

New digital control method for improving dynamic response of synchronous rectified flyback converter with CCM and DCM mode

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Abstract—In order to improve the dynamic response of synchronous rectified primary-side regulation (PSR) flyback converter, a novel digital control method is proposed. When the output voltage is lower than the lower limit, a large power is transferred from the input to the output. When the output voltage is higher than the upper limit, a large power is transferred from the output to the input with synchronous rectification. During the dynamic control, the load is detected by the output voltage slope. The steady working condition is used as the starting point of normal multimode control when the output returns to the reference voltage. The following output voltage resonance is eliminated. With the proposed control method, the dynamic performance is greatly improved. A FPGA controlled 20V/5A synchronous rectified PSR flyback converter is established to verify the proposed control method. Compared to traditional multimode control, the maximum undershoot voltage and overshoot voltage of the proposed control scheme are improved from 5.02 to 1.63 V and 2.20 to 1.55 V, respectively. The maximum undershoot and overshoot recovery times are reduced from 83.43 to 1.16ms and 25.60 to 1.78ms, respectively.

Keywords—flyback converter; synchronous rectified; digital control; dynamic response

I. INTRODUCTION

Primary-side regulation (PSR) flyback converter is widely used in small power supplies, as adapters, LED drivers and chargers with higher power density, lower cost, and smaller standby power. To comply with various “energy star” (“green” power) requirements and improve the overall efficiency, synchronous rectification is always applied [1-2]. Multimode control methods are also used for flyback converters to reduce the frequency when the load becomes light [3-7]. While the dynamic performance gets worse as low frequency is applied for light load. Besides, the mode transition will consume a large amount of time which leads to larger voltage variations.

To improve the dynamic performance, fuzzy PID and predictive control algorithm are always used [8-11]. But all the proposed methods cannot realize “ideal” dynamic performance. In [12], two main works are used to optimize the dynamic performance. The first is to detect the load variation quickly. The second is to make the output voltage recovery to the reference voltage as soon as possible. Two dynamic modes are used to improve the dynamic performance. The voltage variations and the recovery times are greatly reduced. But the recovery time when the load changes from heavy to light are still too large. And the proposed method only fits for small

power converter with discontinuous conduction modulation (DCM) mode.

In this paper, to realize high dynamic performance, a digital control method is proposed for synchronous rectified PSR flyback converter. Continuous conduction modulation (CCM) mode is introduced for higher output power. When the output voltage is lower than the lower limit, light-to-heavy (LTH) mode is applied. To reduce the recovery time during LTH mode, very high power will be transferred from the input to the output. When the output voltage is higher than the upper limit, heavy-to-light (HTL) mode is used. In HTL mode, with synchronous rectification, large power is transferred from the output to the input resulting in rapid decline of the output voltage. When the output recovers to the reference voltage, normal multimode control method is used, and the stable working parameters will be used for the initial working point. The stable working parameters will be calculated based on the a peak current control method. The following voltage resonance is eliminated. Based on the proposed control method, the dynamic performance is improved greatly.

This paper is structured as follows. In Section II, the operating principle of the proposed dynamic control method is discussed. In Section III, the implementation of the proposed control method is described. In Section IV, the novel digital control scheme is implemented and the optimized dynamic responses are verified by an experimental prototype. This paper will be concluded in Section V.

II. THE PROPOSED CONTROL METHOD

The circuit configuration of the synchronous rectified PSR flyback converter is illustrated in Fig. 1. The output voltage V_o is sampled from the auxiliary circuit which contains the auxiliary winding W_a , resistor R_1 and R_2 [12-13]. Peak current control is used with a DAC to reduce the cost. The primary current i_p is sampled as v_p by resistor R_s . When v_p is larger than V_{pp} which is the output voltage of the DAC, the switch turns off and peak current control is obtained. V_{pk} is another output voltage of the DAC to measure the increasing slope of the primary current i_p for output current estimation during dynamic transition.

In this power supply, multimode control method is used to improve the total efficiency of the converter. The multimode control method can be shown in Fig.2. PWM mode is used when the load is heavy. When the output current is smaller than I_1 but larger than I_2 , PFM mode is applied. When the load

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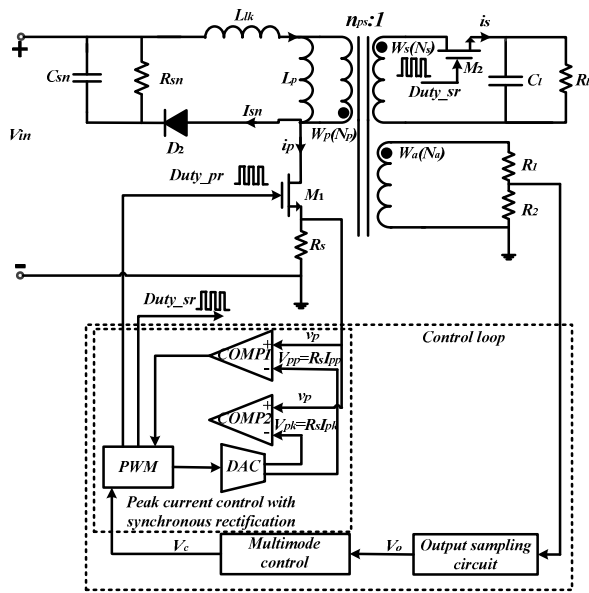


Fig. 1. The synchronous rectified PSR flyback converter

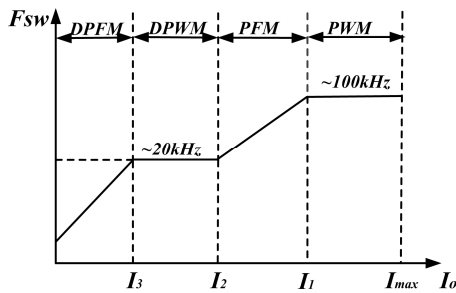
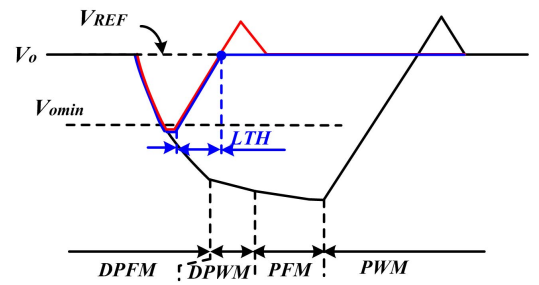


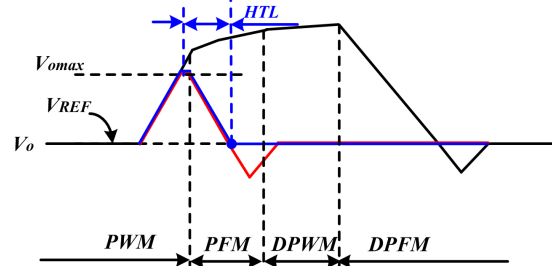
Fig. 2. The multimode control method

current is smaller than I_2 but larger than I_3 , the second PWM mode (namely “deep” PWM or DPWM) is used. When the load current is lower than I_3 , the second PFM mode (namely “deep” PFM or DPWM) is activated. The switching frequency is reduced when the load decreases to improve the efficiency. However, low frequency will degrade the dynamic performance.

The dynamic responses of the proposed dynamic control method and the normal multimode control method are compared in Fig. 3. As the red line shows, when the output voltage is lower than the lower limit V_{omin} ($V_{omin}=V_o-\Delta V$), LTH mode is used immediately. When the output voltage is higher than the upper limit V_{omax} ($V_{omax}=V_o+\Delta V$), HTL mode is used immediately. After V_o returns to the reference output voltage V_{REF} , LTH or HTL mode is replaced by the normal multimode control method. However, as the red line shows, voltage resonances cannot be avoided if the initial working point is not proper. Thus, we choose the stable control condition of the load as the initial working point. Besides, the load is detected by the output voltage slope. As the blue line shows, the voltage variation is limited and the recovery time is reduced in the proposed method.

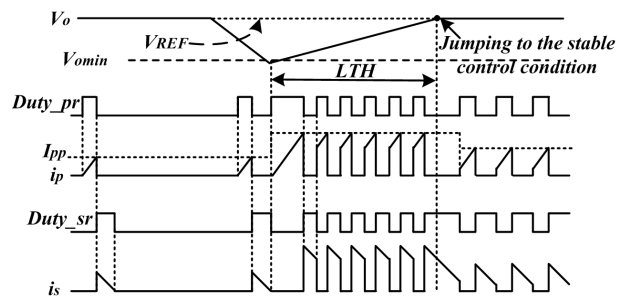


(a) LTH mode when load changes from light to heavy

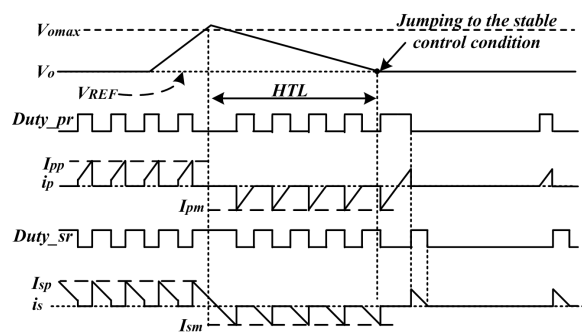


(b) HTL mode when load changes from heavy to light

Fig. 3. The working principles of LTH mode and HTL mode



(a) LTH mode



(b) HTL mode

Fig. 4. The realization LTH and HTL mode

As seen in Fig. 4, LTH and HTL mode are realized by synchronous rectified PSR flyback converters. The drive signal of the primary switch M1 is Duty_pr, and the drive signal of the synchronous rectified switch M2 is Duty_sr.

By increasing the peak current I_{pp} and reducing the switching period T_s , the input power of LTH mode will be increased which helps to reduce the recovery time when load changes from light to heavy. In HTL mode, the output energy is transferred to the input side. To reduce the recovery time, I_{pm} which is the minimum value of the primary current i_p should be as low as enough; the switching period should be as small as enough. As maximum current protection should be guaranteed, only DCM is used in HTL mode. When V_o returns to V_{REF} , normal multimode control will be used instead of LTH or HTL mode. The stable working stage of the load is chosen as the initial working condition of the multimode control method. Thus, the following voltage resonances can be removed. The output load is detected from the slope of the output voltage during LTH or HTL mode.

The dynamic performance can be greatly improved as the variation of the output voltage is limited in ΔV and the recovery time is significantly reduced. This digital control method can be used in other synchronous rectified topologies to improve the dynamic performance.

III. IMPLEMENTATION OF DYNAMIC MODE SWITCHING

The output voltage V_o is sampled based on the feedback voltage from the auxiliary winding. The flowchart of the proposed dynamic control method is shown in Fig. 5. When the output voltage is lower than the minimum voltage limit V_{omin} , LTH mode is applied to pull up the output voltage. After the output voltage reaches V_{REF} , the controller ends LTH mode and enters into the starting state which is the stable condition after the load changes. k_{up} represents the voltage increasing slope of V_o during LTH mode which is used to calculate the control parameters of the starting state. If the output voltage is higher than the maximum voltage limit V_{omax} , HTL mode is used to pull down the output voltage. After the output voltage reaches V_{REF} , the controller finishes HTL mode and enters into the starting state. k_{down} is the voltage decreasing slope of V_o during HTL mode. Based on k_{down} , the control parameters of the starting state are calculated. Normal multimode control which is shown in Figure 2 is used when LTH or HTL modes are off.

The output load in LTH mode is calculated when V_o reaches the reference output voltage V_{REF} . The output current in LTH is I_{o_LTH} which is firstly calculated as in Fig. 6. I_{pp} and I_{pk} are two reference current values which are set by V_{pp} and V_{pk} outputted from the DAC. The primary increasing slope can be calculated as in (1). t_2 is the time length when i_p increases from I_{pk} to I_{pp} which can be obtained from comparator COMP1 and COMP2. The primary average current during t_{on} period I_{pav} is expressed as in (2). Thus, the second average current of LTH mode can be expressed as in (3). N_p is the turns' number of the primary winding and N_s is turns' number of the secondary winding. The output load can be calculated as in (4). C_1 is the output capacitor. The stable output current I_o is obtained. Based on I_o , the control parameters of starting state can be acquired.

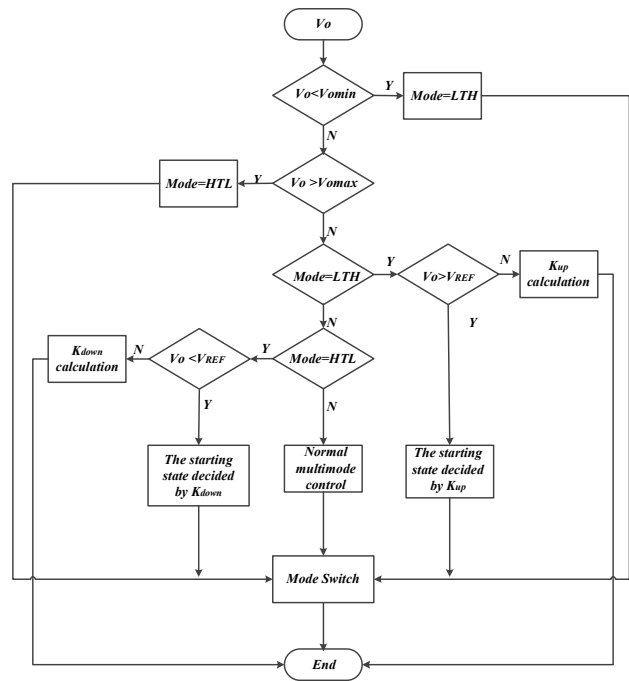
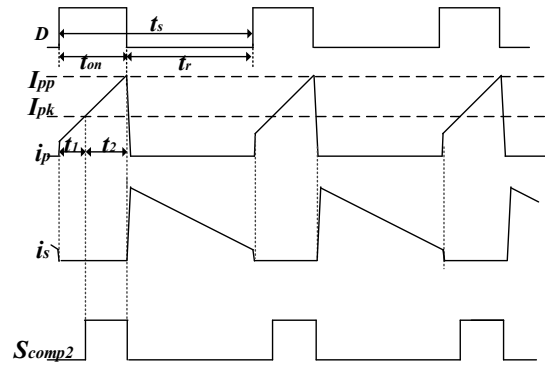
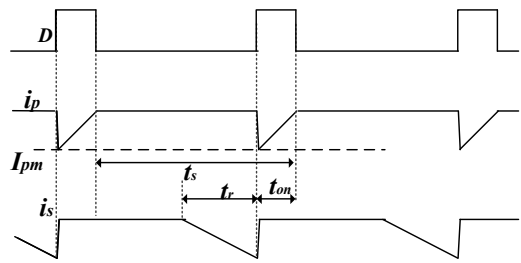


Fig. 5. The flow chart of the proposed dynamic control method



(a) LTH mode



(b) HTL mode

Fig. 6. The calculation of the starting state

$$k_{ip} = \frac{I_{pp} - I_{pk}}{t_2} \quad (1)$$

$$I_{pav} = I_{pp} - \frac{k_{ip} t_{on}}{2} \quad (2)$$

$$I_{sav} = \frac{N_p}{N_s} I_{pav} \frac{t_r}{t_s} \quad (3)$$

$$I_{o_LTH} = I_{sav} - C_l \frac{dv_o(t)}{dt} = I_{sav} - C_l k_{up} \quad (4)$$

Similarly, the minimum current I_{pm} of HTL mode can be expressed as in (5). k_{ip} is seen as a constant which is obtained in normal multimode control method as the input voltage is nearly constant. Thus, second average current of HTL mode can be expressed as in (6). The stable output current can be obtained from (7). Based on I_o , the control parameters of starting state can be acquired.

$$I_{pm} = -k_{ip} t_{on} \quad (5)$$

$$I_{sav} = \frac{N_p}{N_s} \frac{I_{pm}}{2} \frac{t_r}{t_s} \quad (6)$$

$$I_{o_HTL} = -C_l \frac{dv_o(t)}{dt} + I_{sav} = -C_l k_{down} + I_{sav} \quad (7)$$

With the control parameters of starting state acquired, when the output voltage reaches V_{REF} , the following voltage resonances are eliminated and the dynamic performance is optimized.

IV. EXPERIMENTAL VERIFICATION

To verify the above analysis, experiments are done for synchronous rectified PSR flyback converter. The parameters of this prototype for calculation and experiment are listed in Table I.

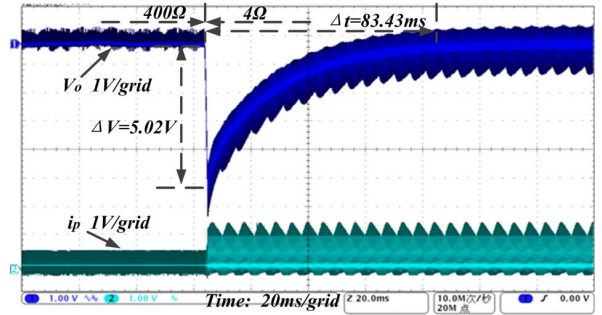
As shown in Fig. 7, when the load changes from 400Ω to 4Ω , the dynamic performances of traditional multimode control and the proposed control are compared. When LTH mode is used, the output voltage increases immediately. When V_o reaches 20V, the stable working state of the load is set as the initial working station of the multimode control method. The following voltage resonance is eliminated. As the lower limit V_{omin} is 18.5V. The undershoot voltage is around 1.5V. In experiment, the undershoot voltage is reduced from 5.02V to 1.63V and the recovery time is reduced from 83.43ms to 1.16ms. The dynamic performance is improved greatly.

As shown in Fig. 8, when the load changes from 4Ω to 400Ω , the dynamic performances of normal multimode control and the proposed control are compared. When HTL mode is used, as the output energy is transferred to the input, the output voltage decreases vert fast. When V_o reaches 20V, the stable working state of the output load is set as the initial working station of the multimode control method. The following voltage resonance is eliminated. As the upper limit V_{omax} is

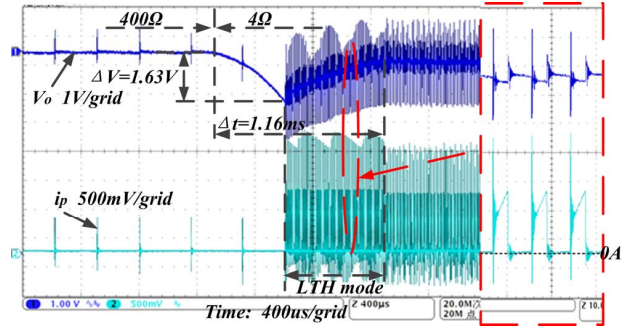
21.5V. The overshoot voltage is around 1.5V. In experiment, the overshoot voltage is reduced from 2.20V to 1.55V and the recovery time is reduced from 25.60ms to 1.78ms. The dynamic performance is improved greatly.

TABLE I. PARAMETERS OF THE MODEL AND PROTOTYPE

Quantity	Value	Unit	Remarks
Q	--	--	STF13NM60ND
V_{ac}	90~265	V	--
R_s	0.2	Ω	--
V_o	20	V	--
I_o	0~5	A	--
$N_p:N_s:N_a$	34:6:4	--	--
L_p	420	μ H	--
L_{lk}	20	μ H	--
C_1	680	μ F	--
D_1	--	--	NTST30100CTG
R_1	9k	Ω	--
R_2	1k	Ω	--

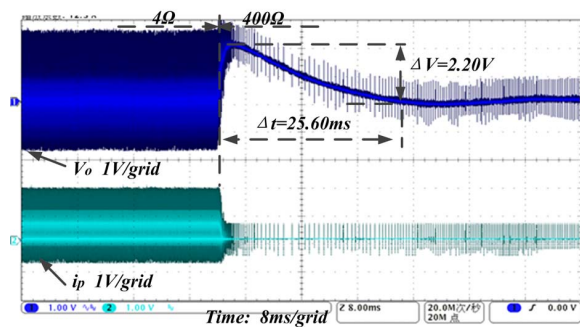


(a) the traditional multimode control

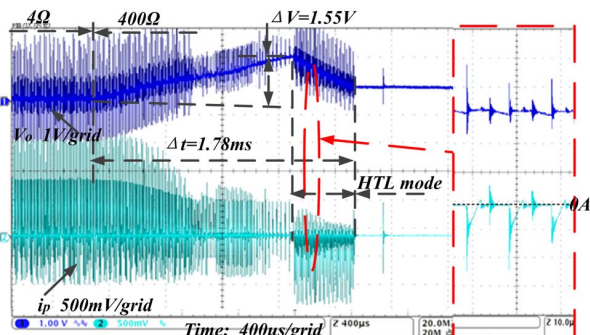


(b) the proposed digital control

Fig. 7. The comparison between the proposed control method and the normal multimode control method when load changes from light load to heavy load with 220Vac input.



(a) the traditional multimode control



(b) the proposed digital control

Fig. 8. The comparison between the proposed control method and the normal multimode control method when load changes from 4Ω to 400Ω with 220Vac input.

The performances of the traditional multimode control method and the proposed dynamic control method were evaluated and compared. The experimental results of the two control strategies are shown in Table II. Compared to the traditional multimode control method, the dynamic performance of the proposed dynamic control method is greatly improved.

TABLE II. THE EXPERIMENTAL RESULTS

Load changes	Undershoot voltage		Recovery time	
	Traditional	Proposed	Traditional	Proposed
400Ω→4Ω	5.02V	1.63V	83.43ms	1.16ms
400Ω→20Ω	1.746V	1.275V	7.22ms	1.18ms
Load changes	Overshoot voltage		Recovery time	
	Traditional	Proposed	Traditional	Proposed
4Ω→400Ω	2.20V	1.55V	25.60ms	1.78ms
4Ω→800Ω	3.15V	1.73V	64.32ms	2.30ms

The efficiency test of the proposed synchronous rectified PSR flyback converter is shown in Fig. 9. The input voltage is 220Vac. The peak efficiency is 95.4% as synchronous rectification greatly reduced the output diode loss in traditional diode rectification. The average efficiency is 93.5% which is greatly improved by the multimode control method.

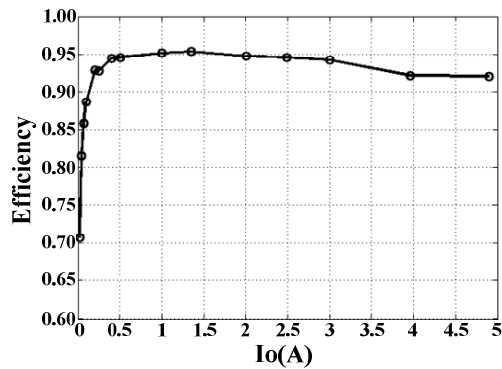


Fig. 9. The efficiency test of the proposed synchronous rectified PSR flyback converter

V. CONCLUSIONS AND FUTURE WORK

In this paper, a digital control method is proposed to improve the dynamic performance of synchronous rectified PSR flyback converters. Two dynamic modes, LTH mode and HTL mode, are used. When the output voltage is lower than the lower limit V_{omin} , LTH mode will transfer high power from the input to the output. When the output voltage is high than the upper limit V_{omax} , HTL mode will transfer high power from the output to the input. After LTH mode or HTL mode, the stable control parameters are directly used for the initial working point. Thus, the following voltage resonances are eliminated. The digital control method is verified in a FPGA controlled 20V/5A synchronous rectified PSR flyback converter. Compared to traditional multimode control, the maximum undershoot voltage and overshoot voltage of the proposed control scheme are reduced from 5.02 to 1.63 V and 2.20 to 1.55 V, respectively. The maximum undershoot and overshoot recovery times are reduced from 83.43 to 1.16ms and 25.60 to 1.78ms, respectively. Future work mainly focus on improving the power of LTH mode and the reversed power of HTL mode to realize nearly “ideal” dynamic performance. ΔV will also be reduced for improvement of dynamic performance.

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