Sensorless Twelve Sector Implementation of DTC Controlled IM for Torque Ripple Reduction

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Abstract—A Direct Torque Control (DTC) drive allows direct and independent control of flux linkage and electromagnetic torque by the selection of optimum inverter switching tables. There is no need for any complex transformation of current or voltage. However, each vector selected from the switching table cannot produce the required accurate stator voltage vector to provide the desired torque and flux. This results in the production of ripples in the torque as well as flux waveforms. In this study, we propose a method to reduce torque fluctuations. In this method, the circular flux vector is divided into twelve sectors of 30 degrees and is compared to conventional DTC method. Speed is estimated from MRAS. The conventional MRAS-based sensorless DTC and the twelve sectors method are simulated and the comparison of their performances is presented.

Keywords—Induction motor, Direct torque control, Twelve sector method, MRAS, Torque ripple.

I. INTRODUCTION

Nowadays, induction motors are widely used in the industry due to their simple form and low maintenance need. Many different methods have been tried to control the induction motors. For years, the induction motor control market is dominated by the vector control methods. However, the latest trend is the development of the direct torque control (DTC) because it is simple, fast and more advantageous [2], [5]. The direct control method is sufficient to control with respect to changes in the machine parameters without using reverse current regulation in addition to providing fast dynamic torque response. The Direct Torque Control strategy does not require axes transformation and voltage decoupling blocks [1].

However, the generation of only six non-zero voltage vectors by the voltage source inverter is a drawback. The required torque is met for only few switching instants and mostly the generated voltage vectors produce a torque that is either more or less than the required torque. As a result, ripples are generated in the torque as well as flux waveforms [6]. Increasing the inverter switching frequency by a space vector modulation scheme is proposed for the torque ripple reduction [7]-[8]. The concept of dead beat controller is used to increase the switching frequency. But this approach introduces complexity.

In this study, sensorless twelve sectors DTC method will be introduced. First, we will illustrate conventional DTC. Then, the concept of torque ripple reduction method will be discussed. The switching table for the selection of optimum voltage vector, MRAS speed estimation schema and balance equations will be presented. The simulated results will be then given for comparing the performance of the basic sensorless scheme and the new sensorless scheme.

II. CONVENTIONAL DTC METHOD

Direct torque control method (DTC) is based on applying a switching series, which shall directly eliminate errors, which shall occur in torque, through the reference given as value and the calculated flux, to the power switching elements in the inverter [10], [11]. Other vector control methods are mostly based on stator flux while DTC method is based on stator flux.

This may be realized by using motor model on the fixed α-β axis set. Stator flux, torque and stator flux sector zone may be calculated with the help of currents and voltages measured in the motor’s stator as the following [9].

\[ v_{s\alpha} = R_i i_{s\alpha} + \frac{d\psi_{s\alpha}}{dt} \]
\[ v_{s\beta} = R_i i_{s\beta} + \frac{d\psi_{s\beta}}{dt} \]
\[ T_e = p \left( i_{s\alpha} i_{s\beta} - i_{s\beta} i_{s\alpha} \right) \]
\[ \psi_{s\alpha} = \int \left( \psi_{s\alpha} - R_s i_{s\alpha} \right) dt \]
\[ \psi_{s\beta} = \int \left( \psi_{s\beta} - R_s i_{s\beta} \right) dt \]
\[ |\psi_s^*| = \sqrt{|\psi_{s\alpha}^2 + \psi_{s\beta}^2|} \]

Herein, Rs is stator phase resistance, \( p \) is the number of pole couple, \( i_{s\alpha}, i_{s\beta}, \psi_{s\alpha}, \psi_{s\beta}, V_{s\alpha}, V_{s\beta} \) are current, flux and voltage values on the axis of α-β. \( T_e \) is momentum. Amplitude of the vector of the torque and the stator flux calculated with the help of the above equations. The reference value of the stator flux magnitude is compared with the actual flux magnitude. The error obtained is given to a two-level hysteresis comparator. If the error is positive, it implies that the flux magnitude has to be
increased and this is denoted as \( d\psi = 1 \). If the error is negative, it implies that the flux magnitude has to be decreased and this is denoted as \( d\psi = 0 \). The flux comparator conditions are given as

\[
d\psi = 1 \quad \text{for} \quad |\psi_{ref} - |\psi_s| \geq |\Delta \psi| / 2
\]

\[
d\psi = 0 \quad \text{for} \quad |\psi_{ref} - |\psi_s| \geq |\Delta \psi| / 2
\]

The rotor reference speed is compared with the feedback speed and by a suitable PI controller this error is converted into reference torque. The reference torque is compared with the real torque and the error obtained is fed to a three-level hysteresis comparator. If the error is positive, it implies that the torque has to be increased and this is denoted by \( dt_e = 1 \). If the error is negative, it implies the torque has to be reduced and this is denoted by \( dt_e = -1 \). It the error is zero, it implies the torque needs to be constant and this is denoted by \( dt_e = 0 \). The torque comparator conditions are given as

\[
dt_e = 1 \quad \text{for} \quad |t_{ref} - |t| \geq |\Delta t_e| / 2
\]

\[
dt_e = -1 \quad \text{for} \quad |t_{ref} - |t| \leq |\Delta t_e| / 2
\]

\[
dt_e = 0 \quad \text{for} \quad |\Delta t_e| / 2 \leq |t_{ref} - |t|| \leq |\Delta t_e| / 2
\]

To accomplish optimum switching process, one of the 8 different voltage vectors consisting of 8 different switching is selected as seen in Figure 2. \( V_i \) (Sa, Sb, Sc) \((i=0,1,2...7)\) Besides 6 switching levels, there are \( V_0(0,0,0) \) and \( V_7(1,1,1) \) levels not producing a voltage at the output when they are applied [4].

Figure 2: Voltage Space Vector and Sector Representation

Assuming the stator flux linkage space vector to be in sector I and is rotating in counter clockwise direction, the resultant effect of generating different voltage vectors at this instant is given in the Fig.3

Figure 3: Voltage Space Vector for Flux and Torque Variation

Table 1, which is seen below, shows switching logics when the motor is desired to counter clockwise.

**TABLE I: OPTIMAL SWITCHING LOGICS FOR MOTOR ROTATING**

<table>
<thead>
<tr>
<th>( dt_e = 0 )</th>
<th>( V_0 )</th>
<th>( V_1 )</th>
<th>( V_2 )</th>
<th>( V_3 )</th>
<th>( V_4 )</th>
<th>( V_5 )</th>
<th>( V_6 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( dt_e = 1 )</td>
<td>( V_1 )</td>
<td>( V_2 )</td>
<td>( V_3 )</td>
<td>( V_4 )</td>
<td>( V_5 )</td>
<td>( V_6 )</td>
<td>( V_7 )</td>
</tr>
<tr>
<td>( dt_e = -1 )</td>
<td>( V_1 )</td>
<td>( V_2 )</td>
<td>( V_3 )</td>
<td>( V_4 )</td>
<td>( V_5 )</td>
<td>( V_6 )</td>
<td>( V_7 )</td>
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### III. TWELVE SECTOR STRATEGY

In the conventional DTC, every sector has two cases. This creates an uncertainty in the torque and flux within a 60 degree band. If we seek for a more stable switching by using all six active vectors within a sector, the flux trajectory should be divided into twelve sector instead of six sectors. This division is illustrated in the Figure 4. Here, we also need to define the concept of small and large for the torque[3]. For instance, at the sector 0(3) \( V_6 \) switching generates a large flux increase and a small torque reduction. On the other hand, \( V_5 \) switching reduces the torque for a larger amount and keeps the flux in the same value. Therefore, the hysteresis band of the torque is divided into four parts as follows: \( \tau = 1 \) for small increase in the torque, \( \tau = 2 \) for large increase in the torque, \( \tau = -1 \) for small reduction in the torque and \( \tau = -2 \) for large reduction in the torque. Thus, the error in the torque is measured in four different values.
Figure 4: Switching vector for twelve sector DTC

Table 2
SWITCHING TABLE FOR SECTORS 1 TO 6

<table>
<thead>
<tr>
<th>( \psi =1 )</th>
<th>( \tau =2 )</th>
<th>( \tau =1 )</th>
<th>( \tau =-1 )</th>
<th>( \tau =-2 )</th>
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</thead>
<tbody>
<tr>
<td>( \theta(1) )</td>
<td>( \theta(2) )</td>
<td>( \theta(3) )</td>
<td>( \theta(4) )</td>
<td>( \theta(5) )</td>
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</tbody>
</table>

Table 3
SWITCHING TABLE FOR SECTORS 7 TO 12

<table>
<thead>
<tr>
<th>( \psi =1 )</th>
<th>( \tau =2 )</th>
<th>( \tau =1 )</th>
<th>( \tau =-1 )</th>
<th>( \tau =-2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \theta(7) )</td>
<td>( \theta(8) )</td>
<td>( \theta(9) )</td>
<td>( \theta(10) )</td>
<td>( \theta(11) )</td>
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</tbody>
</table>

The same block diagram described in the Figure 1 is used but the optimum switching table and the torque control hysteresis band are varied to be in the four levels given as

\[
\begin{align*}
    dt_e &= 2 \quad \text{for} \quad |f_{\text{ref}}| - |f_x| \geq |\Delta t_e| / 2 \\
    dt_e &= 1 \quad \text{for} \quad |\Delta t_e| / 2 \geq |f_{\text{ref}}| - |f_x| \geq 0 \\
    dt_e &= -1 \quad \text{for} \quad 0 \geq |f_{\text{ref}}| - |f_x| \geq |\Delta t_e| / 2 \\
    dt_e &= -2 \quad \text{for} \quad |f_{\text{ref}}| - |f_x| \leq -|\Delta t_e| / 2
\end{align*}
\] (12) (13) (14) (15)

Table 2-3 presents the twelve sectors DTC switching table.

IV. MODEL REFERANCE ADAPTIVE SYSTEM (MRAS)

The MRAS technique is used in sensorless IM drivers, at the first time, by Schauder[14]. Figure 3 since this, it has been a topic of many applications [1]. In a MRAS system, some state variables, \( x_d, x_q \) (e.g. rotor flux-linkage components, \( \psi_{rd}, \psi_{rq} \) or back e.m.f. components, \( e_d, e_q \), etc.) of the induction machine (which are obtained by using measured quantities, e.g. stator voltages and currents) are estimated in a reference model and are then compared with state variables \( \hat{x}_d, \hat{x}_q \) estimated by using an adaptive model. The difference between these state variables is then used in an adaptation mechanism, which outputs the estimated value of the rotor speed (\( \omega_r \)) and adjusts the adaptive model until satisfactory performance is obtained. Such a scheme is shown in Fig. 5 where the actual implementation, and here the components of the space vectors are shown. The adaptation mechanism in the Figure 5 is a PI controller[15].

4.1. Rotor Speed Estimator

The rotor speed can be estimated by using two types of estimators (a reference-model-based estimator and an adaptive-model- based one). They independently determine the rotor flux-linkage components in the stator reference frame (\( \psi_{rd}, \psi_{rq} \)), and the difference between these flux-linkage estimates are used to drive the speed of the adaptive model. The rotor flux linkages in the stationary reference frame can be obtained by using the stator voltage and current equations of the induction machine in the stationary reference frame. These equations are shown below:

Reference Model:

\[
\begin{align*}
    \psi'_{rs} &= \frac{L_m}{L_{su}} \left[ \int (v_r - R_i_r) dt - L'_s i'_r \right] \\
    \psi'_{r\beta} &= \frac{L_m}{L_{su}} \left[ \int (v_{r\beta} - R_i_{r\beta}) dt - L'_s i'_{r\beta} \right]
\end{align*}
\] (16) (17)

Adaptive Model:

\[
\begin{align*}
    \hat{\psi}'_{rs} &= \frac{1}{T_s} \int \left( L_m i_{r\beta} - \psi'_{rs} - \omega_r T_s \psi'_{r\beta} \right) dt \\
    \hat{\psi}'_{r\beta} &= \frac{1}{T_s} \int \left( L_m i_{r\beta} - \psi'_{r\beta} - \omega_r T_s \psi'_{rs} \right) dt
\end{align*}
\] (18) (19)
Herein, \( T_r \) is rotor time constant, \( L_s \) is stator circuit leakage inductance, \( L_{rtr} \) is rotor circuit reduced leakage inductance, \( L_m \) is magnetization inductance. The reference and adaptive models are used to estimate the rotor flux – linkages and the angular difference of the outputs of the two estimators \( \varepsilon_\omega = \text{Im}(\psi_x, \dot{\psi}_x) = (\psi_{r, \alpha} \dot{\psi}_{r, \alpha} - \psi_{r, \beta} \dot{\psi}_{r, \beta}) \) is used as the speed tuning signal. This tuning signal is the input to a linear controller (PI controller) which outputs the estimated rotor speed as shown in Figure 6.

\[
\dot{\omega}_r = K_p \varepsilon_\alpha + K_i \int \varepsilon_\alpha \, dt \quad (20)
\]

Arbitrary \( K_p \) and \( K_i \) cannot be used to obtain satisfactory performance in this equation. The complete scheme of the flux based MRAS rotor speed observer is shown in Fig. 7.

![Flux estimator reference model](image1)

![Speed tuning signal](image2)

![Flux estimator adaptive model](image3)

![K_p + K_i](image4)

**Figure 6**: MRAS-based rotor speed observer flux linkages for the speed tuning signal

When the rotor speed to be estimated \( (\dot{\omega}_r) \) is changed in the adjustable model in such a way that the difference between the output of the reference model and the output of the adjustable model becomes zero, then the estimated rotor speed is equal to the actual rotor speed \( (\omega_r) \). The error signal actuates the rotor-speed identification algorithm, which makes this error converge to zero. Estimated speed can be expressed as

**Figure 8**: Simulation of estimated speed (a)20 rpm, 40 rpm (b)60 rpm, 120 rpm

**Figure 9**: Simulation results of stator fluxes (a) CDTC (b)Twelve sector DTC

**Figure 10**: Simulation results of stator flux locus (a)CDTC (b)Twelve sector DTC

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**V. SIMULATION RESULTS**

The basic DTC and the new 12 sector method of DTC are simulated and the results obtained are compared for their performance in Fig. 8-12 for starting and steady state cases. Speed were estimated with flux-based MRAS.

In the steady state, the high magnitude ripples are quite absent. Also the number of oscillations in current and flux waveform is reduced. The 12-sector method is observed to give slightly better results.
VI. CONCLUSION
In this study, we present a method to reduce the torque fluctuations by increasing the number of the sectors in the conventional DTC. Two types of the conventional DTC methods and the twelve sectors DTC method are compared with respect to their torques, currents and fluxes and the speed estimation is obtained from the flux based MRAS. It is observed that increasing the number of the sectors and changing the switching table have partially improved the torque and the flux.

APPENDIX
The parameters of the three-phase Induction motor, employed for simulation purpose, in SI units are $P_{\text{max}}=3000\text{W}$, $R_s=1.93$, $R_r=1.45$, $L_s=12.2\times10^{-3}\text{H}$, $L_r=0.19734\text{H}$, $L_m=0.1878$, $p=2$, $J=0.03\text{Kg}\cdot\text{m}^2$, $T_T=L_t/R_r$.

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