

Robust Speed-Controlled Permanent Magnet Synchronous Motor Drive using Fuzzy Logic Controller

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Abstract—The Permanent Magnet (PM) Synchronous Motor is ideal in the field of the low power high performance servo, since it is controllable and its vigorous performance is excellent. However, the variations of moment inertia, load torque, and motor internal parameters have been a major difficulty to deal with speed control. This paper investigates the fuzzy logic controller based speed control for a vector-controlled PM synchronous motor drive. The fuzzy logic is based on the speed error and change of speed error measured between the actual motor speed and the reference speed. The robust control performance of the fuzzy logic controller is evaluated for various operating conditions using the parameters of a prototype PM synchronous motor and compared to that of conventional PI controller. The design and application of the fuzzy logic controller are considered and discussed.

Keywords - *fuzzy logic controller; permanent magnet synchronous motor; vector control ; robustness*

I. INTRODUCTION

Fuzzy logic can be regarded as a mathematical approach based on intelligent reasoning, probability theory, and multi-valued logic to mimic the human nature in inferring problems. The theoretical development of fuzzy logic has gone through significantly and there have been numerous applications of this mathematical framework to a variety of fields [1]-[3]. In control system, fuzzy logic is considered as an alternative for classical control theory in the control of complex nonlinear plants where accurate mathematical modeling is difficult, if not impossible [2]. At present, fuzzy logic speed controller is renowned with its superior performance in the research community worldwide. It has been demonstrated by various publications with diversity of industrial drive applications such as high performance dc drives [4], vector controlled induction motor [5]-[7], permanent magnet (PM) Synchronous Motor [8]-[12], brushless dc motor [13] and switched reluctance motor [14]. It has been suggested that fuzzy controllers are more robust to plant parameter changes than classical PI controllers. The merit of fuzzy logic control as compared to conventional control approach resides in the fact that there is no need of mathematical models to deal with a problem, but skill is required to create the rules in a particular fuzzy logic controller [1].

Brushless ac servo drives using PM synchronous motor are increasingly utilized in high-performance positioning systems such as in robotics due to their excellent characteristics compared to dc motor or ac induction motor drives. Many researches have been studied the comparison between the operation of drive with speed control by fuzzy logic and PI techniques. Then the main conclusion verified that fuzzy logic control determines superior performance [6], [7], [12]. Vector control is typically used in these drives to improve the dynamic response. However, the papers are focused on the speed performance while only load torque varies. In this paper, a fuzzy logic controller for a vector-controlled PM synchronous motor drive is investigated. It is applied to the speed control with variation of moment inertia, stator resistance, and load torque. As in all variable-controlling schemes, the very ultimate goal is to minimize error between the desired and actual value. Therefore, the error and change of error measured between the actual motor speed and the reference speed are applied to a fuzzy logic adaptation mechanism. This intelligent behavior will force the system to behave a more satisfactory performance than that of conventional PI controller. The robustness to parameters variation of the fuzzy logic controller is evaluated by simulation for various operating conditions using the parameters of a prototype PM synchronous servo drive. The design and implementation of the fuzzy logic controller are considered and discussed.

II. MODELING OF PERMANENT MAGNET SYNCHRONOUS MOTOR DRIVE

A. Drive Configuration

Fig. 1 shows a block diagram of a typical vector-controlled PM synchronous motor drive. The PM synchronous motor is fed by a current-controlled voltage-source pulse width modulated (PWM) inverter. The motor phase currents waveforms are imposed by current controllers having reference input signals generated from rotor position sensor signals. The synchronous motor is thus fed with sinusoidal currents having phase and frequency locked to the rotor position. As a result, synchronism is obtained for all speeds. The motor currents are decomposed into i_d and i_q components which are respectively flux and torque components in the rotor-based d-q coordinates

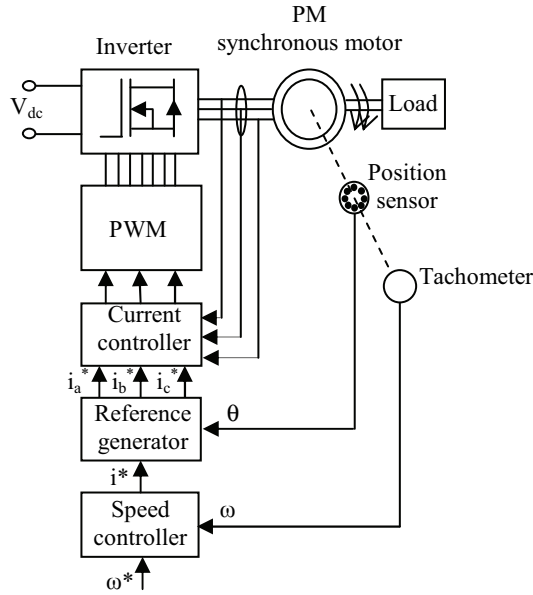


Fig.1 Vector-controlled PM synchronous motor drive

system. 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 a current-controlled dc motor.

B. Mathematical Model in d-q frame

In synchronous rotating d-q frame, one might decouple the flux-producing current (I_d) and torque-producing current (I_q). When I_{ds} constant, PM Synchronous Motor might be treated the same as dc motor. Hereafter, the modeling will be conducted in d-q frame. The electrical equation for the PM synchronous motor can be written as

$$V_d = R_s i_d + L_d \frac{di_d}{dt} - \omega_s L_q i_q \quad (1)$$

$$V_q = R_s i_q + L_q \frac{di_q}{dt} + \omega_s (L_d i_d + \psi_f) \quad (2)$$

By taking Laplace transformation, one might yield

$$\frac{i_d(s)}{V_d(s) + \omega_s L_q i_q(s)} = \frac{1}{(R_s + L_d s)} = \frac{1/R_s}{(\tau_s s + 1)} \quad (3)$$

$$\frac{i_q(s)}{V_q(s) - \omega_s (L_d i_d(s) + \psi_f)} = \frac{1}{(R_s + L_q s)} = \frac{1/R_s}{(\tau_s s + 1)} \quad (4)$$

where R_s is the stator resistance, L_d is the direct-axis inductance, L_q is the quadrature-axis inductance, ω_s is the electrical angular speed, ψ_f is the rotor-stator flux linkage, and $\tau_s = \frac{L_d}{R_s} = \frac{L_q}{R_s}$.

The electromechanical torque equation can be expressed as

$$T = \frac{3}{2} p [\psi_f i_q + (L_d - L_q) i_d i_q] \quad (5)$$

Since in the case of PM Synchronous Motor, $L_d = L_q$, (5) can be simplified as

$$T = \frac{3}{2} p \psi_f i_q = k_T i_q \quad (6)$$

The Laplace transformation of (6) is

$$\frac{T(s)}{i_q(s)} = \frac{3}{2} p \psi_f = k_T \quad (7)$$

where p = number of pole pairs.

The dynamic equation is

$$T - T_L = J \frac{d\omega}{dt} + B\omega \quad (8)$$

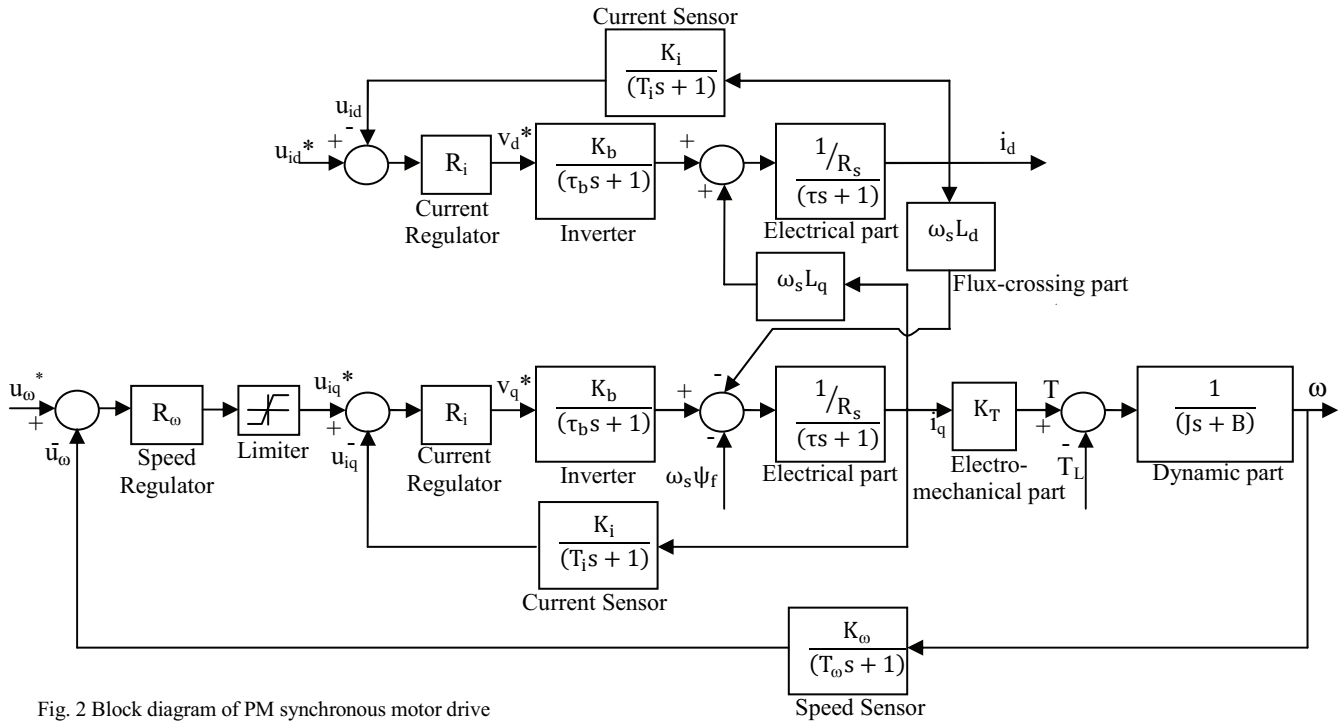


Fig. 2 Block diagram of PM synchronous motor drive

Laplace transformation is taken on (8), yield

$$\frac{\omega(s)}{T(s) - T_L} = \frac{1}{(Js + B)} \quad (9)$$

where, T_L is load torque, J = moment inertia, and B = friction coefficient

C. Block Diagram

An equivalent block diagram can be established according to (1)-(9) as shown in Fig. 2. This drive configuration also contains the transfer functions of speed sensor, current sensor, and inverter. A limiter is aimed to limit the maximum current fed to motor drive for safety concern.

III. DESIGN OF FUZZY LOGIC CONTROLLER

Fig. 3 shows a simplified block diagram of speed control system based on a fuzzy logic controller. This controller has two inputs, namely speed error $e\omega$ and change in speed error $ce\omega$, and one output ci_q^* which represents the change in quadrature reference current i_q^* .

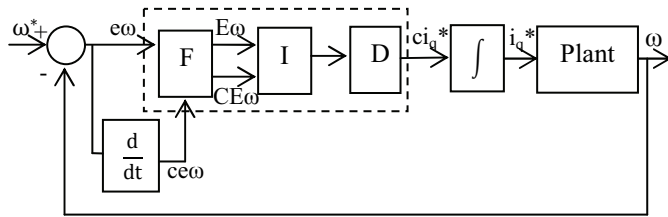


Fig. 3 Diagram block of fuzzy logic speed control scheme

The speed error and change of error are evaluated at instantaneous time as:

$$e\omega = \omega^* - \omega \quad (10)$$

$$ce\omega = \frac{de\omega}{dt} \quad (11)$$

where ω^* is the reference speed, and ω is the actual speed. As shown in Fig. 3, the fuzzy logic controller consists of three phases: fuzzification (F), inference (I), and defuzzification (D).

In the first phase, the crisp variables $e\omega$ and $ce\omega$ are transformed into fuzzy variables $E\omega$ and $CE\omega$ using triangular membership functions shown in Fig. 4. The universes of discourse of the input fuzzy variables, $E\omega$ and $CE\omega$, are respectively $[-10, 10]$ and $[-1.2, 1.2]$. Whereas, the universe of discourse of the output variable CI_q^* is $[-8, 8]$. For convenience, per-unit scaling factors are utilized to normalize all universe of discourse to $[-1, 1]$. Each universe of discourse is then divided into seven fuzzy sets: NL (Negative Large), NM (Negative Medium), NS (Negative Small), Z (Nearly Zero), PS (Positive Small), PM (Positive Medium), PL (Positive Large). Each fuzzy variable is a member of the subsets with a degree of membership μ varying between 0 (nonmember) and 1 (full member). For example, the degree of membership of element x in fuzzy set Y of the universe of discourse X is expressed as $\mu_Y(x)$ with $0 \leq \mu_Y(x) \leq 1$.

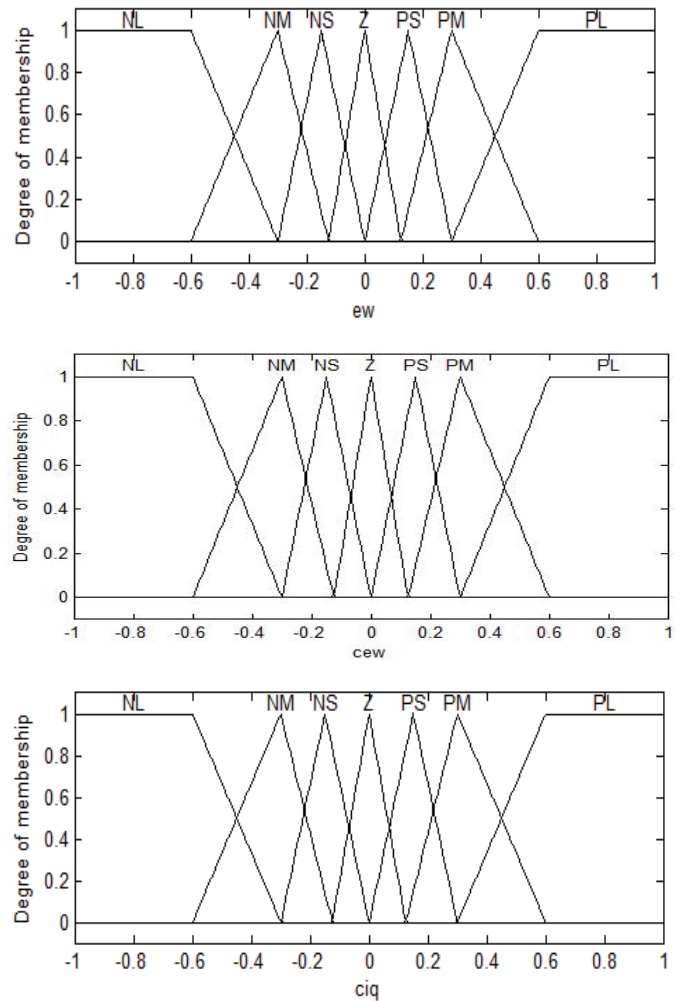


Fig. 4 Membership functions of $E\omega$, $CE\omega$, and CI_q^*

In the second phase, in order to determine the controller output from the measured system variables, a fuzzy relation matrix is established. The fuzzy relation matrix gives a relationship between fuzzy set characterizing controller inputs and fuzzy set characterizing controller outputs. The fuzzy variables $E\omega$ and $CE\omega$ are thus processed by an inference engine that performed a set of control rules contained in a (7×7) rule base as shown in Fig. 5.

$CE\omega \backslash E\omega$	NL	NM	NS	Z	PS	PM	PL
NL	NL	NL	NL	NL	NM	NS	Z
NM	NL	NL	NL	NM	NS	Z	PS
NS	NL	NL	NM	NS	Z	PS	PM
Z	NL	NM	NS	Z	PS	PM	PL
PS	NM	NS	Z	PS	PM	PL	PL
PM	NS	Z	PS	PM	PL	PL	PL
PL	Z	PS	PM	PL	PL	PL	PL

Fig. 5 Fuzzy control rules

These 7 fuzzy sets of input and output have been chosen to give adaptability during the decision inference. The control rules are formulated using the knowledge of the PM synchronous motor behavior and the experience of control engineers. Each rule is assigned in the form shown in the following example: IF ($E\omega$ is Positive Medium) AND ($CE\omega$ is Negative Large) THEN (CI_q^* is Negative Small). Different inference algorithms can be utilized to produce the fuzzy set values for the output fuzzy variable CI_q^* . In this study, the max-min inference algorithm is utilized in which the membership degree of CI_q^* is equal to the maximum of the minimum between $E\omega$ and $CE\omega$ membership degrees:

$$\mu[(CI_q^*)_k] = \max [\min \{\mu(E\omega_i), \mu(CE\omega_j)\}] \quad (12)$$

for $1 \leq i \leq n, 1 \leq j \leq n$

In the third phase, the inference output variable CI_q^* is transformed back into a crisp value ci_q^* . Various defuzzification algorithms have been proposed in many literatures. Here, the Mamdani centroid defuzzification algorithm is utilized in which the crisp value is calculated as the center gravity of the membership function of CI_q^* :

$$ci_q^* = \frac{\int \mu(CI_q^*) CI_q^* dCI_q^*}{\int \mu(CI_q^*) dCI_q^*} \quad (13)$$

The reference current i_q^* for the vector control system is obtained by integrating ci_q^* :

$$i_q^* = \int ci_q^* dt \quad (14)$$

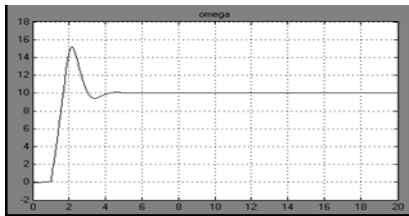
IV. SIMULATION RESULTS

The control performance of the prescribed fuzzy logic controller was evaluated by simulation using a test drive system with the following parameters: $P = 1$ kW, $V_d = 300$ V, $R_s = 1.4 \Omega$ (including power switch equivalent resistance), $L_s = 9.5$ mH, $J_{\min} = 0.03$ kgm², $J_{\max} = 0.23$ kgm², $B = 0.4E-3$ kgm²/s.

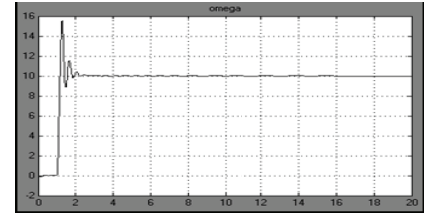
The parameters that vary are the system moment of inertia, stator resistance, and load torque. To evaluate the effectiveness of the proposed scheme, the step response of the speed control system is obtained for the varying parameters for two cases: (a) conventional PI controller, (b) fuzzy logic controller. All of the approaches described above were simulated in the Simulink environment.

A. Conventional PI Controller

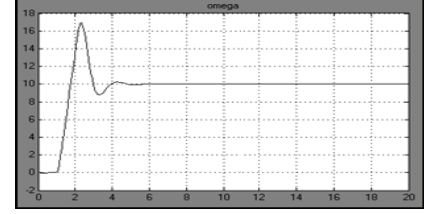
For this study, the PI coefficients for current controller and speed controller are $K_p=1$ $T_i = 0.2$, and $K_p = 0.8$ $T_i = 0.5$, respectively. The obtained results for these cases are presented in Fig. 6.



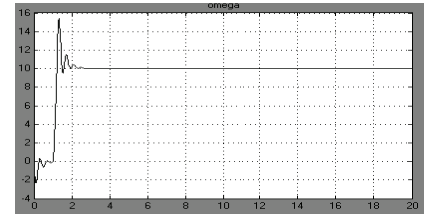
(a)



(b)



(c)



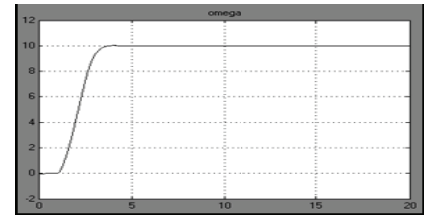
(d)

Fig. 6. Response of the system with PI speed controller (a) $J=0.03$ kgm² (b) $J=0.23$ kgm² (c) $R_s=2.8 \Omega$ (d) $T_L=3$ Nm

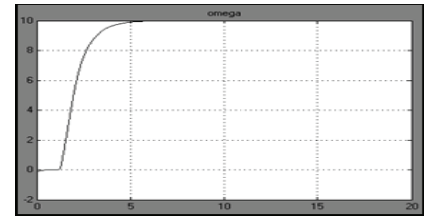
Fig. 6(a) and 6(b) demonstrate the system response with minimum and maximum moment inertia, respectively. It is obvious that the change of moment inertia influences greatly the system performance. As shown in Fig. 6(c), the variation of stator resistance also hurts the overall performance, particularly the extent of overshoot. Fig. 6(d) also shows undesirable ripples when an additional load torque is attached to the PM synchronous motor.

B. Fuzzy Logic Controller

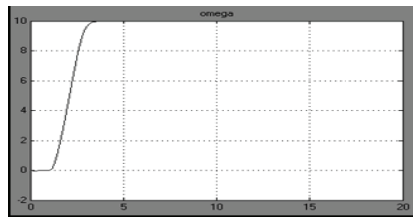
The obtained results for the fuzzy logic based scheme are presented in Fig. 7.



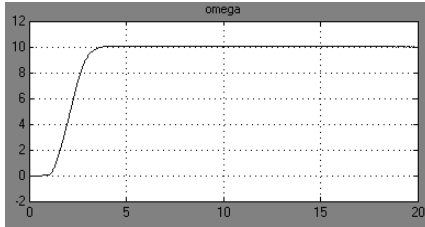
(a)



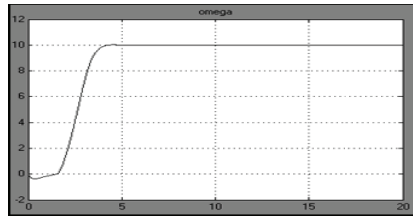
(b)



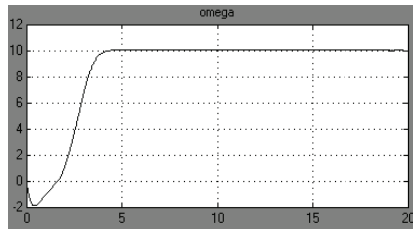
(c)



(d)



(e)



(f)

Fig. 7. Response of the system with fuzzy logic controller (a) $J=0.03 \text{ kgm}^2$ (b) $J=0.23 \text{ kgm}^2$ (c) $R_s=2.8 \Omega$ (d) $R_s=4.2 \Omega$ (e) $T_L=3 \text{ Nm}$ (f) $T_L=6 \text{ Nm}$

Fig. 7(a) and 7(b) show the system response with minimum and maximum moment inertia, respectively. It is shown that the variation of moment inertia affects slightly in the fact that the system response in maximum moment inertia is a little bit more sluggish. However this influence does not hurt the overall performance. As shown in Fig. 7(c) and 7(d), the variation of stator resistance up to 200% is not an issue for fuzzy logic controller. And finally, Fig. 7(e) and 7(f) no longer shows undesirable ripples which occurs for that of PI controller.

V. CONCLUSION

A fuzzy logic control scheme has been studied for the speed control of a vector-controlled PM synchronous motor drive. Speed error and change of speed error measured between the actual motor speed and the reference speed were used as the fuzzy inputs. The simulation results have confirmed the efficiency and robustness of the fuzzy logic controller against the varying moment inertia, stator resistance, and load torque. Due to its simplicity and effortlessness, this scheme is applicable to industrial environment using conventional microprocessor.

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