NEW 24-PULSE DIODE RECTIFIER SYSTEMS FOR UTILITY INTERFACE OF HIGH POWER AC MOTOR DRIVES

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Abstract - This paper proposes two new passive 24-pulse diode rectifier systems for utility interface of PWM ac motor drives. The first approach employs an extended delta transformer arrangement which results in near equal leakage inductance in series with each diode rectifier bridge. This promotes equal current sharing and improved performance. A specially tapped interphase reactor is then introduced with two additional diodes to extend the conventional 12-pulse operation to 24-pulse operation from the input current point of view. The proposed system exhibits clean power characteristics with 5th, 7th, 11th, 13th, 17th and 19th harmonics eliminated from the utility line currents. The second scheme is a reduced kVA approach employing autotransformers to obtain 24-pulse operation. The kVA rating of the polyphase transformer in the second scheme is 0.18 P₀ (PU). Detailed analysis and simulations verify the proposed concept and experimental results from a 208V, 10kVA rectifier system are provided.

I. INTRODUCTION

A number of methods have been proposed to lower harmonics generated by diode rectifier type utility interface to power electronic system [2-6]. One approach is to use a conventional twelve-pulse converter which requires two six-pulse converters connected through Δ-Y and Δ-Δ isolation transformers (Fig. 1). An interphase reactor is required to ensure 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. However, the THDs of input line currents are still high and do not qualify as clean power.

In this paper, to further increase the pulse number and cancel several lower order harmonics, a specially tapped interphase reactor is introduced with two additional diodes connected as shown in Fig. 2 (Scheme-I). The taps on the interphase reactor are chosen such that 24-pulse characteristics with the elimination of 5th, 7th, 11th, 13th, 17th and 19th harmonics in the input line currents occur. Thus, the proposed approach extends the conventional 12-pulse operation to 24-pulse operation from the input current point of view with slight complexity in hardware. Further, a reduced kVA 24-pulse system employing an autotransformer configuration is introduced as shown in Fig. 6 (Scheme-II). The kVA rating of the polyphase transformer in the second scheme is 0.18 P₀ (PU), which drastically reduces the cost, weight and volume. Both Scheme-I and II exhibit clean power characteristics and is considered as an important contribution.

Detailed analysis of the tapped interphase reactor design and the resulting 24-pulse diode rectifier systems are discussed. The proposed systems are simulated on SABER and experimental results from a 208V, 10kVA laboratory systems are also provided.

II. PROPOSED 24-PULSE APPROACH (SCHEME - I)

Fig 2 shows the proposed 24-pulse system which is identical to the conventional 12-pulse system with the

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exception of a modified transformer configuration and the two diodes connected to a specially tapped interphase reactor. The secondary windings of the input transformer are configured in extended delta and generate balanced sets of three-phase voltages with 30 degrees phase shift for the diode rectifiers. The extended delta arrangement provides equal leakage reactances in series with rectifier I and II. More details on transformer winding arrangements are discussed in section II.B.

A. Operation of the tapped-interphase reactor

The tapped interphase reactor has been discussed in reference [2] for SCR converters with multiple taps along with a complicated firing scheme. In this paper it is shown that by employing only two taps and two additional diodes the conventional 12-pulse operation can be extended to 24-pulse operation with the 5th, 7th, 11th, 13th, 17th and 19th harmonics eliminated in the input line currents. The resulting systems exhibit high performance with clean power characteristics. Fig. 3 shows the practical winding configuration of the two diodes tapped on the interphase reactor and the operation of the interphase reactor according to two modes: P-mode (Fig. 3 (a)) and Q-mode (Fig. 3 (b)).

Fig. 2 Proposed 24-pulse system (Scheme-I)

Fig. 3 Operation of the interphase reactor with two tapped-diodes (a) P-mode (b) Q-mode

From (1) and (2) the output currents of the two diode bridge rectifiers are given by,

$$I_{o1} = (0.5 - k)I_o$$

$$I_{o2} = (0.5 + k)I_o$$

where $k = \frac{N_t}{N_o}$ and $k = 0$ signifies the conventional center-tapped interphase reactor and 12-pulse operation. When voltage across the interphase reactor, $V_m$ is negative, diode $D_b$ is forward biased and is turned on, $D_a$ is reversed biased and is off (P-mode). Similarly, for Q-mode the output currents of the two diode bridge rectifiers becomes,
\[ I_{o1} = (0.5 + k)I_o \]  
\[ I_{o2} = (0.5 - k)I_o \]

Therefore, depending on the polarity of voltage \( V_m \), the magnitudes of rectifier output currents \( I_{o1} \) and \( I_{o2} \) are modulated as shown in Fig. 7 (b) and this changes the shapes of rectifier input currents as shown in Fig. 7 (c). Finally, the rectifier system exhibits 24-pulse characteristics as shown in Fig. 7 (d). The next sections describe details on the analysis of input currents and the selection of \( k \) required for 24-pulse operation.

\[ \sin 150^\circ = \frac{\sin 15^\circ}{k_1} \]

Therefore, \( k_1 = 0.5176 \) (PU) (8)

\[ k_2 = \sqrt{3} k_1 = 0.8966 \) (PU) (9)

\[ \sqrt{3} I_{1x} = k_x (I_{o1} + I_{o2}) + \frac{1}{3} k_x (I_{o1} - I_{o1} + I_{o2} - I_{o2}) \]

Similarly, for core limbs B and C, the MMF equations become,

\[ \sqrt{3} I_{2x} = k_x (I_{o1} + I_{o2}) + \frac{1}{3} k_x (I_{o1} - I_{o1} + I_{o2} - I_{o2}) \]

\[ \sqrt{3} I_{3x} = k_x (I_{o1} + I_{o2}) + \frac{1}{3} k_x (I_{o1} - I_{o1} + I_{o2} - I_{o2}) \]

Then, from (10) and (11), input line current \( I_o \) can be obtained by.

Fig. 4 Vector diagram of the extended delta transformer

B. Extended delta transformer arrangement

Fig. 2 shows the proposed scheme I. For scheme I to operate successfully as a 24-pulse system, the two diode rectifier bridges should be balanced and rectifier output currents \( I_{o1} \) and \( I_{o2} \) be more or less equal in magnitude. In order to achieve this, the input transformer leakage reactances in the secondary winding should be nearly equal. The conventional 12-pulse \( \Delta \)-Y transformer shown in Fig. 1 suffers from unequal secondary turns, and this contributes to inequality in leakage reactances for the two diode bridge rectifiers. In order to overcome these limitations, an extended delta transformer is presented in scheme I.

The vector diagram of the extended delta transformer arrangement for rectifier-I and rectifier-II in Fig. 3 are shown in Fig. 4. The required phase shift angle between the two sets of three phase voltages is 30 degree to obtain 12-pulse operation. The extended delta arrangement shown in Fig. 4 and 5 presents equal number of turns in the secondary windings, hence near equal leakage reactances in each line of the transformer secondary. This in turn ensures equal loading of the two rectifier bridges resulting in \( I_{o1} \) and \( I_{o2} \) being equal. Assuming that the magnitude of the line to neutral voltages of the secondary winding such as \( V_{a1} \) is 1 (PU), the extended length \( k_1 \) can be obtained from the geometric relationship of,
C. kVA rating of the extended delta transformer and design example

The extended delta transformer utilized in the proposed approach is designed and the kVA rating is calculated in this section. Assuming output power \( P_o = 10 \text{kVA} \) and input line-to-line rms voltage \( V_{LL} = 208 \text{ V} \), output voltage \( V_o \) of the proposed rectifier system becomes,

\[
V_o = 135 \times V_{LL} = 280.8 \text{ V}
\]

Output current \( I_o \) becomes,

\[
I_o = \frac{P_o}{V_o} = 35.6 \text{ A}
\]

Assuming that output current \( I_o \) has negligible ripple, rms values of each of the winding voltages and currents can be obtained and listed as in Table-I.

<table>
<thead>
<tr>
<th>Winding</th>
<th>Expression</th>
<th>Rms Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>(</td>
<td>I_1</td>
</tr>
<tr>
<td>winding current</td>
<td>(</td>
<td>V_a</td>
</tr>
<tr>
<td>Voltage</td>
<td>(\frac{2}{3}</td>
<td>I_1 - I_2</td>
</tr>
<tr>
<td>Secondary</td>
<td>(</td>
<td>V_2</td>
</tr>
<tr>
<td>delta</td>
<td>(</td>
<td>I_1</td>
</tr>
<tr>
<td>winding current</td>
<td>(</td>
<td>V_{kl}</td>
</tr>
<tr>
<td>Voltage</td>
<td>(</td>
<td>I_1</td>
</tr>
</tbody>
</table>

Then the total kVA of the extended delta transformer becomes,

\[
kVA_{ext} = 3 \cdot |I_1| \cdot |V_a| + 6 \cdot \frac{1}{3} |I_1 - I_2| \cdot |V_2| + 6 \cdot |I_1| \cdot |V_{kl}| = 20.94 \text{ (kVA)}
\]

Hence, the equivalent kVA rating of the extended delta transformer is,

\[
kVA_{eq} = \frac{1}{2} kVA_{ext} = 10.47 \text{ (kVA)}
\]

This illustrates that the required transformer kVA for the proposed scheme is almost the same as the conventional delta-wye transformer kVA of 10.35 kVA [9].

D. Input line current of the proposed approach

In this section the input line currents are analyzed and the interphase reactor tapping ratio \( k \) is selected so that the proposed scheme performs as a 24 pulse system from the input current point of view.

From the rectifier input current \( I_a \) of Fig. 7 (b) it can be seen that the waveforms have half-wave and quarter-wave symmetry. Therefore, the Fourier series of the rectifier input current, \( I_a \) shown in Fig. 7 (c) can be represented as a function of \( k \),

\[
I_a(t) = \sum_{n=odd, \text{non-ripple}} b_n(k) \sin(n\omega t)
\]

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

\[
I_a(t) = \sum_{n=odd, \text{non-ripple}} b_n(k) \sin(n\omega t + 120)\]

Then, from (12) and (17)-(20), input line current \( I_a(t) \) becomes,

\[
I_a(t) = \sum_{n=odd, \text{non-ripple}} b_n(k) \sin(n\omega t + \phi_n)
\]

where \( b_n(k) \), \( g_n \) and \( \phi_n \) are given by,

\[
b_n(k) = \frac{4}{n\pi} \left\{ (0.5 - k)(\cos \frac{n\pi}{12} - \cos \frac{s_n\pi}{12}) + 2k(\cos \frac{n\pi}{6} - \cos \frac{s_n\pi}{3}) \right\}
\]

\[
g_n = \sqrt{\left( \frac{\cos \frac{n\pi}{6} + \frac{2}{\sqrt{3}} \sin \frac{n\pi}{3} \cos \frac{n\pi}{3} \right)^2 + \left( \sin \frac{n\pi}{6} + \frac{2}{\sqrt{3}} \sin \frac{n\pi}{3} \cos \frac{n\pi}{3} \right)^2}
\]

\[
\phi_n = \tan^{-1} \left( \frac{-\sin \frac{n\pi}{6} - \frac{2}{\sqrt{3}} \sin \frac{n\pi}{3} \cos \frac{n\pi}{3}}{\cos \frac{n\pi}{6} + \frac{2}{\sqrt{3}} \sin \frac{n\pi}{3} \cos \frac{n\pi}{3}} \right)
\]
From (22) \( g_n = 0 \) for \( n = 5, 7, 11, 13, 17, 19, 29, 31, \ldots \) (i.e. \( n = 6m \pm 1, \ m = 1, 3, 5, \ldots \)) and the value of \( k \) for \( b_n(k) = 0 \) for \( n = 11 \) and \( 13 \) can be found to be,

\[
k = \frac{V_i}{V_o} = 0.2457
\]

Therefore, substituting the value of \( k \) in (23) into (22) results in the elimination of the 5th, 7th, 11th, 13th, 17th and 19th harmonics in the input line current \( I \), yielding 24-pulse characteristics from the input current standpoint.

### III. PROPOSED 24-PULSE APPROACH (SCHEME - II)

Fig. 6 (a) shows a reduced kVA approach of the proposed 24-pulse system. This approach employs a polyphase autotransformer to provide 30 degree phase-shifted voltages to rectifier bridges 1 and II. The kVA transmitted by the actual magnetic coupling is only a portion of the total kVA and is shown to be 0.18 P (PU) [11]. This results in 82% reduction in size of the phase-shifting transformer compared to scheme I.

To ensure independent operation of the two diode bridge rectifiers with input autotransformer, a zero sequence blocking transformer (ZSBT) becomes necessary [9] and is shown in Fig. 6 (b). The ZSBT exhibits high impedance to zero sequence currents and provides 120 degree conduction for each rectifier diode. The design of ZSBT is straightforward, and its kVA rating is around 3% of the total output power [9]. Now, with the use of the specially tapped interphase reactor described in section II.A, the proposed Scheme-II in Fig. 6 also exhibits 24-pulse characteristics. The value of \( k \), tap ratio of the interphase reactor, and input current expression for \( I_a \) are identical to Scheme-I. Thus Scheme-II ensures the elimination of the 5th, 7th, 11th, 13th, 17th and 19th harmonics in the input line currents. It should be noted that Scheme-II does not provide input isolation, however the resulting system employs reduced kVA components contributing to lower cost, weight and volume.

### IV. SIMULATION RESULTS

The scheme I and II of the proposed 24-pulse approach are simulated on SABER and the results are presented in this section. Fig. 7 (a) shows the voltage across the interphase reactor. The rectifier output current \( I_o \) is shown in Fig. 7 (b). Notice the current is modulated due to the action of tapped interphase reactor and the alternative conduction of diodes \( D_a \) and \( D_b \). Fig. 7 (e) shows the rectifier-I input current \( I_{a1} \). Fig 7 (d) and (e) shows input line current \( I_a \) and its frequency spectrum, respectively. Thus, Fig. 7 (d) demonstrates 24-pulse operation with the 5th, 7th, 11th, 13th, 17th and 19th harmonics eliminated in the input line currents.
V. EXPERIMENTAL RESULTS

A 208V, 10kVA 24-pulse rectifier system (scheme-II) shown in Fig. 6 has been implemented in the laboratory. Rectifier output currents $I_{o1}$ and $I_{o2}$ are nearly identical in magnitude as shown in Fig. 8 (a) and (b). Rectifier input current $I_{a1}$ is modulated according to rectifier output currents and is shown in Fig. 8 (c). Fig 8 (d) shows the resulting utility line current $I_a$. Fig. 8 (e) shows the frequency spectrum of $I_a$. It should be noted that the input line current is near sinusoidal in shape. The leakage inductances of the transformer and reactance of the input line contribute to improved characteristics, i.e. the 24-pulse edges shown in Fig. 7 (d) are rounded off. The resulting system exhibits clean power characteristics.

Fig. 7 Simulation results of the proposed approach
(a) voltage across the interphase reactor (b) rectifier output current $I_{o1}$ (c) rectifier input current $I_{a1}$ (d) input line current $I_a$ (e) FFT of $I_a$
REFERENCES


VI. CONCLUSION

In this paper two new 24-pulse diode rectifier system have been proposed for high power motor drives. In the proposed scheme-I, it has been shown that a conventional 12-pulse system can be transformed to a 24-pulse system by employing a tapped interphase reactor. In scheme-II, a passive 24-pulse rectifier system has been shown with the use of a reduced kVA autotransformer. The resulting systems exhibit clean power characteristics with the elimination of 5th, 7th, 11th, 13th, 17th and 19th harmonics in the input line currents and is low cost in nature. Analysis and simulation results verify the basic concept. Experimental results demonstrate the superiority of the proposed schemes-I and -II.