculate the turns ratio $n_1$, $n_2$ of the coupled inductor. The condition (26) should be examined following the design of the resonant capacitor $C_s$ and the magnetizing inductance $L_m$. The equations in “Stresses analysis of the proposed converter” section is used to choose all active components. Similar to a traditional PWM boost converter, the values for $L_p$ and $C_o$ are obtained based on the desired current and voltage ripple.

Furthermore, to compare the proposed snubber cell with its counterparts in terms of voltage gain, output power, switching frequency, efficiency, and component counts, such as the number of auxiliary switches and diode, capacitor, inductor, and coupled inductors, a comprehensive comparison is made, and the results are presented in Table 1.

Experimental Results

A 200 W implementation with supply voltage of 90 V, output voltage of 200 V, and switching frequency of 100 kHz has been constructed and evaluated to corroborate the findings of the theoretical analysis of the suggested circuit. The experimental specifications for this converter are shown in Table 2, and the actual converter’s circuit. The experimental specifications for this converter are shown in Table 2, and the actual converter’s circuit schematic is shown in Fig. 7. The magnetizing inductance $L_m$ 100 uH and the resonant capacitor $C_s$ 10 nF are both meant for the auxiliary circuit. The linked inductor is also selected with a 2:16 turns ratio. The input inductor is set to have a value of 400 uH in the interim.

Table 1: proposed converter and its counterpart’s comparison

<table>
<thead>
<tr>
<th>Refs</th>
<th>Efficiency [%]</th>
<th>$V_{out}/V_{in}$</th>
<th>$P_{out}$ [W]</th>
<th>$f_{sw}$ [kHz]</th>
<th>Switch</th>
<th>Diode</th>
<th>C</th>
<th>L</th>
<th>Coupled Ind.</th>
</tr>
</thead>
<tbody>
<tr>
<td>[12], [13]</td>
<td>96.23</td>
<td>2.67</td>
<td>600</td>
<td>30</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>[16]</td>
<td>96</td>
<td>2</td>
<td>200</td>
<td>100</td>
<td>0</td>
<td>4</td>
<td>1</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>[17]</td>
<td>97</td>
<td>1.5</td>
<td>300</td>
<td>180</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>[20]</td>
<td>93.9</td>
<td>-</td>
<td>300</td>
<td>20</td>
<td>1</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>[23]</td>
<td>&gt;97</td>
<td>1.07</td>
<td>1200</td>
<td>80</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>[24]</td>
<td>98</td>
<td>1.29</td>
<td>1000</td>
<td>100</td>
<td>1</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>[25]</td>
<td>96</td>
<td>1.6</td>
<td>2000</td>
<td>30</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>[27]</td>
<td>97</td>
<td>2</td>
<td>100</td>
<td>100</td>
<td>0</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>[30]</td>
<td>98.28</td>
<td>2</td>
<td>200</td>
<td>32.2</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

Proposed 95.9 2.2 200 100 1 2 1 0 1
As can be observed, the auxiliary switch has an output voltage-equivalent voltage stress, operates under ZCS, and shuts off with low switching losses. Additionally, the peak current of the auxiliary switch is a little bit higher than that of the main switch.

The charge and discharge situation of the resonant capacitor in terms of voltage to achieve the soft switching condition are shown in Fig. 5c. Fig. 5d demonstrates the waveforms of coupled inductors, where the core is charged first, then is discharged when the auxiliary switch is turned off.

To depict the volume and dimensions of this converter, the implemented prototype of the proposed circuit is shown in Fig. 6.

Furthermore, the part number of all active devices and the values of passive devices are noted and presented in Fig. 7.

In Fig. 8, the measured efficiency of this converter is provided. The nominal load of 200 W yields a maximum efficiency of 95.9\%, an increase of 6.3\% in efficiency over a traditional boost converter.

Notably, all circumstances, including input voltage, switching frequency, and voltage gain, are considered the same for a fair comparison of the efficiency between this article and the conventional boost converter.

Table 2: The parameters of the experimental prototype

<table>
<thead>
<tr>
<th>Description</th>
<th>Symbol</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Input Voltage</td>
<td>$V_{in}$</td>
<td>90 V</td>
</tr>
<tr>
<td>Output Voltage</td>
<td>$V_{o}$</td>
<td>200 V</td>
</tr>
<tr>
<td>Max. Output Power</td>
<td>$P_{o}$</td>
<td>200 W</td>
</tr>
<tr>
<td>Frequency of main switch</td>
<td>$f_s$</td>
<td>100 kHz</td>
</tr>
<tr>
<td>Frequency of auxiliary switch</td>
<td>$f_{sa}$</td>
<td>100 kHz</td>
</tr>
<tr>
<td>Input Inductor</td>
<td>$L_1$</td>
<td>400 uH</td>
</tr>
<tr>
<td>Resonance Capacitor</td>
<td>$C_s$</td>
<td>10 nF</td>
</tr>
<tr>
<td>Magnetizing Inductance</td>
<td>$L_m$</td>
<td>100 uH</td>
</tr>
<tr>
<td>Output Capacitor</td>
<td>$C_o$</td>
<td>100 uF</td>
</tr>
<tr>
<td>Coupled Inductor Core</td>
<td>$T_1$</td>
<td>E34/14/9</td>
</tr>
<tr>
<td>Turn Ratio of CI</td>
<td>$n_1/n_2$</td>
<td>2/16</td>
</tr>
</tbody>
</table>

Fig. 5a shows the experimental voltage and current of the primary switch. The primary switch turns on under ZVS conditions, and switches off under ZCS situations. As previously mentioned, the snubber circuit also prevents any voltage or current strains from being applied to the primary switch. Fig. 5b displays the auxiliary switch's voltage and current.

![Fig. 5a: Main Switch Voltage and Current](image1)

![Fig. 5b: Auxiliary Switch Voltage and Current](image2)

![Fig. 5c: Resonant Capacitor Voltage](image3)

![Fig. 5d: Coupled Inductor Current](image4)

Fig. 5: A 200 W experimental result of the suggested active snubber cell, (a) the main switch’s voltage and current, (b) the auxiliary switch’s voltage and current, (c) voltage of resonant capacitor, (d) measured current of coupled inductors which passed the auxiliary snubber switch and the auxiliary output diode.
Conclusion

This paper provides a new low-stress soft-switching boost converter using a simple coupled-inductor in the auxiliary circuit. Moreover, the auxiliary part consists of two diodes, one switch, one resonance capacitor, and a coupled inductor. The suggested auxiliary circuit provides soft switching condition for the main switch, which provides ZVS in turn-on transient and ZCS in turn-off transient, while in this situation, the soft-switching condition is provided for the auxiliary switch in which turns on under ZCS and also turns off with practically ZVS conditions. The auxiliary circuit does not impose additional voltage or current stress to the main switch. A 200 W prototype is implemented to validate the performance of this snubber cell. The experimental data reported here support the theoretical analysis. The best point of efficiency is 95.9% which is occurred at maximum load, and is 6.3% greater than the traditional counterparts. The number of components in this topology is more efficient than other counterparts. Still, the auxiliary switch, a high-side switch, could be considered one of the main challenging issues in this topology. On the other hand, this auxiliary switch operates under ZCS, which is suitable for IGBT switches, not MOSFET.

Author Contributions

Mohammad Ali Latifzadeh in collaboration with Hesamodin Allahyari and Hadi Faezi, designed, simulated, carried out the data analysis, implemented the prototype and wrote the manuscript thoroughly under supervising of dr. Parviz Amiri.

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Conflict of Interest

Regarding the publishing of this study, the authors state that there are no possible conflicts of interest. The authors have also fully observed all ethical difficulties, such as plagiarism, informed consent, misconduct, data fabrication or falsification, duplicate publishing or submission, and redundancy.

Abbreviations

- **ZVT**: Zero Voltage Transient
- **ZVS**: Zero Voltage Switching
- **ZCS**: Zero Current Switching
- **PWM**: Pulse Width Modulation
- **EMI**: Electro-Magnetic Interference
- **CL**: Coupled Inductors

References


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Biographies

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