# A Digitally Controlled DCM Flyback Converter With a Low-Volume Dual-Mode Soft Switching Circuit

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*Abstract*—**This paper introduces a dual-mode hybrid zero-voltage/zero-current switching (ZVS/ZCS) circuit and a complementary controller for flyback converters operating in discontinuous conduction mode (DCM). The new ZVS/ZCS solution provides soft switching feature and high efficiency throughout the whole operating range. It also requires smaller components than other soft switching solutions [1]-[6]. To achieve these benefits, the dual-mode ZVS/ZCS flyback combines a low power passive snubber and a novel secondary side circuit. The secondary side circuit provides ZCS on the primary side and ZVS on the secondary. A digital controller governs the operation of this converter. At light loads the ZVS/ZCS is disabled to minimize conduction losses. At medium and heavy loads ZVS/ZCS provides soft switching and at the same time minimizes power losses of the snubber, by capturing energy that would have been lost otherwise. Experimental results obtained with a 50W, 200KHz, universal input (85V-264V) programmable output PFC prototype demonstrate efficiency improvement of up to 15% compared to a conventional flyback PFC rectifier and about five times smaller snubber circuit.**

## I. INTRODUCTION

A flyback converter operating in discontinuous conduction mode (DCM) is widely used in power factor correction rectifiers processing power less than 100 W [7]. This is mostly due to the controller and system simplicity, a low component count, and the existence of galvanic isolation [8]-[13]. Flyback PFC rectifiers operating in DCM mode also have some shortcomings. Those are mainly related to relatively high switching losses and a high voltage stress across the switches, caused by the transformer leakage inductance [1]-[6].

Various methods have been developed to reduce switching losses and the voltage stress across the flyback switch [1]-[6] and to recycle the leakage inductance energy. Most conventional solutions use relatively bulky and lossy passive snubbers. Zero voltage switching (ZVS) solutions [4]-[6] eliminate the snubber by utilizing an active clamp circuit on the primary side, which, usually, require high side gate drivers and high blocking voltage switches. The zero current switching (ZCS) can be implemented without the high side

gate drivers and high voltage transistors [1]-[2]. Still, the ZCS solutions require an additional, i.e. third, winding and a small snubber, to absorb voltage ringing at the transistor's switching node. Both of these solutions significantly improve power processing efficiency but, as a penalty, introduce additional losses at lighter loads. In both cases the excessive conduction losses occur due to the resonant currents [14].

The main goal of this paper is to introduce the DCM flyback converter of Fig.1 that features soft switching on the both transformer sides and does not require an additional winding. The new dual-mode solution also improves light load efficiency by eliminating additional conduction losses occurring in conventional soft switching solutions.

The simple ZCS/ZVS circuit of Fig.1 is a hybrid structure utilizing principles presented in [1], [3]. The circuit shown here is formed by placing the switch $SW_2$ and $C_r$ on the secondary side and through the utilization of the leakage inductance of the transformer $L_{lk}$. On the primary side, a small snubber is placed. A digital controller governs the operation of the ZCS/ZVS circuit.

At light loads efficiency improvements are achieved by disabling the ZCS and, thus, eliminating the penalty related to the excessive conduction losses. In this mode, the small snubber circuit absorbs leakage inductance energy, which, due
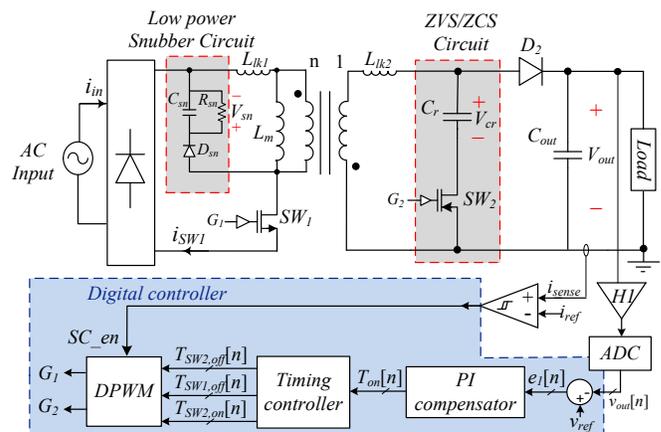


Fig.1. Block diagram of the introduced soft switched single stage flyback converter.

to relatively low current in the circuit, is low. At medium and heavy loads the controller activates the ZCS/ZVS that not only provides soft transistor and diode switching but also takes the energy from the leakage inductance reducing the power circulating through the snubber. As described later, in this case the snubber is only used to eliminate the voltage ringing across the main switch caused by stray capacitance and leakage inductance. The energy of this ringing is much smaller than that processed by conventional snubbers. Therefore, a drastic reduction in the snubber power rating requirements is achieved. The introduced control method for the ZCS/ZVS circuit does not require measurements on the transformer primary side. Therefore, it offers advantage of placing the controller on the low voltage secondary side and sharing the ground with the load.

## II. PRINCIPLE OF OPERATION

In this section, the leakage-inductance-caused losses of the DCM flyback converter are briefly addressed and the related converter waveforms are used to describe the operation of the ZCS/ZVS circuit.

Fig.2 demonstrates the key waveforms for the main switch of the flyback converter during a turn-off transition in the absence of a snubber circuit (Fig.2b) and after the snubber is added (Fig.2c). Without the snubber, the energy stored in the leakage inductance prior the turn on of the switch results in excessive voltage ringing at the switching node. The snubber circuit eliminates the voltage spikes by absorbing the leakage inductance energy and burning it with the snubber resistor [15]. Also, due to hard turn off of the switch, during commutation time, $t_1<t<t_2$ a noticeable energy loss occurs in each switching cycle.

To analyze operation of the new ZCS solution, an equivalent converter circuit, shown in Fig.3, can be observed. In this circuit a simplification was made by reffering all ZCS circuit elements to the primary. The operation of this circuit is initiated by turning $SW_2$ on before the main flyback switch $SW_1$ is turned off. As a result, a resonant circuit is formed by $L_{lk1}$, $L_{lk2}$ and $C_r$. This circuit superimposes a resonant component on the current passing through $SW_1$. The zero current switching is obtained by turning off $SW_1$ when its total current (and hence $L_{lk1}$) is zero. Therefore, aforementioned drawbacks of the flyback topology related to the energy stored in $L_{lk1}$ are eliminated.
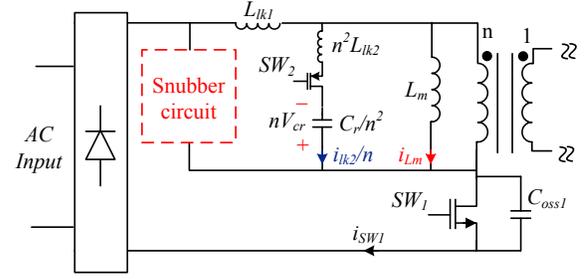
Fig.3. The soft switching circuit referred to the primary side of the flyback transformer.

The rest of this section covers the details of operation of this circuit and explains the reasons why a small snubber is still needed in this and in other previously presented ZCS solutions.

### A. Soft switching circuit operation

The operation of the flyback converter with the introduced soft switching circuit during one switching cycle can be described by looking at the five states the circuit passes through during each switching cycle, described with Figs.4 and 5.

**State 1**, occurring during $t_0<t<t_1$, corresponds to the main switch 'on' state of a conventional flyback. During this time, $SW_1$ is on while the switch $SW_2$ and $D_2$ are turned, off as shown in Fig.4a. During this time primary side current is ramping up and the current on the secondary side of the transformer $i_{lk2}(t)$ is zero. The voltage across resonant capacitor $v_{Cr}$(t) is not changing and is kept at the previously set $V_{out}$ value, equal to the converter output voltage. **State 2** starts at $t=t_1$, when $SW_2$ is turned on and a resonant circuit is formed by $C_r$ and the secondary side leakage inductance $L_{lk2}$. Form Fig.4b it can be seen that the sinusoidal current $i_{lk2}(t)$ of the resonant circuit is superimposed on the main switch current through the transformer. This state continues over a fixed interval $T_r=3\pi\sqrt{L_{lk}C_r}$ , i.e. until the resonant current reaches its minimum value at, $t=t_2$, resulting in a negative current of $SW_1$, $isw_1=i_{Lm}+i_{Llk2}/n$. At this point, the switch $SW_1$ is turned off and the **state 3** is initiated. During this state, the negative $i_{sw1}$ passes through the body diode of the main switch, as shown in Fig.4c. When $i_{sw1}$ reaches zero again, at $t=t_3$, the body diode stops conducting, meaning that the switch
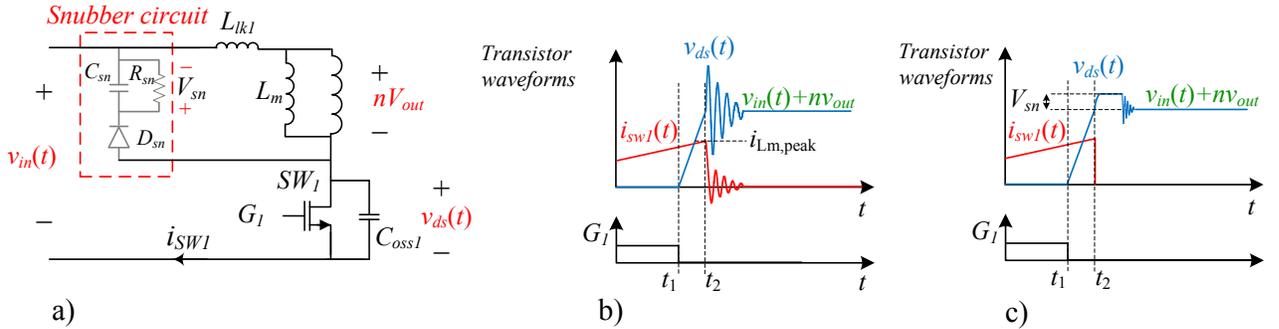
Fig.2. Switching waveforms of a flyback snubber at the switch turn off transition. a) Primary side of a flyback; Current and voltage waveforms of the main switch without snubber (b) and with snubber circuit (c).
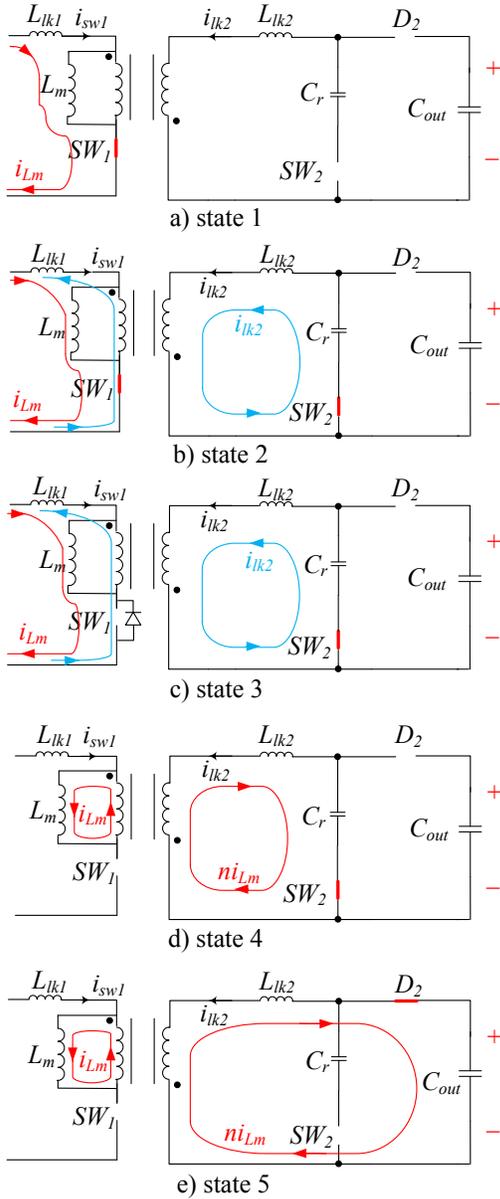
Fig.4. Five different converter states during one switching cycle of soft-switched.



Fig.5. Key converter waveforms during soft switching circuit operation.

softly turns off and the **state 4** begins. During this state, $SW_1$ is turned off and the magnetizing inductance current, $i_{Lm}$, charges $C_r$ until $t=t_4$. At this point $v_{cr}(t)$ reaches $V_{out} + V_{FD}$, where $V_{FD}$ is forward voltage drop of $D_2$ and the diode softly turns on. As a result, the diode-caused switching losses, existing in conventional solutions, are avoided. The start of $D_2$ conduction initiates **state 5**. Over this period the converter operates as a conventional DCM flyback causing the magnetizing inductance current to fall. During this state $SW_1$ is off and the diode $D_2$ conducts. In the practical implementation, $SW_2$ is turned off after a small delay (labelled as $T_d$ in Fig.5) after turning off $SW_1$, to allow enough time for $D_2$ to start conducting, i.e. $SW_2$ is turned off at $t_4<t<t_5$. This results in ZCS for $SW_2$.
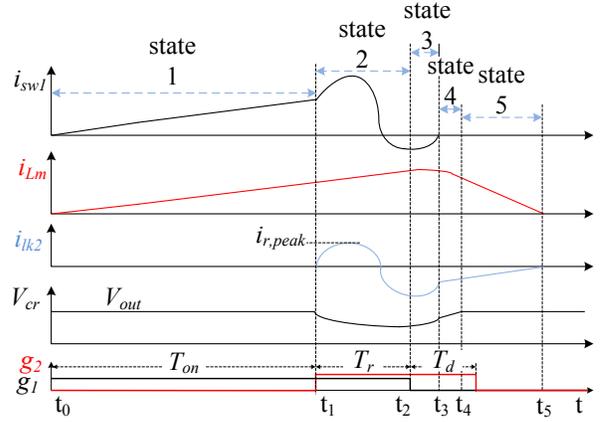
### B. Small snubber circuit function

In the case of zero current switching of $SW_1$ voltage ringing still appears across the switch. This is due to the charging of the parasitic capacitances of the switching node, $C_{oss1}$ (Fig.6) from close to 0V at $t=t_2$ (Fig.5) to its blocking voltage, i.e. $V_{in}(t)+nV_{out}$, through a resonant circuit formed by $C_{oss1}$ and $L_{lk1}$. This resonance results in a voltage overshoot across the flyback switch, (Fig.6b). Therefore, a small snubber circuit is still needed. The snubber eliminates this resonance by clamping the voltage across the switch at $v_{ds}(t)=V_{in}(t)+V_{sn}$, as shown in Fig.6c, similar to the mechanism the conventional flyback snubber. However, as shown in the following section, the energy absorbed by this snubber is significantly smaller than that of the conventional solution.

### III. PRACTICAL IMPLEMENTATION

### A. Controller architecture

As shown in previous section, the amplitude of the peak resonant current, i.e. $i_{r,peak}$ of Fig.5, created by the soft-switching circuit depends on circuit parameters and has to be designed such that it provides ZCS for the maximum load condition. This is usually achieved by properly selecting performed by selecting the resonant capacitor value, $C_r$. This high current causes additional losses under no load and light load conditions. To eliminate this problem, the ZVS/ZCS circuit is disabled during light load conditions, i.e. $i_{Lm,peak}<i_{ref}$ as shown in Fig.1, through $SC\_en$ signal of Fig.1 and the flyback operates as a conventional system. It is worth mentioning that $i_{ref}$ is selected such that the power that is absorbed by the snubber when soft-switching circuit is disabled does not exceed the snubber rated power as calculated in the following sub-section.

The controller architecture for the soft switched DCM flyback is shown in Fig.1. Based on the output voltage error information received from the *ADC,* a PI compensator determines the 'on' time period for main switch, i.e. $t_1-t_0=T_{on}$ The timing controller block of Fig.1 generates the proper time intervals to switch on/off $SW_1$ and $SW2$ according to Fig.7 and sends them to the *DPWM* block. The dual output *DPWM* block of Fig.1 creates gating signals for $SW_1$ and $SW_2$ based on the timing diagram of Fig.7 upon receiving information from the *timing controller* block.
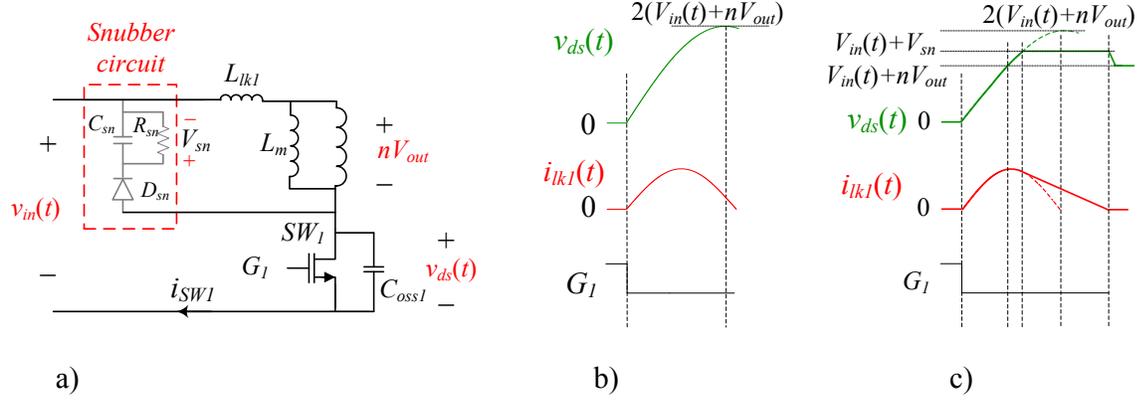
Fig.6. Circuit and waveforms of the primary side of the flyback transformer with soft-switching circuit enabled a) The primary side circuit b) Voltage overshoot across main switch due to $L_{lk1}$ and $C_{oss1}$ resonance in absence of a snubber circuit c) in presence of the snubber circuit.

### B. Comparison of the snubber circuits

The energy that has to be absorbed by the snubber circuit is proportional to the leakage inductance current at the time the snubber diode ($D_{sn}$ of Figs 3a and 6a) starts conducting. This happens when $V_{ds}(t)$ raises up to $V_{sn}+nv_{out}$ in Fig.3c for conventional flyback converter or in Fig.6c in case of the soft switching flyback converter.

In a conventional flyback converter this current is equal to the peak magnetizing inductance current, i.e. $i_{LM,peak}$, and hence the energy absorbed by the snubber, $E_{snubber2}$, is found by Eq.1 [16].

$$E_{snubber1} = \frac{1}{2}L_{lk1}i_{LM,peak}^2 \frac{V_{sn}}{V_{sn}-nV_{out}}, \quad (1)$$

where the snubber is usually designed to have a $V_{sn}$ in the range of 2~2.5 times of $nV_{out}$ [16].

In the case of the soft switching flyback converter the leakage inductance current after the flyback switch is turned off, Fig.6b, can be found as:

$$i_{lk1}(t) = \sqrt{\frac{C_{oss1}}{L_{lk1}}}(v_{in}(t) + nV_{out})\sin(\frac{t}{\sqrt{L_{lk1}C_{oss1}}}) \cdot \quad (2)$$

Since the snubber voltage, $V_{sn}$, is designed to be greater than $nV_{out}$ [16], depending on the design of parameter $V_{sn}$, this current can be equal or smaller than $i_{lk1,peak}$ which happens where $V_{ds}=V_{in}+nV_{out}$ as seen from Fig.6c.

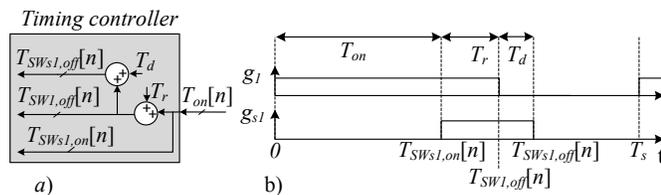$$i_{lk1,peak} < \sqrt{\frac{C_{oss1}}{L_{lk1}}}(v_{in}(t) + nV_{out}) \cdot \quad (3)$$



Fig.7.) Implementation of the *timing controller* block. b) the timing diagram gating signals of $SW_1$ and $SWs_1$.

Following the same method used in [16] for the conventional flyback case, the maximum energy absorbed by the snubber of soft-switched flyback is found to be:

$$E_{snubber2} = \frac{1}{2}C_{oss1}(vin(t) + nVout)^2 \frac{V_{sn}}{V_{sn} - nV_{out}}, \quad (6)$$

Comparison of the energy requirements of the snubber of the conventional flyback, $E_{snubber1}$, given in Eq.1 with that of a soft-switched flyback converter given in Eq.4, $E_{snubber2}$, for practical design cases reveals that the volume of soft-switched converter flyback is significantly smaller. For instance for the prototype board used in this work with $V_{in,max}$=220V$_{rms}$, $V_{out}$=5V, $P_{out,max}$=25W, $C_{oss1}$=100pF, $L_{lk1}$=2.5uH, $L_m$=80uH, $n$=6, $V_{sn}$=2$nV_{out}$, it can be found that $E_{snubber1}\approx5E_{snubber2}$, resulting in proportional reduction of snubber volume for soft-switched flyback converter and also the losses due to the snubber circuit operation.

### IV. EXPERIMENTAL SETUP AND RESULTS

An experimental prototype has been developed to verify the functionality of the introduced soft switching flyback PFC. Also, its performance is compared to a conventional flyback converter. Table.I demonstrates the parameters of the prototype board.

Table 1. Parameters of the prototype setup

| Parameter | $L_m$ | $L_{lk1}$ | $C_r$ | $V_{out}$ | $f_s$ |
|-----------|-------|-----------|-------|-----------|-------|
| Value | 80uH | 2.5uH | 47nF | 5,20V | 200Khz |

Fig.8 illustrates the operation of the soft switched DCM PFC rectifier in steady state. Fig.9 shows the key waveforms of the ZVS/ZCS circuit during one cycle at peak input current, 25W, 110Vrms to 20V operation which is in accordance to the expected waveforms from Fig.5. As seen from Fig.9, after $t=t_2$, there is a rise in $i_{sw1}$ due to existence of parasitic capacitances. The energy induced in $i_{lk1}$ due to that rise of current is absorbed by the small snubber. As can be seen from the results, this current is much smaller than the peak current of $i_{lk1}$ during $SW_1$ conduction time, resulting in the much smaller energy loss and hence volume of the small snubber compared to the snubber circuit in conventional flyback. The

Fig.8. PFC operation of the soft-switched flyback converter.



Fig.9. Steady-state operation of soft-switched flyback converter. $i_{lk2}$ is the transformer secondary side current, $v_{ds1}$ is the voltage across flyback converter main switch, $SW_1$, and $v_{Cr}$ is the voltage across the resonant circuit capacitor.

efficiency of the soft switching converter is also compared to conventional flyback for the case of operation with input voltage of 110Vrms $V_{out}$ of 20V. For both cases a $V_{sn}$ of ~$2nV_{out}$ is achieved by using $R_{sn}$=4Kohm,3W, $C_{sn}$=2 uF for conventional flyback converter snubber and $R_{sn}$=20Kohm, 0.5W, $C_{sn}$= 400nF for the case of the soft-switched flyback converter. As seen from the results, by operating only the small snubber at light loads and activating the soft switching circuit for medium to heavy loads an improved efficiency is achieved by the soft switched flyback converter over the full range of loads which is shown by the purple dotted line on Fig.10.

## V. CONCLUSIONS

A dual-mode hardware efficient soft switching solution for DCM flyback rectifiers with power factor correction is introduced. It provides soft switching for all switches and achieves improved efficiency over the entire load range compared to conventional solutions. The new ZVS/ZCS circuit that operates at medium to heavy loads is implemented on the secondary side of the flyback transformer, reducing circuit complexity, volume and cost compared to conventional soft switching solutions. By utilization of an already present
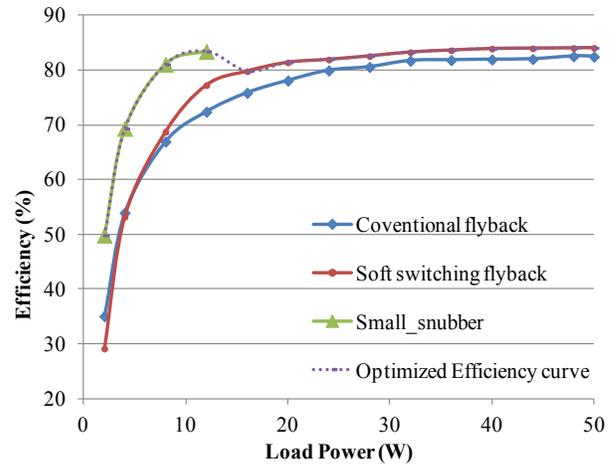


Fig.10. Efficiency measurements for the three cases at 110Vrms to 20V operation.

low-power snubber and disabling the ZVS/ZCS circuit at light loads, the controller optimizes the overall system efficiency and eliminates the drawback of excessive conduction losses in conventional soft switching solutions. The introduced controller circuit for ZVS/ZCS circuit does not require any measurements from the transformer primary side, allowing for the implementation of the entire controller on the secondary side. Experimental comparisons with a conventional DCM flyback PFC verify drastically smaller volume and better power processing efficiency.

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