Research on the PFC Mechanism of Forward-Flyback Converter

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Abstract. The forward-flyback converter is used in power factor correction to improve the performance of conventional forward PFC and flyback PFC converters. By analyzing the working principle of a single-transistor single-transformer forward-backward combined PFC converter in one power frequency cycle, it is pointed out that there are two working modes—flyback mode and forward flyback mode; through its PFC mechanism research. The relationship between the duty cycle of each operating mode when achieving unity power factor is obtained, and the duty cycle when operating in flyback mode is the maximum duty cycle within a power frequency cycle. Finally, the open-loop control model of the forward-flyback PFC converter is established by using MATLAB. The duty cycle is changed according to the specified rules and the PFC is implemented, which verifies the correctness of the theoretical analysis.

1. Introduction

Single-phase active power factor correction (PFC) technology can greatly improve the power factor of the uncontrolled rectifier circuit, effectively reduce the harmonic content of the grid-side current, and it is an important means to improve power quality [1].

Flyback PFC converters have the advantages of input and output isolation, simple structure and low cost, it have become one of the most commonly used single-stage PFC converters [2-5]. However, due to transformer leakage inductance and power device stress and other factors, it is mainly used for applications below 100W [6].

The forward PFC converter has the characteristics of isolate the input and buck output and it has a high energy transmission efficiency [7]. However, due to its inherent structure, it is necessary to add a magnetic reset circuit. When the instantaneous input voltage is low, the converter cannot achieve energy transfer, a dead zone with zero input current occurs, and the dead time is long at low voltage input, causing its cannot satisfy the harmonic requirements of IEC61000-3-2 [8].

The forward-flyback converter can work in both forward and flyback modes and significantly improve the circuit performance. It has been widely studied and concerned by people in the industry[9-11]. It works in flyback mode when the input voltage instantaneous value is low in PFC, the unity power factor can be obtained [12] and the input current has no dead zone. The transformer core not only resets naturally, but also transfers the magnetizing energy to the load with the high energy transmission efficiency [13].The documents [6-7] studied the forward-flyback PFC converters with dual secondary windings in resonant control, the performance of the forward and flyback parts of the converter are compared in critical mode (CRM), respectively. It was pointed out that when the flyback
part works in CRM, it can obtain higher energy transmission efficiency and power factor, and its parameter design methods were summarized. Reference [12] compares the input current distortion degree and power factor of the forward-flyback combined PFC converter with constant duty cycle and variable duty cycle control, and points out that the former can obtain the best working performance. At present, a variety of forward-back converter converter configurations have been proposed [14-16]. Among which the single-transistor single-transformer configuration [16] is the simplest, and it has higher research value with the advantages of dual-transformer structure and double-secondary-side winding structure.

Therefore, the forward-flyback application in PFC was studied, the working mode of the converter in a power frequency cycle and the mechanism of unity power factor were analyzed. Finally, the simulation of an open-loop control model verified the correctness of theoretical analysis.

2. Work mode analysis

The main circuit topology of a single-tube single-transformer forward-flyback combined PFC converter is shown in Figure 1. Its forward part can only work in current discontinuous conduction mode (DCM). The main working waveform in a power frequency cycle is shown in Figure 2, where: \(v_g\) and \(i_g\) are the input voltage and input current after rectification and filtering; \(i_{o, \text{for}}\) and \(i_{o, \text{fly}}\) are the output currents of the forward and flyback sections, respectively.

![Forward-flyback PFC converter](image1.png)

**Figure 1.** Forward-flyback PFC converter

![Waveform of forward-flyback PFC converter](image2.png)

**Figure 2.** Waveform of forward-flyback PFC converter

It can be seen that the converter has two operating modes: flyback mode and forward-flyback mode.
Flyback mode: When the input voltage $v_g$ is lower than $nV_o$, the diodes VD2 and VD4 are reversed during the switch on period, and the forward part cannot work. At this point, only the flyback part powers the load, and the converter shows the operating characteristics of the flyback PFC converter.

Forward-flyback mode: When the input voltage $v_g$ is higher than $nV_o$, both the forward and flyback parts can provide energy for the load.

3. Power factor correction

The mechanism of power factor correction implemented by the forward-flyback converter is analyzed following. To simplify the analysis, the following assumptions is made first.

(1) All devices are ideal, regardless of the effects of parasitic parameters.
(2) The switching frequency is much larger than the power frequency. In a switching cycle, the input voltage can be regarded as a constant value approximately.
(3) The output filter capacitor is large enough that the output voltage remains constant during one power cycle during steady-state operation.

In order to ensure the output voltage stability and obtain the unity power factor, the following relationship should be satisfied.

$$
\begin{align*}
\cos \theta & = \frac{i_o(\theta)}{I_{in\_rms}} = \frac{v_o(\theta)}{V_{in\_rms} \sin \theta}
\end{align*}
$$

(1)

Where $v_i(\theta)$ is the AC input voltage; $i_i(\theta)$ is the AC input current; $v_o(\theta)$is the output voltage; $V_{in\_rms}$ is the AC input voltage rms value; $I_{in\_rms}$ is the AC input current rms value.

According to instantaneous power conservation, the following equation can be obtained:

$$
\begin{align*}
P_o(\theta) & = v_o(\theta)i_o(\theta) = V_o i_o(\theta) \\
& = P_{in}(\theta) = 2V_{in\_rms}I_{in\_rms} \sin^2 \theta
\end{align*}
$$

(2)

Among them, $P_o(\theta)$ is the output average power in one switching period; $P_{in}(\theta)$ is the instantaneous input power; $i_o(\theta)$ is the average output current in one switching period.

Therefore, the following equation can be obtained according to equation (2).

$$
\begin{align*}
i_o(\theta) & = 2 \frac{V_{in\_rms}}{V_o} I_{in\_rms} \sin^2 \theta = i_o(\theta)_{for} + i_o(\theta)_{fly}
\end{align*}
$$

(3)

A. Flyback mode power factor correction mechanism

The input power frequency sinusoidal AC voltage rectified by the diode rectifier bridge can be expressed as:

$$
v_g(\theta) = \sqrt{2}V_{in\_rms} \sin \theta
$$

(4)

Let $v_g(\theta) = nV_o$, and the critical phase angle $\theta_c$ of the converter operating in positive-flyback mode is:

$$
\theta_c = \arcsin \frac{nV_o}{\sqrt{2}V_{in\_rms}}
$$

(5)

In the formula, $n$ is the transformer turns ratio; $V_o$ is the direct current output voltage.

When $(n-1)\pi + \theta_c < \theta < n\pi - \theta_c$, the converter operates in the forward-flyback mode; otherwise it operates in the flyback mode.

When the converter works in flyback mode, the flyback part first works in DCM as $v_g(\theta)$ rises from zero. According to the relationship between the input voltage and output voltage, the following equation can be obtained:

$$
\begin{align*}
i_o(\theta) & = i_o(\theta)_{fly} = \frac{v_g(\theta)^2 d(\theta)^2}{2L_m V_o f}
\end{align*}
$$

(6)
where, $d(\theta)$ is the switch conduction ratio (duty cycle); $L_m$ is the transformer magnetizing inductance; $f$ is the switching frequency.

The equation (3) can be brought into the above formula. To achieve unity power factor, the duty cycle $d(\theta)$ should be

\[ d_1 = \sqrt{\frac{2fL_m}{V_{in\_rms}}} \]  

(7)

It can be seen that the duty cycle is constant as the instantaneous value of the input voltage increases.

With the increase of $\theta$, if the flyback part enters continuous current mode (CCM), according to the relationship between the input voltage and output voltage, the duty cycle $d(\theta)$ should be changed according to the following formula.

\[ d_2(\theta) = \frac{nV_o}{V_g(\theta) + nV_o} \]  

(8)

The expression of the output current of the converter can be expressed by the formula (3) at this point, and the unity power factor also can be achieved.

B. Forward-flyback mode power factor correction mechanism

The converter operates in the forward-flyback mode when $V_g(\theta) > nV_o$. During the on-time of the switch, the current through the inductor $L$ rises linearly, and the peak current is:

\[ I_{LP}(\theta) = \frac{v_g(\theta) - nV_o}{nLf} d(\theta) \]  

(9)

During the off-time of the switch, the time required for the inductor current to drop to zero is $t_d(\theta)$.

\[ t_d(\theta) = \frac{I_{LP}(\theta)}{V_o / L} = \frac{v_g(\theta) - nV_o}{nfV_o} d(\theta) \]  

(10)

Therefore, the average output current of the forward part of a switching cycle is:

\[ i_{o,for}(\theta) = \frac{1}{2T} \left[ v_g(\theta) \ast d(\theta) \right] I_{LP}(\theta) \]  

\[ = \frac{d^2(\theta) V_{in\_rms}^2 \sin^2 \theta}{Lt_m f} \left[ \frac{1}{V_o} \left( \frac{1}{n^2 L} - \frac{1}{nL} \right) \frac{1}{\sqrt{2V_{in\_rms} \sin \theta}} \right] \]  

(11)

If the forward part and the flyback part both work in DCM at the same time, the average output current of the converter in one switching cycle is:

\[ i_o(\theta) = i_{o,\_fly}(\theta) + i_{o,\_for}(\theta) \]  

(12)

Equations (6) and (11) can be brought into the above formula to obtain formula (13).

\[ i_o(\theta) = \frac{d^2(\theta) V_{in\_rms}^2 \sin^2 \theta}{L_m f} \left[ \frac{1}{V_o} \left( \frac{1}{n^2 L} - \frac{1}{nL} \right) \frac{1}{\sqrt{2V_{in\_rms} \sin \theta}} \right] \]  

(13)

Conclusions are drawn combine the formulas (3) and (13). when the forward part and the flyback part both work in the DCM at the same time, the duty ratio of the unity power factor should be changed by the following relationship.

\[ d_3(\theta) = \frac{d_1}{\sqrt{1 + \frac{1}{n^2 L} - \frac{1}{nL} \frac{V_o}{\sqrt{2V_{in\_rms} \sin \theta}}}} \]  

(14)

It can be seen that when $\theta = \theta_c$, $d_3(\theta_c) = d_1$, and when $\pi - \theta_c > \theta > \theta_c$, $d_\theta < d_{FB}$. Therefore, $d_1$ is the maximum duty cycle in this mode.
When the flyback enters the CCM as \( v_{gb}(\theta) \) rises, the relationship between the input voltage and the output voltage is:

\[
V_o = \frac{d(\theta) \sqrt{2V_{in\_rms}} \sin \theta}{1-d(\theta)} \frac{n}{n} \tag{15}
\]

and its duty cycle changes according to the following rules at this time:

\[
d_4(\theta) = \frac{nV_o}{v_{gb}(\theta)+nV_o} \tag{16}
\]

The expression of the output current is shown in equation (3). It also enables unity power factor. Synchronous formulas (14) and (16) yield the following formula.

\[
\frac{nV_o}{\sqrt{2V_{in\_rms}} \sin \theta + nV_o} = \frac{2/LL_i}{V_{in\_rms}} \left[ 1 + \frac{L_2}{n^2L} \frac{V_vL_4}{\sqrt{2nV_{in\_rms}L \sin \theta_d}} \right] \tag{17}
\]

According to the above formula, the critical angle \( \theta_d \) of the flyback part entering the CCM can be obtained.

4. Example and simulation analysis

An example circuit of 24V/100kHz is designed to verify the theoretical analysis aforementioned and use MATLAB performs simulation analysis. The circuit parameters are shown in Table 1.

| Parameter                  | Setting value |
|----------------------------|---------------|
| Input voltage \( (v_i) \)  | 220V \(_{ac}\) |
| Output voltage \( (V_o) \) | 24V \(_{dc}\) |
| Output current \( (I_o) \) | 3A            |
| Switch frequency \( (f) \) | 100kHz        |
| Inductance \( (L) \)       | 40uH          |
| Secondary inductance \( (L_2) \) | 200uH |
| Transformer ratio \( (n) \) | 2             |

For simplicity, the AC input voltage and the full-bridge rectification part are directly operated by using a sine signal source, and the output is connected to a voltage control source to provide power for the component model. To make the simulation closer to the ideal situation, use an ideal switch instead of a power switch and set the diode's turn-on voltage drop to zero, and replace the output filter capacitor with an ideal voltage source in order to ignore the effects of twice power-frequency ripple. The simulation circuit is shown in Figure 3.
According to the formulae (5) and (17), the critical phase angles of the converter operating in the forward-flyback mode and the flyback part entering the CCM are: \( \theta_c = 8.875^\circ \) and \( \theta_d = 31.143^\circ \). In order to verify the PFC mechanism of the converter, open-loop control was used for simulation analysis. The open-loop control model is shown in Figure 4.

According to the above control method, the duty cycle of the inverter operating in the flyback mode is constant and its expression is as shown in Equation (7); when the converter is operating in the forward-flyback mode, the duty cycle of the flyback part operates in the DCM and CCM is shown as the formulas (14) and (16), respectively. The simulation results are shown in Figure 5.

**Figure 3.** Circuit of simulation

**Figure 4.** Open-loop control model

(a) Input voltage and current waveform

(b) Converter input voltage/current waveform and transformer secondary current waveform
The simulation results are consistent with the theoretical analysis. The duty cycle changes according to the specified rule in each mode of the converter, and the input current follows the input voltage, and the unity power factor can be achieved.

5. Conclusion
The forward-flyback converter combines the characteristics of the forward and flyback converters. There are two working modes of the converter during one power frequency cycle when applied to PFC: the flyback mode and the forward-flyback mode. And unity power factor is realized as long as the duty cycle changed according to a specified law in each mode of the converter. Maximum duty cycle is obtained when the converter is operating in DCM of the flyback part in one power frequency cycle, and then the duty cycle gradually decreases as the input voltage rises.

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