A New Three-Phase Power-Factor Correction (PFC) Scheme Using Two Single-Phase PFC Modules

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Abstract—In this paper, a new three-phase power-factor correction (PFC) scheme is proposed using two single-phase PFC modules. In this approach, the “three” phase input is first transformed to “two” phase by means of a 0.14-pu-rated autotransformer. Two standard single-phase PFC modules are then employed to process the “two” phase power to dc output. Split inductors and diodes are employed to limit interaction between the two PFC stages. Due to cascade operation of two PFC stages, low-frequency (120 Hz) ripple in the dc-link capacitor is cancelled. Detailed analysis and simulation results are presented. A 220-V 1.5-kVA design example along with experimental results is shown.

Index Terms—Harmonics, power-factor correction, power quality.

I. INTRODUCTION

THREE-PHASE switch-mode power supplies (SMPSs) employing diode-rectifier-type utility interface are widely used in telecommunications, data processing, and other industrial systems [1], [2]. The diode-rectifier-type utility interface generates lower order harmonics of the order 6k ± 1, i.e., 5, 7, 11, 13, etc. IEC 61000-3-4 and IEEE 519-1992 detail acceptable limits [3], [4] of such nonlinear loads. Several approaches have been studied and summarized in [5]–[8] to improve the total harmonic distortion (THD). They are broadly categorized into two groups: 1) rectifier circuitry capable of producing low level of harmonic content or 2) conventional rectifier circuitry with additional filter. Three single-phase power-factor correction (PFC) stages for a three-phase system, a single-switch PFC with discontinuous mode (DCM) control, and a six-switch PWM rectifier can be considered in the first category. A single-switch PFC with DCM control suffers from high switch current rating and high electromagnetic interference (EMI) [6], [7]. A pulsewidth modulation (PWM) rectifier needs complicated measurements and feedback control [5].

This paper proposes a new three-phase PFC scheme using two standard single-phase PFC modules. “Two” phase is produced by means of a 0.14-pu-rated autotransformer from a “three” phase input. Two standard single-phase PFC modules are employed, one on each phase to process the power. Split inductors and diodes are used to limit interaction between the two PFC stages. The outputs of the two PFC modules are connected.
Fig. 3. Equivalent circuits at each switching period. (a) Equivalent circuit in which $S_1$ is on while $S_2$ is on. (b) Equivalent circuit in which $S_1$ is on while $S_2$ is off. (c) Equivalent circuit in which $S_1$ is off while $S_2$ is on. (d) Equivalent circuit in which $S_1$ and $S_2$ are off.

to the common dc output. Due to cascade operation of the two PFC stages, low-frequency (120 Hz) ripple components in the dc-link capacitor cancel each other. The advantages of the proposed scheme are as follows.

- The proposed approach is modular and employs two standard single-phase PFC modules. Input current waveforms are nearly sinusoidal at unity power factor and are in compliance with IEEE 519, IEC 1000-3, and IEC-6000-3-2 limits.
- In this scheme, the second-order harmonic current component in the dc-link capacitor is cancelled. This significantly reduces capacitor heating and improves its operating life.
- The voltampere (VA) rating of the autotransformer employed is low.
- The dc output is regulated and is immune to voltage sags and other power quality disturbances.

II. PROPOSED SYSTEM

Fig. 1(a) shows the topology of the proposed approach. The three-phase input $v_a$, $v_b$, and $v_c$ (120° phase shift) is first transformed to two phase $v_{ab}$ and $v_{ck}$ (90° phase shift) by means of a center-tapped autotransformer. From the vector diagram in Fig. 1(b), it is clear that voltage $v_{ab}$ and $v_{ck}$ are 90° apart.

Two single-phase boost PFC stages are connected to the “two” phase voltages $v_{ab}$ and $v_{ck}$, as shown in Fig. 1(a). Single-phase PFC module 1 consists of a bridge rectifier, inductors $L_{1f}$ and $L_{1b}$, and diodes $D_{1f}$ and $D_{1b}$. Single-phase PFC module 2 consists of a bridge rectifier, inductors $L_{2f}$ and $L_{2b}$, and diodes $D_{2f}$ and $D_{2b}$. Split inductors and diodes are employed at the two PFC stages to limit interaction between the two when the output stages are combined [8].

Although $|V_{ab}| \neq |V_{ck}|$ [Fig. 1(b)], the two boost PFC stages are suitably controlled with different gains to supply one-half of the output power. This feature enables cancellation of low-frequency second-order harmonic current component in the capacitor.

A. Analysis

Fig. 2(a) shows the phase voltages. Single-phase PFC module 1 sees the voltage $v_{ab}$ as in Fig. 2(b) and single-phase PFC module 2 sees the voltage $v_{ck}$ in Fig. 2(b) via the autotransformer. Fig. 3 shows the possible equivalent circuits from the input to the output.
In the interval of $\pi/18 < \omega t < \pi/2$ (gray area in Fig. 2), the rectified output has the following relationship:

\[
|v_{ob}| > |v_{ck}|
\]

\[
\frac{d_{ab}}{2} = 1 - \frac{|v_{ob}|}{V_o} \quad \text{(2.a)}
\]

\[
\frac{d_{ck}}{2} = 1 - \frac{|v_{ck}|}{V_o} \quad \text{(2.b)}
\]

where $d_{ab}$ and $d_{ck}$ are the duty cycles of each converter.

When both $S_1$ and $S_2$ switches are on, there is no current path to the output and the two single-phase PFC modules work independently as in Fig. 3(a). Also, when one of the switches, i.e., $S_1$ or $S_2$ is off [the equivalent circuit is shown in Fig. 3(b) and (c)], the PFC modules operate independently. However, when both switches are off the two PFC modules are simultaneously connected to the output.

The equivalent circuit for this condition is shown in Fig. 3(d). For this equivalent circuit,

\[
\frac{v_{ob}}{2} - \frac{L_{1,2}}{L} \frac{d_{1,2}}{dt} - V_o \cdot \frac{d_{1,2}}{dt} = 0
\]

\[
\frac{v_{ck}}{2} - \frac{L_{1,2}}{L} \frac{d_{1,2}}{dt} - V_o \cdot \frac{d_{1,2}}{dt} = 0
\]

\[
-\frac{v_{ob}}{2} + \frac{L_{1,2}}{L} \frac{d_{1,2}}{dt} - L_{1,2} \frac{d_{1,2}}{dt} = 0
\]

\[
\frac{d_{1,2}}{dt} + \frac{d_{1,2}}{dt} - \frac{d_{1,2}}{dt} = 0
\]

Assuming that $L = L_{1,2} = L_{1,2} = L_{2,2}$, the inductor current can be derived from (3.a)–(3.d).

\[
\frac{d_{1,2}}{dt} = \left(|v_{ob}| - \frac{|v_{ck}|}{2} - V_o\right) \frac{1}{2L} \quad \text{(4.a)}
\]

\[
\frac{d_{1,2}}{dt} = \left(|v_{ob}| + \frac{|v_{ck}|}{2} - V_o\right) \frac{1}{2L} \quad \text{(4.b)}
\]

\[
\frac{d_{2,2}}{dt} = \left(|v_{ck}| + \frac{|v_{ck}|}{2} - V_o\right) \frac{1}{2L} \quad \text{(4.c)}
\]

\[
\frac{d_{2,2}}{dt} = \left(|v_{ck}| - \frac{|v_{ck}|}{2} - V_o\right) \frac{1}{2L} \quad \text{(4.d)}
\]

Fig. 4 shows the inductor current waveforms for a switching period in the interval, $S_1S_2$ on, $S_1$ off $S_2$ on, $S_1S_2$ off. From this figure, it is clear that the two PFC stages interact during the $S_1S_2$ off region. To minimize this effect, a split inductor configuration is chosen in each PFC stage. By proper design of $L_{1,2}$, $L_{1,2}$, $L_{2,2}$, and $L_{2,2}$, the interaction can be kept to a minimum and the input current quality is not affected.

**B. Staggered PWM**

To overcome the interaction between phases, staggered PWM is used. The two single-phase PFC modules can work independently by avoiding the Fig. 3(d) period. If 180° phase-shifted PWM carrier signals are used and the duty ratio is higher than 0.5 when the two input voltages are the same, the interaction is virtually eliminated. Fig. 5 shows the gating signals of both switches.

The input voltages and the duty ratio have the relationship as in Fig. 6. Since the input voltages become the same at $\pi/18$, minimum output voltage for the staggered PWM is calculated as

\[
V_o \geq \frac{1}{1 - D} V_{in} \left(\frac{\pi}{18}\right) \quad \text{(5.a)}
\]

or

\[
V_o \geq 1.85V_{LL} \quad \text{(5.b)}
\]
C. Control Scheme

Fig. 7 shows the control block for the system. $V_{\text{FF},i}$ is dc voltage proportional to the rectified voltage $V_{\text{Rec},i}$. The rectified input current $I_{\text{Rec},i}$ and the current reference $I_{\text{ref},i}$ can be represented as

$$I_{\text{rec},i} = K_sI_{\text{ref},i}, \quad i = 1, 2$$  \hspace{1cm} (6)$$

$$I_{\text{ref},i} = K_sK_M \frac{V_{\text{rec},i}}{K_{\text{in}}} \cdot \frac{1}{K_{\text{FF}}V_{\text{rec},i}} V_{\text{EA}}$$  \hspace{1cm} (7)$$

where

- $K_s$: PFC power stage gain;
- $K_M$: multiplier gain;
- $K_{\text{FF}}$: feedforward gain;
- $K_{\text{in}}$: waveform input gain;
- $V_{\text{EA}}$: voltage error amplifier output.
From (6) and (7), the rectified current \( I_{\text{rec},i} \) is proportional to the reciprocal of \( V_{\text{rec},i} \). Therefore, the input power \( P_i \) is

\[
P_i = V_{\text{rec},i} I_{\text{rec},i} = \frac{K_i K_M}{K_{\text{in}} K_{\text{FT}}} V_{E_{\Delta}} \quad i = 1, 2. \tag{8}
\]

Each PFC module can carry the same amount of power simply by sharing the same voltage error amplifier output.

D. Power Flow and Autotransformer Rating

Fig. 8 shows the power-flow diagram in the proposed approach. \( K_1 \) and \( K_2 \) represent the boost block. \( F_o \) is the output filter and \( T \) the autotransformer. Each boost PFC module supplies the same power \((P_1 \) and \( P_2)\), which flows to the dc side as dc power \((P_{1,d} \) and \( P_{2,d})\) and to the filter \( F_o \) as the power oscillating at twice the line frequency \((P_{1,2f} \) and \( P_{2,2f})\).

The relationship between the sources and each single-phase PFC module is

\[
P_a + P_b = \frac{1}{3} P_1 + \frac{2}{3} P_2 \tag{9}
\]

\[
P_c = \frac{2}{3} P_2. \tag{10}
\]

Since the two input voltages \( v_{ib} \) and \( v_{ck} \) of the two single-phase PFC modules are in right angle, the second-order harmonic power components are cancelled each other. Therefore, the output filter capacitor \( F_o \) sees only switching frequency component \( (P_F) \).

The power processed in each module is shown in Fig. 9. The solid line represents output power. Dashed lines are the power via the single-phase PFC module 1 \( (P_1) \) and the power via the single-phase PFC module 2 \( (P_2) \).

The rms currents through the single-phase PFC module 1 and the single-phase PFC module 2 can be calculated as

\[
P_1 = \frac{1}{2} P_m \tag{11}
\]

\[
V_{LL} I_1 = \frac{1}{2} \left( \sqrt{3} V_{LL} I_a \right) \tag{12}
\]

or

\[
I_1 = \frac{\sqrt{3}}{2} I_a = 0.8660 I_a. \tag{13}
\]

From the vector diagram,

\[
V_2 = \frac{\sqrt{3}}{2} V_{LL}. \tag{14}
\]

Since the two PFC modules process the same power,

\[
P_2 = \frac{1}{2} P_m \tag{15}
\]

or

\[
\left( \frac{\sqrt{3}}{2} V_{LL} \right) I_2 = \frac{1}{2} \left( \sqrt{3} V_{LL} I_a \right). \tag{16}
\]

Therefore,

\[
I_2 = I_a. \tag{17}
\]

With high power factor, the voltage and current waveforms are in phase by definition. Thus, the instantaneous input powers of the single-phase PFC module 1 \( (P_{m1}) \) and the single-phase PFC module 2 \( (P_{m2}) \) are calculated as the following:

\[
P_{m1} = \left( \sqrt{2} V_{LL} \sin \omega t \right) \left( \sqrt{2} \frac{\sqrt{3}}{2} I_a \sin \omega t \right)
= \sqrt{3} V_{LL} I_a \sin^2 \omega t
= \frac{\sqrt{3}}{2} V_{LL} I_a (1 - \cos 2\omega t) \tag{18}
\]

\[
P_{m2} = \left( \sqrt{2} V_{LL} \cos \omega t \right) \left( \sqrt{2} \frac{\sqrt{3}}{2} I_a \cos \omega t \right)
= \sqrt{3} V_{LL} I_a \cos^2 \omega t
= \frac{\sqrt{3}}{2} V_{LL} I_a (1 + \cos 2\omega t). \tag{19}
\]
The output capacitor is considered to be large enough to hold the dc-link voltage $V_{dc}$ fairly constant. The power outputs to the output capacitor from each boost PFC ($p_{ch1,1}$ and $p_{ch2,2}$) are

$$p_{ch1,1} = V_{dc}i_{ch1,1}.$$  \hspace{1cm} (20)

Since $p_{dc,1} = p_{ch1,1}$,

$$i_{ch1,1} = p_{ch1,1}/V_{dc} = \left(\frac{\sqrt{3}}{2}V_{LL}I_{o}(1-\cos 2\omega t)\right)/V_{dc}. \hspace{1cm} (21)$$

$i_{ch2,2}$ can be calculated by the same way

$$i_{ch2,2} = \left(\frac{\sqrt{3}}{2}V_{LL}I_{o}(1+\cos 2\omega t)\right)/V_{dc}. \hspace{1cm} (22)$$

Therefore, the current at the output capacitor $i_{ch2}$ can be calculated by adding these two current components

$$i_{ch2} = i_{ch1,1} + i_{ch2,2} = \left(\sqrt{3}V_{LL}I_{o}\right)/V_{dc}. \hspace{1cm} (23)$$

Equation (23) shows that there is only dc current component at the output capacitor.

The current fed through the center-tapped autotransformer by phases $a$ and $b$ returns through phase $c$. Therefore, the rms value of the winding current is half of $I_c$. The voltage across the end of the autotransformer is line-to-line voltage. The power handled by the autotransformer is

$$P_{TR} = \frac{1}{2}\left(\frac{1}{2}V_{LL}\right)\ast \left(\frac{1}{2}I_{o}\right)\ast 2 = \frac{1}{4}V_{LL}I_{o}. \hspace{1cm} (24)$$

Then, the VA rating of the autotransformer is

$$V_{A_{TR}} = \frac{P_{TR}}{P_{a1}} = \frac{\frac{1}{4}V_{LL}I_{o}}{\sqrt{3}V_{LL}I_{o}} = 0.1443. \hspace{1cm} (25)$$

### III. SIMULATION RESULTS

Fig. 10 shows the simulation result of the proposed system. A simple proportional plus integral (PI) controller is used for the inner current control loop. The voltage control loop feeds the current references of the two single-phase PFC modules forcing current sharing between them.

The amplitudes of input currents at each PFC [Fig. 10(a)] are different to carry the same power. The input line current waveforms are near sinusoidal [Fig. 10(b)], which demonstrates the proposed approach.

### IV. DESIGN EXAMPLE

Table I summarizes the VA rating of the autotransformer and the operating condition of each PFC module. For an output power of 1.5 kVA, each PFC module supplies 750 VA. Design of each PFC modules follows the single-phase boost PFC operating in continuous conduction mode (CCM) [10]. Since the low-frequency power components cancel each other, the output capacitor handles only high-frequency ripple elements.

### V. EXPERIMENTAL RESULTS

The proposed three-phase PFC rated at 220 V, 1.5 kVA (Fig. 1) has been implemented and the results are discussed in this section. Both PFC modules are controlled by Unitrode UC3854A controllers. Fig. 11(a) shows the input currents $I_{a1}$ and $I_{c}$ of each PFC which are 90° phase shifted and the amplitudes are different so that their respective output powers are equal. Fig. 11(b) shows the line currents $I_{a}$, $I_{b}$ and $I_{c}$. They are nearly sinusoidal in shape. Fig. 11(c) and (d) shows the voltage $V_{db}$ and current $I_{a1}$; $V_{dc}$ and current $I_{c}$, respectively. It is clear from the figure that each PFC stage operates in CCM at unity power factor.

### VI. CONCLUSION

In this paper, a new three-phase PFC scheme using two standard single-phase PFC modules has been presented. Each PFC module is rated for half the output power and operates in CCM with unity power factor. With staggered PWM, the...
interaction between PFC modules is virtually eliminated. The resulting input line currents are nearly sinusoidal in shape. The experimental result from a laboratory prototype demonstrates the performance of the proposed system.

REFERENCES


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