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

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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 (0.03 per unit) 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. It is further shown that a low kVA, 12-pulse system with an autotransformer arrangement (kVA rating of 0.18 per unit) can be implemented with the proposed modification. 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.

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].

Fig. 1 Circuit diagram of the proposed clean power utility interface Scheme I. Current I1 is near sinusoidal in shape with less than 1% THD.

A number of methods have been proposed to overcome the presented problems [2-12]. One approach is to use a standard twelve-pulse converter which requires two six-pulse converters connected via Y-A 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 standard twelve-pulse converter 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 per-unit 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 (0.03 per unit) PWM-controlled active current source, $I_a$, 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 $I_a$ (Fig. 3 (a)) can be computed to alter the utility line current $I_L$ to a perfect sinewave. It is further shown that an approximation to the exact waveshape of $I_a$ is a triangular wave (Fig. 4 (a)). Therefore by injecting a triangular shaped current $I_a$ 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 degree 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 per unit. 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. Detailed analysis of the proposed schemes is discussed.

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 per unit) 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 standard 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, $I_a$, disabled (i.e. $I_a = 0$) the system operates as a standard 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 $I_a$, 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.
\[ I_n = \frac{1}{2} \left( I_0 - \frac{N_s}{N_p} I_0 \right) \]
\[ I_{\alpha} = \frac{1}{2} \left( I_0 + \frac{N_s}{N_p} I_0 \right) \]

Fig. 2 shows switching function \( S_{\alpha} \) for phase “a” of Rectifier-I shown in Fig. 1. The Fourier series expansion for \( S_{\alpha} \) is given by,
\[
S_{\alpha}(t) = \frac{2\sqrt{2}}{\pi} \left[ \sin \omega t - \frac{1}{5} \sin 5\omega t - \frac{1}{7} \sin 7\omega t + \frac{1}{11} \sin 11\omega t + \frac{1}{13} \sin 13\omega t + \ldots \right]
\]
and for phase “b” and “c”, the switching functions can be written as,
\[
\begin{align*}
S_{\alpha} &= S_{\alpha},_\alpha - 120^\circ \\
S_{\alpha} &= S_{\alpha},_\alpha + 120^\circ
\end{align*}
\]

Similarly, the switching functions for Rectifier-II in Fig. 1 with a 30 degree phase shift are,
\[
\begin{align*}
S_{\alpha} &= S_{\alpha},_\alpha - 30^\circ \\
S_{\alpha} &= S_{\alpha},_\alpha - 30^\circ \\
S_{\alpha} &= S_{\alpha},_\alpha - 30^\circ
\end{align*}
\]

The input currents for Rectifier I and II can now be expressed in terms of switching functions as,
\[
\begin{bmatrix}
I_n \\
I_{\alpha} \\
I_{\beta}
\end{bmatrix} =
\begin{bmatrix}
S_{\alpha} \\
S_{\beta} \\
S_{\gamma}
\end{bmatrix}
\begin{bmatrix}
I_0 \\
I_0 \\
I_0
\end{bmatrix}
\]
and
\[
\begin{bmatrix}
I_{\alpha} \\
I_{\gamma}
\end{bmatrix} =
\begin{bmatrix}
S_{\alpha} \\
S_{\gamma}
\end{bmatrix}
\begin{bmatrix}
I_0 \\
I_0
\end{bmatrix}
\]

Equation (1) can now be modified using (5) and the switching functions described in (6)-(10) as,
\[
I_n = \frac{1}{2\sqrt{3}} (S_{\alpha} - S_{\beta}) \left( I_0 - \frac{N_s}{N_p} I_0 \right) + \frac{1}{2} S_{\alpha} (I_0 + \frac{N_s}{N_p} I_0)
\]

Equation (11) illustrates the relationship between \( I_n \) and input current \( I_0 \). For input current \( I_0 \) to be sinusoidal,
\[
I_0 = \sqrt{3} V_{\text{in}} I_{\alpha},_0 = V_{\text{in}} I_{\alpha}
\]

Note \( I_n \) is replaced by \( I_{\alpha},_0 \), where \( I_{\alpha},_0 \) is the fundamental rms component of \( I_n \). Therefore, equation (12) describes the exact shape of \( I_n \) for a given load current \( I_0 \). Since input power is equal to output power, we have
\[
\sqrt{3} V_{\text{in}} I_{\alpha},_0 = V_{\text{in}} I_{\alpha}
\]

Now, for input current \( I_0 \) to be sinusoidal, i.e.,
\[
I_n = \sqrt{3} I_{\alpha},_0 \sin \omega t
\]

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

**B. Simulation results of the proposed approach**

![Simulation results](image)

Fig. 3 (a) Injected current \( I_n \) calculated from (12)
(b) Input line current \( I_0 \) (pure sinusoidal)

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 \( I_n \) is near triangular in shape. Simplifying the injected current \( I_n \) to a triangular wave shape (Fig. 4(a)) yields a near sinusoidal input current \( I_0 \) (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) and (c) show the respective input currents of the rectifier blocks I and II (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.

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 (e)) of less than 1% THD. The kVA rating of the injected current is small and is computed in the next section.
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 $V_m = V_{d2} - V_{d1}$

C. kVA rating of the injected current source, $I_c$

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,

$$V_m = V_{d2} - V_{d1}. \quad (16)$$

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],

$$V_{d1} = \sqrt{2} V_{ll} \sum_{n=1,3,5,...}^{\infty} \frac{2}{n \pi} \cos \left(\frac{n \pi}{2}\right) \sin \left(\frac{n \pi}{12}\right) \sin \left(\frac{n \pi}{12}\right) \quad (17)$$

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

$$V_m = -5.4018 V_{ll} \sum_{n=1,3,5,...}^{\infty} \frac{2}{n \pi} \cos \left(\frac{n \pi}{2}\right) \sin \left(\frac{n \pi}{12}\right) \sin \left(\frac{n \pi}{12}\right) \quad (18)$$

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

$$V_{m,\text{rms}} = 0.1553 V_{ll}. \quad (19)$$

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

$$V_s = \frac{N_s}{N_p} V_m. \quad (20)$$

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

$$V_{s,\text{rms}} = 0.1553 V_{ll} \frac{N_s}{N_p}. \quad (21)$$

From the results in the previous section, the peak value of the current $I_c$ of Fig. 4 (a) is 0.5 $I_d$ for $N_s / N_p = 1$. Therefore, the rms value of $I_c$ for a triangular waveshape is,

$$I_{c,\text{rms}} = \frac{0.5}{\sqrt{3}} = 0.2887 \text{ per unit} \quad (22)$$

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

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

$$kVA_{I_c} = V_{s,\text{rms}} I_{c,\text{rms}}, \quad (23)$$

$$= 0.0448 \text{ per unit}$$

From (13) the output power for the 12 pulse system in Fig. 1 is,

$$P_o = V_o I_d = 135 \text{ per unit} \quad (24)$$

Therefore, the percentage kVA rating of the injected current source with respect to the output power becomes,

$$kVA_{I_c,\%} = \frac{kVA_{I_c}}{P_o} \times 100 \quad (25)$$

Equation (25) shows that the kVA rating of the injected current source $I_c$ 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. 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 $\pm 15$ degrees 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 per unit.

Fig. 6 shows the resulting active interphase reactor implementation with the autotransformer arrangement. A current source $I_c$ 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 Scheme II shown in Fig. 6. Input current $I_a$ can be expressed as,
For the triangular-shaped injected current $I_i$ of Fig. 4 (a), the input line current $I_i$ expressed as (26), becomes near sinusoidal in shape and approximates that shown in Fig. 4 (e). The clean power rectifier Scheme II discussed in this section employs low kVA magnetics and is currently undergoing active evaluation in the Power Electronics Laboratory of Texas A&M University.

**IV. Implementation of the active current source $I_i$**

Fig. 8 shows the circuit topology of the PWM-controlled active current source for $I_i$ in Scheme I. A six pulse injection current $I_i$ of triangular in shape (Fig. 4 (a)) is generated with a PWM-controlled current source. Fig. 9 shows the block diagram of the PWM current loop.

**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 (0.03 per unit) active current source $I_i$ 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 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.

References


