NEURO-FUZZY APPLIED TO THE DIRECT TORQUE AND REACTIVE POWER CONTROL OF DOUBLY FED INDUCTION MOTOR

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Abstract—This paper proposes a Takagi-Sugeno neuro fuzzy inference system for direct torque and stator reactive power control applied to a doubly fed induction motor (DFIM). The control variables (d-axis and q-axis rotor voltages) are determined through a control system composed by a neuro-fuzzy inference system and a first order Takagi-Sugeno fuzzy logic controller. Experimental results are presented to validate the controller operation for variable speed under no-load and load conditions and stator reactive power variation under load condition. For this last validation, a PI controller is used to control the rotor speed, thereby its output is used to manipulate the torque in order to follow the demanded speed value.

Keywords— Doubly fed induction motor, direct torque control, reactive power control, ANFIS, neuro-fuzzy control.

LIST OF SYMBOLS

\begin{align*}
\begin{array}{ll}
\mathsf{r}_s, \mathsf{r}_r & \text{stator and rotor resistances;} \\
\mathsf{L}_s, \mathsf{L}_r, \mathsf{L}_m & \text{stator, rotor, and mutual inductances;} \\
\sigma & \text{total leakage factor;} \\
\omega_1, \omega_2, \omega_r & \text{synchronous, slip, and rotor angular frequency;} \\
\theta_1, \theta_2, \theta_r & \text{stator flux, slip, and rotor angles;} \\
P, Q & \text{active and reactive power;} \\
T_{em} & \text{electromagnetic torque;} \\
\mathbf{V}, \mathbf{I}, \mathbf{ψ} & \text{voltage, current, and flux space vectors;} \\
v, i, \psi & \text{voltage, current, and flux components;} \\
p & \text{number of poles.}
\end{array}
\end{align*}

Superscripts

\begin{align*}
* & \text{reference value;} \\
\hat{\text{~}} & \text{estimated value.}
\end{align*}

Subscripts

\begin{align*}
s, r & \text{stator and rotor;} \\
\alpha, \beta & \text{direct- and quadrature-axis expressed at stationary reference frame;} \\
d, q & \text{direct- and quadrature-axis expressed at synchronous reference frame;} \\
m, n & \text{direct- and quadrature-axis expressed at rotor reference frame;} \\
1, 2 & \text{synchronous and slip.}
\end{align*}

1 INTRODUCTION

Doubly Fed Induction Machine (DFIM) is an attractive alternative to cage rotor induction and synchronous machines in high power applications. The interest occurs mainly in applications such as: generator for renewable energy (Blaabjerg and Iov, 2007; Datta and Ranganathan, 2002) and motor for ventilation systems and pumps (Vas, 1998).

For such applications, the stator windings are directly connected to the three phase grid with constant frequency and the rotor windings are supplied by a bidirectional power converter. This one is designed to handle about ±25% of the machines rating (Blaabjerg and Iov, 2007), becoming attractive the utilization of DFIM in large power systems.

Among all methods of electromagnetic torque and reactive power control for DFIM, the direct control techniques have become the preferred strategies for high dynamic performances. The techniques consist of an algorithm that generates directly the required rotor control voltage and their errors.

Based on the technique of Direct Torque Control (DTC) applied to induction machines (Takahashi and Noguchi, 1986), the Direct Power Control (DPC) using hysteresis controllers associated with a switching table was the first control strategy applied to the DFIM (Datta and Ranganathan, 2001; Xu and Cartwright, 2006). These controllers have the disadvantage of operating with variable switching frequency. This fact is overcome in (Zhi and Xu, 2007), where the constant switching frequency is obtained by calculating the required rotor control voltage for each switching period from the estimated stator flux, stator active and reactive power, and their errors.

In this context, this paper proposes a neuro-fuzzy controller based on direct torque and reactive power control for DFIM. Differing from (Jacomini and Bim, 2011), in this paper the control strategy is applied to DFIM as a motor instead of generator. The controller proposed consisting of a Neuro-Fuzzy Inference System (NFIS) combined to Takagi-Sugeno Fuzzy Logic Con-
controller (T-S FLC). From electromagnetic torque, stator reactive power, and rotor speed, the NFIS generates the direct and quadrature axes reference values of rotor voltage components in the stator-flux-oriented reference frame. The T-S FLC determines the increments in the voltage rotor components necessary to minimize the electromagnetic torque and stator reactive power errors.

This paper is organized as follows: Besides the introductory section, Vector control of DFIM is shown in section 2; The proposed control scheme is presented in section 3; Main simulated and experimental results are considered in section 4 in order to validate the proposed control scheme; and Finally, section 5 concludes the work.

2 BASIC CONCEPTS OF DFIM

VECTOR CONTROL

2.1 Stator-flux-oriented control

The modeling of DFIM is obtained at Stator-Flux-Oriented (SFO) reference frame. This approach implies the alignment of the direct axis with the stator flux vector, i.e., \( \overline{\psi}_{s,dq} = \psi_{sd} \), and therefore, \( \psi_{sq} = 0 \). In this way, the stator and rotor voltages, stator and rotor flux linkages equations can be written as:

\[
\bar{V}_{s,dq} = r_s \bar{T}_{s,dq} + \frac{d\psi_{sd}}{dt} + j\omega_1 \psi_{sd} \tag{1}
\]

\[
\bar{V}_{r,dq} = r_r \bar{T}_{r,dq} + \frac{d\psi_{rq}}{dt} + j\omega_2 \bar{\psi}_{r,dq} \tag{2}
\]

\[
\overline{\psi}_{s,dq} = \psi_{sd} = L_s \bar{T}_{s,dq} + L_m \bar{T}_{r,dq} \tag{3}
\]

\[
\overline{\psi}_{r,dq} = L_s \bar{T}_{r,dq} + L_m \bar{T}_{s,dq} \tag{4}
\]

According to the equations (3) and (4), the stator and rotor currents can be calculated as:

\[
\bar{T}_{s,dq} = \frac{\psi_{sd}}{\sigma L_s} - \frac{k_v}{\sigma L_s} \overline{\psi}_{r,dq} \tag{5}
\]

\[
\bar{T}_{r,dq} = \frac{\overline{\psi}_{r,dq}}{\sigma L_r} - \frac{k_s}{\sigma L_r} \psi_{sd} \tag{6}
\]

The electromagnetic torque, stator active and reactive power can be expressed by:

\[
T_{em} = \frac{3}{2} p \frac{L_m}{2} \psi_{sd} i_{rq} \tag{11}
\]

\[
P_s = \frac{3}{2} L_m \omega_1 \psi_{sd} i_{rq} \tag{12}
\]

\[
Q_s = \frac{3}{2} L_m \omega_1 \psi_{sd} \left( \frac{\psi_{rd}}{L_m} - i_{rd} \right) \tag{13}
\]

Under balanced grid voltage condition, taking into consideration equation (1), and if the voltage drop across the stator resistance is neglected, the equation for the stator voltage in steady-state conditions is given by:

\[
\bar{V}_{s,dq} = j\omega_1 \psi_{sd} \tag{10}
\]

It represents that the stator flux \( \psi_{sd} \) is a constant determined by the supply voltage magnitude and synchronous frequency \( \omega_1 \). Therefore, from equations (3), (7), (8), and (10), the electromagnetic torque and stator active power can be expressed, in terms of rotor current component \( i_{rq} \), as:

\[
T_{em} = -\frac{3}{2} \frac{L_m}{L_s} \psi_{sd} i_{rq} \tag{11}
\]

\[
P_s = -\frac{3}{2} \frac{L_m}{L_s} \omega_1 \psi_{sd} i_{rq} \tag{12}
\]

\[
Q_s = \frac{3}{2} \frac{L_m}{L_s} \omega_1 \psi_{sd} \left( \psi_{rd} - \frac{L_m}{L_s} \psi_{sd} \right) \tag{13}
\]

As a result, the model according to the orientation of the stator flux allows independent control of electromagnetic torque/stator active and reactive power through the rotor current components. In summary, \( T_{em} \) or \( P_s \) is controlled by \( i_{rq} \) and \( Q_s \) by \( i_{rd} \). Therefore, the rotor current components can be controlled to regulate the electromagnetic torque/stator active and reactive power.

2.2 Direct torque and reactive power control

In contrast to Stator-Flux-Oriented Control (SFOC), which the rotor current components are used as control variables, in DTC, the rotor flux components are used as control variables. From equations (5), (10), (7), and (9), the electromagnetic torque and stator reactive power can be expressed by:

\[
T_{em} = -\frac{3}{2} k_s \psi_{sd} \psi_{rq} \tag{14}
\]

\[
Q_s = k_s \omega_1 \psi_{sd} \left( \psi_{rd} - \frac{L_r}{L_m} \psi_{sd} \right) \tag{15}
\]

where: \( k_s = 1.5 \frac{L_m}{\sigma L_s L_r} \).

It is observed that the electromagnetic torque and stator reactive power are controlled by the rotor flux components \( \psi_{rq} \) and \( \psi_{rd} \), respectively, due to \( \psi_{sd} \) to be constant. For a clear understanding, it is used a vector diagram of DFIM, where the \( \delta_{\psi} \) is the angle between rotor and flux vectors.
3 PROPOSED DIRECT TORQUE AND STATOR REACTIVE POWER CONTROL BASED ON NEURO-FUZZY STRATEGY

From the electromagnetic torque and stator reactive power references, the control strategy based on neural-fuzzy inference system calculates the required rotor voltage components \(v_{rd}^*\) and \(v_{rq}^*\). The input variables of control strategy are \(T_{em}^*\), \(Q_s^*\) and rotor angular speed \(\omega_r\). To minimize the error of steady-state and to have a fast dynamic response of the torque and reactive power, it is added a Takagi-Sugeno fuzzy logic controller, which determines the increment necessary in the components of direct axis and quadrature rotor voltage \(\Delta v_{rq}\) and \(\Delta v_{rd}\).

3.1 Adaptive neural-fuzzy inference system and training

The rules base and membership functions are obtained in an automated process by an Adaptive Neural-Fuzzy Inference System (ANFIS) by using input-output data set. The parameters associated with the output and input membership functions are adjusted by the combination of backpropagation learning algorithm with a least squares type algorithm (Jang, 1993).

According to the property of ANFIS, it is only suitable to the multiple input and single output system. Therefore, as the proposed system requires three inputs and two outputs, it is necessary to use two ANFIS: one to provide \(v_{rd}^*\) (ANFIS 1) and another to provide \(v_{rq}^*\) (ANFIS 2).

![Figure 1: Implemented NFIS architecture.](image)

Fig. 1 shows this structure, when can be observed that it contains eight fuzzy Takagi-Sugeno if-then rules (Takagi and Sugeno, 1985) and two membership functions for each input variable. The functions of the nodes for each layer are described as follows:

- **Layer 1**: All nodes in this layer are adaptive, with the function defined by:

\[
O_{1,i} = \mu^{A_i}(T_{em}^*), \quad i = 1, 2
\]

\[
O_{1,i+2} = \mu^{B_i}(Q_s^*), \quad i = 1, 2
\]

\[
O_{1,i+4} = \mu^{C_i}(\omega_r), \quad i = 1, 2
\]

where: \(T_{em}^*, Q_s^*\) and \(\omega_r\) are the inputs in the nodes \(O_1\) and \(A_i\). The \(B_i\) and \(C_i\) are linguistic variables associated with these nodes. At the implementation the linguistic variables are denoted triangular function.

- **Layer 2**: The outputs of each node in this layer are the firing strength \(w_j\), that are determined by T-norm operators, defined by algebraic product (II Neuron).

\[
O_{2,j} = w_j = \mu^{A_i}(T_{em}^*) \times \mu^{B_i}(Q_s^*) \times \mu^{C_i}(\omega_r),
\]

for \(j = 1, 2, \ldots, 8\).

- **Layer 3**: The firing strength of each rule are normalized via \(N\) neuron, resulting in:

\[
O_{3,j} = \overline{w}_j = \frac{w_j}{w_1 + w_2 + w_3 + \ldots + w_8},
\]

for \(j = 1, 2, \ldots, 8\).

- **Layer 4**: All nodes in this layer are adaptive. The outputs of the nodes are calculated by the product of the normalized firing strengths and value of membership function for a first-order Sugeno fuzzy model.

\[
O_{4,j} = \overline{w}_j(p_j \cdot T_{em}^* + q_j \cdot Q_s^* + r_j \cdot \omega_r + s_j)
\]

for \(j = 1, 2, \ldots, 8\). Where: \(O_{4,j}\) is \(v_{rd,j}\) or \(v_{rq,j}\), and \(p_j, q_j, r_j, s_j\) are the parameters of the consequent parameter set.

- **Layer 5**: In this last layer, the output \(O_5\) of the neuro-fuzzy system is given by:

\[
O_5 = \sum_{j=1}^{8} \overline{w}(j)O_{4,j}
\]

where: \(O_5\) is \(v_{rd}\) or \(v_{rq}\).

3.2 Training data

The required input-output training data are obtained from a DFIM employing PI, using for this a SFOC simulation. From this simulation is sampled 135 training data for 27 Operation Points (OP), as shown in Table 1.
As presented in Fig. 3, the membership functions generated by ANFIS 1 and ANFIS 2, after training, are equal. Therefore, it simplifies the system shown in Fig. 1 for the compact one shown in Fig. 2. The number of training data and operating points were determined by Heuristic.

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<th>$T_{em}$</th>
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<th>$\omega$</th>
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<th>$v_{rd}$</th>
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### 3.3 The proposed T-S FLC

The proposed T-S FLC determines the increments $\Delta v_{rq}$ and $\Delta v_{rd}$ from the error of electromagnetic torque $\Delta T_{em}$ and stator reactive power $\Delta Q_s$, respectively. In Fig. 4 is shown the implemented architecture of the T-S FLC.

The architecture uses two gains for the inputs with fixed values ($G_{te}$ and $G_{qs}$) and for the outputs are introduced the gains $G_{vrd}$ and $G_{vrq}$ to match the values generated by weighting with the actual values of controller output variables.

#### 3.3.1 Membership functions

Fig. 5(a) uses a triangular membership functions for both inputs, where linguistic values are negative ($N$), positive ($P$), and zero ($ZE$).

#### 3.3.2 The fuzzy rule base

The T-S FLC has three rules (R1, R2, and R3). The set of $\Delta v_{rd}$ and $\Delta v_{rq}$ increments appears as follows:
using equations (8) and (9). The stator flux and torque and stator reactive power are calculated using the equation (25).

Fig. 5(b) illustrates the behavior of the output variables \(\Delta v_{rd}\) and \(\Delta v_{rq}\), which depends on the input variables \(\Delta Q_s\) and \(\Delta T_r\), respectively.

### 3.3.3 Aggregation process

The output of T-S FLC acts to reduce the error. If the error of the electromagnetic torque and stator reactive power is positive, then, their outputs will have a decrement. If the error is zero, the outputs will be zero.

The overall output of the T-S FLC implemented is the weighted average of the three individual outputs, given by:

\[
\Delta v_{rd}(\Delta Q_s) = \frac{\mu_N \Delta v_{rd}^{(1)} + \mu_{ZE} \Delta v_{rd}^{(2)} + \mu_P \Delta v_{rd}^{(3)}}{\mu_N + \mu_{ZE} + \mu_P} \\
\Delta v_{rq}(\Delta T_{rm}) = \frac{\mu_N \Delta v_{rq}^{(1)} + \mu_{ZE} \Delta v_{rq}^{(2)} + \mu_P \Delta v_{rq}^{(3)}}{\mu_N + \mu_{ZE} + \mu_P} \tag{24}
\]

In T-S FLC controller, it is not necessary the defuzzification interface (D. Driankov and Reinfrank, 1996). This occurs due to in Takagi-Sugeno fuzzy controllers each rule is already crisp and the total result is determined by the weighted sum of each rule, as is shown in equations (24).

### 3.4 Description of the implemented control system

In DFIM applications as motor, the speed control may be appropriate. Therefore, a speed control loop is employed by the use of a PI controller, in which delivery the demanded value for the reference electromagnetic torque. The schematic of the proposed DTC strategy is shown in Fig. 6.

The three-phase stator voltage and currents are obtained using the NFIS and T-S FLC algorithms. Thereafter, they are converted to the rotor (\(mn\)) reference frame using the stator flux and rotor angles given by:

\[
\overrightarrow{V}_{r, mn}(k) = \overrightarrow{V}_{r, dq}(k) \cdot e^{j[\theta_s(k) - \theta_r(k)]}. \tag{26}
\]

The control algorithm output yields the references values of the \(d\)-axis and \(q\)-axis rotor voltage, \(v_{r, dq}^{*}(k)\) and \(v_{r, dq}^{*}(k)\). Then, they are transformed into their two-axis components in the rotor reference frame \((v_{r, rm}^{*}(k)\) and \(v_{r, rq}^{*}(k)\)). Therefore, these signals are used to generate the PWM switching patterns by a SVM.

### 4 SIMULATED AND EXPERIMENTAL RESULTS

This section presents simulated and experimental results in order to validate the proposed DTC control strategy. With this objective, it is chosen and performed four tests. The experimental setup comprises a 2.25 kW DFIM mechanically coupled to a DC machine as load. The DFIM parameters are given in Table 2.

A power electronic converter comprised of Insulated-Gate Bipolar Transistor (IGBT) switches is used to supply the machine rotor. The DTC strategy is implemented with a Texas Instruments (TI) board (DSP TMS320F2812). In Digital Signal Processor (DSP) programming, two interruptions are used: 1) Interruption of 50\(\mu\)s for voltages and currents measurements, \(abc\) to \(\alpha\beta\) conversion of these variables, and angular position estimation; 2) Interruption of 200\(\mu\)s for calculation of rotor parameters (speed and position) through reading pulses generated by encoder, execution of the algorithms T-S FLC and NFIS that generates the values of \(v_{r, dq}^{*}\) and \(v_{r, rq}^{*}\) transformation of \(\overrightarrow{V}_{r, dq}\) to \(\overrightarrow{V}_{r, mn}\), and finally the execution of SVM algorithm.

<table>
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<th>Table 2: DFIM nominal values and parameters</th>
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<td>(P_s, V_s, f_s)</td>
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<tr>
<td>(r_s, r_r)</td>
</tr>
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<td>(L_s, L_r, L_m)</td>
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### 4.1 Performance test for the control strategy

In this first test, simulated and experimental results are verified to evaluate the steady-state performance and dynamic response of the control strategy. Initially, simulations are performed as tuning tests for the gain values \(G_{qs}, G_{ps}, G_{rd},\) and \(G_{rq}\) of the T-S-FLC. The results are presented side by side for a better comparison. Fig. 7 shows results for torque reference alternately varying from 10 Nm to -10 Nm, inside a period of 100m
seconds, while the stator reactive power reference is maintained at zero level. For this test the DFIM is driven by a DC motor. Fig. 7(a), (b), (g), and (h) show the torque and stator reactive power responses. It can be noted that both, experimental and simulated responses perfectly follow their respective references.

The three-phase instantaneous stator and rotor currents are shown in Fig. 7(c), (d), (i), and (j). Fig. 7(e) and (l) show the phase change between stator voltage and current, due to alteration of operating mode, from motor (positive torque) to generator (negative torque). Fig. 7(f) and (m) show the speed change, caused by torque manipulation. Depending on the torque balance between the DC motor and the DFIM, the machine sets accelerates or decelerates.

### 4.2 Load test

In this third test, the load used is a DC machine operating as generator. The response for a 9 Nm load torque is shown in Fig. 8, with the motor operating at 192 rad/s and the stator reactive power reference equal to 0 VAR. The speed response, Fig. 8(a), shows a null steady-state error. Fig. 8(b) and (c) shows stator reactive power and torque, respectively. It can be verified that the torque $T_{em}$ increases to account for load torque. In Fig. 8(d) and (e) is shown the three-phase instantaneous currents of stator and rotor, respectively. The load insertion causes a current increase as expected.
Figure 7: Simulated (a, b, c, d, e, and f) and experimental (g, h, i, j, l, and m) results under various torque steps with stator reactive power reference maintained at zero level.
5 CONCLUSION

In this paper was proposed a control scheme that combines NFIS with Takagi-Sugeno fuzzy logic controller. This strategy has shown that is possible decoupling torque and reactive power control of a DFIM by direct manipulation of rotor voltages, without the need of current controllers. The simulated and experimental results confirm the effectiveness of the control during several operating conditions. The performance is good, inclusively attending the requirements of fast dynamic response and minimal oscillation around the steady-state. Thus, this control strategy is an interesting tool for DFIM operational applications as motor.

The required input-output training data are obtained from a DFIM employing PI controllers cascaded, using for this a SFOC simulation. This in turn implies that the computational intelligence is forced to mimic the behavior of the classic PI control system, with the advantages of using only one control loop (advantage of not requiring current sensors), which is the power, unlike the control strategies using PI cascaded, which use two control loops. Moreover, proposed control strategy has met fast dynamic response.

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