A 24-Pulse AC–DC Converter Employing a Pulse Doubling Technique for Vector-Controlled Induction Motor Drives

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ABSTRACT

This paper deals with various multipulse AC–DC converters for improving the power quality in vector-controlled induction motor drives (VCIMDs) at the point of common coupling. These multipulse AC–DC converters are realized using a reduced rating autotransformer. Moreover, DC ripple reinjection is used to double the rectification pulses resulting in an effective harmonic mitigation. The proposed AC–DC converter is able to eliminate up to 21st harmonics in the supply current. The effect of load variation on VCIMD is also studied to demonstrate the effectiveness of the proposed AC–DC converter. A set of power quality indices on input AC mains and on the DC bus for a VCIMD fed from different AC–DC converters is also given to compare their performance.

Keywords: Autotransformer, Multipulse AC–DC converter, DC ripple reinjection, Pulse doubling, VCIMD.

1. INTRODUCTION

The advances in power semiconductor devices have led to the increased use of solid-state converters in various applications such as air conditioning, refrigeration, pumps, etc. employing variable frequency induction motor drives [1]. These variable frequency drives generally use the three-phase squirrel cage induction motor as the prime mover due to its advantages like rugged, reliable, maintenance free, etc. These induction motor drives are mostly operated in a vector control mode [2] due to its capability of giving a performance similar to that of a DC motor. These drives are fed by a six-pulse diode bridge rectifier, which results in injection of harmonics in the supply current, thus deteriorating the power quality at the point of common coupling (PCC), thereby affecting the nearby consumers. To have a control on these harmonics, an IEEE Standard 519 [3] has been reissued in 1992, giving the benchmark for limiting current and voltage distortion.

Harmonics can be reduced using different active or passive waveshaping techniques. The active waveshaping techniques result in an increased loss, complex control and higher overall cost. The passive waveshaping techniques use passive filters consisting of tuned L–C circuits. However, they require careful application and may produce unwanted side effects, particularly in the presence of power factor (PF) correction capacitors. The most rugged, reliable and cost effective solution to mitigate these harmonics is to use multipulse methods [4-12]. In multipulse converters, the autotransformer-based configurations provide the reduction in magnetics rating as the transformer magnetic coupling transfers only a small portion of the total kVA of the induction motor drive. Various 12-pulse-based rectification schemes have been reported and used in practice for the purpose of line current harmonic reduction [7-12]. With the use of a higher number of multiple converters, the power quality indices show an improvement, but at the cost of large magnetics resulting in a higher cost of the drive. To achieve similar performance in terms of harmonic current reduction, DC ripple reinjection has been used [13-15].

This paper presents an autotransformer-based 24-pulse AC–DC converter with reduced rating magnetics. A pulse multiplication technique is used to improve various power quality indices to comply with the IEEE standard 519 [3]. The scheme needs two additional diodes along with a suitably tapped interphase reactor for increasing the number of pulses. This arrangement results in elimination up to the 21st harmonic in the input line current.

Moreover, the effect of load variation on the vector-controlled induction motor drive (VCIMD) is also studied. The proposed AC–DC converter is able to achieve near unity PF in a wide operating range of the drive. A set of tabulated results giving the comparison of different power quality parameters such as total harmonic distortion (THD) and crest factor (CF) of AC mains current, PF, displacement factor and distortion factor, and THD
of supply voltage at PCC is presented for a VCIMD fed from an existing six-pulse AC–DC converter, as shown in Figure 1, referred to as Topology ‘A’, 12-pulse converter, Topology ‘B’ and proposed 24-pulse AC–DC converter, Topology ‘C’.

2. **CIRCUIT CONFIGURATIONS OF 12-PULSE AC–DC CONVERTERS**

For harmonic elimination, the required minimum phase shift is given by [5]

\[
\text{Phase shift} = \frac{60^\circ}{\text{number of converters}}.
\]

For achieving a 12-pulse rectification, the phase shift between the two sets of voltages may be either 0° and 30° or ±15° with respect to the supply voltages. In this work, an autotransformer based on the 0° and 30° phase shift has been studied to reduce the size of the magnetics, as shown in Figure 2.

Figure 3 shows the schematic diagram of a 12-pulse autotransformer-based AC–DC converter with a phase shift of +0° and 30°, referred to as Topology ‘B’. Similarly, Figure 4 shows the schematic diagram of a 12-pulse autotransformer-based AC–DC converter with a phase shift of +0° and 30° along with the pulse multiplication circuit, referred to as Topology ‘C’.

3. **DESIGN OF THE PROPOSED 24-PULSE AC–DC CONVERTER**

This section presents the design technique for achieving 12-pulse rectification in the proposed AC–DC converter.

3.1 **Design of an Autotransformer for the 24-Pulse Converter**

To achieve the 12-pulse rectification, the necessary requirement is the generation of two sets of line voltages of equal magnitude that are 30° out of phase with respect to each other. The number of turns required for the 0° and 30° phase shift is calculated as follows: Consider phase ‘a’ voltages in Figure 2 as

\[
V_a' = V_a + K_1 V_{ca} - K_2 V_{bc} \tag{1}
\]

\[
V_b' = V_b + K_1 V_{ab} - K_2 V_{ca} \tag{2}
\]

Assume the following set of voltages:

\[
V_a = V\angle0^\circ, V_b = V\angle120^\circ, V_c = V\angle240^\circ, V_{ab} = 1.732V\angle30^\circ, V_{bc} = 1.732V\angle90^\circ, V_{ca} = 1.732V\angle-30^\circ \tag{3}
\]

Similarly,
A phase-shifted voltage (e.g., $V_a'$) is obtained by tapping a portion (0.0843) of line voltage $V_{bc}$ and connecting one end of approximately 0.229 of the line voltage (e.g., $V_{ca}$) to this tap. The kVA rating of the transformer is calculated as

$$kVA = 0.5 \sum V_{\text{winding}}I_{\text{winding}} \quad (6)$$

where $V_{\text{winding}}$ is the voltage across one winding and $I_{\text{winding}}$ is the current flowing at full load through the same winding. The kVA rating of the interphase transformer and the zero sequence blocking transformer (ZSBT) is also calculated using the above relationship.

4. **DC RIPPLE REINJECTION IN 12-PULSE AC–DC CONVERTERS**

Figure 4 shows a reduced rating autotransformer-based 24-pulse AC–DC converter fed VCIMD. This configuration needs one ZSBT to ensure an independent operation of the two diode rectifier bridges. It exhibits a high impedance to zero sequence currents, resulting in a 120° conduction for each diode and also results in equal current sharing in the output. An interphase reactor tapped suitably to achieve pulse doubling [15] has been connected at the output of the ZSBT. The rectifier output voltages $v_{d1}$ and $v_{d2}$ shown in Figure 4, are identical except for a phase shift of 30° (required for achieving 12-pulse operation), and these voltages contain ripples of six times the source frequency. The AC–DC converter output voltage $v_{dc}$ is given by

Figure 2: Proposed autotransformer winding connection diagram.

$$V_a' = V \angle +30°, V_b' = V \angle -90°, V_c' = V \angle 150° \quad (4)$$

where, $V$ is the rms value of the phase voltage.

Using the above equations, $K_1$ and $K_2$ can be calculated. These equations result in $K_1 = 0.0843$ and $K_2 = 0.229$ for the desired phase shift in the autotransformer.

The phase-shifted voltages for phase 'a' are

$$V_a' = V_a + 0.0843 V_{bc} + 0.229 V_{ca} \quad (5)$$

Figure 3: Proposed autotransformer based 12-pulse converter (with phase shift of 00 and 300) fed VCIMD. (Topology B).
\[
v_{dc} = \frac{(v_{d1} + v_{d2})}{2} \quad (6)
\]

Similarly, the voltage across the interphase reactor is given as

\[
v_m = v_{d1} - v_{d2} \quad (7)
\]

\(v_m\) is an AC voltage ripple of six times the source frequency, as shown in Figure 5.

### 4.1 Design of the Interphase Reactor

Pulse multiplication has been obtained [13-14] for controlled converters with a tapped interphase reactor and two additional diodes. The details of pulse multiplication arrangement for diode bridge rectifiers are presented in Figure 6. The voltage appearing across the interphase reactor \(v_m\) is an AC voltage ripple of six times the source frequency. Thus, depending on the polarity of the impressed voltage across the interphase reactor, diodes D1 or D2 conduct. Figure 7 shows the waveforms of the diode currents showing the changeover of currents through the diodes, which results in achieving the 24-pulse characteristics. The turns ratio of the interphase reactor is given by [16]

\[
N_1/N_o = 0.2457 \quad (8)
\]

### 4.2 Design of the ZSBT

The ZSBT helps in achieving an independent operation of the two rectifier bridges, thus eliminating the unwanted conducting sequence of the rectifier diodes. The ZSBT offers a very high impedance for zero sequence current components. Figure 5 shows the voltage waveform across the ZSBT. It contains only triplen frequency components resulting in a smaller size, weight and volume of the transformer.

### 5. VCIMD

Figure 1 shows the schematic diagram of an indirect VCIMD. In the rotor flux-oriented reference frame, the reference vector \(i_{sx}\) (flux component of the stator current) is obtained as

\[
i_{sx} = i_{mr} + \tau_s \frac{\Delta i_{mr}}{\Delta T} \quad (9)
\]

where \(i_{mr}\) is the magnetizing current. The closed loop proportional-integral (PI) speed controller compares the reference speed \(\omega_{ref}\) with motor speed \(\omega_r\) and generates the reference torque \(T\) (after limiting it to a suitable value) as

\[
T_{(n)} = T_{(n-1)} + K_p (\omega_{e(n)} - \omega_{e(n-1)}) + K_I \omega_{e(n)} \quad (10)
\]

where, \(T_{(n)}\) and \(T_{(n-1)}\) are the outputs of the PI controller (after limiting it to a suitable value) and \(\omega_{e(n)}\) and \(\omega_{e(n-1)}\) refer to the speed error at the \(n^{th}\) and \((n-1)^{th}\) instants. \(K_p\) and \(K_I\) are the proportional and integral gain constants. The torque component of the stator current reference vector \(i_{sy}\) is obtained from the output of the PI controller as

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**Figure 4: The proposed 24-pulse ac-dc converter fed VCIMD (Topology C).**

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**Figure 6: 6-Pulse Diode Bridge Rectifier**

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**Figure 7: 6-Pulse Diode Bridge Rectifier**

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**Figure 8: 3 Phase, 415V, 50 Hz**

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**Figure 9: Autotransformer**

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**Figure 10: ZSBT**

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**Figure 11: ZSBT**

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**Figure 12: IGBT Based Inverter**

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**Figure 13: 3 phase, VC IMD**

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**Figure 14: The proposed 24-pulse ac-dc converter fed VCIMD (Topology C).**
Figure 5: Voltage waveforms \( V_m \) (across IPT) and \( V_{ZSBT} \) (across ZSBT) at full load.

\[
\Psi(n) = \Psi(n-1) + (\omega_2^* + \omega_1) \Delta T
\]

\[
i_{as}^* = -i_{sy}^* \sin \Psi + i_{sx}^* \cos \Psi
\]

\[
i_{bs}^* = \left[ -\cos \Psi + \sqrt{3} \sin \Psi \right] i_{sx}^* (1/2) + \left[ \sin \Psi + \sqrt{3} \cos \Psi \right] i_{sy}^* (1/2)
\]

\[
i_{cs}^* = -(i_{as}^* + i_{bs}^*)
\]

These three-phase reference currents \((i_{as}^*, i_{bs}^*, i_{cs}^*)\) are compared with the sensed motor currents \((i_{as}, i_{bs}, i_{cs})\).

Figure 6: Tapped interphase reactor along with diodes.

Figure 7: Diodes \( D_1 \) and \( D_2 \) current waveforms.

\[
i_{sy}^* = T^*/(k i_{sx}^*)
\]

where \( k = (3/2)(P/2)(M/(1 + \sigma_2)) \)

P, M and \( \sigma_2 \) are the number of poles, mutual inductance and rotor leakage factor, respectively. These current components \((i_{sx}^* \text{ and } i_{sy}^*)\) are converted to a stationary reference frame using a rotor flux angle calculated as the sum of the rotor angle and the value of slip angle as

\[
\omega_2^* = \frac{i_{sy}^*}{i_{sx}^*}
\]

\[
\Psi(n) = \Psi(n-1) + (\omega_2^* + \omega_1^*) \Delta T
\]

\( \Psi(n) \) and \( \Psi(n-1) \) are the values of the rotor flux angles at the \( n^{th} \) and \((n-1)^{th}\) instants, respectively, and \( \Delta T \) is the sampling time taken as 100 µs.

The proposed AC–DC converter along with the VCIMD has been designed for retrofit applications where presently a six-pulse diode bridge rectifier is being used. The input current of a six-pulse diode bridge rectifier fed VCIMD is shown in Figures 9–10. Figure 9 shows the supply current waveform along with its harmonic spectrum at full load, showing a THD of the AC mains current as 32.1%, which deteriorates to 66.66% at light load (20%), as shown in Figure 10. Moreover, the PF at full load is 0.936, which deteriorates to 0.812 as the load is reduced to 20%, as shown in Table 1. These results show that there is a need for improving the power quality at the AC mains to replace the existing six-pulse converter.

6. MATLAB-BASED SIMULATION

The proposed AC–DC converter along with the VCIMD is simulated in a MATLAB environment along with Simulink and Power System Blockset toolboxes. Figure 8 shows the MATLAB model of the proposed AC–DC converter based on a pulse multiplication circuit connected on the DC side to improve the power quality. The simulated results have been presented to study the effect of load variation on the drive on various power quality indices and to show the reduction in the rating of magnetics in the proposed configuration.

7. RESULTS AND DISCUSSION

The proposed AC–DC converter along with the VCIMD has been designed for retrofit applications.
Table 1: Comparison of power quality parameters of a VCIMD fed from different ac-dc converters

<table>
<thead>
<tr>
<th>Sr. no.</th>
<th>Topology</th>
<th>THD $V_s$ (%)</th>
<th>$I_s$ (A)</th>
<th>THD of $I_s$ (%)</th>
<th>DF</th>
<th>DPF</th>
<th>PF</th>
<th>DC link voltage (V) Average</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>FL</td>
<td>LL (20%)</td>
<td>FL</td>
<td>LL</td>
<td>FL</td>
<td>LL (20%)</td>
<td>FL</td>
</tr>
<tr>
<td>1</td>
<td>A</td>
<td>6.94</td>
<td>42.6</td>
<td>10.22</td>
<td>31.1</td>
<td>.955</td>
<td>.824</td>
<td>.983</td>
</tr>
<tr>
<td>2</td>
<td>B</td>
<td>4.04</td>
<td>40.7</td>
<td>8.54</td>
<td>9.51</td>
<td>.995</td>
<td>.988</td>
<td>.972</td>
</tr>
<tr>
<td>3</td>
<td>C</td>
<td>3.37</td>
<td>39.4</td>
<td>8.45</td>
<td>4.18</td>
<td>.999</td>
<td>.997</td>
<td>.997</td>
</tr>
</tbody>
</table>


7.1 Performance of a 12-Pulse Rectification-Based AC–DC Converter

To improve the power quality indices, a 12-pulse AC–DC converter fed VCIMD has been modelled and simulated. Figure 11 shows the waveform of the supply current along with its harmonic spectrum at full load. At full load, the THD of the AC mains current is 9.51% and the PF obtained is 0.988. At light load, the THD of the AC mains current is 15.66%, as shown in Figure 12 and the PF is 0.9864. It shows that the power quality parameters are not within the IEEE standard 519 limits [3].

7.2 Performance of the Proposed 24-Pulse Rectification-Based AC–DC Converter

To improve the power quality, pulse doubling has been used in the above configuration, referred to as Topology ‘C’. Figure 13 shows the dynamic performance of the proposed AC–DC converter (Topology ‘C’) at start and at load perturbation on VCIMD. It consists of supply voltage $v_s$, supply current $i_s$, rotor speed $\omega_r$ (in electrical rad/s), three-phase motor currents $i_{abc}$, motor developed torque $T_e$ (in N-m) and DC link voltage $v_{dc}$ (V).
The supply current waveform at full load along with its harmonic spectrum is shown in Figure 14 (Topology ‘C’), which shows that the THD of the AC mains current is 4.18\% and the PF obtained is 0.996. At light load condition, the THD of the AC mains current is 6.94\%, as shown in Figure 15 and the PF is 0.996. Table 2 shows the effect of load variation on the VCIMD to study various power quality indices. It shows that the proposed AC–DC converter is able to perform satisfactorily under load variation on VCIMD with almost unity PF in the wide operating range of the drive and the THD of the supply current is always less than 8\%. This is within the IEEE standard 519 [3] limits for short circuit ratio (SCR) >20.

The variation of the THD of the AC mains current and PF with load on VCIMD fed from a six-pulse, 12-pulse and the proposed 24-pulse AC–DC converter is shown in Figures 16 and 17, respectively, showing a remarkable improvement in these power quality indices for the 24-pulse AC–DC converter.

The proposed 24-pulse converter needs an autotransformer of 8.39 kVA, an interphase reactor of 0.432 kVA and a ZSBT of 2.08 kVA, totalling to a magnetics of
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10.91 kVA, which is only 35.6% of the drive rating. The comparison of magnetics rating in different converters is shown in Table 3. Moreover, normally, the winding loss and core loss in the magnetics are approximately of the order of 3–5% of the magnetics rating. Because the magnetics rating is only 35.6% of the drive rating, therefore these losses are to be only of the order of 1.5–1.8% of the drive rating. Therefore, these losses generally lie in the range of 2–2.5% of the drive rating. It is also worth mentioning that the proposed converter configuration results in reduction in the AC mains current in the range of 7–17%, depending on the load on the drive. Therefore, it can be concluded that the overall energy consumption required for a particular process is expected to reduce in the proposed converter configuration.

Table 3: Comparison of rating of magnetics in different converter fed VCIMD

<table>
<thead>
<tr>
<th>Topology</th>
<th>Transformer rating (kVA)</th>
<th>Interphase reactor rating (kVA)</th>
<th>ZSBT rating (kVA)</th>
<th>Rating of magnetics (% of drive rating)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>B</td>
<td>10.1</td>
<td>2.0</td>
<td>0.0</td>
<td>39.5</td>
</tr>
<tr>
<td>C</td>
<td>8.39</td>
<td>0.432</td>
<td>2.1</td>
<td>35.6</td>
</tr>
</tbody>
</table>

VCIMD: Vector controlled induction motor drive, ZSBT: Zero sequence blocking transformer

8. CONCLUSIONS

Reduced rating autotransformer-based 12- and 24-pulse AC–DC converters have been designed, modelled and compared with a six-pulse AC–DC converter feeding VCIMD. DC ripple reinjection technique for pulse doubling has been used for harmonic reduction in VCIMD. The pulse doubling technique needs only two additional diodes along with a suitably tapped inductor. The proposed AC–DC converter has resulted in a reduction in the rating of the magnetics, leading to the saving in the overall cost of the drive. The proposed AC–DC converter is able to achieve close to unity PF along with a good DC link voltage regulation in the wide operating range of the drive. The proposed AC–DC converter has demonstrated its capability in improving various power quality indices at the AC mains in terms of THD of the supply current, THD of the supply voltage, PF and CF. It can easily replace the existing six-pulse converters without much alteration in the existing system layout and equipments.

APPENDIX

Motor and controller specifications:
Three-phase squirrel cage induction motor:
30 hp (22 kW), three-phase, four-pole, Y-connected, 415 V, 50 Hz, 
$R_s = 0.2511$ ohms, $R_r = 0.2489$ ohms, $X_{ls} = 0.4389$ ohms,
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\[ X_s = 0.4389 \text{ ohms}, \ X_p = 13.08 \text{ ohms}, \ J = 0.305 \text{ kg-m}^2. \]

Controller parameters:

- PI controller: \( K_p = 15.0, \ K_i = 0.038. \)

DC link parameters:

- \( L_d = 1.0 \text{ mH}, \ C_d = 3200 \mu \text{F}. \)

Magnetics ratings:

- 24-pulse-based converter:
- Autotransformer rating 8.39 kVA, interphase transformer 0.432 kVA, ZSBT 2.08 kVA.

REFERENCES


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