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INDUCTION MACHINE SPEED CONTROL USING FUZZY ADAPTIVE CONTROLLER

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Abstract

This paper investigates fuzzy adaptive control of induction machine (IM) speed. The proposed controller consists of two parts: the first is classical fuzzy logic controller (FLC) constituted by fuzzy If-Then rules. The second part is adaptation mechanism, which adjusts the fuzzy controller parameters in order to minimize the error between the reference speed and the machine speed. The fuzzy adaptive controller (FAC) can be started without prior information on the machine, and can learn and tune rapidly the fuzzy controller rules to meet the desired performance, even when the machine parameters change. Simulation studies for various operating conditions show the superior performance of the FAC compared to PI controller.

1 Introduction

In last years, the IM has found an increasing interest in many industrial applications, due to considerations of cost, size, low maintenance, speed capability and simplicity of design. However, the IM presents a coupled nonlinear multivariable control structure that calls for complex nonlinear design in order to achieve good dynamic performance. Control based on linear approximation do not always meet high dynamical performance requirements for variable speed regulation [1], [2]. Presently, typical control strategy for the IM is the field oriented control [3][4], where suitable transformation of control inputs allows linear dynamic model and partly linear rotor speed to be obtained. The fundamental drawback of this decoupling approach is that highly accurate values of the machine parameters, such as rotor resistance or inductance and the rotor flux are required in order to produce the control signal. The controller performance is sensitive to “Inaccurate Decoupling”.

In electric machine drives and motion control, the Fuzzy controller is considered as promising alternative for conventional control approaches in the control of complex nonlinear plants [5]. The Fuzzy controller is applied to static power converters, AC and DC machines [6], [7] and [8]. It has been reported that fuzzy controllers are more robust to plant parameter changes and have better disturbance rejection. The main advantage of fuzzy control as compared to conventional control resides in the fact that no mathematical model of the plant is required and human experience can be implanted in the controller as fuzzy rules [9]. However, classical fuzzy controllers can not adapt themselves to change in their environment or in operating conditions. Then, it is necessary to add some form of adaptation that updates the controller parameters in order to maintain and improve the control performance in wide range of changing conditions.

This work investigates new form of fuzzy adaptive control for vector-controlled IM speed. The FAC consists in tow components: First, classical fuzzy logic controller whose inputs are the error and change of error measured between the machine speed and the reference speed, and its output is the reference torque. The fuzzy controller processes fuzzy version of the inputs through the rule base to produce the adequate output for any input situation. The adaptation mechanism uses the error signals to adjust the parameters of the fuzzy controllers in the direction that minimizes the given cost function. In that way, no initial qualitative knowledge is required for the design of the controller. The control performances are evaluated by simulation for various operating conditions.

2 Induction Machine Model

It is well known that the dynamic performance of the induction machine can be analysed mathematically by using the d-q axis theory [4]. By choosing the synchronous reference frame d-q, which is rotating synchronously with the supply voltage phasor, the electrical and mechanical instantaneous characteristics are given by the following equations

$$\begin{cases} \dot{x} = Ax + Bu \\ \dfrac{d\Omega}{dt} = -\dfrac{D}{J}\Omega + \dfrac{1}{J}\left(T_{em} - T_L\right) \end{cases} \quad (1)$$

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where

$$x = \begin{bmatrix} i_{qs} & i_{ds} & \phi_{qr} & \phi_{dr} \end{bmatrix}^T, \qquad u = \begin{bmatrix} v_{qs} & v_{ds} \end{bmatrix}^T$$

$$A = \begin{bmatrix} -\beta & -\omega_s & \frac{\alpha}{T_r} & \alpha\omega_r \\ \omega_s & -\beta & -\alpha\omega_r & \frac{\alpha}{T_r} \\ \frac{L_m}{T_r} & 0 & -\frac{1}{T_r} & -\omega_{sl} \\ 0 & \frac{L_m}{T_r} & \omega_{sl} & -\frac{1}{T_r} \end{bmatrix}, \quad B = \begin{bmatrix} \frac{1}{\sigma L_s} & 0 \\ 0 & \frac{1}{\sigma L_s} \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

and

$$T_{em} = \text{np}\frac{L_m}{L_r}\left(\phi_{dr} i_{qs} - \phi_{qr} i_{ds}\right) \tag{2}$$

where i_{qs}, i_{ds} are stator currents; ϕ_{qr}, ϕ_{dr} are rotor flux; v_{qs}, v_{ds} are stator voltages; ω_s, ω_r and ω_{sl} are synchronous, rotor and slip speed, respectively; T_{em} is the electromechanical torque, T_L is the load torque, Ω is the mechanical speed and np is the number of pair of poles. The rotor time constant T_r and the parameters σ, β and α are defined as follows:

$$T_r = \frac{L_r}{R_r}, \; \sigma = 1 - \frac{L_m^2}{L_s L_r}, \; \beta = \frac{R_s}{\sigma L_s} + \frac{1-\sigma}{\sigma T_r}, \text{ and } \alpha = \frac{L_m}{\sigma L_s L_r}.$$

R_s, R_r represent the stator (resp. rotor) resistance; L_s, L_r and L_m are respectively stator, rotor and mutual inductance. J is the rotor moment of inertia and D is the damping coefficient.

According to the decoupling theory, the machine currents can be decomposed into i_{ds} and i_{qs} components, which are respectively, flux and torque components. When the decoupling conditions are satisfied, namely, $\phi_{qr} = 0$ and $\phi_{dr} = \phi_r$ (the rotor flux is oriented following the d-axis). Hence, the flux and the electromechanical torque are decoupled from each other and can be separately controlled as desired. The operation of the drive is then similar to that of a current controlled dc machine. The drive behaviour can be adequately controlled by using the following simplified electromechanical torque expression

$$T_{em} = \left(\text{np}\frac{L_m}{L_r}\phi_r\right) i_{qs} \tag{3}$$

3 Fuzzy Speed Control

A typical topology of fuzzy speed controller is shown in Figure 1. The fuzzy controller is constituted by three stages: fuzzification, rules execution and defuzzification. The rule base is the principal component of the fuzzy controller; it indicates how the controller behaves to response to any input situation (the control strategy). The rule base is constituted by collection of If-Then rules of the form

$$R_j : \mathit{If}\; E(k)\, \mathit{is}\, A_j \;\mathit{and}\; CE(k)\, \mathit{is}\, B_j \;\mathit{Then}\, TE(k+1)\, \mathit{is}\, C_j \quad j = 1..M$$

where A_j, B_j and C_j are fuzzy sets such as: NL (negative large), NM (negative medium), etc. defining fuzzy partition on the controller input space (see Figure 2), and $E(k)$ and $CE(k)$ are scaled and normalized version of the error $e(k)$ and the change of error $ce(k)$ given by

$$\begin{cases} E(k) = \text{ge}.e(k) \\ CE(k) = \text{gce}.ce(k) \end{cases} \tag{4}$$

where $e(k) = \Omega_{ref}(k) - \Omega(k)$, and $ce(k) = e(k) - e(k\text{-}1)$. ge and gce are the controller scaling factors that can be constants or variables.

The expression "$E(k)\, is\, A_j$" is implemented by membership function indicating the grade of membership of $E(k)$ in the fuzzy set A_j as in Figure 2, this operation is called fuzzification. The shape of the membership function is quite arbitrary and depends on the user's preference. For simplicity, triangular and trapezoidal shapes are usually used. The rules are derived from engineer experience or created automatically by adaptation procedure.

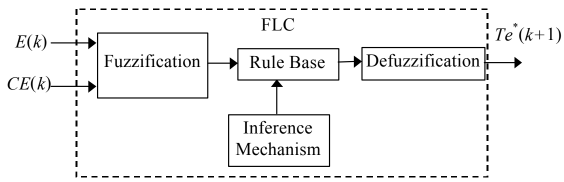

Figure 1: Basic structure of fuzzy logic controller.

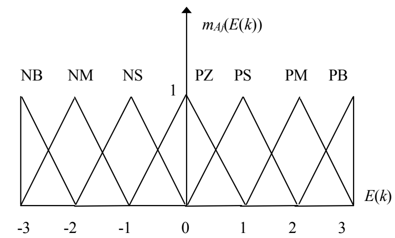

Figure 2: Membership functions.

The logical operators "*and*" and "*Then*" can be interpreted as *min* or algebraic product, and various inference and defuzzification algorithms can be used to produce crisp output value [9], [10]. If the operators "*and*" and "*Then*" are implemented as algebraic product, and the *max*-product inference and the centroid defuzzification algorithms are used, then the crisp value of the controller output is

$$Te^*(k+1) = \frac{\sum_{j=1}^{M} m_{A_j}(E(k)).m_{B_j}(CE(k)).c_{0j}}{\sum_{j=1}^{M} m_{A_j}(E(k)).m_{B_j}(CE(k))} \qquad (5)$$

where c_{0j} is the center of the membership function of the fuzzy set C_j, such that $m_{C_j}\left(c_{0j}\right) = 1$. The above equation can be written as

$$Te^*(k+1) = \sum_{j=1}^{M} m_j(k).c_{0j} \qquad (6)$$

where $m_j(k)$ is the normalized degree of contribution of the *j*th rule to the FLC output given by

$$m_j(k) = \frac{m_{A_j}(E(k)).m_{B_j}(CE(k))}{\sum_{j=1}^{M} m_{A_j}(E(k)).m_{B_j}(CE(k))} \qquad (7)$$

then (6) can formulated in the following matrix form

$$Te^*(k+1) = \mathbf{m}(k)\mathbf{c}_0 \qquad (8)$$

where

$$\mathbf{m}(k) = \lfloor m_1(k) \quad m_2(k) \quad \cdots \quad m_M(k) \rfloor \qquad (9)$$

and

$$\mathbf{c}_0 = \left[c_{01} \quad c_{02} \quad \cdots \quad c_{0M}\right]^T \qquad (10)$$

4 Adaptation Mechanism

When the qualitative knowledge used to construct the rule base is false or incomplete, then the controller can't drive correctly the machine to the desired performance. More if the rule base is static (i.e., with fixed rules), the controller can't cope with variations of the environment and the parameters of the machine. In those cases a mechanism of adaptation must be added to correct and complete the rules. In the FAC, the adaptation mechanism adjusts at each sample *t* the fuzzy controller output (i.e., the rules consequences parameters $\mathbf{c}_0$) to move them in the direction that minimizes the following criterion

$$V(k) = e^2(k)/2 \qquad (11)$$

then the gradient algorithm can be used to move the parameters values in the direction of the minimum of *V*(*k*). The parameter adaptation can be done using the following usual formula [11]:

$$\mathbf{c}_0(k+1) = \mathbf{c}_0(k) - \gamma \frac{\partial V(k)}{\partial \mathbf{c}_0(k)} \qquad (12)$$

where γ is the learning step size, controlling the convergence rate.

From (12) it is clear that the adaptation algorithm involves the computation of the partial derivatives of *V*(*k*) with respect to $\mathbf{c}_0$, which are given by

$$\frac{\partial V(k)}{\partial \mathbf{c}_0(k)} = -e(k)\frac{\partial \Omega(k)}{\partial \mathbf{c}_0(k)} \qquad (13)$$

Because, no direct relation exists between $\Omega(k)$ and $\mathbf{c}_0(k)$, the expression (13) can be written as

$$\frac{\partial V(k)}{\partial \mathbf{c}_0(k)} = -e(k)\frac{\partial \Omega(k)}{\partial Te^*(k)}\frac{\partial Te^*(k)}{\partial \mathbf{c}_0(k)} \qquad (14)$$

where

$$\frac{\partial Te^*(k)}{\partial \mathbf{c}_0(k)} = (\mathbf{m}(k))^T \qquad (15)$$

the expression (14) involves the computation of the gradient of $\Omega(k)$ with respect to $Te^*(k)$. From the engineering qualitative and quantitative knowledge, it is known that speed and torque can be assumed to vary linearly in the same sense. Thus, this gradient can be approximated by some positive constant value. Because only the sign of the gradient is critical to the iterative algorithm convergence, the gradient value can be set simply to (+1). This approximation does not alter the convergence of the iterative process; this will be seen in the simulation results. Then, the adaptation algorithm can be written as

$$\mathbf{c}_0(k+1) = \mathbf{c}_0(k) + \gamma e(k)(\mathbf{m}(k))^T \qquad (16)$$

Because the relation between the error and the parameter vector $\mathbf{c}_0$ is assumed linear, the mean squared error surface is quadratic. Then, the gradient algorithm is guaranteed to converge rapidly to the single global minimum. The implementation of the gradient algorithm is the same for each

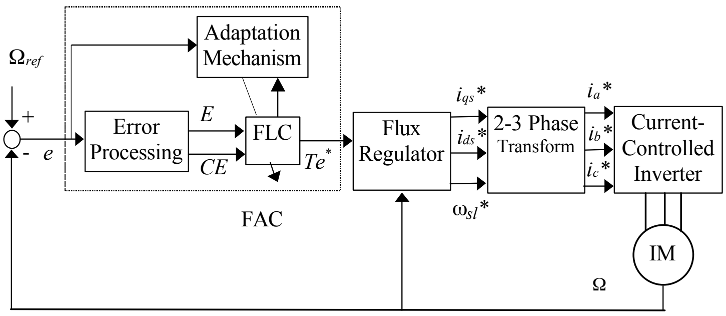

Figure 3: Fuzzy adaptive control of induction machine.

parameter and does not change as rules are added or removed from the FLC rule base. This means that the algorithm scales easily and the computational cost increases linearly with the number of rules.

V. SIMULATION RESULTS

The performance of FAC control of IM speed (see Figure 3) is compared to conventional PI regulator by extensive simulation for various operating conditions using IM whose parameters are: R_s= 2.4Ω, R_r= 1.452, L_s= 0.121H, L_r= 0.121H, L_m= 0.1198H, ϕ_r= 0.15Wb, np= 2, J= 0.0013Kgm², D= 0.00038Nms. The coefficients of the designed PI are k_p=1.04 and k_i=20.8. The sampling period is T=1 ms. The speed error and change of the error are normalized and fuzzified using seven fuzzy sets as in Figure 2, and then used as the FLC inputs. The FLC rule base is initialized with null actions (no initial qualitative knowledge is used).

First, transient responses to step change in reference speed or speed inversion are obtained for both FAC and PI control under different operating conditions. In Figure 4, the load torque is changed from zero to 12 Nm at 0.5 s, and back to zero at 1.5 s. It can be seen that the FAC provides mush fast and robust speed response compared to the PI. The Figure 5 shows that the FAC achieves better performance also when the rotor resistance is changed from 1.452 Ω (the nominal value) to 3×1.452 Ω.

Second, The efficiency of the adaptation mechanism is evaluated by using a trapezoidal speed profile as reference speed. The Figure 6 and 8 show that in the FAC case the machine speed tracks closely the reference speed in spit of the disturbance applied during the movement (load torque or inertia change). As can be noted form Figure 7 and 9, the FAC control achieves small speed error compared to the PI, and that the transient response of the adaptation mechanism is very short (i.e., the FAC learns rapidly the correct output actions to be applied for any error situation).

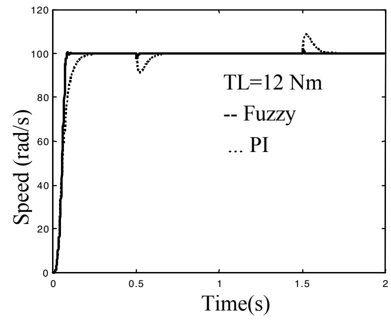

Figure 4: Speed response (load torque change)

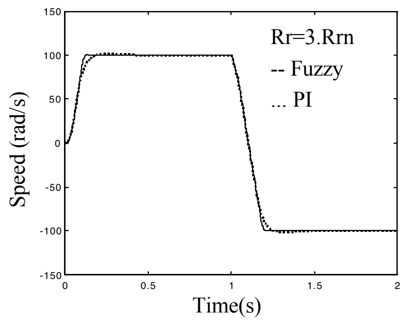

Figure 5: Speed response (rotor resistance change).

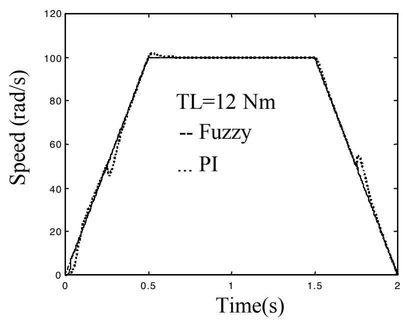

Figure 6: Speed response (load torque change).

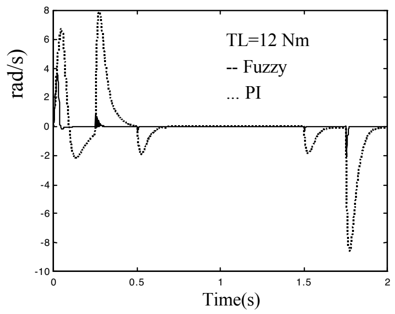

Figure 7: Speed error (load torque change).

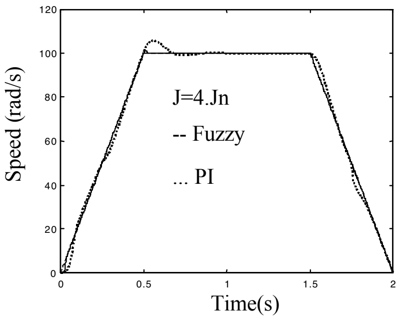

Figure 8: Speed response (inertia change).

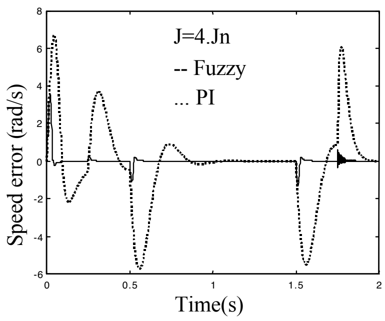

Figure 9: Speed error (inertia change).

VI. CONCLUSION

A direct fuzzy adaptive control of IM drive is proposed. In the derived scheme, the adaptation mechanism adjusts the consequent parameters of static FLC using the speed error signal, to force the machine speed to behave like the given reference speed, which provides learning capability to the FAC. The simulations have confirmed the efficiency of the proposed fuzzy adaptive scheme for change in operating conditions, without use of any qualitative knowledge. Because this fuzzy adaptive controller is relatively simple and does not requires complex mathematical operations. It can be readily implemented using conventional microprocessors or microcontrollers.

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