Field-Oriented Control of Five-Phase Induction Motor Fed From Space Vector Modulated Matrix Converter

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ABSTRACT This paper presents the field-oriented control (FOC) of a five-phase induction motor (FPIM) fed from a three-to-five phase direct matrix converter (DMC). The article focuses on the modulation and control of the three-to-five phase DMC, which discusses minimizing the problems associated with switching vector selection, sector identification, switching sequence selection, and dwell-time calculations. The DMC is controlled from the space vector pulse width modulation (SVPWM) technique, eliminating the x-y components of space vectors. Moreover, the matrix converter can perform unity power factor control at the input side. The FPIM is sourced from a DMC, and the FOC technique is applied to control the drive. The dynamic characteristics of the drive are succeeded for different loading conditions. The proposed work is simulated in Simulink/Matlab environment and further verified through practical experimentation. The control signals of the IGBTs are generated through FPGA embedded in dSPACE 1006. The experimental and the simulation results prove the practicability of the FOC to FPIM fed from a DMC.

INDEX TERMS Direct matrix converter, five-phase induction motor, field-oriented control, multiphase, space vector pulse width modulation.

I. INTRODUCTION

Easy availability, simple construction, cost-effectiveness, and ruggedness are the main reasons for the preference for three-phase drive systems. However, with the advance in power electronics, the number of phases of a drive system has also become a design parameter. From the literature, it is obtained that the multiphase offers additional advantages such as higher reliability, improved harmonic performance, precise control, higher torque density, and minimizing the effect of torque pulsations by shifting them further up on the frequency domain. Various works have shown that a multiphase drive system with a stator having a higher phase number enables smooth and independent vector control operation for speed control [1]–[4].

Performance factors such as dc bus utilization, switching losses, harmonic performance, etc., are decided by the modulation method of the converter in the drive system. There are two main categories of pulse width modulation methods available in the literature. For a three-phase motor drive, sine–triangle PWM (SPWM) is the simplest modulation method. However, the switching signal duty cycles are derived from other PWM strategies, such as SVPWM. This method is categorized with higher dc bus utilization by achieving more
induction motor uses PWM and linear controllers and has the voltage vectors without a modulator. FOC applied for DTC is a nonlinear control scheme that directly produces resistance information for their control [16]–[18]. However, classical direct torque control (DTC) system requires only stator general methodologies for induction motor drives. The classical drives, direct torque and field-oriented control are two of the motor to achieve a fast dynamic response. For traditional power factor and the output voltage.

Control technique provides complete control of both the input and auxiliary space vectors for realization. Indirect MC, when operated with a suitable modulation technique, eliminates the need for special commutation. However, this dc-link capacitor limits the system’s reliability as these bulky capacitors have a short lifespan, deprived performance at a higher temperature, and are prone to dangerous failures.

Additionally, the dc-link capacitor also occupies a significant power board space to limit the power density. For addressing these concerns, direct ac-ac converters called matrix converters (MC) are introduced. A detailed discussion of two variants of MC, namely direct and indirect MC, is available in the literature [9], [10]. Matrix converters offer various benefits, including input power factor control, bidirectional power flow, higher power density, etc.

Indirect MC uses a lesser number of active switches and current sensors for realization. Indirect MC, when operated with a suitable modulation technique, eliminates the need for special commutation. However, non-linear modulation response and higher power losses are the problems associated with indirect MC. Several research outcomes have been described on multiphase MC modeling, control, and applications [11]–[15]. In SVPWM, instantaneous representation of output voltages and input currents are considered. SVPWM control technique provides complete control of both the input power factor and the output voltage.

Like conventional drive systems, MC-based FPIM drives also need to employ independent control of flux and torque of the motor to achieve a fast dynamic response. For traditional drives, direct torque and field-oriented control are two general methodologies for induction motor drives. The classical direct torque control (DTC) system requires only stator resistance information for their control [16]–[18]. However, DTC is a nonlinear control scheme that directly produces the voltage vectors without a modulator. FOC applied for induction motor uses PWM and linear controllers and has more popularity than DTC [19]–[22]. Many research work focusing on the FOC of FPIM supplied from a single voltage source-based two-level inverter are present. A detailed discussion of conventional FPIM based drive controlled with DTC and FOC is given in Table 1.

The work done in the area of a multiphase systems powered by a matrix converter is very limited. Recently, a paper focuses on controlling a five-phase induction motor fed from a three-to-five phase matrix converter. The control is based on the direct torque control method, where, controlling the virtual vectors are controlled by selecting the active voltage vectors of the matrix converter [23]. Further, a case study has been presented in a research paper where it is obtained that there is possible to reduce the computational burden and precise control by using the model predictive control method. The virtual vectors control concept has been utilized to perform the model predictive direct torque control for a five-phase induction motor fed from a direct matrix converter [24].

Only a few FOC of three-phase matrix converter-based drive systems have been discussed in the existing literature [25]–[27]. Due to the deficiency of technical advancement, controlling multiphase induction motor fed from matrix converter is a significant issue. Therefore, this paper presents the field-oriented control of a five-phase drive fed from a three-to-five-phase matrix converter. Compared to a conventional three-phase system, in the case of FPIM, the additional xy components adversely impact the electromagnetic flux, thereby distorting the stator current. This research work proposes SVPWM based FOC method to eliminate this xy component by using the volt-sec balance technique to modulate active voltage vectors in a switching cycle [28], [29]. For this implementation, the paper presents a precise modulation of three-to-five phase DMC, which can solve the problems related to switching states, sector identification, switching sequence selection, and dwell-time calculations.

**TABLE 1.** General discussion of FOC versus DTC for conventional five phase induction motor performance.

| Features              | FOC                        | DTC [31]–[34] |
|-----------------------|----------------------------|---------------|
| Current THD [34]      | Low (2.73%)                | High (5.42%)  |
| Tracking error        | Very low                   | High          |
| Torque ripple (4kHz)  | 6%                         | 4.24%         |
| Torque Dynamic        | Fast                       | Very fast     |
| Dynamic performance   | Setting time (<0.5)        | Setting time (<0.32 s) |
| Low speed behaviour   | Good with position or speed sensor | Required speed sensor for braking |
| Controlled variables  | Stator flux, torque current, rotor flux | Rotor flux current, rotor current, vector components, rotor flux |
| Steady state distortion | Low                     | Low (high features current sensors requires) |
| Parameter sensitivity | Rotor resistance, d, q inductances, flux (near zero speed only) | Rotor resistance, d, q inductances, flux (near zero speed only) |
| Rotor position measurement | Required either estimator or sensor | Not required |

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The effectiveness of the modulation strategy-based FOC of FPIM is validated using a laboratory prototype of 2-hp rated FPIM. Experimental results showing the elimination of flux weakening is there, the correct \( \rho \) one has to go to the induction motor’s actual speed and current. The motor currents are sensed and converted to \( \alpha \beta \) and further to \( dq \). The output of the transformed \( dq \) block gives \( I_{ds} \) \( (I_{mr}) \) and \( I_{qs} \) for feedback. The \( I_{mr} \) will be equal to the \( I_{mr\: ref} \) in a steady-state; however, if any transient flux weakening is there, the correct \( I_{mr} \) becomes \( I_{mr\: ref}/(1+sT_{r}) \).

To compute the slip information from \( I_{qs} \) with the help of slip computational block, which gives slip speed in output. To find the synchronous speed, the slip speed is added with motor speed. Which further gives ‘\( \rho \)’ after the integration of speed. This ‘\( \rho \)’ can be needed in transformation blocks.

### III. FOC IN THREE-TO-FIVE PHASE MATRIX CONVERTER FED FIVE-PHASE IM

The general equation for machine expressions can be written as (1). After the disturbance in the machine, one can get (2)-(3). Where \( V_{0} \) is a point where the system was operating and \( \Delta V \) is the disturbance in voltage.

\[
V = RI + L_{p}I + G_{1}\omega_{s}I + G_{2}\omega I
\]

\[
V_{0} + \Delta V = R(I_{0} + \Delta I) + L_{p}(I_{0} + \Delta I) + G_{1}(\omega_{s0} + \Delta \omega_{s})
\]

\[
\times (I_{0} + \Delta I) + G_{2}(\omega_{s0} + \Delta \omega_{s})(I_{0} + \Delta I)
\]

\[
\Delta V = R\Delta I + L_{p}\Delta I + G_{1}\Delta \omega_{s}I_{0} + G_{1}\omega_{s0}\Delta I
\]

\[
+ G_{2}\omega_{s0}\Delta I + G_{2}\Delta \omega_{s}I \]

The torque can be written as (4), and to get the disturbing value of the torque, (6) is given.

\[
T = I^{T}G_{2}I \]

\[
T_{0} + \Delta T = (I_{0} + \Delta I)^{T}G_{2}(I_{0} + \Delta I)
\]

\[
\Delta T = G_{3}\Delta I
\]

The machines’ mechanical equation can be written as,

\[
J \frac{d\omega}{dt} = T - T_{L} - B\omega
\]

\[
Jp\Delta \omega_{r} = \Delta T - \Delta T_{L} - B\Delta \omega_{r}
\]

Combining (3), (6), and (8), one can get state variable notation. Equation (9) is the state variable representation of the small vector. Here \( \Delta I \) is a 4 \times 1 vector if zero sequences are neglected. It should be ignored as there is no ground wire connected to the star of the stator neutrals.

\[
P \begin{bmatrix}
\Delta I \\
\Delta \omega
\end{bmatrix} = 
\begin{bmatrix}
L^{-1}(R + G_{1}\omega_{s0} + G_{2}\omega_{s}) & -L^{-1}G_{2}I_{0} \\
\frac{G_{1}}{T} & -R
\end{bmatrix}
\begin{bmatrix}
\Delta I \\
\Delta \omega_{r}
\end{bmatrix}
\]

\[
\times 
\begin{bmatrix}
\Delta I \\
\Delta \omega_{r}
\end{bmatrix} + 
\begin{bmatrix}
L^{-1} & 0 & 0 & 0 \\
0 & L^{-1}G_{1}I_{0} & 0 & 0 \\
0 & 0 & \frac{\Delta V}{\omega_{s}} & 0 \\
0 & 0 & 0 & \frac{\Delta T_{L}}{\omega_{s}}
\end{bmatrix}
\]

By transforming in Laplace domain,

\[
pX = Ax + Bu
\]

\[
sX(s) = Ax(s) + Bu(s),
\]

\[
X(s) = (sI - A)^{-1}Bu(s)
\]

From (12), for any input ‘\( u \)’, we can find the response ‘\( x \)’. \( \alpha_{s} \) and \( \beta_{s} \) are the stator axis in the stationary reference frame and transform the equations in the synchronous reference frame shown by axis \( d_{s} \) and \( q_{s} \) in Fig. 3. The angle between \( \alpha_{s} \) and \( d_{s} \) is \( \rho (\rho) \) and its rate of change, i.e., \( \Delta \rho \). 

Neglecting zero-sequence voltage, d-axis stator voltage can be written as (13).

\[
V_{ds} = (r_{s} + L_{ms}p)\dot{I}_{ds} - \omega_{s}L_{ms}i_{qs} + L_{ns}p\dot{i}_{ds} - L_{ms}\omega_{s}\dot{i}_{qs}
\]

\[
\psi_{ds} = L_{ms}i_{ds} + L_{ms}p_{ds}
\]
\[ V_{ds} = (r_s + L_{ss}p - \frac{L_m^2}{L_{rr}})i_{ds} - \omega_r(L_{ss} + \frac{L_m^2}{L_{rr}})i_{qs} \]

\[ + L_m p \frac{\psi_{ds}}{L_{rr}} - L_m \omega_s \frac{\psi_{qs}}{L_{rr}} \]  

(21)

Suppose the \( d_s \) component is chosen along with the \( \psi_{ds} \) then \( \psi_{qs} = 0 \). The final equation (27) tells that the generated torque equals the multiplication of stator q-axis current and rotor flux, similar to the separately excited DC motor. Here the orientation is done along the rotor field vector.

\[
\begin{bmatrix}
V_{ds} \\
V_{qs} \\
V_{qs}
\end{bmatrix}
\]  

\[
= \begin{bmatrix}
\frac{r_s + \sigma L_{ss}p - \omega_r \sigma L_{ss}}{L_{rr}} & -\omega_r \sigma L_{ss} & \frac{L_m p}{L_{rr}} & -\frac{L_m \omega_s}{L_{rr}} \\
\frac{\omega_r \sigma L_{ss}}{L_{rr}} & \frac{r_s + \sigma L_{ss}p - \omega_r \sigma L_{ss}}{L_{rr}} & \frac{L_m p}{L_{rr}} & -\frac{L_m \omega_s}{L_{rr}} \\
-\frac{\sigma L_{ss} p}{L_{rr}} & 0 & \frac{r_r L_m}{L_{rr}} & \frac{r_r L_m}{L_{rr}} + p - \omega_s - \omega_r \\
0 & -\frac{\sigma L_{ss} p}{L_{rr}} & \omega_s - \omega_r & \frac{r_r L_m}{L_{rr}} + p
\end{bmatrix}
\]

(22)

\[ i_{ds} = i_{qs} \psi_{ds} + i_{qs} \psi_{qs} \]  

(23)

\[ V_{qs} = 0 = r_r L_m \frac{i_{qs}}{L_{rr}} + (\omega_s - \omega_r) \psi_{ds} \]  

(24)

\[ V_{ds} = 0 = -r_r L_m \frac{i_{ds}}{L_{rr}} + (\frac{r_r}{L_{rr}} + p) \psi_{ds} \]  

(25)

\[ \psi^s = \psi_{ds} = r_r L_m \frac{i_{ds}}{L_{rr}} - \frac{1}{s + \frac{r_r}{L_{rr}}} i_{ds}(s) \]  

(26)

\[ T = \frac{L_m}{L_{rr}} i_{qs} \psi^s \]  

(27)
IV. MODULATION OF THREE-TO-FIVE PHASE DMC

In the direct MC, any output phase can be connected with any of the input phases. Fifteen bidirectional switches are there in an MC combination, encompassing a total 2^{15} switching possibilities. Out of these, only 93 switching arrangements are established to control the input current and output voltage [12]. The switching function considering the switching constraints \( S_{ak} + S_{bk} + S_{ck} = 1 \) is well-defined as: \( S_{jk} = \{1, 0\} \) for closed and open switch, respectively. Here, \( j \) is input phase \( \{a, b, c\} \) and \( k \) is output phase \( \{A, B, C, D, E\} \). The objective of the SVPWM is to accomplish five-phase harmonic free output voltages and currents. The SVPWM algorithm is established on demonstrating the three input phase currents and five output line voltages on the space vector planes. There are six sectors of the input current and ten sectors of output voltage. The complete control of the MC is possible by governing the common vectors between input current and output voltage sectors [12]–[14]. These are 16 in number, forming large and second large (medium) length vectors. Table 2 presents these common vectors in the first sector of the input current and output voltage, where vectors of medium length and large length are \( \pm 1, \pm 13, \pm 3, \pm 15 \) M and \( \pm 1, \pm 13, \pm 3, \pm 15 \) L, respectively. Vectors are numbered sequentially, starting from the horizontal axis anticlockwise. “\( \pm \)” sign indicates two vectors separated by 180° in phases having the same magnitude. The output reference voltage has a projection of \( V' \) and \( V'' \) at two sides of the sector. At any fixed position, suppose +1M, there are three voltage vectors 0.25 \( V_{ab}, V_{bc}, \) and \( V_{ca} \).

These have three different magnitudes at an instant. Among these, having the largest and medium magnitude is selected for the implementation. Selected vectors in the direction of \( V' \) and \( V'' \) must be of the same input phase connection. Therefore, these vectors +1M, –3M, –13M, +15M, and +1L, –3L, –13L, +15L are common in sector I. These vectors are presented in Fig. 4. Where, for the current first sector \( \alpha \) vary from \( -\pi /6 \) to \( +\pi /6 \) and for voltage vector \( V_o \) varies from \( -\pi /10 \) to \( +\pi /10 \). The input current and output voltages can be presented in terms of space vectors as,

\[
\vec{V}_i = \frac{2}{3} \left( V_{ab} + V_{bc} \cdot e^{\frac{2\pi}{3}} + V_{ca} \cdot e^{\frac{4\pi}{3}} \right) = V_i \cdot e^{j\alpha_i} (28)
\]

\[
\vec{l}_i = \frac{2}{3} \left( I_a + I_b \cdot e^{\frac{2\pi}{3}} + I_c \cdot e^{\frac{4\pi}{3}} \right) = I_i \cdot e^{j\alpha_i} (29)
\]

The maximum voltage transfer ratio can be obtained as 0.7886 times the input voltage. To achieve the power factor-controlled operation, let \( \vec{V}_i \) be the input line voltage and \( \vec{V}_o \) the desired output line voltage space vector instantly. The input phase \( \vec{e}_i \) voltage vector is given by (31).

\[
\vec{e}_i = \frac{1}{\sqrt{3}} \vec{V}_i \cdot e^{-j\frac{\pi}{6}} (31)
\]

For input power factor control, the direction of the input current space vector \( \vec{l}_i \) has to be controlled according to \( \vec{e}_i \). For unity power factor operation, \( \vec{l}_i \) and \( \vec{e}_i \) should be in the same phase. Consider \( \vec{l}_i \) and \( \vec{V}_o \) are in sector 1, large and medium vector configurations comprising of \( \vec{V}_o \) are shown in Fig. 4. Similarly \( \vec{l}_i \) is determined into components \( \vec{l}'_i \) and \( \vec{l}''_i \) along with the two adjoining vector directions. Possible switching to produce the resolved currents and voltages are,

\[
\vec{V}'_o = \pm 1L, \pm 2L, \pm 3L \text{ and } \pm 1M, \pm 2M, \pm 3M
\]

\[
\vec{V}''_o = \pm 13L, \pm 14L, \pm 15L \text{ and } \pm 13M, \pm 14M, \pm 15M
\]

\[
\vec{l}'_i = \pm 3L, \pm 6L, \pm 9L, \pm 12L, \pm 15L \text{ and } \pm 3M, \pm 6M, \pm 9M, \pm 12M, \pm 15M
\]

\[
\vec{l}''_i = \pm 1L, \pm 4L, \pm 7L, \pm 10L, \pm 13L \text{ and } \pm 1M, \pm 4M, \pm 7M, \pm 10M, \pm 13M
\]

Complete control is possible by controlling the common switching states of input current and output voltage components. The common switching states are,

\[
\pm 1L, \pm 3L, \pm 1M, \pm 3M \text{ and } \pm 13L, \pm 15L, \pm 13M, \pm 15M
\]

The sign “\( \pm \)” indicates the corresponding space vectors are in opposite directions. Out of these two switching vectors with opposite signs, only one is used at a time. For example, the duty cycle is calculated for switching states with positive signs; if it comes positive, then the switching vector corresponding to positive sign switching state is selected for reference modulation; otherwise, a space vector with a switching state with a negative sign is carefully chosen. The desired \( \vec{V}'_o \) can be estimated by applying two medium and two large switching patterns conforming to four space vectors \( \vec{V}'_o \). Out of four possible switchings, two contribute.
the higher voltage values corresponding to large vectors. The reaming two arrange for the medium voltage meeting the requirements to medium vectors with the same sense of \( \vec{V}_o \) being chosen. Correspondingly, one zero and four different switching configurations define \( \vec{V}'_o \).

Table 3, \( V'_o \) is obtained from the pattern \(+1M, -3M\) for medium and \(+1L, -3L\) for large vectors while for \( \vec{V}_o \) these are \(+3M, -15M\) and \(+13L, -15L\). These eight patterns determine the output voltage and input current.

Applying the SVPWM technique, the calculation of duty ratio ‘d’ has been explained in detail [16]. It is obtained in (32) and (33), where the voltage transfer ratio is transferred.

It is noteworthy that the obtained results are effective for

\[-\frac{\pi}{10} \leq \alpha_o \leq \frac{\pi}{10}\] and \(0 \leq \alpha_i \leq \frac{\pi}{3}\).

\[
\begin{align*}
\begin{aligned}
d^{+1}_L &= q.L \cdot \frac{10}{3\sqrt{3}} \sin \left( \frac{\pi}{10} + \alpha_o \right) \cdot \sin \left( \frac{\pi}{3} - \alpha_i \right) \\
d^{-3}_L &= q.L \cdot \frac{10}{3\sqrt{3}} \sin \left( \frac{\pi}{10} - \alpha_o \right) \cdot \sin \left( \alpha_i \right) \\
d^{+1}_M &= q.M \cdot \frac{10}{3\sqrt{3}} \sin \left( \frac{\pi}{10} + \alpha_o \right) \cdot \sin \left( \frac{\pi}{3} - \alpha_i \right) \\
d^{-3}_M &= q.M \cdot \frac{10}{3\sqrt{3}} \sin \left( \frac{\pi}{10} - \alpha_o \right) \cdot \sin \left( \alpha_i \right)
\end{aligned}
\end{align*}
\]

Similarily for \( \vec{V}''_o \),

\[
\begin{align*}
\begin{aligned}
d^{+13}_L &= q.L \cdot \frac{10}{3\sqrt{3}} \sin \left( \frac{\pi}{10} + \alpha_o \right) \cdot \sin \left( \frac{\pi}{3} - \alpha_i \right) \\
d^{-15}_L &= q.L \cdot \frac{10}{3\sqrt{3}} \sin \left( \frac{\pi}{10} - \alpha_o \right) \cdot \sin \left( \alpha_i \right) \\
d^{+13}_M &= q.M \cdot \frac{10}{3\sqrt{3}} \sin \left( \frac{\pi}{10} + \alpha_o \right) \cdot \sin \left( \frac{\pi}{3} - \alpha_i \right) \\
d^{-15}_M &= q.M \cdot \frac{10}{3\sqrt{3}} \sin \left( \frac{\pi}{10} - \alpha_o \right) \cdot \sin \left( \alpha_i \right)
\end{aligned}
\end{align*}
\]

Similarly, the obligatory switchings and their duty ratio of can be calculated. The sum of the proportions must be less than unity.

\[
d^{+1}_L + d^{-3}_L + d^{+13}_L + d^{-15}_L + d^{+1}_M + d^{-3}_M + d^{+13}_M + d^{-15}_M \leq 1
\] (34)

V. RESULTS AND DISCUSSION

The proposed FOC scheme is simulated and verified on a 2-hp five-phase IM. The three-to-five phase MC is used as a source of voltage for the induction motor. The developed model is tested for different set speeds. Moreover, the disturbance is also used externally by applying load torques in a stepped manner, and the system’s response is noted and analyzed.

Supply voltage 230V is given to the matrix converter, and

---

**TABLE 3. Switching sequence of output voltage vector in sector 1.**

| Vec. No. | Input | Output phases | Output line voltage |
|----------|-------|---------------|---------------------|
| 0        | b, b  | A B          | VAB VRC VCD VDE VEA |
| +1 M     | a, b  | a b b b b b  | 0 0 0 0 0           |
| -13 L    | a, b  | a b b b b b  | VAB 0 0 0           |
| -13 L    | a, b  | a a a a a a  | 0 0 0 0 0           |
| +15 M    | a, c  | a a a a a a  | 0 0 Vca 0           |
| -3 L     | a, c  | a c c c a a  | Vca 0 0 0           |
| +15 L    | a, c  | a c c c c c  | Vca 0 0 0           |
| -3 M     | e, c  | c c c c c c  | 0 0 0 0 0           |

FIGURE 4. Space vectors diagram for three-phase to five-phase DMC

(a) All active output voltages (b) input currents and for sector 1 (c) input currents (d) output voltages space vectors.
FIGURE 5. Simulation results (a) Speed response of the controlled drive system, (b) torque response of the controlled drive system, (c) Stator current, (d) Rotor flux of the five-phase induction motor.

TABLE 4. Simulation parameters.

| Parameter | value |
|-----------|-------|
| $P$       | 2 HP  |
| $V_c$ (V) | 230   |
| Pole pairs| 2     |
| $R_n$, $R_s$ (Ω) | 6.4, 7.2 |
| $L_s$ (mH) | 103.1 |
| $L_r$ (mH) | 92.2  |
| $o_s$ (rad) | 157   |
| $L_m$ (H)  | 1.013 |
| $J_m$ (kgm²) | 0.021 |

The machine gradually rises to meet the requisite steady-state speed. Once the speed reaches its steady-state value, a load torque of 13 N-m is applied. Momentarily, a speed dip is observed at the load application. The control process helps to reinstate the speed to the reference value. The reference speed is increased at $t = 3$ sec. From Fig. 5, it is shown that the rotor speed tracks the reference speed, and corresponding more torque is required. That is observed in Fig. 5(b).

Further, it is observed that the drive tracks the reference speed at all the points in different speed and torque changing conditions. The actual speed of the rotor tracks the reference speed, thus displaying the dynamic behavior of the scheme.

At different loading conditions, stator current $i_{ds}$ momentarily change; however, it restores its previous steady-state value.

The drive’s control is confirmed by restoring the stator current and rotor flux in Fig. 5(c) and Fig. 5(d) at different torque and speed conditions. It can be observed that there is no demagnetization of flux, and the actual rotor speed follows the reference speed.

The stator phase ‘A’ current of five-phase IM at different loading conditions is shown in Fig. 6(a). At time 4.5 seconds, the load torque is changed from 13 N-m to 6.5 N-m at 90 rad/sec. It confirms the low current required to maintain the drive at the same speed. The locus of the five-phase stator current of $a\beta$ and $xy$ components is shown in Fig. 6(b). It is found that the five-phase current is balanced and sinusoidal since the $xy$ component is insignificant. The output voltage of
the three-to-five phase matrix converter for the control drive at different operating conditions is shown in Fig. 6(c) for the load change from 13 N-m to 6.5 N-m, and Fig. 6(d) is for steady-state operation at 70 rad/sec speed at 6.5 N-m torque.

The FPIM is changed from 90 rad/sec to 30% of synchronous speed at rated load torque to demonstrate robustness and accuracy of speed tracking performance. The response of the system is shown in Fig. 7.

In the FOC of five-phase IM, the reference torque and flux calculate the stator current $i_{ds}$ and $i_{qs}$. To get the controlled operation of the drive, $i_{ds}$ should remain controlled irrespective of the loading conditions of the drives. Fig 5(c) shows the stator current direct axis component $i_{ds}$ and the loss component $i_{xs}$, corresponding to the speed and torque.

To reach the desired speed within minimum time, maximum torque is applied on the motor resulting in fast acceleration. However, the torque decreases when the motor gets near the desired speed, and steady tracking is observed within 0.5 seconds.

When the speed reference is reduced, maximum negative torque is applied on the motor resulting in fast deceleration. An undershoot is observed in the FPIM response before settling at 30% of synchronous speed.

Harmonic spectrum of motor torque (at rated load torque of 10Nm) at switching frequencies of 4 kHz, 2 kHz, and 1 kHz are shown in Fig. 8(a) – Fig. 8(c), respectively. Here, all low-frequency components (<10 * fundamental frequency) are eliminated due to the PWM operation of the matrix converter. Conclusively, the process at a higher switching frequency results in low THD content. However, a higher switching frequency operation leads to higher switching losses in the converter (which requires more oversized heat sinks). Thus, the selection of switching frequency plays a crucial role in motor drive performance, and it must be selected depending upon the desired requirements of size, cost, and performance reliability.
The existence of torque ripple leads to vibration issues that can hamper the life of the motor drive. Conventionally, low-frequency torque ripples are more damaging than high-frequency torque ripples easily filtered out by the motor inertia.

The proposed scheme is also validated through the experiments. A 2 kW five-phase IM with a rated torque of 15 N·m and six poles is used for testing purposes. The control algorithm is implemented using the dSPACE 1006 board, giving the user to program at the FPGA level. For feedback of current...
and voltage into the dSPACE, LEM 55A and LEM 25P are used. For loading of five-phase IM, a separately excited DC generator is employed, which indirectly loads the IM through electrical loads connected at the terminal of the generator. For a sampling of flux and torque, the sample time \( T_s = 90\mu s \) is used. The switching frequency is fixed at 2 kHz. The speed of 500 RPM and respective torque is given with a load of 5 N-m, and the motor’s actual speed also reaches the reference speed. Then at time \( t = 22 \) s load of the motor is reduced from 5 N-m to 2.5 N-m, the motor’s actual speed retracts to the reference speed after some initial deviation.

Responses are shown in Fig. 9(a). At \( t = 5 \) s reference speed reaches the desired speed within minimum time, maximum torque is applied on the motor resulting in fast acceleration.

However, the torque decreases when the motor gets near the desired speed, and steady tracking is observed within 0.5 seconds. When the speed reference is reduced, maximum negative torque is applied to achieve fast deceleration. An undershoot is observed in the FPIM response before settling at 30% of synchronous speed. The existence of torque ripple leads to vibration issues that can hamper the life of the motor drive. Conventionally, low-frequency torque ripples are more damaging than high-frequency torque ripples easily filtered out by the motor inertia.

At \( t = 35 \) s, the reference speed is reduced from 500 RPM to 400 RPM keeping the constant electrical load to the motor’s overloading as the speed decreases. Similarly, the motor’s actual speed follows the reference speed for the transition states marked in Fig. 9(a). The torque ripple of the motor is shown in Fig. 9(b) for different load conditions. The torque ripple is about 0.9 volts, whereas the rated torque is 15 N-m, i.e., 6 volts. Thus the torque ripple is around 15% of the rated torque. The \( xy \) flux trajectory is shown in Fig. 9(c), and it is observed that the maximum magnitude of \( xy \) flux is almost negligible compared to the rated flux. The \( xy \) flux is eliminated because of the volt-second balance technique applied in the modulation of the converters. The actual current tracks the desired value without delay. The unity power factor of the matrix converter is confirmed from the Fig. 9(d) shows input voltage and current, ensuring almost zero phase delay.

Moreover, the stator currents and line voltage have been included in the experimental results. The dynamics of stator currents have been presented when the reference speed is changed. Fig. 10 shows the corresponding output line voltage \( V_{AB} \), and stator currents with its zoomed waveform for five-phase induction motor at the transition states of speed and torque. Apart from that, the spectrum of the input current of the matrix converter is presented. The THD of matrix converter input current is 9.4% at 0.8 modulation index.

**VI. CONCLUSION**

The field-oriented control of a five-phase induction motor is performed. The drive is fed from an SVPWM controlled three-to-five phase DMC. The analytical results are verified using simulation and experiments. The modulation of three-to-five phase DMC is achieved with minimum possible switchings. There are at least ten switching transitions during a switching cycle. The \( xy \) component of flux is eliminated, reducing the spoiling of stator current distortion and improving the reliability. Applying the volt-second principle in the modulation of space vectors of the matrix converter eliminates the \( xy \) flux component. The dynamic characteristics of the motor is confirmed for different load torque and speed conditions. The matrix converter control achieved the
input side current in phase with the input voltage and better dynamic performance of the FPIM with low torque ripple and almost zero xy flux.

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