Analysis and design of a novel tri-state Flyback PFC converter with high load power

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Abstract. A novel tri-state pseudo-continuous conduction mode (PCCM) Flyback power factor correction (PFC) converter and its corresponding control strategy are proposed to improve load power. The proposed converter is built with double MOSFET formed half bridge and operated in PCCM, which provides an additional degree of control freedom for simplifying the PFC controller. The tri-state PCCM Flyback converter can improve the load power effectively compared with the conventional DCM Flyback PFC converter at constant switching frequency. Analyses and 200W prototypes of the tri-state PCCM Flyback PFC converter and conventional DCM Flyback PFC converter have been presented. The results show that the proposed tri-state PCCM Flyback PFC converter is suitable for heavier load power compared with conventional DCM Flyback PFC converter.

1. Introduction

Power factor correction (PFC) converter has been popularly applied to satisfy the required harmonic standards [1, 2]. The constant switching frequency PFC converter can either operate in continuous conduction mode (CCM) or discontinuous conduction mode (DCM). The CCM operation of PFC converter is optimal for medium and high power applications because of minimal cost and bulk, and the DCM PFC converter is optimal for small power and low cost applications [3-6]. For CCM PFC converter, both current control loop and voltage control loop are required, where the current control loop controls the average input current of the converter to follow in phase with the input voltage to achieve unity power factor, and the voltage control loop is used to stabilize the output voltage. DCM PFC converter has been more widely used compared with CCM PFC converter, because the average input current of DCM PFC converter automatically follows the sinusoidal shape of input voltage without current control loop in steady state [7]. In addition, compared with CCM operation, DCM operation avoids output diode reverse recovery problem. However, DCM PFC converter suffers from high current stresses, which restrict the power range of single DCM PFC converter to lower power range (<100W) [8].

A two-stage structure including PFC converter and voltage regulator is typically employed in simultaneously performing PFC and fast output regulation by using two independent controllers. However, conversion efficiency is reduced and an extra PFC stage adds components and complexity because of these two processing stages. Consequently, in order to reduce the overall size and cost, a
number of single-stage PFC circuits have been developed [3-5]. The isolated converters such as Flyback or Forward converter are used to achieve isolated AC-DC conversion.

Apart from CCM and DCM operation mode, pseudo-continuous conduction mode (PCCM) is also discussed in [9]. Similar to DCM converter, PCCM converter has three operation stages in each switching cycle and does not have the right-half-plane (RHP) zero in the control-to-output Transfer function. It is reported that PCCM converter benefits with larger load-bearing ability than DCM converter and faster dynamic response than CCM converter [10-14]. The tri-state boost and two-switch buck-boost PFC converter with faster dynamic response have been introduced in [14-16], also a PCCM voltage-fed single-stage PFC full-bridge battery charger operating without a low-frequency ripple is reported in [17].

In order to improve load power of the Traditional DCM Flyback PFC converter, the tri-state PCCM Flyback PFC converter and its corresponding control strategy are proposed in this paper. The proposed tri-state PCCM Flyback PFC converter utilizing the half bridge MOSFET switch to provide an additional degree of control freedom has three operation modes in each switching cycle, which can improved the load power. The organization of this paper is shown as follows: Section II briefly analyzes the performance of Traditional DCM Flyback PFC converter. The operation modes and detail circuit design of the proposed tri-state PCCM Flyback PFC converter are demonstrated in section III and section VI, respectively. Excellent load-bearing abilities of the tri-state PCCM Flyback PFC converter are illustrated through experimental verification on a 200W prototype in Section V. Section VI summarizes the conclusion remarks as well as the overall evaluation of the proposed converter.

2. Traditional DCM Flyback PFC converter

The circuit diagram of the traditional DCM Flyback PFC converter is shown figure 1(a), where the converter consists of rectifier bridge, transformer $T_1$, primary main switch $S_1$, secondary freewheeling diode $D_1$, output capacitor $C$, error amplifier, photo-coupler, PWM pulse generator etc.

For simplicity, the following assumptions are defined: 1) All the devices and components including switch, diodes, transformer and capacitors are ideal; 2) the switching frequency $f$ is much higher than the line frequency $f_{line}$; and 3) the output voltage is regulated at a constant $V_o$, the rectified input voltage is $v_{in}(t)=V_M \sin(\omega t)$, where $V_M$ is the amplitude of the input voltage, $\omega$ is the angular frequency of the input voltage.

Figure 1(b) shows the main operation waveforms of the traditional DCM Flyback PFC converter. At the beginning of each switching cycle, the primary main switch $S_1$ is turned on and the freewheeling diode $D_1$ is reverse-biased, which causes the primary current $I_1$ ramps up from zero, the transformer $T$ stores energy, and output capacitor $C$ is discharged to supply power to the load. The PWM pulse generator produces sawtooth wave at the positive input port of comparator, when the voltage of sawtooth waveform increases to $V_{compt}$, the primary main switch $S_1$ is turned off and the freewheeling diode $D_1$ is forward-biased, which causes the transformer $T$ releases energy, the secondary current $I_2$ ramps down to supply power to the load, and output capacitor $C_1$ is charged. When the secondary current $I_2$ decreased to zero, the primary main switch $S_1$ and the freewheeling diode $D_1$ are turned off, which causes the output capacitor $C_1$ is discharged to supply power to the load again until the PWM pulse generator produces new switching cycle pulse.

When Traditional DCM Flyback PFC works at steady state, on-time $T_{on}$ of switch $S_1$ is constant. Hence the primary peak current $I_{1,p}(t)$ of Transformer $T_1$ can be given by

$$I_{1,p}(t) = \frac{T_{on}V_M \sin(\omega t)}{L_M}$$

where $L_M$ is the primary magnetic inductance of the Transformer $T_1$.

Thus, the primary average current $I_1(t)$ of the Transformer $T_1$ can be derived as

$$I_1(t) = \frac{1}{2} I_{1,p}(t)T_{on} = \frac{T_{on}V_M \sin(\omega t)}{2L_M T}$$

(2)
where $T$ is the switching cycle of the switch $S_1$. Since the primary average current of the transformer $T$, is the output rectified current of rectifier bridge, the average input current $I_{in}(t)$ can be given by

$$I_{in}(t) = \frac{T^2 v_{in} \sin(\omega t)}{2L_M T}$$  \hspace{1cm} (3)

Therefore, the average input current $I_{in}(t)$ of the Traditional Flyback PFC converter will naturally follow the sinusoidal shape of the input voltage and unity power factor can be obtained.

3. Tri-state PCCM Flyback PFC converter

By adding power switch $S_2$ and diode $D_2$, two variations of the proposed tri-state PCCM Flyback PFC converter derived from conventional Flyback PFC converter is shown in figure 2.

For tri-state PCCM Flyback PFC converter under cyclic steady state, there are three operation modes in each switching cycle as shown in figure 3 (a)–(c). In the $D_A T$ interval, the power switch $S_1$ and $S_2$ are turned ON and the diode $D_1$ and $D_2$ are reverse-biased, which causes the primary current $I_1$ ramps up, the transformer $T$ stores energy, and output capacitor $C$ is discharged to supply power to the load. In the $D_B T$ interval, the power switch $S_1$ and $S_2$ are turned OFF, the diode $D_1$ is forward-biased and the diode $D_2$ is reverse-biased. In this operation mode, the transformer $T$ releases energy, the secondary current $I_2$ ramps down to supply power to the load, and output capacitor $C_2$ is charged. In the $D_C T$ interval, the switch $S_1$ is turned OFF and $S_2$ is turned ON. Due to the freewheeling path formed by power switch $S_2$ and the diode $D_2$, the stores energy of the transformer $T$ is transfer from secondary winding to the primary winding, the diode $D_1$ is reverse-biased again and the diode $D_2$ is reverse-biased. In this operation mode, the primary current $I_1$ maintains constant, capacitor $C$ is discharged again to supply power to the load. Figure 4 shows the major waveforms of the tri-state PCCM Flyback PFC by assuming that the rectified line voltage $v_{in}(t)$ and output voltage $V_o(t)$ remain constant within each switching cycle.

It should be noted that

$$D_A T + D_B T + D_C T = T$$  \hspace{1cm} (4)
Due to the constraint in (4), it can be seen that any two time intervals of the three time intervals during one switching cycle can be controlled independently, provided that the $D_CT$ time interval does not vanish to zero. Thus, compared with conventional DCM Flyback PFC converter, the tri-state PCCM Flyback PFC converter gains one more degree of control freedom provided by the freewheeling interval of the primary current $I_1$.

![Figure 2. Tri-state PCCM Flyback PFC converter.](image)

![Figure 3. Equivalent circuits of tri-state PCCM Flyback PFC converter in different operation interval: (a) $D_AT$ interval, (b) $D_BT$ interval and (c) $D_CT$ interval.](image)

4. Characteristic analysis and circuit design

4.1. DC steady-state characteristics

Referring to figure 2, figure 3 and figure 4, the instantaneous voltage $v_{lm}(t)$ across the primary magnetic inductance $L_M$ of the transformer $T_1$ can be given as

$$v_{lm}(t) = \begin{cases} v_2(t) & t_0 \leq t < t_0 + D_AT \\ -v_2(t) & t_0 + D_BT \leq t < t_0 + (D_A + D_B)T \\ 0 & t_0 + (D_A + D_B)T \leq t < t_0 + T \end{cases}$$

$$v_{lm}(t) = \begin{cases} v_2(t) & t_0 \leq t < t_0 + D_AT \\ -v_2(t) & t_0 + D_BT \leq t < t_0 + (D_A + D_B)T \\ 0 & t_0 + (D_A + D_B)T \leq t < t_0 + T \end{cases}$$
where \( t_0 \) represents the instant time at the moment of the switch \( S_1 \) initiates its on-time operation. The time-averaged voltage \( V_{LM} \) across the inductor can be given by

\[
V_{LM} = \frac{1}{T} \int_{t_0}^{t_0+D_1T} v_{in}(t)dt - \frac{1}{T} \int_{t_0+D_1T}^{t_0+D_2T} v_{o}(t)dt
\]

which can further be simplified as

\[
V_{LM} = D_1V_n - D_2V_o
\]  

(6)

(7)

According to time-averaging equivalent principle, in each switching cycle, the volt-second balance of inductor gives rise to

\[
V_{LM} = 0
\]

(8)

Hence, from equations (7) and (8), we can obtain the DC steady-state characteristics of the tri-state PCCM Flyback PFC converter as follows

\[
\frac{V_o}{V_n} = \frac{D_1}{D_2} = \frac{D_{Q1}}{1 - D_{Q2}}
\]

(9)

where \( D_{Q1} \) and \( D_{Q2} \) express duty cycle of power switch \( S_1 \) and \( S_2 \), respectively. From (9), it can be seen that the output voltage \( V_o \) of the converter can be regulated by varying ON duty cycle \( D_{Q1} \) of power switch \( S_1 \) and OFF duty cycle \( (1-D_{Q2}) \) of power switch \( S_2 \).

4.2. Input current analysis and controller design
As shown in figure 4(a), the average input current \( I_{in,T}(t) \) of the tri-state PCCM Flyback PFC converter is the average value of shadow area in a switching cycle. Hence, from (3), the average input current \( I_{in,T}(t) \) can be derived as
\[ I_{in,t} = D_{QS} I_{ref} + \frac{D_{QS}^2 T}{2L_d} V_o \sin(\omega t) = D_{QS} I_{ref} + \frac{D_{QS}^2 T}{2L_d} V_o \sin(\omega t) \]  

From (10), if the duty cycle \( D_{QS} \) of the power switch \( S_1 \) keeps constant and the reference current \( i_{ref} \) follows in phase with the input line voltage \( v_{in}(t) \), the average input current \( I_{in,t}(t) \) will naturally follow the sinusoidal line voltage waveform and unity power factor can be obtained.

According to two control-freedom of the tri-state PCCM PFC converter [13-16], figure 5 shows the schematic of the controller of the tri-state PCCM Flyback PFC converter. The first control loop is used to regulate the duty cycle \( D_{QS} \) to stabilize output voltage. The second control loop is used to control the reference current \( i_{ref}(t) \) to make it in wave-shape too, and in phase with the input line voltage \( v_{in}(t) \) to achieve unity power factor of the PFC converter.

In the first control loop, the voltage error \( v_o \) between output voltage \( v_o \) and its reference voltage \( V_{ref} \) is fed to the voltage control loop (PI-controller) to generate control pulse of the power switch \( S_i \). As the same as DCM Flyback PFC converter, by ignoring output voltage ripple, the on-time interval \( D_{QS} T \) of the power switch \( S_i \) within a switching cycle is essentially constant over one ac line cycle (rectified 50Hz) [7]. The output voltage \( v_o(t) \) of the tri-state PCCM PFC converter is also constant.

The reference current \( i_{ref}(t) \) is the key factor in the second control loop, which should larger than the load current \( i_o(t) \) to ensure the PCCM operation [17]. The bigger the reference inductor current \( i_{ref}(t) \) is set, the longer the time interval \( D_{c} T \) is obtained. However, on the other hand, time interval \( D_{c} T \) should be kept as small as possible to shorten inductor freewheeling time. Hence, in order to regulate the reference current \( i_{ref}(t) \) sinusoidal and directly proportional to the load power, the reference current \( i_{ref}(t) \) is produced by multiplying the input voltage \( v_{in}(t) \) with the proportional coefficient \( k \). When the secondary current \( I_2 \) decreases to the reference current \( i_{ref}(t) \), the comparator generates control pulse to turn on power switch \( S_1 \) and \( S_2 \) until the next switching cycle. Hence, the average input current \( I_{in,t}(t) \) can be rewritten as

\[ I_{in,t} = (D_{QS} k + \frac{D_{QS}^2 T}{2L_d} V_o) \sin(\omega t) = I_M \sin(\omega t) \]  

where \( I_M \) is the amplitude of the input current. According to power conservation principle of the converter, the output power \( P_o \) of the tri-state PCCM PFC Flyback converter is

\[ P_o = \frac{V_o^2}{R_L} = \frac{V_{in}^2}{R_L} = \frac{V_M I_M}{2\eta} \]  

where \( \eta \) is the efficiency of the tri-state PCCM PFC Flyback converter, \( R_L \) is the load of the tri-state PCCM PFC Flyback converter. From equation (11) and (12), the proportional coefficient \( k \) can be derived as

\[ k = \frac{2\eta V_{in}^2}{P_{QS} R_L V_M} \frac{D_{QS}^2 T}{2L_d} \]  

In practical circuit design, the proportional coefficient \( k \) should slightly larger than the calculated value from equation (13) to ensure the tri-state PCCM PFC Flyback converter operate in PCCM steadily.

5. Experimental verification

To verify the analysis results given above, experimental investigations of Flyback PFC converter operating in DCM and PCCM are performed with the same circuit parameters as listed in Section V. The main circuit parameters are: \( L_M=200\mu H, n=21:11, C=5400\mu F, f=50kHz, v_{in}=110V \text{ (RMS)}, v_o=48V \) and \( P_o=200W \), and control IC is DSP2812.

Figure 6 shows the zoom-in waveform the drive pulse \( D_{QS} \) of power switch \( S_1 \), drive pulse \( D_{S2} \) of power switch \( S_2 \), primary current \( i_1 \) and secondary current \( i_2 \) at rated 100W output power, from which
it can be known that the tri-state PCCM Flyback PFC converter has three operation states in each switching cycle.  

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{fig6.png}
\caption{Drive pulse $D_{S_1}$ of power switch $S_1$, drive pulse $D_{S_2}$ of power switch $S_2$, primary current $i_1$ and secondary current $i_2$ waveform: (a) the DCM Flyback PFC converter, (b) the tri-state PCCM Flyback PFC converter.}
\end{figure}

Figure 7 and figure 8 show the rectified input voltage $v_{in}$, primary current $i_1$, input current $i_{in}$ and input current $i_{in}$ FFT spectrum analysis waveforms of DCM and PCCM Flyback PFC converter at 100W and 200W output power respectively. From figure 7 and figure 8, it can be known that the tri-state PCCM Flyback PFC converter has the wide load range than the traditional DCM Flyback PFC converter. The tri-state PCCM Flyback PFC converter also can operating in PCCM steadily and high power factor can be obtained at 200W output power, because that input current $i_{in}$ is in phase and in waveform with input voltage $v_{in}$. Thus the tri-state PCCM Flyback PFC converter can therefore work at heavier load than the traditional DCM Flyback PFC converter.

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{fig7.png}
\caption{Rectified input voltage $v_{in}$, primary current $i_1$, input current $i_{in}$ and input current $i_{in}$ FFT spectrum analysis waveform at 100W output power: (a) the DCM Flyback PFC converter, (b) the tri-state PCCM Flyback PFC converter.}
\end{figure}
Figure 8. Drive pulse $D_{S_1}$ of power switch $S_1$, drive pulse $D_{S_2}$ of power switch $S_2$, primary current $i_1$ and secondary current $i_2$ waveform: (a) the DCM Flyback PFC converter, (b) the tri-state PCCM Flyback PFC converter.

As shown in figure 9, the power conversion efficiency of the tri-state PCCM Flyback PFC converter is lower than that of the DCM Flyback PFC converter. The reason for lower efficiency of the tri-state PCCM Flyback PFC converter is that the current path is $D_2$ and $S_2$ during the inductor current freewheeling time interval, not $D_1$ during the inductor current ramps down time interval, and also the current path is both $S_1$ and $S_2$ during the inductor current ramps up time interval.

Figure 9. Efficiency versus load power.

Table 1 summarizes the THD and PF of DCM and PCCM Flyback PFC converter at 100W and 200W output power respectively. From table 1, both the THD and PF of PCCM Flyback PFC converter perform excellent compared with this of DCM Flyback PFC converter at 200W output power.

| Power/W  | THD    | PF    |
|----------|--------|-------|
|          | DCM    | PCCM  |
|          | DCM    | PCCM  |
| 200      | 27.58  | 13.51 |
|          | 0.964  | 0.991 |
| 100      | 10.04  | 11.00 |
|          | 0.995  | 0.994 |
6. Conclusions
In this paper, a novel isolated tri-state PCCM Flyback PFC converter is proposed. By adding a power switch and a diode, the tri-state PCCM Flyback PFC converter has an additional degree of control freedom. Hence, the tri-state PCCM Flyback PFC converter obtains more wider load power range than conventional DCM Flyback PFC converter. The experimental results clearly demonstrate that the tri-state PCCM Flyback PFC converter have higher load bearing performance than that of the traditional DCM Flyback PFC converter.

The proposed converter can be used in applications wherever wide load variation range, high PF and isolation structure are need.

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