Speed Sensorless Control of Induction Motor Using Model Reference Adaptive System

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Abstract

In this paper, we studied the vector control, by orientation of rotor-flux by using fuzzy regulators for an induction machine without speed sensor with adaptation of rotor resistance. The speed is estimated by using the adaptive method with model of reference (MRAS). This method consists in working out two models one of reference and the control adjustable one for the estimate of two components of stator flux starting from the measurement of the currents and stator voltages. The estimated speed is obtained by cancelling the difference between stator-flux of the model of reference and those of the adjustable model. Very satisfactory results of simulation are presented at the end of this paper.

1. Introduction

Due to its simple and robustness structure, the induction machine has become an inevitable part of modern industrial drive systems. Recently, many modern techniques have been developed to command this machine as efficiently as a DC machine. These techniques, however, rely on the accuracy of the machine parameters which are known to vary under different operating conditions. The use of incorrect parameters in controllers can result in errors and improper dynamic behaviors. Therefore, having the accurate parameters of an induction machine becomes essential to accomplish the desired dynamic performance under different operating conditions [1-5].

The electric drives use more and more the engines the order without sensor of the asynchronous machine, requires the design of software sensors for the estimate of the physical variables non accessible to the measurement or whose measurement requires relatively expensive sensors compared to the objective of the application considered, such as the number of revolutions and the rotor time-constant [3,4].

In the control devices, the objectives of estimate and control are very significant. Thus, the objectives of estimate of the parameters are satisfied through a system tolerating with the faults which guarantees the observability of the system in the presence of defects of actuators. As for the objectives of command, they are generally satisfied by the determination of a law of command which ensures certain performances of the closed loop system in presence or not of defects.

These last years, of much research were focused on the problems of tolerant order to the faults using of the powerful controllers [6,7]. In our case, a solution is obtained thanks to the association of the fuzzy regulators with a strategy of indirect rotor-flux orientation of the three-phase asynchronous machine, without speed sensor based on the adaptive method with model of reference (MRAS), estimated on real-time of rotor resistance.

Method MRAS consists in working out two models one of reference and the command adjustable one for the estimate of two components of stator flux starting from the measurement of the currents and stator voltages.

The estimated speed is obtained by cancelling the difference between stator flux of the adjustable model of reference and that, while using the theory of hyperstability to obtain the adaptive mechanism. Very satisfactory results of simulation are presented at the end of this paper.

2. Mathematical Model of the Machine

By utilizing the usually adopted assumptions of linear magnetics, the steady state and transient behavior of an induction motor can be described by the following equations formulated in a Park reference frame linked to rotating field. The components of the state vector are stator flux, stator currents and the rotor speed of the machine. The dynamic model of the machine is obtained by

$$\frac{d}{dt}\begin{bmatrix} i_{ds} \\ i_{qs} \\ \varphi_{ds} \\ \varphi_{qs} \\ \Omega_r \end{bmatrix} = \begin{bmatrix} -\frac{1}{\sigma}(\frac{1}{T_r}+\frac{1}{T_s})i_{ds}+(\omega_s-\omega_r)i_{qs}+\frac{1}{\sigma T_r L_s}\varphi_{ds}+\frac{\omega_r}{\sigma L_s}\varphi_{qs}+\frac{1}{\sigma L_s}V_{ds} \\ -(\omega_s-\omega_r)i_{ds}-\frac{1}{\sigma}(\frac{1}{T_r}+\frac{1}{T_s})i_{qs}-\frac{\omega_r}{\sigma L_s}\varphi_{ds}+\frac{1}{\sigma T_r L_s}\varphi_{qs}+\frac{1}{\sigma L_s}V_{ds} \\ -R_s i_{ds}+\omega_s\varphi_{qs}+V_{ds} \\ -R_s i_{qs}-\omega_s\varphi_{ds}+V_{qs} \\ (C_{em}-C_r-f\Omega_r)/J \end{bmatrix} \quad (1)$$

with
$$\begin{aligned} \varphi_{dr} &= (L_r\varphi_{ds}-\sigma L_s L_r i_{ds})/L_m \\ \varphi_{qr} &= (L_r\varphi_{qs}-\sigma L_s L_r i_{qs})/L_m \end{aligned} \quad (2)$$

and

- i_{ds} and i_{qs} , v_{ds} and v_{qs} are respectively the stator currents and voltages,
- $\varphi_{ds}, \varphi_{qs}, \varphi_{dr}, \varphi_{qr}$ are respectively stator flux and rotor flux,
- ω_s electric pulsation of the stator,

- Ω_r mechanical speed of the rotor; $\omega_r = P\Omega_r$, P a number of pairs of poles: $\omega_{sr} = \omega_s - p\Omega_r = \frac{M}{T_r}\frac{i_{qs}}{\psi_r}$, ω_{sr} sliding speed
- R_s, R_r are rspectively stator and rotor resistance
- T_s and T_r are respectively the time-constant ones of stator and rotor; $T_s = \frac{L_s}{R_s}$; $T_r = \frac{L_r}{R_r}$
- L_s , L_r, L_m are the stator, rotor and mutual inductance,
-i_{dr} and i_{qr} are the rotor currents ; p : Operator of Laplace

3. Strategy of Vector Control Used

To obtain a decoupled system in order to control the torque via stator quadrature current i_{qs} with a similar manner of a DC machine, the rotor field orientation is obtained by imposing as $\varphi_{qr} = 0$ and $\varphi_{dr} = \varphi_r$. After arrangement, the equations of the machine become:

$$\sigma L_s \frac{di_{ds}}{dt} + R_s i_{ds} = V_{dsT} + \sigma L_s \omega_s\ i_{qs} - \frac{L_s(1-\sigma)}{Tr}\left(i_{ds} - \frac{\varphi_r}{L_m}\right) \quad (3)$$
$$\sigma L_s \frac{di_{qs}}{dt} + R_s i_{qs} = V_{qsT} + \omega_s\ \left(\sigma L_s\ i_{ds} - \frac{L_s(1-\sigma)}{L_m}\varphi_r\right)$$

In equations (3), the components of the two axis d-q are coupled; their decoupling is possible by the introduction of two new variables: V_{ds}, V_{qs}

$$V_{ds} = \sigma L_s \frac{di_{ds}}{dt} + R_s i_{ds}$$
$$V_{qs} = \sigma L \frac{di_{qs}}{dt} + R_s i_{qs} \quad (4)$$

Therefore:

$$V_{dsT} = V_{ds} + V_{ds}'$$
$$V_{qsT} = V_{qs} + V_{qs}'$$

With V_{ds} and V_{qs} are the exits of the regulators of currents (fuzzy regulators) and V'_{ds} and V'_{qs} terms of decoupling

$$V_{ds}' = -\sigma L_s \omega_s\ i_{qs} + \frac{L_s(1-\sigma)}{T_r}\left(i_{ds} - \frac{\varphi_r}{L_m}\right) \quad (5)$$
$$V_{qs}' = -\omega_s\ \left[\sigma L_s i_{ds} - L_s \frac{(1-\sigma)}{L_m}\varphi_r\right]$$

If we consider as: $\varphi_r = \varphi_{dr} = \varphi_{ref}$ we obtain the following equations:

$$\varphi_r = \varphi_{ref} \qquad V_{ds}' = -\sigma L_s i_{qsref}\ \omega_s \quad (6)$$
$$i_{dsref} = \frac{\varphi_{ref}}{L_m} \qquad V_{qs}' = \omega_s \frac{L_s}{L_m}\varphi_{ref}$$

4.Estimate Speed by MRAS Technique

To estimate rotor speed, it is judicious to use a reference frame related to the stator (α, β) given by the following equations. This transformation does not call upon the position of the rotor which we estimate by the model reference method [3],[12].

$$\begin{aligned} V_{\alpha s} &= R_s i_{\alpha s} + \frac{d\varphi_{\alpha s}}{dt} \\ V_{\beta s} &= R_s i_{\beta s} + \frac{d\varphi_{\beta s}}{dt} \\ 0 &= R_r i_{\alpha r} + \frac{d\varphi_{\alpha r}}{dt} + \omega_r \varphi_{\beta r} \\ 0 &= R_r i_{\beta r} + \frac{d\varphi_{\beta r}}{dt} - \omega_r \varphi_{\alpha r} \end{aligned} \quad (7)$$

$$\begin{aligned} \varphi_{\alpha s} &= L_s i_{\alpha s} + L_m i_{\alpha r} \\ \varphi_{\beta s} &= L_s i_{\beta s} + L_m i_{\beta r} \\ \varphi_{\alpha r} &= L_r i_{\alpha r} + L_m i_{\alpha s} \\ \varphi_{\beta r} &= L_r i_{\beta r} + L_m i_{\beta s} \end{aligned} \quad (8)$$

While using (8), (7) rewrites itself in the following form

$$\begin{aligned} 0 &= L_s(R_r + p\sigma L_r)i_{\alpha s} - \sigma L_r L_s \omega_r i_{\beta s} + (R_r + pL_r)\varphi_{\alpha s} + \omega_r L_r \varphi_{\beta s} \\ 0 &= \sigma L_r L_s \omega_r i_{\alpha s} - L_s(R_r + p\sigma L_r)i_{\beta s} - \omega_r L_r \varphi_{\alpha s} + (R_r + pL_r)\varphi_{\beta s} \end{aligned} \quad (9)$$

Basing on the dynamic model of the asynchronous machine, formulated in a stator reference frame, and by using measurements of the stator currents and tensions, we build two estimators of stator flux. The first is based on (7) and the second on (9), such as:

$$\begin{aligned} \varphi_{\alpha s} &= \int_0^t (V_{\alpha s} - R_s i_{\alpha s})dt \\ \varphi_{\beta s} &= \int_0^t (V_{\beta s} - R_s i_{\beta s})dt \end{aligned} \quad (10)$$

$$\begin{aligned} \hat{\varphi}_{\alpha s} &= \frac{T_r}{1 + T_r p}\left(\sigma L_s \omega_r i_{\beta s} + \frac{L_s}{T_r}(1 + \sigma T_r p)i_{\alpha s} - \omega_r \hat{\varphi}_{\beta s}\right) \\ \hat{\varphi}_{\beta s} &= \frac{T_r}{1 + T_r p}\left(\sigma L_s \omega_r i_{\alpha s} + \frac{L_s}{T_r}(1 + \sigma T_r p)i_{\beta s} - \omega_r \hat{\varphi}_{\alpha s}\right) \end{aligned} \quad (11)$$

In the system (10) relating to the stator observations, it is easy to notice that it does not depend on the rotor speed ω_r. This model is retained as a reference. In the rotor estimators relating to the system (11), we notice the existence of the rotor speed ω_r. It is the adjustable model. The system (11) can be written in the following form:

$$p[\hat{\varphi}_s] = [A][\hat{\varphi}_s] + [B][I_s] \quad (12)$$

$$[\hat{\varphi}_s] = \begin{bmatrix} \hat{\varphi}\alpha s \\ \hat{\varphi}\beta s \end{bmatrix};\ [A] = \begin{bmatrix} -\frac{1}{T_r} & -\omega_r \\ \omega_r & -\frac{1}{T_r} \end{bmatrix};\ [I_s] = \begin{bmatrix} i\alpha s \\ i\beta s \end{bmatrix}$$

$$[B] = \begin{bmatrix} (1 + \sigma T_r p)\frac{L_s}{T_r} & \sigma L_s \omega_r \\ -\sigma L_s \omega & (1 + \sigma T_r p)\frac{L_s}{T_r} \end{bmatrix}$$

By using the same inputs (stator currents and voltages) for the two models (reference and adjustable), we define the flux variations by the expressions

$$\begin{cases} \varepsilon_d = \varphi_{\alpha s} - \hat{\varphi}_{\alpha s} \\ \varepsilon_q = \varphi_{\beta s} - \hat{\varphi}_{\beta s} \end{cases} \quad (13)$$

These variations are used by the adaptation mechanism to generate the estimated speed and to make it converge towards its actual value. The adaptation mechanism must be designed in order to obtain a fast and a stable time response. The following figure represents the estimation technique principle.

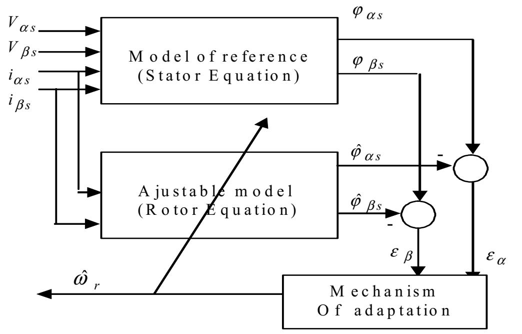

Fig.1. Structure of the estimator by adaptive method with model of reference

The derivative of the components of error[ε] (13) is defined by

$$p\begin{bmatrix} \varepsilon_\alpha \\ \varepsilon_\beta \end{bmatrix} = \begin{bmatrix} -\dfrac{1}{T_r} & -\omega_r \\ \omega_r & -\dfrac{1}{T_r} \end{bmatrix} \begin{bmatrix} \varepsilon_\alpha \\ \varepsilon_\beta \end{bmatrix} + \begin{bmatrix} -\hat{\varphi}_{\beta s} + \sigma L_s i_{\beta s} \\ \hat{\varphi}_{\alpha s} - \sigma L_s i_{\alpha s} \end{bmatrix} (\omega_r - \hat{\omega}_r)$$

In the form of state

$$p[\varepsilon] = [A][\varepsilon] + [W] \quad (14)$$

According to the general structure of the adaptive mechanism, the speed estimation is a function of the error[ε]. It is given by:

$$p\hat{\omega}_r = A_1 + PA_2 \quad (15)$$

Functions A_1 and A_2 , are calculated starting from the inequality of Popov , one obtains:

$$\begin{aligned} A_1 &= K_2 \left[\varphi_{\beta s}\hat{\varphi}_{\alpha s} - \varphi_{\alpha s}\hat{\varphi}_{\beta s} - (i_{\alpha s}\varepsilon_\beta - i_{\beta s}\varepsilon_\alpha)\sigma L_s\right] \\ A_2 &= K_1 \left[\varphi_{\beta s}\hat{\varphi}_{\alpha s} - \varphi_{\alpha s}\hat{\varphi}_{\beta s} - (i_{\alpha s}\varepsilon_\beta - i_{\beta s}\varepsilon_\alpha)\sigma L_s\right] \end{aligned} \quad (16)$$

where K_1 and K_2 , are positive constants called profits of adaptation.

5. Estimate of Rotor Resistance

To estimate resistance of the rotor we used a method which makes it possible to calculate the latter in function to flux (real, reference) and of the electromagnetic torque (real, reference) [13].

To clarify the relation which binds the electromagnetic torque and rotor flux to the variations of the parameters of the machine we let us proceed as follows:

$$\begin{aligned} L_r &= K_l L_r^* \\ R_r &= K_r R_r^* \end{aligned} \quad (17)$$

L_r^*, R_r^* Values used in the command.

The actual value of the rotor time-constant:

$$T_r = \frac{K_l}{R_r} T_r^* = KT_r^*$$

The block of decoupling imposes on the command of the inverter the sizes V_{ds}, V_{qs} and ω_{sr} . In permanent mode we have:

$$\begin{aligned} C_e^* &= \frac{PL_m^*}{L_r^*}\varphi_r i_{qs} = \frac{PL_m^{*2}}{L_r^*} i_{ds} i_{qs} \\ \omega_{sr}^* &= \frac{1}{T_r^*}\frac{i_{qs}}{i_{ds}} \\ \varphi_r^* &= L_m^* i_{ds} \end{aligned} \quad (18)$$

From the equations of Park of the machine we draw the components direct and in squaring from rotor flux and the real torque of the machine with permanent rate:

$$\varphi_{dr} = L_m \frac{i_{ds} + \omega_{sr} T_r i_{qs}}{1 + (\omega_{sr} T_r)^2}$$

$$\varphi_{qr} = L_m \frac{i_{qs} - \omega_{sr} T_r i_{ds}}{1 + (\omega_{sr} T_r)^2}$$

$$C_e = P\frac{K_l^2}{K_r}\frac{L_m^{*2}}{L_r^*} i_{ds} i_{qs} \frac{1 + (\frac{i_{qs}}{i_{ds}})^2}{1 + (K\frac{i_{qs}}{i_{ds}})^2} \quad (19)$$

$$\varphi_r = K_l L_m^* i_{ds} \sqrt{\frac{1 + (\frac{i_{qs}}{i_{ds}})^2}{1 + (K\frac{i_{qs}}{i_{ds}})^2}}$$

The rapports of the real couple and flux on the estimated values are:

$$\frac{\varphi_r}{\varphi_r^*} = K_l \sqrt{\frac{1 + (\frac{i_{qs}}{i_{ds}})^2}{1 + (K\frac{i_{qs}}{i_{ds}})^2}}$$

$$\frac{C_e}{C_e^*} = \frac{K_l^2}{K_r}\frac{1 + (\frac{i_{qs}}{i_{ds}})^2}{1 + (K\frac{i_{qs}}{i_{ds}})^2} = \frac{1}{K_r}\left(\frac{\varphi_r}{\varphi_r^*}\right)^2 \quad (20)$$

$$K_r = \frac{C_e^*}{C_e}\left(\frac{\varphi_r}{\varphi_r^*}\right)^2$$

Therefore the rotor estimate of resistance is given by following relation:

$$R_r = K_r R_r^* \tag{21}$$

6. Controller with Fuzzy Logic and Simulation Results

The structure of the fuzzy controller used that is proposed by Mamdani, because the majority of the developed controllers use the diagram suggested by this last for the systems mono input/mono output. Its basic structure is represented hereafter [8]:

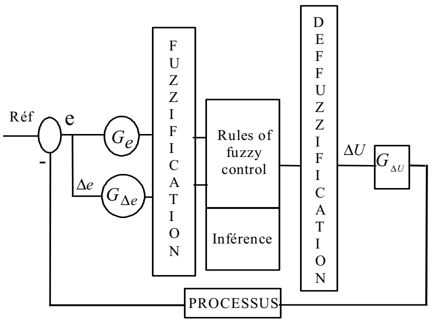

Fig.2. Structure interns of a regulator by fuzzy logic

The variables of entry and exit of the fuzzy controller must be clearly defined. The variables of entry are the error e_k and the variation Δe_k of the error which are as follows:

$$\begin{cases} e_k = Y_{réf} - Y_k \\ \Delta e_k = e_k - e_{k-1} \end{cases} \tag{22}$$

The standardized values are:

$$\begin{cases} e^*_k = G_e * e_k \\ \Delta e^*_k = G_{\Delta e} * \Delta e \end{cases} \tag{23}$$

The general form of this law of command is given by

$$U_{k+1} = U_k + G_{k+1} * \Delta U_{k+1} \tag{24}$$

where $G_e, G_{\Delta e}, G_{\Delta u}$ are a Coefficient of standardization.

We selected seven membership functions with overlap, of triangular shape and of equal width, are used for each input variable, so that a 49-rule base is created.

The input membership functions are presented by the following scheme:

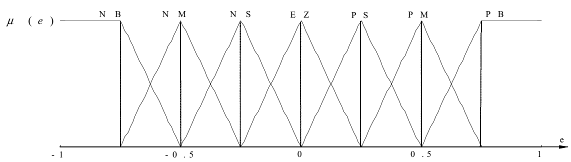

Fig.3. input membershipfunction for variable e

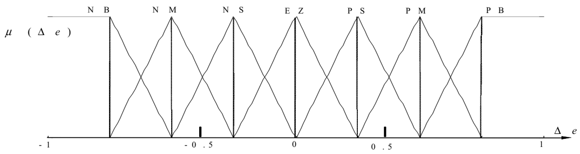

Fig.4. input membershipfunction for variable Δe

For fuzzy PI component output of the controller, again with normalized domain, we elected to use seven singleton functions, spacing them evenly between ±1; inclusive.

The output membership singleton is presented by the following scheme:

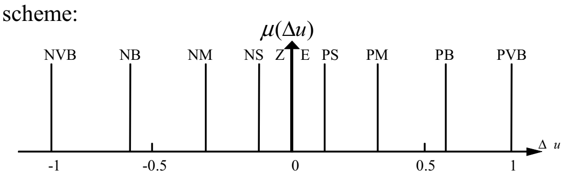

Fig.5. Output membership singletons for variable ΔU

Output singletons are evenly spaced over the domain. Function and singleton definition was largely arbitrary and was not changed as the system was tuned.

Owing to the membership singleton for output variable, gravity center formula is simplified as:

$$\Delta U = \frac{\sum_{i=1}^{m} \mu(\Delta u_i)\,\Delta u_i}{\sum_{i=1}^{m} \mu(\Delta u_i)} \tag{25}$$

Where m is the all number of the rule bases.

In our case, the gains $G_e, G_{\Delta e}, G_{\Delta u}$ from standardization are chosen arbitrarily, for regulators of the currents and speed.

The block diagram without speed sensor of the induction machine supplied by PWM inverter, by using fuzzy logic regulators and rotor-flux orientation control algorithm, is given by the figure6.

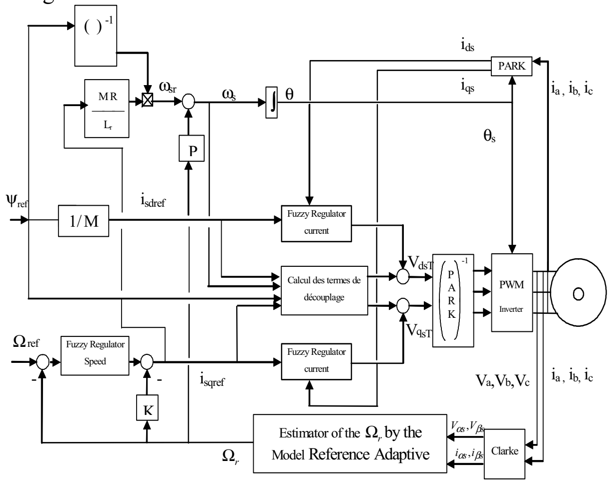

Fig.6. Diagram valve block without speed sensor of the asynchronous machine by using fuzzy logic regulators

Figures 7. a, b, c show the dynamic responses of the adjustment by orientation of the rotor-flux algorithm of the asynchronous machine supplied by PWM inverter. The stator-currents are controlled by using fuzzy regulators.These figures represent the dynamic responses real speed, estimated, of reference, the couple and rotor flux at a step speed of 100 rd/s followed by an application of a load equal to the nominal couple between 1 and 1.5 sec, then of an inversion speed from 2 sec in the following cases:

- Without variation of the rotor time-constant T_r.
- Reduction of 50% of the rotor time-constant T_r.

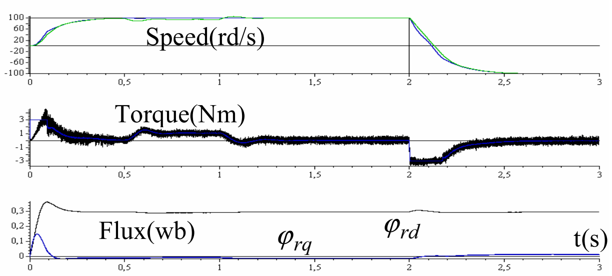

Fig.7.a Simulation of the vector control without speed sensor and without variation of T_r in the induction machine supplied by PWM inverter.

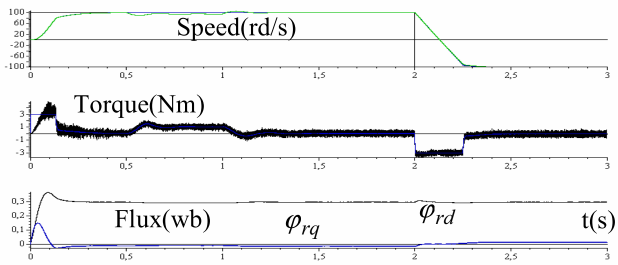

Fig. 7.b Simulation of the vector control without speed sensor with a reduction 50% of T_r in the asynchronous machine supplied by PWM inverter.

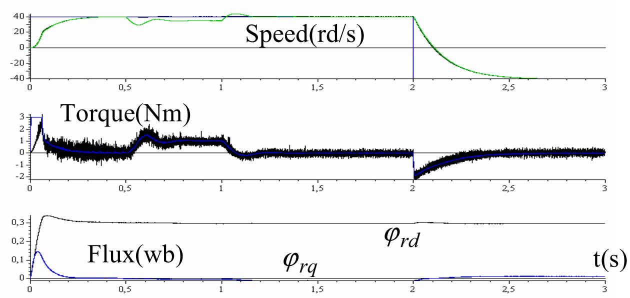

Fig.7.c Simulation of the vector control without speed sensor with a reduction 50% of T_r in the asynchronous machine supplied by PWM inverter. (**low speed**)

7. Conclusion

In this paper, we are proposed and analysed a method of a rotor-flux oriented induction motor drive without speed sensor.

The rotor speed is estimated by using the adaptive method with model of reference (MRAS) and the stator currents are controlled by using fuzzy logic regulators.The results obtained carry out us to conclude that the strategy of control used offers good performances as well as an insensitivity with respect to the disturbances internal and external, such as the level speed, the load torque, in the presence of variations of the parameters of the machine in particular the rotor time-constant, and a speed of adaptation compared to the case of a classical PI regulator. This demonstrates the robustness of the control algorithm used, even in the case of low speed. This association could be used for numerical control machine tools where the parametric variations are frequent.

8. References

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