A Three-Phase Unity-Power-Factor Diode Rectifier With Active Input Current Shaping

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***Abstract*—This paper proposes a new three-phase diode rectifier that actively shapes the input current by means of two direct current dc–dc converters operating at continuous conduction mode. The proposed approach draws sinusoidal input current at unity power factor and has output voltage regulation capability. The size and weight of the magnetic devices is reduced since a low-kilovolt-ampere three-phase autotransformer is incorporated and dc outputs of two bridges are directly connected without using low-frequency interphase transformers (IPTs).**

***Index Terms*—Active waveshaping, autotransformer, diode rectifier, harmonic mitigation, three-phase power-factor correction.**

I. Introduction

Diode rectifiers with smoothing capacitors have been widely used as a front end in many three-phase power electronic systems such as alternating current (ac) drives and switch mode power supplies. Due to inherent nonlinear switching operation, diode rectifiers suffer from large contents of input current harmonics, resulting in many serious problems in power system. There have been many approaches to eliminate the harmonics in the rectifier system. A six-switch pulsewidth-modulation (PWM) rectifier needs complicated measurements and feedback control. Multipulse rectifiers eliminate low-order harmonics without increasing high-order harmonics but require bulk and complicated phase-shifting transformers and corresponding rectifier bridges [1]. Double-connected rectifiers do not require multiple phase-shifting transformers and corresponding rectifier bridges and demonstrate high input power factor [2], [3]. However, these schemes do not have output voltage regulation capability and usually require low-frequency interphase transformers (IPTs) for connection of the direct current (dc) output. Several three-phase high-power-factor rectifier topologies with output voltage regulation have been proposed [4], [5].

II. Proposed Active Diode Rectifier System

Fig. 1(a) shows the basic configuration of the proposed diode rectifier system that employs a three-phase autotransformer and two three-phase diode rectifiers, each followed by a dc-to-dc boost converter operating at continuous conduction mode. The autotransformer has a reduced kilovolt ampere rating of $0.24P_{\rm o}$ while the equivalent $\Delta{-}{\rm Y}$ transformer has a kilovolt ampere rating of $1.035P_{\rm o}$ [2]. The two diodes and inductors in the boost converter prevent the interaction between them. Two dc–dc converter outputs are directly connected without using low-frequency IPTs. Instead, four small high-frequency boost inductors are used.

Each boost converter is operated to shape its inductor current so that the inductor currents are modulated as shown in Fig. 1(b). The two inductor currents have the same wave shape except the 30° phase shift. The rectifier input currents can be expressed in terms of inductor currents and switching functions of the diode bridges as

$$\begin{bmatrix} i_{a_1} \\ i_{b_1} \\ i_{c_1} \end{bmatrix} = \begin{bmatrix} S_{a_1} \\ S_{b_1} \\ S_{c_1} \end{bmatrix} i_{L_1} \qquad \begin{bmatrix} i_{a_2} \\ i_{b_2} \\ i_{c_2} \end{bmatrix} = \begin{bmatrix} S_{a_2} \\ S_{b_2} \\ S_{c_2} \end{bmatrix} i_{L_2}. \tag{1}$$

From the autotransformer connection, the input current can be expressed in terms of rectifier input currents as [2]

$$i_a = i_{a_1} + i_{a_2} + 0.1547\left(i_{c_2} - i_{b_2} + i_{b_1} - i_{c_1}\right). \tag{2}$$

Then, the input current can be expressed in terms of the inductor currents and the switching functions as

$$\begin{aligned} i_a = &\left\{S_{a_1} + 0.1547\left(S_{b_1} - S_{c_1}\right)\right\} i_{L_1} \\ &+ \left\{S_{a_2} + 0.1547\left(S_{c_2} - S_{b_2}\right)\right\} i_{L_2}. \end{aligned} \tag{3}$$

It can be noted from (3) that the input current can be determined by the inductor current. Modulating the inductor current as shown in Fig. 1(b) results in sinusoidal input currents at unity power factor. The wave shape of the inductor current is the same as that of the line-to-line voltages, shown as a thick line in Fig. 1(b). The method of generating reference signals for inductor currents is shown in Fig. 2. The normalized wave shape references, $i_{L_1,{\rm N}}$ and $i_{L_2,{\rm N}}$ are stored in a look-up table and is synchronized with a line-to-line voltage by means of zero-cross detecting and phase-locked loop circuits. The proposed diode rectifier system has output voltage regulation capability. Fig. 2 also shows the block diagram for the voltage regulation and the inductor current control.

The current ratings of the component in the proposed scheme depend on the duty ratio of the main switch. The following input and output relationship on average values can be derived from Fig. 1(b):

$$\frac{V_{\rm o}}{V_{d_1}} = \frac{1}{1-D} = \frac{2I_{L_1,{\rm avg}}}{I_{\rm o}}. \tag{4}$$

The output current $I_{\rm o}$ is given by

$$I_{\rm o} = \frac{P_{\rm o}}{V_{\rm o}}. \tag{5}$$

The root-mean-square (rms) value of the inductor current can also be calculated as

$$I_{L_1,{\rm rms}} = \frac{1}{\sqrt{3}} I_{L_1,{\rm peak}} = \frac{1}{\sqrt{3}} 2I_{L_1,{\rm avg}}. \tag{6}$$

Furthermore, the rectifier output voltage becomes [2]

$$V_{d_1} = 1.035 \times 1.35 \times V_{\rm LL}. \tag{7}$$

As an example, if the line-to-line voltage $V_{\rm LL}$ is 220 V and the desired output voltage $V_{\rm o}$ is 400 V, then the duty cycle D becomes 0.2315 from (4) and (7). In addition, if the output power $P_{\rm o}$ is 10 kW, then the output current $I_{\rm o}$ becomes 25 A from (5). The component ratings along with this design example are listed in Table I, where the voltage

Manuscript received July 9, 2004; revised August 16, 2005. Abstract published on the Internet September 26, 2005.

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Digital Object Identifier 10.1109/TIE.2005.858699

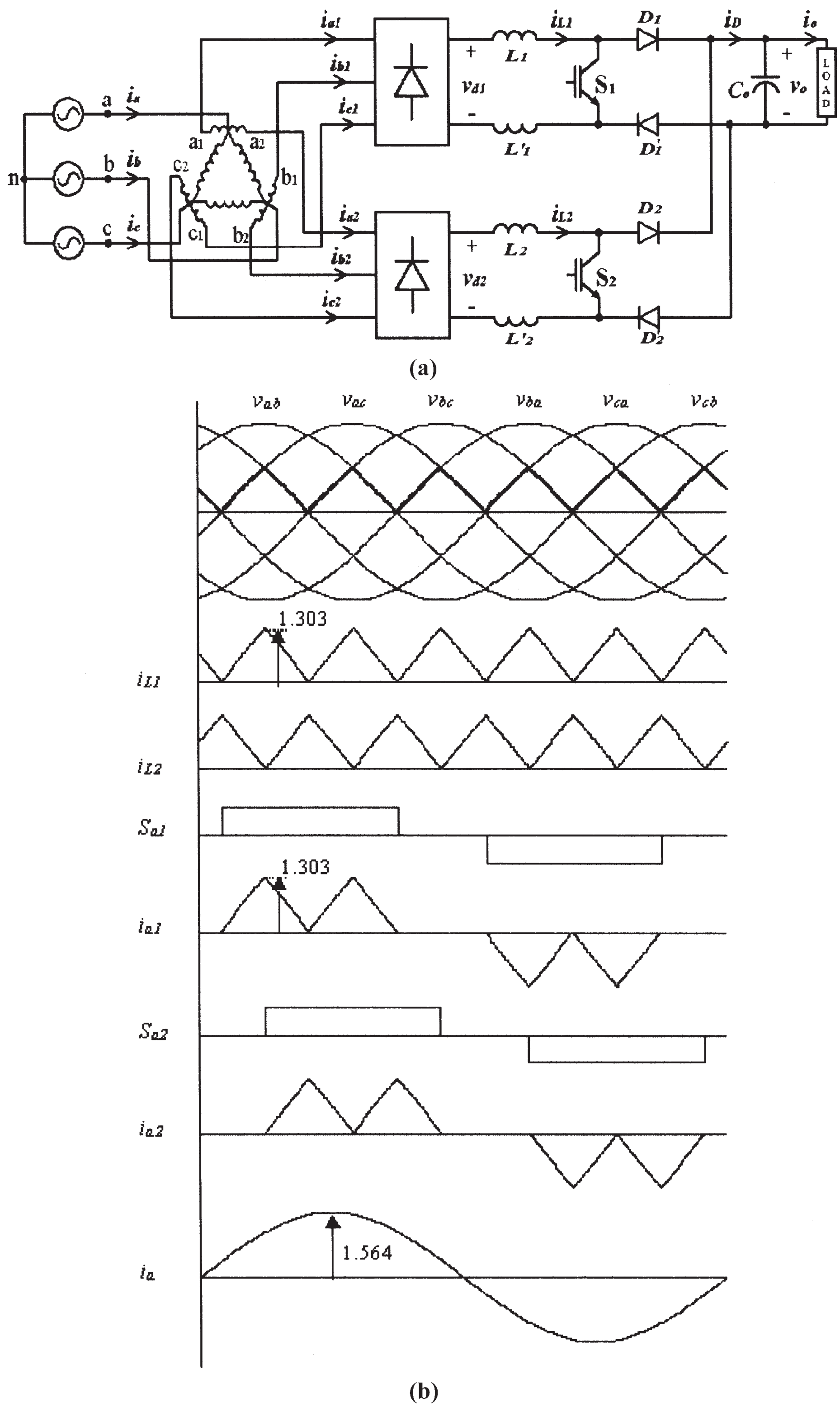

Fig. 1. Proposed diode rectifier system. (a) Power circuit. (b) Various waveforms ($I_{\mathrm{o}} = 1$ p.u. and $D = 0.2315$).

and current ratings are normalized with respect to line-to-line voltage V_{LL} and output current I_{o}, respectively.

III. Experimental Results

A 220-V 1.5-kVA laboratory prototype has been built, and the experimental results are provided. The system parameters for the experiment are as follows: 1) dc-link capacitor $C_{\mathrm{o}} = 3300\ \mu$F and 2) boost inductor L_1, $L_2 = 5$ mH.

Fig. 3(a) shows the inductor current i_{L_1} whose waveform is shaped by the two dc–dc converters. The rectifier input current i_{a_1}, shown in Fig. 3(b), has 120° of discontinuous period. This results in a purely sinusoidal line current, as shown in Fig. 3(c) and (d). The measured total harmonic distortion (THD) of the line current is 2.7%.

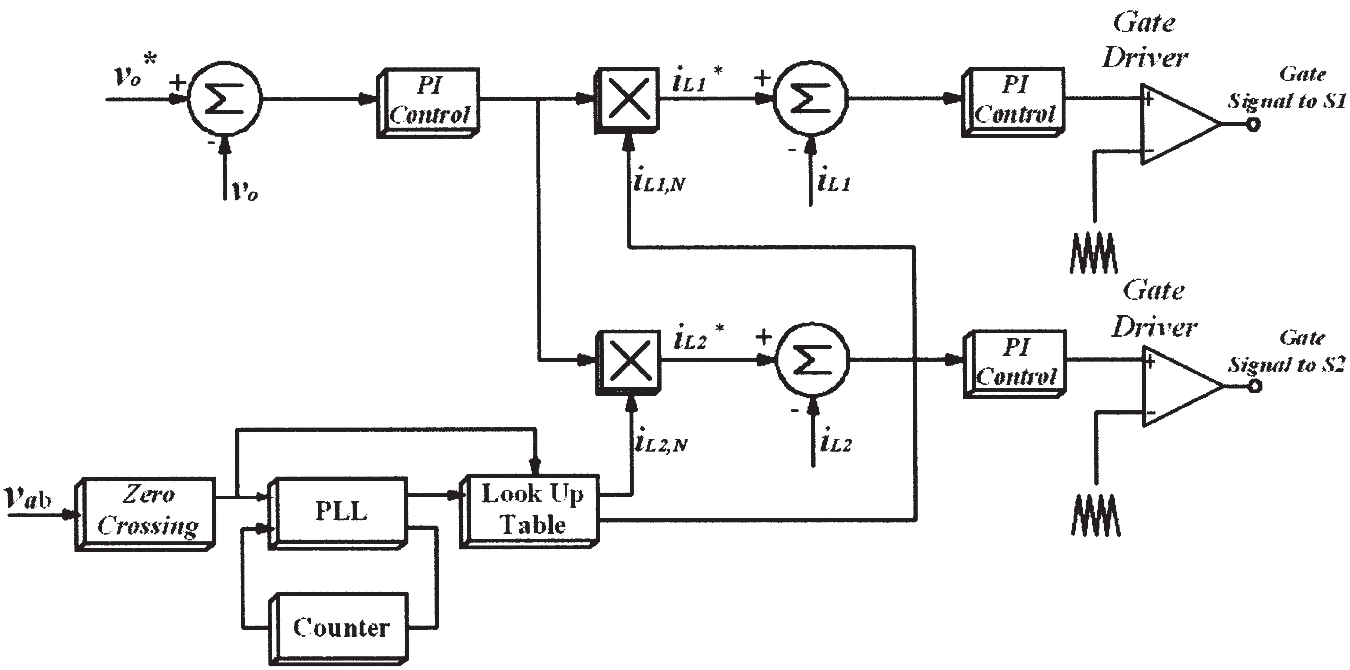

Fig. 2. Control block diagram.

TABLE I
COMPONENT RATING CALCULATION

Component			Expression	P.U. Value	Design Value (10kW)
Auto-transformer	delta winding	rms voltage	V_{LL}	1	220V
		rms current	$\frac{0.083}{1-D} \cdot I_o$	0.108	2.7A
	small winding	rms voltage	$\frac{V_{LL}}{\sqrt{3}} \cdot \tan 15^\circ$	0.154	34V
		rms current	$\frac{0.471}{1-D} \cdot I_o$	0.612	15.32A
	$VA(\%) = \frac{\sum V_{rms} \cdot I_{rms}}{2V_o \cdot I_o} \times 100$			0.24	2.453kW (24.53%)
Boost switch	peak voltage		V_o	1.81	400V
	peak current		$\frac{I_o}{1-D}$	1.3	32.5A
	rms current		$0.751\sqrt{D} \cdot I_o$	0.36	9.03A
Boost diode	peak voltage		V_o	1.81	400V
	peak current		$\frac{I_o}{1-D}$	1.3	32.53A
	rms current		$0.751\sqrt{1-D} \cdot I_o$	0.65	16.46A

IV. CONCLUSION

In this paper, a new active three-phase diode rectifier incorporating dc–dc boost converter operating at continuous conduction mode is proposed, and experimental results on a 1.5-kVA prototype are provided to validate the proposed theory. The advantages of the proposed scheme include the following:

1) sinusoidal input current at unity power factor;
2) regulated output voltage over wide input voltage range;

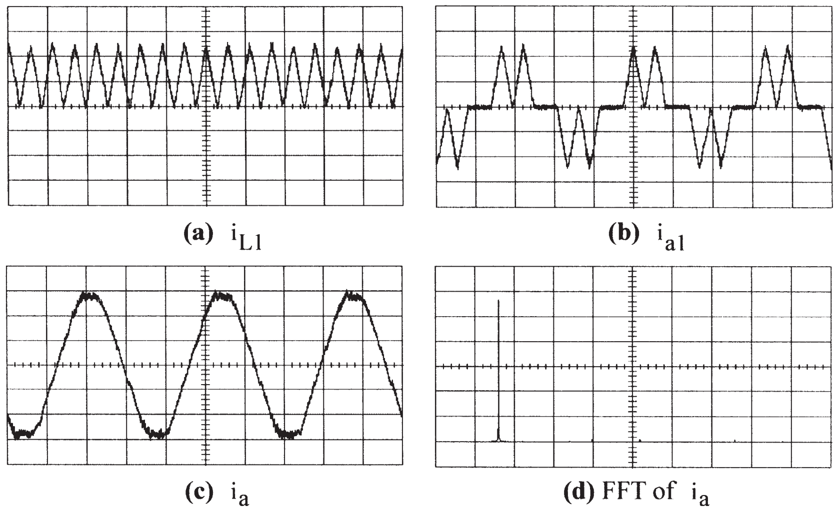

Fig. 3. Experimental waveforms (2 A/div, 100 V/div, 5 ms/div, fast Fourier transform (FFT): 1 A/div, and 100 Hz/div).

3) direct connection of the dc output without using low-frequency IPTs;
4) reduced volt ampere rating ($0.24P_o$) of the phase-shifting transformer.

The efficiency of the proposed scheme could be improved by employing an active zero-current-switching (ZCS) technique proposed in [6].

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