Novel Observer Scheme of Fuzzy-MRAS Sensorless Speed Control of Induction Motor Drive

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Abstract. This paper presents a novel approach Fuzzy-MRAS conception for robust accurate tracking of induction motor drive operating in a high-performance drives environment. Of the different methods for sensorless control of induction motor drive the model reference adaptive system (MRAS) finds lot of attention due to its good performance. The analysis of the sensorless vector control system using MRAS is presented and the resistance parameters variations and speed observer using new Fuzzy Self-Tuning adaptive IP Controller is proposed. In fact, fuzzy logic is reminiscent of human thinking processes and natural language enabling decisions to be made based on vague information. The present approach helps to achieve a good dynamic response, disturbance rejection and low to plant parameter variations of the induction motor. In order to verify the performances of the proposed observer and control algorithms and to test behaviour of the controlled system, numerical simulation is achieved. Simulation results are presented and discussed to shown the validity and the performance of the proposed observer.

1. Introduction

The control and estimation of ac drives in general are considerably more complex than those of dc drives, and this complexity increases substantially if high performances are demanded [1]. However, for high dynamic performance industrial applications, their control remains a challenging problem because they exhibit significant non linearities and it is now well known that uncertainties of plant parameters and influence of unknown external disturbances can degrade significantly the performance of the system with linearizing feedback. To solve problems emerging in the control of such processes, advanced control strategies have researched. In recent years a lot of controllers have been reported in the literature and used in various industrial drive applications [2], and an interesting alternative that could be investigated is to use of artificial intelligence control strategy. In the electrical machines control, it is not possible to measure all the necessary variables in the control implementation. So, the search for observers to obtain state variables which can be used in the algorithm control is actively continued by researchers. The speed information must be reconstituted from the terminal quantities (voltage and current components) of the machine using flux observers which are based on the induction machine model. In the case of the model reference adaptive system (MRAS) methods, a comparison between the outputs of two estimates are made. Then, the output errors are used to derive a suitable adaptation mechanism that generates the estimated speed [3]. Then the rotor time constant is estimated using the stator currents estimation error and the observed rotor flux, based on the Lyapunov stability theory. In fact, fuzzy logic is reminiscent of human thinking processes and natural language.
enabling decisions to be made based on vague information [4]. The salient advantage of fuzzy logic is robustness against structured and unstructured uncertainties. In path tracking systems. In the reaching phase, tracking may be hindered by disturbances or parameter variations. In this paper, an integrate fuzzy logic into model reference adaptive system (MRAS), is proposed on the design of sensorless control schemes of the of induction motor drive to improve the stability and the robustness of the control system. The advantages of speed sensorless induction motor derives are reduced hardware complexity and lower cost, reduce size of derive machine, eliminate of sensor cable, better noise immunity, increasing reliability and less maintenance. The proposed control system is designed and tested through numerical simulation and its effectiveness in tracking application is verified. This paper is organized as follows: the model reference adaptive system observer is presented in Section 2. The section 3 describes the fuzzy logic controller. Finally, in sections 4 and 5, we give some comments and conclusions.

2. Model reference adaptive system observer

Schauder was the first to propose rotor flux MRAS, which is the most popularly used MRAS strategy. A lot of effort by the researchers has been focused on this strategy to further improve its performance [5].

2.1. Modeling of induction motor

Equations describing the induction machine dynamic model in the stationary frame (d,q) and the associated mechanical equation are expressed as follows:

\[
\begin{align*}
\frac{d}{dt} i_{sd} &= \frac{1}{\sigma \cdot L_s} \left[ -\left( R_s + \frac{L_m^2}{L_r \cdot T_r} \right) \cdot i_{sd} + \omega_s \cdot \sigma \cdot L_s \cdot i_{sq} + \frac{L_m}{L_r \cdot T_r} \cdot \phi_{sd} + \frac{L_m}{L_r} \cdot \omega_r \cdot \phi_{rq} + v_{sd} \right] \\
\frac{d}{dt} i_{sq} &= \frac{1}{\sigma \cdot L_s} \left[ -\omega_s \cdot \sigma \cdot L_s \cdot i_{sd} - \left( R_s + \frac{L_m^2}{L_r \cdot T_r} \right) \cdot i_{sq} + \frac{L_m}{L_r} \cdot \omega_r \cdot \phi_{sd} + \frac{L_m}{L_r} \cdot \phi_{rq} + v_{sq} \right] \\
\frac{d}{dt} \phi_{sd} &= \frac{L_m}{T_r} \cdot i_{sd} - \frac{1}{T_r} \cdot \phi_{sd} + (\omega_s - \omega_r) \cdot \phi_{rq} \\
\frac{d}{dt} \phi_{rq} &= \frac{L_m}{T_r} \cdot i_{sq} - (\omega_s - \omega_r) \cdot \phi_{sd} - \frac{1}{T_r} \cdot \phi_{rq} \\
\frac{d}{dt} \omega &= \frac{P}{J} \cdot \frac{L_m}{L_s \cdot J} \left( i_{sq} \phi_{rd} - i_{sd} \phi_{rq} \right) - \frac{F}{J} \omega - \frac{P}{J} \frac{T_i}{T_r}
\end{align*}
\]

where \( \sigma = 1 - \frac{L_m^2}{L_s \cdot L_r}; \frac{T_i}{T_r} = \frac{L_r}{R_r} \).

2.2 Direct field oriented control

Direct Field oriented control (DFOC) technique is intended to control the motor flux, and thereby be able to decompose the AC motor current into “flux producing” and “torque producing” components. The well known direct field orientation strategies provide a linear and decoupled control between the flux and torque of the induction machine [6],[7]. Then the rotor flux orientation process is given by the imposed zero constraint of quadrate rotor flux component. Such as:

\[
\phi_{rq} = 0 \quad \text{and} \quad \phi_{rd} = \phi_r
\]

Hence, the rotor flux can be controlled directly from the stator direct current component \( i_{sd} \), while the torque can be linearly controlled from the stator quadrate current component \( i_{sq} \) when the rotor flux is maintained constant. Separating the real and imaginary parts of (1) by using (2) leads to:
The slip frequency can be calculated from the values of the stator current quadrature and the rotor flux oriented reference frame as follow:

\[ \omega = \omega_s - \omega_t = \frac{L_m \cdot i_{sq}}{T_r \cdot \phi_r} \] (4)

And the rotor flux position is given by:

\[ \theta_r = \int \omega dt \] (5)

The voltages \( v_{sd} \) and \( v_{sq} \) should act on the current \( i_{sd} \) and \( i_{sq} \) separately and consequently the flux and the torque. The two-phase stators current are controlled by two PI controllers taking as input the reference values \( i_{sd}^*, i_{sq}^* \) and the measured values. Thus, the common thought is to realize the decoupling by adding the compensation terms \( e_{sd} \) and \( e_{sq} \) as usually done.

\[
\begin{align*}
    e_{sd} &= \omega_s L_s i_{sd} \\
    e_{sq} &= \omega_s L_s i_{sd} - \omega_s L_m \phi_r 
\end{align*}
\] (6)

The module of rotor flux is obtained by a block of field weakening given by the following non-linear relation:

\[
\phi_r = \begin{cases} 
    \phi_n & \text{if } |\omega| \leq \omega_n \\
    \frac{\phi_n}{|\omega|} & \text{if } |\omega| > \omega_n
\end{cases} \] (7)

The rotor flux is controlled by PI controller taking as input the reference value \( \phi^*_r \) and the calculated value.

### 2.3 Conventional IP controller

To accelerate the dynamic response of speed loop, and stabilize his behavior during transient states, the IP controller is often preferred to PI regulator. It has a good regulation properties and several advantages such as reduction, or even absence of overshoot in tracking trajectory.

The simplified block diagram of the speed loop based a IP controller is shown in Figure 1. This structure avoids the overshoots problem by canceling, in closed loop, the zero term present in the numerator of PI controller while imposing, two poles specified by a judicious choice of the damping ratio \( \xi \) and of natural angular frequency \( \omega_n \).

The closed loop transfer function is determined, considering the reference speed \( \Omega^* \) and a zero load torque \( T_l = 0 \):

\[
F(s)=\frac{\Omega^*_r(s)}{\Omega^*_r(s)} = \frac{\omega_n^2}{s^2 + 2 \xi \omega_n s + \omega_n^2} \] (8)

where: \( K_T = p \frac{\omega_n^2}{R_e} \), \( \omega_n = \frac{K_i K_T}{J} \) and \( \xi = \frac{F + K_p K_T}{2(J \cdot K_i \cdot K_T)^{1/2}} \)
The optimal setting is obtained for a damping ratio of the closed loop system equal to unity ($\xi = 1$), the dynamic of the system is then adjusted by the natural frequency. The proportional and integral coefficients are given by:

$$K_p = \frac{2J\omega_0 - F}{K_T}\text{ et } K_i = J\frac{\omega_0^2}{K_T}$$

(9)

However, although the responses obtained is more stable, they are insufficient for a drive system requiring high performance. Indeed, controller coefficients are fixed and do not adapt to various operating conditions or to parametric variations. Consequently, more sophisticated controllers are required, for this reason the adaptive controllers are an interesting alternative.

![Figure 1. Speed loop based a conventional linear IP controller](image)

### 2.4 MRAS Based For Stator Resistance, Rotor Time Constant and Fuzzy Rotor Speed Estimation

As it is already known, the most difficult aspects concerning the implementation of the electrical drive systems based on the field-orientation theory, are in relation with rotor flux components, speed and resistance parameters estimation. It has been already proved that simultaneous identification of the stator, rotor resistances and the rotor speed is possible only when the rotor flux is time-variant. The overall block diagram of direct field orientation control for induction motor is given in Figure 2. If the model of the induction motor is considered, the rotor speed and stator resistance and rotor time constant can be identified by approach of Model Reference Adaptive Systems (MRAS) [8],[9]. In the classical MRAS estimation method, there needs two models which outputs are to be compared. One is voltage model (or stator equation) and the other is current model (or rotor equation). The reference rotor flux components obtained from the reference model are given by [10]:

$$\phi_{\alpha} = \frac{L_r}{L_m} \left( (v_{sa} - R_i \alpha) dt - \alpha L_i \alpha \right)$$

$$\phi_{\beta} = \frac{L_r}{L_m} \left( (v_{sa} - R_i \beta) dt - \sigma L_i \beta \right)$$

(10)

The reference rotor flux components obtained from the reference model are given by:

$$\frac{d\phi_{\alpha}}{dt} = -\frac{1}{T_r} \phi_{\alpha} - \omega \phi_{\beta} + \frac{L_m}{T_r} i_{sa}$$

$$\frac{d\phi_{\beta}}{dt} = -\frac{1}{T_r} \phi_{\beta} + \omega \phi_{\alpha} + \frac{L_m}{T_r} i_{\beta}$$

(11)
A new structure MRAS is proposed in this paper based to stator resistance, rotor time constant and rotor speed estimation is designed based on the concept of hyperstability, in order to make, the system asymptotically stable. The configuration of the proposed scheme is shown in Figure 3. The reference model, usually expressed by the voltage model for speed estimation and rotor time constant and current model for stator resistance estimation, represents the stator and rotor equations. It generates the reference value of the rotor flux components in the stationary reference frame from the monitored stator voltage and current components.

**Figure 2.** Direct Field-Oriented Control for induction motor equipped with MRAS estimator.

**Figure 3.** Resistance parameters estimation and rotor speed under MRAS approach
The error equations for the voltage and the current model outputs can then be written as:

$$
\begin{align*}
\frac{de}{dt} &= \frac{\phi_r}{\Delta} - d_{\phi_r} \\
\frac{d\phi_r}{dt} &= \frac{e}{\Delta T_r} - d_{\phi_r}
\end{align*}
$$

(12)

The equation (10) can be rewritten in matrix notation by:

$$
\frac{de}{dt} = A \cdot e - W
$$

(13)

$$
A = \begin{bmatrix}
-\frac{1}{T_r} & -\omega & 0 & 0 \\
\omega & -\frac{1}{T_r} & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0
\end{bmatrix}
$$

and

$$
W = \begin{bmatrix}
0 & \left(-\frac{1}{T_r} + \Delta\omega\right) & \frac{\Delta}{T_r} & 0 \\
\left(-\frac{1}{T_r} + \Delta\omega\right) & 0 & \frac{\Delta}{T_r} & 0 \\
0 & 0 & \frac{L_c}{L_m} \Delta R_s & 0 \\
0 & 0 & 0 & \frac{L_c}{L_m} \Delta R_s
\end{bmatrix}
$$

The adaptation mechanism compares the two models and estimates the speed, rotor time constant and stator resistance by an integral proportional regulator. Using Lyapunov stability theory \[9\],[10], we can construct a mechanism to adapt the mechanical speed and stator rotor from the asymptotic convergence’s condition of the state variables estimation errors. The expressions for the speed and resistance tuning signal and the estimated speed and resistance can be given as :

$$
\begin{align*}
et &= \phi_r - \phi_{\hat{r}} \\
\hat{\omega} &= k_p \cdot \frac{\Delta\omega}{p} + k_i \cdot e_{\omega} \\
et_{\hat{r}} &= i_{\alpha} \left(\phi_{\hat{r}} - \phi_{\alpha}\right) + \phi_{\hat{\beta}} \left(\phi_{\hat{r}} - \phi_{\beta}\right) \\
\hat{\omega_{\hat{r}}} &= k_p \cdot \frac{\Delta\omega}{p} + k_i \cdot e_{\omega_{\hat{r}}}
\end{align*}
$$

(14)

$$
\begin{align*}
et &= \phi_r - \phi_{\hat{r}} \\
\hat{\omega} &= k_p \cdot \frac{\Delta\omega}{p} + k_i \cdot e_{\omega} \\
et_{\hat{r}} &= i_{\alpha} \left(\phi_{\hat{r}} - \phi_{\alpha}\right) + \phi_{\hat{\beta}} \left(\phi_{\hat{r}} - \phi_{\beta}\right) \\
\hat{\omega_{\hat{r}}} &= k_p \cdot \frac{\Delta\omega}{p} + k_i \cdot e_{\omega_{\hat{r}}}
\end{align*}
$$

(15)

The rotor resistance can then be written as:

$$
\hat{R}_r = \frac{R_{m\alpha}}{R_{m\beta}} \cdot \hat{R}_s = k \cdot \hat{R}_s
$$

(16)

### 3. Fuzzy logic controller

It appears that fuzzy logic based intelligent control is most appropriate for performance improvement of the ac machines. The main preference of the fuzzy logic is that is easy to implement control that it has the ability of generalisation \[11\],[12],[13]. The fuzzy adaptive control strategy is a new hybrid theory combining traditional linear control and Fuzzy Logic. Also different techniques have been developed in the last years, but they all need a lot of fuzzy rules increasing the complexity and the implementation of the control system.
In this section, a simple but robust, Fuzzy Self Tuning IP Controller is proposed, where the controller coefficients are adjusted on-line by an inference fuzzy system [14]. The proposed structure of the Fuzzy Self-Tuning IP Controller is shown in Figure 4.

![Figure 4. Speed loop based on Fuzzy Self-Tuning IP Controller proposed](image)

The structure of the conventional IP controller is preserved, but it is increased by a fuzzy inference system which must calculate the appropriate coefficients (kp, ki), and then provide them, in every time, to the controller. The transfer function F(s), in closed loop has the same expression as previously, but the values of coefficients are then given by non linear functions, independent of the parameters of the system, but linked to tracking error. This controller should be able to modify its characteristics and to maintain the desired dynamic of the system when the operating conditions evolve or in the presence of variations of motor parameters.

The Fuzzy Self-Tuning IP Controller proposed has the tracking error signal as single input, and two output, the coefficients kp and ki. The input variable is mapped into five fuzzy sets, distributed in the universe of discourse in the normalized range of [-2;+2]. These fuzzy sets are denoted by the followings linguistic variables NB (Negative Big), NS (Negative Small), ZE (Equal Zero), PS (Positive Small) and PB (Positive Big) respectively. For the two outputs variables, the universe of discourse is normalized in the range [0;1] and partitioned in three fuzzy sets S, M and B. These linguistic variables are denoted S (Small), M (Medium) and B (Big). The shapes of the selected membership functions for input are trapezoidal or triangular, and singletons type for the outputs, as shown in Figure 5 and Figure 6.

![Figure 5. Membership function for the tracking error e = Ω* − Ω_m](image)
To describe the overall operation of the controller, an inductive approach has allowed to incorporate into a knowledge base a small set of only five inference rules given below:

1) if (error is ZE) then (kp is B) and (ki is M)
2) if (error is PS) then (kp is S) and (ki is B)
3) if (error is NS) then (kp is M) and (ki is M)
4) if (error is NB) then (kp is M) and (ki is S)
5) if (error is PB) then (kp is M) and (ki is S)

For digital processing inferences, the following choices were privileged to reduce the complexity of the algorithm and computation times:
- for the AND method: mini operator,
- for the OR method: max operator,
- for the implication method: mini operator,
- for the aggregation method: max operator.

Then, the inference engine based on the input and outputs fuzzy sets, uses the inference rules of the knowledge base to determine the two final output fuzzy sets (Aggregated membership function). The centroid defuzzification method was used to obtain the crisp values of the output variables. This defuzzification technique can be expressed as:

$$z^* = \frac{\int \mu_A(z)dz}{\int \mu_A(z)dz} \quad (17)$$

Where $z^*$ is the crisp output, $\mu_A(z)$ is the aggregated membership function and $z$ is the output variable. The single input is transformed from value $e$ to the normalized value $E$ after multiplication with the error gain $G_e$. By the same procedure, the new input $E$ is treated by the rule base process to produce the two new normalized crisp variables $K_p$ and $K_i$, which are converted into the values $k_p$ and $k_i$ after multiplication with the output gains $G_p$ and $G_i$. The gains $G_e$, $G_p$ and $G_i$ are used to normalize the universe of discourse and to adjust the controller’s sensitivity.

4. Performance study

The described observer structure shown in figure 2 was implemented in the environment software Matlab/Simulink, and tested in various operating conditions. This software allows digital simulation of the systems using a same expression of the ordinary differential equations in the dynamic machine model as well as the controller. The numerical method for solving the equations is Runge-Kutta method. Fixed-step mode is chosen for the computational time interval, this will emulate the fixed sampling frequency of the real-time control. The sampling period is 1e-4 sec. The parameters of the induction motor and gains of different controllers used are given in Appendix. Figure 7,a-b-c-d...
shown simulation results of rotor speed an external force of 10 N.m, his disturbance can be seen at t = 0.8 sec and t = 1.2 sec and reference change at t = 2.5 s and 5s. Figure 8,a-b-c-d illustrate a response of sensorless drive system during starting operation with load 5 Nm, under conditions of low speed and with changes in load torque. The reference command imposes a speed step from 15 to -10 rad/s, the results obtained shown excellent performance even at low speeds, with precise estimates motor speed. The results shown very satisfactory performances in tracking trajectory, with a reaction time very low in transient state and a low error. The coefficients $k_p$ and $k_i$ delivered by the fuzzy inference system are variable and fits properly to speed changes. These figures shown clearly very satisfactory performance for the proposed sensorless controller in tracking and a remarkable pursuit between measured and estimated speed of the reference model speed. The control illustrates the correct signal issued by the fuzzy logic controller. There is an excellent direct field orientation consequence of a perfect decoupling between the flux and electromagnetic torque.

Figure 7.a Performance for rotor speed measured and desired with a load torque applied and removed

Figure 7.b Performance for rotor speed estimated and desired with a load torque applied and removed
Figure 7.c Performance for electromagnetic torque and stator current

Figure 7.d Performance for direct and quadratic rotor flux and stator current

Figure 8.a Performance with low speed for rotor speed measured and desired with a load torque applied and removed
Figure 8.b Performance with low speed for rotor speed estimated and desired with a load torque applied and removed

Figure 8.c Performance with low speed for electromagnetic torque and stator current

Figure 8.d Performance with low speed for direct and quadratic rotor flux and stator current

5. Conclusion
The objective of this paper is to design, develop, implement and test a new MRAS-Fuzzy Self-Tuning IP Speed Controller to improve the dynamic response of a three phase induction motor drive. The system was analysed and its performances were studied by numerical simulation to validate the
theoretical concepts. It has been shown that the proposed controller can provide the properties of insensitivity to uncertainties and external disturbances. The performance of the proposed controller scheme have evaluated under a variety of operating conditions of the induction motor drive. System performance, both in steady state error in speeds and dynamic conditions, was found to be excellent and there is not any overshoot. This study proves that it is possible to achieve a robust adaptive speed observer dedicate to sensorless control for induction motor based on combination of artificial intelligence algorithms

Appendix
Motor Parameters
1.5 kW, 3-phase, 220/380 V, 2.8/4.8 A, 50 Hz, 4 poles, 1420 tr/mn. Rs = 4.85Ω, Rr = 3.805Ω, Ls = 0.274 H, Lr=0.274H, Lm = 0.258 H, J = 0.031 kg.m², F = 0.00114 kg.m/s.

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