Simulation and Research on Three-Phase Parallel PFC with Feed-Forward Compensation

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Abstract: In order to enhance the power factor and minimize the complexity of control strategy, the analysis of a novel three-phase parallel power factor correction with feed-forward compensation is presented. According to the working principle of the topology, hysteresis current control strategy has been proposed for the bi-boost crossing converter. The simulation results verify the stability of the system. As a result, the time sequence of the system is so simple that the switches can be easily controlled to achieve stable output voltage, ideal power factor and current harmonic, while only twenty percents of the total power passes through the Boost converter. In order to achieve ideal power factor and low current harmonic, the output power should be constant.

Key-Words: Three-phase power factor correction; Feed-forward compensation; Low current harmonic; Hysteresis current control; Bi-boost crossing converter; Constant-power load

1 Introduction

Owing to the simplicity and reliability of the topology, three-phase uncontrolled rectifier has been widely used in high-power applications. However, three-phase uncontrolled rectifier brings nonlinear and transverses harmonic current into grid [1-3]. It’s necessary to restrict harmonic current and power factor to a certain range as electrical standards.

Both of passive filter and active filter can restrain current harmonic and enhance the power factor. Passive filters made of LC series circuits are simple in working principle and topology. The conception of three-phase rectifier with near sinusoidal input current (RNSIC) can achieve ideal power factor and low current harmonic only by additional inductors and capacitors. But the value of inductors and capacitors are unrealistic, further more RNSIC demands for a constant load [4-5]. Multi-pulse rectifier realize low cost and high efficiency without control system, but the harmonic of input current remains high [6-8]. Active filter consisting of voltage-source or current-source PWM (Pulse-Width Modulation) inverters can overcome the drawbacks of passive filter. For example, PWM rectifier and APFC (Active Power Factor Correction) are both active filters. Compared with passive filter, active filter is more competitive [9]. Although the input current of PWM rectifier is near sinusoidal, it has several drawbacks as follows [10-12]: complex control strategy, high cost and high switching losses, which is serious in high power system.

Presently, the technique of the three-phase APFC isn’t as mature as the single phase, which is recognized by many scholars. Three-phase parallel PFC with feed-forward compensation lack deeply research on working principle and control system, even if it has been put forward by scholars [13-16]. In this paper, working principle is deeply analyzed and then theoretical model is established. According to the theoretical model, a new control scheme has been put forward and the performance characteristic of this topology has been discussed. Furthermore, simulation model has been built to verify the accuracy and feasibility of the new control scheme.

2 Analysis of Working Principle

The topology of three-phase parallel PFC with feed-forward compensation which includes main and subordinate rectifiers is shown in Fig.1. The main rectifier is a common three-phase uncontrolled rectifier, while the subordinate rectifier is a bi-boost crossing APFC circuit. \( S_a, S_b, S_c \) are bi-directional switches. The nomenclature used in Fig.1 is reported here below:

\[ I_{am}, I_{bm}, I_{cm} = \text{Phase currents of main rectifier} \]
\[ I_{aa}, I_{ba}, I_{ca} = \text{Phase currents of subordinate rectifier} \]
\[ I_a, I_b, I_c = \text{Sum of phase currents of main and subordinate rectifier.} \]
\[ I_r = \text{Output current of subordinate rectifier} \]
\[ I_m = \text{Output current of main rectifier} \]
\[ I_o = \text{Output current of bi-boost crossing converter} \]
\[ I_o = \text{Load current} \]
\( V_a \) = Output voltage of subordinate rectifier
\( V_m \) = Output voltage of main rectifier
\( V_0 \) = Output voltage of this topology
\( V_a \) = Input voltage of branch 1 and branch 2
\( U_{32} \) = Output voltage of branch 1
\( U_{14} \) = Output voltage of branch 2
\( U_{34} \) = Voltage between nodes \( ② \) and \( ③ \)
\( U_{14} \) = Voltage between nodes \( ① \) and \( ④ \)
\( U_{34} \) = Voltage between nodes \( ③ \) and \( ④ \)

\[
U_{32} = \frac{1}{1-D_1} V_a \quad (1)
\]

\[
U_{14} = \frac{1}{1-D_2} V_a \quad (2)
\]

\[
V_0 = U_{34} = \frac{1}{1-D_1} V_a + \frac{D_2}{1-D_2} V_a \quad (3)
\]

If \( D_1 = D_2 = D \),

\[
V_0 = \frac{1+D}{1-D} V_a \quad (4)
\]

Compared with the normal boost converter, bi-boost crossing converter has the following advantages:
1) Wider adjustable range of output voltage; 
2) The current stress of switch is half of the one of normal boost converter, the voltage stress is \( 1/(1+D) \) of the one of normal boost converter; 
3) Two branches can be controlled independently to restrain the circulation.

Fig.1 Topology of three-phase parallel PFC with feed-forward compensation

Bi-boost crossing converter whose symmetry boost converters are parallel in input terminal and serial in output terminal is shown in Fig.1 (b) [17]. The symmetry boost converters are independent with each other. If \( D_1, D_2 \) are the duty cycles of switches \( K_1 \) and \( K_2 \) respectively.

Fig.2 Sequence of \( S_a, S_b, S_c \) during a period

A period is divided into twelve intervals. The sequences of \( S_a, S_b, S_c \) during a period are shown in Fig.2. The working phase of main and subordinate rectifier and formulae of \( I_a, I_b, I_c \) are shown in Table 1. The working phase of main rectifier is the one whose absolute value is larger between the two phases with the same polarity and the one with the reverse polarity, while the working phase of subordinate rectifier is the one whose absolute value is smaller between the two phases with the same polarity and the one with the reverse polarity. For example, during \( (0, \pi/6) \) interval, the working phase of main rectifier is phase B and C while the working phase of subordinate rectifier are phase A and C by controlling \( S_a \) and \( S_c \).
### Table 1 Working phase of main and subordinate rectifier and formulas of $I_a$, $I_b$, $I_c$ during a period

<table>
<thead>
<tr>
<th>Working phase of main rectifier</th>
<th>(0, $\pi$/$6$)</th>
<th>($\pi$/$6$, $2\pi$/$6$)</th>
<th>($2\pi$/$6$, $3\pi$/$6$)</th>
<th>($3\pi$/$6$, $4\pi$/$6$)</th>
<th>($4\pi$/$6$, $5\pi$/$6$)</th>
<th>($5\pi$/$6$, $6\pi$/$6$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Working phase of subordinate rectifier</td>
<td>BC</td>
<td>AC</td>
<td>AC</td>
<td>AB</td>
<td>AB</td>
<td>CB</td>
</tr>
<tr>
<td></td>
<td>AC</td>
<td>BC</td>
<td>AB</td>
<td>AC</td>
<td>CB</td>
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</table>

<table>
<thead>
<tr>
<th>$I_a$</th>
<th>$I_{aa}$</th>
<th>$I_{am}$</th>
<th>$I_{aa}$ + $I_{am}$</th>
<th>$I_{am}$</th>
<th>$I_{aa}$</th>
</tr>
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<tbody>
<tr>
<td>$I_b$</td>
<td>$I_{bm}$</td>
<td>$I_{ba}$</td>
<td>$I_{bm}$ + $I_{ba}$</td>
<td>$I_{bm}$</td>
<td>$I_{ba}$</td>
</tr>
<tr>
<td>$I_c$</td>
<td>$I_{cm}$ + $I_{ca}$</td>
<td>$I_{cm}$ + $I_{ca}$</td>
<td>$I_{cm}$</td>
<td>$I_{cm}$</td>
<td>$I_{ca}$</td>
</tr>
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<thead>
<tr>
<th>Working phase of main rectifier</th>
<th>(6$\pi$/$6$, $7\pi$/$6$)</th>
<th>(7$\pi$/$6$, $8\pi$/$6$)</th>
<th>(8$\pi$/$6$, $9\pi$/$6$)</th>
<th>(9$\pi$/$6$, $10\pi$/$6$)</th>
<th>(10$\pi$/$6$, $11\pi$/$6$)</th>
<th>(11$\pi$/$6$, $12\pi$/$6$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Working phase of subordinate rectifier</td>
<td>CB</td>
<td>CA</td>
<td>CA</td>
<td>BA</td>
<td>BA</td>
<td>BC</td>
</tr>
<tr>
<td></td>
<td>CA</td>
<td>CB</td>
<td>BA</td>
<td>CA</td>
<td>BC</td>
<td>BA</td>
</tr>
</tbody>
</table>

The current waveform $I_a$ is shown in Fig.3. The missing current during $(0, \pi/6)$, $(5\pi/6, 7\pi/6)$, $(11\pi/6, 2\pi)$ makes $I_a$ distort. If the missing current is compensated, the harmonic of $I_a$ will reduce obviously. So the bi-boost crossing converter should be controlled to compensate the missing current during $(0, \pi/6)$, $(5\pi/6, 7\pi/6)$, $(11\pi/6, 2\pi)$ and improve the current during $(\pi/6, 6\pi/6)$, $(7\pi/6, 11\pi/6)$. It’s the same with phase B and C.

Based on the above analysis, $I_r$ is in phase with $V_a$, which is presented in Fig.4.

![Fig.3 Phase current waveforms and frequency spectrum of three-phase uncontrolled rectifier without capacitor](image)

![Fig.4 Ideal waveforms of $I_r$ and $V_a$](image)
3 Harmonic Analysis of Input Current

Supposing the peak value of phase voltage is $V$ and the output power is $P$. The following harmonic analysis is based on the constant power load (just like DC-DC converter).

Three phase voltages are
\[
\begin{align*}
U_a &= V \sin(\omega t) \\
U_b &= V \sin(\omega t + 2\pi/3) \\
U_c &= V \sin(\omega t + 4\pi/3)
\end{align*}
\]

If the power factor is unity, three phase input currents are
\[
\begin{align*}
I_a &= k \sin(\omega t) \\
I_b &= k \sin(\omega t + 2\pi/3) \\
I_c &= k \sin(\omega t + 4\pi/3)
\end{align*}
\]

For the output power $P$
\[
P = U_a I_a + U_b I_b + U_c I_c = 1.5Vk, \quad k = \frac{P}{1.5V}
\]

So
\[
\begin{align*}
I_a &= \frac{P}{1.5V} \sin(\omega t) \\
I_b &= \frac{P}{1.5V} \sin(\omega t + 2\pi/3) \\
I_c &= \frac{P}{1.5V} \sin(\omega t + 4\pi/3)
\end{align*}
\]

If the filter capacitors $C_m$ and $C_a$ are ignored and the switching frequency can be as high as possible, the output voltage of subordinate rectifier is close to six-pulse. Since the frequency of $I_r$ is six times as power frequency, the current harmonic is only analyzed during interval $(0, \pi/3)$. The relationship of phase currents is shown in Fig.5 during this interval. The reference direction of input current has been marked in Fig.1.

![Diagram](image)

Fig.5 Relationship of phase currents during $(0, \pi/3) $

(1) Interval $(0, \pi/6)$

The working phases of main rectifier are phase B and C, while phase A and C are the working phases of subordinate rectifier.

\[
\begin{align*}
V_{0} &= V_{bc} = 3\sqrt{3} \sin(\omega t + \pi/2) \\
V_{a} &= V_{ac} = 3\sqrt{3} \sin(\omega t + \pi/3)
\end{align*}
\]

In order to compensate the missing current and achieve unity power factor during this interval, $I_a$ and $I_b$

\[
I_a = I_{ma} = \frac{P}{1.5V} \sin(\omega t)
\]

Due to the power conservation principle, the relationship between $I_a$ and $I_b$

\[
I_b = I_{ba} = \frac{P}{1.5V} \sin(\omega t + \pi/3)
\]

\[
I_c = I_{cm} + I_{ca} = -I_{ma} - I_{ba} = \frac{P}{1.5V} \sin(\omega t - \pi/3)
\]
sinusoidal and the power factor will be unity if the load is constant-power, the filter capacitors $C_m$ and $C_a$ are ignored and the switching frequency is as high as possible.

Actually the switching frequency can’t be as high as possible, so the filter capacitors $C_a$ and $C_m$ should be considered. The formulae of phase A current $I_a$ are shown as follows.

Intervals $(0, \pi / 6)$, $(\pi, 7\pi / 6)$

$$I_a = \frac{P}{1.5V}\sin(\omega t) + \sqrt{3V} \cdot \omega C_a \cos(\omega t + \frac{\pi}{6})$$

(21)

Intervals $(\pi / 6, \pi / 3)$, $(7\pi / 6, 8\pi / 6)$

$$I_a = \frac{P}{1.5V}\sin(\omega t) + \sqrt{3V} \cdot \omega C_m \cos(\omega t + \frac{\pi}{6})$$

(22)

Intervals $(\pi / 3, \pi / 2)$, $(4\pi / 3, 3\pi / 2)$

$$I_a = \frac{P}{1.5V}\sin(\omega t) + \sqrt{3V} \cdot \omega C_m \cos(\omega t + \frac{\pi}{6})$$

(23)

+ $\omega C_a \cos(\omega t - \frac{\pi}{6})$

Intervals $(\pi / 2, 2\pi / 3)$, $(3\pi / 2, 5\pi / 3)$

$$I_a = \frac{P}{1.5V}\sin(\omega t) + \sqrt{3V} \cdot \omega C_m \cos(\omega t - \frac{\pi}{6})$$

(24)

+ $\omega C_a \cos(\omega t + \frac{\pi}{6})$

Intervals $(2\pi / 3, 5\pi / 6)$, $(5\pi / 3, 11\pi / 6)$

$$I_a = \frac{P}{1.5V}\sin(\omega t) + \sqrt{3V} \cdot \omega C_a \cos(\omega t - \frac{\pi}{6})$$

(25)

Intervals $(5\pi / 6, \pi)$, $(11\pi / 6, 2\pi)$

$$I_a = \frac{P}{1.5V}\sin(\omega t) + \sqrt{3V} \cdot \omega C_a \cos(\omega t - \frac{\pi}{6})$$

(26)

It’s concluded that the harmonic current is concerned with gross power $P$, peak value of phase voltage $V$, angular frequency $\omega$ and filter capacitors $C_m$ and $C_a$ if the filter capacitors $C_a$ and $C_m$ are considered.

4 Principle of Control System

It is only needed to control the switch $S_a$, $S_b$, $S_c$, $K_1$ and $K_2$ to achieve ideal power factor and low harmonic current. The system control scheme of subordinate rectifier is shown in Fig.6. In order to achieve ideal power factor and low harmonic current, the average value of $I_{s1}$, $I_{s2}$ and the waveforms of $I_{r+}$, $I_{r-}$ should be controlled by detecting the input current $I_{r+}$ and $I_{r-}$, output current $I_{s1}$ and $I_{s2}$ and three phase voltages.

The time sequence of $S_a$, $S_b$ and $S_c$ which is decided by the phase voltage is shown in Fig.2. Commonly the AC-DC switched converter has three control methods: peak current control, hysteresis current control and average current control. The advantages of hysteresis current control are proposed as follows: simple control, quick dynamic response of current, excellent disturbances attenuation performances and robustness. So the hysteresis current control scheme which is represented in Fig.7 has been chosen for this novel APFC topology. The values of $I_{r+}$ and $I_{r-}$ are the current feedbacks for $K_1$, while the values of $I_{r+}$ and $I_{r-}$ are the current feedbacks for $K_2$. So $K_1$ and $K_2$ are controlled independently, but both of them choose $I_{(wave)}$ as reference phase current. The circulation will be avoided by controlling $K_1$ and $K_2$ independently.
source, while the subordinate rectifier whose output current is controlled is equivalent as a current source. The output voltage of this novel APFC topology is equal to the voltage of the equivalent voltage source. If the load power is constant, the load current $I_0$ will be constant. The missing current can be compensated by controlling $I_r$ and $I_s$.

The power of subordinate rectifier is

$$P_s = \frac{6}{\pi^2} \frac{V}{I_0} \frac{P}{1.5V} \sin(\omega t) \cdot \sqrt{3} \sin(\omega t + \frac{\pi}{6}) d\omega$$

$$= V_m \times I_s = 0.224P$$

(27)

The total output power is $P$, and the power of main rectifier is

$$P_m = V_m \times I_m = P - 0.224P = 0.776P$$

According to (27) and (28)

$$\frac{I_m}{I_s} = \frac{97}{28}$$

(29)

If (29) is valid in this system and $I_r$ is able to track the phase of $I_{\text{wave}}$, ideal power factor and low harmonic current will be achieved.

The relationship between $I_{\text{wave}}$ and $V_a$ is shown in Fig.4. $I_{\text{wave}}$ is decided by phase voltage. $I_{\text{ref}}$ is the reference current of outer current loop. According to (29), $I_{\text{ref}} = 28I_a/97$. The reference current of inductance $l_{\text{ref}}$ is the product of $kl_{\text{wave}}$ and the output of the PI controller of the current outer loop. The principle of hysteresis current control is shown in Fig.8. The upper limit of hysteresis loop is defined as $I_{\text{ref}} + \Delta h$, and the lower limit is $I_{\text{ref}} - \Delta h$. If $I_r > I_{\text{ref}} + \Delta h$, switch will be off and the inductance current will decrease, otherwise switch will be on and the inductance current will increase. The inductance current fluctuate near the reference current $I_{\text{ref}}$ by controlling $K_1$ and $K_2$. How to choose $\Delta h$ for the control system is important, because it’s concerned with current harmonic. In order to improve the switching characteristic of $K_1$ and $K_2$, the sample value of inductance current should be filtered.

5 Simulation Results

The MATLAB/Simulink simulation model consists of a three phase voltage source (with peak phase voltage $V=311V$ and $f=50Hz$) and a three-phase parallel PFC with feed-forward compensation. The output power is 30 KW, and the maximum switching frequency is 20 KHz. For the inductors L, we have adopted the value of 0.5mH. The filter capacitor $C_m$ is 40uF, and $C_a$ is 20uF. For the outer current loop of control system, the scale factor $K_m = 0.015$ and the integral factor $K_i = 5$. The scale factor of phase control loop $K$ is 0.1, and the hysteresis width $\Delta h$ is 3.

The phase current $I_a$ of normal three-phase uncontrolled rectifier, theoretical model and simulation model with hysteresis current control are presented in Fig.9, Fig.10 and Fig.11 respectively. With the filter whose cut-off frequency is 5 KHz, the frequency spectrum of $I_a$ is shown in Fig.12. From theoretical model, the THD (Total Harmonic Distortion) of $I_a$ is 4.65%, while the THD of $I_a$ is 10.84% from simulation model. Compared with 31.2% of normal three-phase uncontrolled rectifier, THD has reduced obviously. The reason why the THD of simulation is higher than the theoretical THD is as follows: the theoretical $I_a$ and $I_m$ are continuous, while $I_o$ and $I_m$ from the simulation model are pulsing, which will generate additional higher harmonic. So from the simulation model, the THD of $I_a$ reduces to 5.86% with the filter whose cut-off frequency is 5 KHz.

The current waveforms of $I_{an}$, $I_{am}$, $I_a$ are shown in Fig.13 and the current waveforms of $I_o$, $I_m$, $I_r$ are shown in Fig.14. $I_{an}$ is the compensation of the missing current. In Fig.13, $I_o$ is the sum of $I_{an}$ and $I_{am}$. The input and output voltage waveforms of bi-boost crossing converter are shown in Fig.15 and 16. The input current waveforms $I_{r+}$, $I_r$, $I_r$, of bi-boost crossing converter are shown in Fig.17 (a) and (b). $V_o$, $I_{r+}$, $I_r$ from simulation model are coincide with the theoretical results which are shown in Fig.4 and the load voltage $V_o$ which is equal to the output voltage of main rectifier is six-pulse during a period. Fig.18 shows the voltage and current waveforms of phase A. As is shown in Fig.18, the power factor is 0.9932, which verify the feasibility of this novel APFC topology. Fig.19 shows the waveform of output power, which verifies the premise that the load power keeps constant in the simulation model. In Fig.20, Fig.21 and Fig.22, the current stress of switch $K_1$ and $K_2$ is half of the one of normal boost converter, the voltage stress of switch $K_1$ and $K_2$ is $1/(1+D)$ of the one of normal boost converter, which is coincide with the analysis mentioned in section 2.
(a) The waveform of phase current $I_a$

(b) The frequency spectrum of $I_a$

Fig. 9 $I_a$ and frequency spectrum of normal three-phase uncontrolled rectifier

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(a) The waveform of phase current $I_a$

(b) The frequency spectrum of $I_a$

Fig. 10 $I_a$ and frequency spectrum from theoretical model under hysteresis current control

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(a) The waveform of phase current $I_a$

(b) The frequency spectrum of $I_a$

Fig. 11 $I_a$ and frequency spectrum from simulation model under hysteresis current control

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(a) The waveform of phase current $I_a$

(b) The frequency spectrum of $I_a$

Fig. 12 $I_a$ and frequency spectrum from simulation model with filter under hysteresis current control
Fig. 13 Current waveforms of $I_{aa}$, $I_{am}$, $I_a$.

Fig. 14 Current waveforms of $I_a$, $I_b$, $I_c$.

Fig. 15 Voltage waveform of $V_a$.

Fig. 16 Voltage waveform of $V_0$.

Fig. 17 Input current waveform of Boost circuit.

Fig. 18 Voltage and current waveforms of phase A.

Fig. 19 Waveform of output power.
6 Conclusion

The novel three-phase PFC topology cooperated with the hysteresis control technique has been proposed. It can stabilize the six-pulse dc output voltage, compensate the missing current during intervals \((0, \pi/6), (5\pi/6, 7\pi/6), (11\pi/6, 2\pi)\) in a period and improve the other two phase current waveforms during the same interval. The theoretical analysis and the simulation results have proved the merits of small current THD and high power factor. However, when the load power has been changed heavily, the power factor and current THD will get worse, and the DC voltage is not adjustable. Approximately twenty percent of power goes through the boost converter and the bi-boost crossing converter can reduce the voltage and current stress of switch. Therefore, the lower power components can be chosen, which reduce the cost and improve the efficiency of the system. The novel APFC topology is suitable for the applications as follows:

1) Strict with power factor;
2) Output power is constant.

In total, the novel APFC topology has wide application prospects.

References:


[3] Li Mingshu, Wan Jianru, Li Guangye et al,


