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A New Speed Sensorless Field Oriented Controller for PMSM Based on MRAS and PSO

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This project proposes a combination of the Model Reference Adaptive System (MRAS) scheme to estimate the speed information of the PMSM and the proportional integral (PI) scheme with the particle swarm optimization (PSO) to tune the PI gains used in the speed control of the PMSM. The adaptation scheme of the MRAS is based on the Takagi- Sugeno Fuzzy Inference System (T-S FIS). The effectiveness of the proposed technique is proved by testing the system with the variation of load torque and motor speed. The proposed technique clearly indicates that the speed error can be reduced close to zero and the estimated rotor position is able to track the actual rotor position.

Keywords: Permanent magnet synchronous motor;Particle swarm optimization; Model reference adaptive system;Takagi- sugeno FIS.

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The notation used throughout the paper is stated below.

Indexes:

v_d	Stator's d- axis voltage	ψ_q	q- axis stator magnetic flux
v_q	Stator's q- axis voltage	ψ_m	Rotor's permanent magnet flux
i_d	Stator's d -axis current	τ_e	Electromagnetic torque
i_q	Stator's q -axis current	τ_L	Load torque
R	Stator phase resistance	P	Number of poles
L_d	d- axis stator inductance	B	Vicious friction
L_q	q- axis stator inductance	ω_m	Rotor mechanical speed
ψ_d	d- axis stator magnetic flux	ω_r	Rotor electrical speed
J	Moment of inertia		

1. Introduction

In numerous applications today, Permanent Magnet Synchronous Motor (PMSM) is the preferred AC drive compared to the others because of its special features, for instance, high power density, high torque to current ratio and high efficiency. Hence, PMSM has been widely used in various fields and applications such as manufacturing equipment, production machines, transportations, etc. In terms of control technology, vector control algorithm has

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become the most importance control strategy for PMSM which is aimed to decouple the flux and torque based on d-axis and q-axis currents [1].

Generally, position sensors that are attached to the motor shaft like optical encoders and resolvers are used to gain the information of high resolution rotor position in order to implement the vector control strategy in PMSM. This feedback is required to maintain the torque of the system and at the same time to isolate it from the noise and vibration. There are many reliability issues related to the usage of speed sensors that link to the cost, maintenance and hardware complexity. To overcome these issues, various types of sensorless technique that involve mathematical algorithms proposed by researchers purposely to estimate rotor position and control of PMSM. There are several types of speed sensorless technique that can be used to control the PMSM [2-5].

The Back EMF was proposed to encounter the vector error by comparing and calculating the back EMF which was used for rotor speed correction [6]. Nonlinear observers such as extended Kalman Filter (EKF), Sliding Modes Observer (SMO) and Model Reference Adaptive System (MRAS) were used to gain information of the rotor position with target to achieve zero estimation error. Each type of the observer had several type of issues such as hard sliding mode control action which led to chattering effect and heavy computation load for EKF although these methodswere able to minimize the noises in the measurement [7].

Non-Ideal Property method like High Frequency (HF) Signal Injection or back EMF zero crossing detection method is suited for low speed application in order to detect the rotor position. This method will increase noise level to the system because of the performance has been downgraded [8]. In addition, the method needs some external hardware to implement it in actual time. Artificial Neural Network (ANN) involves a large number of inputs or neurons as an interconnected system for estimation purpose. Fuzzy Logic Control (FLC) employs a mathematical algorithm that is used to analyse input variables with sets of membership functions. Both methods together base rules are compulsory in order to implement the control strategies [9].

From the literature, MRAS scheme has been widely used as the control method due to its low computational requirement, simplicity and great performance in terms of rotor positioning and speed estimation. Previous research in [10] has proposed a new adaptation scheme for MRAS by using Takagi- Sugeno FIS and they have compared the effectiveness of the proposed technique with the conventional controller which used PI controller [11]. In this project, however, a speed PI gain is tuned by using PSO to get the optimal values of K_p and K_i, and then combined with the MRAS scheme based on the Takagi- Sugeno FIS adaptation scheme to estimate the rotor position angle.

2. Mathematical Model

The d-axis and q-axis based vector control strategy is used to analyse the PMSM model in this project. The voltage and flux equations in d-q axes are stated as below:

$$v_d = Ri_d + L_d \frac{di_d}{dt} - \omega_r \psi_q \tag{1}$$

$$v_q = Ri_q + L_q \frac{di_q}{dt} + \omega_r \psi_d \tag{2}$$

$$\psi_d = L_d i_d + \psi_m \tag{3}$$

$$\psi_q = L_q i_q \tag{4}$$

From the equations above, the d-axis current is specified in (1) and (3), while the q-axis current is specified in (2) and (4). By combining both equations for d-axis and q-axis currents, it will simplify as follows:

$$\frac{di_d}{dt} = -\frac{R}{L_d} i_d + \frac{\omega_r L_q}{L_d} i_q + \frac{1}{L_d} v_d \tag{5}$$

$$\frac{di_q}{dt} = -\frac{R}{L_q} i_q - \frac{\omega_r L_d}{L_q} i_d + \frac{1}{L_q} v_q - \frac{\omega_r \psi_m}{L_q} \tag{6}$$

Equations (5) and (6) can be transformed into matrix form as below:

$$\frac{d}{dt}\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} -\frac{R}{L_d} & \frac{\omega_r L_q}{L_d} \\ -\frac{\omega_r L_d}{L_q} & -\frac{R}{L_q} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} \frac{1}{L_d} & 0 \\ 0 & \frac{1}{L_q} \end{bmatrix} \begin{bmatrix} v_d \\ v_q - \omega_r \psi_m \end{bmatrix} \quad 7)$$

The equivalent state and control variables are defined as follows:

$$i'_d = i_d + \frac{\psi_m}{L_d}$$

$$i'_q = i_q$$

$$v'_d = v_d + \frac{R\psi_m}{L_d} \tag{8}$$

$$v'_q = v_q$$

Current model of PMSM will be derived as below after the transformation:

$$\frac{d}{dt}\begin{bmatrix} i'_d \\ i'_q \end{bmatrix} = \begin{bmatrix} -\frac{R}{L_d} & \frac{\omega_r L_q}{L_d} \\ -\frac{\omega_r L_d}{L_q} & -\frac{R}{L_q} \end{bmatrix} \begin{bmatrix} i'_d \\ i'_q \end{bmatrix} + \begin{bmatrix} \frac{1}{L_d} & 0 \\ 0 & \frac{1}{L_q} \end{bmatrix} \begin{bmatrix} v'_d \\ v'_q \end{bmatrix} \tag{9}$$

The developed motor torque and mechanical torque equations are givenas below:

$$\tau_e = \frac{3}{2}\left(\frac{P}{2}\right)\left(\psi_d i_q - \psi_q i_d\right) \tag{10}$$

$$\tau_L = \tau_e - B\omega_r - J\frac{d\omega_r}{dt} \tag{11}$$

From equation (11), we can get the rotor mechanical speed as:

$$\omega_r = \int \frac{\tau_e - \tau_L + B\omega_r}{J} \tag{12}$$

$$\omega_m = \omega_r \frac{2}{P} \tag{13}$$

3. Proposed Drive System

In this project, Field Oriented Control (FOC) is used to control the speed of the PMSM. The speed PI gain is tuned by the PSO to get the optimum value of the parameters. In addition, the information of the rotor position and speed is observed by using MRAS technique based on the T-S FIS. The overall block diagram of the proposed system is shown in Figure 1.

3.1. MRAS based on TS- FIS

Fuzzy Logic based on Takagi Sugeno FIS is proposed to replace the conventional PI controller in order to tune the errors between the reference model and adjustable model. Takagi Sugeno FIS is chosen because of their ability to solve control issues efficiently in some applications such as in linear technique, mathematical analysis, optimization and adaptive techniques, etc. As depicted in Figure 1, Takagi Sugeno FIS is used to minimize the errors of d- and q-axis currents then, tune that errors to refine the estimated motor speed.

The input and output membership functions used in this project are chosen from triangular type.

They are noted as negative big (NB), negative medium (NM), zero (Z), positive medium (PM) and positive big (PB). The output is constant and the values of the five linguistic functions are shown in Table 1. Table 2 shows the rule base used in this project.

Table 1: Linguistic Fuzzy Value for the Output

Speed	Constant Value
NB	-25
NM	-12.5
Z	0
PM	12.5
PB	25

Table 2: Rule base for fuzzy logic

e \ de/dt	**NB**	**NM**	**Z**	**PM**	**PB**
NB	NB	NB	NB	NM	Z
NM	NB	NB	NM	Z	PM
Z	NB	NM	Z	PM	PB
PM	NM	Z	PM	PB	PB
PB	Z	PM	PB	PB	PB

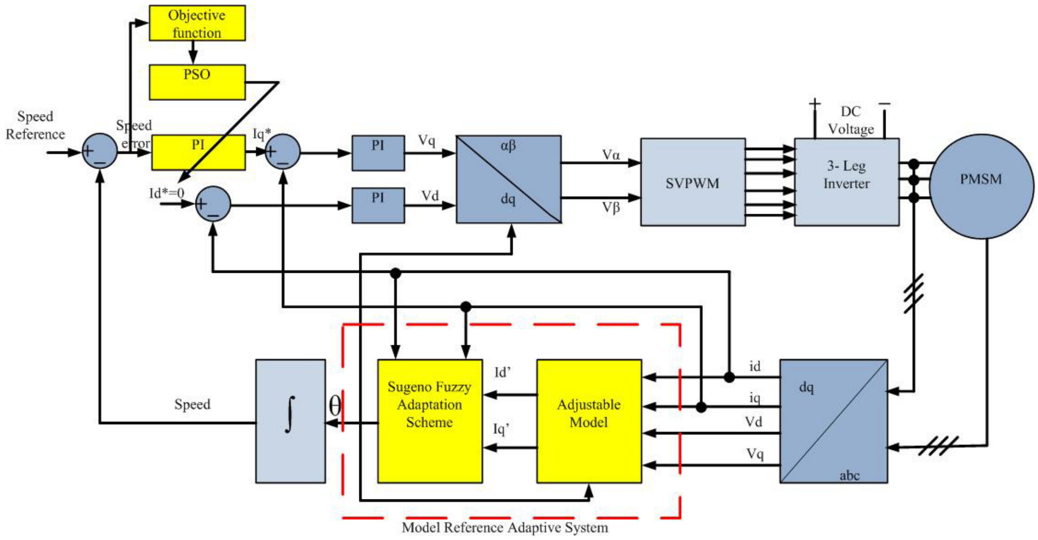

Figure 1Block diagram of the overall system

3.2. Speed PI-PSO

The Particle swarm optimization (PSO) is one of the swarm based optimization technique other than artificial bee colony (ABC) and ant colony optimization (ACO). It was originally designed by Kennedy and Eberhart back in 1995 who were inspired by the movement of the birds flocking and fish shoaling. In PSO, the particles fly in a group or population. Each particle moves toward its next position x with different velocity v. However, their next movement will be referred to their own personal best memory (pbest) and the global best memory in their population (gbest). As a mathematical model, each particle velocity and position can be expressed as (14) and (15), respectively.

$$v_i^{n_p}(k) = w v_i^{n_p}(k-1) + c_1 r_1\left(pbest(k-1) - x_i^{n_p}(k-1)\right) + c_2 r_2\left(gbest - x_i^{n_p}(k-1)\right) \quad (14)$$

$$x_i^{n_p}(k) = v_i^{n_p}(k) + x_i^{n_p}(k-1) \quad (15)$$

where,

$v_i^{n_p}(k)$	: the velocity of n^{th}_pparticle at current iteration k
$x_i^{n_p}(k)$	: theposition of n^{th}_pparticle at current iteration k
c_1	: learning rate for individual ability
c_2	:social influence
r_1, r_2	: random, ϵ[0,1]

The integration of PSO for the optimization of $K_p$and $K_i$in PMSM PI-controller will require the particles to move in multi-dimensional search space area. Figure 2 shows the flowchart of the process to obtain the optimal values of $K_p$and K_i. In the PSO algorithm, the difference between reference speed and simulation speed was made as the fitness function of the optimization process.

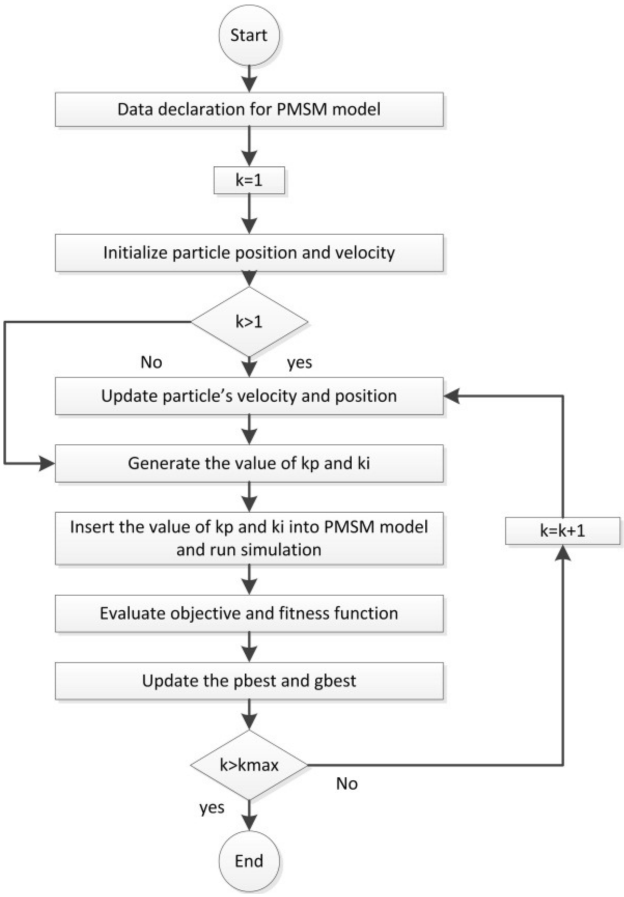

Figure 2The flow chart of PSO process in optimizing the k_p and k_i

4. Results and Discussions

The proposed drive system has been simulated by using Matlab/Simulink software to verify the effectiveness of the system by setting the PMSM with various ranges of speed and torque. The parameters of the motor are same as in [10]. Table 3 tabulates the values of $K_p$and $K_i$used in this analysis.

Table 3: Values of k_p and k_i

Case	k_p	k_i
1	1.5000	0.0392
2	0.6862	0.0499
3	1.0012	0.0524

4.1. Case 1

The speed was set to 1200 rpm for the entire simulation. It is clear from Figure 3 that motor speed is following the reference speed with speed error in between -4 rpm to 4 rpm as shown in Figure 4.

Figure 5 shows the actual and estimated rotor positions with estimated rotor position follow the actual rotor position.

4.2. Case 2

In this analysis, the torque reference is changed from 0 Nm to 2 Nm at 0.5 sec. It can be observed from Figure 6 that speed of the motor is able to follow the reference speed. The speed error is different when the load is changed to 2 Nm as shown in Figure 7 but the estimated rotor position follows the actual rotor position as shown in Figure 8.

4.3. Case 3

The speed was set to 600 rpm while the torque is set at 0 Nm. It shows that the speed follows the speed reference with the speed error of ±3 rpm as shown in Figure 8. It also shows that the estimated rotor position follows closely the actual rotor angle as depicted in Figure 9.

5. Conclusion

In this project, we presented a sensorless speed control of PMSM using a combination of MRAS and PSO. A model reference adaptive system (MRAS) with Takagi- Sugeno FIS was deployed as an adaptation scheme to estimate the rotor position angle. However, the speed controller was effectively tuned for optimal values of PI gains by PSO. The simulation results proved that the proposed drive system has considerably better performances and achieves fast response to load torque and speed variations, and significantly reduces the speed error. Furthermore, this proposed design can also track the rotor position accurately.

Acknowledgment

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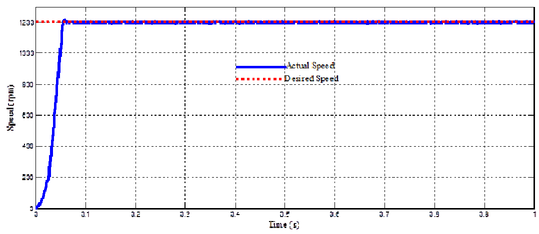

Figure 1 Speed response

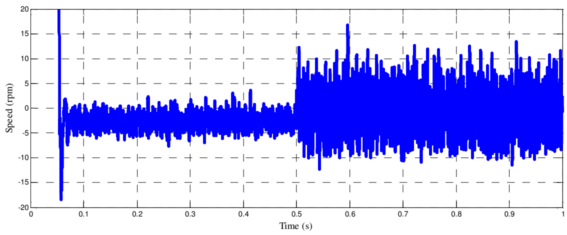

Figure 5 Speed error

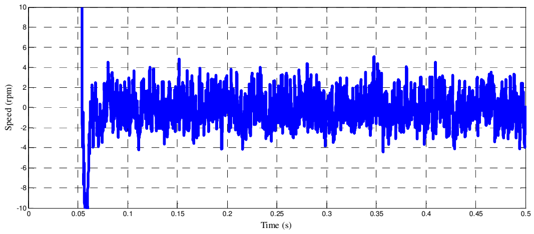

Figure 2 Speed error

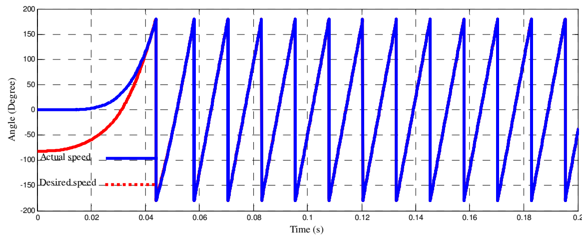

Figure 6 Actual and desired rotor position

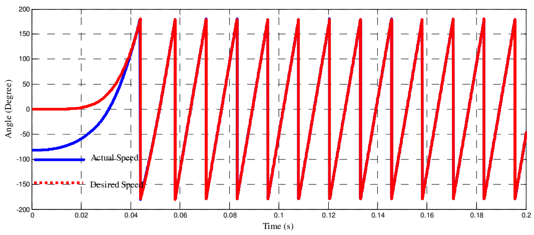

Figure 3 Actual and desired rotor position

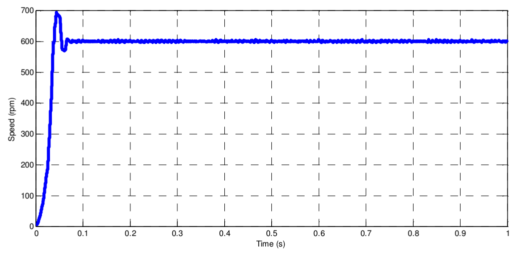

Figure 7 Speed response

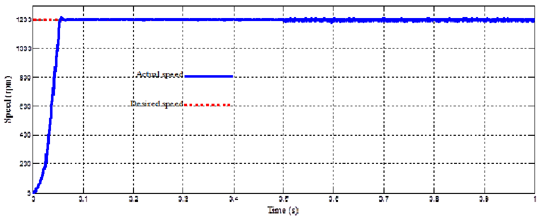

Figure 4 Speed response

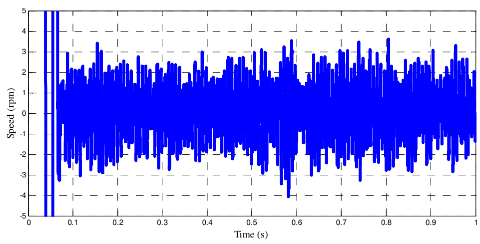

Figure 8 Speed error

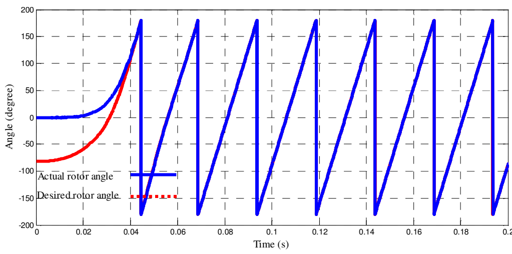

Figure 9 Actual and desired rotor position