

## Experimental Waveforms of Single-Pulse Soft-Switching PFC Converter

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### Abstract

A new driving circuit for the SPSS (Single-Pulse Soft-Switching) PFC converter is proposed. The switching device of a SPSS converter switches once in every half cycle of an AC commercial power source. Therefore, it can be solved many problems caused by the high frequency operation. The proposed SPSS converter achieves the soft-switching operation and the EMI noise can be reduced. The resonant capacitor voltage supplies to the resonant inductor even if the input AC voltage is the vicinity of zero cross voltage. Then, the power factor and input current waveform can be improved without delay time. A new driving circuit achieves the operation of SPSS converter by one switching drive circuit. The proposed converter can be satisfied the IEC standard sufficiently.

### 1. Introduction

Since requirement of harmonic standards such as IEC (International Electrotechnical Commission) has been effective, PFC (Power Factor Correction) techniques have been increased attention. In most cases, PFC converters are constructed by a diode rectifier and a boost chopper[1][2]. The boost converter requires the high voltage circuit devices because the output voltage level must be stepped up beyond the input voltage peak value.

To reduce the converter price and the switching losses, the SPS (Simple Partial Switching) method has been proposed for a single-phase PFC converter[3][4]. The SPS method is applied to a boost converter as shown in Fig.I. The switching device  $T_r$  of a boost converter controlled by the SPS method switches once in every half cycle of an AC commercial power source. Therefore, it can be solved many problems caused by the high frequency operation. In the SPS method, it is impossible to control an

input current in the vicinity of zero cross source voltage. The switching device  $T_r$  of SPS converter is switched on past after the delay time  $T_d$ , which is measured from the zero cross point of the input AC voltage, and it keeps on state during the period  $T_{on}$ . By adjusting  $T_d$  and  $T_{on}$  by the switch  $T_r$ , the power factor of the converter can be improved and the third harmonic included in the input current waveform can be reduced.

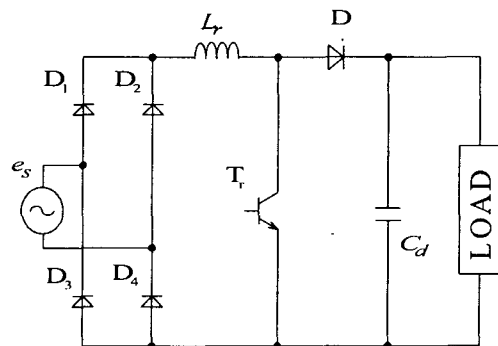


Fig.I Simple partial switching converter.

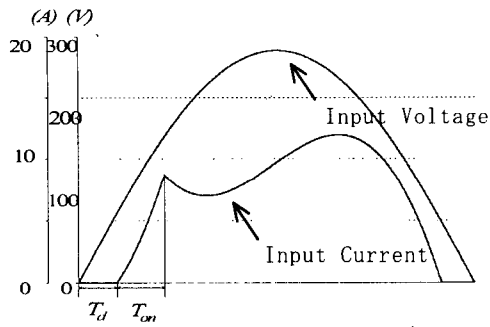


Fig.II Waveforms of input voltage and input current of simple partial switching converter.

## 2. Single-Pulse Soft-Switching PFC Converter

We have proposed a SPSS (Single-Pulse Soft-Switching) PFC converter as shown in Fig.III[5][6]. A soft-switching circuit consists of a series connected switch-diode pair ( $T_{r1} - D_{r2}, D_{r1} - T_{r2}$ ) with resonant capacitor  $C_r$ . To achieve soft-switching operation, SPSS converter shown in Fig.III is replaced a switch of SPS converter shown in Fig.I with the soft-switching circuit. The switching devices ( $T_{r1}$  and  $T_{r2}$ ) of a SPSS converter also switches once in every half cycle of an AC commercial power source. When the switching devices,  $T_{r1}$  and  $T_{r2}$ , are turned off simultaneously, the inductor current charges the capacitor  $C_r$  in the soft-switching circuit. Then, turn-off of  $T_{r1}$  and  $T_{r2}$  is the ZVS (Zero Voltage Switching). Since the input current of the SPSS-PFC converter always begin at zero, turn-on of  $T_{r1}$  and  $T_{r2}$  is the ZCS (Zero Current Switching). Therefore, the proposed SPSS converter achieves the soft-switching operation (ZCS at turn-on and ZVS at turn-off) and the EMI noise can be reduced.

A charged voltage of resonant capacitor  $C_r$  at the end of switching operation is equal to a DC output voltage  $E_d$ . When the switching devices,  $T_{r1}$  and  $T_{r2}$ , are turned on simultaneously, the resonant capacitor voltage  $E_d$  supplies to the resonant inductor  $L_r$  even if the input AC voltage is the vicinity of zero cross voltage. Therefore, the power factor and input current waveform can be improved without delay time  $T_d$ . Fig.IV

shows the waveforms of input voltage and current of the proposed SPSS-PFC converter.

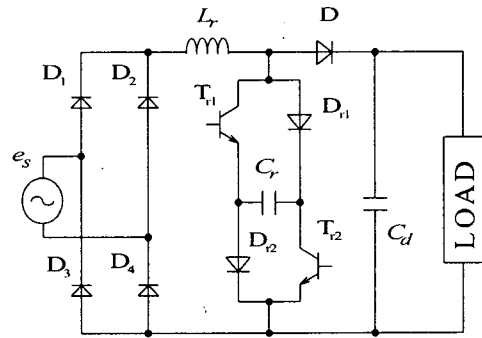


Fig.III Single-Pulse Soft-Switching PFC converter.

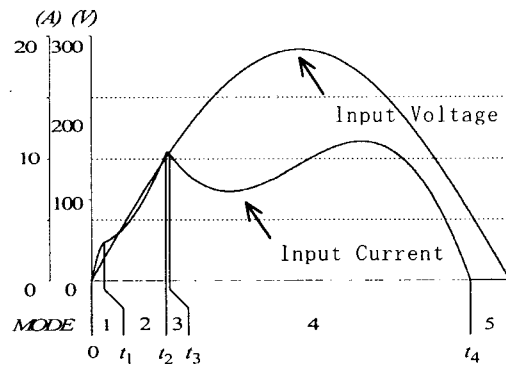


Fig.IV Waveforms of input voltage and input current of SPSS PFC converter.

## 3. Operational modes

Fig.IV shows the input voltage and current waveforms of the proposed converter. The operational modes of SPSS-PFC converter are illustrated in Fig.V. The circuit operation can be divided into five operational modes as follows.

A source voltage is

$$e_s = E_s \sin \omega_s t \quad (1)$$

and initially an input current of the converter is zero. A current of resonant inductor  $L_r$  and a voltage of resonant capacitor  $C_r$  is keeping with following conditions.

$$i_{L_r}(t) = 0 \quad e_{C_r}(t) = E_d \quad (2)$$

### Mode 1 ( $t = 0 \sim t_1$ )

At  $\omega_s t = 0$  the switching devices,  $T_{r1}$  and  $T_{r2}$  are turned on simultaneously, the resonant capacitor voltage  $E_d$  supplies to the resonant

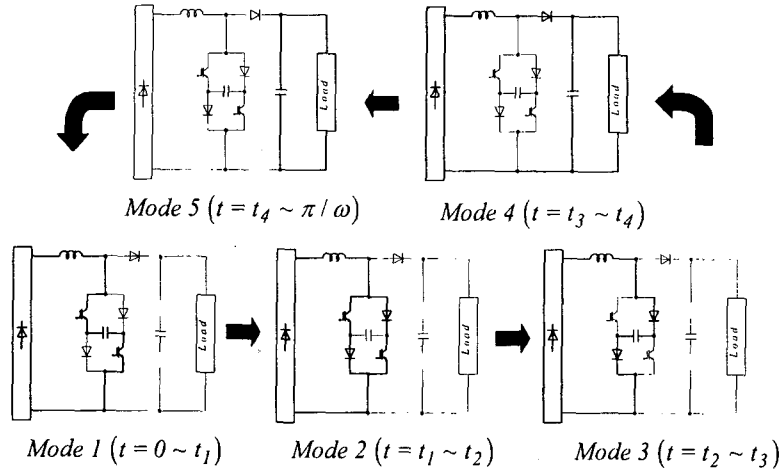


Fig.V The operational modes of SPSS-PFC converter

inductor  $L_r$ , even if the input AC voltage is the vicinity of zero cross voltage. The inductor current,  $i_{L_r}$ , which is equal to the input current,  $i_{s1}$ , is given by

$$i_r = I_A (\cos \omega_s t - \cos m \omega_s t) + I_B \sin m \omega_s t \quad (3)$$

where  $m = \frac{\omega_r}{\omega_s}$ ,  $I_A = \frac{m^2 C_r E_s \omega_s}{m^2 - 1}$ ,  $I_B = \frac{E_d}{X_r}$

$$\omega_r = \frac{1}{\sqrt{L_r C_r}}, \quad X_r = \sqrt{\frac{L_r}{C_r}}$$

The voltage of resonant capacitor  $C_r$  is

$$\begin{aligned} e_{C_r} &= e_r - L_r \frac{di_r}{dt} \\ &= E_s \sin \omega_s t - L_r \left\{ C_r E_d \omega_r^2 \cos \omega_r t \right. \\ &\quad \left. + \frac{\omega_r^2 \omega_s}{\omega_s^2 - \omega_r^2} C_r E_s (\omega_s \sin \omega_s t - \omega_r \sin \omega_r t) \right\} \quad (4) \end{aligned}$$

The capacitor voltage  $e_{C_r}$ , is decreased resonantly until becomes zero. Then this mode is completed and the final time  $t_1$  of this mode can be obtained from the condition of  $e_{C_r}(t_1) = 0$  as a solution of

$$m^2 \sin \theta_1 - m \sin m \theta_1 = \alpha (m^2 - 1) \cos m \theta_1 \quad (5)$$

where  $\theta_1 = \omega_s t_1$ ,  $\alpha = \frac{E_d}{E_s}$

An inductor current,  $I_{r1}$ , at the end of this mode is

$$I_{r1} = I_A (\cos \theta_1 - \cos m \theta_1) + I_B \sin m \theta_1 \quad (6)$$

### Mode 2 ( $t = t_1 \sim t_2$ )

The capacitor voltage  $e_{C_r}$  is zero, and then inductor current  $I_{L_r}$  flows through the  $T_{r1}$ - $D_{r2}$

and  $T_{r2}$ - $D_{r1}$ . The source voltage applies to the resonant inductor  $L_r$ , and increases a current of  $L_r$ . The inductor current  $I_{L_r}$  of this mode is expressed by

$$i_r = I_C (\cos \theta_1 - \cos \theta) + I_{r1} \quad (7)$$

where  $I_C = \frac{E_s}{L_r \omega_s}$

At the time  $t_2$ , the switches,  $T_{r1}$  and  $T_{r2}$ , are turned off with zero voltage switching. The duration  $T_2 = t_0 \sim t_1$  is on interval of the switches  $T_{r1}$  and  $T_{r2}$ . An input current,  $I_{r1}$ , at the time  $t_2$  is given by

$$I_{r2} = I_C (\cos \theta_1 - \cos \theta_2) + I_{r1} \quad (8)$$

where  $\theta_2 = \omega_s t_2$

### Mode 3 ( $t = t_2 \sim t_3$ )

After turned off of the switches,  $T_{r1}$  and  $T_{r2}$ , the  $L_r - C_r$  resonant circuit starts to resonate as follows:

$$\begin{aligned} i_r &= I_{r2} \cos m(\theta - \theta_2) \\ &\quad + I_A \left[ \sin \theta_2 \left\{ m \sin m(\theta - \theta_2) - \sin(\theta - \theta_2) \right\} \right. \\ &\quad \left. - \cos \theta_2 \left\{ \cos m(\theta - \theta_2) - \cos(\theta - \theta_2) \right\} \right] \quad (9) \end{aligned}$$

$$\begin{aligned} e_{C_r} &= X_r I_{r2} \sin m \theta + E_s \cos \theta_2 \left\{ \frac{m \omega_s^2}{(1 - m^2) \omega_s^2} \right\} \sin m \theta \\ &\quad + E_s \cos \theta_2 \left\{ -\frac{m^2 \omega_s^2}{(1 - m^2) \omega_s^2} \right\} \sin \theta \quad (10) \end{aligned}$$

The capacitor voltage  $e_{C_r}$  is increased resonantly until  $e_{C_r}$  becomes  $E_d$ . Then this mode is completed and the time  $t_3$  at the end of

this mode can be obtained from the condition of

$$e_{C_r} = E_d \text{ as a solution of}$$

$$E_d = X_r I_{r2} \sin m\theta_3$$

$$+ E_s \frac{m}{(1-m^2)} \left\{ \cos \theta_2 \left( \frac{1}{m} \sin m\theta_3 - \sin \theta_3 \right) + \sin \theta_2 (\cos m\theta_3 - \cos \theta_3) \right\} \quad (11)$$

An input current  $I_{r3}$  at the end of this mode is

$$I_{r3} = I_{r2} \cos m(\theta_3 - \theta_2)$$

$$+ A \left[ \sin \theta_2 \{ m \sin m(\theta_3 - \theta_2) - \sin(\theta_3 - \theta_2) \} - \cos \theta_2 \{ \cos m(\theta_3 - \theta_2) - \cos(\theta_3 - \theta_2) \} \right] \quad (12)$$

where  $\theta_3 = \omega_s t_3$

**Mode 4** ( $t = t_3 \sim t_4$ )

After the resonant capacitor voltage  $e_{C_r}$  reaches to DC output voltage  $E_d$ , the inductor current  $i_{L_r}$  flows through the diode  $D$ . A difference voltage DC output voltage and the source voltage applies to the inductor  $L_r$ . The inductor current  $i_{L_r}$  is given by

$$i_{L_r} = I_C (\cos \theta_3 - \cos \theta) + I_D (\theta_3 - \theta) + I_{r3} \quad (13)$$

where  $I_D = \frac{E_d}{L_r \omega_s}$

The time  $t_4$  at the end of this mode can be obtained from the condition of  $i_{L_r}(t_4) = 0$ . Therefore, the time  $t_4$  is a solution of

$$I_C (\cos \theta_3 - \cos \theta_4) + I_D (\theta_3 - \theta_4) + I_{r3} = 0 \quad (14)$$

where  $\theta_4 = \omega_s t_4$

**Mode 5** ( $t = t_4 \sim \pi / \omega_s$ )

A current of resonant induct  $L_r$  and a voltage of resonant capacitor  $C_r$  keep the conditions  $i_{L_r}(t) = 0$  and  $e_{C_r}(t) = E_d$  until a time  $\pi / \omega_s$ .

At a time  $\pi / \omega_s$ , the switching devices,  $T_{r1}$  and  $T_{r2}$ , are turned on simultaneously, and another operational modes are started.

An amplitude of the input current at start portion can be controlled by the value of resonant capacitor  $C_r$ . Therefore, the value of resonant capacitor can be use for an improvement of the input current waveform.

#### 4. Proposed new driving circuit

The SPSS-PFC converter requires two level drive circuits for switches  $T_{r1}$  and  $T_{r2}$ . Each

drive circuit must be insulated. To achieve switching operation of  $T_{r1}$ , we propose a new drive circuit shown in Fig.VI. Switching power for  $T_{r1}$  is provided from capacitor  $C_r$ . At the end of the operational mode, capacitor  $C_r$  is always charged up to output DC voltage  $E_d$ . Therefore, the voltage  $E_d$  is applied to  $R_1$  and  $R_2$  at a moment of turned on of  $T_{r2}$ .  $T_{r1}$  turns on by across voltage of  $R_2$ . Stored energy of  $C_r$  is charged the capacitor  $C_{er}$ . After capacitor voltage  $V_{C_r}$  decreases, the capacitor  $C_{er}$  provides an energy to continue turn on of  $T_{r1}$ . Turn on of  $T_{r1}$  must be continued until voltage of capacitor,  $C_r$ , is equal to zero. After turn off of  $T_{r1}$ , the soft-switching circuit is continue a turn on by  $T_{r2}$ . Voltage and current waveforms of each parts of the proposed soft-switching converter are shown in Fig.VII.

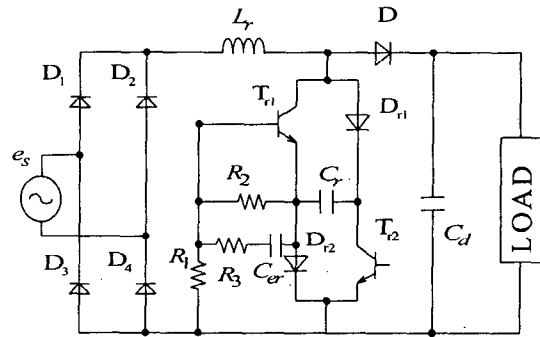


Fig. VI Proposed driving circuit for SPSS-PFC converter.

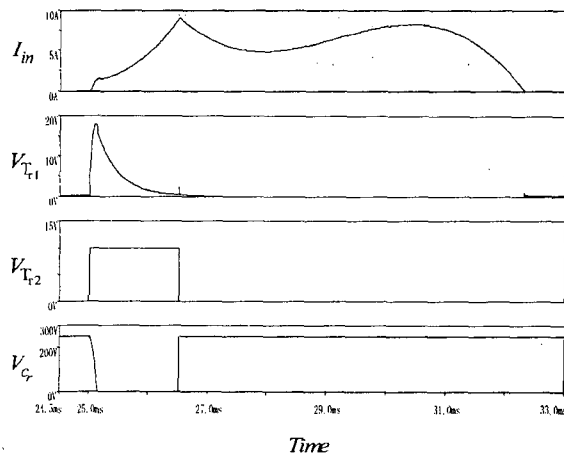


Fig. VII Voltage and current waveforms in each parts of SPSS-PFC converter.

## 5. An analysis of proposed drive circuit

Equivalent circuit for proposed drive circuit is shown in Fig.VIII. Voltage waveforms of  $C_r$  and  $C_{er}$  of the proposed soft-switching converter is shown in Fig.IX. In initial condition, voltages of resonant capacitor  $C_r$  and assist capacitor  $C_{er}$  are kept as follows.

$$e_{C_r}(t) = E_d, e_{C_{er}}(t) = 0 \quad (15)$$

### Mode 1 ( $t = 0 \sim t_1$ )

The voltage  $E_d$  is applied to  $R_1$  and  $R_3$  at a moment of turned on of  $T_{r2}$ .

$$V_{T_{r1}}(0) \cong \frac{R_{23}}{R_1 + R_{23}} E_d \quad (16)$$

where  $R_{23} = \frac{R_2 R_3}{R_2 + R_3}$

$T_{r1}$  turn on by voltage of  $R_2$ . Stored energy of  $C_r$  is charged the capacitor  $C_{er}$ . The voltage of  $C_r$  is given by (4). The maximum voltage of  $V_{C_{er}}$  is given by

$$V_{T_{r1}} \approx V_{C_{er}} \approx \frac{R_2 + R_3}{R_1 + R_2} V_{C_r}(t) \quad (17)$$

where  $R_2 \gg R_3$

After voltage of  $T_{r1}$  becomes maximum voltage, the capacitor voltage  $V_{C_{er}}$  is decreased. The voltage of capacitor  $C_r$  becomes to zero.

### Mode 2 ( $t = t_1 \sim t_2$ )

After voltage of capacitor  $C_r$  is equal to zero, the current flows only resistance  $R_2$ .

$$V_{T_{r1}} \approx E_d \varepsilon^{-\frac{1}{(R_2 + R_3)C_{er}} t} \quad (18)$$

The capacitor  $C_{er}$  provides an energy to continue turn on of  $T_{r1}$ . When the across voltage of  $R_2$  is smaller than turn on voltage of  $T_{r1}$ ,  $T_{r1}$  is turned off. After turn off of  $T_{r1}$ , the soft-switching circuit is continue a turn on by  $T_{r2}$ .

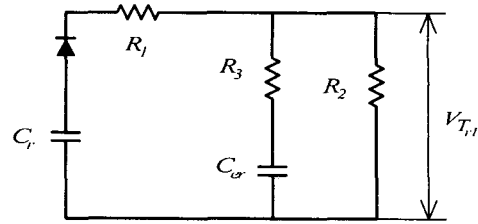


Fig.VIII Equivalent circuit for proposed drive circuit

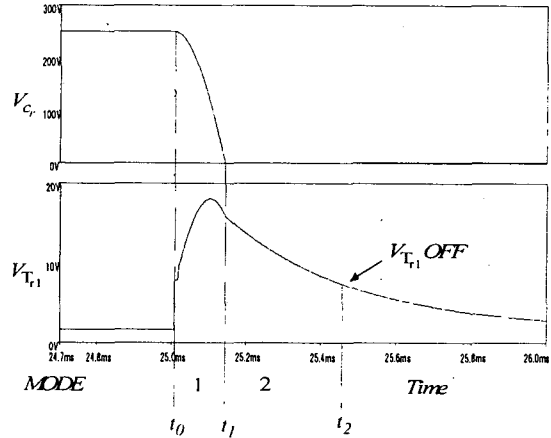


Fig.IX Voltage waveforms of  $C_r$  and  $C_{er}$  of the proposed soft-switching converter

## 6. Characteristics of SPSS-PFS converter

The frequency spectrum of input current waveform is shown in Fig.X. A broken line indicates the IEC Class A standard. It can be confirmed that the frequency spectrum of input current waveform satisfies the IEC Class A standard.

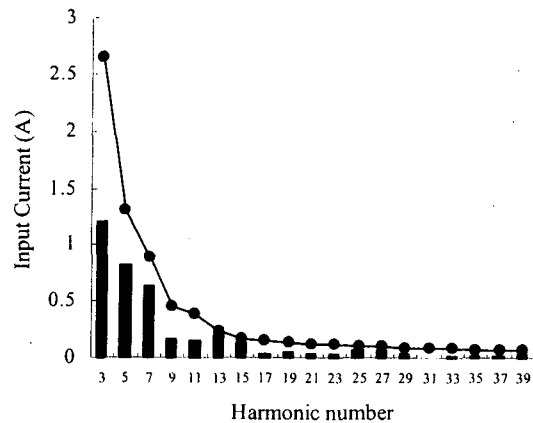


Fig.X Frequency spectrum of input current waveform

## 7. Experimental result

The experimental results are shown as follows. IGBT (100A,1200V) is used for two main switches. Table.I indicates the principal circuit parameters for the testing circuit. Voltage and current waveforms of each parts of the proposed soft-switching converter are shown in Fig.XI, and Fig.XII.

Table.I Principal circuit parameters

Source Voltage $E_s$	$200\sqrt{2}V$
Inductor $L_r$	20mH
Capacitor $C_r$	$0.47\mu F$
On interval $T_{ON}$	1.5ms
Resistance $R_1$	$2k\Omega$
$R_2$	$0.5k\Omega$
$R_3$	$76\Omega$
Capacitor $C_{er}$	$0.47\mu F$

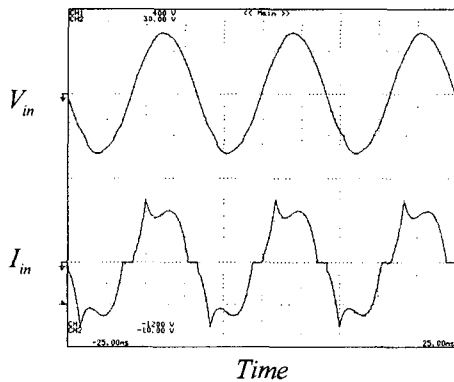


Fig.XI Input voltage and current waveforms.

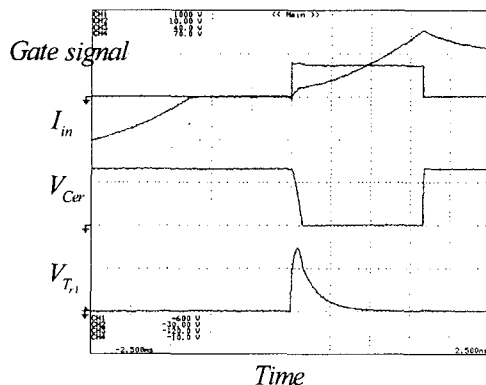


Fig.XII Voltage and current waveforms of each parts: gate signal, input current,  $V_{C_{er}}$ ,  $V_{Tc1}$ .

## 8. Conclusion

A single-pulse Soft-switching (SPSS) PFC converter with a new driving circuit has been proposed. Switching devices of a SPSS-PFC converter are switched on simultaneously once in every half cycle of an AC commercial power source. Therefore, it can be solved many problems caused by the high frequency operation. The SPSS-PFC converter requires two level drive circuits for two main switches. In proposed drive circuit, the other switch can be switched on automatically without two level drive circuit. The proposed SPSS converter achieves the soft-switching operation and then EMI noise can be reduced. The resonant capacitor voltage supplies the resonant inductor even if the input AC voltage is the vicinity of zero cross voltage. Then, the power factor and input current waveform can be improved without delay time. The proposed converter can be satisfied the IEC standard sufficiently.

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