

Improved Model Reference Adaptive Speed Control

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Abstract—This paper presents a novel model reference adaptive control scheme using reference model modification through fuzzy logic to control the speed of an induction motor. The scheme is developed to cope with uncertainties and disturbances that a plant under control might undergo that a single reference model cannot handle. The main concept of the proposed philosophy is to ensure automatic change of the controller parameters so that they correspond to the current plant environment and provide an appropriate control action to improve the overall control system performance. This is carried out through a fuzzy logic evaluation block whose input signals are the command signal and an auxiliary output at each sampling interval. This information is then used in the fuzzy rules to compute the proper values of the reference model parameters for that instant. The effectiveness of the proposed technique is demonstrated through computer simulation. The obtained results fully confirm the validity of the proposed scheme.

Index Terms—model reference adaptive control, multiple models, reference model, fuzzy logic.

I. INTRODUCTION

GREAT attention has been devoted to the use of modern control techniques when dealing with situations where speed and accuracy are important considerations, as in the case of induction motor drives. Adaptive control is one technique which has the important advantage that it can dispense with the need to know *a priori* bounds on the unknown parameters [1].

One of the adaptive control techniques that has demonstrated its capabilities in many interesting applications is the model reference adaptive control (MRAC). The objective of MRAC is to design an adaptive controller such that the behavior of the controlled plant remains close to the behavior of a desirable model despite uncertainties or variations in the plant parameters. This means that the desired performance of the closed loop system is specified through a reference model and the adaptive system attempts to make the output of the plant follow the output of the reference model automatically.

In recent years, many MRAC techniques [2-8] have been developed to improve the performance of induction motor drives. Bellini and Figalli [2] proposed an MRAC where an

exact linearization of the machine model by nonlinear feedback is performed and the linearized model is employed as a reference model. The authors of paper [3] proposed a model reference adaptive speed controller using neural networks. They used a robust observer to establish the training patterns; then, the trained neural networks are used as the adaptive controller to track a reference model for induction motor drives. A mutual MRAC has been proposed in [4]. The system contains two identification models to implement a position sensorless field-orientation control through the identification of both rotor speed and the stator resistance of an induction machine. Papers [5, 6] proposed an MRAC that utilizes a load torque estimator and feed-forward compensation based on neural network for induction motor drives with time delay. To overcome the dead time influence on the PI controller performance, a dead time compensator and a model reference following controller were added to the system. In [7], an adaptive fuzzy-neural-network controller is proposed. The induction motor drive system is identified by a fuzzy-neural-network identifier to provide the system information to an adaptive controller so that the slip frequency is recursively calculated using a gradient descent method. The generated slip frequency will make the tracking error (the error between the outputs of the plant and the reference model) converge to zero to obtain a satisfactory control performance. In [8], an adaptive fuzzy sliding-mode control (AFSMC) has been proposed. The AFSMC system consists of two controllers (a fuzzy controller and a compensation controller), an estimator, an adaptive mechanism and a reference model. In this case, the control signal received contribution from both controllers.

The above research efforts [2-8] have employed different control algorithms and techniques but they have maintained the structure of the classical MRAC system that utilizes a single reference model. The objective of MRAC has been achieved in these papers because the structure of the controlled plant matches the structure of the reference model. However, if the parameters of the plant vary widely due to the presence of uncertainties, structural perturbations, and environmental changes, then a satisfactory performance of the control systems may be obtained over one operating condition, but certainly will fail to provide an acceptable performance under other conditions. In all such situations, there has been a need for improved control systems that can automatically compensate for these variations. This has led to

an appreciation of the need for multiple reference model adaptive techniques in control system design [9, 10].

The approach of multiple models has been presented in many papers [9-14]. However, the approach of those papers is concentrated on multiple identification models linked with correspondent multiple controllers through switching schemes.

In this paper, a new model reference adaptive control scheme using on line modification of the reference model through fuzzy logic evaluation of the model's parameters is proposed.

In this proposed philosophy, the aim is to identify the current operating condition and in turn evaluate the parameters of the reference model through pre-specified fuzzy rules so that the controller can be re-tuned to meet a global performance criterion. This is carried out using a fuzzy logic evaluation block that receives inputs from the command signal and an auxiliary output at each sampling interval. This information is then used in the fuzzy rules to compute the proper values of the reference model parameters for that instant. The effectiveness of the proposed technique is demonstrated through computer simulation studies. The results show that an improvement in the overall system performance is accomplished using the proposed adaptive controller in comparison to those utilizing either a classical model reference adaptive controller or a conventional fixed parameters controller.

II. PROPOSED MRAC SYSTEM

The objective of MRAC with reference model modification is to design an adaptive controller in such a way that the desired performance of the closed loop system in each environment is specified through a reference model. Then the adaptive system attempts to make the output of the plant follow the output of the reference model automatically.

As a general explanation, consider a linear SISO plant described by the following differential equations:

$$\begin{aligned}\dot{x}_p &= A_p x_p + b_p u \\ y_p &= h_p^T x_p\end{aligned}\quad (1)$$

where u is the input, y_p is the plant output, x_p is the n^{th} state vector, A_p is an $n \times n$ matrix, and h_p and b_p are n vectors.

The transfer function of this SISO plant $W_p(s)$ can be expressed as

$$W_p(s) = K_p \frac{Z_p(s)}{R_p(s)} \quad (2)$$

Here $R_p(s)$ is a monic polynomial of order n , defined as

$$R_p(s) = s^n + a_{n-1}s^{n-1} + \dots + a_0 \quad (3)$$

$Z_p(s)$ is a monic polynomial of order $n-1$, defined as

$$Z_p(s) = s^{n-1} + b_{n-2}s^{n-2} + \dots + b_0 \quad (4)$$

where K_p is a constant known as high frequency gain and a_{n-1}, \dots, a_0 and b_{n-2}, \dots, b_0 are the coefficients of the denominator and the numerator of the plant's transfer function respectively.

Now consider a reference model that represents the desired trajectory described by the following differential equations:

$$\begin{aligned}\dot{x}_m &= A x_m + b r \\ y_m &= h^T x_m\end{aligned}\quad (5)$$

where r is the reference input, y_m is the output of the model, x_m is the n^{th} state vector, A is an $n \times n$ matrix, and h and b are n vectors.

The transfer function of the reference model $W_m(s)$ is

$$W_m(s) = K_m \frac{Z_m(s)}{R_m(s)} \quad (6)$$

Here $R_m(s)$ is a monic polynomial of order n , defined as

$$R_m(s) = s^n + a_{n-1}^m s^{n-1} + \dots + a_0^m \quad (7)$$

and $Z_m(s)$ is a monic polynomial of order $n-1$, defined as

$$Z_m(s) = s^{n-1} + b_{n-1}^m s^{n-2} + \dots + b_0^m \quad (8)$$

where K_m is a constant and a_{n-1}^m, \dots, a_0^m and b_{n-1}^m, \dots, b_0^m are the coefficients of the denominator and the numerator of the reference model's transfer function respectively. The aim is to find u such that the output error

$$e = y_p - y_m \quad (9)$$

tends to zero asymptotically for arbitrary initial conditions and arbitrary reference signals $r(t)$ using a combined direct-indirect MRAC approach. This approach has been developed in [15], in which the control parameter vector Θ is adjusted dynamically based on the output error as well as the closed-loop estimation errors.

A. Structure of the control system

The structure of the proposed MRAC system is shown in Fig. 1. This control system consists of a second-order reference model, a fuzzy logic evaluation block, an adjustment mechanism, a plant parameter estimator, and a controller. The reference model will be modified to properly describe the desired input/output properties of the closed-loop plant for different environmental conditions. The identification of the reference model parameters that suit the current environment is performed by a fuzzy logic block that has been added to the structure of the classical MRAC system.

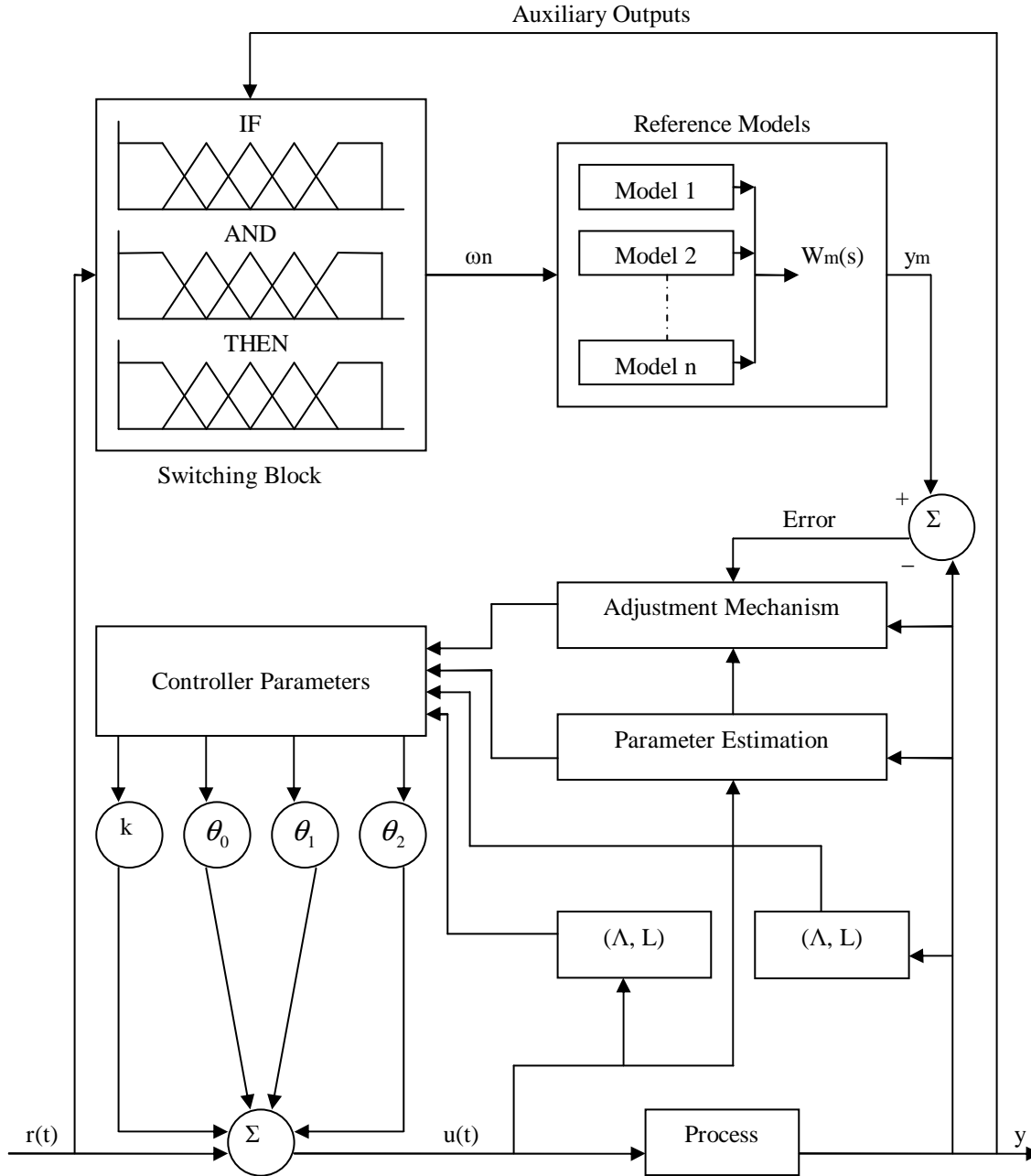


Fig. 1. Structure of the proposed MRAC system

At each instant, the fuzzy logic evaluation block receives information from the command signals and an auxiliary output as a criterion to modify the reference models' transfer function $W_m(s)$ so that the plant output $y_p(t)$ will follow the reference model output $y_m(t)$ for a given command signal $r(t)$.

In this application, the plant output is the rotor speed of the induction motor, and the model output is the desired rotor speed. Then the controller derives the control signal so that the plant closed-loop characteristics from the command signal $r(t)$ to the plant output $y_p(t)$ is equal to the reference model transfer function $W_m(s)$.

This matching of the plant and the reference model characteristics guarantees that the error between their outputs converges to zero with time for any given command signal $r(t)$ [13]. The symbols used in Fig. 1 are defined in the controller structure section, Section II.C.

B. Structure of the reference models

The structure of the reference model in many applications is a second order model with properly chosen parameters. A second order reference model is given as

$$W_m(s) = \frac{\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2}. \quad (10)$$

where $\xi\omega_n$ is called attenuation, ω_n is called the undamped natural frequency and ξ is called the damping ratio of the system. The second order system dynamic behavior can then be described in terms of the two parameters namely ω_n and ξ . The numerical value of ξ in this instance is set to 0.7. This value is chosen because it is used in most practical applications.

By assigning this value, the reference model in (1) becomes:

$$W_m(s) = \frac{\omega_n^2}{s^2 + 1.4\omega_n s + \omega_n^2}. \quad (11)$$

Now if we set a fixed numerical value for ω_n , this will result in a single reference model that is used in the classical MRAC. On the other hand, if we evaluate ω_n on line, that means we will identify different values for ω_n . This results in reference model modification, i.e., a flexible reference model.

C. Structure of the controller

To achieve the control objectives, the structure of the controller that was developed in [15] is considered for this design. The control signal is given by

$$u = \Theta^T \omega. \quad (12)$$

where $\Theta = [k \quad \theta_0 \quad \theta_1^T \quad \theta_2^T]^T$ is the control parameter vector with k and θ_0 as constants, $\theta_1 = [\theta_0^1 \quad \theta_1^1 \quad \dots \quad \theta_{n-2}^1]^T$ and $\theta_2 = [\theta_0^2 \quad \theta_1^2 \quad \dots \quad \theta_{n-2}^2]^T$. The regressor vector, $\omega = [r \quad y_p \quad \omega_1^T \quad \omega_2^T]^T$, can be calculated through the following input and output filters:

$$\dot{\omega}_1 = \Lambda \omega_1 + L u \quad (13)$$

$$\dot{\omega}_2 = \Lambda \omega_2 + L y_p, \quad (14)$$

where Λ is a stable matrix of order $(n-1) \times (n-1)$ such that the determinant $|sI - \Lambda| = Z_m(s)$ or

$$\Lambda = \begin{bmatrix} 0 & & & & & \\ & \cdot & & & & \\ & & I(n-2) & & & \\ & & & \cdot & & \\ & & & & \cdot & \\ 0 & & & & & \\ -\lambda_0 & -\lambda_1 & \cdot & \cdot & \cdot & -\lambda_{n-2} \end{bmatrix} \quad (15)$$

where $\lambda_0, \lambda_1, \dots, \lambda_{n-2}$ are the coefficients of the polynomial $\Lambda(s)$, which is defined as $\Lambda(s) = s^{n-1} + \lambda_{n-2}s^{n-2} + \dots + \lambda_0$, and the vector L is defined as

$$L = [0 \quad 0 \quad \dots \quad 1]^T. \quad (16)$$

The following equations are used to adjust the controller parameters:

$$\dot{k} = -\text{sgn}(K_p)e(t)r - \text{sgn}(K_p)\varepsilon k \quad (17)$$

$$\dot{\theta}_0 = -\text{sgn}(K_p)e(t)y_p + \text{sgn}(K_p)[\varepsilon\theta_0 + b_m^T \varepsilon\theta_2] \quad (18)$$

$$\dot{\theta}_1 = -\text{sgn}(K_p)e(t)\omega_1 - \varepsilon\theta_1 \quad (19)$$

$$\dot{\theta}_2 = -\text{sgn}(K_p)e(t)\omega_2 + \text{sgn}(K_p)\varepsilon\theta_2 \quad (20)$$

$$\dot{a} = -\varepsilon\theta_2 \quad (21)$$

$$\dot{a}_{n-1} = -\varepsilon\theta_0 \quad (22)$$

$$\dot{b} = -\varepsilon\theta_1 \quad (23)$$

$$\dot{K}_p = -k\varepsilon k + \theta_0\varepsilon\theta_0 + \theta_2^T \varepsilon\theta_2 + \theta_0\varepsilon\theta_2^T b_m \quad (24)$$

The estimation errors in the above equations are defined as follows:

$$\varepsilon k = k\hat{K}_p - K_m \quad (25)$$

$$\varepsilon\theta_0 = -\hat{K}_p\theta_0 + \hat{a}_{n-1} - a_{n-1}^m \quad (26)$$

$$\varepsilon\theta_1 = \theta_1 + \hat{b} - b_m \quad (27)$$

$$\varepsilon\theta_2 = -\hat{K}_p\theta_2 - \hat{K}_p\theta_0 b_m + \hat{a} - a_m \quad (28)$$

Now that the overall structure of the control system has been presented and explained, the remaining issue is the fuzzy logic evaluation of the model parameters. The fuzzy evaluation is explained in the next section because the generation of fuzzy rules differs from one application to another.

III. STABILITY

Consider the proposed scheme, and the following equations that represent the plant, the reference model (modified) and the classical model (unmodified) respectively.

$$\begin{aligned}
\text{Plant} \quad & \dot{y} = Ay + Bu \\
\text{Modified model} \quad & \dot{y}_m = A_m y_m + B_m u \\
\text{Classical model} \quad & \dot{y}_c = A_m y_c + B_m u
\end{aligned}$$

The error between the output of the flexible (modified) model and the output of the actual plant can be expressed as:

$$e = y_m - y$$

The error between the output of the classical model and the output of the actual plant can be expressed as:

$$e_1 = y_c - y$$

Finally the error between the output of the classical model and the flexible (modified) model is

$$e_2 = y_c - y_m$$

Assume that

$$e_1(t) \text{ is finite for all } t > 0$$

$$\lim_{t \rightarrow \infty} e_1(t) = 0$$

and

$$e(t) \text{ is finite for all } t > 0$$

$$\lim_{t \rightarrow \infty} e(t) = 0$$

and

$$e_2(t) \text{ is finite for all } t > 0$$

$$\lim_{t \rightarrow \infty} e_2(t) = 0.$$

Then the following equations are valid

$$y_m(t) = \exp[A_m(t-t_0)]y_m(t_0) +$$

$$\int_{t_0}^t \exp[A_m(t-\tau)]B_m u(\tau) d\tau$$

$$y_c(t) = \exp[A_m(t-t_0)]y_c(t_0) +$$

$$\int_{t_0}^t \exp[A_m(t-\tau)]B_m u(\tau) d\tau$$

$$y_c(t_1) = \exp[A_m t_1]y_c(t_0) +$$

$$\int_{t_0}^t \exp[A_m(t_1-\tau)]B_m u(\tau) d\tau$$

$$y_m(t_1^-) = \exp[A_m t_1]y_m(t_0) +$$

$$\int_{t_0}^{t_1} \exp[A_m(t_1-\tau)]B_m u(\tau) d\tau$$

$$= y_c(t_1)y_m(t_1^+) = y_m(t_1^-) - e(t_1^-) = y_c(t_1) - e(t_1^-)$$

$$y_m(t_n^+) = y_c(t_n) - \sum_{i=1}^n \exp[A_m(t_n - t_i)]e(t_i^-)$$

This concludes that

$$e_2(t) = y_c(t) - y_m(t) = \sum \exp[A_m(t_n - t_i)]e(t_i^-)$$

$$\lim_{t \rightarrow \infty} e_2(t) = \lim_{t \rightarrow \infty} \sum \exp[A_m(t - t_i)]e(t_i^-) = 0$$

Based on the above equations, the error converges to zero, which proves the asymptotic stability of the system when the reference model is modified from one transfer function to another to fit the structure of the controlled plant.

IV. APPLICATION TO AN INDUCTION MOTOR

The induction motor is essentially a constant speed motor when connected to a constant frequency supply. But many industrial applications, however, require several speeds or a continuously adjustable range of speeds. In the past, many methods have been devised to control the speed of the induction motor, but in most cases efficiency is generally low or the cost of the equipment is high.

Recently, adaptive control methods have been utilized to improve servo drive performance and to help maintain invariant control behavior in a wide range of operating conditions, such as changes in load or motor parameters or load torque disturbances [16]. However, applying these methods to the drive of the induction motor to achieve quick control response has been somewhat restricted primarily by the control algorithms [16-23]. Therefore, the concept of implementing a flexible model may resolve this problem and provide a rapid control response.

A. Induction motor dynamic model

The voltage equations for an AC induction motor on the basis of direct and quadrature direction (d-q frame) that is rotating synchronously with the magnetic field are given below [16]:

$$v_{ds} = R_s i_{ds} + \dot{\psi}_{ds} - \omega_e \psi_{qs} \quad (29)$$

$$v_{qs} = R_s i_{qs} + \dot{\psi}_{qs} + \omega_e \psi_{ds} \quad (30)$$

$$0 = R_r i_{dr} + \dot{\psi}_{dr} - \omega_s \psi_{qr} \quad (31)$$

$$0 = R_r i_{qr} + \dot{\psi}_{qr} + \omega_s \psi_{dr}. \quad (32)$$

The system's torque equation is:

$$T_e - T_L = J \dot{\omega}_m + B \omega_m, \quad (33)$$

where the flux linkages are defined in the following equations:

$$\psi_{ds} = L_s i_{ds} + L_m i_{dr} \quad (34)$$

$$\psi_{qs} = L_s i_{qs} + L_m i_{qr} \quad (35)$$

$$\psi_{dr} = L_r i_{dr} + L_m i_{ds} \quad (36)$$

$$\psi_{qr} = L_r i_{qr} + L_m i_{qs}. \quad (37)$$

Finally, the slip angular speed is given by:

$$\omega_s = \omega_e - \omega_r. \quad (38)$$

For the sake of clarity and to understand the above equations, the involved parameters are defined in respectively as follows. R_s and R_r are the stator and rotor resistances per phase, L_s and L_r are the stator and rotor inductances per

phase, L_m is the mutual magnetizing inductances per phase, ω_e and ω_s are the synchronous rotating frame and slip angular speeds, ω_r and ω_m are the motor electrical and rotor angular speeds, v_{qs} and v_{ds} are the q-axis and d-axis stator voltages, i_{qs} and i_{ds} are the q-axis and d-axis stator currents, i_{qr} and i_{dr} are the q-axis and d-axis rotor currents, ψ_{qs} and ψ_{ds} are the q-axis and d-axis stator flux linkages, ψ_{qr} and ψ_{dr} are the q-axis and d-axis rotor flux linkages. T_e and T_L are the developed motor and external load torques respectively. J is the system total inertia. B is the system's total viscous coefficient. The typical numerical values of the parameters are as follows. $R_s = 1.1\Omega$, $R_r = 1.3\Omega$, $L_s = 0.145H$, $L_r = 0.145H$, $L_m = 0.136H$, $J = 0.0027 \text{ Kg.m}^2$, and $B = 0.000058 \text{ kg.m/(rad/sec)}$.

B. Flexible models and fuzzy evaluation

In this application, the concern is to maintain a variable speed as desired. The dynamic performance of the induction motor during load torque changes is strongly influenced by the rotor's electric transients, which cause the machine to exhibit damped oscillations about the new operating point. By using flexible models in the control scheme, these oscillations can be reduced. From the new structure of the flexible MRAC (Fig. 1), it can be seen that a fuzzy logic evaluation block has been added to the structure of the classical MRAC. The function of the fuzzy logic evaluation block is to monitor the reference input and the torque level; that is, the command signal and the load torque are the inputs of this block.

The reference model as mentioned earlier has the following form:

$$W_m(s) = \frac{\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2} \quad (39)$$

Recall that the value of ξ is set to 0.7, and that the output value of ω_n will be evaluated on line based upon the two inputs to the fuzzy logic evaluation block.

To evaluate the value of ω_n , fuzzy rules are used. Each fuzzy rule has two inputs and one output. The first input is the command signal of speed, the second input is the load torque, and the single output is ω_n .

To be able to write sufficient rules to perform the evaluation, membership functions of speed, load torque, and ω_n are established. Since the linguistic variables, membership functions, and the rule base stem from the experience of a skilled operator, depending on particular applications, many types of membership functions can be defined. For simplicity, the trapezoidal and triangular

functions are proposed in this work as shown in Fig. 2. The membership function of the speed is defined over a domain interval of [0,120] rad/sec, the membership function of the load torque is defined over a domain interval of [0,12] N.m and the membership function of ω_n is defined over a domain interval of [0,22] rad/sec. Each membership function is covered by five fuzzy sets: Very Small (VS), Small (S), Medium (M), Large (L) and Very Large (VL).

The fuzzy rules are derived from studying and simulating the response of the induction motor. A total of 25 fuzzy rules are used to perform the fuzzy evaluation of the ω_n value. Each fuzzy rule has the following form:

IF Speed is X **AND** load torque is Y **THEN** ω_n is Z

where X , Y and Z belong to the five fuzzy sets. A convenient way to present these rules is by using a fuzzy rule base as shown in Table I.

The center-of-gravity defuzzification method is used which can be expressed as

$$\omega_n = \frac{\sum_{i=1}^n \mu_i C_i}{\sum_{i=1}^n \mu_i}, \quad (40)$$

where μ_i is the grade of membership function at region i , C_i is the center of region i , and n is the number of fired rules.

TABLE I
Fuzzy Rule Base

		Load Torque					
		ω_n	VS	S	M	L	VL
Speed	VS	VS	VS	S	M	M	L
	S	VS	S	M	M	M	L
	M	S	M	L	L	L	VL
	L	M	S	M	M	L	VL
	VL	VL	L	VL	VL	VL	VL

For example, suppose we want to know the reference model that will be appropriate for a speed of 40 rad/sec and a load torque of 7.5 N.m. From Fig. 2, a speed of 40 rad/sec has a membership of 0.333 in VS and 0.667 in S, i.e., $\mu_{VS} = 0.333$ and $\mu_S = 0.667$. A load torque of 7.5 N.m has a membership of 0.833 in L and 0.167 in VL, i.e., $\mu_L = 0.833$ and $\mu_{VL} = 0.167$. Accordingly, the rules that will fire are:

- Rule # 4 (VS/L) with $\mu_1 = 0.333$ in M
- Rule # 5 (VS/VL) with $\mu_2 = 0.167$ in L
- Rule # 9 (S/L) with $\mu_3 = 0.667$ in M
- Rule # 10 (S/VL) with $\mu_4 = 0.167$ in L.

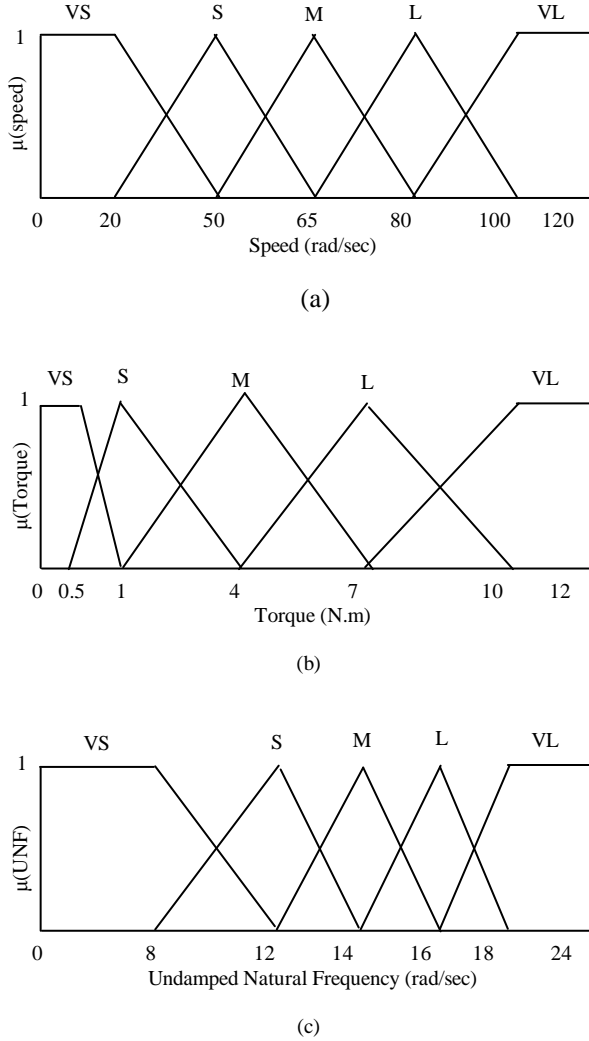


Fig. 2. Membership functions (a) speed (b) torque (c) undamped natural frequency.

Now, applying the center-of-gravity defuzzification results in the value of $\omega_n = 14.5$. Therefore, the reference model for this condition will be:

$$W_m(s) = \frac{210.25}{s^2 + 20.3s + 210.25}.$$

C. Simulation study

Simulation study was carried out through four cases to show the effectiveness of the proposed scheme. The four cases are as follows:

Case 1.

This case shows the ability of the proposed control system scheme in tracking a sinusoidal reference input $r(t) = 1 + 2\sin(t)$

The response is shown in Figure 3. The simulation ran for 50 seconds, and as it can be seen from the figure the actual output of the system (yout) followed the desired trajectory of the reference model (Ym). It took only 3 seconds to perfectly followed the desired output.

Case 2:

This case shows the response of the control system to a constant speed input of 40 rad/s. As shown in Figure 4, the output speed of the induction motor follows the desired speed of the reference model. The simulation ran for 50 seconds and the controller was capable of driving the error between the outputs within two seconds.

Case 3:

Figure 5 shows a response comparison of the induction motor speed using the classical model reference adaptive control (MRAC) and the proposed flexible model reference adaptive control (FMRAC) when there are no any disturbances applied to the induction motor. This case shows the tracking ability of the proposed FMRAC for a variable speed input. As it can be seen from the figure, the FMRAC outperformed its counterpart. The MRAC was unable to handle the speed change from 80 to 100 rad/s as well as the FMRAC.

Case 4:

This case study was performed to show the effectiveness of the proposed control system even with disturbances applied to the induction motor. The system operating conditions are shown in Table II.

The simulation is performed for 50 seconds. The speed command is 50 rad/sec for the first 10 seconds, followed by 80 rad/sec for the next 10 seconds, then 100 rad/sec for the next 20 seconds followed by 20 rad/sec for the last 10 seconds. To simulate a disturbance, a load torque of 1 N.m is applied at 5 seconds and removed after 10 seconds. Another load torque of 10 N.m is applied for the last 20 seconds.

The simulation has been carried out using the popular classical MRAC that utilizes a fixed reference model, and the proposed flexible MRAC (FMRAC).

TABLE II
System Operating Conditions

Time Range (sec)	Desired Speed (rad/sec)	Time Range (sec)	Load Torque (N.m)
0-10	50	0-5	0
10-20	80	5-15	1
20-40	100	15-30	0
40-50	20	30-50	10

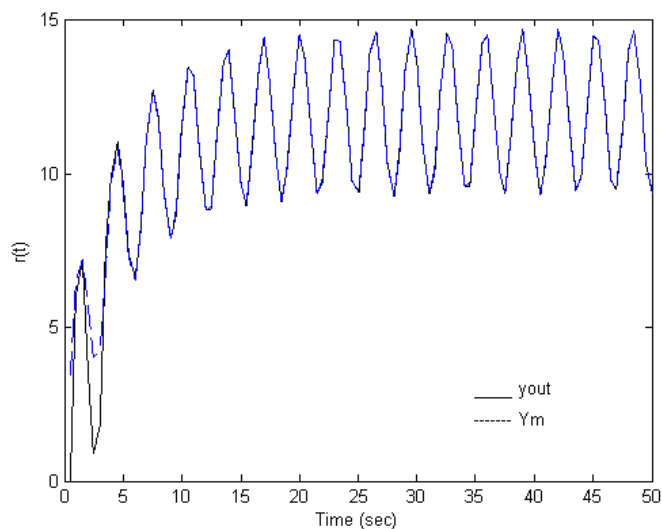


Fig. 3. Trajectory response of a sinusoidal reference input.

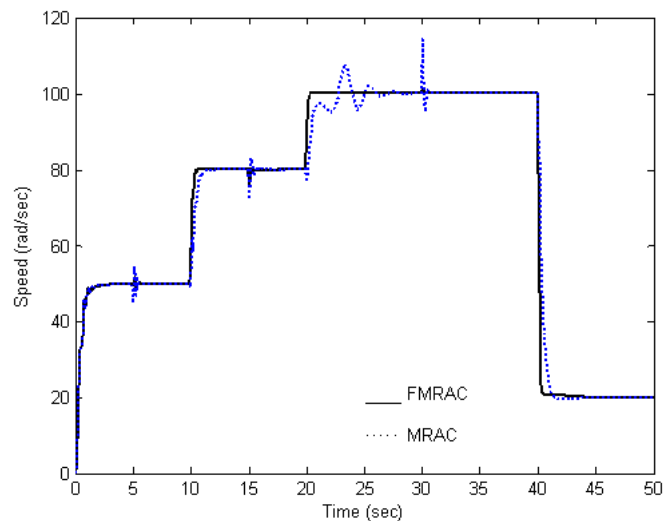


Fig. 3. Induction motor speed response of FMRAC vs. MRAC with disturbances applied.

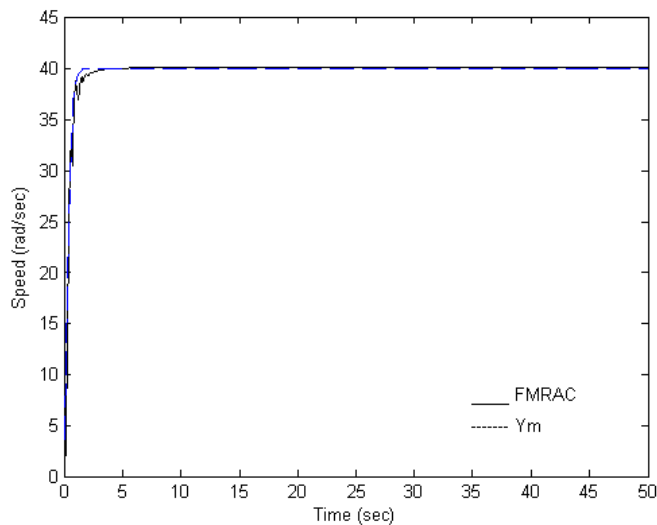


Fig. 4. Response of FMRAC compared to desired trajectory.

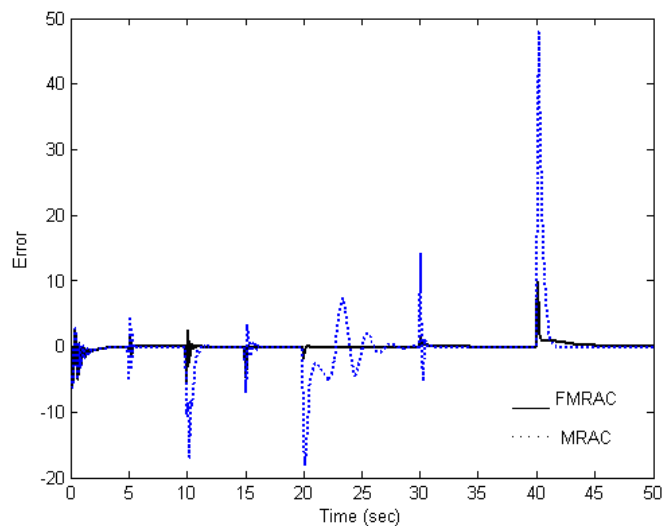


Fig. 4. Induction motor speed error of FMRAC vs. MRAC.

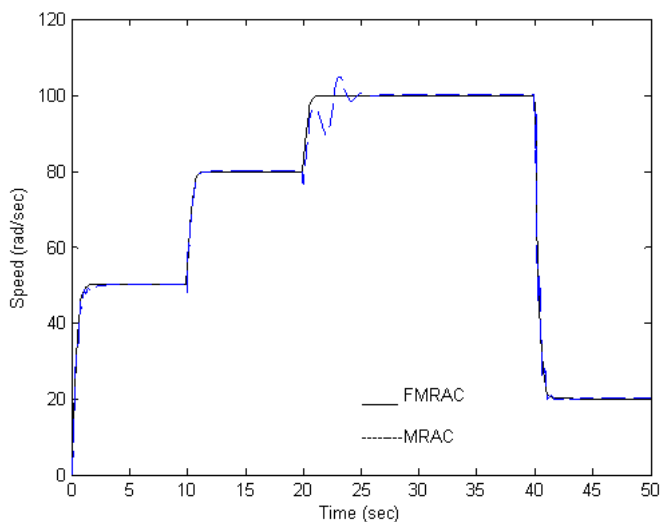


Fig. 4. Induction motor speed response of FMRAC vs. MRAC without disturbances applied.

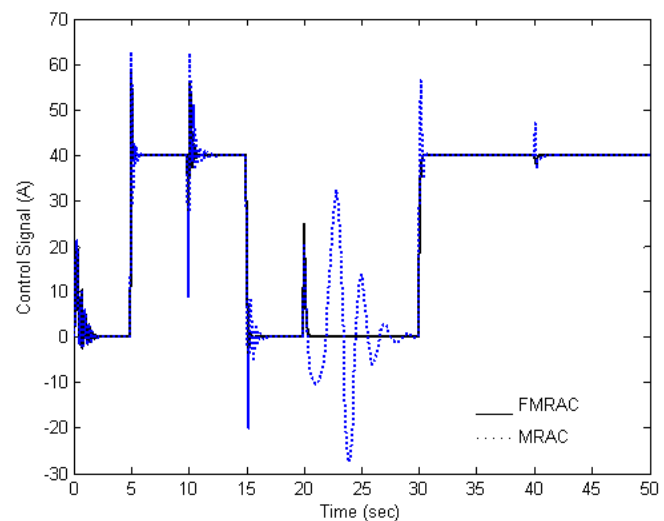


Fig. 5. Control signal of FMRAC vs. MRAC.

As mentioned earlier, the dynamic performance of the induction motor during load torque or speed changes is strongly influenced by the rotor's electric transients, which cause the machine to exhibit damped oscillations about the new operating point. The conducted simulation has shown that the classical MRAC could not handle these oscillations as well as the flexible MRAC (FMRAC) as shown in Figure 6. The FMRAC outperformed its counterpart because the flexible model possesses the capability to properly represent the plant in different environments. This characteristic has led to the elimination of the overshoot and to a smaller error between the output of the plant and its counterpart of the desired trajectory. Comparison of the errors of MRAC and FMRAC is shown in Figure 7. In addition, it resulted in a faster system response and an accurate control action. The control signals of both the FMRAC and the MRAC are shown in Figure 8.

V. CONCLUSION

A new flexible model reference adaptive control using fuzzy logic evaluation of reference model parameters has been presented. This scheme has been developed to cope with complex and difficult environmental conditions that the plant under control might encounter. The main concept of the proposed scheme is to ensure an automatic change of the controller parameters so that they correspond to the current plant environment and provide an appropriate control action to improve the overall control system performance. The results show that an improvement in the overall system performance is obtained using the proposed flexible model reference adaptive controller in comparison to using its counterpart of classical model reference adaptive controller scheme.

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