In this paper, the authors propose a Sensorless Direct Torque and Flux Control (DTFC) of Induction Motor (IM) using two approach intelligent techniques: Mamdani Fuzzy Logic (FL) controller is used for controlling the rotor speed and Artificial Neural Network (ANN) applied in switching select stator voltage. We estimated the rotor speed by using the Model Reference Adaptive Systems (MRAS). The control method proposed in this paper can reduce the torque, stator flux and current ripples and especially improve system good dynamic performance and robustness in high and low speeds.

Keywords: Induction Motor, Sensorless DTFC, Fuzzy Logic Controller, Artificial Neural Network, MRAS.

1 Introduction

The induction motor is one of the most widely used machines in industrial applications due to its high reliability, relatively low cost, and modest maintenance requirements. High performance electric drives require decoupled torque and flux control. This control is commonly provided through Field Oriented Control (FOC), which is based on decoupling of the torque-producing current component and the flux-producing component. FOC drive scheme requires current controllers and coordinate transformations. Current-regulated pulse-width-modulation inverter and inner current loops degrade the dynamic performance in the operating regimes wherein the voltage margin is insufficient for the current control, particularly in the field weakening region [1].

The problem of decoupling the stator current in a dynamic fashion is avoided by DTFC. Direct Torque and Flux Control (DTFC) is nowadays widely used for induction motor drives, her provides a very quick and precise torque response without the complex field orientation block and the inner current regulation loop [2, 3]. The disadvantages of conventional DTC are high torque ripple and slow transient response to the step changes in torque during start-up [4, 5]. For that reason the application of Fuzzy logic and artificial neural network attracts the attention of many scientists from all over the word [6]. The reason for this trend is the many advantages which the architectures of ANN have over traditional algorithmic methods [7]. Among the advantages of ANN are the ease of training...
and generalization, simple architecture, possibility of approximating non linear functions, insensitivity to the distortion of the network, and inexact input data [6, 8].

On the other hand, ongoing research has concentrated on the elimination of the speed sensor at the machine shaft without deteriorating the dynamic performance of the drive control system [9]. The advantages of speed sensorless induction motor drives are reduced hardware complexity and lower cost, reduced size of the drive machine, elimination of the sensor cable, better noise immunity, increased reliability and less maintenance requirements.

In this paper we present the performance of the sensorless speed control of induction motor using a speed proportional integral (PI) Fuzzy controller. The artificial neural network then replaces the switching table of the conventional DTFC while the rotation speed is estimated by the MRAS method. This paper organized as follows: The induction model is presented in the second section, the DTFC based Artificial Neural Network is developed in the third section, the speed PI Fuzzy controller design is performed in the fourth section, section five present a speed MRAS estimator and section six is devoted to illustrating by simulation the performances of this control strategy, a conclusion and reference list end the paper.

2 Induction Motor Model

The state equation of induction motor written in stator reference frame, \((\alpha, \beta)\) coordinates, can be expressed as follows:

\[
\begin{align*}
\dot{X} &= A(\omega).X + B.U \\
Y &= C.X
\end{align*}
\]

Where A, B and C are the evolution, the control and the observation matrices respectively.

\[
X = \begin{bmatrix} i_{s\alpha} & i_{s\beta} & \Phi_{s\alpha} & \Phi_{s\beta} \end{bmatrix}; U = \begin{bmatrix} V_{s\alpha} \\ V_{s\beta} \end{bmatrix}; Y = \begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix}
\]

\[
A = \begin{bmatrix}
-\left(\frac{1}{\sigma T_s} + \frac{1 - \sigma}{\sigma T_r}\right) & 0 & \frac{1 - \sigma}{\sigma M T_r} & \frac{1 - \sigma}{\sigma M} \\
0 & -\left(\frac{1}{\sigma T_s} + \frac{1 - \sigma}{\sigma T_r}\right) & -\frac{1 - \sigma}{\sigma M} & \frac{1 - \sigma}{\sigma M T_r} \\
\frac{M}{T_r} & 0 & -\frac{1}{T_r} & -\omega \\
0 & \frac{M}{T_r} & \omega & -\frac{1}{T_r}
\end{bmatrix}
\]
\[
B = \begin{bmatrix}
\frac{1}{\sigma L_s} & 0 \\
0 & \frac{1}{\sigma L_s} \\
0 & 0 \\
0 & 0
\end{bmatrix}, \quad C = \begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0
\end{bmatrix}
\]

With, \(\omega\) Rotor speed and the machine’s parameters: \(R_s, R_r\) are respectively the stator and the rotor resistance, \(M, L_s, L_r\) are respectively the mutual, the stator and the rotor cyclic inductances; \(p\) denotes the number of pole pairs, with:

\[
T_r = \frac{L_r}{R_r}, \quad T_s = \frac{L_s}{R_s}, \quad \sigma = 1 - \frac{M^2}{L_s L_r}
\]

The mechanical equation is the following:

\[
J \frac{d}{dt} \Omega = C_e - C_r - f \cdot \Omega
\]  \(2\)

In which \(J\) is the inertia coefficient and \(C_r\) is the load torque. Using the Laplace transform, the equation (3) shows that the relation between the stator flux and the rotor flux represents a low pass with time constant \(\sigma T_r\).

\[
\Phi_r = M \frac{\Phi_s}{L_s + \sigma T_r S}
\]  \(3\)

The electromagnetic torque can be expressed as

\[
C_e = \frac{3}{2} \left( \Phi_{sa} i_{s\beta} - \Phi_{s\beta} i_{sa} \right)
\]  \(4\)

### 3 DTFC Scheme for Induction Motor

#### 3.1 DTFC Strategy

The block diagram of the proposed sensorless control scheme is shown in figure 1. The DTFC method was introduced in 1985 by Takahashi [10]. This strategy of control is relatively new and competitive compared to the rotor flux oriented method.

This type of control is based on the directly determination of the sequence of control applied to the switches of a tension inverter. This choice is generally based on the use of hysteresis regulators, whose function is to control the state of the system, and to modify the amplitude of the stator flux and the electromagnetic torque.
The stator flux, as given in equation (5), can be approximated as equation (6) over a short time period if the stator resistance is ignored.

\[
\Phi_s = \Phi_{so} + \int_0^t (V_s - R_s I_s) dt \quad (5)
\]

\[
\Phi_s \approx \Phi_{so} + \int_0^t V_s dt \quad (6)
\]

During one period of sampling Te, vector tension applied to the machine remains constant, and thus one can write

\[
\Phi_s (k + 1) \approx \Phi_s (k) + V_s T_e \quad (7)
\]

Or

\[
\Delta \Phi_s \approx V_s T_e \quad (8)
\]

Therefore to increase the stator flux, we can apply a vector of tension that is co-linear in its direction and vice-versa.
Fig. 2. Definition of stator flux increment and spatial positions of the voltage vectors keeping the flux inside the strip of hysteresis.

Fig. 3. Components of the error of flux at the time of the application of the vector $V_2$ voltage

If the error of flux is projected on the direction of stator flux and on a perpendicular direction (Fig.3), one puts in evidence the components acting on the torque and on the flux. In the Figure 3, the component $\Delta \Phi_{sc}$ gives the electromagnetic Torque of the Induction motor while the component $\Delta \Phi_{sf}$ modifies the magnitude of stator flux.

The torque is produced by the induction motor can be expressed as equation:

$$Ce = \frac{3}{2} p \frac{M}{\sigma L_s L_r} \Phi_s \Phi_r \sin \gamma$$

(9)
The torque depends upon the amplitude of the two vectors stator flux $\Phi_s$ and rotor flux $\Phi_r$, and their relative position $\gamma$. If one succeeds in perfectly controlling the flux $\Phi_s$ (starting with $V_s$) in module and in position, one can subsequently control the amplitude and the relative position of $\Phi_r$ and therefore ultimately, the torque.

When flux is in sector $S_i$, the vectors $V_{i+1}$ or $V_{i-1}$ are selected to increase the amplitude of flux, and $V_{i+2}$ or $V_{i-2}$ to decrease it. What shows that the choice of the vector tension depends on the sign of the error of flux, independently of its amplitude. This explains why the exit of the corrector of flux can be a Boolean variable. One adds a bond of hysteresis around zero to avoid useless commutations when the error of flux is small. Indeed, with this type of corrector in spite of his simplicity, one can easily control and maintain the end of the vector flux, in a circular ring. The switching table proposed by Takahashi [10], as given by Table 1.

<table>
<thead>
<tr>
<th>$\Delta \phi_s$</th>
<th>$\Delta C_e$</th>
<th>$S_1$</th>
<th>$S_2$</th>
<th>$S_3$</th>
<th>$S_4$</th>
<th>$S_5$</th>
<th>$S_6$</th>
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<td>101</td>
<td>100</td>
<td>110</td>
<td>010</td>
<td>011</td>
</tr>
</tbody>
</table>

Table1. Switching table

3.2 Artificial Neural Network DTFC

The Artificial neural network replaces the switching table selector bock. He uses a dense interconnection of computing nodes to approximate nonlinear function [8]. The neural network selector inputs proposed are the position of flux stator vector represented by the number of the corresponding sector, the error between its estimated value and the reference value and the difference between the estimated electromagnetic torque and the torque reference that is to say three neurons of the input layer (Figure 4). The output layer is composed of three neurons, each representing the state $E_i$ of one of the three pairs of switches $T_i$ of the inverter connected to the positive DC bus.
After several tests we take an architecture 3-12-3 with a single hidden layer.

The function $f(n)$ activation of the hidden layer is Tansig:

$$a = \frac{e^n - e^{-n}}{e^n + e^{-n}}$$  \hspace{1cm} (14)

While the activation function of the output layer is Purelin.

$$a = n$$  \hspace{1cm} (15)

The learning of the neural network is done by using the algorithm LVM (levenberg Marquardt) with a number of epochs 500 and an error of $10^{-3}$.

## 4 PI Fuzzy Controller

The block diagram of the PI Fuzzy controller is shown in fig. 5, where the variables $K_p$, $K_i$ and $B$ are used to tune the controller.

One possible initial rule base, that can be used in drive systems for a fuzzy logic controller, consist of 49 linguistic rules, as shown in Table 2, and gives the change of the output of fuzzy logic controller in terms of two inputs: the error ($e$) and change of error ($de$). The membership functions of these variables are given in Fig.6:
In Table 2, the following fuzzy sets are used: NL negative large, NM negative medium, NS negative small, ZR zero, PS positive small, PM positive medium and PL positive large. For example, it follows from Table 2 that the first rule is:

$$\text{IF } \text{e is NL and } \text{de is NL then } \text{du is NL}$$

Table 2. Fuzzy rules base

<table>
<thead>
<tr>
<th>E/de</th>
<th>NL</th>
<th>NM</th>
<th>NS</th>
<th>ZR</th>
<th>PS</th>
<th>PM</th>
<th>PL</th>
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<td>ZR</td>
<td>PS</td>
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<td>PL</td>
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<tr>
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<tr>
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<td>NL</td>
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<td>NS</td>
<td>ZR</td>
<td>PS</td>
<td>PM</td>
</tr>
<tr>
<td>NM</td>
<td>NL</td>
<td>NL</td>
<td>NL</td>
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<td>NS</td>
<td>ZR</td>
<td>PS</td>
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<tr>
<td>NL</td>
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<td>NL</td>
<td>NL</td>
<td>NL</td>
<td>NM</td>
<td>NS</td>
<td>ZR</td>
</tr>
</tbody>
</table>

The linguistic rules are in the form of IF-THEN rules and take form: IF (e is X and de is Y) then (du is Z), where X, Y, Z are fuzzy subsets for the universe of discourse of the error, change of error and change of the output. For example, X can denote the subset NEGATIVE LARGE of the error etc. On every of these universes is placed seven triangular membership functions (fig.6). It was chosen to set these universes to normalized type for all of inputs and output. The range of universe is set to -1 to 1.

5 Speed Estimation with MRAS

A linear state observer for the rotor flux can then be derived as follows by considering the mechanical speed as a constant parameter since its variation is very slow in comparison with the electrical variables.

The symbol * denotes an estimated quantity.
Fig. 7. Adaptive observer structure

Since the reference model doesn't depend on the rotation speed, it allows to calculate the components of rotor flux from the equations of the stator voltage:

\[
\frac{d\Phi_{ra}}{dt} = \frac{1}{a} (V_{s\alpha} - R_s I_{s\alpha} - \frac{1}{\delta} \frac{dI_{s\alpha}}{dt})
\]

\[
\frac{d\Phi_{r\beta}}{dt} = \frac{1}{a} (V_{s\beta} - R_s I_{s\beta} - \frac{1}{\delta} \frac{dI_{s\beta}}{dt})
\]

(17)

With

\[
\delta = \frac{1}{\sigma L_s}, \quad a = \frac{M}{L_r}, \quad k = \frac{R_r}{L_r}
\]

The observer model uses the speed of rotation in its equations and permits to estimate the components of rotor flux:

\[
\frac{d\hat{\Phi}_{ra}}{dt} = -k.\Phi_{ra} - p\hat{\Omega}\Phi_{r\beta} + k.M.I_{s\alpha}
\]

\[
\frac{d\hat{\Phi}_{r\beta}}{dt} = -k.\Phi_{r\beta} + p\hat{\Omega}\Phi_{ra} + k.M.I_{s\beta}
\]

(18)

The adaptation mechanism compares the two models and estimates the speed of rotation by an integral proportional regulator. Using Lyapounov stability theory, we can construct a
mechanism to adapt the mechanical speed from the asymptotic convergence’s condition of the state variables estimation errors.

\[
\dot{\Omega} = K_p (\hat{\Phi}_{ra} \dot{\Phi}_{r\beta} - \Phi_{ra} \dot{\Phi}_{r\beta}) + K_f \int (\hat{\Phi}_{ra} \Phi_{r\beta} - \Phi_{ra} \Phi_{r\beta}) \, dt \tag{19}
\]

\( K_p \) and \( K_f \) are positive gains.

6 Simulation Results

To study the performance of the sensorless speed control, PI fuzzy controller of speed and neural network switching table with direct torque control strategy, the simulation of the system was conducted using Matlab/Simulink, Fuzzy logic Toolbox and neural network Toolbox. The torque and flux hysteresis bands of 0.5Nm and 0.01Wb respectively were used to give a switching frequency close to 10 kHz at the chosen motor speed and load.

6.1 Control Speed

The stator flux reference is fixed to 1Wb and we impose a speed of reference varying between -1146 rpm and +1146 rpm:
6.2 Low Speed functioning

We set the rotor flux to 1Wb and verify the operation at low speed between 10rad/s and -10rad/s;
6.3 High speed functioning

In the high-speed, we use the law of change of stator flux depending on the rotor speed shown in the following figure [14].

![Reference rotor flux law](image)

Fig.10: Reference rotor flux law

With $\Omega_n$: nominal speed of rotation,

$\Phi_{sn}$: face value of the stator flux.

We keep the same condition of the speed control and impose a rotor speed of 1720 rpm:

![Flux plots](image)
Figure 8 shows the estimated speed, stator flux and stator current with DTFC scheme and MRAS technique. Estimated speed follows the reference speed closely. The stator phase current in the induction motor remains sinusoidal and takes appropriate value.

Figure 9 shows simulation results of the proposed approach at low speed (±10rad/s). We can see good dynamic behavior and steady state responses of flux and speed. Some estimated speed oscillations can be observed.

Figure 11 illustrate the performance of this strategy in high speed functioning. The estimated speed follows perfectly the speed reference. It is important to note that the control system remain stable.

With the obtained results we can estimate the rotor speed in the different working especially in low and high speed. The dynamics of stator flux and the speed estimated are better. The stator phase current in the induction motor remains sinusoidal and takes appropriate value. This strategy of control reduces remarkably the flux, current and torque ripples. The stator flux vector describes a trajectory almost circular.

7 Conclusions

The control strategy that we have introduced in this paper presents the following advantages:

- Operating without speed sensor.
- good dynamic behavior and steady state responses of speed and flux even at low and high speed
- The stability of system.
- Limitation of the current amplitude and low distortions for current and torque.
- No flux droppings caused by sector changes circular trajectory.
- Flux and torque ripples reduced.
In comparison with some strategies of control presented in literature (Field oriented control, basic DTC, DTC without fuzzy logic controller), this strategy makes the induction motor based DTFC more robust, more stable and good dynamic performance even in high speed.

Our future research work would take into account the variation of the stator resistance and the implementation of this strategy on the DS1104 board from dSPACE.

8 References


9 Appendix

<p>| | |</p>
<table>
<thead>
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</tr>
</thead>
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</tr>
<tr>
<td>Rated voltage V</td>
<td>220 V</td>
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<tr>
<td>Stator resistance Rs</td>
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<tr>
<td>Rotor resistance Rr</td>
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</tr>
<tr>
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<td>0.160 H</td>
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<tr>
<td>Mutual inductance M</td>
<td>0.058 H</td>
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<tr>
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<tr>
<td>Number of pole pairs p</td>
<td>2</td>
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Table 3. Induction motor data