A New Three-Phase Harmonic-Free Rectification Scheme Based on Zero-Sequence Current Injection

Sewan Choi, *Senior Member, IEEE*, Chung-Yuen Won, *Member, IEEE*, and Gyu-Sik Kim, *Member, IEEE*

***Abstract*—This paper proposes a new three-phase harmonic-free rectification scheme based on a zero-sequence injection technique. The proposed scheme incorporates two half-bridge inverters and two single-phase transformers to actively and individually shape the positive and negative dc rail currents of the rectifier. The shaped zero-sequence harmonic currents are then circulated through the ac side of the rectifier via a zigzag transformer, resulting in pure sinusoidal input currents in the three-phase diode rectifier. A design example along with component ratings calculation are detailed. Experimental results on a 1.5-kVA prototype are provided to validate the proposed technique.**

***Index Terms*—Current injection, harmonic reduction, three-phase diode rectifier, zero sequence.**

I. Introduction

A RAPID proliferation of power electronic equipment which are nonlinear in nature results in large contents of input current harmonics which could cause many serious problems in the power system. There have been many approaches to mitigate the harmonics in the rectifier system. They include the following: 1) active power filters; 2) six-switch pulsewidth-modulation (PWM) rectifiers; 3) power-factor correction (PFC) by boost converters; 4) multipulse rectifiers; and 5) harmonic current injection method. These approaches show advantages and disadvantages in terms of cost, efficiency, performance, complexity, reliability, and application range in size, etc. al. The harmonic current injection method, proposed by Bird [1] and generalized by Ametani [2], has advantages of relatively low cost and high efficiency and can be applied to medium- to high-power rectification over 1 MVA. Passive third-harmonic injection techniques have been proposed in [3] and [4]. A single-switch approach, as shown in Fig. 1, applies a diode rectifier, a boost converter, and a zigzag transformer as a current injection device to circulate the injected harmonic current and, therefore, to reduce the input current harmonics [5]. This scheme is easy to implement and could be used as an add-on solution to a standard adjustable-speed drive (ASD) topology. A drawback to the approach is the dependence of input current total harmonic distortion (THD) upon the value of the dc-link inductance. It can be seen that the zero-sequence triplen-odd harmonics other than only the third harmonic should be injected, and both the positive rail current and the negative rail current of the rectifier should be individually shaped in order to draw pure sinusoidal input currents, which will be clearly discussed in Section II-A. However, the individual control of the rail currents cannot be implemented with this single-switch approach. Due to these reasons, it is not easy to obtain input current THD of less than 10% with this approach. A harmonic injection scheme, as shown in Fig. 2, employs two boost converters and a zigzag transformer to shape the input current by injecting a third harmonic current at the ac side of the diode rectifier [6]. An optimal current programming technique proposed in [7] makes the input current of this scheme purely sinusoidal. The improvement in input current THD results from the injection of zero-sequence triplen-odd harmonics other than

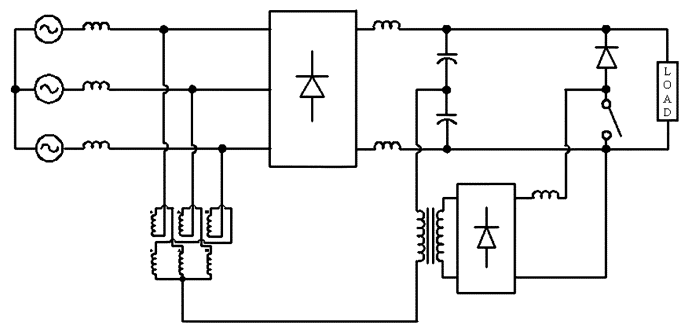

Fig. 1. Single-switch approach for current injection [5].

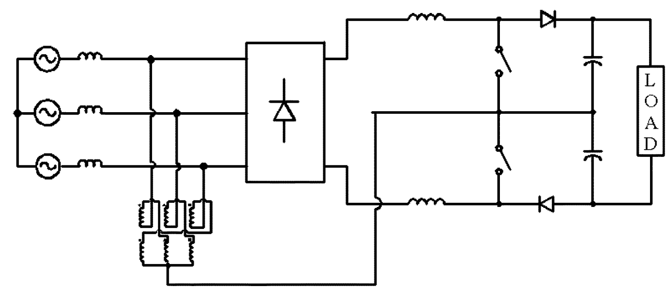

Fig. 2. Current injection method by two boost converters [6], [7].

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the third harmonic and the individual wave shaping of the dc rail currents of the diode rectifier. However, the scheme in [6] and [7] has two diodes in series with the power flow path, which increases the losses. Moreover, the increased dc-link voltage of these schemes due to boost operation may require a redesign of the next stage power converter.

In this paper, a new three-phase rectification scheme is proposed to draw purely sinusoidal input currents. The proposed approach, based on the zero-sequence current injection technique, incorporates two half-bridge inverters and two single-phase transformers to actively and individually shape the positive and negative dc rail currents.

The actively shaped zero-sequence harmonic currents are then circulated through the ac side of the rectifier. This results in purely sinusoidal input current in the three-phase diode rectifier. The proposed scheme exhibits the following features:

- purely sinusoidal input currents due to the proposed zero-sequence triplen-odd harmonic current injection;
- no switching devices in series with the main power flow path;
- no increased dc-link voltage;
- relatively small component rating of the auxiliary circuit.

II. Proposed Zero-Sequence Current Injection Scheme

A. Principles of Zero-Sequence Current Injection

Fig. 3(a) illustrates the basic configuration of the current injection scheme. It consists of a three-phase diode rectifier, two current sources i_p and i_q, and a current injection device. It is assumed that the load is a ripple-free dc current I_o. The third harmonic injection technique is illustrated in Fig. 3(b). Without the injection of current i_p and i_q, the shape of the input current $i_{sa}(i_{ra})$ is a square wave containing harmonics such as the 5th, 7th, 11th, 13th, etc, al. This is because of the discontinuous conduction of the rectifier diodes. The current injection fills up the discontinuity resulting in a reduction of input current THD. According to the optimization method presented in [6], the current sources i_p and i_q are given by

$$i_p = i_q = 0.74 I_o \sin(3\omega t). \tag{1}$$

As shown in Fig. 3(b), the two shaped currents that are identical add up and are circulated through the ac side of the rectifier by the current injection device. The current injection device divides the summed current i_j into three equal currents, and the current i_{ja} is subtracted from the rectifier input current i_{ra} making the input current i_{sa} more sinusoidal. However, it should be noted that the resultant line current waveform is somewhat close to sinusoidal, but not purely sinusoidal with $\text{THD} = 5.1\%$. In order to obtain a purely sinusoidal input current, zero-sequence triplen-odd harmonics other than only the third harmonic should be injected as shown in Fig. 3(c). The optimum magnitudes of each harmonic component of i_j for both current injection techniques are compared in Table I. The injected current i_j for the proposed zero-sequence injection does contain third harmonic as well as other triplen harmonics such as the 9th, 15th, 21th, etc. As shown in Fig. 3(c), the nonidentical currents i_p and i_q which are individually shaped in both

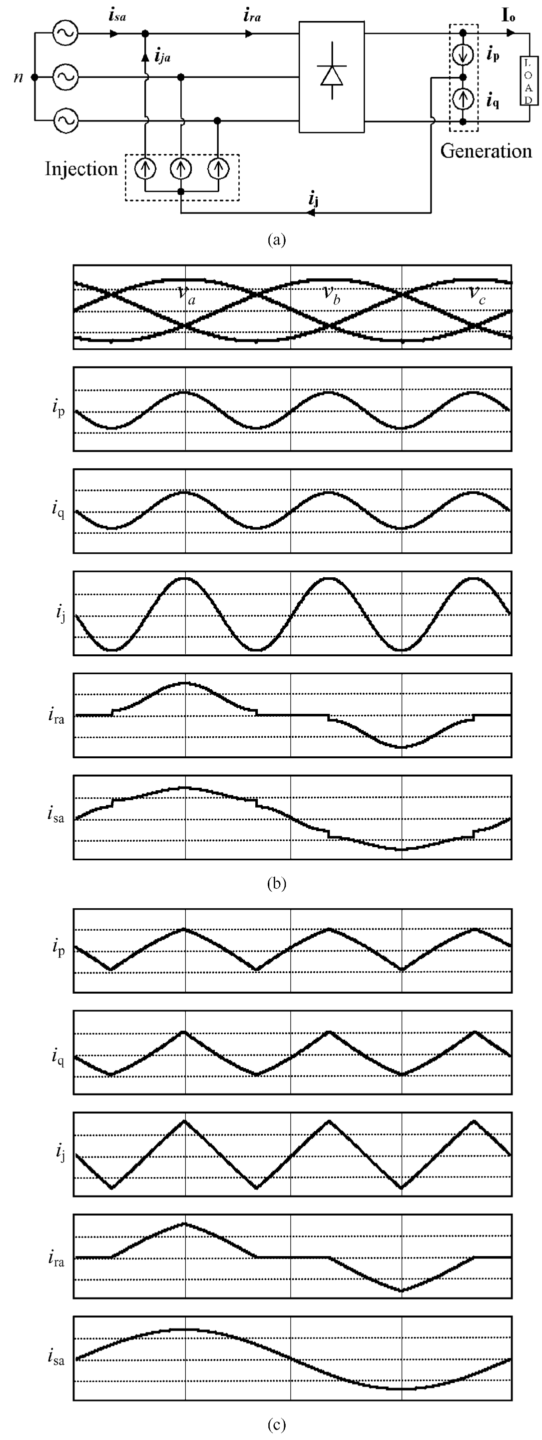

Fig. 3. Principle of harmonic current injection (vertical: $1.0 I_o$/div, horizontal: 4.17 ms/div). (a) Basic configuration. (b) Third harmonic injection. (c) Proposed zero-sequence triplen-odd harmonics injection.

positive and negative rails are injected and circulated through the ac side of the rectifier, resulting in a purely sinusoidal line current.

B. Proposed Rectification Scheme

Fig. 4 shows the power circuit of the proposed three-phase rectification scheme for the zero-sequence triplen-odd harmonics injection. The two nonidentical current sources i_p and

TABLE I
HARMONIC SPECTRUM OF THE INJECTED CURRENT i_j

Order	3rd harmonic injection	Triplen-odd harmonics injection
3	$1.480I_o$	$1.432I_o$
9	-	$0.143I_o$
15	-	$0.051I_o$
21	-	$0.013I_o$
27	-	$0.016I_o$
33	-	$0.011I_o$

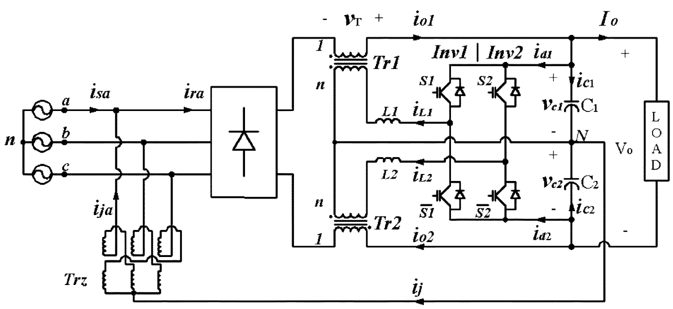

Fig. 4. Proposed harmonic-free rectification scheme for zero-sequence third-harmonic current injection.

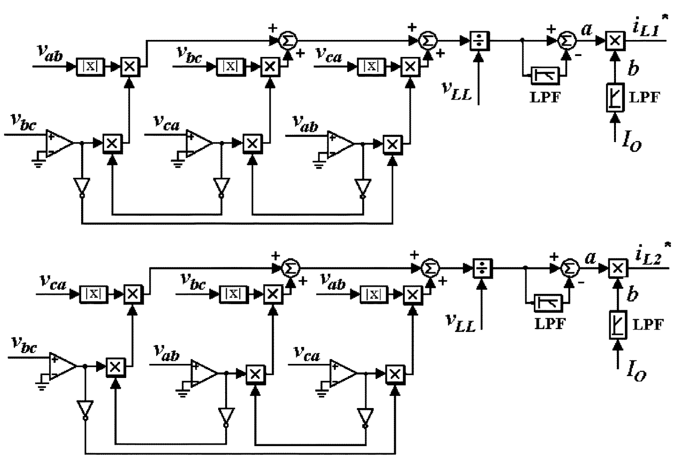

Fig. 5. Reference signal generation.

i_q, shown in Fig. 3(a), are implemented by two half-bridge inverters, two single-phase transformers, and two filter inductors. A zigzag transformer, which presents a low-leakage impedance for the zero-sequence harmonics, is employed to realize the current injection device shown in Fig. 3(a). Each half-bridge inverter is operated to shape each of the inductor currents i_{L1} and i_{L2}. The waveshape of the normalized inductor current reference "a" can be obtained from the line-to-line voltages and the rms value V_{LL} of them as shown in Fig. 5. The output current I_o is passed through a low-pass filter to obtain the magnitude reference "b." The inductor current reference is obtained by multiplying the normalized waveshape reference "a" by the magnitude reference "b." The control block diagram for the

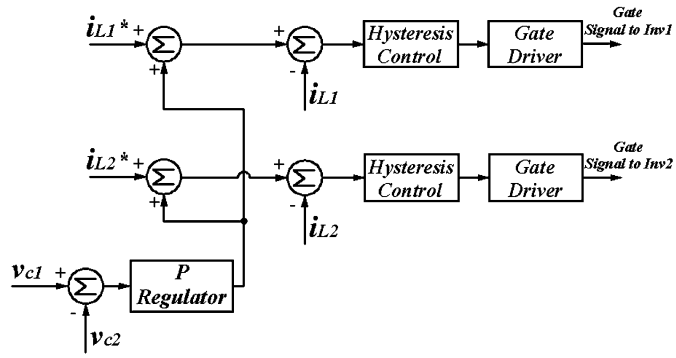

Fig. 6. Control block diagram.

proposed scheme is shown in Fig. 6. A P-regulator is applied to equalize the voltages on the dc-link capacitors C_1 and C_2. The control signal from the P-regulator is added to the inductor current reference obtained from Fig. 5. The resultant current reference is compared with the measured inductor current, and the error resulting from the comparison is then applied to a hysteresis controller to get the gating signals for the inverter switches.

The inverter dc-side currents i_{d1} and i_{d2} can be expressed as

$$\begin{aligned} i_{d1} &= \mathrm{SW}_1 \cdot i_{L1} + \mathrm{SW}_2 \cdot i_{L2} \\ i_{d2} &= \overline{\mathrm{SW}_1} \cdot i_{L1} + \overline{\mathrm{SW}_2} \cdot i_{L2} \end{aligned} \tag{2}$$

where SW_1 and SW_2 are the switching functions of each half-bridge inverter determined by the gating signals for current control shown in Fig. 6. Also, the dc rail currents i_{o1} and i_{o2} are determined to be

$$\begin{aligned} i_{o1} &= I_o + n \cdot i_{L1} \\ i_{o2} &= I_o - n \cdot i_{L2}. \end{aligned} \tag{3}$$

Then, each of the capacitor currents i_{c1} and i_{c2} can be expressed as

$$\begin{aligned} i_{c1} &= n \cdot i_{L1} - i_{d1} \\ i_{c2} &= n \cdot i_{L2} - i_{d2}. \end{aligned} \tag{4}$$

Therefore, the injection current i_j becomes

$$i_j = n \cdot (i_{L1} + i_{L2}). \tag{5}$$

The injection current i_j splits equally in the three legs of the zigzag transformer. Fig. 7 shows the various current waveforms of the proposed scheme shown in Fig. 4. The circulating current i_{ja} subtracts from the diode rectifier input current i_{ra}, resulting in purely sinusoidal line current i_{sa}.

C. Component Ratings

Table II summarizes the component ratings with reference to the line-to-line rms voltage V_{LL} and the output dc current I_o.

Transformers: The winding voltages and currents of transformers $Tr1$ and $Tr2$ are listed in Table II. In general, the VA

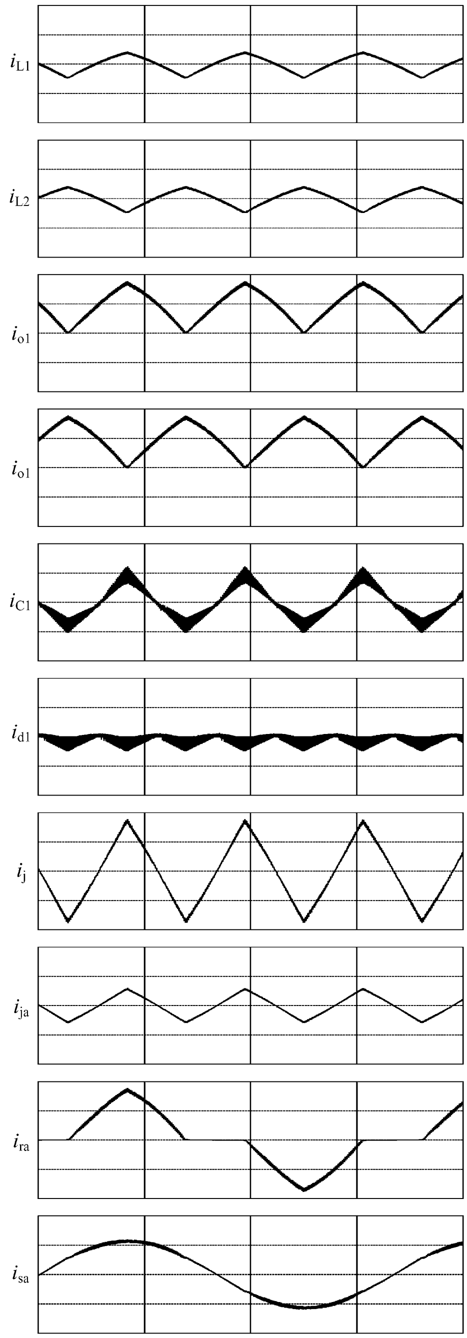

Fig. 7. Various current waveforms of the proposed scheme ($n = 2$, vertical: $1.0I_o$/div, horizontal: 5 ms/div).

rating of a transformer can be calculated as a percentage of the input VA by using the following equation:

$$\mathrm{VA}(\%) = \frac{0.5 \cdot \sum V_{\mathrm{rms}} \cdot I_{\mathrm{rms}}}{\sqrt{3} \cdot V_{\mathrm{LL}} \cdot I_{sa}(=\text{Input VA})} \times 100 \tag{6}$$

where V_{rms} and I_{rms} are the rms values of the winding voltage and current, and I_{sa}, the rms value of the input current in terms of the output current, is shown to be $0.78I_o$. The transformer VA is only 7.4% of the input VA since the primary voltage $0.12V_{\mathrm{LL}}$ is a small ripple component of the diode rectifier output voltage. Further, the size and weight of the transformers are reduced to about 58% of those of a 60-Hz transformer of the same VA

TABLE II
COMPONENT RATINGS

Components			P.U. Value	Design Example (220V, 10kW)
Transformer Tr1, Tr2	PRI.	V_{rms}/V_{LL}	0.123	27.06V
		I_{rms}/I_O	1.160	39.06A
	SEC.	V_{rms}/V_{LL}	0.123n	54.12V
		I_{rms}/I_O	0.511/n	8.60A
	VA(%)		7.4	7.4
Zigzag Transformer Trz	V_{rms}/V_{LL}		0.333	73.26V
	I_{rms}/I_O		0.333	11.21A
	VA(%)		24.6	24.6
IGBT	V_{peak}/V_{LL}		1.350	297V
	I_{peak}/I_O		1/n	16.83A
	I_{rms}/I_O		0.361/n	6.61A
Capacitor C_1, C_2	$V_{c1.dc}/V_{LL}$		0.675	148.5V
	$I_{c1.rms}/I_O$		0.511n	34.41A
	Capacitance		(11)	2615uF
Filter Inductor L_1, L_2	I_{peak}/I_O		1/n	33.67V
	I_{rms}/I_O		0.511n	34.41A
	Inductance		(12), (13)	2.2mH< L_1<4.4mH

rating, since they operate at three times the fundamental frequency [8]. The winding voltage of the zigzag transformer is one-third of the line-to-line voltage, and the winding current is also one-third of the injection current I_j. The VA rating of the zigzag transformer is 24.6% of the input VA rating.

Inverter Switches: The switch VA rating is determined by the peak voltage and the peak current of the switch. The peak voltage of the inverter switch in the proposed scheme is equal to the dc-link voltage V_o. The current rating of the inverter switch is determined by the output current I_o and the turns ratio "n" of the transformer connected in series with the dc rail. For proper current control by the inverters, the peak value of the transformer secondary voltage should be smaller than that of the peak inverter output voltage. That is,

$$n \cdot V_{T,\mathrm{peak}} < 0.5 \cdot V_o. \tag{7}$$

The peak value of the transformer secondary voltage can be obtained by waveform analysis as

$$V_{T,\mathrm{peak}} = 0.5 \cdot V_o - \frac{\sqrt{2}}{\sqrt{3}} \cdot V_{\mathrm{LL}} \cdot \sin 30^\circ. \tag{8}$$

It can be seen from (7) and (8) that the turns ratio "n" should be limited to a value of 2.53. Therefore, if we choose $n = 2$, the peak current rating of the inverter switch is reduced to half of the output current I_o.

Capacitors: As shown in Fig. 7, currents i_{c1} and i_{c2} which are also ac components of the dc rail currents, flow through dc smoothing capacitors C_1 and C_2, respectively. The rms current rating of the capacitors is $0.51I_o$. The capacitor working voltage

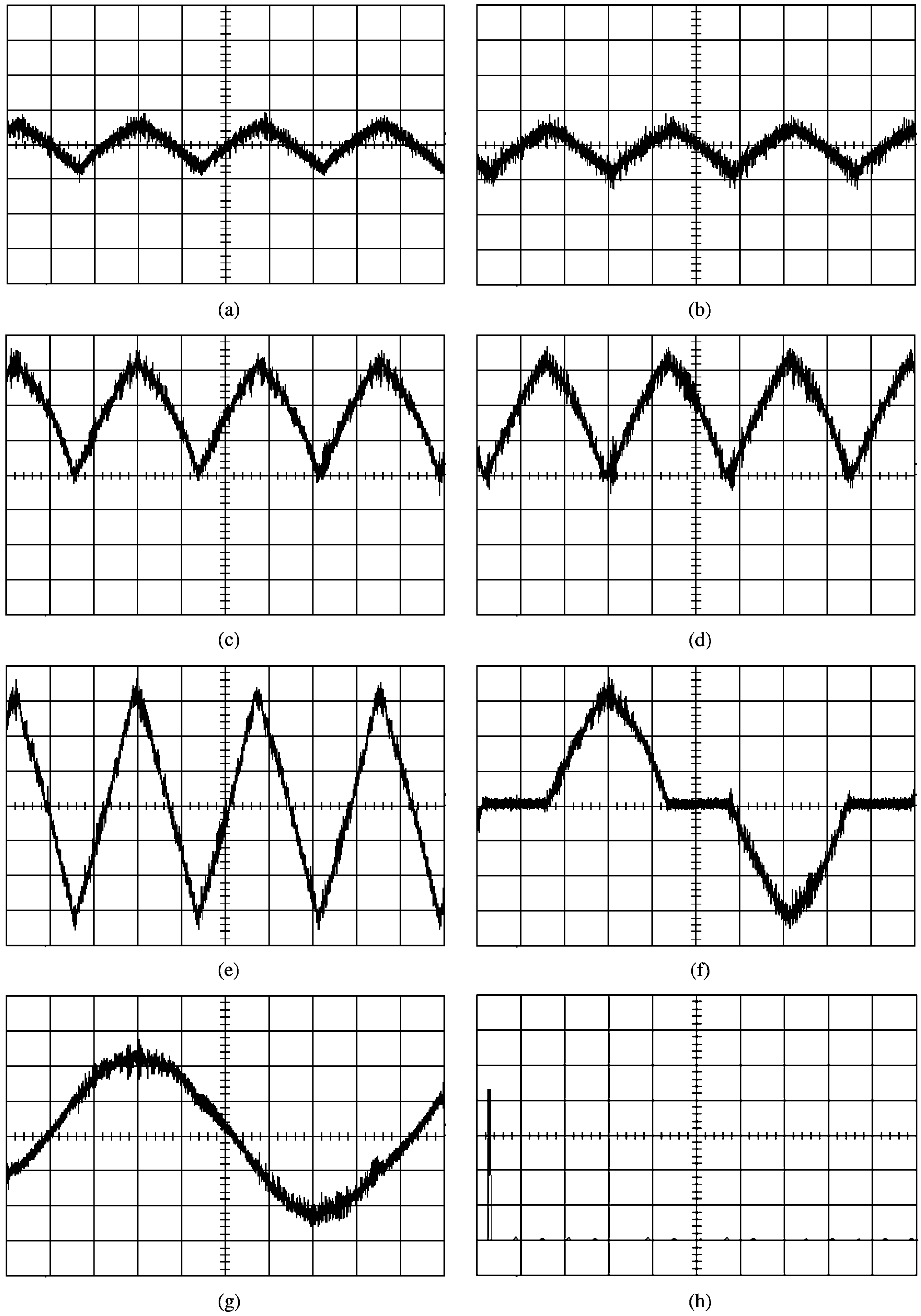

Fig. 8. Experimental waveforms (waveforms : 1 A/div; 2 ms/div; FFT: 0.5 A/div; 100 Hz/div). (a) Inductor current i_{L1}. (b) Inductor current i_{L2}. (c) Positive dc rail current i_{o1}. (d) Negative dc rail current i_{o2}. (e) Injected current i_j. (f) Rectifier input current i_{ra}. (g) Input current i_{sa}. (h) FFT of i_{sa}.

is one-half of the output dc voltage V_o. The capacitances should be determined taking into account the acceptable level of the capacitor ripple voltage caused by currents i_{c1} and i_{c2}. Neglecting the switching ripple component in currents i_{c1} and i_{c2}, the currents can be approximated to a triangular wave, and then the magnitude V_{ripple} of the ripple voltage can be obtained by

$$V_{\text{ripple}} = \frac{1}{\omega C_1} \int_0^{\frac{\pi}{12}} \frac{0.83 \cdot I_o}{\pi/12} \cdot t d(\omega t). \tag{9}$$

Define a ripple factor of

$$K_v = \frac{V_{\text{ripple}}}{V_{c1}} = \frac{V_{\text{ripple}}}{0.5 \cdot V_o}. \tag{10}$$

The capacitance can be determined by

$$C_1 = \frac{0.322 \cdot I_o}{K_v \cdot \omega \cdot V_{\text{LL}}}. \tag{11}$$

Filter Inductors: The peak and rms values of the filter inductor currents i_{L1} and i_{L2} shown in Fig. 7 are dependent upon the transformer turns ratio. Inductance should be chosen properly; if is chosen too small, then the switching ripple of the inductor current would be too large, and if it is chosen too large then the inverter could not shape the current waveform properly. Therefore, the choice of the inductance is based on the following two criteria. The switching frequency component of the inductor current is limited by using the following (7)

$$\frac{V_{\mathrm{sw}}}{I_3 \cdot (f_{\mathrm{sw}}/f) \cdot \omega \cdot L_1} < K_I \tag{12}$$

where V_{sw} is the rms value of the inverter output voltage at the switching frequency, I_3 is the rms value of the third harmonic inductor current, and K_I is the ratio of the switching frequency component to the third harmonic component of the inductor current. The instantaneous di/dt generated by the inverter should be greater than that of the reference inductor current so that proper waveshaping can take place. This yields

$$\left[n \cdot v_T + L_1 \cdot \frac{di^*_{L1}}{dt}\right]_{\mathrm{peak}} < 0.5V_o. \tag{13}$$

Equations (12) and (13) allow for the computation of lower limit and upper limit of the inductance, respectively.

D. Design Example

As a design example of the proposed rectification scheme, the following parameters are assumed:

$$\begin{aligned} &P_o = 10\ \mathrm{kW} \quad V_{\mathrm{LL}} = 220\ \mathrm{V} \quad n = 2\\ &K_I = 0.05 \quad K_V = 0.05\\ &f = 60\ \mathrm{Hz} \quad f_{\mathrm{sw}} = 15\ \mathrm{kHz}.\end{aligned}$$

Then, the output dc voltage is

$$V_o = 1.35 \cdot V_{\mathrm{LL}} = 297\ \mathrm{V}. \tag{14}$$

The output dc current is calculated as

$$I_o = \frac{P_o}{V_o} = 33.67\ \mathrm{A}. \tag{15}$$

The calculated component ratings of the transformers and the inverter switches are shown in Table II. The capacitances C_1 and C_2 can be calculated by using (11). Choosing $n = 2$, the rms value I_3 of the third-harmonic inductor current becomes $0.358I_o$. When the modulation index is chosen equal to 0.9, the rms value V_{sw} of the inverter output voltage at the switching frequency can be obtained using simulation and is $0.419V_o$. The peak of v_T and di^*_{L1}/dt occur at the same time and they are

$$V_{T,\mathrm{peak}} = 0.198 \cdot V_o \tag{16}$$

$$\left[\frac{di^*_{L1}}{dt}\right]_{\mathrm{peak}} = 7\ \mathrm{kA/s}. \tag{17}$$

From (12), (13), (16), and (17) we obtain

$$2.2\ \mathrm{mH} < L_1 < 4.4\ \mathrm{mH}. \tag{18}$$

III. Experimental Results

A 220-V 1.5-kVA laboratory prototype for the proposed rectification has been built and the experimental results are provided. The experimental waveforms for the proposed scheme are shown in Fig. 8. The system parameters for the experiment are as follows:

- turns ratio $n = 2$;
- dc-link capacitor $C_1, C_2 = 470\ \mu\mathrm{F}$;
- filter inductor $L_1, L_2 = 4$ mH.
- switching frequency $f_{\mathrm{sw}} = 15$ kHz.

Fig. 8(a) and (b) shows the inductor currents i_{L1} and i_{L2} which are shaped by the two single-phase half-bridge inverters. The waveshapes of the dc rail currents i_{o1} and i_{o2}, shown in Fig. 8(c) and (d), are the same as those of the inductor currents except they have a dc component of the load current. Only the ac components of them flow through the dc-link capacitors, and the sum i_j of the capacitor currents is shown in Fig. 8(e). The current i_j splits equally in the three legs of the zigzag transformer and is subtracted from the rectifier input current shown in Fig. 8(f). This results in a purely sinusoidal line current, as shown in Fig. 8(g) and (h). The measured THD of the line current is 2.7%.

IV. Conclusion

A new three-phase harmonic-free rectification scheme has been proposed in this paper. The proposed scheme incorporates two single-phase half-bridge inverters to generate zero-sequence harmonics, to inject the zero-sequence harmonic currents through the transformers, and to modulate the positive and negative dc rail currents of the rectifier. This results in purely sinusoidal input currents in the three-phase diode rectifier. There are no switching devices in series with the power flow path, and the dc-link voltage does not change, unlike the method proposed in [6] and [7]. The VA rating of the inverter switches and the transformers are shown to be a small portion of the input VA. A design example along with thorough component rating calculations have been presented. Experimental results on a 1.5-kVA prototype validated the proposed theory.

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