An efficiency optimization method for a high frequency quasi-ZVS controlled resonant flyback converter

Shen Xu, Weidong Shen, Qinsong Qian, Jing Zhu and Weifeng Sun

National ASIC System Engineering Research Center, Southeast University
Nanjing, Jiangsu, 210096, PRChina
E-mail: xus@seu.edu.cn, swffrog@seu.edu.cn

Haisong Li
Wuxi Chipown Micro-electronics limited company
Wuxi, Jiangsu, 210096, PRChina
E-mail: lihs@chipown.com.cn

***Abstract*—A MHz single-switched resonant flyback converter with quasi-ZVS is applied to improve the power density. In the quasi-ZVS control, as the control parameters are adjusted and varying continuously, the conventional efficiency calculation is no longer applicable. A dynamic analytical loss model is thus proposed for the quasi-ZVS control, and an optimized on-off control algorithm is further used for efficiency improvement. Based on the loss model with variable parameters, the efficiency of the quasi-ZVS control under different load can be calculated by iteration of multiple switching cycles, and the highest efficiency working condition can be obtained and used for on-off control to improve the overall efficiency. The efficiency is greatly improved with the optimized on-off control. A FPGA controlled 12V/3A resonant converter with eGaN HEMTs is established to verify the proposed control method. The peak efficiency under the proposed optimized on-off control without synchronous rectification is 90%, and the light load efficiency is more than 80%. Compared with the quasi-ZVS control, there is an improvement of 1.2% under full-load condition, and increases by 6.2% under 10% load condition.**

Keywords—resonant flyback converter; loss model; quasi-ZVS control; on-off control; efficiency improvement

I. INTRODUCTION

Due to the simple circuit structure, flyback converter topology is widely used for low power dc–dc converter. As power density is becoming an important factor of the performance of such converter [1-4], simplifying the circuit structure and increasing the switching frequency are two main methods for high power density.

In order to increase power density, a MHz single-switched resonant flyback converter with ZCS and quasi-ZVS technique is proposed by our research group. Due to the characteristics of the circuit structure, the conventional pulse frequency modulation (PFM) control cannot guarantee the realization of quasi-ZVS under any load conditions, which results in a large turn-on loss and reduces the efficiency of the converter. Thus, a quasi-ZVS control is applied to make sure that the switch turns on when the drain-source voltage is at its valley, which brings a great improvement of efficiency. However, in the quasi-ZVS control, the duty cycle and the magnetizing current is adjusted and varying continuously, therefore, the conventional efficiency calculation for unchanged waveform is no longer applicable [5-11].

To solve the problem and improve the efficiency, for the resonant converter, a dynamic analytical loss model is established and applied in the on-off control algorithm for efficiency improvement. The dynamic analytical loss model is based on variable parameters, including the magnetizing current i_m and the duty information. With the proposed loss model, the highest efficiency of the quasi-ZVS control can be obtained by iteration of multiple switching cycles for the further improvement of efficiency in on-off control.

In this paper, Section II analyzes the working principle of the resonant flyback converter. Section III proposes the dynamic analytical loss model for the quasi-ZVS control. With the proposed model loss, the efficiency-optimal point can be obtained for the quasi-ZVS on-off control. In Section IV, the implementation of the quasi-ZVS on-off control is presented. Section V presents the experimental results on a 1MHz resonant flyback converter. The conclusions are given in Section VI.

II. WORKING PRINCIPLE OF THE RESONANT FLYBACK CONVERTER

The single-switched resonant converter is shown in Fig. 1. Compared to the traditional flyback converter, a resonant inductor *Lr* and a resonant capacitor *Cr* are added to realize the technique of ZCS and quasi-ZVS, which makes a great improvement of efficiency. The switching frequency reaches 1MHz.

The steady-state characteristics of each switching cycle are divided into four operating modes as follows, and the key waveforms are shown in Fig. 2. v_{gs} is the switching signal. v_{ds} represents the drain-source voltage of switch. i_D is the current flowing through the output diode D_1. i_p is the primary winding current, and i_m is the magnetizing current of the transformer.

Mode a, $[t_0,t_1]$: Mode a starts at t_0, and ends at t_1. At t_0, the switch M_1 turns on, and if the drain-source voltage of the switch M_1 (v_{ds}) is at its valley, the switch M_1 realizes quasi-ZVS, otherwise the circuit works in the state of hard-switching. During t_0 to t_1, the voltage of the resonant capacitor Cr (v_{Cr}) is clamped to the output voltage V_o (ignoring the forward voltage of the diode D_1) , and the current flowing through the resonant inductor *Lr* (i_p) increases linearly, at the same time, the current flowing through secondary diode D_1 (i_D)

decreases linearly. At t_1, the current of diode D_1 (i_D) drops to zero, and the diode turns off.

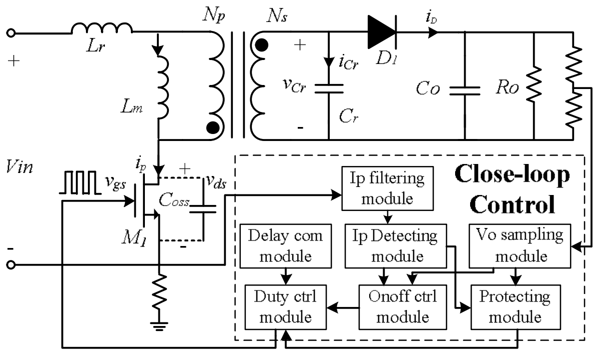


Fig. 1. Single-switched resonant flyback converter

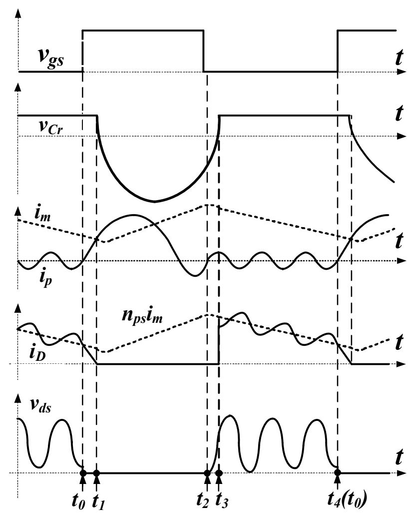


Fig. 2. Key waveforms of the resonant flyback converter

Mode b, [t_1,t_2]: Mode b starts at t_1, and ends at t_2. At t_1, the diode D_1 turns off. During t_1 to t_2, the voltage of the resonant capacitor *Cr* (v_{Cr}) is no longer clamped. The resonant inductor *Lr*, the magnetizing inductance *Lm*, and the resonant capacitor *Cr* start to resonate. At t_2, the switch M_1 turns off, and if the primary current i_p has a zero-crossing point during the conduction period of the switch M_1, the switch M_1 realizes ZCS, otherwise the quasi-ZCS is realized.

Mode c, [t_2,t_3]: Mode c starts at t_2, and ends at t_3. At t_2, the switch M_1 is off. During t_2 to t_3, the resonant inductor *Lr*, the magnetizing inductance *Lm*, the resonant capacitor *Cr* and the drain-source capacitance *Coss* of the switch M_1 start to resonate. At t_3, the voltage across the resonant capacitor *Cr* is charged to the output voltage V_o and the diode D_1 turns on.

Mode d, [t_3,t_4]: Mode d starts at t_3, and ends at t_4. At t_3, the diode D_1 is on. During t_3 to t_4, the voltage of the resonant capacitor *Cr* (v_{Cr}) is clamped to the output voltage V_o. The resonant inductor *Lr* and the drain-source capacitance *Coss* of the switch M_1 start to resonate. At t_4, the switch M_1 turns on at the valley of the drain-source voltage v_{ds}, and the circuit operates for a whole switching cycle.

III. The Proposed Dynamic Analytical Loss Model For The Quasi-ZVS Control

A. Quasi-ZVS control for the improvement of efficiency

For the resonant flyback converter, as shown in Fig. 3, conventional pulse frequency modulation (PFM) control cannot guarantee the realization of quasi-ZVS under any load conditions, which results in a large turn-on loss of the switch and reduces the overall efficiency of the circuit.

To solve this problem, the quasi-ZVS control is shown in Fig. 4. In the pulse frequency modulation (PFM) control, the magnetizing current at t_1 each duty cycle $i_m(t_1)$ is basically unchanged, and $i_m(t_1)\_avg$ represents the constant value. However, in the quasi-ZVS control, the magnetizing current at t_1 each switching cycle $i_m(t_1)$ no longer keep constant, but fluctuates around $i_m(t_1)\_avg$. The average power of the quasi-ZVS control method equals to the power supplied by the PFM control approximately, so that the output voltage can also be stabilized around the reference.

The quasi-ZVS control make sure that quasi-ZVS is realized because the eGaN HEMTs turns on when the drain-source voltage of the switch is at its valley, which brings a great improvement of efficiency.

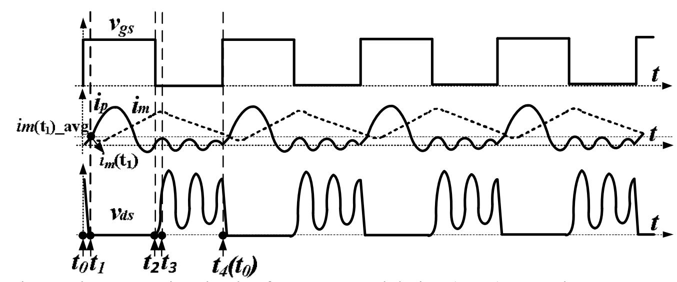


Fig. 3. The conventional pulse frequency modulation (PFM) control

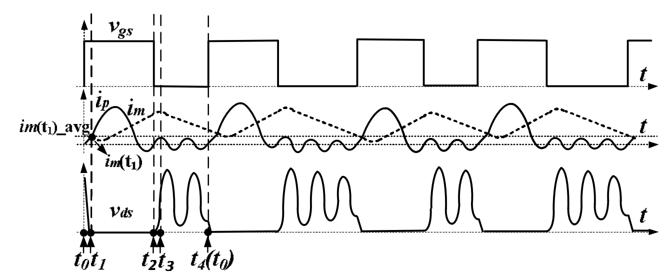


Fig. 4. The quasi-ZVS control method

B. The analytical efficiency model for the converter

With the conventional pulse frequency modulation (PFM) control, the duty and the working waveforms of each switching period are basically stable under a certain load, so that the overall efficiency of the circuit can be approximately equal to the efficiency of one switching cycle, which can be calculated by the traditional efficiency calculation method. However, under the quasi-ZVS control method, since the duty information of per cycle is adaptively adjusted for the realization of quasi-ZVS and the stable output voltage, and the magnetizing current at t_1 $i_m(t_1)$ and duty information of each cycle have a greater influence on the power loss, so that the traditional efficiency calculation method is no longer applicable. Therefore, for the quasi-ZVS control method, an analytical efficiency model based on the magnetizing current at t_1 $i_m(t_1)$ and the number of valleys of drain-source voltage when the switch turns on is proposed.

The loss of the resonant flyback converter includes the reverse conduction loss W_{rev}, the switching loss of the switch W_{sw}, the transformer core loss W_{core}, the transformer winding loss W_{wind}, the gate drive loss of eGaN HEMTs W_g, the conduction loss of eGaN HEMTs W_{con}, and the loss of the secondary diode W_d.

Therefore, the total loss W_{total_loss} can be expressed in (1)

$$W_{total_{loss}} = W_{core} + W_{wind} + W_g + W_{con} + W_{sw} + W_d + W_{rev} \quad (1)$$

Based on the above, the function between the total loss each cycle W_{total_T}, the magnetizing current at t_1 in the current cycle i_{m_cur} and the number of valleys of drain-source voltage when the switch turns on in the current cycle N_{v_cur} can be fitted by a Matlab script, which can be expressed in (2).

$$W_{loss\_T} = f_0(i_{m\_cur}, N_{v\_cur}) \quad (2)$$

Where N_{v_cur} is determined by i_{m_cur} and it can make the magnetizing current at t_1 each duty cycle $i_m(t_1)$ to fluctuate around $i_m(t_1)\_avg$, which can be expressed in (3).

$$N_{v\_cur} = f_1(i_{m\_cur}) \quad (3)$$

Similarly, the output power each cycle W_{o_T} can be expressed in (4).

$$W_{o\_T} = f_2(i_{m_{cur}}, N_{v_{cur}}) \quad (4)$$

The magnetizing current at t_1 in the next cycle i_{m_next} can be expressed in (5).

$$i_{m\_next} = f_3(i_{m\_cur}, N_{v\_cur}) \quad (5)$$

By the fitting function from (1) - (5), with the quasi-ZVS control, it can calculate the efficiency by iterative. The detailed efficiency iterative calculation diagram is shown in Fig. 5.

For (n)-th switching cycle,

$$i_{m\_cur}(n) = f_3(i_{m\_cur}(n-1), N_{v\_cur}(n-1)) \quad (6)$$

$$N_{v\_cur}(n) = f_1(i_{m\_cur}(n)) \quad (7)$$

Therefore,

$$W_{loss\_T}(n) = f_0(i_{m\_cur}(n), N_{v\_cur}(n)) \quad (8)$$

$$W_{o\_T}(n) = f_2(i_{m\_cur}(n), N_{v\_cur}(n)) \quad (9)$$

From (6) to (9), when $i_{m\_cur}(1)$ is equal to $i_m(t_1)\_avg$ which corresponds to different load conditions, the total power loss W_{total_loss} and the total output power in N switching cycles W_{total_o} can be derived that

$$W_{total\_loss} = \sum_{n=1}^{N} W_{loss\_T}(n) \quad (10)$$

$$W_{total\_o} = \sum_{n=1}^{N} W_{o\_T}(n) \quad (11)$$

From (10) to (11) , when the N is large enough, the efficiency with different $i_m(t_1)\_avg$ $\eta(i_m(t_1)\_avg)$ can be expressed in (12)

$$\eta(i_{m(t1)\_avg}) = \frac{W_{total\_o}}{W_{total\_o} + W_{total\_loss}} \quad (12)$$

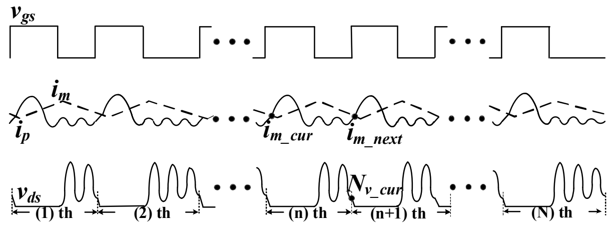


Fig. 5. Efficiency iterative calculation diagram

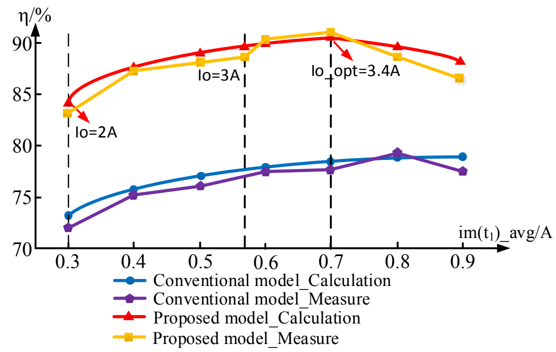


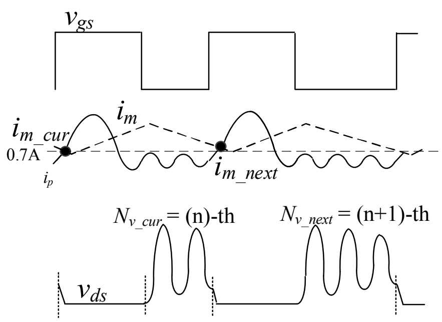
Fig. 6. Efficiency comparison with calculation and measure

The comparison of efficiency with calculation and measure is shown in Fig. 6. The measured efficiency is basically consistent with the calculated result, which verifies the proposed dynamic analytical efficiency model. When $i_m(t_1)\_avg$ is equal to 0.7A, the average output current I_{o_opt} is equal to 3.4A, and the peak efficiency of quasi-ZVS control is 90.9%. It corresponds to the highest efficiency point. Since I_{o_opt} is larger than the full load output current 3A, the quasi-ZVS on-off control under the efficiency-optimal point can be applied for the further improvement in efficiency over the full load range.

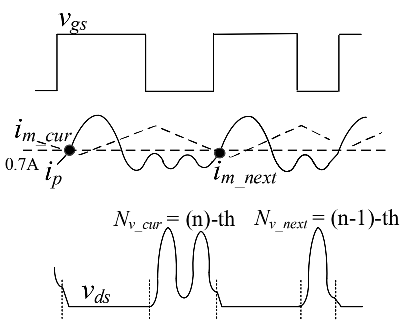
IV. Implementation of The Quasi-ZVS On-off Control

The on-off control is to switch the converter between ON and OFF mode. In the ON mode, the converter works at the efficiency-optimal point. While in the OFF mode, the converter is closed and there is no energy delivered to the load. The average power of the whole on-off period equals to the power required by the load so that the output voltage is stabilized around the reference.

When the output voltage V_o is higher than V_{omax}, OFF mode is applied, and the duty is set to zero. When the output voltage V_o drops to V_{omin}, the circuit works in ON mode. In ON mode, as shown in Fig. 7, the duty is adjusted based on the current circuit state. Assuming that the switch turns on at (n)-th vallays of drain-source voltage in the current cycle, it means that N_{v_cur} is equal to (n)-th, and if the magnetizing current at t_1 in the next cycle $i_{m(t1)\_next}$ is bigger than 0.7A(corresponding to the high efficiency point), the switch turns on at (n+1)-th vallays in the next cycle, otherwise, N_{v_next} is equal to (n-1)-th. Through the above control method, the control of the duty in the ON state can be completed.



(a) $i_{m(t1)\_next}$ > 0.7A (The efficiency-optimal point)



(b) $i_{m(t1)\_next}$ < 0.7A (The efficiency-optimal point)

Fig. 7. Duty in ON mode

V. Experimental Verification

The optimized control strategy is verified on a resonant flyback converter prototype, with V_{in} = 80 V, V_o = 12 V, I_o = 3 A, and the switching frequency is higher than 1MHz. the parameters are given in Table I, and the test board of the converter can be shown in Fig. 8.

Table. I Parameters of the resonant flyback converter

Lr	4.7uH
Lm	22uH
Cr	30nF (Murata)
Co	68uF (Murata)
Np/Ns	9 / 2
D_1	NTST30100CTG (ON)
M_1	GS66504B (GaN System, 650V, 15A)

Fig. 9 shows the closed-loop waveforms at I_o=3A under different control scheme. With the conventional pulse frequency modulation (PFM) control, the duty cycle is basically unchanged, and the average turn-on voltage $v_{ds}(t_0)$ is 182V. The measured efficiency is 78.3%. While with the quasi-ZVS control, the average turn-on voltage $v_{ds}(t_0)$ decreases to 84V, which brings an improvement of 10.5% in efficiency compared with the conventional scheme. Under the proposed optimized on-off control, $i_m(t_1)\_avg$ is equal to 0.7A (corresponding to the high efficiency point) in ON mode, the measured efficiency increases to 90% without SR, and the average turn-on voltage $v_{ds}(t_0)$ is 65V.

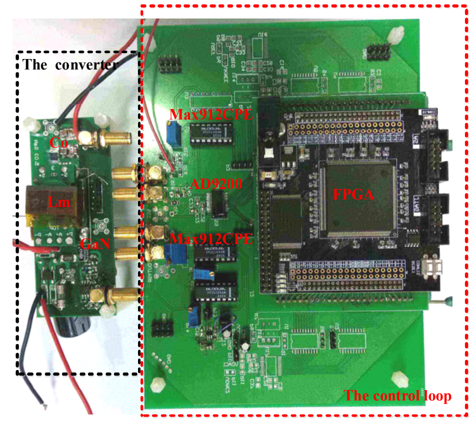
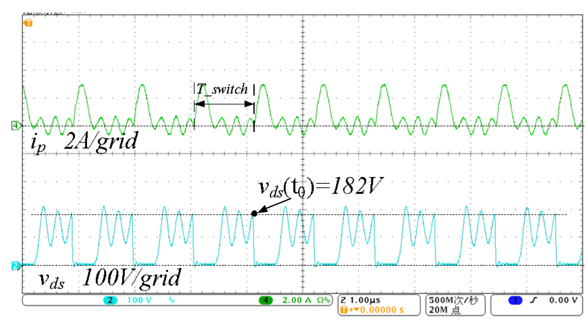
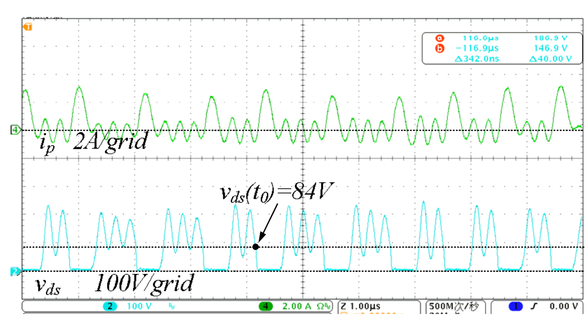


Fig. 8. The test board of the quasi-resonant flyback converter

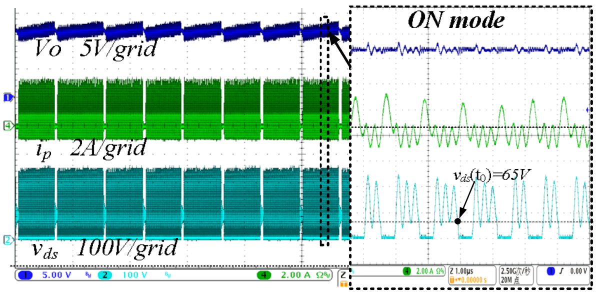
Fig. 10 shows the closed-loop efficiency comparison under different control scheme. The peak efficiency under the proposed optimized on-off control is 90%, and the light load efficiency is higher than 80%. Compared with the pulse frequency modulation (PFM) control, the efficiency of the Quasi-ZVS control increases by more than 10% over the full load range. Compared with the Quasi-ZVS control, the efficiency of on-off control is improved from 88.8% to 90% (an improvement of 1.2%) under full-load condition, and increases by 6.2% under 10% load condition.



(a)Conventional pulse frequency modulation (PFM) control



(b)Quasi-ZVS control



(c) Proposed optimized control with on-off

Fig. 9. Closed-loop waveforms under different control method

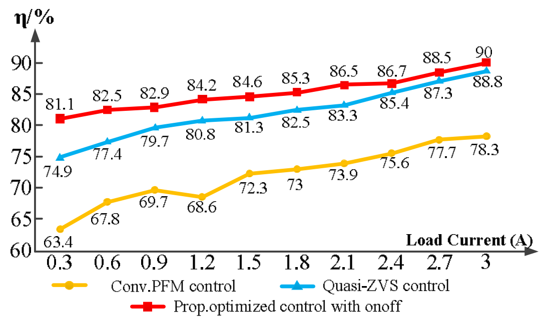
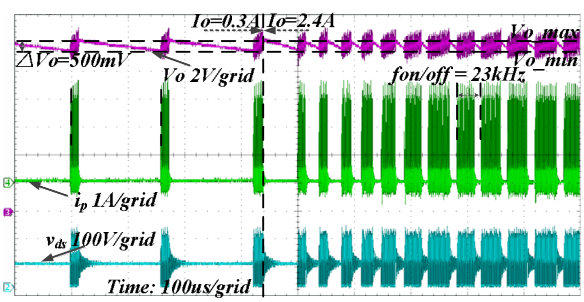
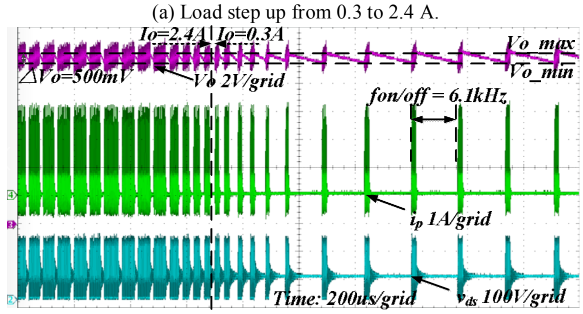


Fig. 10. Closed-loop efficiency comparison

Fig. 11 shows the load transient performance using the proposed optimized control with on-off. There is almost no settling time and voltage undershoot for both the step-up and step-down transient. The output ripple at 12 V output is about 500mV (4% of V_o), which is acceptable in most applications .The on-off frequency is about 23 kHz with 2.4 A output.



(a) Load step up from 0.3 to 2.4 A.



(b) Load step down from 2.4 to 0.3 A.

Fig. 11. Load transient response waveforms

VI. CONCLUTIONS AND FUTURE WORK

In this paper, a single-switched resonant flyback converter under the quasi-ZVS control is proposed to improve the efficiency. Since the control parameters are adjusted and varying continuously for each cycle under the quasi-ZVS control, the conventional efficiency calculation method is no longer applicable. A dynamic analytical model of power loss is established to find the highest efficiency working point of the resonant flyback converter with quasi-ZVS control. And the highest efficiency working parameters are used in on-off mode for overall efficiency improvement. The experimental test verified the dynamic analytical power loss model, and the peak efficiency of the 12V/3A resonant converter under the proposed optimized on-off control without synchronous rectification is about 90%. The light load efficiency is higher than 80%. Compared with the quasi-ZVS control, the efficiency of on-off control is improved from 88.8% to 90% under full-load condition, and the efficiency is increased by 6.2% under 10% load condition. The future work mainly focuses on the analysis of the efficiency drop in light load, and the improvement of the light load efficiency.

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