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Study of a Three-Phase Bridgeless Flyback PFC Converter

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***Abstract*—Traditional power factor correction (PFC) circuit, which limits the power density is often passive components. With the development of power electronics technology, high-frequency, modular, miniaturization is the inevitable trend of development. In pursuit of efficiency and the use of bridgeless topology brought about more complex control method compared with the conventional topology. In this paper a three-phase bridgeless Flyback PFC topology is studied, the use of three-phase input, which greatly reduce the storage capacity of the capacitor, working in discontinuous current mode (DCM), using fixed duty cycle control to achieve unity power factor, with a simple and efficient, simple control advantages. The simulation results from a 250W universal input prototype are given to verify the effectiveness of the analysis.**

***Index Terms*—power factor correction, energy storage capacitor, three-phase input, power density**

I. Introduction

[1]With the popularity of electronic devices, it brings a lot of higher harmonics on the grid and causes pollution. In order to reduce the electronic equipment for the grid harmonic pollution, more and more countries restrictions on input current harmonic content of the electrical equipment and made a lot of criteria to limit the input current harmonics. To reduce the input current harmonics, and then proposed a power factor correction (PFC) technology. But the traditional passive power factor correction to achieve power factor correction by the way of reactive power compensation and relatively large volume. With the development of power electronics technology, a new type of active power factor correction by controlling the switch on and off to force the input current to follow the input voltage to achieve power factor correction (PFC), compared with the traditional passive approach has the advantages of high power density. [1], [2]

In the active factor correction circuit Flyback topology most widely used. According to the transformer primary current continuous or not, Flyback power factor correction (PFC) circuit is divided into Continuous Current Mode (CCM), Critical Continuous Mode (CRM), and Discontinuous Current Mode (DCM). DCM Flyback PFC converter which has a simple control, unity power factor correction, no reverse recovery current, feedback loop stability, fast response, etc., is more applicable in small and medium power applications. [3]-[5]

The advantage of the three-phase input is that the three-phase magnetic core column can be coupled together. Because of the mutual inductance between the magnetic core column, so the three-phase transformer compared with the single phase transformer has the advantage of coupling more closely. As shown in Fig. 1, when the transformer symmetry operation, three-phase transformer tends to three separate single-phase transformer. [6]

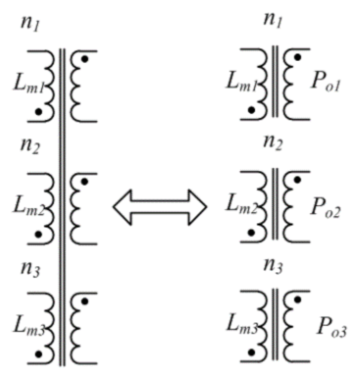

Figure 1. The three-phase transformer tends to three separate single-phase transformer

II. Anaysis of Three-Phase Bridgeless DCM Flyback PFC Converter

Fig. 2 is the main circuit of Three-Phase Bridgeless Flyback PFC converter, in which the switch of each phase is bidirectional switch. In order to facilitate analysis, make the following assumptions: 1) All devices are ideal components; 2) The output voltage ripple is small compared to its direct flow; 3) The switching frequency is much higher than the input voltage frequency.

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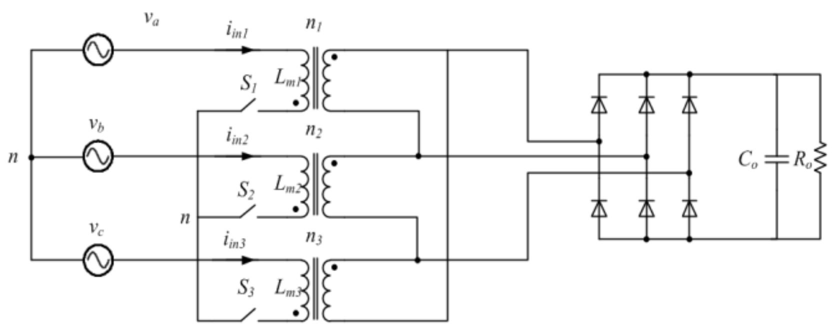


Figure 2. The main circuit of the topology

Fig. 3 is the waveform change of the each phase inductor current and the flux of the DCM Flyback PFC Converter at one period.

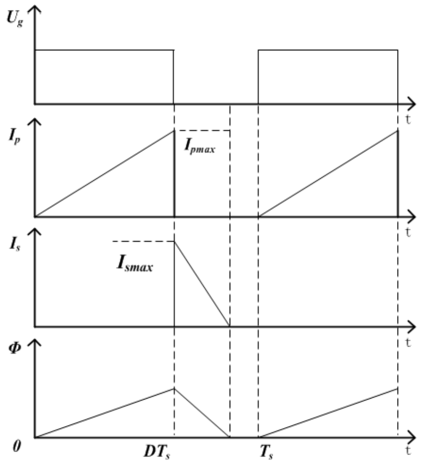


Figure 3. The flux and current of the converter

When the primary side bidirectional switch S is turned on, because the voltage of the storage capacitor is bigger than the three-phase rectifier bridge of three common cathode anode of the diode voltage, the three-phase rectifier bridge withstand reverse voltage cutoff and the secondary winding open circuit. As is show in Fig. 3, the transformer core is magnetized and the flux ϕ and the prime side current I_p increases linearly, the amount of increased magnetic flux can be expressed as:

$$\Delta\varphi = \frac{V_{in}}{N_1} DT_s \tag{1}$$

Energy stored in the transformer and the storage capacitor supply the load.

When the bidirectional switch S is turned off, transformer secondary rectifier conduction and the circuit can be expressed as Fig. 4.

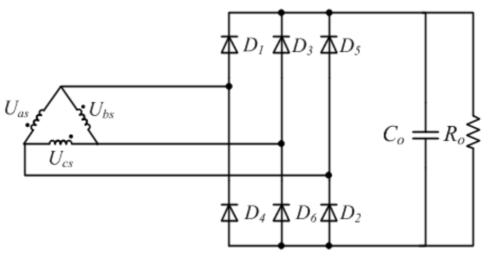


Figure 4. The connection of the secondary transformer

The energy stored in the transformer is transferred to the secondary side. The secondary side of the transformer windings is similar to current source, and because of the secondary side is delta connection, the line current lags the phase current 30^o and the three-phase bridge rectifier can be seen as three independent arms. According to the direction of the line current, it is easy to judge whether the diode conduction or not. Thus one period of the input voltage can be divided into six parts, and each for 60^o, as it shown in the Fig. 5 and Fig. 6.

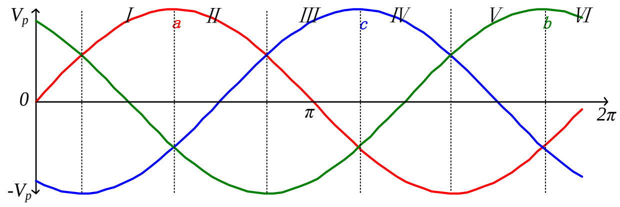


Figure 5. The three-phase input voltage

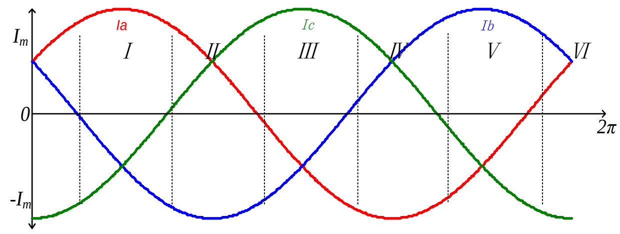


Figure 6. The three-phase line current

The conduction diode of each part is shown in the Table I.

TABLE I. THE CONDUCTION OF THE DIODE

Time	I	II	III
Common cathode Diode Conduction Group	D1	D1,D5	D5
Common Anode Diode Conduction Group	D2,D6	D6	D4,D6
Time	IV	V	VI
Common cathode Diode Conduction Group	D3,D5	D3	D1,D3
Common Anode Diode Conduction Group	D4	D2,D6	D2

At the same time, the transformer core is demagnetized and the flux can be expressed as:

$$\Delta\varphi = \frac{V_o}{N_2} \cdot D_2 \cdot T_s \tag{2}$$

According to the principle of flux balance, the relationship between the output voltage and the input voltage can be expressed as:

$$\frac{V_o}{V_{in}} = \frac{N_2}{N_1} \cdot \frac{D}{D_2} \tag{3}$$

So we can get the conclusion that the working condition of the three-phase DCM Flyback PFC converter is that by adjusting the proper turns ratio to make sure when the primary side bidirectional switch is turn on, the voltage of the secondary side converted by the primary side is less than the voltage of storage capacitor.

At the same time, the voltage stress of the rectifier diode at secondary side of the transformer is only the output voltage. Compared with the single-phase input Flyback PFC Converter, which the voltage stress of the output diode is V_o+nV_{in}. It can get the conclusion that this topology is more superior in the condition of high voltage output. So one of the advantages of the topology is that the efficiency can be improved.

Because of the three-phase input, and the line current is $\sqrt{3}$ times of the phase current in delta connection, so the output power of each phase is 1/3 times of the output power supply.

III. The Power Factor of the Circuit

Assume that the input is $V_{in}(t) = V_m \cdot \sin(\omega t)$, then the input current in one period can be expressed as

$$i_{p\_pk}(t) = \frac{V_m \cdot \sin(\omega t)}{L_p} \cdot D \cdot T_s \tag{4}$$

Among them L_p is the primary magnetizing inductance, D is the duty cycle of the circuit, T_s is the time of one period.

The average input current in one period can be expressed as

$$\begin{aligned} i_{p\_av}(t) &= \frac{1}{2} \cdot I_{p\_pk}(t) \cdot D \\ &= \frac{V_m \cdot D^2 \cdot \sin(\omega t)}{2 \cdot L_p \cdot f_s} \end{aligned} \tag{5}$$

f_s is the frequency of the switch.

The input power in half frequency period can be expressed as

$$P_{in} = \frac{1}{\frac{T}{2}} \cdot \int_0^{\frac{T}{2}} v_{in}(t) \cdot i_{p\_av}(t) dt = \frac{D^2 \cdot V_m^2}{4 \cdot L_p \cdot f_s} \tag{6}$$

In one frequency period the RMS input current can be expressed as

$$I_{rms} = \sqrt{\frac{1}{\pi} \cdot \int_0^{\pi} i_{p\_av}^2(t) \cdot dt} \tag{7}$$

The Power Factor in ideal can be expressed as

$$PF = \frac{P_{in}}{\frac{1}{\sqrt{2}} \cdot V_m \cdot I_{m\_rms}} = 1 \tag{8}$$

IV. Anaysis of the Relationship between Input Power and the Storage Capacitor

In the AC-DC conversion, since the unbalance of the instantaneous input pulsating and average output, leads to a certain output voltage ripple. So, we can get the conclusion of the role of storage capacitor is to balance the instantaneous input power and the average output power

Assume that the input voltage and current in the same phase, and then the power factor is 1, it can be expressed as

$$v_{in}(t) = V_m \sin \omega t \tag{9}$$

$$i_{in}(t) = I_m \sin \omega t \tag{10}$$

The instantaneous input power can be expressed as

$$p_{in}(t) = v_{in}(t) \cdot i_{in}(t) = P_m \sin^2 \omega t \tag{11}$$

When the efficiency is 100%, the output power is the average of the instantaneous input power in one frequency period.

$$P_o = \frac{1}{2\pi} \int_0^{2\pi} p_{in}(t) \cdot dt = \frac{P_m}{2} \tag{12}$$

So we can express the instantaneous input power per unit as

$$p_{in}^*(t) = \frac{p_{in}(t)}{P_o} = 2\sin^2(\omega t) \tag{13}$$

That when $p_{in}^*(t) > 1$, the storage capacitor is charging; When $p_{in}^*(t) < 1$, the storage capacitor is discharging. While in the condition of three-phase input,

$$p_{ina}^*(t) = 2\sin^2(\omega t) \tag{14}$$

$$p_{inb}^*(t) = 2\sin^2(\omega t + \frac{2\pi}{3}) \tag{15}$$

$$p_{inc}^*(t) = 2\sin^2(\omega t + \frac{4\pi}{3}) \tag{16}$$

That the total instantaneous input power can be expressed as $p_{in3}^*(t) = p_{ina}^*(t) + p_{inb}^*(t) + p_{inc}^*(t) = 3$. It can be shown in the Fig. 7.

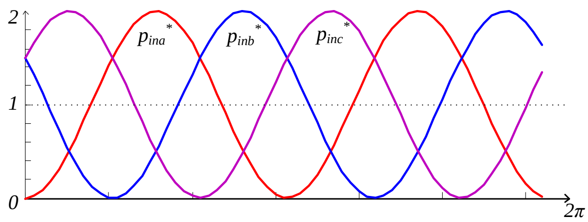


Figure 7. The three-phase input instantaneous power

Because of the three-phase input can achieve a natural balance itself, so we can get the conclusion that

$$\frac{1}{2} C_o u_{o\max}^2(\omega t) - \frac{1}{2} C_o u_{o\min}^2(\omega t) = P_o \cdot DT_s \tag{17}$$

Then

$$C_o = \frac{P_o DT_s}{2U_o \Delta U} \tag{18}$$

Among them $u_{o\max} = U_o + \Delta U, u_{o\min} = U_o - \Delta U$.

It means that the storage capacitor doesn't store any energy in one period, but because the output current of the converter is the average value of the transformer secondary current. So the function of the storage capacitor is change the transformer secondary current to average output current.

In conclusion the storage capacitor can be minimize.

V. The Design and Simulation

In order to ensure the converter operating in the control of DCM, and retain a certain dead time.

$$D_2 < 1 - D \tag{19}$$

Since the equation (3), (5), thus

$$\left(\frac{N_2}{N_1}\cdot\frac{V_{in}(t)}{V_o}+1\right)\cdot\frac{\sqrt{2\cdot L_p\cdot f_s\cdot P_o}}{V_{in\_rms}} < 1 \tag{20}$$

When the input voltage is minimum, we can get

$$L_p < \frac{V_o^2\cdot n^2}{4\cdot f_s\cdot P_o\cdot\left(\frac{n\cdot V_o}{V_{in\_pk\_min}}+1\right)^2} \tag{21}$$

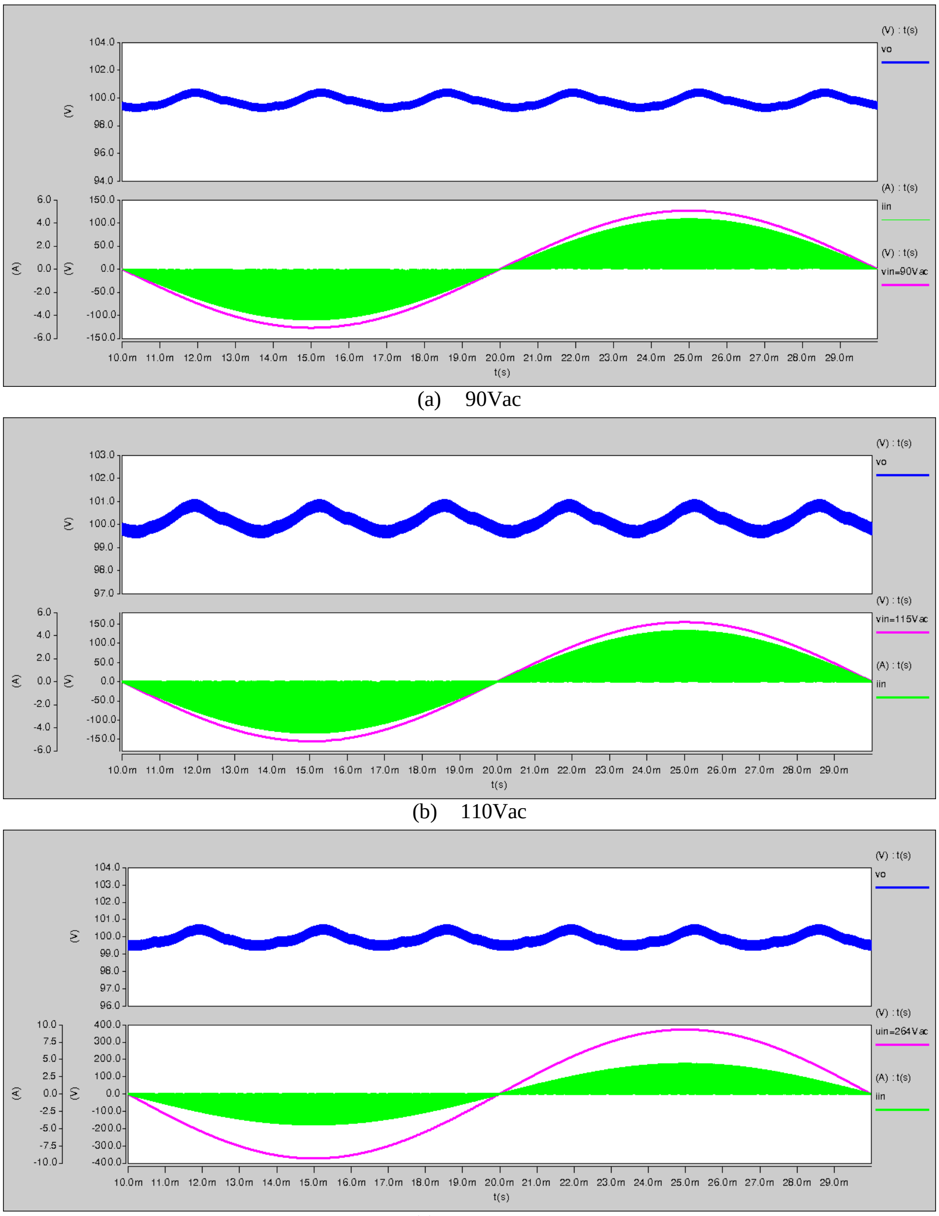
Take the design $L = 0.8 \sim 0.9 L_p$

In order to verify the accuracy of the above analysis, a prototype has been built and simulate in Saber. The parameters of the prototype are as follows:

1) Input voltage: $v_{in} = 90 \sim 264Vac/50Hz$
2) Output voltage: $v_o = 100 \pm 5Vdc$
3) Output power: $P_o = 250W$
4) Switching frequency of the converter: $250kHz$

The parameters of the PFC stage are as follows:

1) Magnetizing inductance: $L_p = 80uH$
2) Turns ratio: $n = 4$
3) Duty cycle: $D = 0.211 \sim 0.675$
4) Storage capacitor: $C_o = 14.3uF$



(a) 90Vac

(b) 110Vac

(c) 264Vac

Figure 8. Simulation waveforms of output voltage, input current and voltage at 90Vac, 110Vac and 264Vac

Fig. 8 shows the waveforms of the output voltage, input voltage and input current at 90Vac, 110Vac, 264Vac input.

And it can be seen that the topology is effective in a wide range of input voltage, the output voltage ripple is well controlled at 1V. The input current follows the input voltage as analyzed.

Because of the Bridgeless structure, the input current is not distorted at input voltage zero cross point, and the efficiency of the topology can be improved.

Fig. 9 shows the current of the diode of each bridge arm, at each part there are three diodes conduction at the same time and it is consistent with the previous analysis.

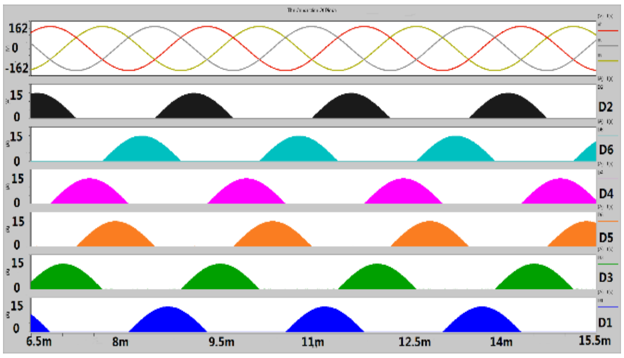


Figure 9. The three-phase input voltage and the current of the diode

VI. Conclusions

Three-Phase Bridgeless Flyback PFC Converter has the advantage of topology simple and efficient, and minimize the storage capacitor. Compared with the single-phase input Flyback PFC Converter, the power density of the converter can be maximum. Further, this kind of bridgeless topology is needed for more analysis, such as the interleaved of the topology is still worth studying.

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