# A New Active Interphase Reactor for 12-Pulse Rectifiers Provides Clean Power Utility Interface

Sewan Choi, *Member, IEEE,* Prasad N. Enjeti, *Senior Member, IEEE,*
Hong-Hee Lee, *Member, IEEE,* and Ira J. Pitel, *Senior Member, IEEE*

*Abstract*—**In this paper, a new active interphase reactor for twelve-pulse diode rectifiers is proposed. The proposed system draws near sinusoidal currents from the utility. In this scheme, a low kVA [0.02 $P_o$ (PU)] active current source injects a triangular current into an interphase reactor of a twelve-pulse diode rectifier. This modification results in near sinusoidal utility line currents with less than 1% THD. It is further shown that a low kVA, 12-pulse system with an autotransformer arrangement [kVA rating of 0.18 $P_o$ (PU)] can be implemented with the proposed active interphase reactor. The resulting system draws clean power from the utility and is suitable for powering larger kVA ac motor drive systems. Detailed analysis of the proposed scheme along with design equations is illustrated. Simulation results verify the concept. Experimental results are provided from a 208 V, 10 kVA rectifier system.**

## I. Introduction

LARGE harmonics, poor power factor, and high total harmonic distortion (THD) in the utility interface are common problems when nonlinear loads such as adjustable speed drives, power supplies, induction heating systems, UPS systems, and aircraft converter systems are connected to the electric utility. In several cases, the interface to the electric utility is processed with a three phase uncontrolled diode bridge rectifier. Due to the nonlinear nature of the load, the input line currents have significant harmonics. For adjustable speed ac motor drive systems with no dc-link smoothing inductor, the discontinuous conduction of the diode bridge rectifier results in a high current THD's which can lead to the malfunction of other sensitive electronic equipment. The recommended practice, IEEE 519, has evolved to maintain utility power quality at acceptable levels [1].

A number of methods have been proposed to overcome the presented problems [2]–[14]. One approach is to use a conventional twelve-pulse diode rectifier which requires two six-pulse diode rectifiers connected via $Y$–$\Delta$ and $Y$–$Y$ isolation transformers. An interphase reactor is required to ensure the independent operation of the two parallel-connected three-phase diode bridge rectifiers. The operation of the conventional twelve-pulse diode rectifier results in the cancellation of the 5th and 7th harmonics in the input utility line currents.

To increase the pulse number further to 18 or 24, additional diode bridge rectifiers along with complicated multiphase transformer arrangements become necessary, which adds to the cost and complexity.

This paper proposes a new three-phase diode rectifier system which draws near sinusoidal input currents from the three phase electric utility. Two possible ways for implementation are shown and are called Schemes I and II. In Scheme I (Fig. 1), a $\Delta$–$Y$ isolation transformer of 0.52 $P_o$ (PU) capacity is employed. The interphase reactor and the line impedances $L_{s1}$, $L_{s2}$ are designed such that stable twelve-pulse operation is obtained with equal current sharing. A low kVA [0.02 $P_o$ (PU)] PWM-controlled active current source, $I_x$ is now injected into the secondary winding of the interphase reactor. It is shown via rigorous mathematical modeling as well as computer simulations that the exact shape of $I_x$ [Fig. 3(a)] can be computed to alter the utility line current $I_a$ to a perfect sinewave. It is further shown that an approximation to the exact waveshape of $I_x$ is a triangular wave [Fig. 4(a)]. Therefore, by injecting a triangular shaped current $I_x$ into the secondary winding of the interphase reactor, near sinusoidal input line currents flow in the utility line with less than 1% THD.

Fig. 6 shows the active interphase reactor implementation in Scheme II. In this scheme, an autotransformer is employed to obtain 30° phase shift between the two diode rectifiers. Two interphase reactors now become necessary due to the absence of electrical isolation [12]. The kVA rating of the proposed autotransformer is 0.18 $P_o$ (PU). With the active interphase reactor installed, the resulting input current with this approach is also near sinusoidal providing clean power utility interface.

Both of the topologies shown in Schemes I and II result in high performance with reduced kVA components and offer clean power utility interface suitable for powering larger kVA ac motor drives and power electronic systems. The proposed scheme has the following advantages:

- A low kVA (0.02 PU) triangular current injected into the secondary winding of the interphase reactor results in less than 1% THD in utility line currents satisfying clean power requirements.
- The active current source can be configured with low cost high current and low voltage single phase half/full bridge MOSFET devices.

Paper ICPSD 95–76, appoved by the Industrial Power Converter Committee of the IEEE Industry Applications Society for presentation at the 1995 IEEE Industry Applications Society Annual Meeting, Lake Buena Vista, FL, October 8–12. Manuscript released for publication June 5, 1996.

S. Choi is with the Samsung Electro-Mechanics Co., Ltd., Kyungki Do 442-743, Korea.

P. N. Enjeti is with the Department of Electrical Engineering, Texas A&M University, College Station, TX 77843 USA.

H.-H. Lee is with the Department of Control and Instrumentation Engineering, University of Ulsan, Ulsam, Korea.

I. J. Pitel is with Magna-Power Electronics, Boonton, NJ 07005 USA.

Publisher Item Identifier S 0093-9994(96)07577-9.

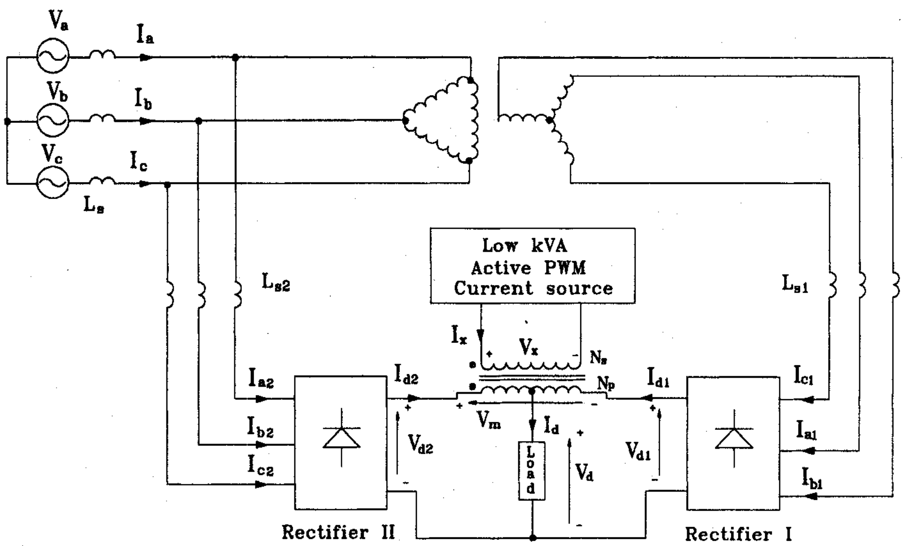


Fig. 1. Circuit diagram of the proposed clean power utility interface Scheme I. Current $I_a$ is near sinusoidal in shape with less than 1% THD.

- The active current source electronics (MOSFET's) located at the secondary of the interphase reactor is not subjected to utility line disturbances, hence the scheme is rugged.
- In the event the active current source malfunctions, the elimination of 5th and 7th harmonics is still guaranteed due to 12-pulse operation.

Detailed analysis of the proposed schemes is discussed in the next sections.

## II. Proposed Clean Power Utility Interface—Scheme I

Fig. 1 shows the circuit diagram of the proposed scheme to shape input line currents. The main transformer has delta-wye winding [kVA rating of 0.52 $P_o$ (PU)] with a $\sqrt{3}$ to 1 turns ratio to maintain an equal per unit voltage. They are connected in such a way that the two diode bridge rectifiers have balanced sets of three-phase voltages with 30° phase shift. The proposed system is identical to a conventional 12-pulse system except that the interphase reactor has an additional winding. The additional winding is used to inject a low kVA PWM current source to shape input line current.

With the PWM current source, $I_x$, disabled (i.e., $I_x = 0$) the system operates as a conventional 12-pulse rectifier providing cancellation of the 5th and 7th harmonics in the input line currents, $I_a$, $I_b$, and $I_c$. The active current source $I_x$, when injected into the interphase reactor (Fig. 1), results in near sinusoidal input current with unity input power factor. The following sections illustrate the proposed concept in more detail.

### *A. Analysis of the Proposed Active Interphase Reactor—Scheme I*

Fig. 1 shows the proposed active interphase reactor Scheme I for a 12-pulse diode rectifier. In this section, waveforms are analyzed to determine the relationship between current $I_x$ and input currents $I_a$, $I_b$, and $I_c$. With $I_x = 0$, input current $I_a$ can be shown to be [2], [5],

$$I_a = I_{a2} + \frac{1}{\sqrt{3}}(I_{a1} - I_{c1}). \quad (1)$$

Equation (1) describes a 12-pulse input line current with 5th and 7th harmonics absent and

$$I_{d1} - I_{d2} = \tfrac{1}{2} I_d. \quad (2)$$

An active current $I_x$ is now injected into the secondary winding of the interphase reactor as shown in Fig. 1. Fig. 8 shows the circuit topology for implementing this scheme. Analyzing the MMF relationship of the interphase reactor, we have

$$N_p(I_{d2} - I_{d1}) = N_s I_x \quad (3)$$

where $N_p$ and $N_s$ are the numbers of turns of the primary and the secondary windings of the interphase reactor. The load current $I_d$ is

$$I_d = I_{d1} + I_{d2}. \quad (4)$$

From (3) and (4) we have

$$I_{d2} = \frac{1}{2}\left(I_d + \frac{N_s}{N_p} I_x\right). \quad (5)$$

Fig. 2 shows switching function $S_{a1}$ for phase "$a$" of Rectifier-I shown in Fig. 1. The Fourier series expansion for $S_{a1}$ is given by

$$S_{a1}(t) = \frac{2\sqrt{3}}{\pi}\left(\sin \omega t - \tfrac{1}{5}\sin 5\omega t - \tfrac{1}{7}\sin 7\omega t + \tfrac{1}{11}\sin 11\omega t + \tfrac{1}{13}\sin 13\omega t \cdots\right) \quad (6)$$

and for phase "$b$" and "$c$," the switching functions can be written as

$$S_{b1} = S_{a1}\angle{-120^\circ}$$
$$S_{c1} = S_{a1}\angle{+120^\circ}. \quad (7)$$

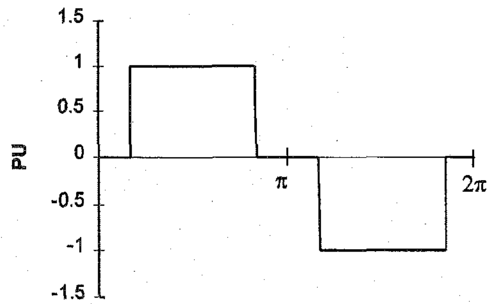


Fig. 2. Switching function $S_{a1}$ for rectifier I in Fig. 1.

Similarly, the switching functions for Rectifier-II in Fig. 1 with a 30° phase shift are

$$\begin{aligned} S_{a2} &= S_{a1}\angle -30^\circ \\ S_{b2} &= S_{b1}\angle -30^\circ \\ S_{c2} &= S_{c1}\angle -30^\circ. \end{aligned} \tag{8}$$

The input currents for Rectifiers I and II can now be expressed in terms of switching functions as,

$$\begin{bmatrix} I_{a1} \\ I_{b1} \\ I_{c1} \end{bmatrix} = \begin{bmatrix} S_{a1} \\ S_{b1} \\ S_{c1} \end{bmatrix} I_{d1} \tag{9}$$

and

$$\begin{bmatrix} I_{a2} \\ I_{b2} \\ I_{c2} \end{bmatrix} = \begin{bmatrix} S_{a2} \\ S_{b2} \\ S_{c2} \end{bmatrix} I_{d2}. \tag{10}$$

Equation (1) can now be modified using (5) and the switching functions described in (6)–(10) as,

$$\begin{aligned} I_a =& \frac{1}{2\sqrt{3}}(S_{a1} - S_{c1}) \cdot \left(I_d - \frac{N_s}{N_p} I_x\right) \\ &+ \frac{1}{2} S_{a2}\left(I_d + \frac{N_s}{N_p} I_x\right). \end{aligned} \tag{11}$$

Equation (11) illustrates the relationship between $I_x$ and input current $I_a$. For input current $I_a$ to be sinusoidal,

$$I_x = \frac{N_p\left[2I_{a,1} - I_d\left(\frac{S_{a1} - S_{c1}}{\sqrt{3}} + S_{a2}\right)\right]}{N_s\left(\frac{S_{c1} - S_{a1}}{\sqrt{3}} + S_{a2}\right)}. \tag{12}$$

Note $I_a$ is replaced by $I_{a,1}$, where $I_{a,1}$ is the fundamental rms component of $I_a$. Therefore, (12) describes the exact shape of $I_x$ for a given load current $I_d$. Since input power is equal to output power, we have

$$\sqrt{3}V_{LL}I_{a,1} = V_d I_d \tag{13}$$

where $V_d = 1.35\,V_{LL}$ and $V_{LL}$ is the line to line rms voltage. Hence, from (13) we have,

$$I_{a,1} = 0.7794 I_d. \tag{14}$$

Now, for input current $I_a$ to be sinusoidal, i.e.,

$$I_a = \sqrt{2}I_{a,1}\sin \omega t. \tag{15}$$

Fig. 3(a) shows the shape of $I_x$ for sinusoidal input current computed from (12) and (15).

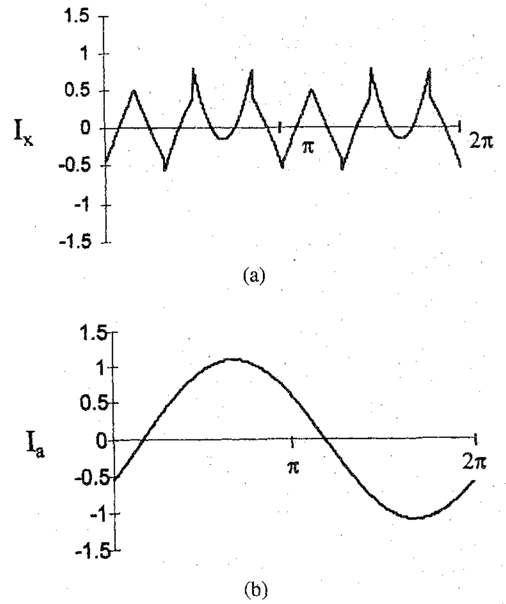


Fig. 3. (a) Injected current $I_x$ calculated from (12). (b) Input line current $I_a$ (pure sinusoidal).

### B. Simulation Results of the Proposed Approach

The proposed active interphase reactor approach shown in Fig. 1 is simulated on SABER and the results are presented in this section. From Fig. 3(a), it is apparent that $I_x$ is near triangular in shape. Simplifying the injected current $I_x$ to a triangular wave shape [Fig. 4(a)] yields a near sinusoidal input current $I_a$ [Fig. 4(c)]. Furthermore, generating a triangular injection current $I_x$ into the secondary of the interphase reactor can be accomplished by means of a PWM-controlled current source (Fig. 9). Fig. 4(b) shows the input current of the rectifier blocks I (Fig. 1) as a result of the injected current $I_x$. Fig. 5(a) and (b) shows the dc output voltages $V_{d1}$ and $V_{d2}$. Fig. 5(c) shows the voltage across the interphase reactor.

It should be noted that injecting active current $I_x$ [Fig. 4(a)] which is triangular in shape yields near sinusoidal input currents [Fig. 4(c)] of less than 1% THD. The kVA rating of the injected current is small and is computed in the next section.

### C. kVA Rating of the Injected Current Source, $I_x$

The line to line rms input voltage $V_{LL}$ and dc output current $I_d$ is assumed to be 1 per unit. The voltage across the interphase reactor $V_m$ (see Fig. 1) can be expressed as,

$$V_m = V_{d2} - V_{d1}. \tag{16}$$

Fig. 5(a) and (b) shows the waveshape of $V_{d1}$ and $V_{d2}$. Furthermore, $V_{d1}$ can be expressed in Fourier series as [3],

$$\begin{aligned} V_{d1} =& \sqrt{2}V_{LL}\frac{6}{\pi}\sin\frac{\pi}{6} \\ &\cdot\left(1 - \sum_{n=6,12,18,\cdots}^{\infty} \frac{2}{n^2-1}\cos\frac{n\pi}{6}\cos n\omega t\right). \end{aligned} \tag{17}$$

Output voltage $V_{d2}$ is phase shifted by 30°. By substituting

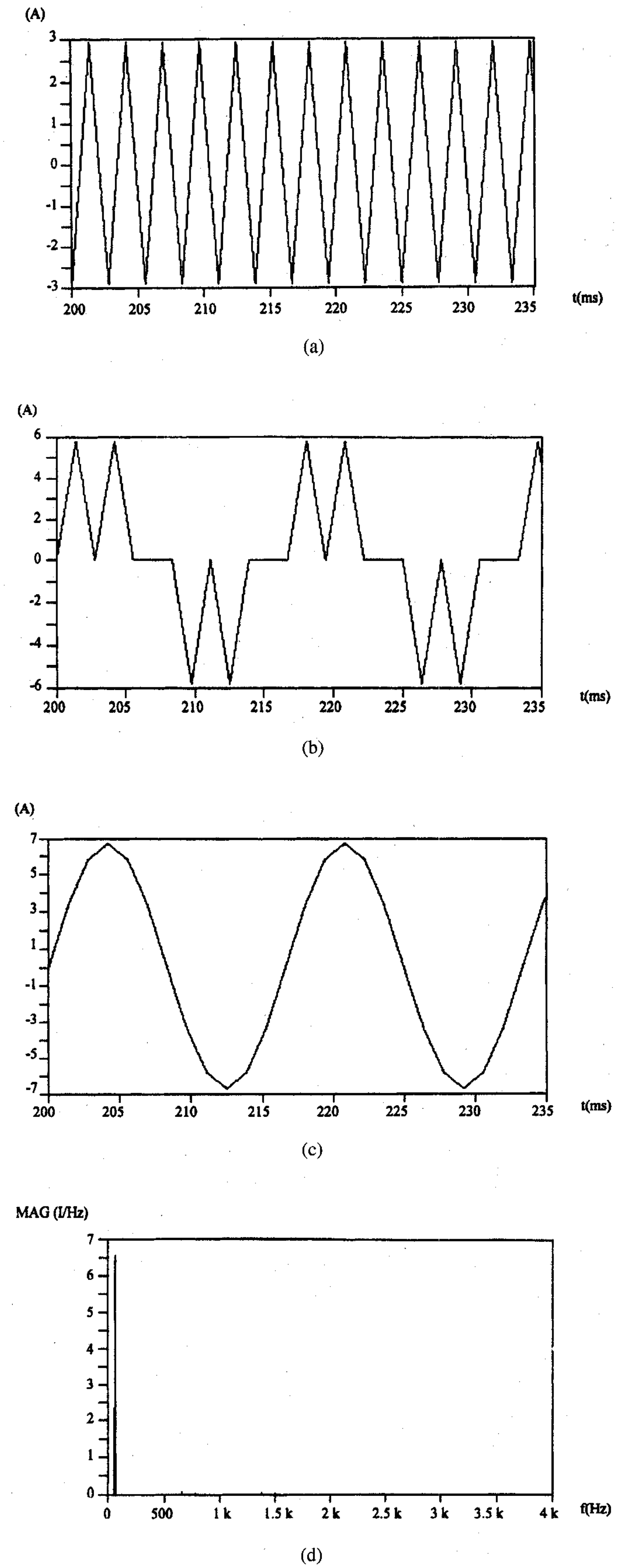


Fig. 4. Simulation results for the proposed Scheme I (Fig. 1). (a) Injected current $I_x$. (b) Rectifier I input current $I_{a1}$. (c) Input line current $I_a$. (d) Frequency spectrum of $I_a$.

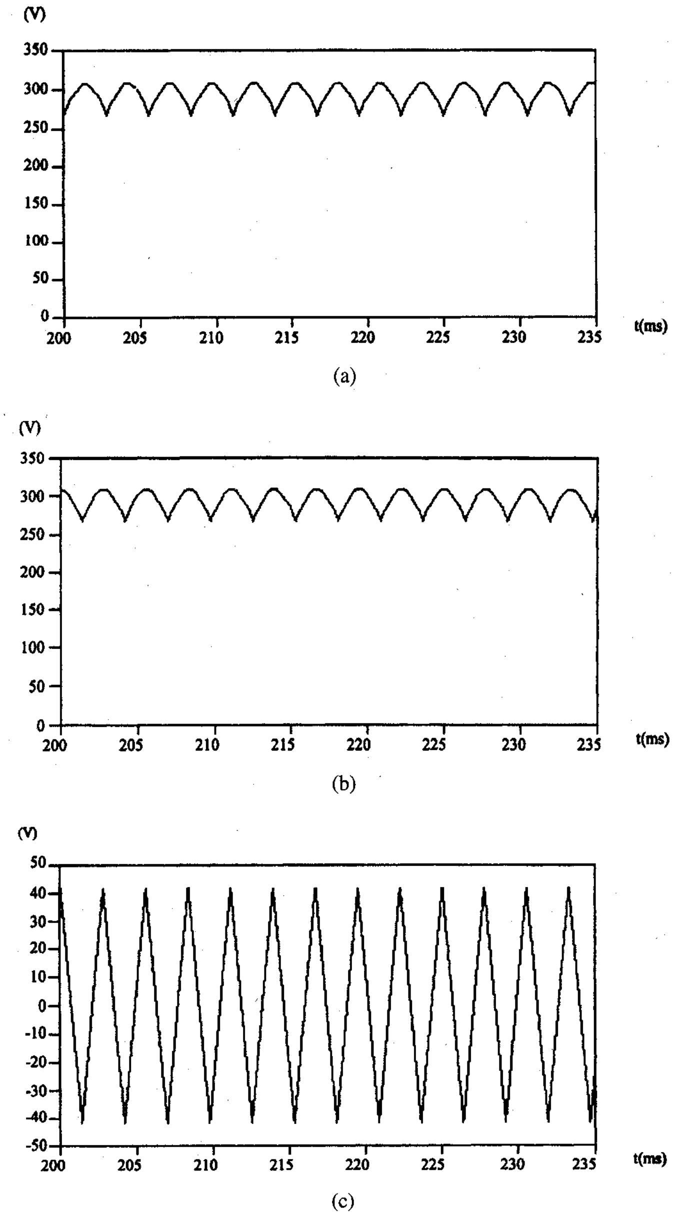


Fig. 5. Simulation results of Scheme I (Fig. 1). (a) Rectifier I output voltage $V_{d1}$. (b) Rectifier II output voltage $V_{d2}$. (c) Voltage across the interphase reactor $V_m = V_{d2} - V_{d1}$.

(17) into (16), $V_m$ can be expressed as

$$V_m = -5.4018\, V_{LL} \sum_{n=6,\,12,\,18,\,\cdots}^{\infty} \frac{1}{n^2-1} \cos\frac{n\pi}{6} \cdot \sin\frac{n\pi}{12} \sin n\left(\omega t - \frac{\pi}{12}\right). \tag{18}$$

From (18), the rms value of $V_m$ can be computed as,

$$V_{m,\,\mathrm{rms}} = 0.1098\, V_{LL}. \tag{19}$$

The voltage across the interphase reactor secondary winding $V_x$ is given by

$$V_x = \frac{N_s}{N_p} V_m. \tag{20}$$

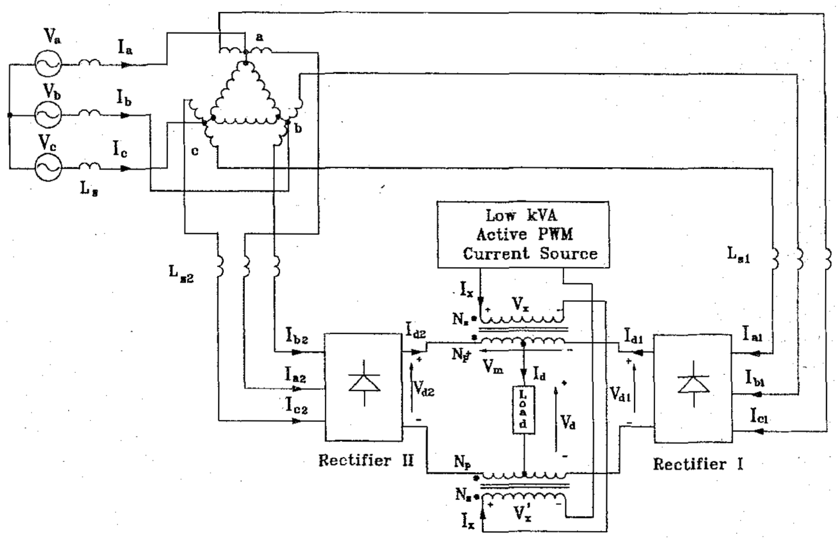


Fig. 6. Circuit diagram of the proposed clean power utility interface Scheme II.

Then, from (19) and (20), the rms value of $V_x$ is

$$V_{x,\,\mathrm{rms}} = 0.1098\, V_{LL}\, \frac{N_s}{N_p}. \tag{21}$$

From the results in the previous section, the peak value of the current $I_x$ of Fig. 4(a) is $0.5\, I_d$. Therefore, the rms value of $I_x$ for a triangular waveshape is,

$$I_{x,\,\mathrm{rms}} = \frac{0.5}{\sqrt{3}}\, I_d\, \frac{N_p}{N_s} = 0.2887\, I_d\, \frac{N_p}{N_s}. \tag{22}$$

The rms value of $I_x$ can be reduced by adjusting turns ratio $(N_p/N_s)$ between the primary and the secondary windings of the interphase reactor.

From (21) and (22), the kVA rating of the injected current source, $\mathrm{kVA_{INV}}$, can be computed as,

$$\begin{aligned}\mathrm{kVA_{INV}} &= V_{x,\,\mathrm{rms}} \cdot I_{x,\,\mathrm{rms}}\\ &= 0.0227\, \mathrm{P}_o\, (\mathrm{PU}).\end{aligned} \tag{23}$$

Equation (23) shows that the kVA rating of the injected current source $I_x$ is a small percentage of the output power. This demonstrates the superior features of the proposed scheme to realize clean power utility interface.

## III. Proposed Active Interphase Reactor—Scheme II

In this section, Scheme II of the active interphase reactor implementation is discussed. Fig. 6 shows the proposed clean power utility interface implementation with an autotransformer connection. Fig. 7(a) shows the vector diagram of the delta type autotransformer. The proposed autotransformer generates two three-phase sets of voltages displaced $\pm 15°$ from the input supply [Fig. 7(a)]. Fig. 7(b) shows the resulting autotransformer winding arrangement on a three-limb core. It has been shown [12] that the kVA rating of the delta type autotransformer is 0.18 $\mathrm{P}_o$ (PU).

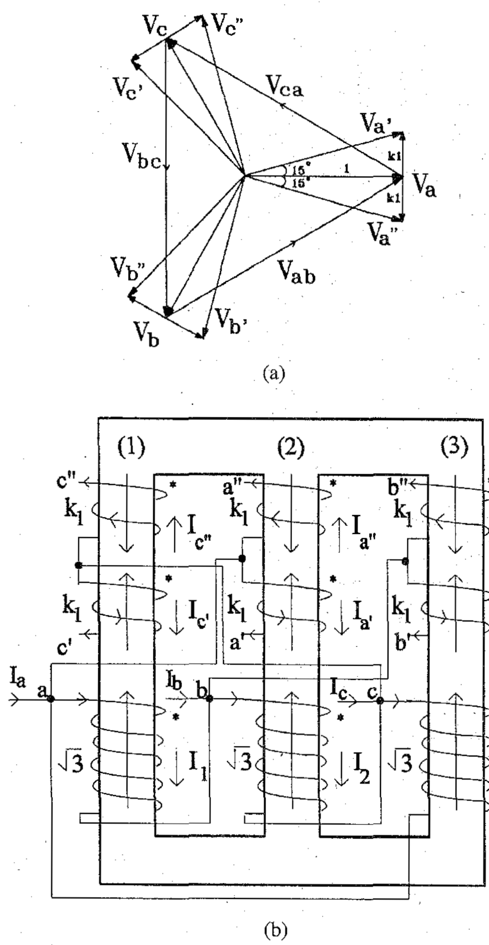


Fig. 7. (a) Vector diagram of the delta-type autotransformer connection. (b) Autotransformer windings on a three limb core.

Fig. 6 shows the resulting active interphase reactor implementation with the autotransformer arrangement. A current source $I_x$ can now be injected such that the utility line current ($I_a$, $I_b$, and $I_c$) are near sinusoidal in shape. The switching function analysis discussed in Section II-A can be repeated for

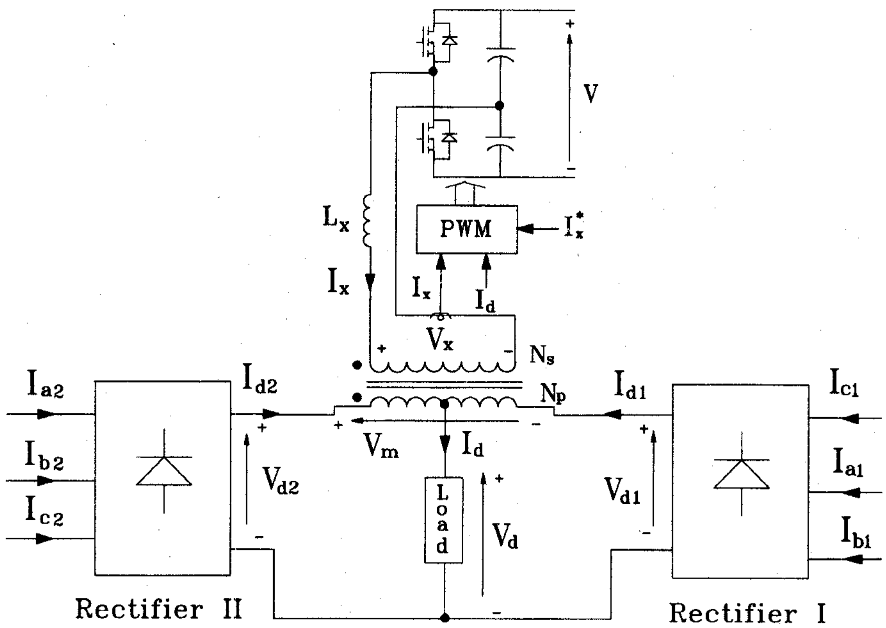


Fig. 8. Circuit diagram for implementation of the proposed schemes.

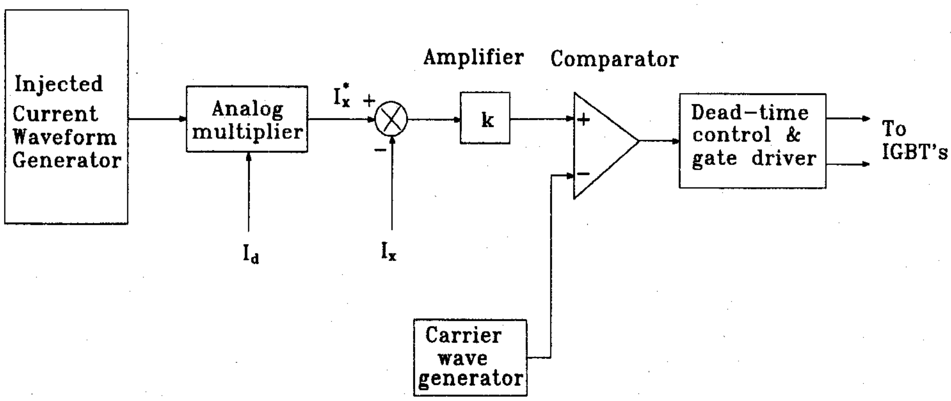


Fig. 9. Block diagram of the current-controlled PWM gating signal generator.

Scheme II shown in Fig. 6. Input current $I_a$ can be expressed as,

$$I_a = \frac{N_s}{2N_p} \cdot [S_{a2} - S_{a1} + 0.1547(S_{c1} - S_{b1} + S_{c2} - S_{b2})] \cdot I_x + \tfrac{1}{2}[S_{a1} + S_{a2} + 0.1547(S_{b1} - S_{c1} + S_{c2} - S_{b2})] \cdot I_d. \quad (24)$$

For the triangular-shaped injected current $I_x$ of Fig. 4(a), the input line current $I_a$, expressed as (24), also becomes near sinusoidal in shape and approximates that shown in Fig. 4(c).

## IV. Implementation of the Active Current Source $I_x$

Fig. 8 shows the circuit diagram for implementing the proposed Scheme I. Injected current $I_x$ shown in Fig. 4(a) is generated via a current controlled PWM inverter.

Block diagram of the gating signal generator for the PWM inverter is shown in Fig. 9. The reference for the injected current ($I_x^*$) is synchronized with the input voltages and is configured with standard digital logic circuits and phase locked loop electronics. The reference current $I_x^*$ and the feedback current $I_x$ are compared and the current error is then compared to a triangular carrier wave (25 kHz) to generate the PWM gating signals for the inverter switching devices. The closed loop operation of this scheme ensures $I_x$ to follow $I_x^*$ to accomplish the clean power characteristics.

## V. Experimental Results

A 208 V, 10 kVA diode rectifier system employing the proposed Scheme I has been implemented in the laboratory. The interphase reactor employed in the experiment was designed with the turns ratio of $N_p : N_s = 1 : 2$.

Fig. 8 shows the experimental setup to verify the operation of Scheme I. Fig. 10 shows the experimental results obtained. Fig. 10(c) shows the injected current $I_x$ and Fig. 10(a) and (b) show the resulting rectifier output currents $I_{d1}$ and $I_{d2}$, respectively. Fig. 10(d) shows the rectifier input current $I_{a1}$. Finally, the experimental utility input current $I_a$ and its frequency spectrum are shown in Fig. 10(e) and (f), respectively. These

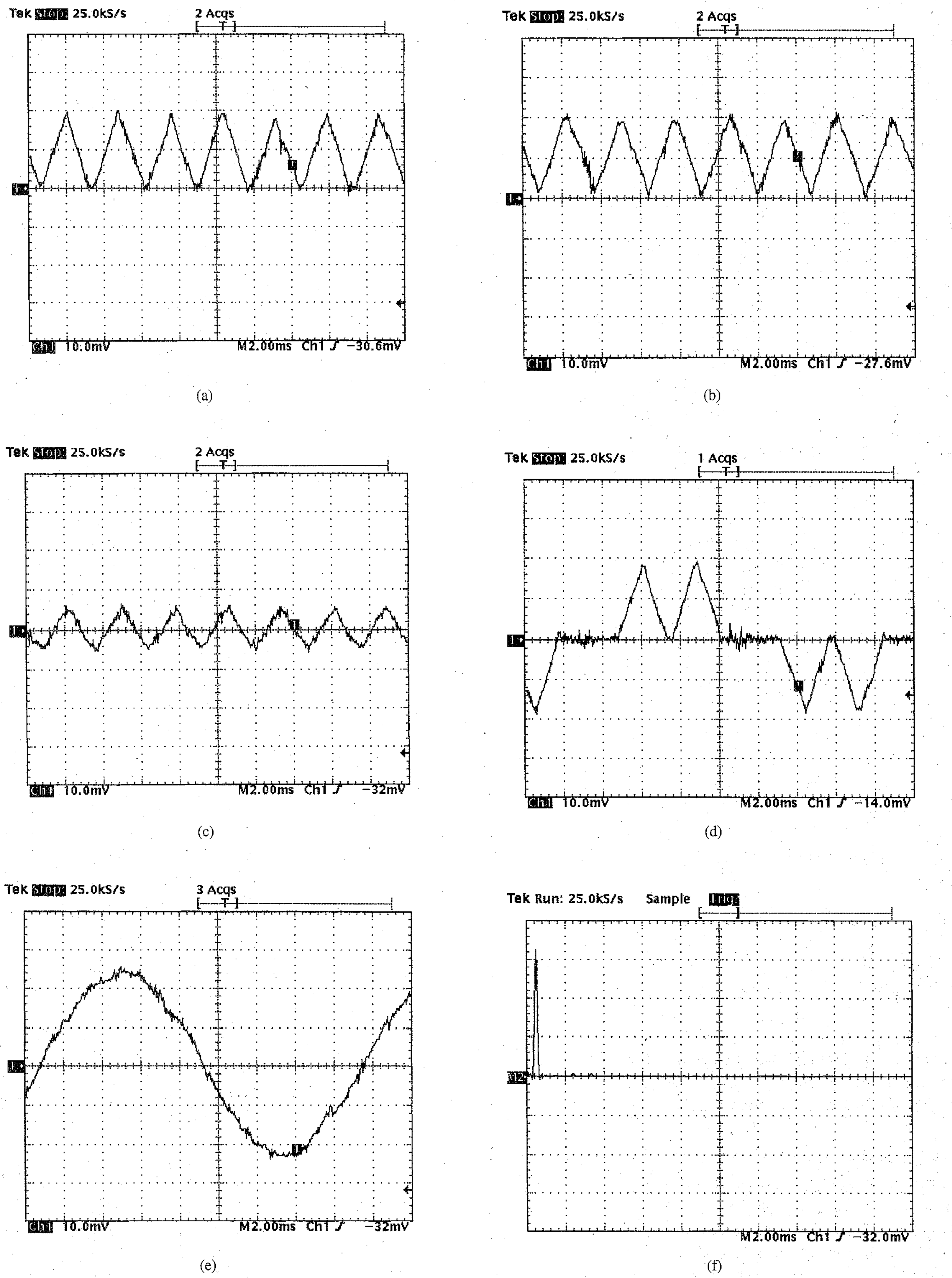


Fig. 10. Experimental results of Scheme I (5A/Div.). (a) Output current $I_{d1}$. (b) Output current $I_{d2}$. (c) Injected current $I_x$. (d) Rectifier input current $I_{a1}$. (e) Input line current $I_a$. (f) Frequency spectrum of $I_a$.

results are similar to the simulation results shown in Fig. 4. Experimental results show good agreement between theory and practice and demonstrate clean power characteristics of the proposed scheme.

## VI. Conclusion

In this paper a new active interphase reactor for a twelve-pulse rectifier system has been proposed. It has been shown that by injecting a low kVA [0.02 $P_o$ (PU)] active current source $I_x$ into the interphase reactor near sinusoidal input currents with less than 1% THD can be obtained. It is further shown that a low kVA twelve-pulse system with the proposed active interphase reactor can be implemented with autotransformers. The resultant system is a high performance clean power utility interface suitable for powering larger kVA ac motor drives and a wide variety of power electronic systems. Detailed analysis of the proposed scheme along with design equations has been illustrated. Simulation results have been shown to verify the proposed concepts. Experimental results have been provided from a 208 V, 10 kVA rectifier system.

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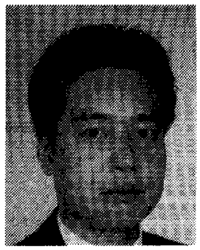
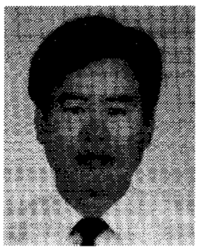


**Sewan Choi** (S'91–M'96) was born in Seoul, Korea, on March 3, 1963. He received the B.S. degree in electronic engineering in 1985 from Inha University, Incheon, Korea, and the M.S. and Ph.D. degrees in electrical engineering in 1992 and 1995, respectively, from Texas A&M University, College Station.

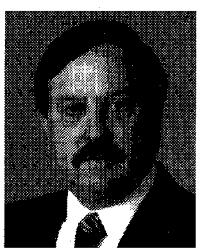
From 1985 to 1990, he was with Daewoo Heavy Industries, Korea, where he was involved in development of several industrial controllers. He is currently a Senior Researcher working on development of Intelligent Power Modules at Samsung Electro-Mechanics, Suwon, Korea. His research interests include active power factor correction and design and control of advanced power converters.

**Prasad N. Enjeti** (SM'88) for a photograph and biography, see this issue, p. 1303.



**Hong-Hee Lee** (S'88–M'91) received the B.S., M.S., and Ph.D. degrees in electrical engineering from Seoul National University, Seoul, Korea, in 1980, 1982, and 1990, respectively.

From 1982 to 1985, he worked with the Hyosung Heavy Industry which is the greatest electric company in Korea, where he has been involved in various projects for the power electronics. He was with the Department of Electrical Engineering at University of Ulsan as Instructor and Assistant Professor from 1985 to 1990. Since 1991, he has been with the Department of Control and Instrumentation Engineering at University of Ulsan as Associate Professor. From 1994 to 1995, he was with the Department of Electrical Engineering at Texas A&M University, College Station, as a Visiting Professor. His current research interests are in electric machine control, fuzzy logic, and neural network applications to power electronics, power converter circuits, and electric vehicle drives.



**Ira J. Pitel** (SM'82) received the B.S. degree from Rutgers—The State University of New Jersey, Piscataway, the M.S. degree from Bucknell University, Lewisburg, PA, and the Ph.D. degree from Carnegie Mellon University, Pittsburgh, PA, in 1972, 1975, and 1978, respectively.

From 1973 to 1976, he was with GTE Sylvania , researching high-frequency ballasting techniques for gaseous discharge lamps. He joined Bell Laboratories in 1978 and Exxon Enterprises in 1979. At Exxon, he was involved in high-power converter structures for ac motor drives, power conditioning for advanced battery systems, and controlled lighting. He was eventually transferred to one of Exxon's subsidiaries, Cornell-Dubilier Electronics, where he was manager of research and development. In 1981, he founded Magna-Power Electronics, Boonton, NJ, a contract research and development company specializing in the fields of power electronics and magnetics. In 1986, he joined Texas A&M University, College Station, as an Adjunct Associate Professor. He research interests are high-power ac to dc converters, static inverters, spacecraft power supplies, specialty lighting controls, and ac and dc drives. He holds 18 patents and has others pending in the field of power electronics.

Dr. Pitel is a member of Eta Kappu Nu and Tau Beta Pi and is Chairman of the Industrial Power Conversion Systems Department of the MS-IEEE.