A New Diode Rectifier Type Utility Interface with Clean Power Characteristics

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Abstract

In this paper, a new active interphase reactor for twelve-pulse diode rectifiers is proposed. 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 proposed system draws near sinusoidal input currents from the utility with less than 1% THD 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 208V, 10kVA diode 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- and Y-Y 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.

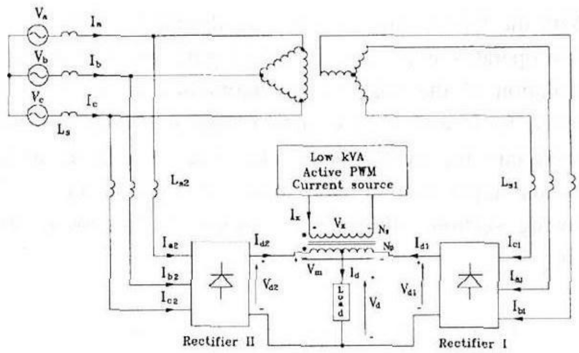

Fig. 1. Circuit diagram of the proposed clean power utility interface. Current I_a is near sinusoidal in shape with less than 1% THD.

This paper proposes a new three-phase diode rectifier system which draws near sinusoidal input currents from the three phase electric utility. In the proposed approach shown in Fig. 1, a 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 shown in Fig. 3 (a) can be computed to alter the utility line current Ia to

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a perfect sinewave. It is further shown that an approximation to the exact waveshape of I_x is a triangular wave shown in 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. This results in high performance with reduced kVA components and offers clean power utility interface suitable for powering larger kVA ac motor drives. Detailed analysis of the proposed schemes is discussed.

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 (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 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 (Fig. 1), results in near sinusoidal input current with unity input power factor. The following sections illustrate the proposed concept in more detail.

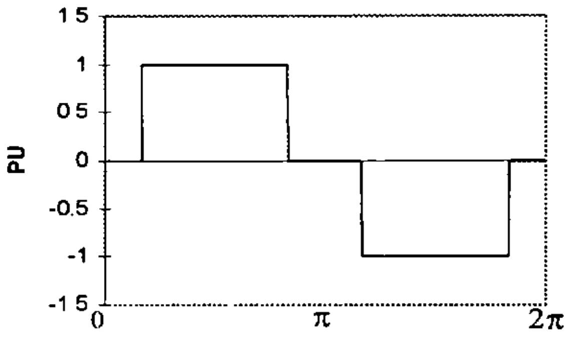


Fig. 2. Switching function S_{a1} for Rectifier I in Fig. 1.

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 Ia 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. 6 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 Id is,

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

From (3) and (4) we have,

$$I_{d1} = \frac{1}{2}(I_d - \frac{N_s}{N_p} I_x)$$
$$I_{d2} = \frac{1}{2}(I_d + \frac{N_s}{N_p} I_x) \tag{5}$$

Fig. 2 shows switching function Sa1 for phase a of Rectifier-I shown in Fig. 1. The Fourier series expansion for S_{a1} is given by,

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

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

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

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

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

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

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

and

$$\begin{bmatrix} I_{a2} \\ I_{b2} \\ I_{c2} \end{bmatrix} = \begin{bmatrix} S_{a2} \\ S_{b2} \\ S_{c2} \end{bmatrix} I_{d2} \quad \textbf{(10)}$$

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

$$I_a = \frac{1}{2\sqrt{3}}(S_{a1} - S_{c1}) \cdot (I_d - \frac{N_s}{N_p} I_x) + \frac{1}{2} S_{s2}(I_d + \frac{N_s}{N_p} I_x) \quad \textbf{(11)}$$

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

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

Note I_a is replaced by $I_{a,1}$,where $I_{a,1}$ is the fundamental component of I_a. Therefore, equation (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

$$\sqrt{3}\, V_{LL} |I_{a,1}| = V_d I_d \quad \textbf{(13)}$$

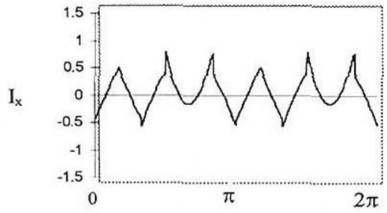
where V_d=1.35V_{LL} and V_{LL} is the line to line rms voltage and $|I_{a,1}|$ is rms value of $I_{a,1}$.
Hence, from (13) we have,

$$|I_{a,1}| = 0.7794\, I_d \quad \textbf{(14)}$$

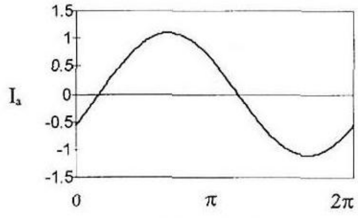
Now, for input current I_a to be sinusoidal, i.e.,

$$I_a = \sqrt{2}\, |I_{a,1}| \sin \omega t \quad \textbf{(15)}$$

Fig. 3 (a) shows the shape of Ix for sinusoidal input current.



(a)

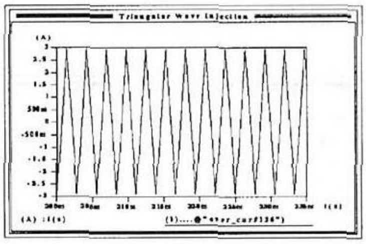


(b)

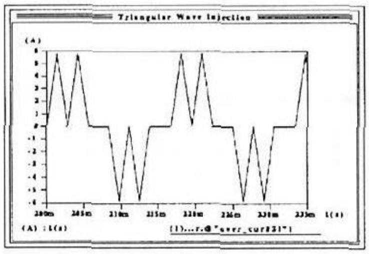
Fig. 3. (a) Injected current I_x calculated from (12) (b) Input line current I_a(pure sinusoidal).

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 Ix 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. 6). 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) show the dc output voltages V_{d1} and V_{d2}. Fig. 5 (c) shows the voltage across the interphase reactor.



(a)



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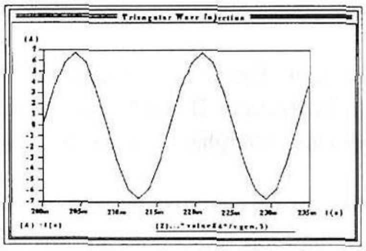
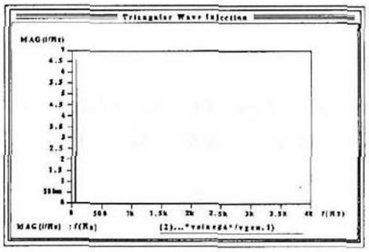


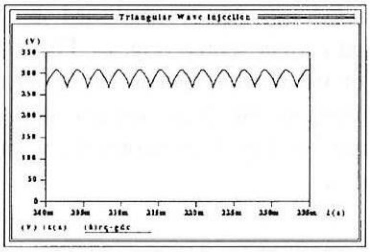
(c)



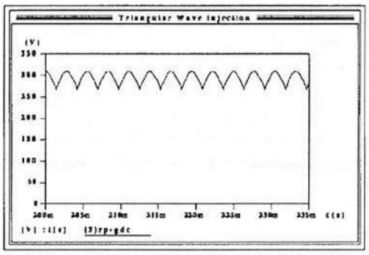
(d)

Fig. 4. Simulation results.
(a) Injected current I_x (b) Rectifier I input current I_{a1} (c) Input line current I_a (d) Frequency specturm of I_a

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.



(a)



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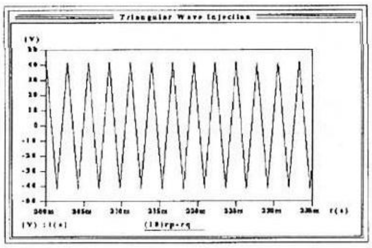

(c)

Fig. 5. Simulation Results (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}.

C. kVA rating of the injected current source, Ix

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) show the waveshape of V_{d1} and V_{d2}. Furthermore, V_{d1} can be expressed in Fourier series as [3],

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

Output voltage V_{d2} is phase shifted by 30 degree. By substituting (17) into (16), V_m can be expressed as,

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

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

$$V_{m,ms} = 0.1098 V_{LL} \tag{19}$$

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

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

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

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

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,

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

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, kVA_{INV}, can be computed as,

$$\begin{aligned} kVA_{INV} &= V_{x,ms} \cdot I_{x,ms} \\ &= 0.0227 P_o (PU) \end{aligned} \tag{23}$$

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 a clean power utility interface.

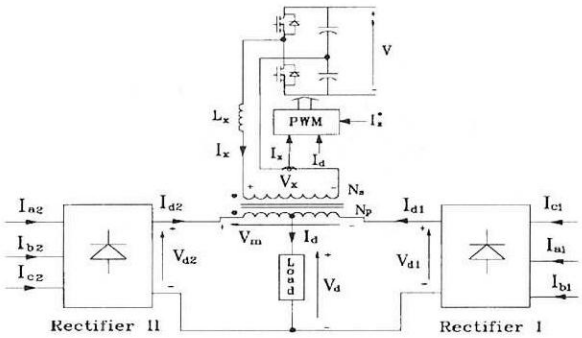

Fig. 6. Circit diagram for implementation of the proposed schemes.

D. Implementation of the active current source Ix

Fig. 6 shows the circuit diagram for implementing the proposed scheme. Injected current I_x shown in Fig. 4 (a) is generated from a current controlled PWM inverter.

Block diagram of the gating signal generator for the PWM inverter is shown in Fig. 7. The reference for the injected current is synchronized with the input voltages. Injected current Ix 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. As the magnitude of output dc current I_d changes, the magnitude is fed back and multiplied by the injected current to make the reference I_x^*.

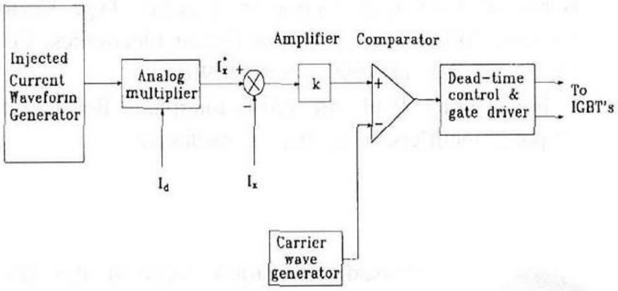

Fig. 7. Block diagram of the current-controlled PWM gating signal generator.

III. 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 $N_p : N_s = 1 : 2$.

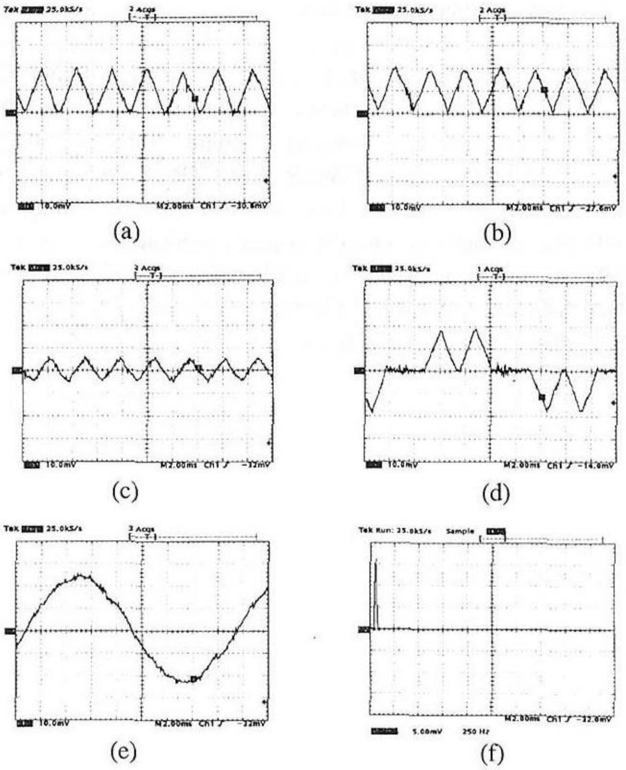

Fig. 8. Experimental results (5A/Div.)
(a) Output current I_{d1}. (b) Output current I_{d2}. (c) Injected current I_x. (d) Rectifier input current I_{a1}. (e) Input line current I_a (f) Frequency spectrum I_a.

Fig. 6 shows the experimental setup to verify the operation of proposed system. Fig. 8 shows the experimental results obtained. Fig. 8 (c) shows the injected current Ix and Fig. 8 (a) and (b) show the resulting rectifier output currents I_{d1} and I_{d2} , respectively. Fig. 8 (d) shows the rectifier input current I_{a1} . Finally, the experimental utility input current Ia and its frequency spectrum are shown in Fig. 8 (e) and (f) , respectively. Experimental results show good agreement between theory and practice and demonstrate clean power characteristics of the proposed scheme.

IV. 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 proposed 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. Simulation results have been shown to verify the proposed concepts. Experimental results have been provided from a 208V, 10kVA rectifier system.

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