Double Fuzzy-Pi Controller Based Speed Control Of Permanent Magnet Synchronous Motor

By Bambang Purwahyudi

DOUBLE FUZZY-PI CONTROLLER BASED SPEED CONTROL OF PERMANENT MAGNET SYNCHRONOUS MOTOR

Bambang Purwahyudi
Department of Electrical Engineering, University of Bhayangkara Surabaya
Jl. A. Yani 114, Surabaya, Indonesia
e-mail: bmp_pur@ubhara.ac.id

ABSTRACT

In high performance industrial application, Permanent Magnet Synchronous Motor (PMSM) becomes the main competitor for AC motor. PMSM has some advantages such as high efficiency, small size, high power density, large torque to inertia ratio, and low maintenance. PMSM is also very popular compared to DC motors in applications of machine tools, servo and robots, electric vehicle, and ship propulsions. Speed control of PMSM widely uses the conventional proportional integral (PI) controller, but PI controller has difficulty in speed changes, parameter variations and load disturbances. This paper presents double fuzzy logic controllers to tune the parameters of PI controller applied in the speed control of PMSM. Double fuzzy-PI (DFPI) controller is verified using simulation process for normal and disturbance conditions. DFPI controller has better performance compared to the conventional PI controller during change of operating condition. Simulation results of DFPI controller show that PMSM quickly achieve the speed reference, has small steady state error, no overshoot and reduce the speed oscillation during load disturbance condition.

Keywords: *Permanent Magnet Synchronous Motor, Speed Control, PI, Double Fuzzy Logic*

1. INTRODUCTION

Permanent Magnet Synchronous Motors (PMSM) are becoming the main competitor to other types of AC motors in high performance motor drives applications. PMSM have some advantages such as high efficiency, small size, high power density, large torque to inertia ratio, and low maintenance. PMSM are also very popular compared to DC motors in applications of machine tools, servo and robots, electric vehicle, and ship propulsions [1,2]. Some criteria of high performance motor drives applications are insensitivity to parameter variation, fast speed responses, and quick speed achievement to a speed reference during load disturbance occurs. The conversional proportional integral (PI) controller has been widely employed as speed controller for PMSM drives. In order to obtain the best results of speed control, the axial reactance parameters of the d-q PMSM should be correctly known. However, the conversional PI controller has difficulty in speed changes, parameter variations and load disturbances [1-6].

To solve these disadvantages of PI controller, various artificial intelligent (AI) techniques have been applied in motor drives systems to control the speed of motor. Fuzzy logic controller (FLC) can be considered to improve the performance of conventional PI controller. FLC can provide nonlinear control action by selecting the appropriate parameters. In this way, the success key of design an FLC is to define well its parameters such as knowledge base, rule base and scale factor (3-9). Nowadays, a method of control at the base of double fuzzy controller and a proportional integral (PI) controller has been developed [10, 11].

This paper presents the usage of AI methods especially double fuzzy logic (FL) to tune the parameters of PI controller applied in the speed control of PMSM. The effectiveness of the proposed systems is verified by simulation process using SIMULINK-MATLAB. Therefore, performance of Double Fuzzy-PI controller is compared with the conventional PI controller during change of operating condition based on the performance of induction motor.

2. SPEED CONTROL OF PMSM

Block diagram of PMSM drives system used in this paper is shown in Figure 1. PMSM is connected to pulse width modulation (PWM) inverter using current control. PMSM currents are decomposed into i_d and i_q components. These components represent flux and torque components in d-q coordinate system.

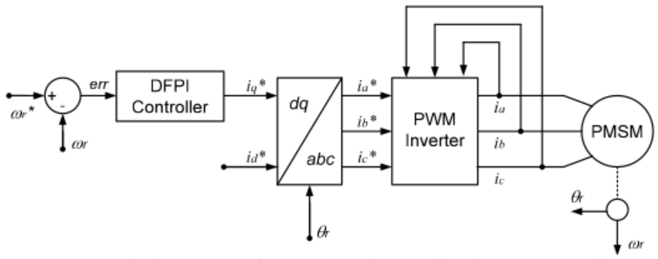

Figure 1. Block Diagram of PMSM Speed Control with DFPI Controller.

3. MATHEMATICAL MODEL OF PMSM

The d-q model of the wound rotor synchronous machines is simply adapted to learn the dynamic performance of PMSM [1,2,4]. Back e.m.f. produced by permanent magnet is equal to produced by excited coil. Therefore, the d-q model of PMSM in the rotor reference frame can be seen in Equation (1).

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = R_s \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \frac{d}{dt}\begin{bmatrix} \phi_d \\ \phi_q \end{bmatrix} + \omega_r \begin{bmatrix} -\phi_q \\ \phi_d \end{bmatrix} \quad (1)$$

where u_d, u_q, i_d, i_q , $\square_r$, R_s, $\square_d$ and $\square_q$ are stator voltage and current in d-q frame, rotor speed, stator resistance, flux linkage in d-q frame, respectively.

Dynamic behaviour and electromagnetic torque of PMSM can be expressed in Equation (2) and Equation (3).

$$\frac{J}{p}\frac{d\omega_r}{dt} + \frac{f}{p}\omega_r = T_{em} - T_L \quad (2)$$

$$T_{em} = \frac{3}{2}p\left\{\phi_f i_q + (L_d - L_q)i_d i_q\right\} \quad (3)$$

where J, p, f, L_d, L_q, T_{em}, and T_L are rotor inertia, pole number, reactance linkage d-q frame, electromagnetic torque and load torque, respectively.

4. DESIGN OF DOUBLE FUZZY PI (DFPI) CONTROLLER

Fuzzy logic controller (FLC) is one of most popular artificial intelligence (AI). FLC is used to solve nonlinear control problem or whenever the system model is unknown or difficult to build. The FLC is built from three steps: fuzzification, control rules evaluation and defuzzification. The fuzzy rules are obtained through knowledge of the process systems which automatically extracted from sample process [3-11]. Figure 2 show the control algorithm of PMSM speed based on a double fuzzy PI controller. The speed of PMSM is compared with the reference to obtain the error speed shown by Equation (4).

$$e(t) = \omega_m^*(t) - \omega_m(t) \quad (4)$$

where $e(t)$, $\square_m^*(t)$ and $\square_m(t)$ are error speed, reference speed, and motor speed respectively.
The change of error speed is given by Equation (5).

$$de(t) = e(t) - e(t-1) \quad (5)$$

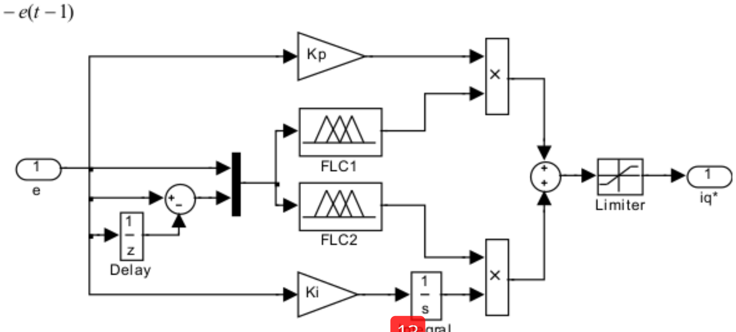

***Figure 2**. The DFPI Controller for speed control of PMSM*

In this paper, FLC has five membership functions (MF) for two inputs and an output. Two inputs and an output are error (e), change of error (de) and promotional parameter (K_p) or integral parameter (K_i) respectively. The membership functions are built to represent its input and output value. The fuzzy sets of two input signals are as follows: ZE = Zero, PB = Positive Big, PS = Positive Small, NB = Negative Big and NS = Negative Small respectively. Whereas, the fuzzy sets of an output signals are as follows: S = Small, MS = Medium Small, M = Medium, MB = Medium Big and B = Big, respectively. Figure 3 and Figure 4 show the fuzzy sets and corresponding triangular MF description of two input signals and an output signals. The rule base of the FLC is shown in Table 1. Table 1 show that there may be 5 x 5 = 25 possible rules.

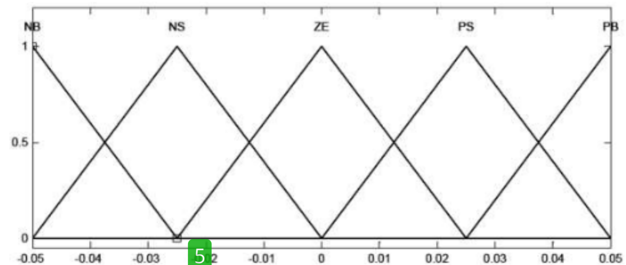

Figure 3. *Membership Functions for inputs of FLC*

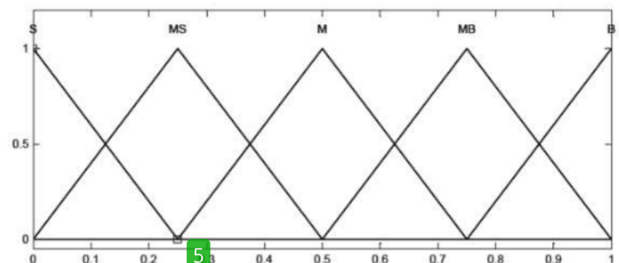

Figure 4. *Membership Functions for output of FLC*

Table 1. *Rule Base of FLC*

error (e)	change of error (de)				
	NB	NS	ZE	PS	PB
NB	S	S	S	MS	M
NS	S	S	MS	M	MB
ZE	S	MS	M	MB	B
PS	MS	M	MB	B	B
PB	M	MB	B	B	B

5. RESULTS

The effectiveness of the proposed Double Fuzzy-PI (DFPI) controller is clarified by simulation process. Simulation process is conducted in conditions of normal and disturbance. The parameters of permanent magnet synchronous motor (PMSM) used in this simulation is as follows: motor power of 1 HP, nominal voltage of 220 V, stator resistance of 2.875 Ω, direct inductance of 0.0085 H, quadrature inductance of 0.0085 H, 4 poles, inertia moment of 0.0008 kg.m^2, friction coefficient of 8x10^{-5} N.m.s, motor flux of 0.175 Weber. Figure 5 shows simulation model in SIMULINK-MATLAB.

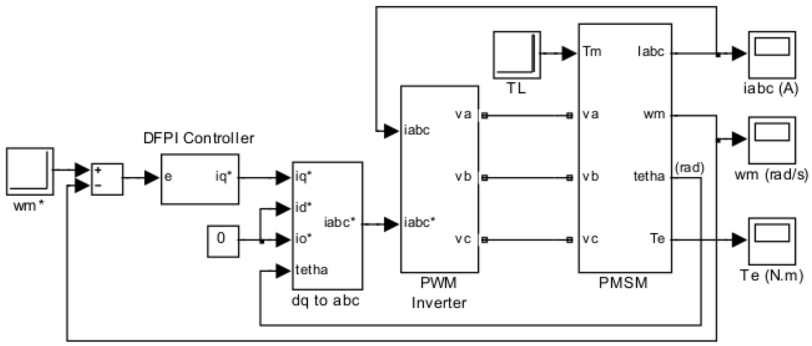

***Figure 5**. Simulation PMSM model using SIMULINK-MATLAB*

Figure 6 shows speed response of PI controller and DFPI controller for speed reference of 700 rad/s. DFPI controller yields settling time of 0.008 s, no overshoot and small steady state error of 0.5 rad/s. Whereas, PI controller yields settling time of 0.013 s, overshoot of 4.1 % and also small steady state error of 1.1 rad/s. From their simulation results show that DFPI controller provide the improvement of performance compared to PI controller.

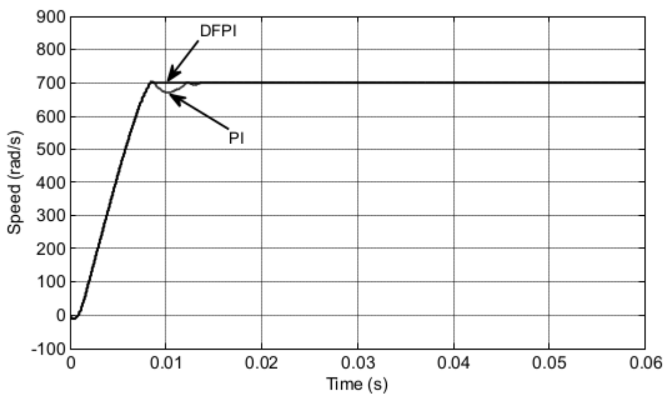

***Figure 6.** Speed response for speed reference of 700 rad/s.*

Figure 7 shows comparison of the electromagnetic torque response between PI controller and DFPI controller. PI controller needs the greater electromagnetic torque than DFPI controller. These electromagnetic torques are used both controller to rapidly reach the speed reference, however PI controller causes speed oscillation.

Current of PMSM for PI and DFPI controllers are shown in Figure 8 and Figure 9. Both figures show that the change of electromagnetic torque causes the change of PMSM current.

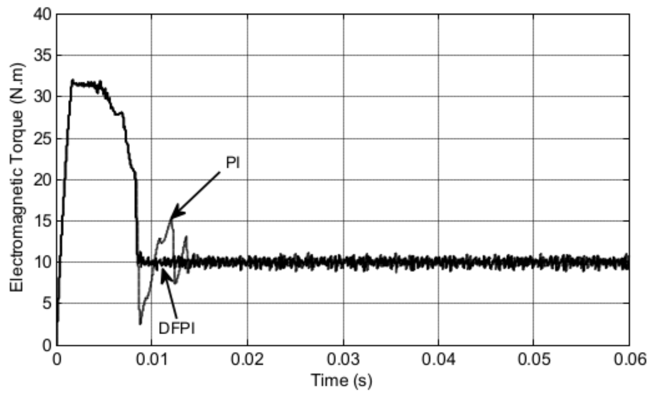

Figure 7. *Electromagnetic torque responses for PI and DFPI controllers.*

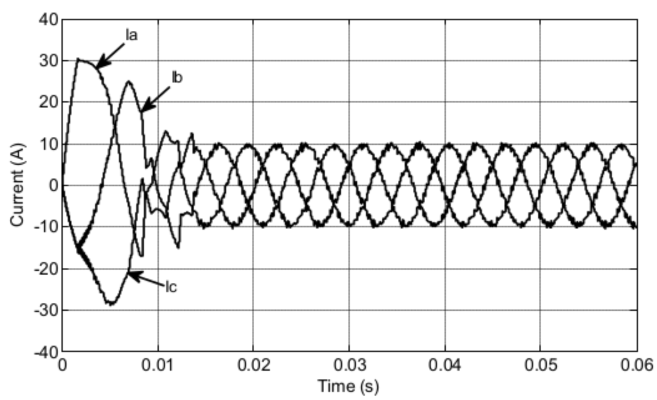

Figure 8. *Current of PMSM with PI Controller*

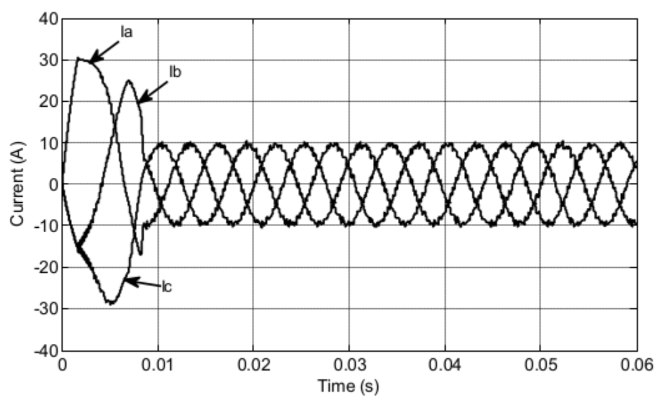

Figure 9. *Current of PMSM with DFPI Controller*

For disturbance conditions, the load torque of PMSM suddenly changes from 10 N.m to 15 N.m at t = 0.04 s and also returns again to 10 N.m at t = 0.041 s. The change of load torque affects the electromagnetic torque of PMSM shown in Figure 10. PI controller requests the greater electromagnetic torque than DFPI Controller. Disturbance also causes change of PMSM speed shown in Figure 11. Simulation result shows that speed error for PI controller is better than DFPI controller but PI Controller still produce speed fluctuation.

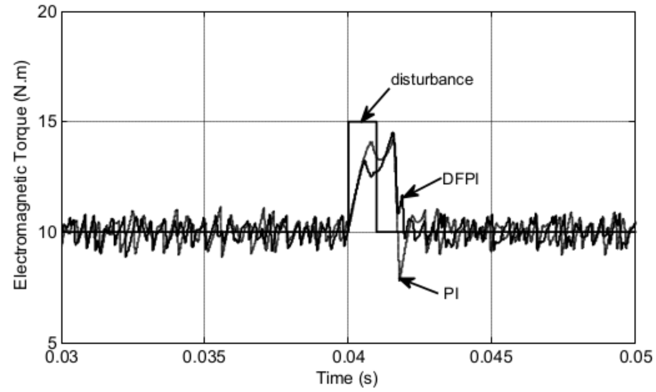

Figure 10. *Electromagnetic torque of PMSM for disturbance condition*

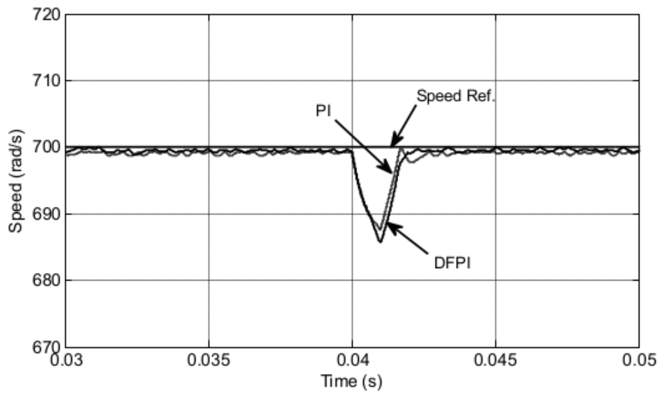

Figure 11. *Speed responses for disturbance condition*

Figure 8 and Figure show PMSM current of PI and DFPI controllers during disturbance condition. Both figures show that the disturbance causes the change of PMSM current. Simulation results show that PMSM current for DFPI controller is better than PI controller.

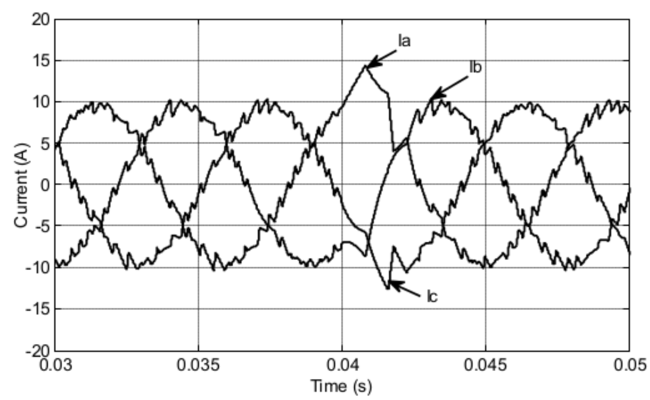

Figure 12. *Current of PMSM for PI Controller*

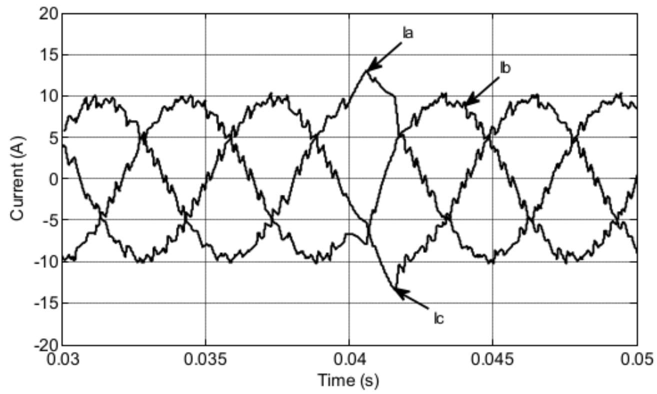

Figure 13. *Current of PMSM for DFPI Controller*

6. CONCLUSION

Double fuzzy proportional integral (DFPI) controller applied in speed control of PMSM has been presented and discussed. Double fuzzy logic technique is used to adjust the parameters of PI controller (*Kp* and *Ki*). Double fuzzy logic can improve the performance of PI controller when there are changes of PMSM parameters. DFPI controller proposed is verified by simulation process. Simulation results show that DFPI controller produces better performance compared to PI controller. DFPI controller rapidly achieves the speed reference, has small steady state error, no overshoot and decreases speed oscillation during load disturbance condition. The settling times of PI and DFPI controllers are 0.008 s and 0.013 s respectively. Whereas, steady state errors of PI and DFPI controllers are 0.5 rad/s and 1.1 rad/s respectively.

REFERENCES

[1] P.C. Krause. (2000). *Analysis of electric machinery*, McGraw-Hill, New York.

[2] M. Kadjoudj, R. Abdessemed, M.E. Benbouzid, and C. Ghennai. (2000). *Current control of PMSM fed by two and three levels VSI*, Proc. of EPE/PEMC, Tuke (Slovakia), Vol. 7, pp. 69-74.

[3] Y.S. Kung and M.H. Tsai. (2007). *FPGA – based speed control IC for PMSM drive with adaptive fuzzy*, IEEE Transactions on Power Electronics, Vol. 22, No. 6, pp.2476-2486.

[4] N.J. Patil, R.H. Chile, and L.M. Waghmare. (2010). *Fuzzy Adaptive Controller for Speed Control of PMSM Drive*, International Journal of Computer Applications, Vol. 1, No.11, pp. 84-91.

[5] Lini Mathew, and Vivek Kumar Pandey. (2011). *Design and development of fuzzy logic controller to control the speed of permanent magnet synchronous motor*, Vol. 3, No. 3, pp. 52-61.

[6] Yue Wang, and Juntao Fei. (2015). *Adaptive Fuzzy Sliding Mode Control for PMSM Position Regulation System*, International Journal of Innovative Computing, Information and Control, Vol. 11, No. 3.

[7] Bambang Purwahyudi, Saidah, and Hasti Afianti. (2013). *Fuzzy Logic Controller For Volts/Hz Induction Motor Control Used In Electrically Driven Marine Propeller*, **Academic Research International, Vol. 4, No. 5, pp.** 258-265**.**

[8] Bambang Purwahyudi, Saidah, and Hasti Afianti. (2014). *Self-Tuning Fuzzy-PI Controller in Volt/Hz Induction Motor Control for Electrically Driven Ship Propeller,* **Academic Research International, Vol. 5, No. 5, pp.** 86-94**.**

[9] Saidah, Bambang Purwahyudi, and Kuspijani. (2017). *Control Strategy for PWM Voltage Source Converter Using Fuzzy Logic for Adjustable Speed DC Motor,* International Journal of Power Electronics and Drive Systems, Vol. 8, No. 1, pp. 51-58.

[10] Nabil Elhaj, M. Brahim Sendra, and Hind Djeghloud. (2016). *DFPI-based Control of the DC-bus Voltage and the AC-side Current of a Shunt Active Power Filter*, Bulletin of Electrical Engineering and Informatics, Vo. 5, No. 4, pp. 430-441.

[11] Dazhi Wang, Shuai Ge, Jun Li, Bo Wang, Kefeng Song, Xiaoli Liu, and Yiqi Li. (2010). *Hybrid active power filter DC bus control based on double fuzzy control*, The 2nd International Conference on Computational Intelligence and Natural Computing, Wuhan, China, pp. 287-290.

Double Fuzzy-Pi Controller Based Speed Control Of Permanent Magnet Synchronous Motor

ORIGINALITY REPORT

21%
SIMILARITY INDEX

PRIMARY SOURCES

1	Benhamida Islam, Ameur Aissa, Kouzi katia, Sayaf Hocine. "Predictive Direct Torque Control Based on New Formulation and Fuzzy Logic for Permanent Magnet Synchronous Machine", 2018 International Conference on Electrical Sciences and Technologies in Maghreb (CISTEM), 2018 Crossref	55 words — 3%
2	www.journal.tfc.kg.ac.rs Internet	47 words — 2%
3	karyailmiah.unipasby.ac.id Internet	24 words — 1%
4	downloads.hindawi.com Internet	23 words — 1%
5	Alka Agrawal. "Analytical Study of the Robustness of the Different Variants of Fractional-Order Self-Tuned Fuzzy Logic Controllers", IOP Conference Series: Materials Science and Engineering, 2021 Crossref	22 words — 1%
6	www.hindawi.com Internet	20 words — 1%
7	Nabil Elhaj, Moulay Brahim Sedra, Tarik Jarou, Hind Djeghloud. "An Improved Double Fuzzy PI Controller	19 words — 1%

For Shunt Active Power Filter DC Bus Regulation", 'Institute of Advanced Engineering and Science', 2017
Internet

8	Waheed Ur Rehman, Shaoping Wang, Xingjian Wang, Lei Fan, Kamran Ali Shah. "Motion synchronization in a dual redundant HA/EHA system by using a hybrid integrated intelligent control design", Chinese Journal of Aeronautics, 2016 Crossref	19 words — 1%
9	www.docstoc.com Internet	17 words — 1%
10	Elhaj, N., T. Jarou, M. B. Sedra, H. Djeghloud, and Y. Terriche. "Contribution of a shunt active power filter control using double fuzzy PI controller", 2014 16th International Power Electronics and Motion Control Conference and Exposition, 2014. Crossref	16 words — 1%
11	iieta.org Internet	16 words — 1%
12	Wei Guo. "A Novel Robust Controller for the Speed Control of Permanent Magnet Synchronous Motor", Lecture Notes in Electrical Engineering, 2011 Crossref	13 words — 1%
13	Marcel Nicola, Claudiu-Ionel Nicola, Marian Duta. "Adaptive Sensorless Control of PMSM using Back-EMF Sliding Mode Observer and Fuzzy Logic", 2019 Electric Vehicles International Conference (EV), 2019 Crossref	12 words — 1%
14	mjee.modares.ac.ir Internet	10 words — 1%

15 Jaswant Singh, Bindeshwar Singh, S. P. Singh, Ravi Chaurasia, Sulabh Sachan. "Performance investigation of Permanent Magnet Synchronous Motor drive using vector controlled technique", 2012 2nd International Conference on Power, Control and Embedded Systems, 2012 — 9 words — < 1%
Crossref

16 Kaneko, T.. "An integrated control method for a wind farm to reduce frequency deviations in a small power system", Applied Energy, 201104 — 9 words — < 1%
Crossref

17 M. Kchaou. "Robust observer-based sliding mode control for nonlinear uncertain singular systems with time-varying delay and input non-linearity", European Journal of Control, 2018 — 9 words — < 1%
Crossref

18 portal.research.lu.se — 9 words — < 1%
Internet

19 Jixun Gao, Jianli Kang. "Modeling and Simulation of Permanent Magnet Synchronous Motor Vector Control", Information Technology Journal, 2014 — 8 words — < 1%
Crossref

20 Li, S., and H. Gu. "Fuzzy Adaptive Internal Model Control Schemes for PMSM Speed-regulation System", IEEE Transactions on Industrial Informatics, 2012. — 8 words — < 1%
Crossref

21 Ying-Shieh Kung, Nguyen Khanh Quang, Le Thi Van Anh. "FPGA-based neural fuzzy controller design for PMLSM drive", 2009 International Conference on Power Electronics and Drive Systems (PEDS), 2009 — 8 words — < 1%
Crossref

22 www.academicjournals.org
Internet
8 words — < 1%

23 www.ijmetmr.com
Internet
8 words — < 1%

24 www.lifesciencesite.com
Internet
8 words — < 1%

25 Bambang Purwahyudi, Kuspijani Kuspijani, Ahmadi Ahmadi. "SCNN Based Electrical Characteristics of Solar Photovoltaic Cell Model", International Journal of Electrical and Computer Engineering (IJECE), 2017
Crossref
7 words — < 1%

26 C. Ilioudis Vasilios. "PMSM sliding mode observer for speed and position estimation using modified back EMF", 2008 13th International Power Electronics and Motion Control Conference, 09/2008
Crossref
7 words — < 1%

27 Emine Doğru Bolat. "Chapter 101 DSP Based Implementation of Current Mode Fuzzy Gain Scheduling of PI Controller for Single Phase UPS Inverter", Springer Science and Business Media LLC, 2006
Crossref
6 words — < 1%

28 Patil, N.J., R.H. Chile, and L.M. Waghmare. "Implementation of model reference adaptive fuzzy controller", IET-UK International Conference on Information and Communication Technology in Electrical Sciences (ICTES 2007), 2007.
Crossref
6 words — < 1%

EXCLUDE QUOTES	ON	EXCLUDE MATCHES	OFF
EXCLUDE BIBLIOGRAPHY	ON		