Sensorless Speed and Position Control with DTFC of Induction Motor using Four Switch Three Phase Inverter and Adaptive Flux Observer

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Abstract—This paper presents sensor-less speed control of induction motor (IM) using four switch three phase inverter (FSTPI) with direct torque and flux control (DTFC). The proposed sensor-less DTFC system consists of an adaptive observer of rotor flux to accurately estimate stator resistance and speed simultaneously, without affecting drive performances. The switching technique for DTFC of IM using FSTPI in low power application is based on the principle of similarity between FSTPI and SSTPI (six switch three phase inverter), where the αβ plan is divided into 6 sectors and the formation of the voltage space vector is done in the same way as for SSTPI by using effective (mean) vectors. This approach allows using the well-known established switching table of SSTPI for FSTPI. The simulation results indicate that the sensor-less speed control of FSTPI fed IM with DTFC and adaptive observer provides accurate estimate, good trajectory tracking with different dynamics performance.

Index Term—Induction motor, Four switch three phase inverter (FSTPI), Six switch three phase inverter (SSTPI), Direct torque and flux control (DTFC), Sensorless control, Adaptive flux observer.

I. INTRODUCTION

In recent years significant advances have been made on the sensor-less control of IM. One of the most well-known methods used for control of AC drives is the Direct Torque Control (DTC) developed by Takahashi in 1984 [1]. DTC of IM is known to have a simple control structure with comparable performance to that of the field-oriented control (FOC) techniques developed by Blaschke in 1972 [2]. Unlike FOC methods, DTC techniques require utilization of hysteresis band comparators instead of flux and torque controllers. To replace the coordinate transformations and pulse width modulation (PWM) signal generators of FOC, DTC uses look-up tables to select the switching procedure based on the inverter states [1]. Direct torque control (DTC) of induction motors requires an accurate knowledge of the magnitude and angular position of the controlled flux.

In DTC, the flux is conventionally obtained from the stator voltage model, using the measured stator voltages and currents. This method, utilizes open loop pure integration suffering from the well known problems of integration effects in digital systems, especially at low speeds operation range. To obtain the simple, effective performances, fast control of torque and flux; a DTFC system for FSTPI-IM has been proposed [3]. In this paper, the optimal switching look-up table is established with four basic space vectors of FSTPI and in accordance with four main sectors in the αβ plan. Comparison with DTFC of induction motor fed by conventional SSTPI confirm that FSTPI topology can be alternative to the conventional topology for low power low cost induction motor drives. DTFC method for SSTPI-IM has been improved in some researches [4-10], while the torque and speed ripples are reduced. In order to reduce the speed (torque) ripple, the space vector modulation (SVM) modulator has been used as shown in [5-9].

The switching technique for DTFC-FSTPI-IM in this paper has been done by using the new approach based on the principle of similarity between FSTPI and SSTPI [11], where the αβ plan is divided into 6 sectors and the formation of the required reference voltage space vector is done in the same way as for SSTPI by using effective (mean) vectors.

In the last decade, many researches have been carried on the design of sensorless control schemes of the IM. Most methods are basically based on the Model Reference Adaptive System schemes (MRAS) [12] [13]. In [14] the authors used a reactive-power-based-reference model derived in both motoring and generation modes but one of the disadvantages of this algorithm is its sensitivity to detuning in the stator and rotor inductances. The basic MRAS algorithm is very simple but its greatest drawback is the sensitivity to uncertainties in the motor parameters. Another method based on the Extended Kalman Filter (EKF) algorithm is used [15].
The EKF is a stochastic state observer where nonlinear equations are linearized in every sampling period. An interesting feature of the EKF is its ability to estimate simultaneously the states and the parameters of a dynamic process. This is generally useful for both the control and the diagnosis of the process. In [17] the authors used the EKF algorithm to simultaneously estimate variables and parameters of the IM in healthy case and under different IM faults. [12-18] used the Luenberger Observer for state estimation of IM. The Extended Luenberger Observer (ELO) is a deterministic observer which also linearizes the equations in every sampling period. There is other type of methods for state estimation that is based on the intelligent techniques is used in the recent years by many authors [19] [20] [21].

In addition, several papers provide sensorless control of IM that are based on the variable structure technique [22] [23] and the High Gain Observer (HGO) [24] that is a powerful observer that can estimate simultaneously variables and parameters of a large class of nonlinear systems and doesn’t require a high performance processor for real time implementation.

DTC improves the induction machine controller dynamic performance and reduces the influence of the parameter variation during the operation [25]. This work deals a sensorless direct torque control for induction motor drives, in particular the performances improvement of adaptive full-order flux and speed observer. This observer includes a mechanism of adaptation based on a conventional PI controller. This observer is used to estimate the rotor flux linkages, rotor speed and stator resistance. The speed estimation is affected by parameter variations especially the stator resistance due to temperature rises particularly at low speeds [26].

The proposed sensorless DTFC for FSTPI fed IM showed a good behavior in the transient and steady states, with an excellent disturbance rejection of the load torque. Simulation results demonstrate the effectiveness of the proposed control over different operating conditions, a precise estimation in low and zero speed. The comparison between DTFC of induction motor fed by conventional SSTPI and FSTPI topology ensures the validity of the proposed technique.

II. SPACE VECTOR ANALYSIS OF FSTPI

According to the scheme in Fig. 1 the switching status is represented by binary variables S₁ to S₄, which are set to “1” when the switch is closed and “0” when open. In addition the switches in one inverter branch are controlled complementary (1 on, 1 off), therefore:

\[ S₁ + S₃ = 1 \]
\[ S₁ + S₄ = 1 \]

Phase to common point voltage depends on the turning off signal of the switch as in (2):

\[ V_{cs} = (2S₁ - 1) \frac{V_s}{2} \]

\[ V_{cs} = 0 \]

Combinations of switching S₁,S₄ result in 4 general space vectors \( \vec{V} \rightarrow \vec{V}' \) (Fig.2, Table 1), components \( \alpha \beta \) of the voltage vectors are gained from abc voltages using Clark’s transformation as in (3):

\[
\begin{bmatrix}
V_{\alpha}' \\
V_{\beta}'
\end{bmatrix} =
\frac{1}{3}
\begin{bmatrix}
1 & -1 & -1 \\
2 & 2 & 0
\end{bmatrix}
\begin{bmatrix}
V_{\alpha} \\
V_{\beta} \\
V_{c}
\end{bmatrix}
\]

(3)

Where \( V_{\alpha}, V_{\beta}, V_{c} \): output voltages on the load star connection, defined by:

\[ V_{\alpha}' = \frac{1}{3} (2V_{cs} - V_{an}) \]
\[ V_{\beta}' = \frac{1}{3} (2V_{cs} - V_{bn}) \]
\[ V_{c}' = \frac{1}{3} (V_{cs} + V_{an}) \]

(4)

![Fig. 2. Voltage space vector of FSTPI in the αβ plane.](image)

**Table 1**

<table>
<thead>
<tr>
<th>Switching Status</th>
<th>Voltage Vectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>S₁</td>
<td>S₃</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

To simulate six non-zero vectors in SSTPI, beside the two \( V₁ \) and \( V₃ \), it can be used the effective vectors.
V_{23M}, V_{43M}, V_{14M} and V_{12M}. These vectors are formed as follows:

\[
V_{23M} = \frac{1}{2}(V_2 + V_3) = \frac{V}{3}e^{\pi j};
\]

\[
V_{43M} = \frac{1}{2}(V_4 + V_3) = \frac{V}{3}e^{\frac{\pi}{2} j};
\]

\[
V_{14M} = \frac{1}{2}(V_1 + V_4) = \frac{V}{3}e^{\frac{3\pi}{2} j};
\]

\[
V_{12M} = \frac{1}{2}(V_1 + V_2) = V/3.
\]

To simulate zero vectors of SSTPI, use the effective vectors as in (6):

\[
V_{0M} = \frac{1}{2}(\overline{V}_1 + \overline{V}_3).
\]

The similarity between space vectors of FSTPI and SSTPI is presented in Table 2.

![Fig. 3. Voltage space vectors for (FSTPI) on the principle of similarity](image)

![Fig. 4. Base space vectors in SSTPI](image)

### Table II

<table>
<thead>
<tr>
<th>Used voltage space vectors for FSTPI</th>
<th>Used voltage space vectors for SSTPI</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1</td>
<td>V23M</td>
</tr>
<tr>
<td>V2</td>
<td>V3</td>
</tr>
<tr>
<td>V3</td>
<td>V4</td>
</tr>
<tr>
<td>V4</td>
<td>V14M</td>
</tr>
<tr>
<td>V5</td>
<td>V1</td>
</tr>
<tr>
<td>V6</td>
<td>V12M</td>
</tr>
<tr>
<td>V0, V7</td>
<td>V0M</td>
</tr>
</tbody>
</table>

The objective of the DTC is to maintain the motor torque and stator flux within a defined band of tolerance by selecting the most convenient voltage space vector from the look-up table (switching table). In the case of the conventional switching table of DTC for FSTPI-IM, one of four active vectors is chosen (Table 3) [3].

### Table III

<table>
<thead>
<tr>
<th>Sector</th>
<th>Switching table for DTC control method</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>I</td>
</tr>
<tr>
<td>-30°</td>
<td>-240°+330°</td>
</tr>
<tr>
<td>+30°</td>
<td>90°</td>
</tr>
</tbody>
</table>

In order to reduce the torque and speed ripples by using the principle of similarity for voltage space vectors, optimum switching table in the modified method is established similarly for the SSTPI switching table. The \( \alpha \beta \) plan is divided into six sectors, and for each sector, the optimal space vector is chosen accordingly to the required torque and flux by using the effective vectors (equations 5, 6). These vectors are synthesized using the basic space vectors with the duty cycle of 50% (switching period is \( T_s \)). The same way is done for effective zero space vector (Table 4).

### Table IV

<table>
<thead>
<tr>
<th>Switching table for DTC control method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sector</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>+30°</td>
</tr>
</tbody>
</table>

The flux and torque calculations remain the same. The stator flux is estimated as follows:

\[
\psi_s = \psi_{s0} + (V_{ss} - l_s R_s)\omega_s
\]

\[
\psi_{\alpha\beta} = \psi_{\alpha\beta} + (V_{ss} - l_s R_s)\omega_s
\]

(7)

The estimated stator flux \( \psi_s \) and flux angle sector are defined as follows:

\[
\psi_s = \sqrt{\psi_{\alpha}^2 + \psi_{\beta}^2}, \theta_s = \arctan(\frac{\psi_{\beta}}{\psi_{\alpha}})
\]

The torque is estimated by the following formula:

\[
t = \frac{3P}{2}(\psi_{ss} \omega_s - \psi_{s0} \omega_s)
\]

Where:
- \( v_s \) Stator voltage and current vectors
- \( R_s \) Stator resistance
- \( P \) Number of pole pair
- \( T \) Electromagnetic torque
- \( \psi_s \) Stator flux vector
- \( T_s \) Sampling time

### IV. Rotor speed, flux and stator resistance estimation based adaptive observer

To define the adaptive observer, stator voltages and currents are used to estimate the rotor flux \( \psi_r \), speed \( \omega_r \), and stator resistance \( R_s \) according to adaptation

\[
I_{12M} = \frac{1}{2}(V_1 + V_2) = \frac{1}{2}(V_3 + V_4) = \frac{1}{2}(V_5 + V_6) = \frac{V}{3}.
\]

\[
V_{0M} = \frac{1}{2}(\overline{V}_1 + \overline{V}_3).
\]
laws that must ensure the stability of the system. Consider then the speed and resistance stator as constant parameters and unknown. The state equation of this observer is then expressed as follows by separating the state matrix in two, one for the speed and the other for rotor resistance [27].

\[
\dot{X} = [A_s(\dot{\omega}_r) + A_R(\dot{R}_s)]X + BU + K(i_r - \hat{i}_r)
\]

(10)

Where

\[
A(\dot{\omega}_r) = \\
\begin{bmatrix}
a_{11} & 0 & -a_3 & a_1 \\
0 & a_{11} & -a_3 & a_1 \\
a_4 & 0 & a_5 & -\dot{\omega}_r \\
0 & a_4 & \dot{\omega}_r & a_5
\end{bmatrix}
\]

And

\[
A(\dot{R}_s) = \\
\begin{bmatrix}
-a_1R_r & 0 & 0 & 0 \\
0 & -a_1R_r & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0
\end{bmatrix}
\]

K is the observer gain matrix which governs the dynamics and the observer’s robustness; it is calculated as follows:

\[
K = \\
\begin{bmatrix}
K_1 & K_2 & K_3 & K_4 \\
-K_2 & K_1 & -K_4 & K_3
\end{bmatrix}
\]

(11)

The coefficients \(K_1, K_2, K_3, \text{and } K_4\) are defined as follows:

\[
K_1 = (k_1 - 1) \left( \frac{1}{\sigma L_s} + \frac{1 - \sigma}{\sigma T_r} + \frac{1}{T_r} \right)
\]

\[
K_2 = (k_1 - 1) \dot{\omega}_r
\]

\[
K_3 = \frac{(1 - k_1^2)}{\sigma a_3} \left( \frac{1}{\sigma L_s} + \frac{1 - \sigma}{\sigma T_r} + \frac{1}{\alpha_3} \right) + \frac{(k_1 - 1)}{a_3} \left( \frac{1}{\sigma L_s} + \frac{1 - \sigma}{\sigma T_r} + \frac{1}{\alpha_3} \right)
\]

\[
K_4 = \frac{(k_1 - 1)}{a_3} \dot{\omega}_r, \quad k_1 > 1
\]

A hat above a symbol in (10) denotes estimated quantities, symbol \(T_r\) is the rotor time constant, \(L_s\) stator inductance, \(L_r\) rotor inductance and leakage coefficient \(\sigma = 1 - \frac{L_r}{m(L_s + L_r)}\). The coefficient \(k_i\) is chosen to impose a dynamic observer faster than the system. The speed adaptive mechanism can be deducted by the Lyapunov theory [28, 29].

If we choose an adequate candidate function, after application of the Lyapunov theory, the following adaptation law for the speed is gotten [28–30]:

\[
\dot{\omega}_r = \left( K_{po} + \frac{K_{10}}{s} \right) e_{isa} \psi_r - e_{isa} \psi_r
\]

(12)

While the stator resistance estimation is given by the adaptation law defined by:

\[
\dot{R}_s = \left( K_{po} + \frac{K_{10}}{s} \right) \left( e_{isa} \psi_r - e_{isa} \psi_r \right)
\]

(13)

With \(e_{isa} = i_s - i_s\) and \(e_{isa} = i_s - i_s\)

Where \(k_{po}, k_{10}, k_{ph}, k_{ph}, \text{are PI controller parameters of rotor speed and stator resistance adaptation mechanisms respectively.}\)

The role of adaptive mechanisms is to minimize the following errors \(e_{oR}, e_{oR}\):

\[
e_{oR} = \left( e_{isa} \psi_r - e_{isa} \psi_r \right)
\]

(14)

\[
e_{oR} = \left( e_{isa} \psi_r - e_{isa} \psi_r \right)
\]

Finally, the value of speed and stator resistance can be estimated by simple PI controllers. The norm of rotor flux and its position are determined by the following relations:

\[
\psi_r = \sqrt{\psi_r^2 + \psi_r^2}
\]

(15)

\[
\theta_r = \arctg \left( \frac{\psi_r}{\psi_r} \right)
\]

(16)

The relation between rotor flux and stator flux as in (17)

\[
\psi_r = \psi_r - j_s \alpha X_s
\]

(17)

Where \(X_s\) is the stator reactance.

V. DRIVE SYSTEM

The block diagram of IM DTFC drive system with proposed adaptive observer is shown in Fig. 5. The system basically comprises two hysteresis controllers for flux linkage and torque control, these controllers, in conjunction with the modified switching table for FSTPI (Table 4) similarly for SSTPI switching table, generate the output signals to the gates of the power switches of the inverter.

Using the optimum switching table for FSTPI reduces the torque and speed ripples. The inverters used in this system are SSTPI and FSTPI.

![Fig. 5. Block diagram of IM DTFC system](image)

The role of the flux controller is to maintain the flux amplitude within a narrow hysteresis band around the
reference value \( \nu_r \). The torque controller receives the information obtained from the torque calculator and compares this value with the reference torque \( T_r \) (output of a speed PI controller). Two current sensors measure the motor currents \( (i_a, i_b) \) while a voltage sensor measure the motor voltages \( (v_a, v_b) \) that, in conjunction with switching table, is used to compute the stator voltages \( (v_{sa} v_{sb}) \). The stator flux linkage \( \psi_s \), its angular position \( \theta_s \) and estimated torque \( \hat{T} \) are given in (7), (8), (9). Also the estimated speed and stator resistance are given in (12), (13).

VI. SIMULATION RESULTS

Modeling and simulation work has been performed to examine the control algorithm of IM DTFC using modified switching table for FSTPI based on adaptive observer for rotor flux, speed and stator resistance estimation using MATLAB/SIMULINK software. For the purpose of full comparison, such work is also done for conventional DTFC using SSTPI. The parameters of the induction motor prototype are listed in Appendix I. The sample period \( T_s \) is \( 50 \mu s \), and the load torque is set to be \( 5.0 \) N.m at \( 50 \) rpm speed and also at zero speed during forward motoring operation when the speed change to \(-50 \) rpm at \( t=4 \) sec the torque change to \(-5.0 \) N.m during reverse motoring operation.

In all simulations, the estimated speed was used for sensor-less speed control and the actual speed is presented for comparison purpose.

A. Performance of IM DTFC fed by a FSTPI under sensorless speed control

Fig. 6 shows the speed waveforms under load operation when the sensorless speed control was performed using the proposed method for FSTPI the speed change from \( 50 \) rpm to \( 0 \) rpm at \( t=2 \) sec with load torque equal to \( 5 \) N.m and also the speed change from \( 0 \) rpm to \(-50 \) rpm at \( t=4 \) sec as well as the load torque changes from \( 5 \) N.m to \(-5 \) N.m in the reverse motoring operation. The speed command applied in the speed controller is shown in Fig. 6 upper diagram (blue) in revolution per minute (rpm) the estimated speed (red) and the actual rotor speed (black). The difference between the actual speed and estimated speed in rpm is shown in Fig. 6 lower diagram. The results show the accuracy of the sensorless speed control during starting with load operation as well as speed change operations.

Fig. 7 upper diagram shows a comparison between the actual rotor angle (black) and the estimated rotor angle (red) during the test depicted in Fig. 6 also Fig. 7 lower diagram shows the load torque (red) and the estimated torque (black) in N.m. The figures show the accuracy of the proposed technique. Fig. 8 upper diagrams shows the actual rotor flux angle (black) and the estimated rotor flux angle (red), Fig. 8 lower diagram shows the error between the actual and estimated rotor flux angles in degrees for the tests depicted in Fig. 6. The steady state error is nearly zero which indicates that the proposed method of sensor-less speed control is very accurate with zero speed error at very low speed as well as zero speed under high load operations.

Fig. 9 shows the motor current in the stationary reference frame \( (\alpha, \beta) \) (upper diagram) and the three phase motor currents \( I_{abc} \) (lower diagram).

Fig. 6. Upper: Reference (blue), estimated (red) and actual (black) rotor speed in rpm. Lower: speed error (rpm).

Fig. 7. Upper: actual rotor angle (black), estimated rotor angle (red) in°. Lower: Load torque (red) and estimated torque (black) in (N.m).
Fig. 8. Upper: actual (black), estimated (red) rotor flux angle in °. Lower: Error between actual and estimated rotor flux angle in °.

Fig. 9. Upper: motor current in stationary reference frame (αβ) in A. Lower: motor currents Iabc in A.

Fig. 10: actual stator resistance (black-dotted) and estimated stator resistance (red) in ohm

Fig. 11. Stator flux linkage locus in (Wb).

Fig. 12. Upper: Reference (blue), estimated (red) and actual (black) rotor speed in rpm. Lower: speed error (rpm).

B. Performance of IM DTFC fed by a SSTPI under sensorless speed control

For comparison purposes the next figures (12-16) shows the performance of IM DTFC using SSTPI with adaptive observer for rotor flux, speed and stator resistance estimator under the same operating condition as in the previous section (part A). It can be seen that DTFC with FSTPI using the modified switching table approach for sensorless speed control IM has the advantages of reduce torque ripples over the conventional DTFC with SSTPI.
Fig. 13. Upper: actual rotor angle (black), estimated rotor angle (red) in °. Lower: Load torque (red) and estimated torque (black) in (N.m).

Fig. 14. Upper: actual (black), estimated (red) rotor flux angle in °. Lower: Error between actual and estimated rotor flux angle in °.

Fig. 15. Upper: motor current in stationary reference frame ($\alpha\beta$) in (A). Lower: motor currents $i_{abc}$ in (A).

VII. CONCLUSION

The paper presents a new approach for sensorless speed control of DTFC IM drive system using FSTPI for low power application. The modified switching table applied in this method is based on the principle of similarity between FSTPI and SSTPI, where the $\alpha\beta$ plan is divided into 6 sectors and the formation of the voltage space vector is done in the same way as for SSTPI by using effective (mean) vectors. This approach allows using the well-knowing established switching table of SSTPI for FSTPI, in order to reduce torque ripples in comparison with the conventional DTC method for FSTPI. The validity of new technique is verified by simulation results which demonstrate the good performance of DTC for FSTPI fed IM, while the good responses of the flux, torque, current and speed are obtained. Also adaptive flux observer used for rotor flux, speed and stator resistance estimation. The sensor-less speed control of DTFC of IM using FSTPI strategy provides fast dynamic responses with no overshoot and negligible steady-state error.

The simulation results verify the accuracy of the proposed method of stator resistance, rotor flux and speed estimation at very low speed as well as zero speed under high load torque operations.

REFERENCES


APPENDIX I

The parameters of applied induction machine

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power</td>
<td>1 kW</td>
</tr>
<tr>
<td>Rated load torque</td>
<td>6 N.m.</td>
</tr>
<tr>
<td>No. of poles</td>
<td>4</td>
</tr>
<tr>
<td>Stator resistance</td>
<td>4.85 ohm</td>
</tr>
<tr>
<td>Rotor resistance</td>
<td>2.6840 ohm</td>
</tr>
<tr>
<td>Rotor leakage inductance</td>
<td>0.0221 H</td>
</tr>
<tr>
<td>Stator leakage inductance</td>
<td>0.0221 H</td>
</tr>
<tr>
<td>Mutual inductance</td>
<td>0.4114 H</td>
</tr>
<tr>
<td>Supply frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Motor speed</td>
<td>1500 r.p.m.</td>
</tr>
<tr>
<td>Supply voltage</td>
<td>380 volts</td>
</tr>
<tr>
<td>Inertia</td>
<td>0.018 kg.m²</td>
</tr>
</tbody>
</table>

Authors

Dr. M. K. Metwally: received his doctoral degree in electrical engineering from Vienna University of Technology, Austria in March 2009. He is a lecturer in the Department of Electrical Engineering, Minoufiya University, Egypt. His research interests cover AC machines control, the transient excitation of AC machines, sensorless control techniques, and signals processing.