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# High Efficiency Soft-Switching Boost Converter Using a Single Switch

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## ABSTRACT

This paper presents a new soft-switching boost converter based on the  $LC$  resonance and passive clamping technique without additional active switches. The circuit achieves high efficiency and low voltage stress by adopting a soft switching method using  $LC$  resonance. This paper gives a mathematical analysis of each mode and a detailed design procedure of the proposed boost converter. First of all, the operational principles are verified through simulation results. Then, according to the design procedure, we designed and built a 1.5[kW] prototype soft switching boost converter. Through the experimental results, we demonstrated the validity and usefulness of the proposed boost converter.

**Keywords:** Soft-switching boost converter, Single switch, Resonance, ZVS, ZCS

## 1. Introduction

Nowadays, switch mode power conversion circuits and systems are being used effectively in renewable energy applications such as photovoltaic, fuel cell and wind-power generation systems, due to major advances in power semiconductor switching devices and their peripheral technologies [1-3]. To reduce the switching losses of DC-DC converters, the soft-switching technique (zero voltage switching or zero current switching) has been researched [4-8]. These converters have an auxiliary circuit, connected in parallel with the main switch, to help it turn-on under the zero voltage switching (ZVS) condition and a snubber capacitor to help the switch turn-off under the ZVS condition. The auxiliary circuit

operates for only a small portion of the switching cycle and it is activated just before the main switch turn on. As a result, the system operates as a conventional PWM converter while reducing switching losses.

Although these converters have the advantage of improved efficiency, by applying the ZVS or zero current switching (ZCS) technique, they require additional switches and have the added complexity of a control circuit. Consequently, it could be difficult for these methods to be adopted by industry due to the cost of the additional switches and the complex control circuit.

A single switch resonant converter has been reported as a possible solution to this problem [9]. However, this topology exhibits high voltage stress while the switch is turned-off. This stress decreases efficiency and introduces EMI.

A soft switching boost converter is proposed, which is constructed based on the  $LC$  elements and the passive clamping diode, without additional active switches. Due to the soft switching technique for a single switch, this

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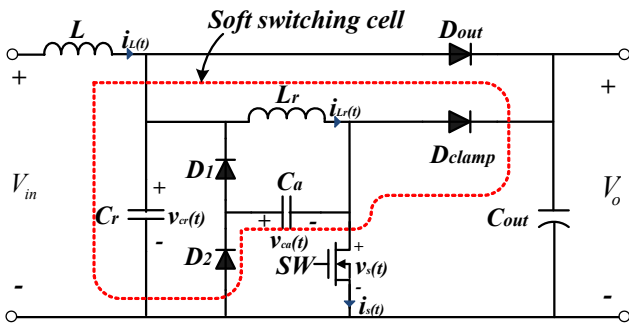


Fig. 1. Proposed soft switching boost converter.

proposed topology raises efficiency and minimizes switching losses, while the high voltage switching stress is reduced and the efficiency of the system is improved. In this paper the operational principles are explained through a mathematical analysis of the operation characteristics and a detailed design is also provided. The validity of the proposed design for a 1.5[kW], 30[kHz] soft-switching boost converter prototype is demonstrated through simulations and experiments.

## 2. Proposed Soft Switching Boost Converter

The circuit diagram of a boost converter employing a soft switching cell is shown in Fig. 1. The soft switching cell consists of one inductor, two capacitors and three diodes, and it is added to a conventional boost converter circuit. On/off control is achieved with one switch, and the switching loss can be reduced by switching at zero-current and zero-voltage, due to the resonances of  $L_r$ ,  $C_a$  and  $C_r$ .

The following assumptions were made to simplify the steady state analysis of the circuit, shown in Fig. 1, during one switching cycle.

1. All switching devices and passive elements are ideal.
2. The parasitic components of all switching devices and elements are ignored.
3. All equations are derived, assuming that the starting point of each mode is zero.

Eleven stages occurred during steady state operation of the proposed converter through one switching cycle. Key waveforms concerning the operation stages are shown in Fig. 2. The operation can be analyzed as 11 modes according to the operating conditions defined in the

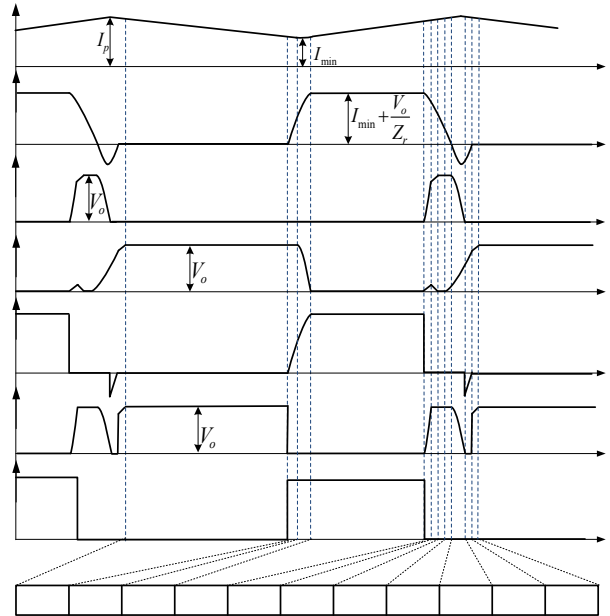


Fig. 2. Key waveforms of the proposed circuit.

following paragraphs.

**Mode 1 ( $t_0 \leq t < t_1$ ):** The switch is in the off state and dc input power is transmitted directly to the load through  $L$  and  $D_{out}$ . During this time, the main inductor voltage becomes  $-(V_o - V_{in})$ . Thus, the main inductor current decreases linearly.

$$i_L(t) = i_L(t_0) - \frac{V_o - V_{in}}{L} t \tag{1}$$

$$i_{Lr}(t) = 0, \quad v_{Cr}(t) = V_o, \quad v_{Ca}(t) = 0 \tag{2}$$

$$i_L(t_1) = I_1 \tag{3}$$

**Mode 2 ( $t_1 \leq t < t_2$ ):** If the switch turns on under the ZCS condition, mode 2 starts. In this case, as the output voltage is supplied to the resonant inductor  $L_r$  and the current increases linearly. If this current reaches the same level as the current of the main inductor  $L$ , the current of the output side diode  $D_{out}$  becomes zero.

$$i_L(t) = I_1 - \frac{V_o - V_{in}}{L} t \tag{4}$$

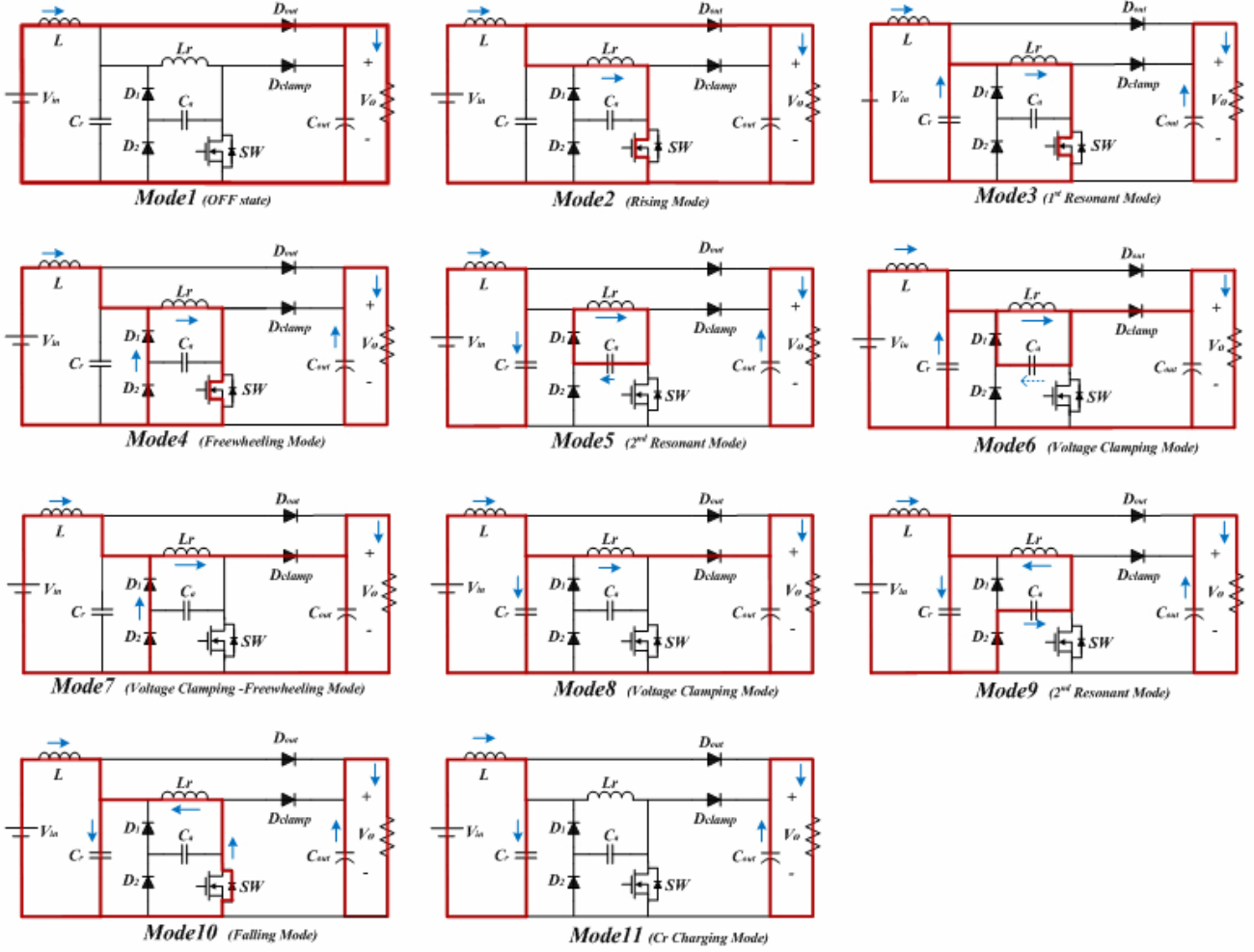


Fig. 3. Operational modes of the proposed converter.

$$i_{L_r}(t) = \frac{V_o}{L_r} t, \quad v_{C_r}(t) = V_o, \quad v_{C_a}(t) = 0 \quad (5)$$

$$i_L(t_2) \approx I_{\min}, \quad i_{L_r}(t_2) \approx I_{\min} \quad (6)$$

**Mode 3** ( $t_2 \leq t < t_3$ , 1<sup>st</sup> Resonant Mode): If the current of  $D_{out}$  becomes zero and turns off, the resonant mode starts. In this mode, the resonant inductor  $L_r$  and the capacitor  $C_r$  resonate and the voltage of  $C_r$  falls from the output voltage  $V_o$  to zero. In this case, the current of the main inductor  $L$  flows through  $L_r$  and the switch. The load is supplied with power continuously as the voltage at  $C_{out}$  discharges.

$$i_L(t) \approx I_{\min}, \quad v_{C_a}(t) = 0 \quad (7)$$

$$i_{L_r}(t) = I_{\min} + \frac{V_o}{Z_r} \sin \omega_r t \quad (8)$$

$$v_{C_r}(t) = V_o \cos \omega_r t \quad (9)$$

$$i_{L_r}(t_3) = I_2, \quad v_{C_r}(t_3) = 0 \quad (10)$$

where the characteristic impedance  $Z_r$  and the resonant angular frequency  $\omega_r$  are defined in Eq. (11).

$$\omega_r = 1/\sqrt{L_r C_r}, \quad Z_r = \sqrt{L_r / C_r} \quad (11)$$

**Mode 4** ( $t_3 \leq t < t_4$ , 1<sup>st</sup> Freewheeling Mode): If the resonant capacitor voltage becomes zero, the two auxiliary diodes  $D_1$  and  $D_2$  turn on, and the freewheeling mode starts. While in this mode, the resonant inductor current is

composed of two currents: the main inductor current and the current through the two auxiliary diodes. The main inductor current increases linearly.

$$i_L(t) = I_{\min} + \frac{V_{in}}{L}t \quad (12)$$

$$i_{Lr}(t) \approx I_2 \quad (13)$$

$$v_{Cr}(t) = 0, \quad v_{Ca}(t) = 0 \quad (14)$$

$$i_L(t_4) = I_3, \quad i_{Lr}(t_4) = I_2 \quad (15)$$

**Mode 5** ( $t_4 \leq t < t_5$ , 2<sup>nd</sup> Resonant Mode): At  $t_4$ , as a result of the PWM algorithm, the switch turns off at the zero voltage condition. At this time, there are two current loops. One is the  $L$ - $C_r$ - $V_{in}$  loop where the voltage of capacitor  $C_a$  increases linearly from zero to the output voltage  $V_o$ . The other is the  $L_r$ - $C_a$ - $D_1$  loop where the second resonance takes place. The energy stored in  $L_r$  moves to  $C_a$ .

$$i_L(t) = I_3 + \frac{V_{in}}{L}t \quad (16)$$

$$i_{Lr}(t) = I_2 \cos \omega_a t \quad (17)$$

$$v_{Ca}(t) = Z_a I_2 \sin \omega_a t \quad (18)$$

$$v_{Cr}(t) = \frac{I_3}{C_r}t \quad (19)$$

$$i_L(t_5) = I_4, \quad i_{Lr}(t_5) = I_5, \quad v_{Cr}(t_5) = V_1 \quad (20)$$

where the characteristic impedance  $Z_a$  and the resonant frequency  $\omega_a$  are defined in Eq. (21).

$$\omega_a = 1/\sqrt{L_r C_a}, \quad Z_a = \sqrt{L_r / C_a} \quad (21)$$

**Mode 6** ( $t_5 \leq t < t_6$ ): If the voltage of SW is equal to  $V_o$ ,  $D_{clamp}$  is turned on, the peak voltage across switch  $SW$  is clamped to  $V_o$ , and the  $L_r$  current flows into  $C_a$  and  $D_{clamp}$ . Since the current of  $C_a$  is very small, most of the  $L_r$  current flow into  $D_{clamp}$ . In this mode, the energy of inductor  $L_r$  is transferred to capacitor  $C_{out}$ .

$$i_L(t) = I_4 + \frac{V_{in}}{L}t \quad (22)$$

$$v_{Ca}(t) = (V_o - V_1) \cos \omega_p t + Z_p (t_5 - t_4) \sin \omega_p t \quad (23)$$

$$v_{Cr}(t) = V_o - (V_o - V_1) \cos \omega_p t - Z_p (t_5 - t_4) \sin \omega_p t \quad (24)$$

$$i_{Lr}(t) = I_4 + (I_5 - I_4) \cos \omega_p t - \frac{V_o - V_1}{Z_p} \sin \omega_p t \quad (25)$$

$$i_L(t_6) = I_6, \quad i_{Lr}(t_6) = I_7 \quad (26)$$

where  $\omega_p = 1/\sqrt{L_r C_p}$ ,  $Z_p = \sqrt{L_r / C_p}$ ,  $C_r + C_a = C_p$ .

**Mode 7** ( $t_6 \leq t < t_7$ ): The voltage of  $C_r$  is zero. The main inductor current  $i_L$  flows to  $C_{out}$  through  $L_r$ . Another current path is  $D_1$ - $D_2$ - $L_r$ - $D_{clamp}$ - $C_{out}$  and the current  $i_{Lr}$  is ( $i_L + i_{D1}$ ). This stage is described by Eqs. (27) ~ (30).

$$i_L(t) = I_6 + \frac{V_o - V_{in}}{L}t \quad (27)$$

$$i_{Lr}(t) = I_7 - \frac{V_o}{L_r}t \quad (28)$$

$$v_{Ca}(t) = V_o, \quad v_{Cr}(t) = 0 \quad (29)$$

$$i_L(t_7) = I_8, \quad i_{Lr}(t_7) = I_9 \quad (30)$$

**Mode 8** ( $t_7 \leq t < t_8$ ): If two inductor currents become equal, the main inductor current is divided between  $C_r$  and  $L_r$ . Until the current  $I_{Dclamp}$  becomes zero, the energy of  $L_r$  is transmitted to  $C_{out}$ . The state equations are as follows:

$$i_L(t) = I_8 + \frac{V_o - V_{in}}{L}t \quad (31)$$

$$v_{Cr}(t) = V_o - V_o \cos \omega_r t \quad (32)$$

$$v_{Ca}(t) = V_o \quad (33)$$

$$i_{Lr}(t) = I_9 - \frac{V_o}{Z_r} \sin \omega_r t \quad (34)$$

$$i_L(t_8) = I_p, \quad i_{Lr}(t_8) = 0, \quad v_{Cr}(t_8) = V_2 \quad (35)$$

**Mode 9** ( $t_8 \leq t < t_9$ ): In mode 9, the voltage of  $C_a$  decreases. It also continuously resonates the  $D_2$ - $C_a$ - $L_r$ - $C_r$

loop and the energy moves from  $C_a$  to  $L_r$ . If the voltage of  $C_a$  becomes zero, the current of  $L_r$  reverses from the current direction of mode 5. If the voltage of  $C_a$  becomes zero, the anti-parallel diode of the switch turns on and it turns over to the next mode. The state equations are:

$$i_L(t) = I_p \quad (36)$$

$$i_{L_r}(t) = \frac{C_s}{C_r} I_p (1 - \cos \omega_s t) - \frac{V_o - V_2}{Z_r} \sin \omega_s t \quad (37)$$

$$v_{C_r}(t) = V_2 + \frac{C_s}{C_r} (V_o - V_2) (1 - \cos \omega_s t) + \frac{I_p}{C_p} t + \frac{C_s I_p}{C_r^2 \omega_s} \sin \omega_s t \quad (38)$$

$$v_{C_a}(t) = V_o - \frac{C_s}{C_a} (V_o - V_2) (1 - \cos \omega_s t) + \frac{I_p}{C_p} t - \frac{I_p}{C_p \omega_s} \sin \omega_s t \quad (39)$$

$$v_{C_r}(t_9) = V_3, \quad i_{L_r}(t_9) = I_{10} \quad (40)$$

where  $C_s = C_r C_a / (C_r + C_a)$ ,  $Z_s = \sqrt{L_r / C_s}$ ,  $\omega_s = 1 / \sqrt{L_r C_s}$ .

**Mode 10 ( $t_9 \leq t < t_{10}$ ):** In mode 10, there are also two current loops. The current of the main inductor  $L$  charges  $C_r$  and decreases linearly. The current of the resonant inductor  $L_r$  transmits its energy to the capacitor  $C_r$  and flows through the anti-parallel diode of the switch. If the current of the inductor  $L_r$  becomes zero, mode 10 ends.

$$i_L(t) = I_p + \frac{V_3 - V_{in}}{L} t \quad (41)$$

$$i_{L_r}(t) = I_p - (I_p + I_{10}) \cos \omega_r t + \frac{V_3}{Z_r} \sin \omega_r t \quad (42)$$

$$v_{C_r}(t) = V_3 \cos \omega_r t + Z_r (I_p - I_{10}) \sin \omega_r t \quad (43)$$

$$v_{C_a}(t) = 0 \quad (44)$$

$$i_L(t_{10}) = I_{11}, \quad i_{L_r}(t_{10}) = 0, \quad v_{C_r}(t_{10}) = V_4 \quad (45)$$

**Mode 11 ( $t_{10} \leq t < t_{11}$ ):** If the voltage of  $C_r$  is less than the output voltage  $V_o$ , mode 11 occurs. Input or main

inductor current charges the capacitor  $C_r$ . In this mode, the voltage of  $C_r$  is the same as the voltage of the switch.

$$i_L(t) = I_p - \frac{V_4 - V_{in}}{L} t \quad (46)$$

$$i_{L_r}(t) = 0, \quad v_{C_a}(t) = 0 \quad (47)$$

$$v_{C_r}(t) = V_4 + \frac{I_{11}}{C_r} t \quad (48)$$

### 3. ZVS Condition and Design Procedures

#### 3.1 ZVS Condition

Fig. 4 shows the key waveforms of the soft-switching boost converter.

To satisfy the ZVS condition, the resonant inductor current must be larger than the main inductor current during the freewheeling interval of mode 4. The ZVS condition of the proposed converter is expressed by:

$$I_2 > I_p \quad (49)$$

where  $I_2 = I_{\min} + V_o / Z_r$ ,  $I_p = I_{\min} + \Delta I_L$ ,

$$\frac{V_o}{Z_r} > \Delta I_L \quad (50)$$

where  $\Delta I_L = I_L / 2.5$ .

In mode 5 ( $t_4 - t_5$ ), the ZVS area depending on  $L_r$  and  $C_a$  can be extended or reduced. As a result, Eq. (18) can be expressed by Eq. (51).

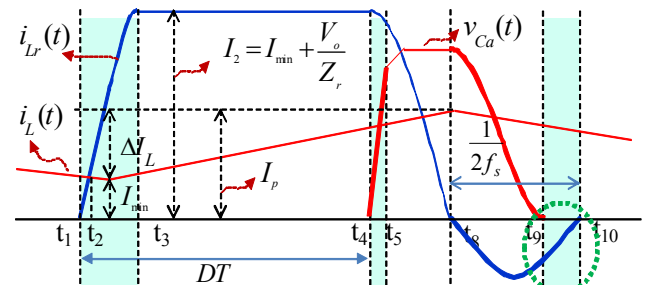


Fig. 4. Key waveforms of ZVS condition.

$$v_{Ca}(t) = \sqrt{\frac{L_r}{C_a}} I_2 \sin \frac{1}{\sqrt{L_r C_a}} t \quad (51)$$

To satisfy the ZVS condition in mode 10, the voltage of  $C_a$  must be less than zero at  $t_{10}$ , as shown in Eq. (52).

$$v_{Ca}(t_{10}) < 0 \quad (52)$$

Therefore, Eq. (39) can be expressed by Eq. (53).

$$V_o - 2 \frac{C_r // C_a}{C_a} (V_o - V_2) + \frac{I_p}{C_r + C_a} \pi \sqrt{L_r C_r // C_a} < 0 \quad (53)$$

where  $t = 1/2f_s = \pi \sqrt{L_r C_r // C_a}$ .

### 3.2 Selection of Resonant Elements ( $C_a$ , $C_r$ & $L_r$ )

When the switch turns off, it provides an alternative path for the main inductor current to reduce switching losses. Since the snubber capacitor incorporates the output capacitance of the switch, the exact capacitance value selected will be affected by the semiconductor devices employed. Usually, a snubber capacitor is selected that has a capacitance value that is more than ten times larger than the output capacitance  $C_{oss}$  of the switch. However, in this topology the capacitor  $C_a$  is charged by the resonant inductor current  $i_{Lr}$ . As a result, it can be more than twice the main inductor current  $i_L$  during switch turn off. Thus, the snubber capacitance value can be 20 times larger than the output capacitance of the switch, and the expression can be written as follows:

$$C_a > 20C_{oss} \quad (54)$$

The resonant inductor current in mode 3, is expressed in Eq. (8). The time duration of mode 3, which is the resonant time of the resonant inductor  $L_r$  and the resonant capacitor  $C_r$ , is defined as one-fourth of the resonant period. Usually, the rising time of the resonant inductor current  $i_{Lr}$  can be set to 10% of the minimum on time but we set it to 50%, because in this topology the capacitance of  $C_r$  should be greater than  $C_a$  to obtain the ZVS

condition. Therefore the following equation can be expressed:

$$t_3 - t_1 = \frac{L_r}{V_o} I_{\min} + \frac{T_r}{4} < 0.5 D_{\min} T \quad (55)$$

where  $T_r = 1/f_s = 2\pi\sqrt{L_r C_r}$ ,  $T = 1/f_{SW}$ ,  $D_{\min} = (V_o - V_{in_{\min}})/V_o$

Solving Eq. (55), the value of the resonant capacitor  $C_r$  can be found.

$$C_r > \frac{D_{\min}^2}{\pi^2 L_r f_{SW}^2} + \frac{I_{\min}^2 L_r}{\pi^2 V_o^2} - \frac{2I_{\min} D_{\min}}{\pi^2 V_o f_{SW}^2} \quad (56)$$

Since  $(2I_{\min} D_{\min})/(\pi^2 V_o f_{SW}^2) \approx 0$  in Eq. (56), this equation can be written as:

$$C_r > \frac{D_{\min}^2}{\pi^2 L_r f_{SW}^2} + \frac{I_{\min}^2 L_r}{\pi^2 V_o^2} \quad (57)$$

$$L_r = \{V_o / (I_2 - I_{\min})\}^2 C_r \quad (58)$$

where  $I_2 - I_{\min} = V_o / Z_r = V_o \sqrt{C_r} / \sqrt{L_r}$

From Eq. (57) and (58),  $C_r$  can be defined as:

$$C_r > \frac{D_{\min}(I_2 - I_{\min})}{\pi^2 V_o f_{SW}^2} / \sqrt{1 - I_{\min}^2 / \pi^2 (I_2 - I_{\min})^2} \quad (59)$$

From Eq. (58), the resonant inductor value is expressed as:

$$L_r < \left\{ (2 \times 0.85 \frac{C_s}{C_a} - 1) V_o / \left( \frac{I_p}{C_r + C_a} \pi \sqrt{C_s} \right) \right\}^2 \quad (60)$$

where  $C_s = C_r C_a / (C_r + C_a)$ ,  $V_o - V_2 \approx 0.85 V_o$ .

### 3.3 Design Procedures and Examples

Based on the derived equations, the design procedure

for the proposed converter is summarized in this section. Table 1 shows the principal design parameters of the proposed boost converter. The design guidelines are presented to aid in the choice of resonant components to ensure appropriate operation of the resonance converter.

Table 1. Design parameters.

Parameter	Symbol	Value	Unit
Input voltage	$V_{in}$	200~350	Vdc
Output voltage	$V_o$	400	Vdc
Input power	$P_{in}$	1.6	kW
Output power	$P_o$	1.5	kW
Efficiency	$\eta$	95	%
Switch output capacitance	$C_{oss}$	320	pF
Switching frequency	$f_{sw}$	30	kHz

According to Table 1, the main inductor average and ripple current values are as follows:

$$I_L = \frac{P_{in}}{V_{in\_min}} = \frac{1,600}{200} = 8 \text{ A} \quad (61)$$

$$\Delta I_L = \frac{I_L}{2.5} = \frac{8}{2.5} = 3.2 \text{ A} \quad (62)$$

The maximum and minimum main inductor currents ( $I_p$  and  $I_{min}$ ) are:

$$I_p = I_L + \frac{\Delta I_L}{2} = 8 + \frac{3.2}{2} = 9.6 \text{ A} \quad (63)$$

$$I_{min} = I_L - \frac{\Delta I_L}{2} = 8 - \frac{3.2}{2} = 6.4 \text{ A} \quad (64)$$

The duty ratio  $D$  and turn on time  $T_{on}$  of the switch are:

$$D_{max} = \frac{V_o - V_{in\_min}}{V_o} = \frac{400 - 200}{400} = 0.5 \quad (65)$$

$$D_{min} = \frac{V_o - V_{in\_max}}{V_o} = \frac{400 - 350}{400} = 0.125 \quad (66)$$

$$T_{on} = D_{max} T = \frac{D_{max}}{f_{sw}} = \frac{0.5}{30 \times 10^3} = 16.667 \times 10^{-6} \text{ s} \quad (67)$$

Therefore, we can find the main inductance  $L$  as follows:

$$L = \frac{V_{in\_min} T_{on}}{\Delta I_L} = \frac{200 \times 16.667 \times 10^{-6}}{3.2} = 1.042 \text{ mH} \quad (68)$$

From Eq. (54), we can calculate the range of the auxiliary resonant capacitor  $C_a$  as:

$$C_a > 20 \cdot C_{oss} = 20 \times 320 \times 10^{-12} = 6.4 \text{ nF} \approx 10 \text{ nF} \quad (69)$$

To find  $C_r$ , we must select a value of  $I_2$  which is less than the rating current of the switch. In this case,  $I_2 = 23 \text{ [A]}$ . From Eq. (59), we can also find the range of the resonant capacitor  $C_r$  as follows:

$$C_r > \frac{D_{min}(I_2 - I_{min})}{\pi \cdot V_o \cdot f_{sw}} / \sqrt{1 - I_{min}^2 / \pi^2 (I_2 - I_{min})^2} \quad (70)$$

$$= \frac{0.125(23 - 6.4)}{400\pi \times 30 \times 10^3 \times 0.9778} = 56 \text{ nF} \approx 100 \text{ nF}$$

From Eq. (60) and (70), the range of values that can be used for the resonant inductor  $L_r$  is:

$$L_r < \left\{ (2 \times 0.85 \frac{C_s}{C_a} - 1) V_o / \left( \frac{I_p}{C_r + C_a} \pi \sqrt{C_s} \right) \right\}^2$$

$$= \left\{ (1.7 \times \frac{9}{10} - 1) 400 / \left( \frac{9.6}{110 \times \sqrt{10^{-9}}} \times 3\pi \right) \right\}^2 \quad (71)$$

$$= 69 \mu\text{H} \approx 50.6 \mu\text{H}$$

where  $C_s = C_r C_a / (C_r + C_a) = 100 \times 10 / (100 + 10) \approx 9 \text{ nF}$

### 4. Simulation Results

We simulated the proposed soft-switching boost converter using PSIM Ver. 6.0 software. To verify the operation of the proposed topology, a simulation model based on a 1.5kW boost converter was used. The simulation parameters are shown in Table 2.

Table 2. Simulation parameters.

Parameter	Symbol	Value	Unit
Input voltage	$V_{in}$	200~350	Vdc
Output voltage	$V_o$	400	Vdc
Output power	$P_o$	1.5	kW
Main inductor	$L$	1,000	$\mu\text{H}$
Resonant inductor	$L_r$	50.6	$\mu\text{H}$
Resonant capacitor	$C_r$	100	nF
Auxiliary capacitor	$C_a$	10	nF
Input capacitor	$C_{in}$	900	$\mu\text{F}$
Output capacitor	$C_{out}$	750	$\mu\text{F}$
Switching frequency	$f_{sw}$	30	kHz

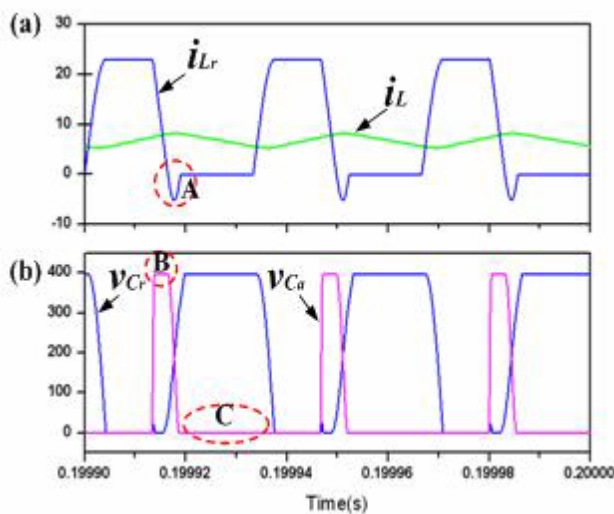


Fig. 5. Waveforms of  $i_L$ ,  $i_{Lr}$ ,  $v_{ca}$  and  $v_{cr}$  in the proposed topology.

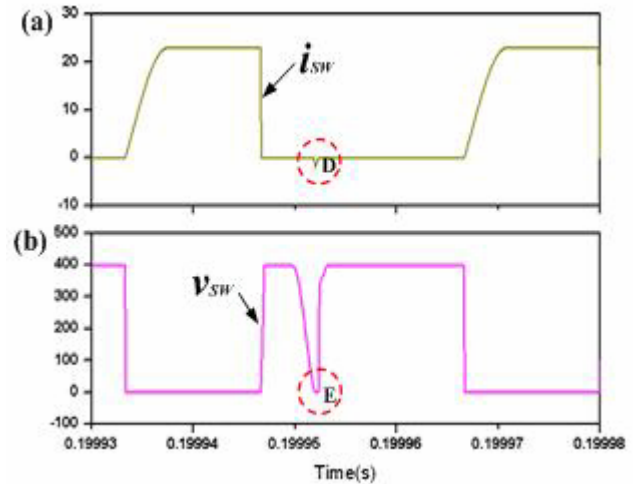


Fig. 6. The current and voltage waveforms of the switching device.

In Fig. 5(a), the current through the main inductor  $L$  increased and decreased linearly according to the on-off state of the switch. The resonant inductor also accumulated and released energy according to the state of the switch.

While the main switch is turned on, the main inductor accumulates energy. When the switch is turned off, this energy is transferred to the output. The current through  $L_r$  is more than twice the main inductor current, and it should drop below zero in area A. Fig. 5(b) shows the voltage waveforms of  $C_a$  and  $C_r$ . Due to the clamping diode  $D_{clamp}$ , area B shows the clamped voltage, where the voltage across the auxiliary capacitor  $C_a$  is clamped at  $V_o$ . In Fig. 5(b) the voltage of  $C_a$  drops down to zero in area C. Therefore ZVS on for the switch  $SW$  can be achieved.

Fig. 6 shows the waveforms of the switch current and voltage. Due to the anti-parallel diode of the switch, the current of the switch is reversed in area D. The voltage waveform of the switch should be similar to the shape of E. To satisfy the ZVS condition in Fig. 6(b), the voltage should drop to zero in area E.

### 5. Experimental Results

A prototype of a 1.5kW 30Hz boost converter was built to verify the operation principle and the theoretical analysis. This converter was regulated at 200Vdc ~ 350Vdc input and 400Vdc output. A CoolMOS



(IPW60R045CP) was used as the switching device. The key components used in the prototype and the operating conditions used for the test are shown in Table 2 and Table 3.

Table 3. Parameters of switch and diode.

Switch Part Number	$I_D$ (25°C)	$I_D$ (100°C)	$V_{DS}$	$R_{ds(on)}$ (max)
IPW60R045CP (CoolMOS)	25A	60A	600V	0.045Ω
Diode Part Number	$I_F$ (95°C)	$V_F$ (MAX)	$V_{RRM}$ (MAX)	$t_{rr}$ (1A,100A/μs)
80EPF06 (fast soft recovery)	80A	1.25V	600V	70ns

The key experimental waveforms of the proposed boost converter are shown in Fig. 7~10.

Fig. 7 shows the main and resonant inductor currents at full load. The waveforms obtained from the prototype are very close to those shown in Fig. 5(a).

Compared with the simulation result in Fig. 5(b), there is a charging voltage of  $C_a$  shown in area F of Fig. 8. The difference was caused by the output capacitance of the switch (IPW60R045CP).

Fig. 9 shows the waveforms of the main switch current and voltage. ZCS/ZVS operation and voltage clamping are demonstrated. The ZCS waveforms of the switch at turn on are shown in Fig. 10. It is clear that turn-on switching takes place under the ZCS condition, if we compare this with Fig. 11 which shows the waveforms of voltage and current in a conventional hard switching boost converter under the same operating conditions.

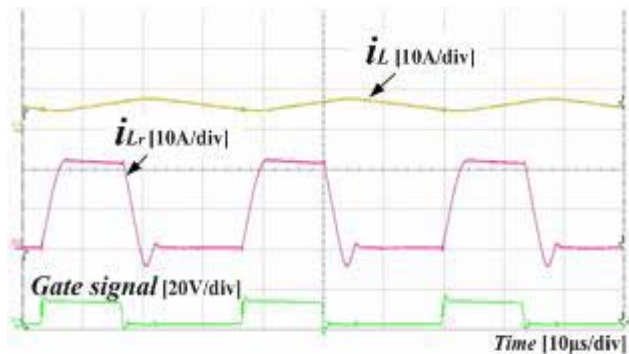


Fig. 7. Experimental result of current waveforms of  $L$ ,  $L_r$  and gate signal.

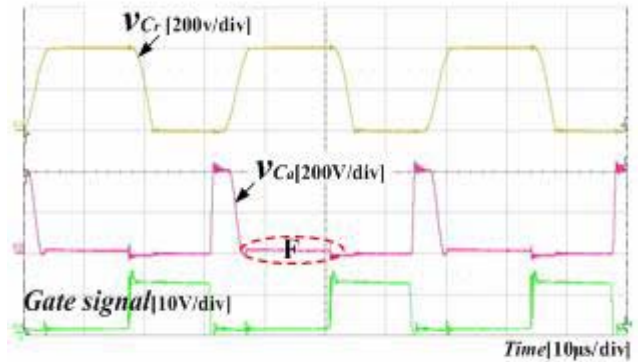


Fig. 8. Experimental result of voltage waveforms of  $C_r$ ,  $C_a$  and gate signal.

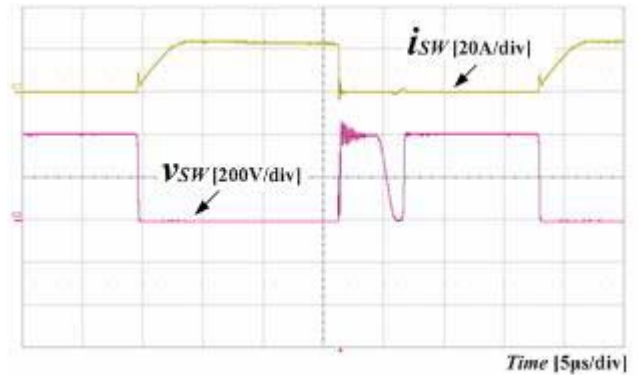


Fig. 9. Experimental waveforms of the current and voltage of switching device.

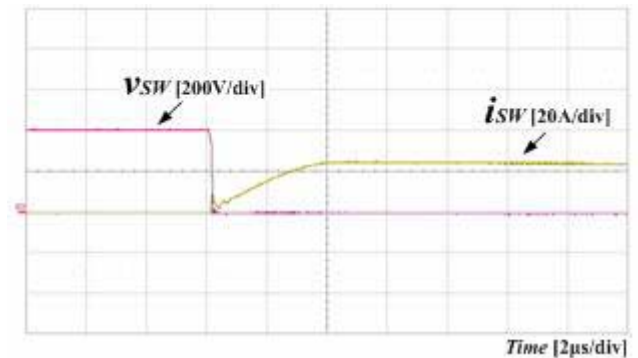


Fig. 10. Zero current switching waveforms.

Fig. 12 shows the efficiency of the proposed converter with duty and load variation. The measured maximum efficiency reached 97% under the full load condition.

Fig. 13 shows the efficiency of the conventional hard switching boost converter topology with duty and load variation. The measured maximum efficiency reached 95% under the full load condition.

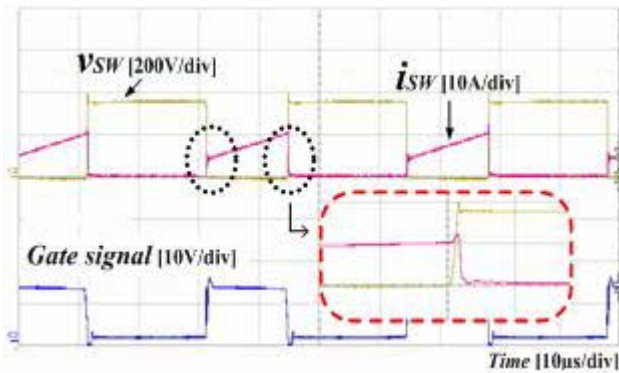


Fig. 11. Experimental result of voltage and current waveforms for conventional hard switching boost converter.

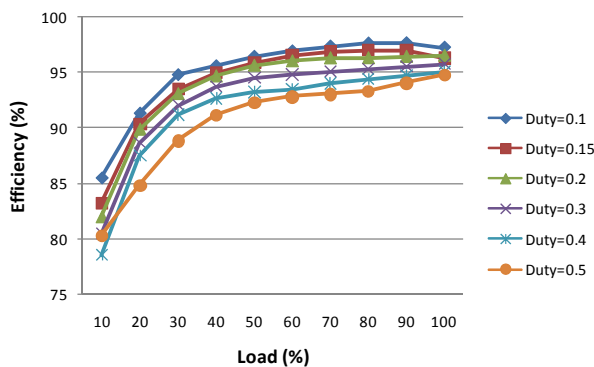


Fig. 12. The efficiency of the proposed boost converter topology.

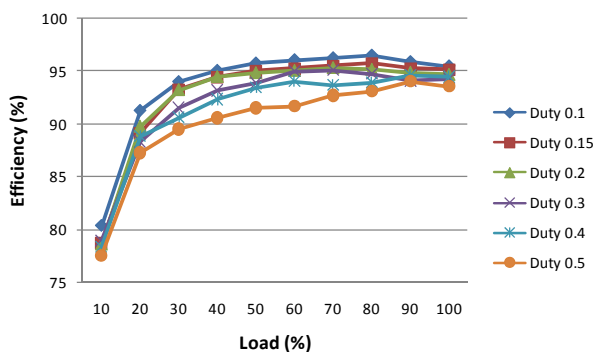


Fig. 13. The efficiency of the conventional (hard switching) boost converter topology.

## 6. Conclusions

This paper presents a soft-switching boost converter using resonance. It was constructed based on the proposed soft-switching cell designed using the  $LC$  resonance and

passive clamping technique, without additional active switches. The proposed topology increases efficiency and reduces switching loss and high voltage stress. By analyzing the operation of this converter, the principles of this topology were proven. Using the soft-switching technique, the efficiency of the system is higher than 95% under the full load condition. The circuit composition and operational principles were explained through a mathematical analysis of each mode, and a detailed description of the proposed boost converter was provided. This paper analyzed the operational characteristics of the topology and presented detailed design procedures. The validity of the proposed design was demonstrated by building a 1.5[kW], 30[kHz] soft-switching boost converter prototype regulated at 200[V] dc input and 400[V] dc output and experimentally verifying the analysis.

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