정전력 변환시스템에서 정현파 입력전류를 얻기위한 전류주입형 인터페이스 리액터

최 세완*　　　이 홍희**　　　김 상욱***
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A New Active Interphase Reactor with Sinusoidal Input Current in the Static Power Converter System

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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. The modification results in near sinusoidal input current with less than 1% THD. Experimental results are provided from a 208V, 10kVA 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 THD and can lead to the malfunction 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 [2-12]. One approach is to use a conventional twelve-pulse diode rectifier which requires two six-pulse diode rectifiers connected via Y-Δ 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. In this scheme (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 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. 2 (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. 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.

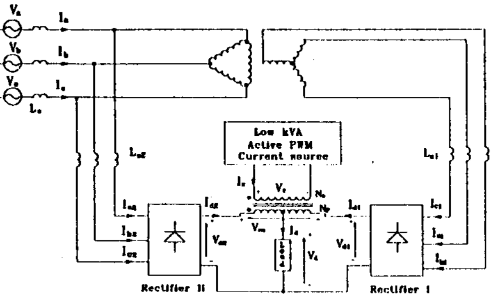


Fig. 1 Circuit diagram of the proposed clean power utility interface.

II. Proposed clean power utility interface

Fig. 1 shows the circuit diagram of the proposed scheme to shape input line currents. The main transformer has delta-wye winding 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 degrees 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, 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

Fig. 1 shows the proposed active interphase reactor 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],

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

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

$$I_{d1} = I_{d2} = \frac{1}{2} I_d \tag{2}$$

An active current I_x is now injected into the secondary winding of the interphase reactor as shown in Fig. 1. Fig. 3 shows the circuit topology for implementing this scheme. Analyzing the MMF relationship of the interphase reactor, we have,

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

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,

$$I_d = I_{d1} + I_{d2} \tag{4}$$

From (3) and (4) we have,

$$I_{d1} = \frac{1}{2}\left(I_d - \frac{N_s}{N_p} I_x\right) \tag{5}$$

$$I_{d2} = \frac{1}{2}\left(I_d + \frac{N_s}{N_p} I_x\right) \tag{6}$$

A switching function S_{a1} for phase "a" of Rectifier-I in Fig. 1 is defined and the Fourier series expansion for S_{a1} is given by,

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

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

$$S_{b1} = S_{a1}\angle -120^\circ \qquad S_{c1} = S_{a1}\angle +120^\circ. \tag{8}$$

Similarly, the switching functions for Rectifier-II with a 30 degree phase shift are,

$$S_{a2} = S_{a1}\angle -30^\circ \qquad S_{b2} = S_{b1}\angle -30^\circ \qquad S_{c2} = S_{c1}\angle -30^\circ. \tag{9}$$

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

$$\begin{bmatrix} I_{a1} \\ I_{b1} \\ I_{c1} \end{bmatrix} = \begin{bmatrix} S_{a1} \\ S_{b1} \\ S_{c1} \end{bmatrix} I_{d1} \tag{10}$$

and

$$\begin{bmatrix} I_{a2} \\ I_{b2} \\ I_{c2} \end{bmatrix} = \begin{bmatrix} S_{a2} \\ S_{b2} \\ S_{c2} \end{bmatrix} I_{d2} \tag{11}$$

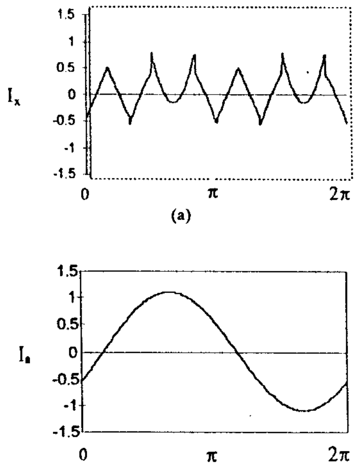
Equation (1) can now be modified using (5) and (6) and the switching functions described in (7)-(11) as,

$$I_a = \frac{1}{2\sqrt{3}}(S_{a1} - S_{c1})\cdot\left(I_d - \frac{N_s}{N_p} I_x\right) + \frac{1}{2} S_{a2}\left(I_d + \frac{N_s}{N_p} I_x\right) \tag{12}$$

Equation (12) illustrates the relationship between I_x and input current I_a. For input current I_a to be sinusoidal,

$$I_x = \frac{N_p\left[2I_{a,1} - I_d\left(\frac{S_{a1} - S_{c1}}{\sqrt{3}} + S_{a2}\right)\right]}{N_s\left(\frac{S_{a1} - S_{c1}}{\sqrt{3}} + S_{a2}\right)}. \tag{13}$$

Note that I_a is replaced by $I_{a,1}$, where $I_{a,1}$ is the fundamental rms component of I_a. Therefore, equation (13) describes the exact shape of I_x for a given load current I_d. Fig. 2 (a) shows the shape of I_x for sinusoidal input current. Fig. 2 (b) shows the input current waveform when the exact shape of current I_x is injected into the interphase reactor. From Fig. 2 (a), it is apparent that I_x is near triangular in shape. Simplifying the current I_x to a triangular wave shape and injecting it into the secondary winding of the interphase reactor yields a near sinusoidal input current I_a. 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 as shown in Fig. 3.



(b)

Fig. 2 (a) Injected current I_x calculated from (13)

(b) Input line current I_a (pure sinusoidal)

B. 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,

$$V_m = V_{d2} - V_{d1}. \tag{14}$$

$$V_m = -5.4018 V_{LL} \sum_{n=6,12,18,\ldots}^{\infty} \frac{1}{n^2 - 1}\cos\frac{n\pi}{6}\sin\frac{n\pi}{12}\sin n\left(\omega t - \frac{\pi}{12}\right) \tag{15}$$

From (15), the rms value of V_m can be computed as,

$$V_{m,rms} = 0.1098 V_{LL} \tag{16}$$

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

$$V_x = \frac{N_s}{N_p} V_m . \tag{17}$$

Then, from (16) and (17) the rms value of V_x is,

$$V_{x,rms} = 0.1098 V_{LL} \frac{N_s}{N_p} . \tag{18}$$

From the results in the previous section, the peak value of the current I_x is known to be 0.5 I_d. Therefore, the rms value of I_x for a triangular waveshape is,

$$I_{x,rms} = \frac{0.5}{\sqrt{3}} I_d \frac{N_p}{N_s} = 0.2887 I_d \frac{N_p}{N_s} \tag{19}$$

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 (18) and (19), the kVA rating of the injected current source, kVA_{INV}, can be computed as,

$$kVA_{INV} = V_{x,rms} \cdot I_{x,rms} = 0.0227 P_o \text{ (PU)} \tag{20}$$

Equation (20) 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 a clean power utility interface.

III. Implementation of the active current source I_x

Fig. 3 shows the circuit diagram for implementing the proposed scheme. Approaximated injected current I_x is generated from a current controlled PWM inverter.

Block diagram of the gating signal generator for the PWM inverter is shown in Fig. 4. The reference for the injected current is synchronized with the input voltages. Injected current I_x is fed back to the gating signal generator and the current error is compared to a triangular carrier wave (25kHz) to generate the PWM gating signals for the inverter switching devices.

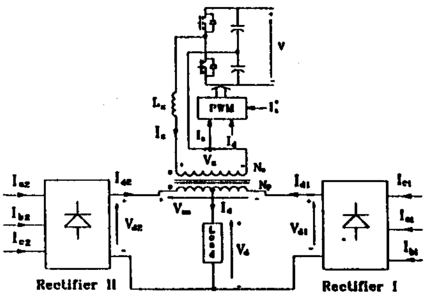


Fig. 3 Circuit diagram for implementation of the proposed scheme.

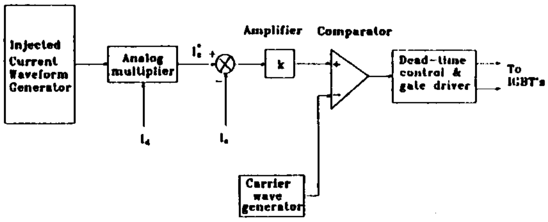
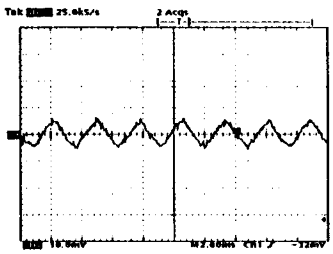


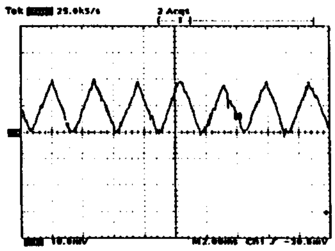
Fig. 4 Block diagram of the current-controlled PWM gating signal generator.

IV. Experimental results

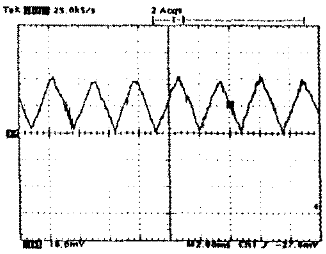
A 208V, 10kVA diode rectifier system employing the proposed scheme has been implemented in the laboratory. The interphase reactor employed in the experiment was designed with the turns ratio of $N_p : N_s = 1 : 2$.
Fig. 5 shows the experimental results obtained. Fig. 5 (a) shows the injected current I_x and Fig. 5 (b) and (c) show the resulting rectifier output currents I_{d1} and I_{d2}, respectively. Fig. 5 (d) shows the rectifier input current I_{a1} . Finally, the experimental utility input current I_a and its frequency spectrum are shown in Fig. 5 (e) and (f) , respectively. Note that input current I_a is near sinusoidal in shape and has less than 1% THD. Experimental results show good agreement between theory and practice and demonstrate clean power characteristics of the proposed scheme.



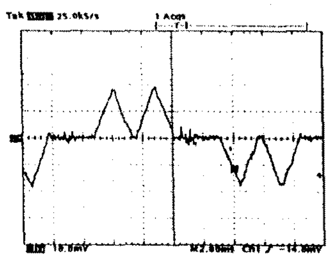
(a)



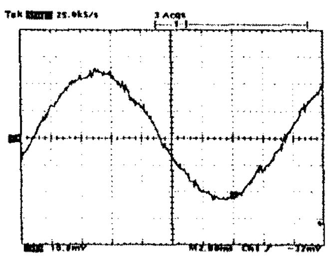
(b)



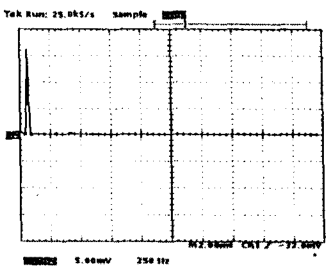
(c)



(d)



(e)



(f)

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

V. 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. The resultant system is a high performance clean power utility interface suitable for powering larger kVA ac motor drive systems. Detailed analysis of the proposed scheme along with design equations has been illustrated. Experimental results have been provided from a 208V, 10kVA rectifier system.

References

[1] "IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems", IEEE PES and Static Converter Committee of IAS, Jan. 1993

[2] J. Schaefer, " Rectifier Circuits: Theory and Design", John Wiley & Sons, Inc., 1965

[3] B. R. Pelly, "Thyristor Phase-Controlled Converters and Cycloconverters, John Wiley & Sons, 1971.

[4] R. W. Lye, etc. al, " Power Converter Handbook", Power Delivery Department, Canadian General Electric Company Ltd., 1976

[5] G. Seguier," Power Electronic Converters AC/DC conversions", McGraw-Hill, New York, NY, 1986.

[6] G. Oliver, etc. al, "Novel Transformer Connection to Improve Current Sharing on High Current DC Rectifiers", pp. 986-992, IEEE IAS conf., 1993.

[7] S. Miyairi, etc. al, " New Method for Reducing Harmonics Involved in Input and Output of Rectifier with Interphase Transformer", IEEE Trans. on Industry Applications, pp. 790-797, Vol. IA-22, No. 5, Sep./Oct. 1986

[8] A. R. Prasad, P. D. Ziogas, S. Manias, " An Active Power Factor Correction Technique for Three-Phase Diode Rectifiers ", pp. 83-92, IEEE Trans. on Power Electronics, Vol. 6, No. 1, Jan. 1991

[9] Ned Mohan, "A Novel Approach to Minimize Line-Current Harmonics in Interfacing Renewable Energy Sources with 3-Phase Utility Systems", IEEE APEC Annual meeting, 1992, pp.852-858.

[10] S. Kim, P. Enjeti, P. Packebush and I. Pitel, " A New Approach to Improve Power Factor and Reduce Harmonics in a Three-Phase Diode Rectifier Type Utility Interface", pp. 1557-1564, IEEE Trans. on Industry Applications, Vol. 30, No. 6, Nov./Dec. 1994.

[11] I. Pitel and S. N. Talukdar, " A Review of the Effects and Suppression of Power Converter Harmonics", IEEE IAS Conference, May 1977.

[12] S. Choi, A. Jouanne, P. Enjeti, I. Pitel, "New Polyphase Transformer Arrangements with Reduced kVA Capacities for Harmonic Current Reduction in Rectifier Type Utility Interface", IEEE PESC conf. ,1995

[13] P. Enjeti and I. Pitel, " An Active Interphase Reactor for 12-pulse rectifiers", U.S. Patent disclosure