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Performance improvement of ANFIS with sliding mode based on MRAS sensorless speed controller for induction motor drive

Abstract: *This paper is focused on a performance improvement of ANFIS with sliding mode based on MRAS sensorless speed controller for induction motor drive associated with the IFOC strategy. The control strategy consists of the combination of the sliding mode with the ANFIS strategy. In order to estimate the speed of the IM, MRAS sensorless strategy associated with ANFIS system is used. This controller has high accuracy, suitable performance, high robustness and high tracking efficiency. To provide a numerical comparison between different controllers, a performance index based on speed error is assigned. The obtained results show that ANFIS Controller associated with MRAS observer overcome the problem of estimation of the speed of the motor particularly at low speed. The main advantages of the proposed method are the robustness to parameter variations and load changes.*

Streszczenie. *W artykule analizowano możliwość poprawy systemu ANFIS ze ślizgowym bezczujnikowym sterownikiem prędkości silnika indukcyjnego. Dla porównania różnych sterowników wprowadzono indeks bazujący na błędzie prędkości. Wykazano że system ANFIS z obserwatorem MRAS rozwiązuje problem określania prędkości szczególnie przy małych prędkościach.* ***Poprawa właściwości systemu ANFIS w sterowaniu silnikiem indukcyjnym w trybie ślizgowym bezczujnikowym z obserwatorem MRAS***

Key words: Induction motor (IM), Adaptive Neuro-Fuzzy Controller (ANFIS), sliding mode controller (SMC), MRAS observer.
Słowa kluczowe: silnik indukcyjny, ANFIS system, obserwator MRAS

Introduction

Nowadays, the AC Induction Motor is one of the most popular motors used in industrial applications. The induction machines are the most important group of all industrial electrical machines, converting approximately 70-80% of all electrical energy into mechanical form. The training of Induction Motor with Sliding Mode Control (SMC) has become very important in the field of electric vehicles [1]-[2]. The SMC has largely proven its effectiveness through several studies; it is robust in relation to disturbances and parameter variation [3]. However, it remains limited in the case of very strong oscillations which cause the chattering phenomenon [4]. The measurement of the speed of the induction machine as well as the electrical vehicle, requires the installation of a mechanical sensor. However, the introduction of this sensor leads to an additional cost that can be so important as that of the machine itself. So the sensorless control must be a good solution for this problem. The MRAS observer developed by Schauder [5] is used to estimate the speed [6]-[7]. In [8], a comparative study of three observers applied to the estimate the speed of the IM of an electric vehicle. Nevertheless the estimation of the speed raises a problem at low speed. From the first work on the order sensorless with state observers, engineers and researchers have noticed that the performance of the control is declined under certain operating conditions, particularly at low speeds [8]-[9].

Artificial intelligent controller combined with the sliding mode controller could be the best controller for IM drives [10]-[11]. This is due to artificial intelligent controller processes advantages as compared to the conventional controller PID-type and their adaptive schemes [12]. It has been well known that Proportional Integral Derivative (PID) controllers can be effectively used for linear systems, but usually cannot be used for higher order and nonlinear systems [13].Neural networks and fuzzy logic technique are quite different, and yet with unique useful capabilities in information processing by specifying mathematical relationships among numerous variables in a complex system, performing mappings with degree of imprecision, control of nonlinear system to a degree not possible with conventional linear systems. To overcome the drawbacks of neural networks and fuzzy logic, Adaptive Neuro-Fuzzy Inference System (ANFIS) was proposed in this paper. The ANFIS is, from the topology point of view, an implementation of a representative fuzzy inference system using a Back Propagation neural network structure. In this research we use Neuro-Fuzzy as the controller and reference model. Neural controller use Multilayer Perception (MLP) Back propagation type while fuzzy controller is used for improving the system performance. This paper surveys a model of ANFIS associated with sliding mode control based on MRAS sensorless speed controller for an IM drive. In view of the aforementioned facts, the contribution of this paper lies on the salient features highlighted below:

1- To allow the system to work in accordance with industrial.

2- To improve the performances of robustness and tracking of trajectory and the effectiveness of the model developed and estimated speed of the motor under different operating conditions, especially at low speed.

This paper is organized as follows: starting with an introduction, the IFOC control, sliding mode controller and the MRAS observer of IM are presented in section 2. The Neuro-control and MRAS-Neuro-Fuzzy observer are described in section 3. Section 4 shows the results and discussion of the strategy presented in this paper. Finally, in section 5 we present a conclusion.

Sensorless control

Indirect field oriented control

The dynamics of the IM drive in the *d-q* motor reference frame, which is rotating at the synchronous speed, can be simply given by the nonlinear differential equations is shown in the appendix 2. [4]-[18].

The electromagnetic torque of the IM drive can be expressed in the case of all types of electrical machines, by a vector product:

$$T_{em} = P(\vec{\phi}_s \otimes \vec{i}_s) \quad (1)$$

where: $\vec{\phi}_s$ - flux vector and $\vec{i}_s$: current vector

The current consists of the reactive current and the active current; the reactive current or the magnetization current is a generator of the flux. The active current generates electromagnetic torque.

The IFOC of the IM aims a similar control of a DC Motor [18]. So, the rotor flux must be quadrature oriented with respect to the current at the origin of the torque.

The rotor flux can be controlled directly from the stator direct current component i_{sd}, while the torque can be linearly controlled from the quadratic stator current component i_{sq} when the rotor flux is maintained constant. [3-4-18].

(2)

$$\begin{cases} v_{sd} = \sigma L_s \frac{d}{dt} i_{sd} + \left(R_s + R_r \frac{L_m^2}{L_r^2} \right) i_{sd} - \omega_s \sigma L_s i_{sq} - \frac{L_m}{L_r^2} R_r \phi_r \\ \quad = v_{sd}^r - \omega_s \sigma L_s i_{sq} \\ v_{sq} = \sigma L_s \frac{d}{dt} i_{sq} + \omega_s \sigma L_s i_{sd} + \left(R_s + R_r \frac{L_m^2}{L_r^2} \right) i_{sq} + \frac{L_m}{L_r^2} p \, \Omega \, \phi_r \\ \quad = v_{sq}^r - \omega_s \sigma L_s i_{sd} + \frac{L_m}{L_r^2} p \, \Omega \, \phi_r \end{cases}$$

The slip frequency can be calculated from the values of the stator quadrate current and the rotor flux-oriented reference frame as follow:

(3)
$$\omega = \omega_s - \omega_r = \frac{L_m}{\tau_r} \frac{i_{sq}}{\phi_r}$$

and the rotor flux position is given by:

(4)
$$\theta_s = \int \omega_s dt$$

The rotor flux is controlled by PI controller taking as input the reference value ϕ_r^* and the calculated value.

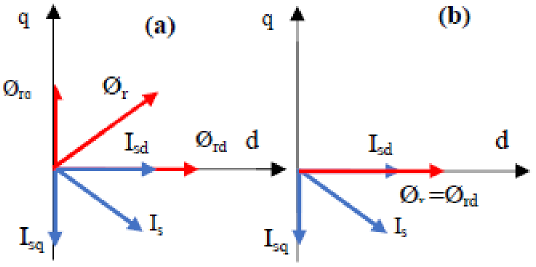

Fig.1. Rotor flux oriented (b) and non oriented (a)

Sliding mode controller

With SMC, the system is controlled in such a way that the error in the system states always moves towards a sliding surface [17]. The sliding surface is defined with the tracking error e1 of the state and its rate of change ė1 as variables. [4]- [17]

(5) $S = \dot{e}_1 + \lambda . e_1$

where λ is a constant. The distance of the error trajectory from the sliding surface and its rate of convergence are used to decide the control input U to the system [14]. Determine a switching control strategy to drive the state trajectory into the equilibrium surface and maintain it on the surface S. This strategy has the form: [2-4].

(6) *U= -k sign(S) +Ueq*

where Ueq : equivalent control which is used when the system state is in the sliding mode. k is a constant and it is the maximal value of the controller output. S is the switching function because the control action switches its sign on the two sides of the switching surface S=0. *Sign (s)* is a sign function, which is defined as:

(7)
$$Sign\ (S) = \begin{cases} -1 \ if \ S < 0 \\ \ 1 \ if \ S > 0 \end{cases}$$

In practice, the sign function causes chattering .One solution is to introduce a sat function. [2-3-4].

The vector control with directed rotor flux can act on the flux and the electromagnetic torque via the stator voltage components Vsd and Vsq. In order to adjust the speed of the MAS using the fuzzy sliding mode control, two sliding surfaces are required, represented by the size of the control vector U, namely the voltages Vsd and Vsq. The variables to be adjusted are the speed Ω and the rotor flow ϕr. [2-3-4].The stability theory of Lyapunov is used to ensure the attractiveness and invariance of S, the following condition must be satisfied: [16]

(8) $S.\dot{S} < 0$

Model reference of an adaptive system

We adopt the MRAS method, based on the machine rotor flux as it presents more performance compared to other methods, besides it is simpler to implement, in practice, [4-5].Two models are selected to build the rotor flow:

• Reference model: This does not depend explicitly on the speed and uses the stator equations of the machine.

(9)
$$\begin{cases} \frac{d}{dt} \phi_{rd} = \frac{L_r}{L_m} v_{sd} - \sigma L_s \frac{d}{dt} i_{sd} - R_s i_{sd} \\ \frac{d}{dt} \phi_{rq} = \frac{L_r}{L_m} v_{sq} - \sigma L_s \frac{d}{dt} i_{sq} - R_s i_{sq} \end{cases}$$

• Adaptive model: which depends explicitly on the speed and uses the rotor equations of the machine.[4]

(10)
$$\begin{cases} \frac{d}{dt} \hat{\phi}_{rd} = \frac{L_m}{\tau_r} i_{sd} - \frac{1}{\tau_r} \hat{\phi}_{rd} + (\omega_s - p\Omega_{est}) \hat{\phi}_{rq} \\ \frac{d}{dt} \hat{\phi}_{rq} = \frac{L_m}{\tau_r} i_{sq} - (\omega_s - p\Omega_{est})(\hat{\phi}_{rd} - \frac{1}{\tau_r} \hat{\phi}_{rq}) \end{cases}$$

The estimator stability is proven by the criterion of Popov hyper stability. The adaptation law proposed by Schauder [5] is given as follows:

(11)
$$e = \phi_{rq} \hat{\phi}_{rd} - \phi_{rd} \hat{\phi}_{rq}$$

An estimation of the speed expression can be written as:

(12)
$$\hat{\Omega} = K_p e + \int K_i e dt$$

K_p and K_i are positive gains.

Sensorless control system description

Fig.2 shows the global structure of the system control block diagram incorporating the proposed MRAS neuro–fuzzy observer, for sensorless control IM equipped with ANFIS controller. Where $V_{sd.n}$, $V_{sq.n}$ calculated by a Neuro-Fuzzy inference mechanism (ANFIS), and $V_{sd.eq}$, $V_{sq.eq}$ calculated by a sliding mode controller sf((SMC) [3-4] The control system scheme is composed of vector control transformation, pulse width modulation PWM, MRAS observer, sliding-mode controller and three ANFIS controllers. The control scheme principle can drive the dynamics of the IMD's into a designed sliding surface in finite time and guarantee the property of asymptotical stability.

Neuro–fuzzy control

Combining the learning power of neural network with knowledge representation of fuzzy logic gives Neuro-Fuzzy control (NFC) [19]. In this section, a brief review of the adaptive neuro fuzzy inference system concepts to control and observer various system parameters of the IM is presented. In this work, the development of the control strategy for control of various parameters of the induction machine such as the Vsd.n, Vsq.n and speed observer, are presented using the concepts of ANFIS control scheme, the block diagram of the ANFIScontrol scheme is shown in the Fi.3. [19].The inputs to the ANFIS controller are the error and the change in error. The FLC membership functions for inputs are presented in Fig. 4. By using SUGENO method, the input membership functions of the ANFIS uses 25 rules for getting the suitable output [12]. The output from the first ANFIS is the modified reference Vsd.n , Vsq.n in second controller ANFIS and the speed observer in the third controller.The rule base block is connected to the neural network block. Back propagation algorithm is used to train the neural network to select the proper set of rule base. The inputs are fuzzified using the fuzzy sets are given as input to ANFIS controller. The advantage of the backpropagation algorithm is that it is easy to understand and can be successfully used in many applications [22] .This algorithm is based on error back propagation computes the weight changes by starting with the last layer and workingbackward layer by layer [23].The neuro-fuzzy system based on the error back-propagation training algorithm is adopted to perform control [24].This last is based on the gradient descent search technique that minimizes a cost function of the mean square errors

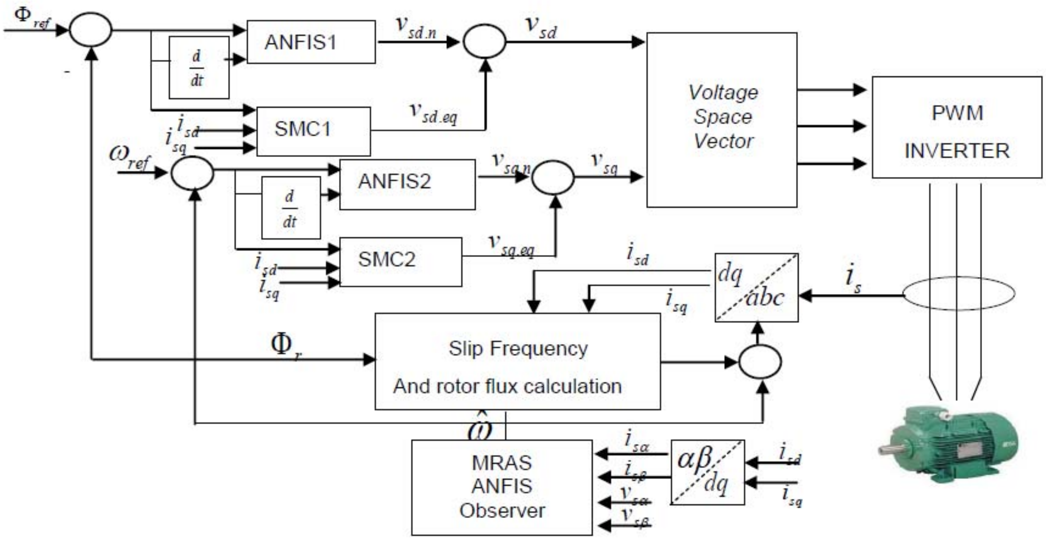

Fig.2- Global structure of the Sensorless MRAS-ANFIS observer associated with Sliding Mode controller of the IM Drive

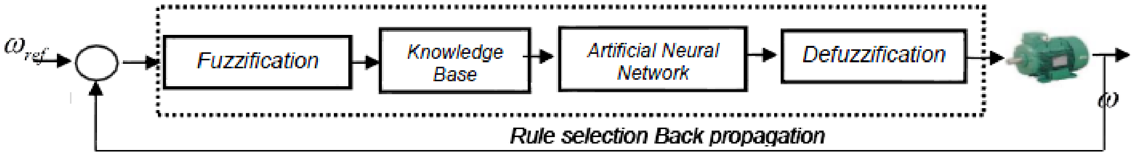

Fig.3-Block diagram of the ANFIS control

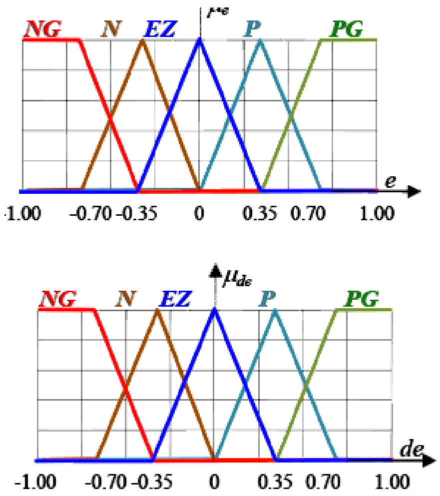

Fig.4 Fuzzy controller Input membership functions speed error e and change in speed de

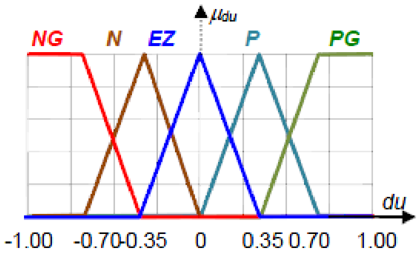

Fig.5-Fuzzy controller Output membership functions control du.

Table 1. Rule base for learning algorithm to elaborate ANFIS controller.

E / dE	NG	N	EZ	P	PG
NG	NG	NG	N	N	EZ
N	NG	N	N	EZ	PG
EZ	NG	N	EZ	P	PG
P	NG	EZ	P	P	PG
PG	EZ	P	P	PG	PG

The minimization process is through by adjusting the weighting vector of the neural network. The cost function being minimized is the error between the network output and the desired output show in function below:

(13)
$$E = \frac{1}{2}\sum_{j} e_j^2(k) = \frac{1}{2}\sum_{j}[y_j^* - y_j(k)]^2$$

where $y_j(k)$ is the output of neuron j and $y_j^*(k)$ is the desired pattern for that neuron. Let $\eta ji(k)$ denote the learning rate parameter assigned to synaptic weight wji(k) at iteration number k. Equation (14) leads to a sequence of update weight vector. The weights of the interconnections between two adjacent layers can be update by the following function:

(14)
$$\omega_{ji}(k+1) = \omega_{ji}(k) - \eta_{ji}(k+1)\frac{\partial E(k,w)}{\partial \omega_{ji}(k)} + \alpha\Delta\omega_{ji}(k)$$

α is the momentum gain , is susceptible to local minima and needs additional computation for gradient evaluation and Δwji(k) is weight change based on gradient of the cost function $E_{k,w}$ and k is the iteration number. The inputs are fuzzified using the fuzzy sets are given as input to ANFIS controller. The rule base for selection of proper rules using the Back Propagation algorithm is written as shown in the Table 1.The proposed ANFIS structure of SUGENO [14-19-20] type with five layers. The structure which is illustrated in fig.6, designs a combination of gradient descent and least squares estimator techniques [21]. Fig.6 shows the adaptive NF inference system structure. It is composed of five functional blocks (rule base, database, a decision making unit, a fuzzification interface and a defuzzification interface) which are generated using five network layers [14-19-20-21]:

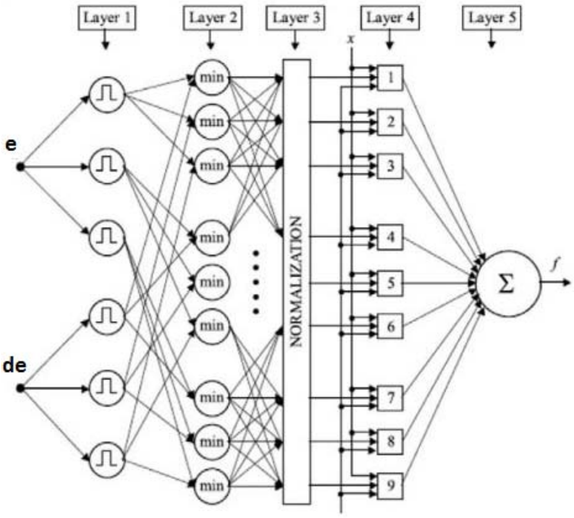

Fig.6-ANFIS inputs structure

***Layer* 1**. Each input node in this layer corresponds to the specific input variable. These nodes only pass input signals to the second layer.

***Layer* 2**. Each node performs a membership function that can be referred to as the fuzzification procedure.

***Layer* 3**. This layer is called as the rule layer. Each node (each neuron) in this layer performs the pre-condition matching of the fuzzy rules, i.e., they compute the activation level of each rule, the number of layers being equal to the number of fuzzy rules. Each node of these layers calculates the weights which are normalized.

***Layer* 4**. This layer acts as a defuzzifier. The single node is denoted by Σ and sums all incoming signals.

***Layer* 5**. This layer is called as the output layer which sums up all the inputs coming from the layer 4 and transforms the fuzzy classification results into a crisp (binary).

The error back-propagation process consists of two passes through the different layers of the network: a forward pass and a backward pass. In the first step (forward pass), the inputs are propagated through the network layer by layer, and the consequent parameters are estimated by the least squares method, assuming that the precursor parameters are constant. In the second stage (backward pass), the input samples are reproduced and the secondary parameters are assumed to be constant and the precursor parameters are changed by the gradient descent method.

MRAS neuro-fuzzy observer

Fig.7 gives the detailed functional diagram of the neuro–fuzzy MRAS observer indicated in Fig.2. Note that this Note that this control becomes effective only at steady-state condition, which can be detected by the flux error.

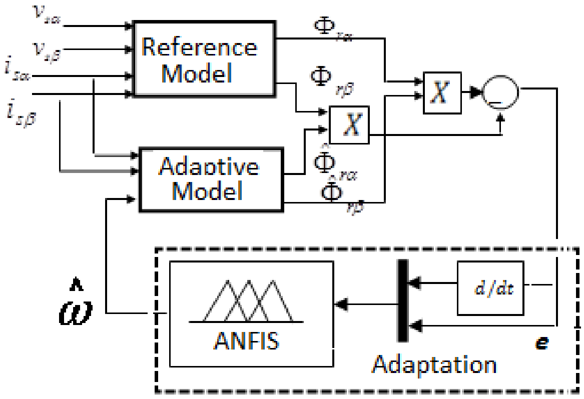

Fig.7-MRAS- ANFIS structure

The neuro-fuzzy network is trained using an off-line learning algorithm. The NFC has two inputs, the flux error and the derivative of flux error. The output is rotor speed. For the

NFC of rotor speed is similar with ANFIS controller [14-19]. The equivalent neuronal structure proposed with Matlab software environment is shown in Fig.8.

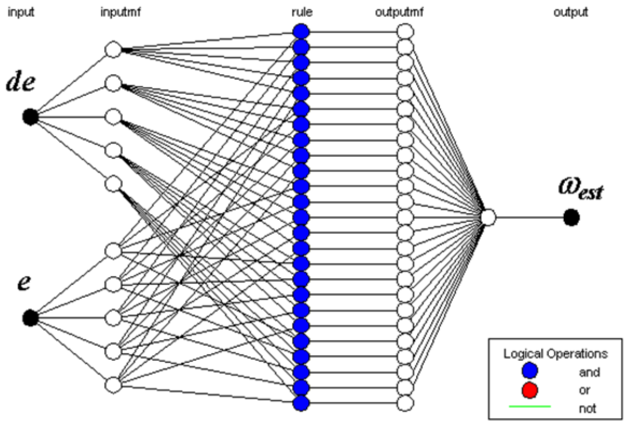

Fig.8-Equivalent neuronal structure proposed under Matlab

Results and interpretation

In this section, the results of the performance improvement of ANFIS with sliding mode based on MRAS sensorless speed controller for induction motor drive are presented. The IM parameters used to develop the model are summarized in the appendix1- Table.2.Fig.10 depicts the speed response of the IM under three case: reference speed, actual speed and estimated speed, we note that the signal of the estimated speed is superimposed with the signal of the reference speed only in the moment when we apply the load torque T_r (5 $N.m$ during the time interval (5s - 5.8s), but after this, the signal pick up again. We note also an excellent quality of the estimate under different operating conditions, especially in low speeds regime as shown in the zoom figure and the error speed estimation signals (Fig.9). Current stator response and the electromagnetic torque of the IM are shown in figure 11. We note that both two signal show good result when applying the load torque (5 $N.m$ during the time interval (5s-5.8s), the regime of the signal changes but after this the signal picks up again. We also note that the chattering phenomenon is null. Figures 11 and 12 show the results of this strategy of speed, electromagnetic torque and the stator current responses of the IM using design and analysis of robust sensorless control of induction motor using MRAS-ANFIS with sliding mode control, under parameter variation of the rotor resistance (Rr) and the motor Inertia (J) about 20% of the nominal value. We note that despite the change of the rotor resistance and the Inertia about 20% of the nominal value, this method remains robust and shows an excellent quality of the estimate under different operating conditions, including at low and zero speeds regime.

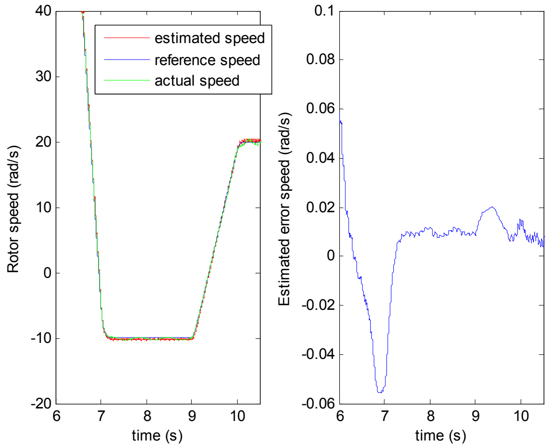

Fig.9-Rotor Speed, speed error estimation, of the IM at low speed region

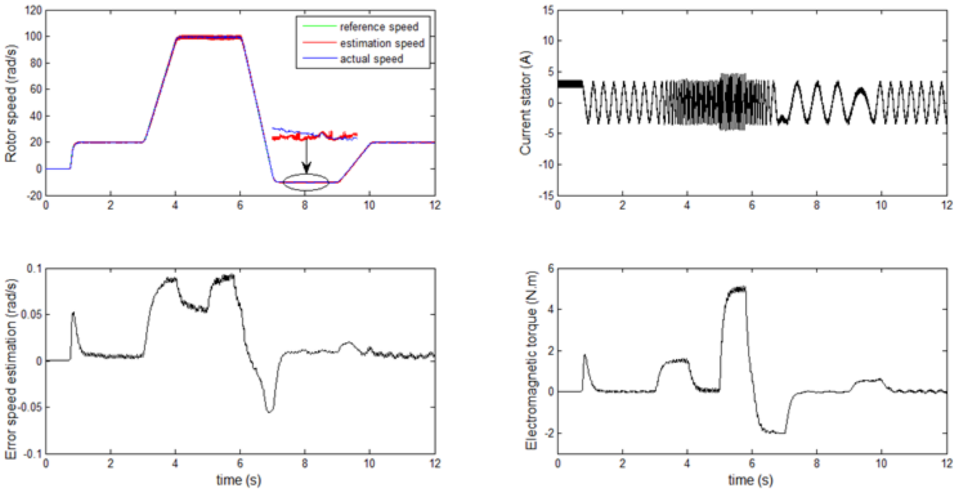

Fig.10-Rotor Speed, error speed estimation, stator current and the electromagnetic torque reponses of the IM using the proposed strategy

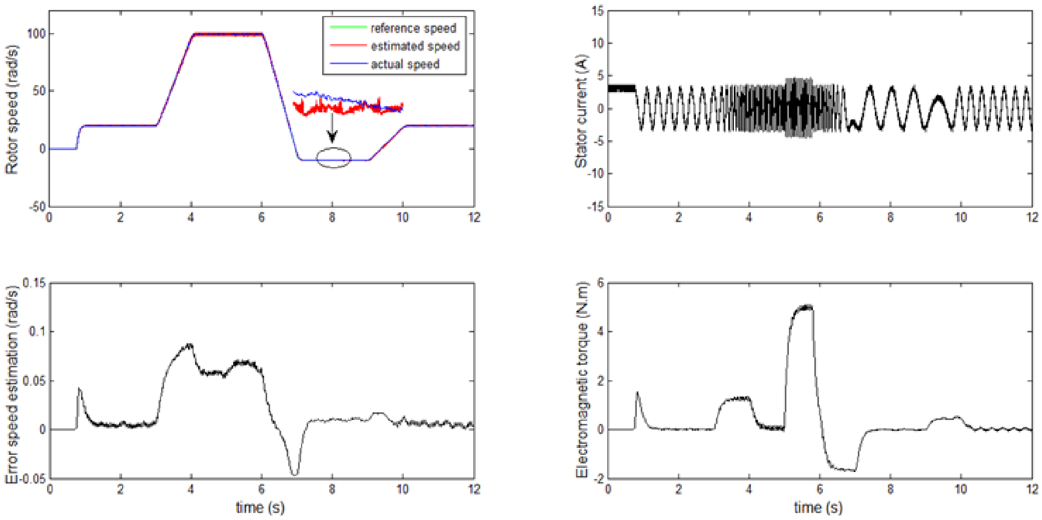

Fig.11-Rotor Speed, error speed estimation, stator current and the electromagnetic torque reponses of the IM using the proposed strategy under the rotor resistance variation about 20% of its nominal value

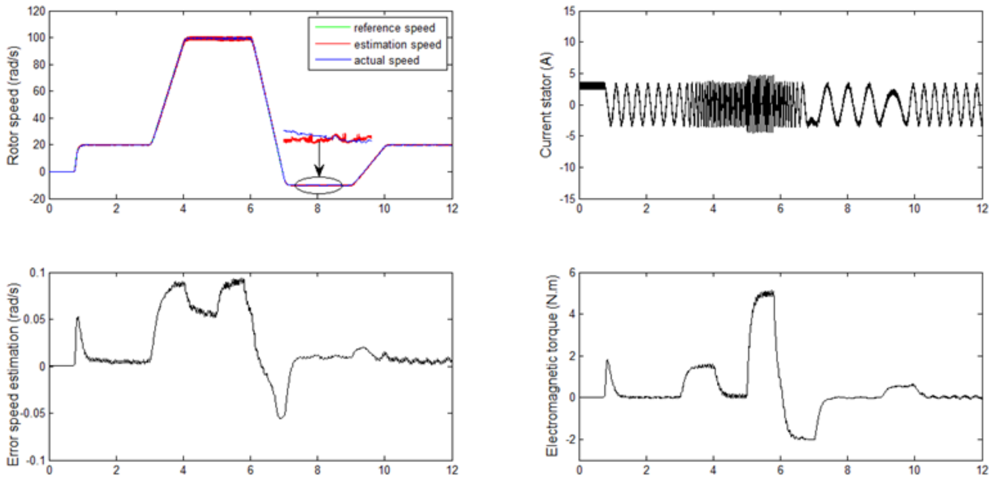

Fig.12- Rotor Speed, error speed estimation, stator current and the electromagnetic torque reponses of the IM using the proposed strategy under the Inertia variation about 20% of its nominal value

Concluding remarks

In this paper, we provide some performance improvement of ANFIS with sliding mode based on MRAS sensorless speed controller for induction motor drive associated with the IFOC strategy taking into account the speed and motor parameters variations. The results obtained under dynamic Operating conditions show the effectiveness of the proposed approach. The results prove that the proposed strategy has sufficient chattering reduction with a good estimation accuracy, a fast response and robustness to the parameter variations as resistance rotor; Inertia (J) and load changes. This study also show a good quality of the estimate and a good tracking of speed trajectory under different operating conditions.

So the main improvements shown are:

- Improve the robustness performance of parameters as temperature that influence the motor resistance and tracking trajectory of the speed and the estimated speed of the motor in different operating conditions, especially at the critical zero and low speeds estimation sensorless induction motor.
- Reduction of torque ripples in transient and steady state response.
- Fast and robust response speed in transient state; Tracking predetermined of the desired speed trajectory.

APPENDIX 1: *Table.2-* The Induction Motor parameters.

Parameters	Rated Value	Unity
Power	1.5	*kW*
Frequency	50	*Hz*
Voltage	220/380	*V*
Current	6.1/3.5	*A*
Motor speed	1420	*rpm*
Pole pair (*P*)	2	
Stator resistance *Rs*	4.85	*Ω*
Rotor resistance *Rr*	3.805	*Ω*
Stator induction *Ls*	0.274	*H*
Rotor induction *Lr*	0.274	*H*
Magnetizing inductance *M*	0.258	*H*
Load Torque *Tr*	5	*N.m*
Moment of inertia *J*	0.031	*kg.m²*
Friction coefficient *F*	0.00114	*kg.m/s*

APPENDIX 2: Dynamical Model of the Induction MOTOR

$$\frac{d}{dt}i_{sq}=\frac{1}{\sigma\cdot L_s}\Big[\,-\omega_s\cdot\sigma\cdot L_s\cdot i_{sd}-\left(R_s+\frac{L_m^2}{L_r\cdot\tau_r}\right)\cdot i_{sq}$$

$$-\frac{L_m}{L_r}\omega\cdot\phi_{rd}+\frac{L_m}{L_r\cdot\tau_r}\cdot\phi_{rq}+v_{sq}\,\Big]$$

$$\frac{d}{dt}i_{sd}=\frac{1}{\sigma\cdot L_s}\Big[-(R_s+\frac{L_m^2}{L_r\cdot\tau_r})\cdot i_{sd}+\omega_s\cdot\sigma\cdot L_s\cdot i_{sq}$$

$$+\frac{L_m}{L_r\cdot\tau_r}\cdot\phi_{rd}+\frac{L_m}{L_r}\cdot\omega\cdot\phi_{rq}+v_{sd}\,\Big]$$

$$\frac{d}{dt}\phi_{rd}=\frac{L_m}{\tau_r}\cdot i_{sd}-\frac{1}{\tau_r}\cdot\phi_{rd}+(\omega_s-\omega)\cdot\phi_{rq}$$

$$\frac{d}{dt}\phi_{rq}=\frac{L_m}{\tau_r}\cdot i_{sq}-(\omega_s-\omega)\cdot\phi_{rd}-\frac{1}{\tau_r}\cdot\phi_{rq}$$

$$\frac{d}{dt}\omega=\frac{P^2\cdot L_m}{L_r\cdot J}\left(i_{sq}\phi_{rd}-i_{sd}\phi_{rq}\right)-\frac{F}{J}\omega-\frac{P}{J}T_r$$

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