A Novel ZVT PWM Čuk Power-Factor Corrector

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Abstract—A novel zero-voltage-transition (ZVT) pulsewidth modulated (PWM) Čuk power-factor corrector (PFC) is proposed to achieve unity power factor under zero-voltage-switching (ZVS) operations. In the proposed ZVT PWM Čuk PFC, not only the power switch, but also the power diode, commutate under ZVS. The proposed topology has the shortest ZVT time and, thus, the shortest minimum duty cycle compared with other ZVT PWM topologies. The resonant inductor can be discharged regardless of the state of the main switch. Extremely short ZVT time and robust discharge of the resonant inductor make the proposed topology well qualified for variable-duty and high-switching-frequency applications. Analytical studies, design rules, and experimental waveforms of the ZVT PWM Čuk PFC are presented in detail.

Index Terms—Converters, pulsewidth modulation, switching circuits.

I. INTRODUCTION

The pulsewidth-modulated (PWM) technique has been widely used on dc–dc converters and power-factor correctors (PFC’s) in industrial applications. It is praised for the high-power capability and ease of control. To achieve higher power density and faster transient response, PWM converters should operate under higher switching frequency. However, as the switching frequency increases, so do the switching losses and EMI noises. High switching losses reduce the power-handling capability and serious EMI noises interfere with the control of PWM converters. Several kinds of soft-switching techniques, such as passive snubbers [1] and resonant converters [2], have been proposed in recent years to reduce switching losses and EMI noises. The zero-voltage-transition (ZVT) PWM techniques are the most commendable ones among them [3]–[8]. One auxiliary switch and other passive components are used to form a shunt resonant ZVT cell in a ZVT PWM converter. Switching losses and EMI noises are reduced because the ZVT cell works during switching transient to perform zero-voltage-switching (ZVS) or zero-current-switching (ZCS). Advantages of both the conventional PWM technique and the resonant technique are maintained in ZVT PWM converters.

To satisfy the forthcoming harmonic standards, such as IEC 1000-3-2, PFC’s serving as front-end converters have been attracting more and more attention. Among various PFC topologies, the Čuk PFC is deemed desirable for its continuous input and output currents, ripple-free input current, small output filter, and wide output voltage range [9]–[10]. However, the switch utilization factor of the Čuk topology is much lower than other topologies, such as the buck topology and the boost topology [11]. In other words, the power-handling capability requirements of the semiconductor devices of a Čuk PFC are much higher than those of a buck PFC or a boost PFC with the same output power. Reduction of switching losses and EMI noises are of particular importance to a Čuk PFC. To further improve the performance, it is indispensable to apply soft-switching techniques to Čuk PFC’s.

By applying the proposed ZVT PWM topology to a Čuk PFC, a novel ZVT PWM Čuk PFC is presented in this paper. In the proposed circuit, not only the power switch, but also the power diode, commutate under ZVS. The proposed ZVT PWM topology uses one switch, one diode, one capacitor, and one inductor to form a shunt resonant ZVT cell. Without additional components, compared with the conventional ZVT topology [3], the proposed ZVT topology dramatically improves the drawbacks of the conventional one through shorter ZVT time and more robust discharge of resonant inductor. Theoretical analysis and design rules of the ZVT PWM Čuk PFC are studied in depth. Experimental waveforms of a 400-W prototype built in the laboratory are used to verify the analysis.

II. ZVT PWM Čuk PFC

A. Circuit Operation Analysis

Shown in Fig. 1 is the proposed ZVT PWM Čuk PFC. It is the combination of a conventional PWM Čuk PFC and a shunt resonant ZVT cell, which is encircled by dotted lines. The ZVT cell consists of a resonant inductor \( L_r \), a resonant capacitor \( C_r \), an auxiliary switch \( S_2 \), and an auxiliary diode \( D_2 \). The resonant capacitor \( C_r \) incorporates the output capacitance of the power switch. Body diode \( D_{S1B} \) of the main switch \( S_1 \) is also utilized in this converter.

To analyze the steady-state operation of the circuit shown in Fig. 1, the following assumptions are made during one switching cycle.


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1) Input voltage $V_s$ is constant.
2) Output capacitor $C_o$ is large enough to assume that the output voltage $V_o$ is constant and ripple free.
3) Inductor $L_1$ and $L_2$ are much greater than resonant inductor $L_r$.
4) Capacitor $C_1$ is much greater than resonant capacitor $C_r$.
5) All semiconductor devices are ideal, except the main diode $D_1$.

Based on these assumptions, circuit operations during one switching cycle can be divided into seven stages, which are shown in Fig. 2(a)–(g), respectively.

Stage 1 [Fig. 2(a); $t_0 < t < t_1$]: The auxiliary switch $S_2$ turns on at $t_0$. During the turn-on process of $S_2$, injected charges in the low-doped middle region of diode $D_1$ cause transient reverse-recovery current flowing in reverse through diode $D_1$. The growth rate of the reverse-recovery current is restricted by the resonant inductor $L_r$ to achieve ZCS turn-on of the auxiliary switch $S_2$. Switching losses and EMI noises are reduced due to smoother current slope. Assuming that the current of the resonant inductor $I_{L_r}$ is zero before $t_0$, $I_{L_r}$ can be given by

$$I_{L_r}(t) = \frac{V_{C_1}}{L_r}(t - t_0).$$  

(1)
Assuming that \( t_{rr} \) is the reverse recovery time of \( D_1 \), the peak value of the reverse-recovery current \( I_{rr} \) and the time interval of Stage 1 \( t_{01} \) can be given by

\[
I_{rr} = I_{Lr}(t_1) - I_{L1} - I_{L2} \approx \frac{V_{C1} t_{rr}}{2L_r}
\]

\[
t_{01} = t_1 - t_0 \approx \frac{(I_{L1} + I_{L2}) L_r}{V_{C1}} + \frac{t_{rr}}{2}.
\]

Stage 2 [Fig. 2(b); \( t_3 < t < t_2 \):] The reverse-recovery phenomenon finishes at \( t_3 \). As soon as \( D_1 \) is turned off, \( C_r \) starts to discharge to \( L_r \) through \( S_2 \). The growth rate of the voltage across \( D_1 \), which is equal to \( V_{C1} - V_{C_{rr}} \), is restricted by \( C_r \) to achieve ZVS turn-off of \( D_1 \). Assuming that the inductor current \( I_{L1} \) and \( I_{L2} \) are both constant in this stage, resonant inductor current and resonant capacitor voltage are

\[
I_{Lr}(t) = \frac{V_{C1}}{Z_1} \sin(\omega_1(t - t_2)) + I_{rr} \cos(\omega_1(t - t_2)) + I_{L1} + I_{L2}
\]

\[
V_{C_{rr}}(t) = V_{C1} \cos(\omega_1(t - t_1)) - I_{rr} Z_1 \sin(\omega_1(t - t_1))
\]

where

\[
Z_1 = \sqrt{\frac{L_r}{C_r}}
\]

\[
\omega_1 = \frac{1}{\sqrt{L_r C_r}}.
\]

The time interval of Stage 2, \( t_{12} \), can be given by

\[
t_{12} = t_2 - t_1 = \sqrt{L_r C_r} \sin^{-1} \left( \frac{C_r V_{C1}^2}{L_r P_{L1}^2 + C_r V_{C1}^2} \right)
\]

\[
= \sqrt{L_r C_r} \cos^{-1} \left( \frac{L_r P_{L1}^2}{L_r P_{L1}^2 + C_r V_{C1}^2} \right).
\]

Stage 3 [Fig. 2(c); \( t_2 < t < t_3 \):] When \( V_{C_{rr}} \) is discharged to zero at \( t_2 \), body diode of the main switch, \( D_{S1B1} \), is turned on simultaneously. The drain–source voltage of \( S_1 \) remains zero after \( t_2 \), \( I_{Lr} \) remains its peak value in this stage and is given by

\[
I_{Lr,p} = I_{L1} + I_{L2} + \sqrt{\frac{L_r P_{L1}^2}{L_r P_{L1}^2 + C_r V_{C1}^2}}.
\]

Stage 4 [Fig. 2(d); \( t_3 < t < t_4 \):] \( S_1 \) turns on and \( S_2 \) turns off at \( t_3 \). Resonant inductor \( L_r \) starts to discharge to the output through the auxiliary diode \( D_2 \). \( I_{Lr} \) decreases linearly because the voltage across \( L_r \) is equal to the constant output voltage. When \( S_1 \) turns on at \( t_3 \), since the main switch \( S_2 \) is not on the discharge path of \( L_r \), the current of \( S_1 \) raises immediately to the normal turn-on current, which equals the sum of \( I_{L1} \) and \( I_{L2} \). Circuit operation is identical to the turn-on state of a conventional PWM Cuk PFC, except that \( I_{Lr} \) is discharging to the output.

Stage 5 [Fig. 2(e); \( t_4 < t < t_5 \):] \( S_1 \) turns off at \( t_4 \). After \( t_4 \), \( I_{L1} \) and \( I_{L2} \) start to charge the resonant capacitor \( C_r \) to achieve ZVS turn-off of \( S_1 \). Discharge of \( L_r \) can still be executed in this stage, even if \( S_1 \) is off. The time interval of Stage 5, \( t_{55} \), is given by

\[
t_{55} = \frac{C_r V_{C1}}{I_{L1} + I_{L2}}.
\]

Stage 6 [Fig. 2(f); \( t_5 < t < t_6 \):] The main diode \( D_1 \) is turned on under ZVS when \( V_{C_{rr}} \) is charged to \( V_{C1} \) at \( t_5 \). The resonant inductor \( L_r \) can keep discharging in this stage without the influence of the state of \( S_1 \) and \( D_1 \).

Stage 7 [Fig. 2(g); \( t_6 < t < t_0 \):] The energy recovery process will be finished after \( I_{Lr} \) is discharged to zero at \( t_6 \). Auxiliary diode \( D_2 \) is also turned off under ZCS at the same time. After that, circuit operation is identical to the turn-off state of a conventional PWM Cuk PFC. It returns back to Stage 1 when the auxiliary switch \( S_2 \) turns on again at \( t_0 \) in the next switching cycle.

Based on the analysis presented above, key waveforms of the proposed ZVT PWM Cuk PFC are shown in Fig. 3.

### B. Basic Features of the Circuit

- **Minimum ZVT Time:** The major difference between the conventional ZVT Cuk topology [3] and the proposed ZVT Cuk topology is the discharge path of the resonant inductor. In the proposed topology, discharge current does not flow through the main switch. Circuit operation becomes the same as in the normal on state of a common Cuk circuit as soon as the main switch turns on. The ZVT time \( t_{02} \), which equals \( t_2 - t_0 \), is comparatively short. In the conventional topology, since the discharge current flows through the main switch, the current of the
main switch increases slowly after the main switch turns on. The ZVT time is lengthened by the discharge time of the resonant inductor. Assuming that $I_{tr}$ is comparatively small, ZVT time of the proposed topology $T_{ZVT1}$ can be given by

$$T_{ZVT1} = t_0 + t_{12} \approx \frac{(I_{L1} + I_{L2})L_r}{V_{C1}} + \frac{\pi}{2} \sqrt{L_r C_r}$$  \quad (11)$$

and that of the conventional topology $T_{ZVT2}$ is given by

$$T_{ZVT2} \approx \frac{(I_{L1} + I_{L2})L_r}{V_{C1}} + \frac{t_{tr}}{2} + \frac{\pi}{2} \sqrt{L_r C_r} + \frac{I_{tr} V_{D1}}{V_{C1}}$$

$$= \frac{2(I_{L1} + I_{L2})L_r}{V_{C1}} + \frac{t_{tr}}{2} + \frac{\pi}{2} \sqrt{L_r C_r} + \frac{1}{2} \sqrt{\frac{V_{D1}^2}{R_{on}} + 4L_r C_r}$$

$$\approx 2T_{ZVT1}.$$  \quad (12)
It is shown that the ZVT time of the proposed topology is only half of the conventional one. Actually, the proposed ZVT topology has the shortest ZVT time of all of the ZVT topologies which can be applied to a Cuk PFC so far. The voltage and current waveforms of both the main and the auxiliary switches are essentially square waves, except during the ultrashort ZVT time. This desirable feature makes the proposed ZVT topology particularly suitable to be employed under PWM control strategies.

- **Short Minimum Duty Cycle of Main Switch:** The minimum duty cycle of the main power switch is very important in PFC applications because it establishes how high the output voltage must be for linear operation. The output voltage during light load is also more stable with a shorter minimum duty cycle. In the conventional ZVT PWM Cuk topology [3], the minimum duty cycle is dominated by the discharge time of the resonant inductor \( L_r \). In the proposed one, however, since the discharge current of \( L_r \) does not flow through the main switch \( S_1 \), discharge of \( L_r \) can be executed even if \( S_1 \) is off. In other words, the minimum duty cycle of the main switch can be shortened, regardless of the discharge time of \( L_r \). Due to the extremely short minimum duty cycle, the proposed ZVT Cuk topology is particularly suitable to be employed under variable-duty and high-switching-frequency applications, such as PFC’s.

- **Constant Operating Frequency:** Since the proposed ZVT topology is based on the PWM technique, the operating frequency is constant. Constant operating frequency makes design optimization of the EMI filter easily attainable. Various control strategies designed for the PWM technique, such as current mode control, are also applicable for the proposed ZVT Cuk PFC. UC3855 and ML4822, which are current mode control IC’s designed for the conventional ZVT PWM topology [3], can, therefore, be employed in the proposed circuit.

- **Robust Discharge of the Resonant Inductor:** One drawback of the conventional ZVT PWM topology [3] is that the resonant inductor cannot be discharged when the main switch turns off. The main diode and the auxiliary diode are essentially in parallel in the conventional topology. When the main diode is conducting, a certain percentage of current will flow through the auxiliary diode. When the auxiliary switch turns on, this undesirable feature will cause considerable switching losses, unless an additional saturable reactor is placed in series with the resonant inductor. The situation is quite different in the proposed ZVT topology. In the proposed ZVT PWM Cuk PFC, the resonant inductor can keep discharging, even if the main switch turns off. It ensures that the current through the resonant inductor and the auxiliary diode remains zero after the resonant inductor has been completely discharged. The turn-on loss of the auxiliary switch is successfully limited. Contrarily, since a larger inductor value of the resonant inductor can be used due to long discharge duration, it actually decreases turn-on loss of the auxiliary switch.

- **Soft Switching for Wide Line and Load Ranges:** One drawback of other soft-switching techniques is that the soft-switching condition is strongly dependent on load current and input voltage. At light load, ZVS is usually difficult to maintain, since the energy stored in the resonant inductor at light load is not sufficient to completely discharge the resonant capacitor prior to turn-on of the active switch. At high line, ZVS is easier to lose, since it needs more energy to discharge the resonant capacitor. Although losing ZVS at light load or high line does not always cause serious thermal problems, EMI due to switching noises may be intolerable in a practical circuit. In the conventional [3] and the proposed ZVT topologies, soft switching is maintained in wide load and line ranges, as long as they have been designed for high load or low

### TABLE I

<table>
<thead>
<tr>
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<td>D2</td>
<td>HFA151B60</td>
<td>C1</td>
<td>4.7μF</td>
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<tr>
<td>S2</td>
<td>2SK2198</td>
<td>L</td>
<td>800μH</td>
<td>L1</td>
<td>30μH</td>
</tr>
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<td>HFA151B60</td>
<td>C2</td>
<td>660μF</td>
<td>C3</td>
<td>3.3nF</td>
</tr>
</tbody>
</table>

![Key experimental waveforms of the hard-switching Cuk PFC operated under 300-W loading.](image)

(a) 

(b) 

Fig. 6. Key experimental waveforms of the hard-switching Cuk PFC operated under 300-W loading. \( V_S \), \( V_D \): 100 V/div; \( I_S \), \( I_D \): 4 A/div; time: 2 μs/div. (a) \( V_S \) and \( I_S \). (b) \( V_D \) and \( I_D \).
line. This desirable feature makes ZVT topologies more suitable in PFC applications. For wide line and load range, in particular, in a PFC, a wide variation range of duty cycle is necessary. Since the proposed ZVT Ćuk topology has shorter ZVT time, it can be operated with wider line and load range compared with the conventional one.

C. Isolated Single-Stage ZVT PWM Ćuk PFC

The proposed ZVT PWM Ćuk PFC can be extended to an isolated single-stage form, as shown in Fig. 4. To ensure complete isolation, the resonant inductor \( L_r \) is replaced by the coupled inductors \( L_{r1} \) and \( L_{r2} \). In deriving the isolated ZVT topology of Fig. 4, two key characteristics of the nonisolated ZVT topology of Fig. 1 were preserved [12]. First, the ZVT time and the minimum duty cycle are extremely short. Second, discharge current of the coupled resonant inductors \( L_{r1} \) and \( L_{r2} \) does not flow through the main switch. Circuit operations are similar to those of its nonisolated counterpart.

To avoid large overvoltages across switch \( S_2 \) at turn-off, a very small leakage inductance and a very high coupling between the primary and the secondary windings should be achieved when designing the coupled inductors \( L_{r1} \) and \( L_{r2} \). Since good dynamic characteristics are necessary for the diode \( D_2 \), a fast forward- and reverse-recovery diode is required.

III. DESIGN PROCEDURE

Since design of the conventional Ćuk circuit has been well presented in literature, it is more significant to focus on the design rules of the proposed ZVT cell. The resonant inductor and the resonant capacitor are the most important components when designing the ZVT cell. The resonant inductor is designed to provide soft turn-on of the main switch and the auxiliary switch, while the resonant capacitor is designed to provide soft turn-off of the main switch.

A. Resonant Inductor

The resonant inductor value can be obtained by determining how fast the main diode can be turned off. However, it is difficult to calculate accurately, because the recovery characteristics vary among different rectifiers. A widely adopted estimate is to allow the current through the resonant inductor to ramp up to the diode current within three times the diode’s specified reverse-recovery time. One constraint on the maximum inductance value is its effect on the minimum duty cycle [7]–[8].

The resonant inductor design is limited by core loss instead of saturating flux density due to the high ac component and the relatively high operating frequency. High-frequency response and low-loss core materials, such as molly–permalloy powder (MPP), are adequate. However, since the resonant ringing at turn-off of the auxiliary switch is not easily generated by high-loss material inductors, some cheaper materials which have higher loss than MPP are also acceptable. The resonant inductor peak current has already been shown in (9), which determines the radius of winding wire.

Compared with the conventional ZVT Ćuk circuit [3], since the discharge path of the resonant inductor of the proposed circuit has been improved, the resulting ZVT time is also significantly shortened. A larger value of the resonant inductor can, therefore, be chosen to maintain the same ZVT time compared with the conventional circuit. According to (11) and (12), it can be seen that the inductor value can be increased to two times, or higher, than that of the conventional design. With a higher resonant inductor value, the turn-on loss of the auxiliary switch can be further reduced. The physical size will not be increased, since only the amount of windings is increased without changing the core size.

B. Resonant Capacitor

The resonant capacitor is designed to control \( dv/dt \) of the drain–source voltage of the main switch. It provides an alternative path for the inductor current when the main switch turns off to reduce switching losses and \( dv/dt \) EMI noises.
High-frequency-response capacitors with low equivalent series resistance (ESR) and equivalent series inductance (ESL), such as polypropylene film, are required. A good estimate is to determine the total capacitor value by setting the turn-off transient time \( t_{\Delta} \):

\[
C_{\text{total}} = \frac{(I_{L1} + I_{L2})t_{\Delta}}{V_{C1}}, \tag{13}
\]

Since the resonant capacitor incorporates the output capacitance of the main switch and the main diode, the resonant capacitor value can be obtained by subtracting the output capacitor value of the main switch and main diode from the total capacitor value \( C_{\text{total}} \).

C. Auxiliary Switch and Diode

The voltage stresses of the auxiliary switch and diode are equal to \( V_{C1} + V_o \). The current stresses of the auxiliary switch and diode are equal to the peak current of the resonant inductor, as shown in (9). Since the short duty cycle of the auxiliary switch makes the conduction loss comparatively low, a MOSFET smaller than the main switch is sufficient [6]. The auxiliary diode needs to be a fast-recovery diode to prevent the resonant inductor from resonating with the output capacitor after discharge.

IV. EXPERIMENTAL RESULTS

A prototype of a 400-W 50-kHz 110-V ac input and 200-V dc output ZVT PWM Cuk PFC, as shown in Fig. 1, has been built to verify the principle of operation and the theoretical analysis. The components specifications are listed in Table I. A hard-switching Cuk PFC with the same specifications is also built in the laboratory.

Key experimental waveforms of the proposed ZVT PWM Cuk PFC and the hard-switching counterpart operated under 300-W loading are shown in Figs. 5 and 6, respectively. The efficiencies of these two circuits under different loadings are also shown in Fig. 7. Efficiency of 95.2% has been measured at full load. It can be seen from Fig. 5 that the waveforms agree well with the predicted ones shown in Fig. 3. The operation analysis is guaranteed to be valid. Compared with Fig. 6(a), Fig. 5(a) shows that the main switch \( S_1 \) commutates under ZVS turn-on and turn-off, since all of the nonideals such as the parasitic capacitance of the main switch and the auxiliary diode and the reverse-recovery current of the auxiliary diode are small compared with the resonant inductor.

The auxiliary switch makes the conduction loss comparatively low, a MOSFET smaller than the main switch is sufficient [6]. The auxiliary diode needs to be a fast-recovery diode to prevent the resonant inductor from resonating with the output capacitor after discharge.

A comparatively large inductor value of \( L_r \) is used to emphasize the desirable peculiarity of the proposed ZVT topology. The large \( L_r \) effectively decreases the turn-on loss and the current stress of \( S_2 \), while still keeping the ZVT time short. It can be seen from Fig. 5(b) and (d) that the auxiliary switch \( S_2 \) and the auxiliary diode \( D_2 \) are activated for a short ZVT time duration. The ZVT PWM converters are identical to common PWM converters during the remainder of the time. Control strategies and design rules of common PWM converters can be directly applied to ZVT PWM converters.

Current ratings of auxiliary semiconductor devices can also be reduced due to short ZVT time.

V. CONCLUSION

A novel ZVT PWM Cuk PFC has been proposed in this paper. In the proposed circuit, no switching loss is generated from the main switch and the main diode. Constant switching frequency eases the design of EMI filters and control circuits. Wide line and load ranges are also achieved, since ZVS and ZCS are easily maintained at not only low line and heavy load, but also high line and light load. The merits of both ZVT PWM converters and Cuk PFC’s are obtained in the proposed circuit. In addition, to apply soft switching to PFC’s more appropriately, the proposed topology has an extremely short ZVT time. Discharge of the resonant inductor is more robust and more stable than the conventional ZVT topology. A prototype of a 400-W ZVT PWM Cuk PFC has been built in the laboratory to experimentally verify the analysis. It has been shown from the experimental oscillograms that soft switching is successfully applied to the ZVT PWM Cuk PFC.

REFERENCES

Ching-Jung Tseng was born in Taipei, Taiwan, R.O.C., in 1972. He received the B.S. and Ph.D. degrees in electrical engineering from National Taiwan University, Taipei, Taiwan, R.O.C., in 1994 and 1998, respectively.

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Chern-Lin Chen (S’86–M’90), for a photograph and biography, see p. 118 of the February 1999 issue of this Transactions.