# A New Multi-pulse Diode Rectifier Front End with Tapped Interphase Reactor Draws Near Sinusoidal Input Currents

**Sewan Choi**

## Abstract

In this paper, a new multi-pulse diode rectifier system is proposed. The proposed approach extends the conventional 12-pulse rectifier to a 24-pulse system and draws near sinusoidal currents from the utility line with 5th, 7th, 11th, 13th, 17th and 19th harmonics eliminated. With the addition of two controlled switches such as IGBT's, the pulse number is extended beyond 24 pulses. A generalized PWM technique is presented and an example 48-pulse system is demonstrated. Simulation results verify the proposed concept and experimental results are provided from a 208V, 10kVA rectifier system.

## I. Introduction

Large harmonics, poor power factor and high total harmonic distortions (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 interfaces to electric utilities are three phase uncontrolled diode bridge rectifier front end. 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 THD and can lead to the mal-function of 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 [2-4]. One approach is to use a conventional twelve-pulse converter which requires two six-pulse converters connected through Y-△ and Y-Y isolation transformers (Fig. 1). The interphase reactors are required to ensure the independent operation of the two three-phase diode bridge rectifiers. The operation of the conventional twelve-pulse converter results in the absence of the fifth and seventh harmonics in the input utility line current. To increase further the pulse number or improve the performance of the input line currents, the number of the diode bridge rectifiers therefore increased and/or additional transformers are arranged to make the necessary phase shift [2-4].

The approach of tapping on interphase reactor [2] does not require additional phase-shift transformers and diode bridges. However, as the desired pulse number increases, the number of thyristors in the interphase reactor side must be increased.

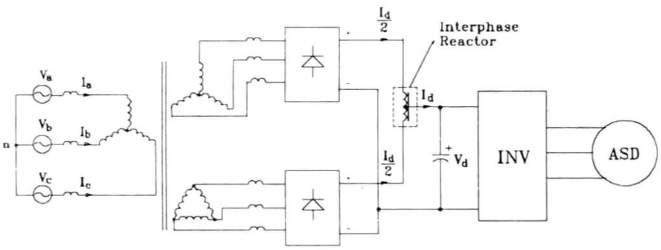


**Fig. 1.** Conventional twelve-pulse system.

In this paper, a new multi-pulse diode rectifier system is proposed to significantly reduce the harmonic current content in the utility line. The proposed approach involves the tapped-interphase reactor and there is no need to increase the number of diode bridge rectifiers or the size of the phase-shifting transformers. Furthermore, the input line current harmonics can be selectively eliminated to specified harmonics with only two gate turn-off switching devices at the interphase reactor side.

For example, with two diodes in the interphase reactor, 24-pulse operation is obtained. Replacing the diodes by con-

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S. W. Choi is with the Dept. of Control and Instrumentation, Seoul National Polytechnic University.

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trolled switches such as IGBTs, multi-pulse operation higher than 24 pulse can be obtained. Section 3 demonstrates an example 48-pulse operation via simple PWM with five switchings per quarter-cycle. This significantly reduces the harmonic content of the utility input line currents. Simulation results verifying the proposed concept are presented, and experimental results are provided.

## II. Principles of the Proposed 24-Pulse System(Passive Approach)

### *1. Operation of the Tapped-Interphase Reactor*

Fig. 2 shows the proposed 24-pulse system which is identical to the standard 12-pulse system with the exception of the two diodes connected to the interphase reactor. Fig. 3 shows the operation of the two diodes connected to the interphase reactor and the practical winding configuration of the interphase reactor

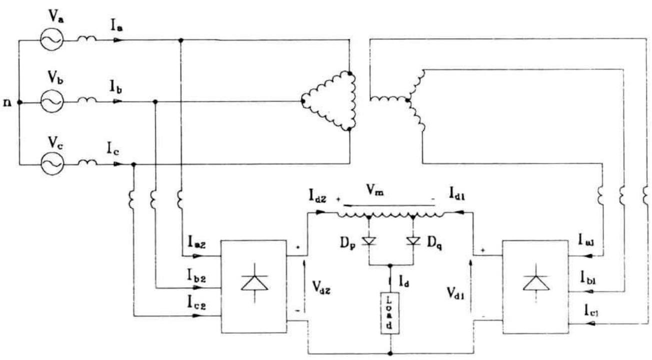
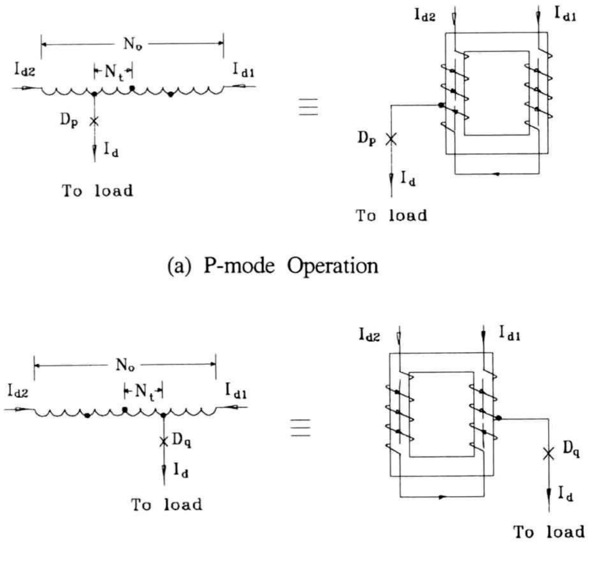



**Fig. 2.** Proposed 24-pulse system(Passive approach).




(a) P-mode Operation

(b) Q-mode Operation

**Fig. 3.** Operation of the interphase reactor with two tapped-diodes.

according to two modes : P-mode(Fig. 3 (a)) and Q-mode(Fig. 3 (b)). Fig. 4(a) shows the voltage waveform across the interphase reactor.

Whenever the voltage across the interphase reactor goes positive ($V_m > 0$), diode $D_p$ is turned on and $D_q$ is turned off (P-mode) and therefore diode $D_p$ carries load current $I_d$. The MMF relationship of the interphase reactor for the P-mode gives the following equations,

$$I_{d2}(0.5N_o - N_t) = I_{d1}(0.5N_o + N_t) \tag{1}$$

$$I_{d1} + I_{d2} = I_d \tag{2}$$

where $N_o$ is the total number of turns of the interphase reactor and $N_t$ is the number of turns between the midpoint and the tapped points of the interphase reactor. From (1) and (2) the output currents of the two diode bridge rectifiers is given by,

$$I_{d1} = (0.5 - k)I_d \tag{3}$$

$$I_{d2} = (0.5 + k)I_d \tag{4}$$

where $k = \dfrac{N_t}{N_o}$

Whenever $V_m < 0$, diode $D_q$ is turned on, and $D_p$ is turned off and therefore diode $D_q$ carries load current $I_d$ (Q-mode). Similarly, for Q-mode the output currents of the two diode bridge rectifiers can be obtained by,

$$I_{d1} = (0.5 + k)I_d \tag{5}$$

$$I_{d2} = (0.5 - k)I_d \tag{6}$$

In the center tapped interphase reactor (k = 0) of the conventional 12-pulse system shown in Fig. 1, rectifier output currents $I_{d1}$ and $I_{d2}$ are identical. The variation of $I_{d1}$ and $I_{d2}$, as shown in (5) and (6), gives changes in the rectifier input currents and in turn the input line currents.

### *2. Analysis of the Input Line Current*

In this section the input line currents are analyzed and the turns $N_o$ and $N_t$ are determined so that the proposed scheme acts as 24 pulse system. From the MMF equation of the main transformer as shown in Fig. 2, the input line current for phase 'a' can be expressed in terms of the rectifier input currents as,

$$I_a = I_{a2} + \frac{1}{\sqrt{3}}(I_{a1} - I_{c1}) \tag{7}$$

From the rectifier input current $I_{a1}$ of Fig. 4(c) it can be seen

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that the waveforms have half-wave and quarter-wave symmetry, which means that all the even harmonics are absent in the rectifier input currents. Furthermore, the folding symmetry around 60 degree and 120 degree guarantees the nonexistence of all triplen harmonics [7]. Therefore, the Fourier series of the rectifier input current, $Ia_1$ can be represented as,

$$I_{a1}(t)=\sum_{\substack{n=odd,\\ non-triplen}}^{\infty} b_n(k)\sin(n\omega t) \quad \textbf{(8)}$$

Since the waveforms of each input currents are identical except for 120 degree of phase differences,

$$I_{c1}(t)=\sum_{\substack{n=odd\\ non-triplen}}^{\infty} b_n(k)\sin(n(\omega t+120)) \quad \textbf{(9)}$$

$$I_{a2}(t)=\sum_{\substack{n=odd,\\ non-triplen}}^{\infty} b_n(k)\sin(n(\omega t-30)) \quad \textbf{(10)}$$

where $b_n(k)$ is the sine term coefficient of the Fourier series and can be expressed as,

$$b_n(k)=\frac{4}{\pi}\int_0^{\frac{\pi}{2}} I_{a1}(\omega t)\sin(n\omega t)d(\omega t) \quad \textbf{(11)}$$

Then, from (7), input line current $I_a(t)$ becomes,

$$I_a(t)=\sum_{\substack{n=odd,\\ non-triplen}}^{\infty} b_n(k)g_n\sin(n\omega t+\phi_n) \quad \textbf{(12)}$$

where $g_n$ and is given by,

$$g_n=\sqrt{[\cos(\frac{n\pi}{6})+\frac{2}{\sqrt{3}}\sin^2(\frac{n\pi}{3})]^2+[\sin(\frac{n\pi}{6})+\frac{2}{\sqrt{3}}\sin(\frac{n\pi}{3})\cos(\frac{n\pi}{3})]^2} \quad \textbf{(13)}$$

$$\phi_n=\tan^{-1}\left(\frac{-\sin(\frac{n\pi}{6})-\frac{2}{\sqrt{3}}\sin(\frac{n\pi}{3})\cos(\frac{n\pi}{3})}{\cos(\frac{n\pi}{6})+\frac{2}{\sqrt{3}}\sin^2(\frac{n\pi}{3})}\right) \quad \textbf{(14)}$$

It can easily be observed that $g_n$ = 0 for n = 5, 7, 17, 19, 29, 31, etc ⋯ Now, input line current $I_a$ has harmonics of n = 11, 13, 23, 25, etc ⋯ Also, from (11) $b_n(k)$ is a function of k which is determined by tapping factors $N_o$ and $N_t$. Therefore, the value k can be obtained by solving $b_{11}(k)$ = 0,

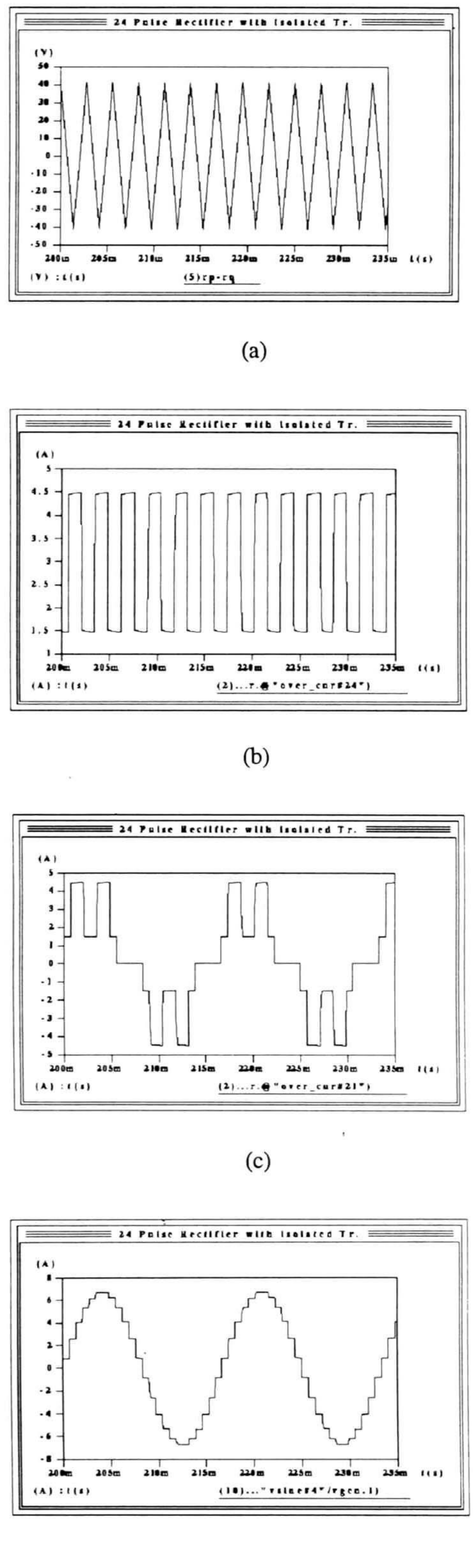


**Fig. 4.** Simulation results for the passive approach (a) voltage across interphase reactor $V_{pq}$ (b) rectifier output current $I_{d1}$ (c) rectifier input current $I_{a1}$ (d) input line current $I_a$.

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$$k=\frac{N_t}{N_o}=0.2457 \qquad \textbf{(15)}$$

The value k obtained in (15) also makes $b_{13}(k)$ zero. Finally, the harmonics of input line current $I_a$ are absent up to n = 22. In other words, the proposed scheme acts exactly like the 24-pulse system.

*3. Simulation Results*

The simulation results of the proposed 24-pulse approach are presented in this section. Due to the variation of the rectifier output currents, as shown in Fig. 4(b), the rectifier input currents change their waveshapes as shown in Fig. 4(c). Finally, input line currents become more sinusoidal as shown in Fig. 4(d). Note that all the harmonics of input line current $I_{a1}$ are absent up to n = 21 acting as a 24-pulse system.

## III. Principles of the Proposed 48-Pulse System(Active Approach)

To further increase the performance of the input line current, an active approach is proposed in this section. The proposed approach requires two additional gate turn-off devices such as IGBT's and a simple gating signal generator. This approach provides virtually infinite-pulse system without increasing hard ware. That is, the desired harmonic to which all the harmonics are absent can arbitrarily be selected by the employed PWM technique.

*1. Generation of PWM Gating Signals*

In this section, as an example of realization of the proposed approach, a 48-pulse system is presented. The circuit diagram of the active approach is shown in Fig. 5. Note that the circuit configuration of the active approach is the same as the passive approach only except two gate turn-off devices in the interphase reactor side.

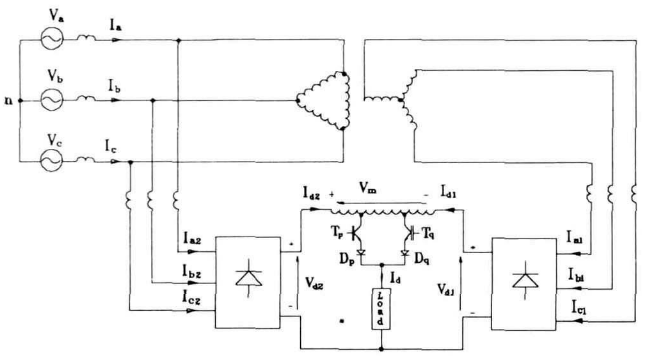
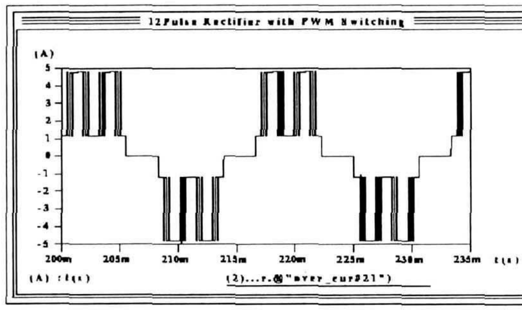
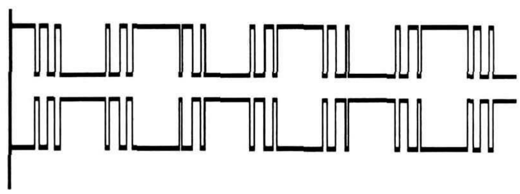



**Fig. 5.** Proposed 48-Pulse(N-Pulse) system(Active approach).

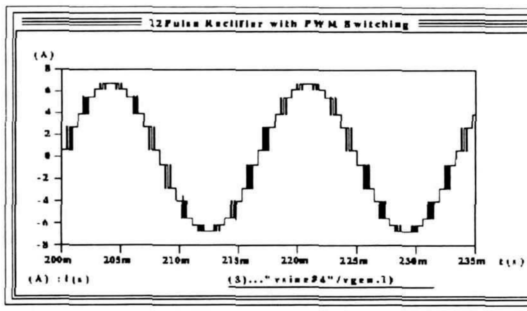
The PWM technique for generating the gating signals for the two gate turn-off devices is based upon the folding symmetry of the TLL method [7]. The rectifier input current $I_{a1}$ employing the proposed PWM technique is shown in Fig. 6(a). The switching angles $a_1$, $a_2$, $\cdots$, $a_5$ and the tapping factor, k, are determined so that all the harmonics up to n = 46 are absent in the input line current. The waveform of rectifier input current $I_{a1}$ has half-wave and quarter-wave symmetry, and therefore, all the even harmonics are absent. Also, due to the folding symmetry around 60 degree and 120 degree, there are no triplen-odd harmonics in the rectifier input currents. Further, the input line current does not have harmonics for n = 5, 7, 17, 19, 29, 31, etc. since (7) holds without regard to the number of switching or the wave shape of the rectifier input current. Hence, we are only concerned about harmonics of n = $12m\pm1$, where m = 1, 2, 3, etc $\cdots$.




(a)



(b)




(c)

**Fig. 6.** Simulation results for the active approach (a) rectifier input current $I_{a1}$ (b) gating signals for gate turn-off switching devices $T_p$ and $T_q$ (c) input line current $I_a$.

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Now, we have six unknowns ($a_1$, $a_2$, ⋯, $a_5$, k) and six equations ($b_n(a_1, a_2, \cdots, a_5, k) = 0$ for n = 11, 13, 23, 25, 35, 37). The nonlinear equations can be solved by an optimization method with the following constraints for the unknowns.

$$\frac{\pi}{6} < a_1 < a_2 < \cdots < a_5 < \frac{\pi}{3} \quad (16)$$

$$a_2 - a_1 = a_5 - a_4 \quad (17)$$

$$a_3 - a_2 = a_4 - a_3 \quad (18)$$

$$0 < k < 0.5 \quad (19)$$

The optimized solution angles are given by $a_1$ = 0.6849, $a_2$ = 0.7214, $a_3$ = 0.7845, $a_4$ = 0.8486, $a_5$ = 0.8791(rad) and k = 0.3539.

*2. Simulation Results*

The simulation results of the proposed 48-pulse approach are presented in this section. Fig. 6(a) shows the PWM rectifier input currents and Fig 6(b) shows the PWM gating signals for the two gate turn-off switching devices. Finally, input line current Ia are shown in Fig. 6(c). Note that all the harmonics are absent up to n = 46 and the significant harmonics are n = 47, 49, etc ⋯

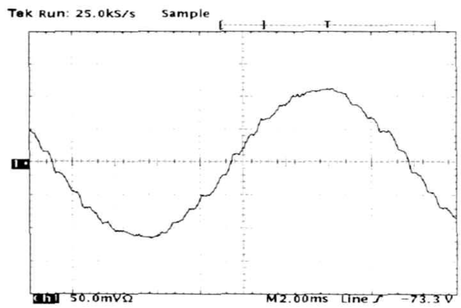
## Ⅳ. Generalization of the Proposed Active Approach for N-Pulse System

The proposed active approach can easily be a pplied to the N-pulse system without increasing hardware components. The general means of determining M switching angles and a tapping factor is described below.

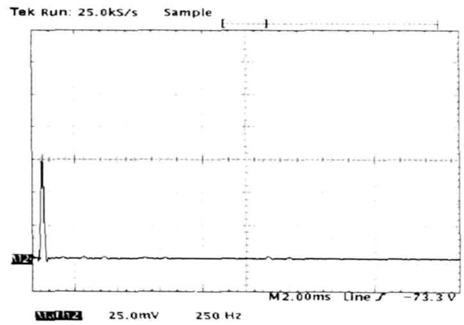
Suppose we want N-pulse system. It can be seen from the previous section that since the rectifier input currents have half-wave, quarter-wave symmetry and the folding symmetry with the proposed PWM technique, all the even and triplen-odd harmonics are absent. Further, the input line current does not have harmonics for n = 5, 7, 17, 19, 29, 31, etc. without regard to the number of switching or the wave shape of the rectifier input current as far as (7) holds. Then, the harmonics which are going to be eliminated by choosing switching angles ($a_1$, $a_2$, ⋯ $a_M$) and the tapping factor k are n = 11, 13, 23, 25, 35, 37, etc. where the number of switching angles M (an odd number) depends upon the value of N with the relationship of,

$$M = \frac{N}{6} - 3 \quad (20)$$

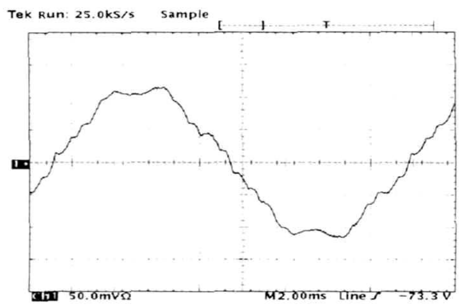
Now, we have M+1 unknowns and M+1 equations from (11). That is,



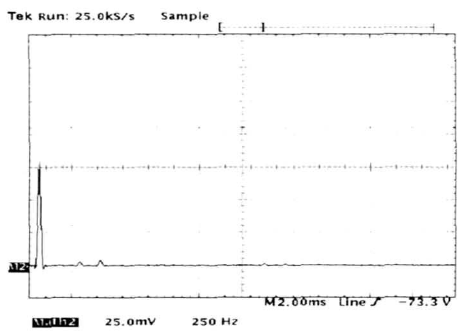

(a)




(b)




(c)




(d)

**Fig. 7.** Experimental results for the passive approach (a) $I_a$ (b) FFT of $I_a$ for the resistive load. (c) $I_a$ (d) FFT of $I_a$ for the capacitive load. (10mV:1A).

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$$\begin{aligned} &b_{11}(a_1, a_2, \cdots, a_M, k) = 0 \\ &b_{13}(a_1, a_2, \cdots, a_M, k) = 0 \\ &b_{23}(a_1, a_2, \cdots, a_M, k) = 0 \\ &b_{25}(a_1, a_2, \cdots, a_M, k) = 0 \\ &\quad \vdots \\ &b_{N-11}(a_1, a_2, \cdots, a_M, k) = 0 \end{aligned} \tag{21}$$

The nonlinear equations can be solved by an optimization method with constraints for the unknowns. The constraints are,

$$\begin{aligned} &\frac{\pi}{6} < a_1 < a_2 < \cdots < a_M < \frac{\pi}{3} \\ &a_2 - a_1 = a_M - a_{M-1} \\ &a_3 - a_2 = a_{M-1} - a_{M-2} \\ &\quad \vdots \\ &a_{\frac{M+1}{2}} - a_{\frac{M-1}{2}} = a_{\frac{M+3}{2}} - a_{\frac{M+1}{2}} \\ &0 < k < 0.5 \end{aligned} \tag{22}$$

Table 1 shows the solutions of the nonlinear equations for N-Pulse System obtained by an optimization method. Note that the solution is also valid for the passive 24-Pulse system.

**Table 1.** Solutions of the Nonlinear Equations in (21) for N-Pulse Systems (N = 12 (p + 1), where p = 1, 2, 3 ⋯).

| N | k | Solution Angles (Rad) | First Dominant Harmonics |
|---|---|---|---|
| 24 | 0.246 | 0.785 | 23,25 |
| 36 | 0.316 | 0.729, 0.787, 0.841 | 35,37 |
| 48 | 0.354 | 0.685, 0.721, 0.785, 0.849, 0.879 | 47,49 |
| 60 | 0.381 | 0.663, 0.683, 0.744, 0.786, 0.825, 0.887, 0.906 | 59,61 |

## V. Experimental Results

A 208V, 10kVA rectifier system of Fig. 2 has been built in the laboratory. Fig 7(a) and Fig. 7(b) shows input line current $I_a$ and FFT of $I_a$ for a resistive load. Fig 7(c) and Fig. 7(d) shows input line current $I_a$ and FFT of $I_a$ for a capacitive load. Since the rectifier output currents $I_{d1}$ and $I_{d2}$ are unbalanced for the capacitive load, the input line current is slightly distorted. Nevertheless, the input line currents for both of the cases have 24 pulse characteristic which is near sinusoidal in shape.

## VI. Conclusion

In this paper, a new multi-pulse diode rectifier front end has been proposed. A 24-pulse rectifier system has been demonstrated with 5th, 7th, 11th, 13th, 17th and 19th harmonics eliminated in the utility line currents. Further, with the addition of two IGBT switches higher pulse operation (>24) can be obtained. A generalized PWM technique has been presented to eliminate several lower order harmonics. Simulation results verify the proposed concept and experimental results have been presented from a 208V, 10kVA rectifier system.

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**Sewan Choi** was born is Seoul, Korea on March 3, 1963. He received the B. S. degree in electronic engineering from Inha University, Incheon, Korea in 1985, and the M. S. and Ph. D. degrees in electrical engineering from Texas A & M University, College Station in 1992 and 1995, respectively. From 1985 to 1990, he was with Daewoo Heavy Industries as a research engineer. From 1996 to 1997, he was a principal research engineer at Samsung Electro-Mechanics. He is currently a Full-time Instructor in the Department of Control and Instrumentation, Seoul National Polytechnic University, Seoul, Korea. His research interests include clean power utility interface, active power factor correction, and microprocessor control of power converters.

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