A 12-Sector Space Vector Switching Scheme for Performance Improvement of Matrix Converter Based DTC of IM Drive

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S. Sina Sebtahmadi, Member, IEEE, Hossein Pirasteh, S.Hr. Aghay Kaboli, Ahmad Radan, Member, IEEE, S. Mekhleif, Senior Member, IEEE

Abstract—This article presents a direct torque control (DTC) switching scheme based on direct matrix converter (DMC) using 12-side polygonal space vector for variable speed control of an induction motor (IM). The conventional DTC scheme based matrix converter (MC) is limited by 60° sectors of both flux and voltage vectors which introduce high torque ripple. The proposed method utilizes twelve 30° sectors of both flux and voltage vectors to increase the degrees of freedom for selection of proper vectors and reduce the torque ripple. The proposed switching scheme for MC based DTC of IM drive select the appropriate switching vectors for control of torque with small variations of the stator flux within the hysteresis band. This improves the degrees of freedom in selecting the vector algorithm and the torque ripple as well. Furthermore, during the large torque demand, the probabilities of transgressing reference vector limits, which are enclosed by 12-side polygonal space vector, are reduced. Extensive simulation and experimental results are presented to verify the effectiveness of the 12-sector space vector switching scheme for DTC of IM fed by DMC.

Index Terms—Matrix Converter, direct torque control, induction motor, space vector, switching scheme, torque ripple.

I. INTRODUCTION

The requirement of torque control to adjust the speed in industrial applications resulted in the high demand for a controlling scheme with fast transient, less torque ripple and accurate control of torque for an induction motor (IM) with compact and high reliability adjustable speed drive [1].

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Note: all the motor parameters are referred to stator side.

\( H_p \)  
Flux hysteresis output controller

\( H_r \)  
Torque hysteresis output controller

\( K \)  
Flux vector sector number

\( L \)  
Voltage vector sector number

\( L_m \)  
Mutual inductance

\( L_r \)  
Rotor leakage inductance

\( L_s \)  
Stator leakage inductance

\( P \)  
Number of poles

\( S_k \)  
Switching states

\( T_e \)  
Electromagnetic torque of the induction machines

\( T_e^* \)  
Torque command

\( \Delta T_e \)  
Variation of electromagnetic torque

\( \Delta T_{e,pu} \)  
Torque variation in per unit

\( V_m \)  
Rated voltage

\( V_{m1} \)  
Minimum voltage vector for conventional (60°) scheme

\( V_{m2} \)  
Minimum voltage vector for proposed (30°) scheme

\( V_d & V_{d1} \)  
Radial and tangential components of stator-voltage space vector

\( \vec{V}_s \)  
Stator-voltage space vector

\( V_{sα} & V_{sβ} \)  
\( \alpha \) and \( β \) components of stator voltage, respectively

\( k_1 & k_2 \)  
Flux and torque variation coefficient, respectively

\( k_T \)  
Constant value

\( t_0 \)  
Initial time

\( Δt \)  
Time interval

\( v_{s1} & v_{s2} \)  
Voltage vector first order in (+)ve and (-)ve regions, respectively

\( α & β \)  
Real and imaginary components of the transformation from 3-phase stationary coordinate system to the 2-phase coordinate system

\( γ \)  
Load angle

\( γ_1 \)  
Angle between stator and rotor-flux vectors

\( Δγ \)  
Variation of load angle

\( Δγ \)  
Variation of rotor-flux vector angle

\( θ \)  
Angle of stator-flux vector

\( Δθ \)  
Variation of stator-flux vector angle

\( σ \)  
Leakage factor

\( ψ_m \)  
Maximum flux of stator

\( \psi_s \)  
Stator-flux vector

\( \psi_f \)  
Rotor-flux vector

\( \hat{\psi}_s \)  
Stator-flux command

\( \Delta \psi \)  
Stator-flux vector variation

\( \Delta \psi \)  
Stator-flux variation in per unit

\( \omega_s \)  
Synchronous speed
A matrix converter (MC) enables control of torque and flux via various vector-selection criteria. This gives rise to various switching strategies, each affecting drive torque ripple, current ripple, and switching frequency. The MC has been an appropriate candidate for interfacing of two ac systems with a compact and reliable design [2] as compared to the voltage source inverters (VSI) which conventionally are used to drive IM [3]. In addition, the matrix converter has a long lifetime and can operate in hostile environments due to absence of dc-link electrolytic capacitors [4]. These features of matrix converter could offer advantages in military [5], transportation, renewable energy [6] and aerospace applications, where weight, volume and reliability are important criteria [7].

While, the researches chiefly concern direct matrix converters (DMC) an indirect matrix converter (IMC) can be considered as an option for the DMC [8, 9]. Still, the main circuit of the IMC has drawbacks compared to the DMC, e.g. power losses of the IMC are larger with most loading situations. In addition, its output/input voltage ratio is more non-linear than the ratio of the DMC, which reduces its suitability to the speed sensor-less drive of IM [10]. One of the biggest difficulties in the operation of this converter was the commutation of the bidirectional switches. This problem has been solved by introducing intelligent and soft commutation techniques, giving new momentum to research in this area, while with a suitable modulation method there is no need for special commutation methods of MCs [11]. The most relevant modulation methods developed up to now, for the MC, are the scalar techniques and pulse width modulation methods (PWM). These MC modulations are efficient, but complex to understand, and synthesize compared to the three phase VSI modulations, thereby heavy to implement in digital processors. An alternative solution conventionally in use is to apply space vector modulation (SVM) for MCs [3, 12-14].

The two elegant and powerful controlling methods currently are used to control the speed of IM fed by MC, are field oriented control (FOC) and direct torque control (DTC). The advantages of DTC are no requirements for coordinate transformations and decoupling processes for both voltage and currents, robust and fast torque response, robustness against parameter variation, no requirements for PWM pulse generation and current regulators [15]. However, the main drawback of the DTC scheme is the high current and torque ripple. The disadvantages of DTC scheme also include variable switching frequency, and difficult-to-control torque and flux at very low speeds [16]. In the conventional DTC the circular locus is divided into 6 sectors and a total of 8 voltage vectors are used. However, the discrete inverter switching vectors cannot always generate exact stator voltage required to obtain the demanded electromagnetic torque and stator flux linkages. This results in production of ripples in the flux as well as torque.

The researchers have reported various voltage-vector-selection strategies for matrix converter based DTC scheme [17-19]. The advantages of the matrix converter were combined with the advantages of the DTC schemes in [17]. The use of matrix converter input voltages with different amplitudes in order to reduce the inherent torque ripple that appears when direct torque control is applied to drive PMSM was investigated in [18]. An improved DTC-SVM method for sensor-less matrix converter drives using an over modulation strategy and a simple nonlinearity compensation was proposed in [19] to overcome the degrading of dynamic torque response as compared to the basic DTC method and improve the phase-current distortion due to the nonlinearity of the matrix converter. However, in all the above mentioned researches, the authors utilized conventional (60°-sector) voltage vector selection algorithm which limits the degrees of freedom to select voltage vectors. Thus, the torque ripple is significant, which may not be acceptable for high-performance drives.

Lately, researchers have proposed the switching strategy by dividing the space vector into twelve 30° sectors [20-27]. The switching loss for three-phase VSI by re-carving the six sectors up into twelve ones were minimized in [20]. The total harmonic distortion (THD) of line-to-line output voltage and peak value of common-mode voltage for an RL load powered through the matrix converter was reduced [21]. In [22, 23], neutral point clamped (NPC) multi-level inverter combined with 12 sector methodology was performed for DTC of IM drive. In [24], a novel DTC of MC-Fed permanent-magnet synchronous motor drives using duty cycle control for torque ripple reduction was proposed. In [25-27], the authors applied 12-sided polygonal space vector based instead of hexagonal based voltage vectors for IM drive by implementing voltage source inverter (VSI). However, in all listed publications, the focus has not been on development of switching strategy for matrix converter based DTC of IM drive. Moreover, the development of switching strategy, switching time table, stator flux variation, torque variation and improvement of degrees of freedom are not discussed profoundly.

In this paper, to take advantage of the DMC base on DTC with SVM and reduce the torque ripple of IM at the same time, a novel switching strategy is developed based on twelve 30° sectors for the circular locus of space vector to increase the degrees of freedom in selecting voltage and flux vectors, hence the torque ripple is reduced. The simulation and experimental results demonstrate that the proposed switching strategy provides additional degrees of freedom to select voltage vectors, consequently the torque ripple reduces significantly. Additionally, the performance of the proposed switching strategy is compared to that of the hexagonal boundary space vector modulation based direct matrix converters for direct torque control of induction motors.

II. MODELING OF IM FOR THE PROPOSED DTC SCHEME

Neglecting stator-resistance voltage drop, an induction machine’s flux equation can be expressed as:

$$\Delta \psi_s = \bar{V}_s \cdot \Delta t$$

(1)

Radial component ($V_{sr}$) of the stator-voltage space vector ($\bar{V}_s$) changes the stator-flux magnitude, and the tangential component ($V_{st}$) changes the stator-flux angle as shown in Fig. 1. They can be expressed as:

$$V_{sr} = V_{sr} \cos \theta + V_{s\theta} \sin \theta$$

(2)

$$V_{st} = -V_{sr} \sin \theta + V_{s\theta} \cos \theta$$

(3)

where, $\theta$ is the angle of stator-flux vector $\bar{\psi}_s$. 
After applying a new voltage vector \( \vec{V_s} \) for \( At \) time, the differential change in stator-flux linkage can be written as:

\[
\Delta \vec{\psi}_s = |\vec{\psi}_{s2} - |\vec{\psi}_{s1}| \approx \vec{V}_{sr} \cdot \Delta t
\]  
(4)

Substituting \( V_{sr} \) from (2) in (4) gives:

\[
\Delta |\vec{\psi}_s| = (V_{sa} \cos \theta_1 + V_{sb} \sin \theta_1) \cdot \Delta t
\]  
(5)

which reveals the influencing characteristics of each voltage vector on magnitude variation of the stator-flux vector.

The developed electromagnetic torque of IM can be expressed by:

\[
T_e = \frac{3}{2} \cdot \frac{P}{2} \cdot \frac{L_m}{\sigma \cdot L_s \cdot L_r} \cdot |\vec{\psi}_r| \cdot |\vec{\psi}_s| \cdot \sin \gamma
\]  
(6)

where, \( \gamma \) and \( \sigma \) are load angle and leakage factor, respectively.

In order to see the torque variation caused by applying voltage space vector \( \vec{V}_s \) during \( At \), equation (6) is differentiated, assuming constant magnitude for rotor-flux vector during \( At \) owing to rotor’s large time constant \[27\]. Thus, the following equation is obtained:

\[
\Delta T_e = k_r \cdot |\vec{\psi}_r| \cdot \left( \frac{d|\vec{\psi}_s|}{dt} \cdot \sin \gamma \right) \Delta t
\]  
(7)

where, \( t_0 \) is the initial time, which is the time just before applying voltage vector. \( k_r \) is a constant defined as:

\[
k_r = \frac{3}{2} \cdot \frac{P}{2} \cdot \frac{L_m}{\sigma \cdot L_s \cdot L_r}
\]  
(8)

Rearranging (7) gives:

\[
\Delta T_e = k_r \cdot |\vec{\psi}_r| \cdot \left( \frac{d|\vec{\psi}_s|}{dt} \cdot \sin \gamma_1 + \frac{dy}{dt} \cdot \cos \gamma_1 \cdot |\vec{\psi}_{s1}| \right) \cdot \Delta t
\]  
(9)

where, subscript ‘1’ indicates the magnitude of specified variables at exactly \( t_0 \).

Equation (5) leads to:

\[
\frac{d|\vec{\psi}_s|}{dt} = V_{sa} \cos \theta_1 + V_{sb} \sin \theta_1
\]  
(10)

where, \( \theta_1 \) is the angle of stator-flux vector \( \vec{\psi}_s \) just before applying voltage vector \( \vec{V}_s \).

During \( At \), variation of load angle \( \Delta \gamma \) is given by:

\[
\Delta \gamma = \Delta \theta - \Delta \zeta
\]  
(11)

where \( \Delta \theta \) and \( \Delta \zeta \) are variation of stator and rotor flux angle respectively, due to the application of the new voltage vector, \( \vec{V}_s \).

Again,

\[
\Delta |\vec{\psi}_s| = \Delta \theta \cdot |\vec{\psi}_{s1}| \approx V_{st} \cdot \Delta t
\]  
(12)

Substituting \( V_{sr} \) from (3) in (12) yields:

\[
\Delta \theta = \frac{-V_{sa} \sin \theta_1 + V_{sb} \cos \theta_1}{|\vec{\psi}_{s1}|} \cdot \Delta t
\]  
(13)

Hence:

\[
\frac{d\theta}{dt} \bigg|_{t_0} = \frac{-V_{sa} \sin \theta_1 + V_{sb} \cos \theta_1}{|\vec{\psi}_{s1}|}
\]  
(14)

Considering rotor flux rotating with synchronous speed \( \omega_s \) while magnitude remains nearly constant during \( At \), \( \Delta \zeta \) can be written as:

\[
\Delta \zeta = \omega_s \cdot \Delta t \implies \frac{d\zeta}{dt} \bigg|_{t_0} = \omega_s
\]  
(15)

(11), (14), and (15) can be written as:

\[
\frac{dy}{dt} \bigg|_{t_0} = \frac{d\theta}{dt} \bigg|_{t_0} - \frac{d\zeta}{dt} \bigg|_{t_0} = \frac{-V_{sa} \sin \theta_1 + V_{sb} \cos \theta_1}{|\vec{\psi}_{s1}|} - \omega_s
\]  
(16)

By substituting (10) and (16) in (9), expression for the torque variation becomes:

\[
\Delta T_e = k_r \cdot |\vec{\psi}_r| \cdot (x - y) \cdot \Delta t
\]  
(17)

where, \( x \) and \( y \) are:

\[
x = (V_{sa} \cos \theta_1 + V_{sb} \sin \theta_1) \cdot \sin \gamma_1
\]  
(18)

\[
y = (V_{sa} \sin \theta_1 - V_{sb} \cos \theta_1 + \omega_s \cdot |\vec{\psi}_{s1}|) \cdot \cos \gamma_1
\]  

For normalization of (5) and (17), rating values of the machine can be selected as base values:
\[ V_m = \omega \cdot \psi_m \Rightarrow \psi_{\text{base}} = \frac{V_{\text{base}}}{\omega_{\text{base}}} = \frac{V_m}{\omega} \]  

(19)

and,

\[ T_{r,\text{base}} = \frac{3}{2} \cdot \frac{P}{2} \cdot \frac{L_m}{\sigma \cdot L_1 \cdot L_2} \cdot \left| \vec{\psi}_{r,\text{base}} \right| \left| \vec{\psi}_{s,\text{base}} \right| \sin \gamma_{\text{base}} \]  

(20)

where, the subscript ‘base’ indicates the base value.

\[ \Delta \left| \vec{\psi}_s \right|_{pu} = \frac{\Delta \left| \vec{\psi}_s \right|}{\psi_{\text{base}}} = \left( \frac{V_{sa} \cos \theta_1 + V_{sb} \sin \theta_1}{V_{\text{base}}/\omega_{\text{base}}} \right) \Delta t \]  

(21)

Per-unit equation for flux variation results:

\[ \Delta \left| \vec{\psi}_s \right|_{pu} = \left( V_{sa,pu} \cos \theta_1 + V_{sb,pu} \sin \theta_1 \right) \cdot k_i \]  

(22)

where, \( k_i = \omega_{\text{base}} \cdot \Delta t \).

Torque variation can be expressed in per-unit from (6) and (17) as follows:

\[ \Delta T_{e,pu} = \frac{\Delta T_e}{T_{e,\text{base}}} = \frac{k_T}{k_T} \cdot \left| \vec{\psi}_r \right| \cdot \left( x - y \right) \cdot \Delta t \]  

(23)

\[ \Delta T_{e,pu} = \left| \vec{\psi}_{r,pu} \right| \cdot \left( x_{pu} - y_{pu} \right) \cdot \Delta t \]  

where,

\[ x_{pu} = \left( V_{sa,pu} \cos \theta_1 + V_{sb,pu} \sin \theta_1 \right) \cdot \frac{\sin \gamma_1}{\sin \gamma_{\text{base}}} \cdot \omega_{\text{base}} \]  

(24)

\[ y_{pu} = \left( V_{sa,pu} \sin \theta_1 - V_{sb,pu} \cos \theta_1 \right) \cdot \frac{\sin \gamma_1}{\sin \gamma_{\text{base}}} \cdot \omega_{\text{base}} \cdot \omega_{\text{base}} - \omega_{\text{base}} \cdot \left| \vec{\psi}_{s1} \right|_{pu} \]  

Equation (23) for torque variation per-unit can be rewritten as:

\[ \Delta T_{e,pu} = \left| \vec{\psi}_{r,pu} \right| \cdot \left( \Delta \left| \vec{\psi}_s \right|_{pu} \left( \sin \gamma_1 \right)_{pu} - \left( V_{sa,pu} \sin \theta_1 - V_{sb,pu} \cos \theta_1 \right) + \left( 2/3 \right) \cdot \omega_{\text{pu}} \cdot \left| \vec{\psi}_{s1} \right|_{pu} \cdot k_2 - \left( \sin \gamma_1 \right)_{pu}^2 \cdot k_i \right) \]  

(25)

where, \( k_2 = \frac{1}{\left( \sin \gamma_{\text{base}} \right)^2} \).

Expression (25) is applicable to any size IM drive, but because of its dependency on \( \gamma_{\text{base}} \), influencing characteristics of voltage vectors can differ in low and high power applications.

III. FUNDAMENTALS OF MATRIX CONVERTER BASED DTC SCHEME

The direct matrix converter as shown in Fig. 2(a) is of the highest practical interest as it connects a three-phase voltage source with a three-phase load (typically a motor). There are 27 possible switching configurations, but only 21 of them are useful in DTC algorithm, which are given in Table 1. Fig. 2(b) shows the first 18 active voltage vectors having fixed directions. As shown in Table 1, the magnitudes of voltage vectors depend on the input voltages. The fourth and fifth columns of Table 1 show real (\( \alpha \)) and imaginary (\( \beta \)) components of the matrix converter’s output voltage vectors in stationary reference frame. The last three switching configurations correspond to zero-output voltage vectors.

Based on the earlier torque and flux equations, the block diagram of the proposed matrix converter based DTC scheme for IM drive is shown in Fig. 3.

IV. EFFECT OF VOLTAGE VECTOR ON FLUX AND TORQUE

A. Effect of voltage-vector on flux

The IM parameters used for simulation are shown in Table 2. For flux variation in different voltage vectors, \( \alpha \) and \( \beta \) components of each vector were substituted based on per-unit, and equations obtained. e.g., voltage vector of first order in (+)ve region is obtained from:

\[ \psi_+ = \frac{2}{3} V_{AB} \leq 0 = \frac{2}{3} \left( V_A - V_B \right) \left( \cos(0) + j \sin(0) \right) \]  

(26)

Equation (26) converted into per-unit based on machine’s rated voltage (\( V_{\text{base}} \)), \( \alpha \) and \( \beta \) components of \( \psi_+ \) yields:

\[
\left\{ \begin{array}{l}
V_{\alpha,pu} = \frac{V_{\alpha} \cdot \alpha}{V_m} = \frac{1}{\sqrt{3}} \cos(\alpha t + \pi/6) \\
V_{\beta,pu} = 0
\end{array} \right.
\]  

(27)
From (22) and (27) the flux variation can be obtained as:

$$\Delta \psi_s|_{pu,v_1} = \frac{2}{\sqrt{3}} (\cos(\omega t + \pi/6) \times \cos \theta) \times (120\pi) \times 10^{-6}$$ \hspace{1cm} (28)

In (28), rated frequency of motor is considered as 50Hz, and sampling time-interval is considered 1µs. The comparison of stator flux variation between the conventional (60° sector) and the proposed (30° sector) switching schemes is shown in Figs. 4 and 5, respectively. It is seen from Figs. 4(a) and 5(a) that the peak-to-peak flux variation in both conventional and proposed switching scheme is the same. However, there is 180° phase difference between Figs. 4(a) and 5(a) by applying voltage vectors $v_{+i}$ and $v_{-i}$, respectively. In Fig. 4(b) the colour area indicates the (+)ve ($\Delta \psi_s|_{pu,v_i} > 0$) variation and white area indicates the (-)ve b ($\Delta \psi_s|_{pu,v_i} < 0$) variation of stator flux. Note that in some sectors, applying the voltage vector when the space vector is divided into six 60° sectors is impossible because the flux increases and decreases at the same time in the sectors. For example, (when $\omega t < 120^\circ$ and $60^\circ < \theta < 120^\circ$), flux in one half of this sector is positive which means that $v_{+i}$ increases the stator flux while in the other half it is negative which means that $v_{+i}$ decreases the stator flux. So, the use of $v_{+i}$ in this sector is not allowed. Hence, for the conventional switching scheme the degree of freedom to choose the stator-voltage vector is limited. Fig. 5(b) shows flux vector variations of voltage vector $v_{+i}$ for the proposed 30° sector based switching scheme. It is clearly seen from the figures that there is no sector when the flux is increasing and decreasing simultaneously. Thus, the stator-voltage vector can be applied for each sector for the proposed 30° sector scheme. Therefore the degrees of freedom to choose the stator-voltage vector with the proposed 30° sector switching scheme is increased significantly as compared the conventional 60° sector scheme. For stator-voltage vector $v_{+i}$, the stator flux variation is exactly opposite to that of voltage vector $v_{+i}$. This statement is true for all stator-voltage vectors (e.g., $v_{+s}$ and $v_{-5}$, etc.)

<table>
<thead>
<tr>
<th>switching combinations</th>
<th>on switches</th>
<th>voltage-vector values</th>
<th>$a$ component value</th>
<th>$b$ component value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$+1$</td>
<td>$S_{ha}$ $S_{ib}$ $S_{ic}$</td>
<td>$2/3v_{2p}$ $0$</td>
<td>$2/\sqrt{3}V_m\cos(\alpha t + \pi/6)$</td>
<td>$0$</td>
</tr>
<tr>
<td>$-1$</td>
<td>$S_{ha}$ $S_{ib}$ $S_{Ac}$</td>
<td>$-2/3v_{2p}$ $0$</td>
<td>$-2/\sqrt{3}V_m\cos(\alpha t + \pi/6)$</td>
<td>$0$</td>
</tr>
<tr>
<td>$+2$</td>
<td>$S_{ha}$ $S_{ib}$ $S_{Cc}$</td>
<td>$2/3v_{2c}$ $0$</td>
<td>$2/\sqrt{3}V_m\cos(\alpha t - \pi/2)$</td>
<td>$0$</td>
</tr>
<tr>
<td>$-2$</td>
<td>$S_{Ca}$ $S_{ib}$ $S_{bc}$</td>
<td>$-2/3v_{2c}$ $0$</td>
<td>$-2/\sqrt{3}V_m\cos(\alpha t - \pi/2)$</td>
<td>$0$</td>
</tr>
<tr>
<td>$+3$</td>
<td>$S_{Ca}$ $S_{ib}$ $S_{Ac}$</td>
<td>$2/3v_{2s}$ $0$</td>
<td>$2/\sqrt{3}V_m\cos(\alpha t + 5\pi/6)$</td>
<td>$0$</td>
</tr>
<tr>
<td>$-3$</td>
<td>$S_{Ca}$ $S_{ib}$ $S_{Cc}$</td>
<td>$-2/3v_{2s}$ $0$</td>
<td>$-2/\sqrt{3}V_m\cos(\alpha t + 5\pi/6)$</td>
<td>$0$</td>
</tr>
<tr>
<td>$+4$</td>
<td>$S_{ha}$ $S_{ib}$ $S_{bc}$</td>
<td>$2/3v_{2s}$ $\pi/3$</td>
<td>$-1/\sqrt{3}V_m\cos(\alpha t + \pi/6)$</td>
<td>$V_m\cos(\alpha t + \pi/6)$</td>
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<tr>
<td>$-4$</td>
<td>$S_{ha}$ $S_{ib}$ $S_{Ac}$</td>
<td>$-2/3v_{2s}$ $\pi/3$</td>
<td>$1/\sqrt{3}V_m\cos(\alpha t + \pi/6)$</td>
<td>$-V_m\cos(\alpha t + \pi/6)$</td>
</tr>
<tr>
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<td>$2/3v_{2c}$ $\pi/3$</td>
<td>$-1/\sqrt{3}V_m\cos(\alpha t - \pi/2)$</td>
<td>$V_m\cos(\alpha t - \pi/2)$</td>
</tr>
<tr>
<td>$-5$</td>
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<td>$-2/3v_{2c}$ $\pi/3$</td>
<td>$1/\sqrt{3}V_m\cos(\alpha t - \pi/2)$</td>
<td>$-V_m\cos(\alpha t - \pi/2)$</td>
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<td>$2/3v_{2s}$ $\frac{2\pi}{3}$</td>
<td>$-1/\sqrt{3}V_m\cos(\alpha t + 5\pi/6)$</td>
<td>$V_m\cos(\alpha t + 5\pi/6)$</td>
</tr>
<tr>
<td>$-6$</td>
<td>$S_{Ca}$ $S_{ib}$ $S_{Cc}$</td>
<td>$-2/3v_{2s}$ $\frac{2\pi}{3}$</td>
<td>$1/\sqrt{3}V_m\cos(\alpha t + 5\pi/6)$</td>
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<td>$V_m\cos(\alpha t + \pi/6)$</td>
</tr>
<tr>
<td>$-7$</td>
<td>$S_{Ca}$ $S_{ib}$ $S_{bc}$</td>
<td>$-2/3v_{2p}$ $\frac{4\pi}{3}$</td>
<td>$1/\sqrt{3}V_m\cos(\alpha t + \pi/6)$</td>
<td>$-V_m\cos(\alpha t + \pi/6)$</td>
</tr>
<tr>
<td>$+8$</td>
<td>$S_{ca}$ $S_{ib}$ $S_{bc}$</td>
<td>$2/3v_{2s}$ $\frac{4\pi}{3}$</td>
<td>$-1/\sqrt{3}V_m\cos(\alpha t - \pi/2)$</td>
<td>$-V_m\cos(\alpha t - \pi/2)$</td>
</tr>
<tr>
<td>$-8$</td>
<td>$S_{ha}$ $S_{ib}$ $S_{Cc}$</td>
<td>$-2/3v_{2s}$ $\frac{4\pi}{3}$</td>
<td>$1/\sqrt{3}V_m\cos(\alpha t - \pi/2)$</td>
<td>$V_m\cos(\alpha t - \pi/2)$</td>
</tr>
<tr>
<td>$+9$</td>
<td>$S_{ha}$ $S_{ib}$ $S_{Ac}$</td>
<td>$2/3v_{2c}$ $\frac{4\pi}{3}$</td>
<td>$-1/\sqrt{3}V_m\cos(\alpha t + 5\pi/6)$</td>
<td>$-V_m\cos(\alpha t + 5\pi/6)$</td>
</tr>
<tr>
<td>$-9$</td>
<td>$S_{Ca}$ $S_{ib}$ $S_{Cc}$</td>
<td>$-2/3v_{2c}$ $\frac{4\pi}{3}$</td>
<td>$1/\sqrt{3}V_m\cos(\alpha t + 5\pi/6)$</td>
<td>$V_m\cos(\alpha t + 5\pi/6)$</td>
</tr>
<tr>
<td>$0_n$</td>
<td>$S_{ha}$ $S_{ib}$ $S_{Ac}$</td>
<td>$0$ $\ldots$</td>
<td>$0$</td>
<td>$0$</td>
</tr>
<tr>
<td>$0_s$</td>
<td>$S_{ha}$ $S_{ib}$ $S_{bc}$</td>
<td>$0$ $\ldots$</td>
<td>$0$</td>
<td>$0$</td>
</tr>
<tr>
<td>$0_c$</td>
<td>$S_{ca}$ $S_{ib}$ $S_{Cc}$</td>
<td>$0$ $\ldots$</td>
<td>$0$</td>
<td>$0$</td>
</tr>
</tbody>
</table>
Fig. 3 Block diagram of the proposed DTC based switching strategy by matrix converter.

Torque variation by applying vectors \( v_{+1} \) and \( v_{+2} \) are shown in Figs. 7 (a) and 7 (c), respectively, for the proposed switching scheme. It is clearly seen from these figures that the torque variation not deflected when the voltage vector switches from \( v_{+1} \) to \( v_{+2} \). The corresponding torque variations on \( \theta_{r} \)-\( o l \) plane are shown in Figs. 7(b) and 7(d), respectively. In Figs. 7(b) and 7(d) two colour pericyles indicate the (+)ve torque variation and the white area indicates the (-)ve torque variation. The area of colour regions is the same in both Figs. 7 (b) and 7 (d) except their positions are changed. In other words, with the application of various voltage vectors, there is no additional torque variation. It means that with applying a different voltage vector, the torque ripple remains constant.

Fig. 6 Instantaneous basic voltage vectors for both conventional (60° sector) and proposed (30° sector) switching scheme, and the zoom-in view of the first sector.

### Table 2 Specifications and parameters of the 3-phase test induction-motor, referred to the stator side.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power</td>
<td>1100 VA</td>
</tr>
<tr>
<td>Rated torque</td>
<td>6.3 Nm</td>
</tr>
<tr>
<td>Rated voltage</td>
<td>380 V</td>
</tr>
<tr>
<td>Number of poles</td>
<td>2P</td>
</tr>
<tr>
<td>Rated frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Stator resistance</td>
<td>1.405 Ω</td>
</tr>
<tr>
<td>Stator reactance</td>
<td>1.834 Ω</td>
</tr>
<tr>
<td>Mutual reactance</td>
<td>54.09 Ω</td>
</tr>
<tr>
<td>Rotor resistance</td>
<td>1.395 Ω</td>
</tr>
<tr>
<td>Rotor reactance</td>
<td>1.834 Ω</td>
</tr>
<tr>
<td>Friction factor</td>
<td>0.0131 kg/m²</td>
</tr>
</tbody>
</table>
It is found that the developed torque of the motor is stable at different load and speed conditions. Additionally, it is clearly seen from these figures that the torque for \(v_{e1}\) and \(v_{e2}\) have same space-dependent expression, and for time-dependent expression. The torque variation by applying vectors \(v_{e2}\) lags the torque variation as a result of applying \(v_{e1}\) by \(\pi/3\).

V. VECTORS SUITABLE FOR CONTROL

To examine the effect of 18 active voltage vectors produced by the matrix converter on the flux and torque, a procedure similar to that applied for \(v_{e1}\) is applied. Voltage vectors with stable characteristic in the 30\(^\circ\) sectors are then chosen as suitable for control of motor torque and flux. Based on the earlier result analysis, the proposed switching technique is extracted, and shown in Table 3. \(H_\sigma\) and \(H_T\) are the outputs of flux and torque hysteresis controllers, respectively, as shown below:

\[
\begin{align*}
T_e &< T_e^*, H_T = +1 \\
T_e &> T_e^*, H_T = -1 \\
\varphi &< \varphi^*, H_\varphi = +1 \\
\varphi &> \varphi^*, H_\varphi = -1
\end{align*}
\]

Table 3 is produced for the stator flux in the first and the second sectors, but owing to symmetry conditions in space vector the results are valid also for the remaining sectors. It is to be noted that \(H_\sigma=+1\) indicate the flux needs to increase and \(H_\sigma=-1\) indicate the flux needs to decrease. Similarly \(H_T=+1\) indicate that the torque needs to increase and \(H_T=-1\) indicate that the torque needs to decrease.

Table 3 lists the results for the first 6 sectors of the input voltage. The results for the remaining sectors contrast, those of the first 6 sectors, e.g., in 7th sector \((L=7)\) the voltage vector is \(-9\) while, the voltage vector is \(+9\) in the first voltage sector \((L=1)\) and this logic is true for all remaining sectors \((L=7, 8, 9, ..., 12)\).

Table 4 shows the switching scheme codes corresponding to each voltage vector.

VI. SELECTION OF OPTIMUM VECTORS TO MINIMIZE THE SWITCHING LOSSES

As can be seen from Table 3, there are multiple vectors for switching selection in some sectors which increases the degrees of freedom in selection of space-vector voltage for DTC of IM by matrix converter.

The enhanced degrees of freedom improve the IM drive performance. In addition, the proposed 12-sector switching method is independent of the load and speed variation, in the expense of introducing of no use sectors which are included in Table 3 when \(k\) is equal to an even number, \(H_\sigma=1\) and \(H_T=+1\). These redundancies of vectors for switching selection provide an additional option, to optimize the switching losses by proposed 12-sector method compares to the conventional switching. While the switching is fixed in conventional method and there is no redundancy of vectors for switching selection, the proposed method can provide the optimum switching losses due to exist of multiple vectors for switching selection. In order to obtain minimum switching frequency which provides optimum switching loss, the space-vector voltage with lowest flux variation is selected from Table 3 as the best switching vector. This selection increases the switching period by extending time to reach the hysteresis band in both flux and torque. Accordingly, the switching frequency is optimized hence the switching losses are diminished.
The lowest average values in each sector of the contour-map are chosen for switching by comparing the variation rates of the flux correspond to each input voltage in different flux sectors.

VII. SIMULATION RESULT OF THE PROPOSED DTC BASED IM DRIVE

The proposed DTC based IM drive is simulated extensively at different operating conditions using Matlab/Simulink software. The sample results are presented below.

Figs. 8 compares the starting responses of the DTC based IM drive at rated speed under full load and 20% of load conditions for the proposed (30°-sector) and conventional (60°-sector) switching scheme, respectively. Fig. 8(a) depicts how actual speed follows the reference speed. It is seen from Figs. 8(b) and 8(c) that the torque ripple is less for the proposed switching scheme as compared to the conventional switching under full load terms and also in Figs. 8(d) and 8(e) the comparison has been applied between suggested and conventional methods for 20% of loading conditions. Thus, the proposed switching scheme introduces lower vibration to the motor. As the input current of the matrix converter is an important variable that should be monitored, the waveform of input current and its harmonic spectrum in the steady-state operation of the motor for both proposed and conventional methods at rated load are shown in Figs. 8(f) and 8(g), respectively and then for 20% of rated load illustrated in Fig. 8(h) and 8(i). The components of the input filter are inductance \(L_i=4mH\) and capacitor \(C_i=40\mu F\). It can be seen that the distortion of input current for the conventional method is more severe than that of the proposed method. The THDs of the conventional and proposed methods under full load condition are 8.56% and 5.15%, respectively as well as one fifth of rated load are similarly 24.19% and 40.27%.

Fig. 9 shows the responses of the proposed DTC based IM drive at step changes of load conditions. It is seen from Fig. 9(a) that the motor can follow the command speed in spite of changes of the load from no-load to full-load conditions. Thus, the proposed drive is insensitive to load variations. It is also seen from Fig. 9(b) that the torque ripple is very low at different load conditions. It is found that the flux remains constant while the load changes and the stator current changes with load, accordingly. Figs. 9(c) and (d) show the produced flux and stator currents, respectively.

It is found that the motor can follow the command speed even if it changes to the reverse direction. Therefore, the performance of the proposed switching based matrix converter for IM drive is found robust at different operating conditions. Fig. 10 shows the speed, produced electromagnetic torque, flux and stator currents, respectively.
Fig. 8 Responses comparison of the proposed switching method with conventional switching method at rated speed (1473 rpm), rated load (6.3 Nm), and 20% of rated load. (a) speed. (b) torque response of the proposed method under rated load. (c) torque response of the conventional method under rated load. (d) torque response of the proposed method under 20% of rated load. (e) torque response of the conventional method under 20% of rated load. (f) input current and its THD spectrum of the proposed method under rated load. (g) input current and its THD spectrum of the conventional method under rated load. (h) input current and its THD spectrum of the proposed method under 20% of rated load. (i) input current and its THD spectrum of the conventional method under 20% of rated load.

Fig. 9 Responses of the proposed DTC based IM drive for step changes of load condition. (a) speed. (b) electromagnetic torque. (c) stator flux. (d) stator-phase currents.
Fig. 10 Responses of the proposed DTC based IM drive for step changes of command speed. (a) speed. (b) electromagnetic torque. (c) stator flux. (d) stator-phase currents. (e) output voltage and its THD spectrum of the proposed method. (f) output voltage and its THD spectrum of the conventional method.

Table 4 Matrix converter switching status for proposed switching scheme.

<table>
<thead>
<tr>
<th>switching code</th>
<th>vector number</th>
<th>on switches</th>
<th>equivalent vector in odd sectors</th>
<th>equivalent vector in even sectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$v_{s1}$</td>
<td>$S_{Ab}$</td>
<td>$S_{Bb}$</td>
<td>$S_{Cb}$</td>
</tr>
<tr>
<td>2</td>
<td>$v_{s2}$</td>
<td>$S_{Ab}$</td>
<td>$S_{Bc}$</td>
<td>$S_{Cb}$</td>
</tr>
<tr>
<td>3</td>
<td>$v_{s3}$</td>
<td>$S_{Ab}$</td>
<td>$S_{Bc}$</td>
<td>$S_{Cb}$</td>
</tr>
<tr>
<td>4</td>
<td>$v_{s4}$</td>
<td>$S_{Ab}$</td>
<td>$S_{Bc}$</td>
<td>$S_{Cb}$</td>
</tr>
<tr>
<td>5</td>
<td>$v_{s5}$</td>
<td>$S_{Ab}$</td>
<td>$S_{Bc}$</td>
<td>$S_{Cb}$</td>
</tr>
<tr>
<td>6</td>
<td>$v_{s6}$</td>
<td>$S_{Ab}$</td>
<td>$S_{Bc}$</td>
<td>$S_{Cb}$</td>
</tr>
<tr>
<td>7</td>
<td>$v_{s7}$</td>
<td>$S_{Ab}$</td>
<td>$S_{Bc}$</td>
<td>$S_{Cb}$</td>
</tr>
<tr>
<td>8</td>
<td>$v_{s8}$</td>
<td>$S_{Ab}$</td>
<td>$S_{Bc}$</td>
<td>$S_{Cb}$</td>
</tr>
<tr>
<td>9</td>
<td>$v_{s9}$</td>
<td>$S_{Ab}$</td>
<td>$S_{Bc}$</td>
<td>$S_{Cb}$</td>
</tr>
<tr>
<td>10</td>
<td>$v_{s10}$</td>
<td>$S_{Ab}$</td>
<td>$S_{Bc}$</td>
<td>$S_{Cb}$</td>
</tr>
<tr>
<td>11</td>
<td>$v_{s11}$</td>
<td>$S_{Ab}$</td>
<td>$S_{Bc}$</td>
<td>$S_{Cb}$</td>
</tr>
<tr>
<td>12</td>
<td>$v_{s12}$</td>
<td>$S_{Ab}$</td>
<td>$S_{Bc}$</td>
<td>$S_{Cb}$</td>
</tr>
<tr>
<td>13</td>
<td>$v_{s13}$</td>
<td>$S_{Ab}$</td>
<td>$S_{Bc}$</td>
<td>$S_{Cb}$</td>
</tr>
<tr>
<td>14</td>
<td>$v_{s14}$</td>
<td>$S_{Ab}$</td>
<td>$S_{Bc}$</td>
<td>$S_{Cb}$</td>
</tr>
<tr>
<td>15</td>
<td>$v_{s15}$</td>
<td>$S_{Ab}$</td>
<td>$S_{Bc}$</td>
<td>$S_{Cb}$</td>
</tr>
<tr>
<td>16</td>
<td>$v_{s16}$</td>
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<td>$S_{Bc}$</td>
<td>$S_{Cb}$</td>
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<tr>
<td>17</td>
<td>$v_{s17}$</td>
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<td>$S_{Bc}$</td>
<td>$S_{Cb}$</td>
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<tr>
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<td>$v_{s18}$</td>
<td>$S_{Ab}$</td>
<td>$S_{Bc}$</td>
<td>$S_{Cb}$</td>
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<tr>
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<td>$v_{s19}$</td>
<td>$S_{Ab}$</td>
<td>$S_{Bc}$</td>
<td>$S_{Cb}$</td>
</tr>
<tr>
<td>20</td>
<td>$v_{s20}$</td>
<td>$S_{Ab}$</td>
<td>$S_{Bc}$</td>
<td>$S_{Cb}$</td>
</tr>
<tr>
<td>21</td>
<td>$v_{s21}$</td>
<td>$S_{Ab}$</td>
<td>$S_{Bc}$</td>
<td>$S_{Cb}$</td>
</tr>
</tbody>
</table>

It is clear that the motor can reverse rotation direction smoothly without any overshoot/undershoot or steady state error. In addition, the waveform of output voltage and its harmonic spectrum in the steady-state operation of the motor for both proposed and conventional methods are shown in Figs. 10(e) and 10(f), respectively. It can be seen that the harmonics of the proposed method are mainly in the vicinity of the switching frequency (10 kHz) as shown in Fig. 10(e), while the harmonics of the conventional method are mainly distributed within the range of 0.5–6 kHz as shown in Fig. 10(f). The result shows that the output voltage THDs of the conventional and proposed methods are 58.1% and 61.9%, respectively. To evaluate performance of the proposed method precisely and entirely, the comparison of the proposed method and the conventional switching method is summarized and tabulated in Table 5.

Table 5 Comparison of proposed switching method and conventional method

<table>
<thead>
<tr>
<th>parameters of comparison</th>
<th>proposed method</th>
<th>conventional method[3]</th>
</tr>
</thead>
<tbody>
<tr>
<td>THD of MC input current</td>
<td>5.15%</td>
<td>8.56%</td>
</tr>
<tr>
<td>THD of MC output voltage</td>
<td>61.9% harmonics are mainly in the vicinity of the switching frequency (10 kHz)</td>
<td>58.1%, harmonics are mainly distributed within the range of (0.5–6 kHz)</td>
</tr>
<tr>
<td>torque ripple reduction</td>
<td>60% reduction</td>
<td>fixed</td>
</tr>
<tr>
<td>maximum limit of reference voltage within circular locus of space vectors without over modulation</td>
<td>$V_{sm1} \times 1.11$</td>
<td>$V_{sm1}$</td>
</tr>
<tr>
<td>degrees of freedom to select appropriate voltage vectors for DTC</td>
<td>intensified</td>
<td>fixed</td>
</tr>
</tbody>
</table>
VIII. EXPERIMENTAL RESULTS

To verify the feasibility and effectiveness of the proposed DTC scheme based on 12-side polygonal space vector of voltage and flux, a matrix converter connected to 3-phase network through a variable AC power supply to feed a 1kw 3-phase IM was implemented. The experimental setup is shown in Fig. 11 while the motor parameters are same as the parameters for simulation and listed in Table 2. In order to attenuate the harmonics of switching, an LC input filter was designed based on the values extracted from simulation. The matrix converter bidirectional switching is configured using IGBTs as in Fig. 1. The proposed control algorithm is implemented by using TMS320F28335 digital signal processor (DSP).

Fig. 11 photograph of experimental setup

A. Steady-State performance

Fig. 12 presents the steady-state performance of the proposed switching scheme under rated conditions of the motor, speed (1473 rpm) and load (6.3 Nm). The there-phase waveform of the output voltage and stator current are shown in Figs. 12(a) and 12(b), respectively. Fig. 12(c) shows the three-phase input currents of the matrix converter at the steady-state performance under rated conditions of IM. The electromagnetic torque and speed waveforms of induction motor at rated condition are shown in Figs. 12(d) and 12(e), respectively. As it is evident in the zoom-in view, the ripples for both speed and electromagnetic torque are rather acceptable despite of high-frequency ripples.

B. Dynamic performance

Fig. 13 shows the waveforms of the speed, electromagnetic torque and stator current of the IM drove by proposed method with speed reference value stepping up from no-load to full-load, while the reference speed is kept constant at rated speed of 1475 rpm. The experimental results show that with the abrupt change of load, the electromagnetic torque increases rapidly and the speed reaches to the reference value only after a short period of time.

Fig. 12 experimental waveforms of steady-state performance of proposed method at rated speed (1473 rpm) and rated load (6.3 Nm). (a) output voltage. (b) stator current. (c) input current. (d) electromagnetic torque. (e) speed
IX. CONCLUSIONS

A novel space vector modulation based on twelve 30° sectors of both flux and voltage vectors within a circular locus of space vector for speed control of an IM fed by matrix converter based DTC was developed. The performance of the proposal switching strategy was compared to the hexagonal boundary space vector modulation based matrix converter for direct torque control of IM. The method provides additional degrees of freedom to select appropriate voltage vectors which resulted in 60% reduction of torque ripple. The simulation and experimental results verify the applicability of the 12-sector space vector switching scheme for direct torque control of IM fed by matrix converter for different industrial application where, there is high demand for fast transient response of controlling scheme, less torque ripple and accurate control of torque with compact and high reliability adjustable speed drive.

REFERENCES

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