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Fuzzy Rule – Based Model Reference Adaptive Control for PMSM Drives

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Abstract: The objective of the model reference adaptive fuzzy control (MRAFC) is to change the rules definition in the direct fuzzy logic controller (FLC) and rule base table according to the comparison between the reference model output signal and system output. The MRAFC is composed by the fuzzy inverse model and a knowledge base modifier. Because of its improved algorithm, the MRAFC has fast learning features and good tracking characteristics even under severe variations of system parameters. The learning mechanism observes the plant outputs and adjusts the rules in a direct fuzzy controller, so that the overall system behaves like a reference model, which characterizes the desired behavior. In the proposed scheme, the error and error change measured between the motor speed and output of the reference model are applied to the MRAFC. The latter will force the system to behave like the signal reference by modifying the knowledge base of the FLC or by adding an adaptation signal to the fuzzy controller output. In this paper, the MRAFC is applied to a permanent magnet synchronous motor drive (PMSM). High performances and robustness have been achieved by using the MRAFC. This will be illustrated by simulation results and comparisons with other controllers such as PI, classical and adaptive fuzzy controller based on gradient method controllers.

Keywords: PMSM drive, MRAFC, FLC, Robustness.

1 Introduction

As results of the progress in power electronics, software engineering, and materials, the PMSM, based on modern rare earth variety, becomes serious competitor to the induction motor and conventional wound rotor synchronous motor. PMSM drives are used in many applications. They are receiving increased attention because of their high torque density, high efficiency, and small size. The PMSM is preferred, in industrial servo applications, to the DC motor due to considerations of the cost, size, low maintenance, maximum speed capability, and simplicity of design.

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The fuzzy logic can be considered as a mathematical theory combining multi-valued logic, probability theory, and artificial intelligence to simulate the human approach in the solution of various problems by using an approximate reasoning to relate different data sets and to make decisions. In this paper, the adaptive control of fuzzy logic controller for a vector controlled PMSM is investigated. First FLC principle is presented and its application to the speed control is considered [1].

It has been reported that fuzzy controllers are more robust to plant parameter changes than classical PI or PID controllers and have better noise rejection capabilities. The proposed scheme exploits the simplicity of the Mamdani type fuzzy systems that are used in the design of the controller and adaptation mechanism.

The fuzzy adaptive strategies are closer to the experts, reflecting their knowledge and experience. As the modern conventional control strategies grow in complexity, the fuzzy controllers are very competitive in high performance applications. As a result, the performance/complexity ratio is generally higher for adaptive fuzzy controllers [2].

An alternative approach in traditional adaptive control, which needs a rather accurate model of the system, is the FLC. A standard FLC is usually defined by a set of fuzzy parameters which specifies which control action to take for a given process state. It has been proved that the FLC can provide any nonlinear control action with proper choice of the parameters. In this way, the key issue to design an FLC is to well define its parameters such as the knowledge base and scaling factors. However, the optimal setting of parameters varies under different working conditions. When the parameters are fixed, ideal performance cannot be achieved in all cases. A solution to this problem is addressed by the adaptive FLC, whose aim is to maintain consistent performance of a system by adjusting the controller parameters adapting to varying conditions [2,3].

A model reference adaptive scheme is proposed in which the adaptation mechanism is executed by fuzzy logic based on the error and change of error measured between the motor speed and the output of a reference model. The control performance of the adaptive fuzzy controller is evaluated by simulation for various operating conditions.

A comparison between FMRAC, classical FLC, and fixed gain PI controller is presented by simulation results that verify appropriateness of the approach under various operating situations and provide the fast and robust control.

2 Mathematical Model and Vector Control

The well established dq model of the wound rotor synchronous machine is easily adapted to study the performance of PMSM. There is no difference between the back e.m.f. produced by a permanent magnet and that produced by an excited coil. Hence, the mathematical model of a PMSM is similar to that of the wound rotor synchronous machine. The stator dq equations in the rotor reference frame of the PMSM are:

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = R_s \begin{bmatrix} I_d \\ I_q \end{bmatrix} + \frac{\mathrm{d}}{\mathrm{d}t} \begin{bmatrix} \phi_d \\ \phi_q \end{bmatrix} + \omega_r \begin{bmatrix} -\phi_q \\ \phi_d \end{bmatrix}. \tag{1}$$

The dq axis stator flux linkages are:

$$\begin{bmatrix} \phi_d \\ \phi_q \end{bmatrix} = \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix} \begin{bmatrix} I_d \\ I_q \end{bmatrix} + \begin{bmatrix} \phi_f \\ 0 \end{bmatrix}. \tag{2}$$

The model is nonlinear, because it contains product terms such as speed with i_d or i_q which are stator variables.

$$\begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix} \frac{\mathrm{d}}{\mathrm{d}t} \begin{bmatrix} I_d \\ I_q \end{bmatrix} = \begin{bmatrix} V_d \\ V_q \end{bmatrix} - \begin{bmatrix} R_s & -\omega_r L_q \\ \omega_r L_d & R_s \end{bmatrix} \begin{bmatrix} I_d \\ I_q \end{bmatrix} - \begin{bmatrix} 0 \\ \omega_r \phi_f \end{bmatrix}. \tag{3}$$

The dynamic behavior and electromagnetic torque equations are expressed by:

$$\frac{J}{p} \frac{\mathrm{d}\omega_r}{\mathrm{d}t} + \frac{f}{p} \omega_r = C_{em} - C_{st}, \tag{4}$$

$$C_{em} = \frac{3}{2} p \left\{ \phi_f I_q + (L_d - L_q) I_d I_q \right\}. \tag{5}$$

The dq model of PMSM has been used to examine the transient behavior of a high performances vector controlled PMSM servo drive. The direct or 'd' axis is aligned with permanent magnet flux linkage phasor ϕ_f, so that the quadrate or 'q' axis is orthogonally aligned with the resulting back e.m.f. phasor. If I_d is forced to be zero, then:

$$\begin{aligned} \phi_d &= \phi_f, \\ \phi_q &= L_q I_q. \end{aligned} \tag{6}$$

For constant flux operation, the electromagnetic torque is

$$C_{em} = \frac{3}{2} p \phi_f I_q. \tag{7}$$

Note that this torque equation for PMSM resembles that of the regular DC motor. Therefore, it may facilitate very efficiently the control of the machine. The motor currents are decomposed into I_d and I_q components in the rotor based dq coordinates system. The maximum torque is obtained with $I_d = 0$ which corresponds to the case when the rotor and stator fluxes are perpendicular. The operation of the drive is then similar to that of armature current controlled DC motor. The drive behavior can be adequately described by a simplified model expressed by equation (7).

3 Direct Fuzzy Logic Controller

Fig. 1 shows a block diagram of a speed control system using a FLC. The FLC has two inputs speed error $e(k)$ and change in speed error $\mathrm{d}e(k)$ and one output $C_{ref}(k)$ which represents the change in quadrature reference current $I_q(k)$.

$$\begin{aligned} e(k+1) &= \omega_{ref} - \omega(k+1) \\ \mathrm{d}e(k+1) &= e(k+1) - e(k) \end{aligned} . \tag{8}$$

To obtain normalized inputs and output for fuzzy logic controller, the constant gain blocks are used as scaling factors C_{oef1}, C_{oef2}, C_{oef3} as shown in Fig. 1.

$$\begin{aligned} E(k+1) &= C_{oef1} e(k+1) \\ \mathrm{d}E(k+1) &= C_{oef2}\, \mathrm{d}e(k+1) \end{aligned} . \tag{9}$$

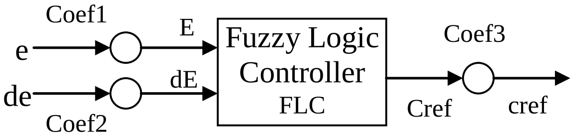

Fig. 1 – *Scaling factors.*

The FLC consists of three stages: the fuzzification, rule execution, and defuzzification. In the first stage, the crisp variables $e(k)$ and $\mathrm{d}e(k)$ are converted into fuzzy variables $E(k)$ and $\mathrm{d}E(k)$ using the triangular membership functions shown in Fig. 2.

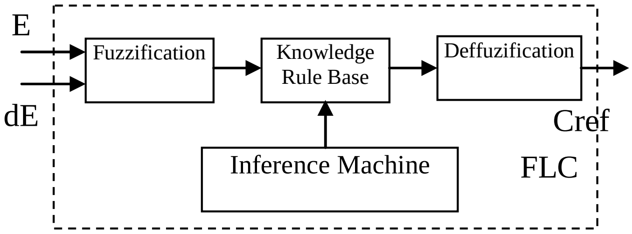

Fig. 2 – *Fuzzy logic controller topology.*

Each universe of discourse is divided into five fuzzy sets: NL (negative large), NS (negative small), ZE (zero), PS (positive small) and PL (positive large). Each fuzzy variable is a member of the subsets with a degree of membership varying between 0 (non-member) and 1 (full-member).

In the second stage of the FLC, the fuzzy variables E and $\mathrm{d}E$ are processed by an inference engine that executes a set of control rules contained in (5×5) rule bases. The control rules are formulated using the knowledge of the PMSM behavior. Each rule is expressed in the form

Rule 1: If x is A and y is B then z is C.

Different inference algorithms can be used to produce the fuzzy set values for the output fuzzy variable C_{ref}. In this paper, the max-min inference algorithm is used, in which the membership degree is equal to the maximum of the product of E and $\mathrm{d}E$ membership degree.

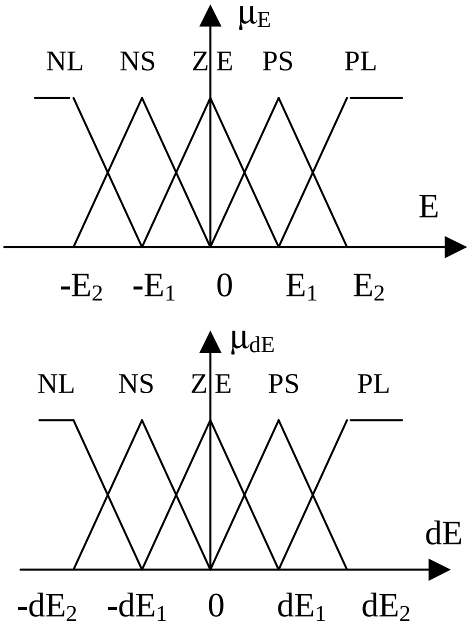

Fig. 3 – *Membership functions of the controller.*

The inference engine output variable is converted into a crisp value c_{ref} in the defuzzification stage. Various defuzzification algorithms have been proposed in the literature. In this paper, the centroid defuzzification algorithm is used, in which the crisp value is calculated as the centre of gravity of the membership function.

The definition of the spread of each partition, or conversely the width and symmetry of the membership functions, is generally a compromise between dynamic and steady state accuracy. Equally spaced partitions and consequently symmetrical triangles are a very reasonable choice. The universe of discourse are normalized over the interval $[-2, 2]$. So, we need to multiply the controller input and output variables by adjusting gains in order to accommodate these variables into the normalized intervals [3,4].

4 Fuzzy Model Reference Adaptive Control (FMRAC)

Fuzzy control systems based on model reference adaptive control have been reported by a number of researchers. The principal components of this system are the reference model, a primary or direct fuzzy logic controller (FLC), and an adaptation mechanism. The reference model embodies the desired performance characteristics of the overall system. Typically, this is a first order or well damped second order linear system although it could alternatively be nonlinear [4].

The direct fuzzy logic controller is implemented using a simple adaptive control based on the gradient algorithm method. The role of the adaptation mechanism is to adjust the characteristic of the FLC in response to the error $e_m(t)$ between the outputs of reference model and plant, in order to minimize that error in some sense. The adaptation mechanism may be subdivided into an inverse plant model designed to give an indication of the required correction, $\Delta U(t)$, to the output signal $U(t)$ and an updating algorithm in order to affect that correction via the direct FLC [5,6].

The updating algorithm modifies the FLC characteristic such that its output $U(t)$ is altered by the correction value $\Delta U(t)$. The FMRAC is depicted in Fig. 4. It is presented as learning a more global control function with faster convergence. The adaptation is affected by adjusting the centre values of the output fuzzy sets [4,5,7].

In the proposed scheme, the error and change of error measured between the motor speed and the output of a reference model are applied to a fuzzy logic adaptation mechanism. The latter will force the system to behave like the model by modifying the knowledge base of the fuzzy controller or by adding an adaptation signal to the fuzzy controller output [6,7].

$$\begin{aligned} e_m(k+1) &= \omega_m(k+1) - \omega(k+1) \\ \mathrm{d}e_m(k+1) &= e_m(k+1) - e_m(k) \end{aligned} \quad . \tag{10}$$

The internal structure of the FMRAC is identical to that of the direct FLC: the fuzzification, rule execution, and defuzzification. As in the case of FLC, FMRAC rules are formulated based on the knowledge of the drive behaviour and common sense.

These quantities are processed by the fuzzy logic adaptation mechanism to produce a correction term ΔI_q. The correction term is added to the FLC output.

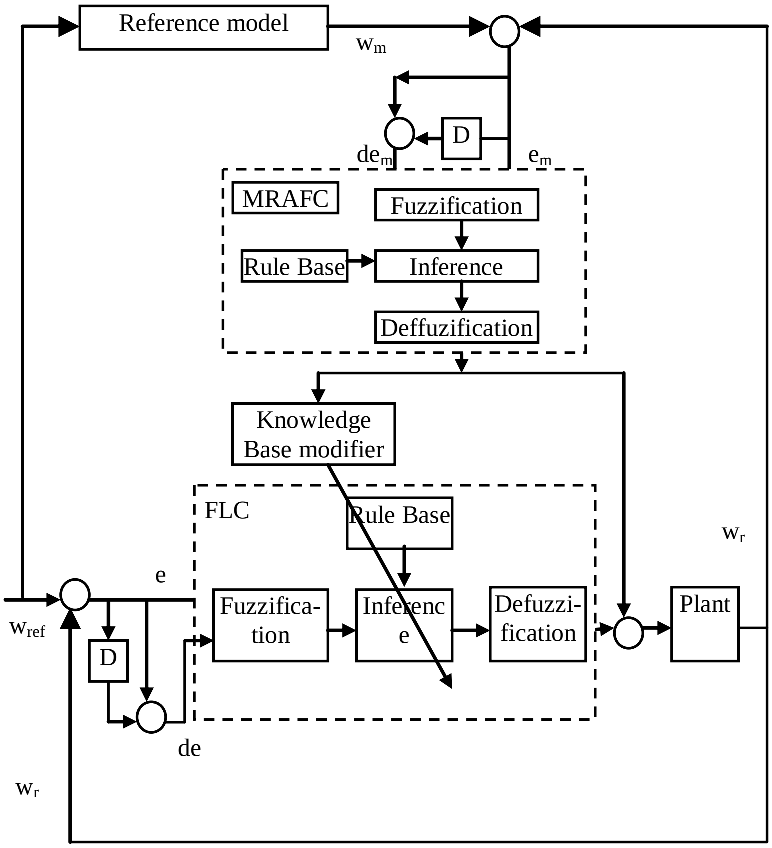

Fig. 4 – *Model reference adaptive fuzzy controller*.

5 Simulation Results

The simulation of the FLC algorithm has been carried out using MATLAB. The performance of PMSM speed control using FLC is compared to a conventional PI controller by extensive simulation for various operating conditions. The PMSM parameters are:

$$P = 1\,[\text{HP}],\ U = 220\,[\text{V}],\ R_S = 1.5\,[\Omega],\ L_d = 0.0424\,[\text{H}],\ L_q = 0.0795\,[\text{H}],$$

$$n_p = 2,\ J = 0.003\left[\text{kg}\,\text{m}^2\right],\ f = 8\cdot 10^{-5}\,[\text{Nms}],\ \phi_f = 0.314\,[\text{Wb}].$$

This work proposes a simple and efficient adaptive fuzzy control method, where the adaptation mechanism is a fuzzy logic system. The objective of the FMRAC is to change the rules definition in the FLC rule base table, according to the comparison between a reference model output signal and the system output. So, the learning algorithm defines the output linguistic values for each rule of the controller rule base table, based on a desired trajectory.

Simulation results have been obtained for the test where a repetitive step change in the load torque (from $0\,[\mathrm{Nm}]$ to $3.5\,[\mathrm{Nm}]$ and then back to $0\,[\mathrm{Nm}]$) was applied during the movement. In Fig. 5, the transient response of the proposed adaptive FMRAC is relatively short and robust compared with the PI controller.

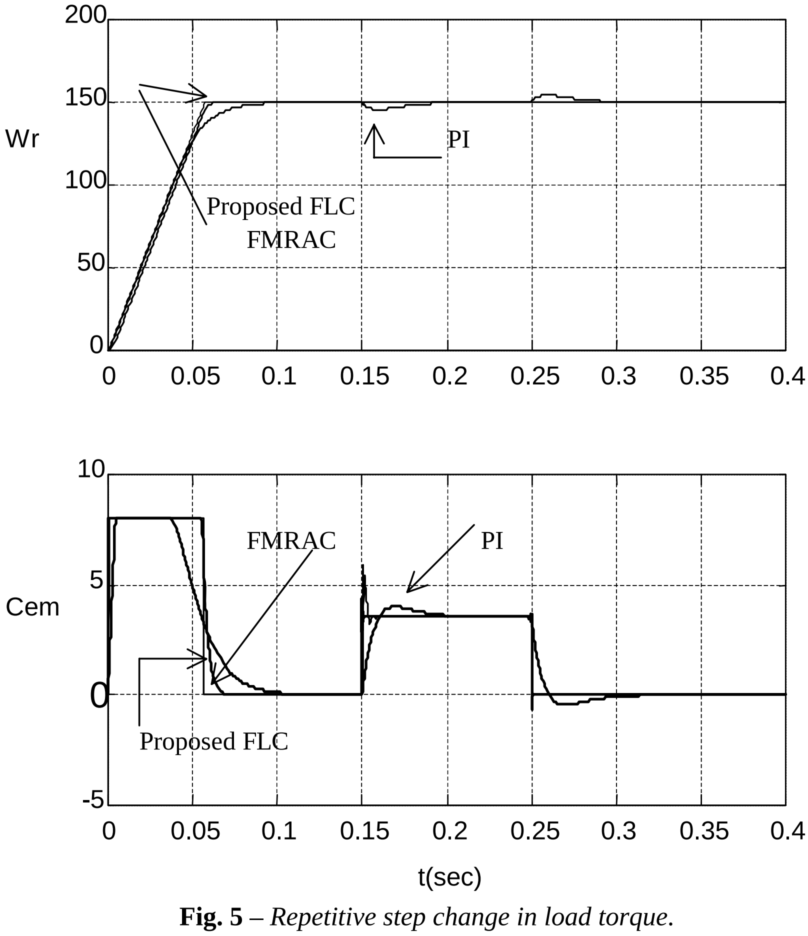

Fig. 5 – *Repetitive step change in load torque.*

The efficiency of the proposed and FMRAC controllers are evaluated and compared using a trapezoidal speed profile as the command input. A repetitive step change in the load inertia (from J_n to $3J_n$ and back to J_n) was applied during the movement. Fig. 6 shows that the systems output tracks very closely the reference model in spite of the disturbance.

The proposed adaptive fuzzy controller is simple compared to the FMRAC scheme and does not require complex mathematical operations.

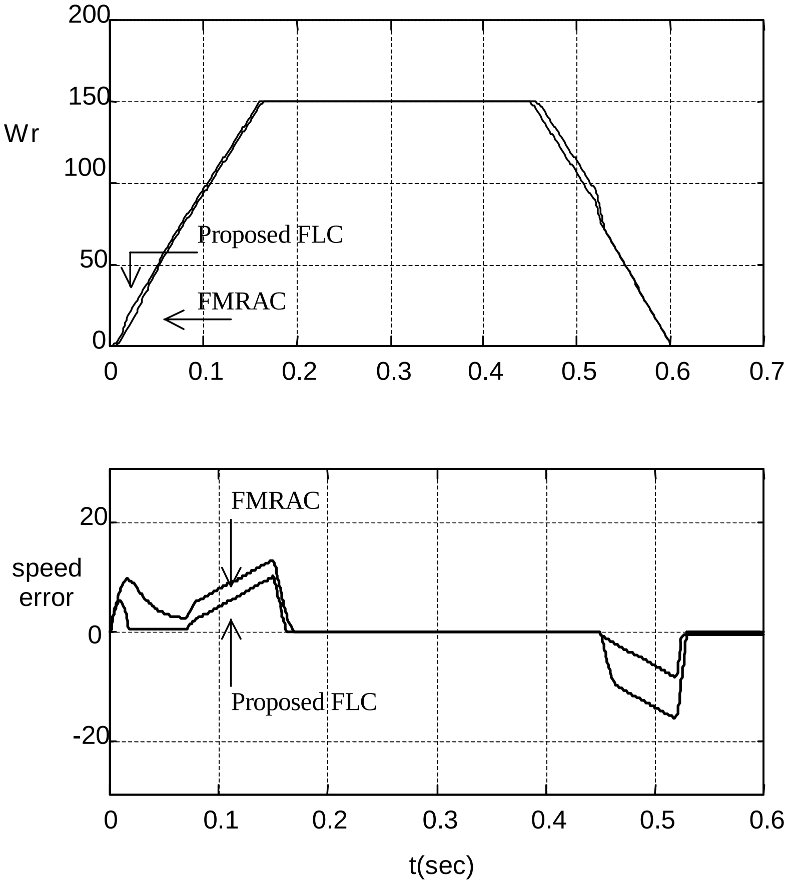

Fig. 6 – *Repetitive step change in load inertia.*

6 Conclusion

A FMRAC has been studied for the control of a vector controlled PMSM drive. In the proposed scheme, the adaptation mechanism produces a compensation signal which is added to the output signal of the direct fuzzy controller to force the system to behave like the model.

The simulation results have confirmed the efficiency of the proposed fuzzy adaptive scheme for changing load torque. The presented FMRAC has proved to be very efficient when applied in motion control. The improved algorithm demands little, although reasonable, modifications in the original mechanism based on the fuzzy inverse model approach. At each simple instant the FMRAC will affect only the active rules, taking into account its weight in the control signal.

7 References

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