Ahmad Asri Abd Samat*, **M.N. Fazli**[1], **N.A. Salim**[1], **Abdul Malek Saidina Omar**[1], **Muhammad Khusairi Osman**[1]

J. Electrical Systems 13-4 (2017): 689-695

Journal of Electrical Systems

Regular paper

Speed Control Design of Permanent Magnet Synchronous Motor using Takagi-Sugeno Fuzzy Logic Control

This paper proposes a speed control design of Permanent Magnet Synchronous Motor (PMSM) using Field Oriented Control (FOC). The focus is to design a speed control using Takagi – Sugeno Fuzzy Logic Control (T-S FLS). These systems will replace the conventional method which is proportional-integral (PI). The objective of this paper is to study the T–S Fuzzy Inference System (FIS) speed regulator and acceleration observer for PMSM. The scope of study basically is to design and analyse the Takagi Sugeno FLC and the PMSM. This paper also will describe the methodology and process of modelling the PMSM including data analysis. The simulation work is implemented in Matlab-Simulink to verify the control method. The effectiveness of this proposed control method was confirmed through various range of speed and torque variation.

Keywords: PMSM, Speed Control, Takagi Sugeno, FOC, Matlab-Simulink

Article history: Received 8 May 2017, Accepted 9 November 2017

1. Introduction

PMSM was a motor that famously used for industrial applications such as for industrial equipment and production machine. The PMSM was widely used because of it features, for instance, high power, small inertia, and small maintenances cost. To achieve the targeted performance of PMSM is not easy because of load torque variation, and PMSM servo operation. Because of that, the control method like PI controller is not strongly suggested to achieve the PMSM best performances. Fortunately, the Field-Oriented Control (FOC) was introduced as the solution for this problem [1].

The speed of PMSM is not easy to control due to the parameter and load torque variations. The control method like PID and PI cannot certainty give satisfying performances to control PMSM due to the non-linearity of PMSM servo systems [2]. To overcome this problem, the Takagi Sugeno FLC was introduced and successfully controls the non-linear or incompletely model. The focus of this paper is to learn the behaviour of the PMSM and the FOC, to achieve the targeted speed by using the T-S FLC system and to analyses the performances of T-S FLC and FOC for PMSM. The scope of the project is to create a fuzzy logic controller for PMSM and develop a simulation model to test the Takagi – Sugeno FLC performance by using MATLAB-Simulink. The impact of this method affected the speed and torque control system efficiency which can be improved significantly [3].

In the industrial robot control system, one of the most important factors is to make a final impression on the desired path in allowed precision. The most reasonable way to attain

* Corresponding author: Ahmad Asri Abd Samat, Faculty of Electrical Engineering, UniversitiTeknologi Mara, 13500, PermatangPauh, Penang, Malaysia, E-mail: ahmadasri759@ppinang.uitm.edu.my

[1] Faculty of Electrical Engineering, UniversitiTeknologi Mara, 13500, PermatangPauh, Penang, Malaysia

precision is to create a system to control the speed and current motion of PMSM [4,5]. The results indicate that it can be used effectively to the application, such as in the control of industrial robots.

2. Methodology

The process start when the motor produce phase current (i_a and i_b) and go to the Clark Transformation. Then, the Clark Transformation is converted the phase current (i_a and i_b) current to the current vector ($i_{s\alpha}$ and $i_{s\beta}$). Then the Park Transformation will convert the vector current (isα and isβ) to the torque current (i_{sq}) and flux current (i_{sd}). This flux and torque current depend on the current vector component and the rotor flux position. This two current also can be controlled independently. Then, the flux and torque current will be compared with the current flux and torque reference (i_{sdref} and i_{sqref}) that were produce from the T-S FLC [6]. At this point, the current will be used to control the synchronous or HPVM machine by changing the flux and torque reference current. Meanwhile, the T-S FLC is starting with the reference speed which is 1000rad/s. The T-S FLC basically has two inputs and one output [7,8,9]. The program set the speed error as the first input and the change in error as the second input. After that, the membership function will be program by use the 49 rule base function editor that were through the fuzzication and defuzzication process. The output current of the T-S FLC will go to the PI regulator and it will produce the V_{sqref} and Vsdref. By using the inverse transformation, the voltage reference in change to *Vsαref* and *Vsβref*. This output voltage will become the input of the SPVWM and use as a signal to drive the PMSM [10,11,12].

2.1. Mathematical Model of PMSM of PMSM Drive System

The Permanent Magnet Synchronous Motor (PMSM) can be express mathematically by the following equation:

$$\begin{bmatrix} V_q \\ V_d \end{bmatrix} = \begin{bmatrix} R + pL_q & Pw_r L_d \\ -Pw_r L_q & R + pL_d \end{bmatrix} \begin{bmatrix} i_q \\ i_d \end{bmatrix} + \begin{bmatrix} Pw_r \psi_f \\ \mathbf{0} \end{bmatrix} \quad (1)$$

$$\frac{d\theta_c}{dt} = Pw_r \quad (2)$$

$$Te = \frac{\mathbf{3}P}{\mathbf{2}}\left[\psi_f i_q + (L_d - L_q) i_d i_q\right] \quad (3)$$

$$Te = J_m P w_r + B_m w_r + T_L \quad (4)$$

Where Vq and Vd represent q & d axis voltage. Lq and Ld represent q & d axis inductances. iq & id represent q and d currents stator axis. R is the stator resistance was representing flux constant. Wr is the rotor speed. θ is rotor position in electrical degrees or radians, P represent the pole number, p is differential operator, Tc represent torque, TL represent the load torque, Bm are rotor damping coefficient and Jm is constant rotor inertia. In order to make the linear equation and therefore torque control tasks much easier, d-axis current id is set to zero in the vector control scheme. In PWM voltage controlled current source inverter, iq present as input to the motor [8].

2.2. Design of Takagi Sugeno Fuzzy Logic Control

The most important part to design the fuzzy logic control system is to detect position direction by giving convenient instructions speed ⍰r that also depend on the operational conditions. Usually the phase current (ia, ib, and ic) are controlled by the speed controller that usually known as q axis current (iq and id) [11]. The next step after the scaling factor selected is to choose the membership function which is modelled in equation 5 and 6.

$$e(k) = \omega_{ref} - \omega_r \qquad (5)$$

$$\Delta e(k) = e(k) - e(k - \mathbf{1}) \qquad (6)$$

Where ω_{ref} is the speed reference, ω_r is the real speed, e(k) is the speed error and Δ e(k) is change in error. Basically T-S FLC is created with two inputs and single output. The speed error and a change in error are labelled as a first and the second input respectively. This 49 rule base is used for the decision making [9]. Membership function used for input and output fuzzy sets are shown in Fig. 1 and Fig. 2. Fig. 3 shows the rule view that shows the data based on the 49 rule base. Fig. 4 shows the plot surface for the speed error, change in error and also the output. The fuzzy set used the trapezoidal function as the membership function to reduce calculation for on-line operation [7]. Table 1 shows the rule base for the decision making unit. The example of Takagi-Sugeno fuzzy rules developed (7 × 7 = 49) are defined as an algorithm as follows:

1. If e(k) is NB and Δe(k) is NB, then the output is NS.
2. If e(k) is PB and Δe(k) is NM, then the output is PS.
3. If e(k) is zero and Δe(k) is NS, then the output is NS.
4. If e(k) is NS and Δe(k) is NB, then the output is NS.

Where NB is negative big, NM is a negative medium, NS is a negative small, ZE is zero, PS is positive small, PM is positive medium, and PB is positive big. e(k) is the speed error and ⍰e(k) is change in error.

Table 1: Rule Base for Speed Control

E / ΔE	NB	NM	NS	ZE	PS	PM	PB
NB	NS	NS	NS	NB	NM	NS	ZE
NM	NS	NS	NB	NM	NS	ZE	PS
NS	NS	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PS
PM	NS	ZE	PS	PM	PB	PS	PB
PB	ZE	PS	PM	PB	PS	PB	PB

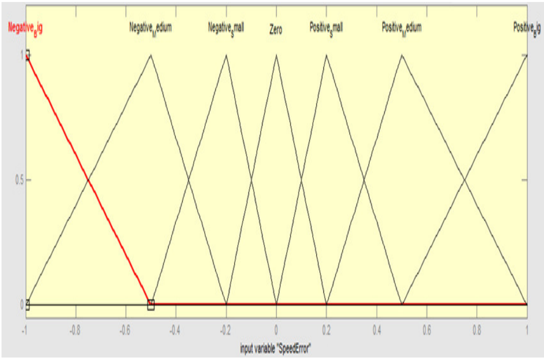

Fig. 1: Speed Error Membership Function Editor

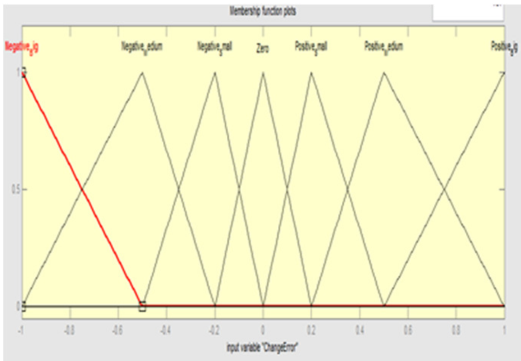

Fig. 2: Change in Error Membership Function Editor

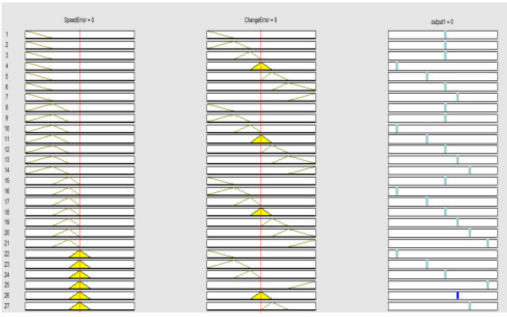

Fig. 3: Rule Viewer

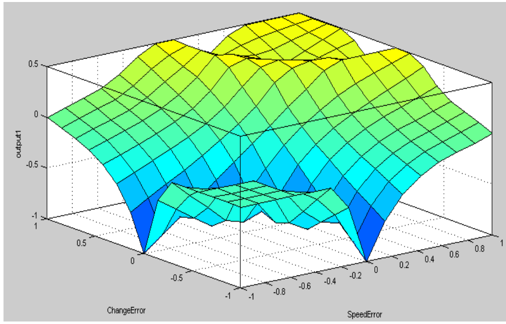

Fig. 4: Surface Viewer

2.3. Development of Simulink Model Control

The simulation for this project was developed by using the Matlab-Simulink library version R2008a. This electrical drive model consists of several type of model. The type of model used is fuzzy model, Clark Transformation model, Park Transformation model, PMSM model, and Clark & Park Inverse Transformation model.

3. Results and Discussions

The simulation was developed by using a Matlab-Simulink. The result of speed, torque, and current was observed and analyzed. The characteristic of the system is observed under different cases which is motor is started from 0 rad/s with constant torque, motor is started from 0 rad/s with varied torque, and the motor is started with varied speed but with constant torque. The motor parameter that been used in this project is shown in Table 2.

Table 2: PMSM Parameters

Description	**Parameter**	**Value**
Stator phase resistance	Rs	2.875 Ω
q-axis Inductance	Lq	0.0085 H
d-axis Inductance	Ld	0.0085 H
Flux linkage	λaf	0.175 V.s
Rated voltage	VL	126.96 V
Rated Torque	TL	1.05 N.m
Inertia	J	0.0008 J
Friction factor	B	0.001 F
Poles	P	4

3.1. Motor is started from rest to 1000 rpm with 0 Nm

The speed reference and torque value was set to 1000 rpm and 0 N-m respectively. The system responses were shown respectively in Fig. 5 until Fig. 8. Fig. 5 shows that the settling time was 0.5 s. The overshoot (OS %) for Takagi Sugeno FLC adaptation scheme was 2.3% and the speed error was 0.0044 rpm as shown in Fig. 6.

Fig. 7 shows the torque response of the system. Referring to the Fig. 7, the settling time for torque to reach their steady state is 0.53 s with starting at 2.5 N-m. The stator current for this motor are shown in Fig. 8. The value of starting current is about 5 A and reaches their steady state value at 0.53 s.

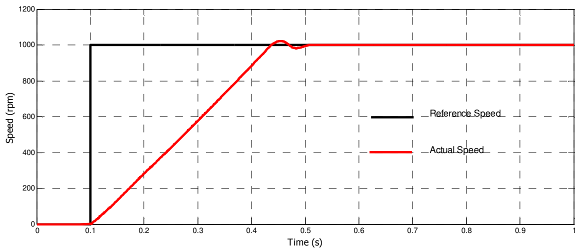

Fig. 5: T-S FLC Speed Response

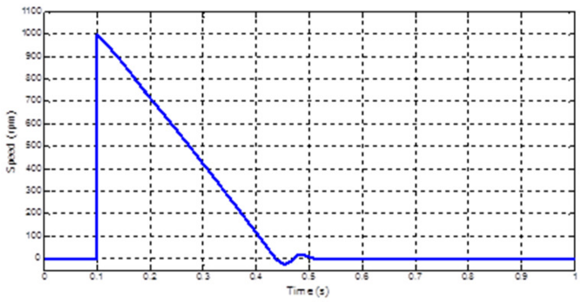

Fig. 6: T-S FLC Speed Error

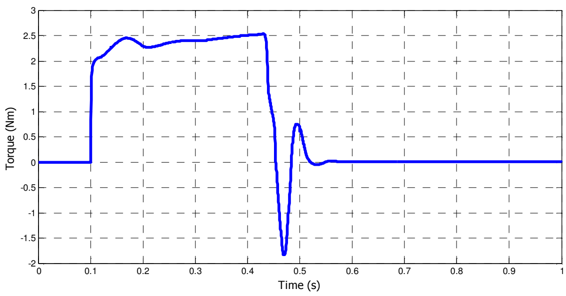

Fig. 7: T-S FLC Torque Response

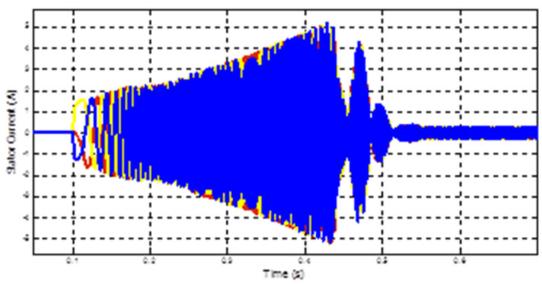

Fig. 8: T-S FLC Stator Current Response

3.2. Motor is started from rest to 1000 rpm with 2 Nm

The speed reference is set to 1000 rpm with the 2 N-m torque. The speed response and the speed error are shown in Fig. 10 and Fig. 11 respectively. The speed response shows it takes 0.6 s to reach the targeted speed. The overshoot (OS %) value was 2.4% and the value of speed error was 0.002689 rpm as depicted in Fig.11. The value of starting torque is 4.5 N-m until it reaches the reference torque (2N-m) at t = 0.62 s as shown in Fig.12. By referring at Fig.13, the starting current reach until 7 A and reach their steady state value at 0.62 s.

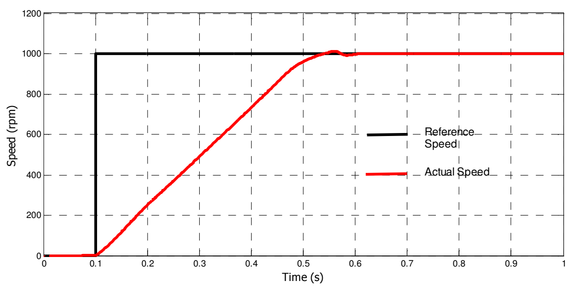

Fig. 1: T-S FLC Speed Response

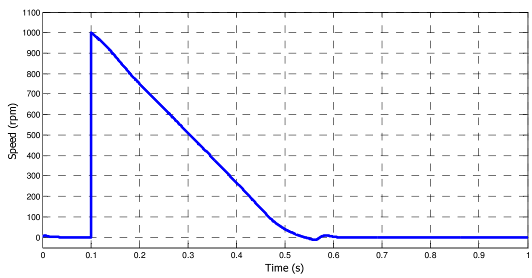

Fig. 2: T-S FLC Speed Error

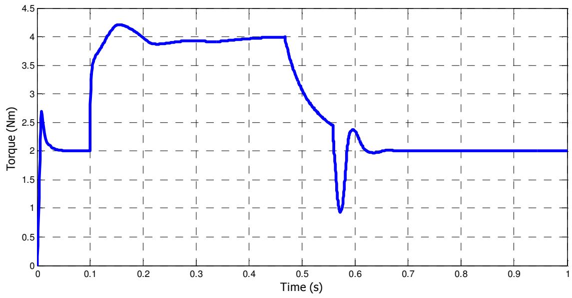

Fig. 3: T-S FLC Torque Response

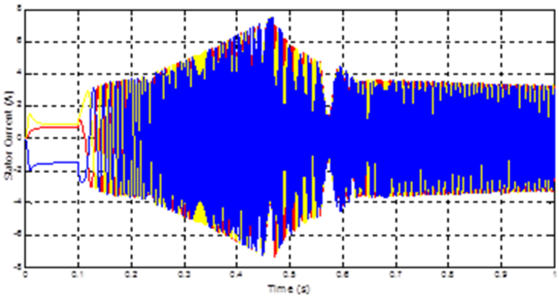

Fig. 4: T-S FLC Stator Current Response

3.3. Motor is operated from the 500 rpm to 1000rpm with 0 Nm Motor

In the third case, the speed was set with two different values but with a constant torque. The torque was set with 0 N-m. At the beginning, the motor runs to 500 rpm from the 0 s. Then, at t = 0.5 s, the motor speed was increased to 1000 rpm. Fig. 14 and Fig.15 show the speed response and the speed error for the system. The value of speed error at 500 rpm and 1000 rpm is 0.0011 rpm 0.0017 rpm respectively. The overshoot (OS %) was about 0 % at 500 rpm and 2.3% at 1000 rpm.

Fig. 16 shows the torque response with 0 N-m reference torque and two different speeds. The value of starting torque is 2.3 N-m until it reaches the reference torque (0 N-m) at 0.2 s. Then, the value of torque increase again to 4.5 Nm when the speed was increased to 1000 rpm and reaches the steady state value at 0.75 s.

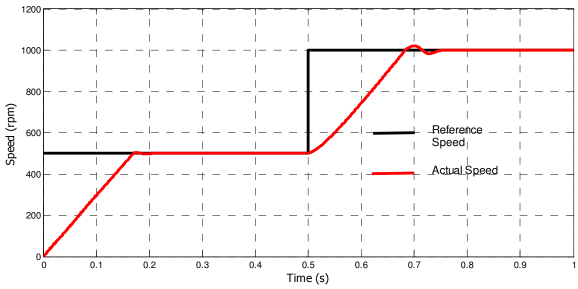

Fig. 5: T-S FLC Speed Response

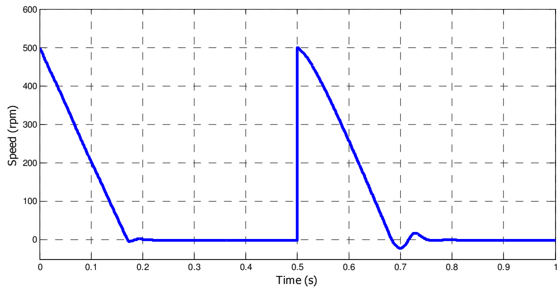

Fig. 6: T-S FLC Speed Error

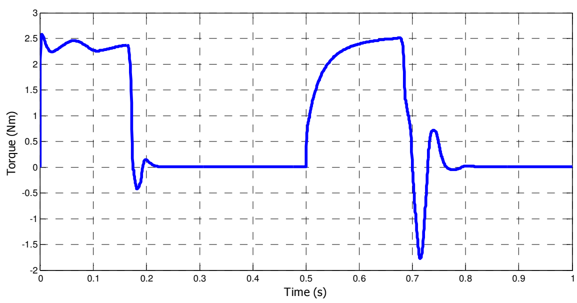

Fig. 7: T-S FLC Torque Response

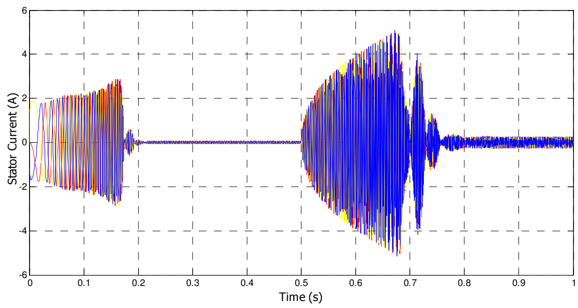

Fig. 8: T-S FLC Stator Current Response

4. Conclusion

From the simulation result, it shows the good performance of the T-S FLC method for the PMSM. For all three cases, the value of settling time only takes below 0.6 s to become stable. The speed error for all three cases is approximately close to 0 rpm which is good for the motor performance. The desired speed to achieve based on the objective also successfully targeted. From the analysis done, it shows that the Takagi Sugeno FLC can be used and replace the conventional method like PI controller. For the recommendation to getting a better result in the future, the flexible neuro FLC that newly invented is highly recommended to control the behavior of PMSM parameter.

Acknowledgment

The authors would like to thank the Research Management Institute (RMI), Universiti Teknologi MARA, Malaysia and the Ministry of Higher Education (MOHE), Malaysia through research grant 600-RMI/RAGS 5/3 (192/2014) for the financial support of this research.

References

[1] Microsemi, "Field Oriented Control of Permanent Magnet Synchronous Motors," vol. 3, no. 3, pp. 269–275, 2012.
[2] H. H. Choi and J. W. Jung, "Discrete-Time Fuzzy Speed Regulator Design for PM Synchronous Motor," IEEE Trans. Ind. Electron., vol. 60, no. 2, pp. 600–607, 2013.
[3] O. Process, M. Forms, R. P. Tank, S. Regulating, and O. Models, "PI Control," 2007.
[4] H. H. Choi and J.-W. Jung, "Takagi–Sugeno fuzzy speed controller design for a permanent magnet synchronous motor," Mechatronics, vol. 21, no. 8, pp. 1317–1328, 2011.
[5] P.-I.- Digital and Control, "Cohen-Coon Tuning Method PID Controller Design for Controlling DC Motor Speed in the Project."
[6] A. A. Abd Samat, D. Ishak, S. Iqbal, and A. I. Tajudin, "Comparison between Takagi Sugeno FIS and PI Controller: An Adaptation Scheme of MRAS for Speed Sensorless Control of PMSM," Appl. Mech. Mater., vol. 785, pp. 193–197, Aug. 2015.
[7] M. N. Uddin, T. S. Radwan, M. A. Rahman, and G. H. George, "Fuzzy logic based position control of permanent magnet synchronous motor," 2000 Can. Conf. Electr. Comput. Eng. Conf. Proceedings. Navig. to a New Era (Cat. No.00TH8492), vol. 1, pp. 93–97, 2000.
[8] B. G. Burgio, R. Busch, U. Christen, and T. Rambow, "Permanent Magnet Synchronous Machine Modeling and Control," pp. 65–70, 2012.
[9] S. Preit, R. E. Precup, and Z. Preit, "Development of conventional and fuzzy controllers and takagi-sugeno fuzzy models dedicated for control of low order benchmarks with time variable parameters," Acta Polytech. Hungarica, vol. 2, no. 1, pp. 75–92, 2005.
[10] A. Report, "Sensorless Field Oriented Control of 3-Phase Permanent Magnet Synchronous Motors," no. July, pp. 1–43, 2013.
[11] B. Swathi and D. H. Guruprasad, "Fuzzy logic based position control of permanent magnet synchronous motor," Int. J. Comput. Sci., vol. 2, no. 5, pp. 49–53, 2014.
[12] Abd Samat, A. A., Ishak, D., Saidina Omar, A. M., Iqbal, S., & Abdul Razak, M. A. (2016). A New Speed Sensorless Field Oriented Controller for PMSM Based on MRAS. J. Electrical Systems, 12(3), 565– 573.