A Magnetically Coupled AC/DC Boost Converter with Low Reverse Recovery and Conduction Losses

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Abstract

A modified boost converter with magnetic coupling is presented to reduce the reverse recovery loss while maintaining low conduction loss of the rectifiers. By utilizing a coupled inductor and a set of diodes, the current passing the boost rectifier is transferred to an auxiliary loop before turn-off, allowing low *di/dt* for reduced recovery loss. Moreover, the boost inductor is brought inside the bridge rectifier to reduce conduction loss by decreasing the number of conducting diodes during switch turn-off. Experimental results of a 500W prototype are provided to verify the increase in efficiency and validity of the proposed converter.

1. Introduction

A conventional boost converter is widely adopted as a front-end of a power supply, especially with Power Factor Correction (PFC), due to the lack of cross distortion compared to a buck converter and continuous input current compared to both buck and buck-boost converters [1]. However, the problem still remains with the reverse recovery current of the silicon diode, which introduces unwanted surge current to the switch during diode turn-off, causing high EMI noise and losses.

Several solutions have been introduced to resolve this issue, including passive snubbers, active snubbers, and lossless snubbers. Of the three, passive snubbers have the simplest configuration but also have the worst efficiency, due to power dissipation through a resistor [2]. Active snubbers perform quite the opposite in having the highest performance with zero voltage switching, but also has the worst reliability and highest complexity due to the increased number of active components [3]. A lossless snubber is a type of configuration where it tends to sit between the two. It does not have the issues with active components but has higher performance than a passive snubber [4].

Several papers regarding a lossless snubber for the boost converter has been published in the past. Of the few, a magnetically coupled boost converter has shown reasonable performance to be of interest [5]. In this paper, an attempt has been made to further increase the efficiency of the magnetically coupled AC/DC PFC boost converter by bringing the coupled inductor inside the bridge rectifier. Experimental results show an increase of XXX% in efficiency of a 500W prototype.

2. Operation Analysis

The circuit diagram of the proposed converter is shown in Fig. 1. Compared with the conventional AC/DC PFC boost converter, two auxiliary branches are added, with an inductor placed inside the bridge rectifier. A branch is composed of a diode and is coupled to the inductor. The turn ratio of the of windings for L_{m12} : L_{m34} is 1:N (N<<1), and is the same for L_{m12} : L_{m56}. For the coupled inductor, a leakage inductance exists on the auxiliary side to control the *di/dt*

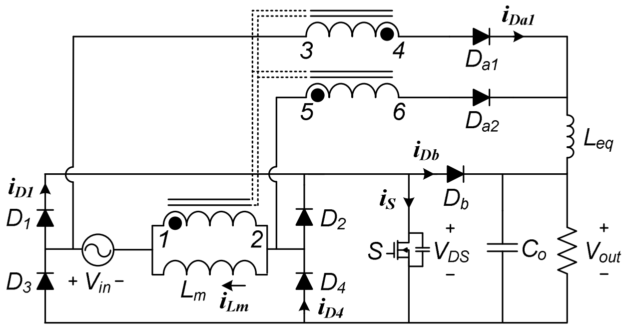


Fig. 1. Circuit diagram of the proposed converter.

of the auxiliary diodes. However, the number of windings is small and may not have sufficient inductance. Thus, a small auxiliary inductor may be added, and shared between the branches. For the case of the inclusion, an equivalent inductance, notated as L_{eq}, is used to replace the sum of the leakage and the auxiliary inductance.

The operation of the proposed converter is based on shifting the current of the original boost diode for low reverse recovery loss, while maintaining low conduction loss of diodes.

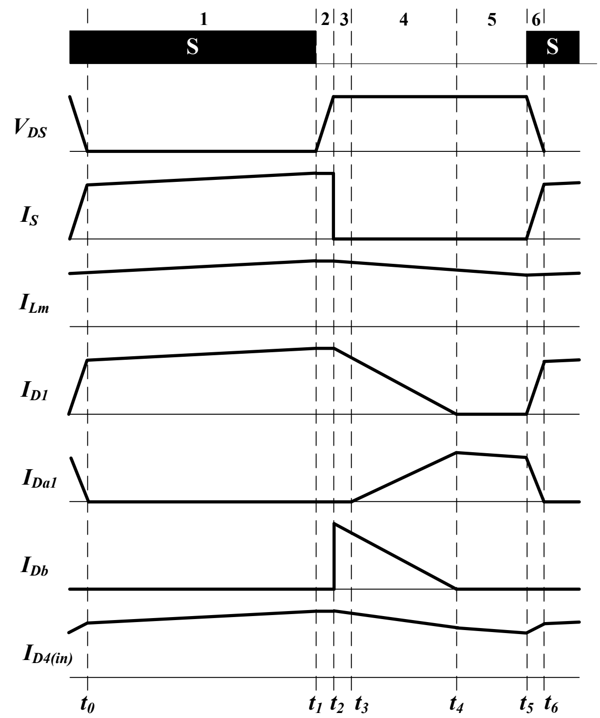
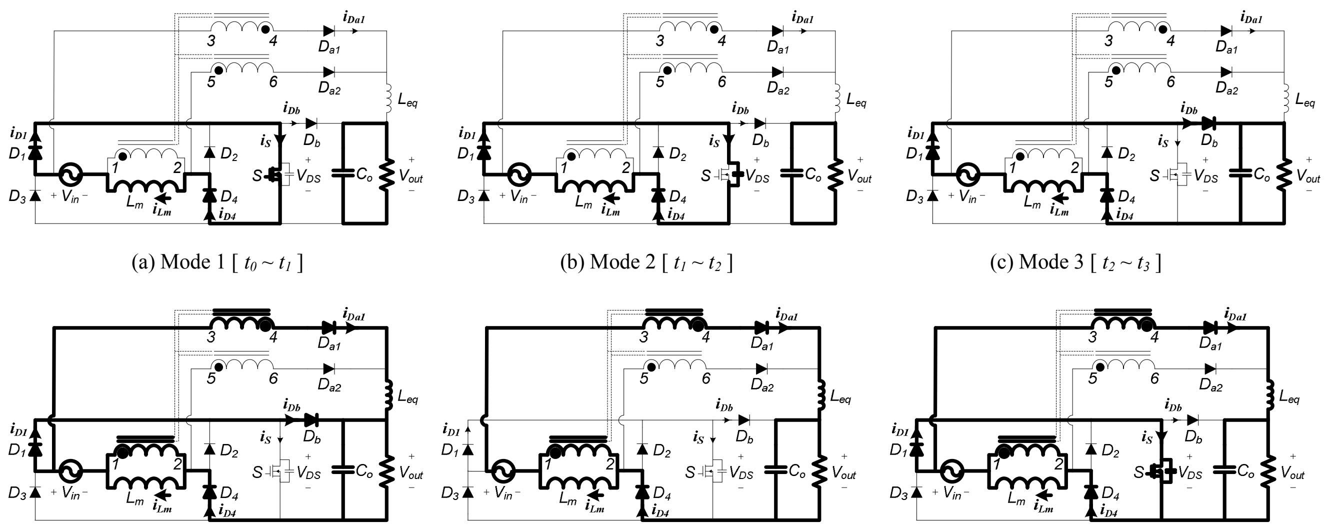


Fig. 2. Key waveforms of the operation modes.



(a) Mode 1 [$t_0 \sim t_1$] (b) Mode 2 [$t_1 \sim t_2$] (c) Mode 3 [$t_2 \sim t_3$]

(d) Mode 4 [$t_3 \sim t_4$] (e) Mode 5 [$t_4 \sim t_5$] (f) Mode 6 [$t_5 \sim t_6$]

Fig. 3. Operation modes of the proposed converter.

Low reverse recovery loss is achieved by magnetically driving i_{Db} to an auxiliary branch including D_{a1} or D_{a2} before turn-off, allowing the switch for soft turn-on. The reverse recovery issue in the auxiliary diode during turn-off is reduced by controlling its *di/dt* with the leakage inductance of the coupled inductor.

Low conduction loss is achieved by bringing the coupled inductor inside the bridge rectifier. By doing so, two of the bridge diodes only partially conduct during switch turn-off instead of full conduction as in the conventional converter. Additionally, despite the usage of additional diodes, its alternate conduction on a 120Hz basis allows improved thermal management.

Since only a different current path is introduced, for N<<1, the basic input/output voltage characteristics remain the same as in a conventional continuous conduction mode boost converter of:

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

where, D is the duty cycle.

The topological states of the converter for one switching cycle in half period of the input voltage is described in Fig. 3. The corresponding key waveforms are shown in Fig. 2. The mode analysis is as follows.

Mode 1 [$t_0 \sim t_1$] : The main switch S is already turned on. The magnetizing current i_{Lm} as well as the switch current i_s increases linearly by the input voltage source V_{in}. The boost diode D_b is reversed biased by the output voltage V_{out}, while the voltage stress on the auxiliary diode D_{a1} is:

$$V_{Da1} = V_{out} + NV_{in} \tag{2}$$

and on auxiliary diode D_{a2} is:

$$V_{Da2} = V_{out} - NV_{in} \tag{3}$$

Mode 2 [$t_1 \sim t_2$] : S is turned off at t_1. The output capacitance of the switch is linearly charged to V_{out}. Powering to the output begins at t_2.

Mode 3 [$t_2 \sim t_3$] : The voltage across L_m is V_{out} -V_{in}. D_b is forward biased and conducts all of i_{Lm}.

Mode 4 [$t_3 \sim t_4$] : The voltage at the anode of D_{a2} reaches higher than the voltage at the anode of D_{a1} to V_{out} + $(V_{out}$ - $V_{in})N$, and a positive voltage of $(V_{out}$ - $V_{in})N$ is applied to L_{eq}. Thus, the current through L_{eq}, or i_{Da1}, increases linearly, while reducing the current through D_b at the rate of:

$$\frac{di_{Db}}{dt} = -\frac{N\left(V_{out} - V_{in}\right)}{L_{eq}} \tag{4}$$

The sum of the two currents makes up for the capacitor charging current, which is also equal to i_{D4}. Note that only a minimal number of N is required for a positive voltage for the shifting to take place, which is to be discussed later.

Mode 5 [$t_4 \sim t_5$] : With sufficient time and voltage on L_{eq}, all of the boost current from D_b is shifted to D_{a1} by t_4. There is no remaining current in D_b for reverse recovery and a soft turn-on can be achieved by switch S.

Mode 6 [$t_5 \sim t_6$] : S is turned on again at t_5. A negative voltage of - $(V_{out} + NV_{in})$ is applied to L_{eq}. Since the decreasing rate of i_{Da1} is:

$$\frac{di_{Da1}}{dt} = -\frac{V_{out} + NV_{in}}{L_{eq}} \tag{5}$$

the reverse recovery problem of D_{a1} can be controlled by proper selection of L_{eq}. D_{a1} is reverse biased at t_6 and the circuit is ready for the next switching period.

3. Design Considerations

Besides the design considerations of a conventional boost converter, the proposed converter requires careful selection in the turn ratio N and the equivalent inductance L_{eq}. As represented in (5), a larger L_{eq} would allow a lower slope for less reverse recovery loss. However, this would require a higher N for enough voltage to drive the current down to zero. As mentioned in (4), only a small N of much less than 1 is required to shift the current. Having a high N not only increases the voltage stress on the auxiliary diodes as in (2), but also increases the ripple of i_{in} during the powering mode ($t_2 \sim t_5$), due to the circulating configuration of the coupled inductor. This would result in more conduction loss and require a higher duty ratio. Therefore, an optimal point with high L_{eq} and low N is desirable.

The optimal N and its corresponding L_{eq} can be obtained by finding the conditions in reducing i_{Db} to zero where most reverse recovery loss is expected. Using (4), the condition to reduce $i_{Db}(t2)$ to zero during switch turn-off is:

$$\frac{N\left(V_{out} - V_{in,pk}\sin(\omega t)\right)V_{in,pk}\sin(\omega t)}{L_{eq} f_{sw} V_{out}} > i_{Db}(t_2) \tag{6}$$

where, $V_{in,pk}$ is the peak input voltage, ω is the angular frequency, and f_{sw} is the switching frequency. $i_{Db}(t2)$, which is also the peak of the inductor current, can be represented as:

$$i_{Db}(t_2) = I_{Lm,avg} + \frac{\Delta I_{Lm}}{2} = \frac{2P_o}{V_{in,pk}}\sin(\omega t) + \frac{V_{in,pk}\sin(\omega t)}{2L_m f_{sw}} \quad (7)$$

Then from (6) and (7), the minimum N required is obtained as:

$$N > \frac{L_{eq}V_{out}}{\left(V_{out} - V_{in,pk}\sin(\omega t)\right)}\left(\frac{2f_{sw}P_o}{V_{in,pk}^2} + \frac{1}{2L_m}\right) \quad (8)$$

which is a function of L_{eq}. An example showing the relationship between N and L_{eq} for a 500W converter is shown in Fig. 4. The worst case should be considered at the peak where the most reverse recovery loss is expected.

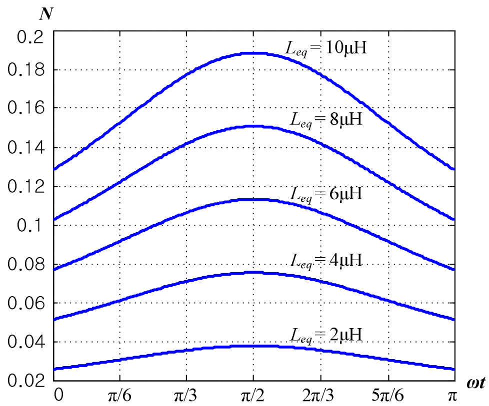


Fig. 4. Relationship between N and L_{eq} for a 500W converter.

In addition, an approximation of the power saved by bringing the coupled inductor inside the bridge rectifier can be made. For high input current, the ripple can be neglected. Then an estimation of 0.5*(1-D)* x100[%] ~ *(1-D)* x100[%] of the average input current can be saved for the diode reduced during switch turn-off, depending on the selection of L_{eq}. A graphical representation of the current saved is shown in Fig. 5, where shaded.

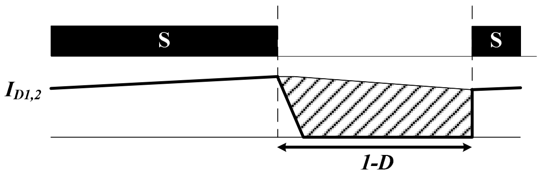


Fig. 5. Area of the current reduced for the proposed converter.

Using the values obtained in Fig. 4, the minimum power saved can be calculated as:

$$P_{saved} = 0.5V_f \frac{1}{\pi}\int_0^{\pi}\left((1-D)i_{in}\right)d(\omega t) = \frac{V_f P_o}{V_{out}} \quad (9)$$

where V_f is the forward voltage of the diode. Up to nearly twice the power can be saved with lower L_{eq} and is independent of the input voltage variation, e.g. 90~265V$_{ac}$, since higher input current for lower input voltage results in a shorter switch turn-off time and vice versa.

4. Experimental Results

A 500W prototype of the proposed converter has been built with the following parameters and components; V_{in}: 90~265V$_{rms}$, V_{out}: 400V, f_{sw}: 100kHz, $D_{1,2,3,4,b,a1,a2}$: RHRP1560, MOSFET: IRFP450A, L_m: 0.5mH, L_{eq}: 10μH, N_{12}:$N_{34,56}$ = 35:2, C_o: 330μF. The waveform in Fig. 6 shows i_{Db} decreasing to zero before switch turn-on for nearly zero reverse recovery, i_{Da1} with controlled *di/dt* for low reverse recovery, and i_{Db} of the original boost configuration with high reverse recovery. The efficiency curve is shown in Fig. 7, comparing efficiency of the conventional boost converter, magnetically coupled boost converter, and the proposed converter. Results show more increase in efficiency with lower input voltage where higher reverse recovery loss is occurred.

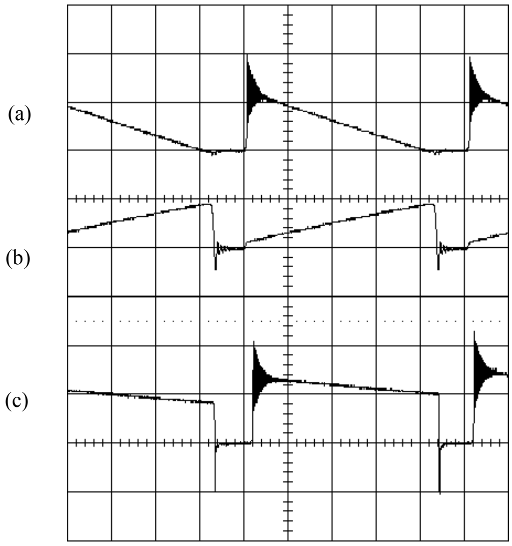


Fig. 6. Experimental waveforms of the rectifier reverse recovery: (a) i_{Da}, (b) i_{Db} of proposed converter, (c) i_{Db} of conventional converter.

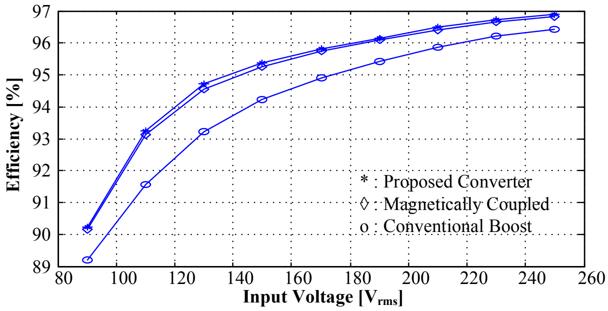


Fig. 7. Efficiency comparison under wide input variation.

5. Conclusion

A magnetically coupled AC/DC PFC boost converter with low reverse recovery and conduction losses is proposed. By utilizing two additional diodes, which share current periodically, and two coupled windings, the featured converter shows increased efficiency with low reverse recovery losses. With its simple configuration, the proposed converter is expected to be suitable for high power applications requiring tight thermal management.

References

[1] V. Grigore, "Topological issue in single-phase power factor correction," Doctoral dissertation, Helsinki University of Technology, Espoo, Finland, 2001.

[2] S.J. Finney, B.W. Williams, and T. C. Green, "The RCD snubber revisited," IEEE-IAS Annu. Meeting Conf. Rec., pp. 1267-1273, 1993.

[3] G. Hua and F.C. Lee, "Soft-switching techniques in PWM converters," IEEE Trans. Ind. Electron., vol. 42, pp. 595-603, Dec. 1995.

[4] N. Machin, and T. Vescovi, "Very high efficiency techniques and their selective application to the design of a 70A rectifier." IEEE-INTELEC Conf. Rec., pp. 126-133, 1993.

[5] G. Mantov and K. Wallace, "Diode recovery current suppression circuit," IEEE INTELEC Conf. Rec., pp. 125-129, 2000.