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Optimization of Fuzzy Controller of Permanent Magnet Synchronous Motor

[1]Kuang-Cheng Yu, [1]Shou-Ping Hsu and [2]Yung-Hsiang Hung
[1]Department of Refrigeration and Air Conditioning,
[2]Department of Industrial Engineering and Management,
National Chin-Yi University of Technology, 411 Taiwan, Republic of China

Abstract: Present study aims at discussing how to optimize the fuzzy controller of Permanent Magnet Synchronous Motor (PMSM). By reducing the influence of parameter changes of plant using Technique for Order Performance by Similarity to Ideal Solution (TOPSIS) of Taguchi Method and Multi-Criteria Decision Making (MCDM), it shall be possible to improve robust characteristics of control system, thus promoting the output quality and performance of PMSM plant. Meanwhile, an analytical model for the parameters and output quality of fuzzy controllers was set up and optimal parameters were designed using Genetic Algorithm (GA). Generally speaking, PMSM controller has a long-lasting infrastructure without complex computation, of which the Small-The-Better (STB) output features of PMSM include: Overshoot, rise time and settling time. In previous design of controllers, only individual quality characteristics were considered without overall output design of multiple quality characteristics. By using a controller based on fuzzy logic method in cooperation with parameterization method of TOPSIS, this study intended to discuss how to ensure optimum output quality and performance (overshoot, rise time and settling time) under different noise factors (speeds and loads, etc.). With a PC-based infrastructure that combines PC-based motor controller system and Matlab/Simulink software for simulation process, it seeks to obtain optimum parameters of controllers and implement a PMSM fuzzy control system with vector control function. The computer simulation results have proved the validity and feasibility of entire infrastructure with possible desirable effects.

Key words: PMSM, fuzzy controller, multiple quality characteristics, Taguchi Method, genetic algorithm

INTRODUCTION

DC motors were commonly used due to reliable speed and position control and cost-effective driver system. With rapid development of semiconductors, microprocessors and control technology, a more complex control method has been implemented to improve the disadvantages of DC motors. Now, AC motor has become a leading motor in the industrial applications. As one type of AC motor, PMSM features lower maintenance cost, longer service life, improved efficiency and response speed, etc, while having maintenance-free brushes and commutators (Slemon, 1992). In recent years, Vector Control theory is well-proven in Permanent Magnet Synchronous Motor (PMSM) (Novotny and Lipo, 1996) and traditional vector control methods and Proportional-Integral (PI) controllers present good results in speed control of PMSM. However, PI controllers shall be adjusted according to the running state, leading to changing load torque. In other words, PI controllers cannot achieve good output performance under wide range of operating conditions (Uddin *et al*., 2002).

PMSM with Fuzzy Controller has been widely applied to high-performance Server drive systems (Kadjoudj *et al*., 2001; Heber *et al*., 1997; Cerruto *et al*., 1997; Miki *et al*., 1991; Kung and Liaw, 1994). Since Fuzzy Sets was proposed by Zadeh (1965), there was a fast growing trend of study and applications related to fuzzy theory, such as: Artificial Intelligence (AI), Control engineering, decision analysis, medical diagnosis, automaton and pattern recognition, etc. (Singh *et al*., 1998; Cerruto *et al*., 1997; Erenay *et al*., 1998; Uddin and Rahman, 2000; Emami *et al*., 1998; Bolognani and Zigliotto, 1996; Yi and Chung, 1998), especially in terms of controller design. In general, traditional design process of controllers requires an understanding of the controlled system, namely, describing the controlled system with mathematical models of Differential Equation (DE) or Difference Equation. When the controlled system becomes more complex, modeling is impossible through System Identification (ID). The advantage of fuzzy control is that it can integrate the knowledge of anthropologists into the design process of controllers, without the need of accurate vmathematical models. During fuzzy control, the

Corresponding Author: Yung-Hsiang Hung, Department of Industrial Engineering and Management, National Chin-Yi University of Technology, 35, Lane 215, Section 1, Chung-Shan Road, Taiping, Taichung, 411, Taiwan, Republic of China Tel: +886-04-23924505 Ext. 7628 Fax: 886-4-23934620

behavior of controlled system could be described using a set of linguistic fuzzy rules. Therefore, the knowledge of anthropologists could be converted to fuzzy control rule, reducing the complexity of design control system. According to state error between system and feedback, a controller designed with fuzzy theory can select proper rules to achieve an expected motor output response and high-performance PMSM speed control system, irrespective of the changes of electrical parameters or load of motor. Thus, this study applies fuzzy control to design a fast-response controller and improve traditional PI controllers with poorer response.

The output quality characteristics of PMSM generally include overshoot, rise time and settling time, featuring Small-The-Better of multi-response. In previous design of controllers, only individual quality characteristics were compared without consideration of Interaction amongst control parameters and trade-off of multiple quality characteristics. So, the relationship between control parameters and overall multi-quality characteristics output is difficult to measure. By combining Taguchi Method and MCDM of TOPSIS (Technique for Order Performance by Similarity to Ideal Solution) (Hwang and Yoon, 1981), this study set up an analytical model for PMSM fuzzy controller parameters and output quality characteristics and used Genetic Algorithm (GA) to design optimum parameter levels and PMSM controller parameters featuring robustness and high output quality (Chou *et al*., 2004; Margaliot and Langholz, 1999; Zhou *et al*., 2000). Finally, this study demonstrated its methods with the help of Matlab/Simulink software, under a PC-based infrastructure comprising PC Based motor control systems.

MATHEMATICAL MODELS OF PMSM

The PMSM in this study has a permanent magnet rotor and sinusoidal stator windings with a spacing of 120°. Under a synchronous reference coordinate system, the voltage equation of PMSM is expressed by Eq. (1) (Uddin and Rahman, 2000):

$$\begin{bmatrix} v_{da} \\ v_{qa} \end{bmatrix} = \begin{bmatrix} R_a + PL_a & -\omega_{re} L_a \\ \omega_{re} L_a & R_a + PL_a \end{bmatrix} \begin{bmatrix} i_{da} \\ i_{qa} \end{bmatrix} + \begin{bmatrix} 0 \\ \omega_{re}\phi_{fa} \end{bmatrix} \tag{1}$$

where:

- R_a, L_a : Motor's armature resistance and inductance
- V_{da}, V_{qa} : d-axis and q-axis armature voltage
- i_{da}, i_{qa} : d-axis and q-axis armature currents
- e_{da}, e_{qa} : Electromotive Force (EMF) d-axis and q-axis armature coil
- P : Differential operators (d/dt)
- ω_{re} : Rotor electrical radian speed
- ϕ_{fa} : Field flux linkages

$e_{da} = 0$

$e_{qa} = \omega_{re}\phi_{fa}$

Eq. (1) is rearranged into:

$$p\begin{bmatrix} i_{da} \\ i_{qa} \end{bmatrix} = \begin{bmatrix} -\dfrac{R_a}{L_a} & \omega_{re} \\ -\omega_{re} & -\dfrac{R_a}{L_a} \end{bmatrix} \begin{bmatrix} i_{da} \\ i_{qa} \end{bmatrix} + \frac{1}{L_a}\begin{bmatrix} v_{da} \\ v_{qa} \end{bmatrix} - \frac{1}{L_a}\begin{bmatrix} 0 \\ e_{qa} \end{bmatrix} \tag{2}$$

It is observed from Eq. (2) that d-axis and q-axis Armature Current i_{da}, i_{qa} is controllable, but $e_{qa} = \omega_{re}\phi_{fa}$ is uncontrollable, since e_{qa} is EMF generated by Field Flux Linkages of Permanent Magnet. PMSM's torque T_e is:

$$\begin{aligned} T_e &= p_n\phi_{fa}\left\{-i_{ua}\sin\theta_{re} - i_{va}\sin\left(\theta_{re} - \frac{2\pi}{3}\right) - i_{wa}\sin\left(\theta_{re} + \frac{2\pi}{3}\right)\right\} \\ &= p_n\phi_{fa}\left\{-i_{\alpha a}\sin\theta_{re} + i_{\beta a}\cos\theta_{re}\right\} = p_n\phi_{fa} i_{qa} \end{aligned} \tag{3}$$

where, p_n is number of pole pairs. It can be seen from above deduction process that, after change of coordinate, PMSM allows to decouple the electrical equation and then obtain 2-axis current i_{da}, i_{qa}. Given a constant ϕ_{fa}, it is only required to control armature current i_{qa} in order to control the torque of PMSM. It is learnt from Eq. (3) that, if the position of magnetic pole is measured, two-phase d-and q-axis armature voltage V_{da}, V_{qa} can be converted into three-phase output voltage (V_{ua}, V_{Va}, V_{Wa}) using Eq. (4).

$$\begin{bmatrix} v_{ua} \\ v_{va} \\ v_{wa} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta_{re} & -\sin\theta_{re} \\ \cos\left(\theta_{re} - \frac{2}{3}\pi\right) & -\sin\left(\theta_{re} - \frac{2}{3}\pi\right) \\ \cos\left(\theta_{re} + \frac{2}{3}\pi\right) & -\sin\left(\theta_{re} + \frac{2}{3}\pi\right) \end{bmatrix} \begin{bmatrix} v_{da} \\ v_{qa} \end{bmatrix} \tag{4}$$

Thus, it should be possible to control motors easily with V_{da} and V_{qa} under d, q coordinate. It is also learnt from Eq. (1) that, there exists mutual interference

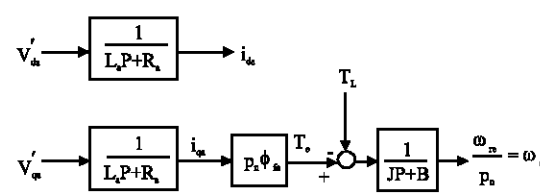

Fig. 1: Block diagram of PMSM with noninterference control

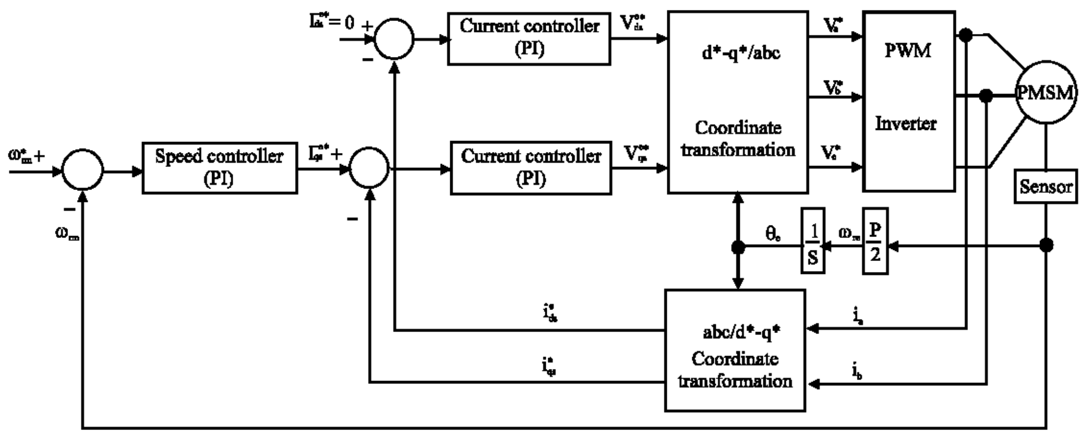

Fig. 2: Vector control framework of PMSM

of d-q-axis of PMSM. For the purpose of control, non-interference control is discussed below. Let V_{da}, V_{qa}:

$$\begin{aligned} v_{da} &= v'_{da} - \omega_{re} L_a i_{qa} \\ v_{qa} &= v'_{qa} + e_{qa} + \omega_{re} L_a i_{da} = v'_{qa} + \omega_{re}\left(\phi_{fa} + L_a i_{da}\right) \end{aligned} \quad (5)$$

Substituting Eq. (5) into Eq. (1) to obtain Eq. (6), with the relationship shown by Fig. 1:

$$\begin{bmatrix} v'_{da} \\ v'_{qa} \end{bmatrix} = \begin{bmatrix} R_a + PL_a & 0 \\ 0 & R_a + PL_a \end{bmatrix} \begin{bmatrix} i_{da} \\ i_{qa} \end{bmatrix} \quad (6)$$

It is learnt from Eq. (6) and Fig. 1 that, the current of two axes generates no interference and can be controlled individually. Figure 2 depicts a vector control framework of common PMSM.

FUZZY LOGIC CONTROLLER

The design of fuzzy controller generally includes three steps: Fuzzification, inference engine and defuzzification, as shown in Fig. 3. Use linguistic value (or fuzzy sets) to convert input variables into fuzzy representation, then use inference engine library to convert these linguistic values into fuzzy sets of fuzzy variables and finally into identifiable controlled variables for the controlled system.

Determination of fuzzification control strategy: The fuzzification process is to convert the input Map of a definite value into a fizzy set, with the relationship represented by a Membership Function. The definite value of fuzzy controller must be related to speed. In a

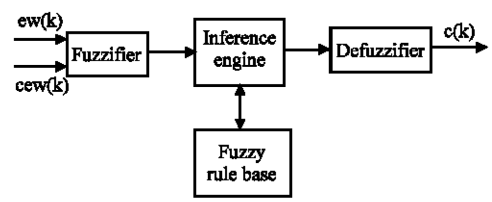

Fig. 3: Block diagram of fuzzy controller

PMSM vector control infrastructure, input and output of a speed controller is: the difference of speed command ω^*_{rm} and actual speed ω_{rm} and command torque T^*_e. So, the speed error ew(k) is taken as an input and the variable of speed error cew(k) as the other input. c(k) is used to replace command torque T^*_e as the output of speed controller. So, two inputs for every sampling time are:

$$ew(k) = \omega^*_{rm}(k) - \omega_{rm}(k) \quad (7)$$

$$cew(k) = ew(k) - ew(k-1) \quad (8)$$

where, ω^*_{rm} and ω_{rm} is separately speed command and actual speed of PMSM. The block diagram of speed control system with fuzzy controller infrastructure is illustrated in Fig. 4.

To convert definite variables ew(k) and cew(k) into fuzzy variables ew and cew during fuzzification phase, proper Membership Function shall be used. However, Membership Function is a subjective design element of fuzzy controller. Firstly, it is required to decide which kind of function is used e.g., triangular Membership Function in this study. Then, decide the number of fuzzy sets and respective range.

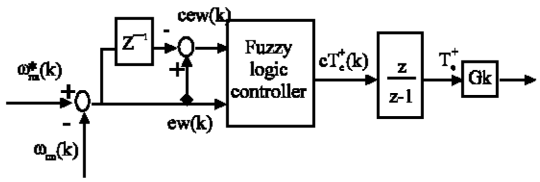

Fig. 4: Block diagram of fuzzy speed controller applied to vector control PMSM

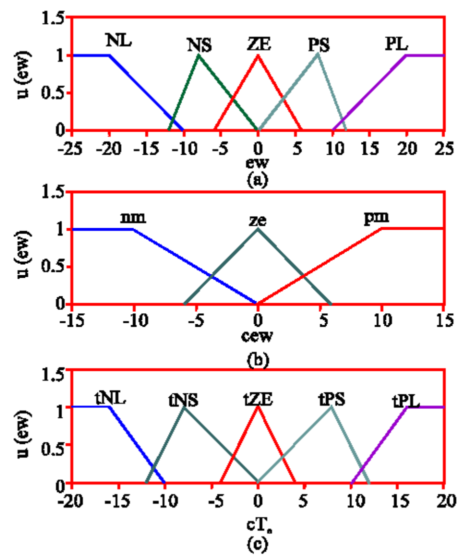

Fig. 5: Illustrates (a) speed error (ew) (b) speed error behavior variables (cew) (c) membership function diagram for output cT_e, while fuzzy controller is adopted to PMSM

In this study, five fuzzy sets of NL, NS, ZE, PS and PL are chose for ew and three fuzzy sets of nm, ze and pm are chose for cew. However, five fuzzy sets of tNL, tNS, tZE, tPS and tPL are chose for cT_e, as shown in Fig. 5. The value of Membership Function, u, for each fuzzy variable ranges between 0 and 1. The speed error, ew, for the designed fuzzy speed controller is at the range from -25 to 25. However, error behavior variables, cew, are at the range from -15 to 15 and the range of the output, cT_e, is set between -20 and 20.

Design of inference engine: The key point for the fuzzy controller is the establishment of knowledge base, because the knowledge base is established according to the experience of expert system. For fuzzy speed controller, the input and output relationships of optima results for different controllers in the motor system are stored in the knowledge base. Through the inference engine, a suitable rule from rule base is adopted and then optima controlled variables are generated. In this study, the input variables, ew, for the designed fuzzy control rule possess five membership functions and cew possesses three membership functions. The rule is expressed with the form of If-then and fifteen control rules are included in the rule, as shown in Table 1. The description of the rule adopted in this study is expressed as following:

Table 1: Control rule table for fuzzy speed controller

Te		ew NL	NS	ZE	PS	PL
cew	nm	tNL	tNL	tNS	tZE	tPS
	ze	tNS	tNS	tZE	tPS	tPS
	pm	tNS	tZE	tPS	tPL	tPL

R^i: GIf ew is A_{i1} and cew is A_{i2}, then cT_e is B_i i = 1,2,…..,15

where, i is the number of the control rule, ew and cew are input variables. cT_e is output variables and A_i and B_i are fuzzy sets.

Defuzzification: During the defuzzification procedure, the output of the fuzzy sets has to be transferred into identifiable value. In this study, center of gravith method of Eq. (9) is used to obtain the identifiable increment torque (cT_e).

$$cT_e^* = \frac{\sum_{i=1}^{m} cT_{ei} u(cT_{ei})}{\sum_{i=1}^{m} u(cT_{ei})} \tag{9}$$

Through the integration of Eq. (10), the torque, $T^*_e(k)$, can be obtained.

$$T_e^*(k) = T_e^*(k-1) + cT_e^*(k) * T \tag{10}$$

where, cT^*_e is the output of the fuzzy controller, cT_{ei} is the membership value of the input membership function corresponding to the ith control rule. $u(cT_{ei})$ is the membership value of the output membership function corresponding to the ith control rule. T is sampling time.

COMPUTER SIMULATION OF TAGUCHI METHOD

To demonstrate the feasibility of aforementioned fuzzy speed control methods with Matlab/Simulink, computer-aided simulation is performed according to the controller infrastructure of Fig. 2 and by taking the parameters of PMSM in Table 2 as the controlled objects.

Table 2: Parameters of PMSM

Rating torque	2.39 Nm	Armature resistance	3.27 Ω
Rating output	750 W	Armature inductance	0.0102H
Electrical time constant	3.12 m sec	Pole pair number	4
Torque constant	7.92 kgf. cm A^{-1}	Moment of inertia	0.002432 kg m^2

The Taguchi experiments have recently offered a cost-effective strategy for the study of interactions between reaction variables in electronic engineering quality improvement (Phadke, 1989). This method using signal-to-noise ratios (SN ratio) takes both the mean and the variability into account. The SN equation depends on the criterion for the quality characteristic to be optimized and provides accurate prediction of component levels for excellent performance. The orthogonal arrays are designated by the notation L (L for Latin squares) with a subscript, the SN ratio (η) is an index of robustness in experimental processing and the definition of SN ratio for NTB response is as follows (Phadke, 1989):

$$SN_{STB} = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) = \eta \tag{11}$$

where, n is the number of tests for various test level combinations, y_i is i-th observed value of the test level combination. In addition to optimization of individual quality characteristics, it is also recommended to use Taguchi Method for analysis of multi-response quality characteristics. For instance, in the case of conflict among various factor levels, engineering knowledge or experience shall be required for optimized level selection and setting. However, such a subjective method may not be suitable for all multi-response quality characteristics, while the selected settings of parameter levels may not present optimum conditions (Tong *et al*., 1997). To reduce the interference and influence upon operating environment and improve the output quality of PMSM, Kid, Kiq of current controller and Gk of fuzzy controller are taken as control factors, each of which has set three levels. In addition, motor load and speed are taken as noise factor. The motor load is set at 1.0N-m and 2.0N-m, speed set at 1800, 900 and 50 rpm, with the test results shown in Table 3. The simulation test with L_9 (3^4) Orthogonal Array is shown in Table 4.

To set up an analytic model of fuzzy controller and overall output quality, this study converted the quality characteristics of PMSM Plant (overshoot, rise time and settling time) into individual quality target values using TOPSIS. As listed in Table 4, this research has used 9 test level combinations (i = 1, 2,... , 9), each of which must consider the speed and loading conditions. Thus, each combination requires 6 repetitive tests (n = 6), totalizing 56 times of tests. In this research, η_{OH}, η_{RT} and η_{ST} represents SN values of overshoot, rise time and settling time, respectively. TOPSIS of PMSM output quality is performed in the following steps:

Table 3: Control factors, noise factors and level combinations

	Level		
	1	2	3
Control factor			
Kid	900	1000	1100
Kiq	900	1000	1100
Gk	0.35	0.6	0.8
Noise factor			
Speed	50 rpm	900 rpm	1800 rpm
Loading	1.0 N-m	2.0 N-m	-

Table 4: L_9 (3^4) Orthogonal array of Taguchi Method

Variables			SN			
Kid	Kiq	Gk	η_{OH}	η_{RT}	η_{ST}	QI
900	900	0.35	35.27	38.89	13.94	0.434
900	1000	0.6	40.78	39.99	39.01	0.489
900	1100	0.8	45.45	28.26	47.05	0.425
1000	900	0.6	40.81	40.23	39.01	0.465
1000	1000	0.8	45.49	25.93	45.31	0.415
1000	1100	0.35	35.25	38.98	13.94	0.435
1100	900	0.8	45.45	25.19	47.05	0.424
1100	1000	0.35	35.02	39.16	13.93	0.437
1100	1100	0.6	40.78	39.65	39.01	0.527

where: η_{OH} : Denotes a SN value of Overshoot
η_{RT} : Denotes a *SN* value of Rise Time
η_{ST} : Denotes a *SN* value of Settling Time
η_{OH} : Denotes an optimum quality index at various factor level combination
Kid, Kiq : Are the control factor of current controller

Step 1: set up a Quality Decision Matrix: D

$$D = \begin{bmatrix} S_{1,1} & S_{1,3} \\ \vdots & \vdots \\ S_{9,1} & S_{9,3} \end{bmatrix} = \begin{bmatrix} \eta_{OH}^1 & \eta_{RT}^1 & \eta_{ST}^1 \\ \vdots & \vdots & \vdots \\ \eta_{OH}^9 & \eta_{RT}^9 & \eta_{ST}^9 \end{bmatrix} \tag{12}$$

where, $S_{i,k}$ represents η of k-th quality characteristics in i-th test level combination.

Step 2: standardize Quality Decision Matrix: D

$$Y = \begin{bmatrix} Y_{1,1} & Y_{1,3} \\ \vdots & \vdots \\ Y_{9,1} & Y_{9,3} \end{bmatrix} \tag{13}$$

Where:

$$Y_{i,k} = , w_k \times \frac{S_{i,k}}{\sqrt{\sum_1^9 S_{i,k}^2}}$$

w_K is weight of k-th quality characteristics.

Step 3: Calculate ideal solution D^+_1 and negative ideal solution D^-_1

$$D_i^+ = ,\sqrt{\sum_{i=1}^{i=9}\left(Y_{i,k} - Y_k^+\right)^2} \quad D_i^- = \sqrt{\sum_{i=1}^{i=9}\left(Y_{i,k} - Y_k^-\right)^2} \tag{14}$$

Step 4: Decide an optimum Taguchi factor level combination using quality index QI. A bigger QI means better quality.

$$QI_i = \frac{D_i^+}{D_i^+ + D_i^-} \tag{15}$$

This research combined η_{OH}, η_{RT} and η_{ST} using quality index QI of TOPSIS. The results of Taguchi Method are shown in Table 4 and Fig. 6. The important factors affecting output quality of PMSM are GK, Kid and Kiq, of which Gk has the strongest influence as illustrated in Fig. 6. The optimum level combination of orthogonal array of Taguchi Method is Kid = 1100, Kiq = 1100, Gk = 0.6 and output quality index QI = 0.527 is an optimum value of test combinations. The 9th test results are listed in Table 4 and the speed simulation response diagram is shown in Fig. 7 and 8 depict different speed-load response diagrams under optimum level combinations (Kid = 1100, Kiq = 1100, Gk = 0.6), with simulation time as 0.0~1.0 and 0.0~0.1 sec, of which Fig. 7 depicts a simulation response diagram of motor speed, with 0.5 sec instantaneous loading of 1.0 and 2.0 Nt-m and speed command of 50, 900, 1800 rpm; Fig. 8 depicts a simulation response diagram of motor speed, with full-distance loading of 1.0 and 2.0 Nt-m and speed command of 50, 900, 1800 rpm. The results in Fig. 8 show that, under different speeds, Rise Time of Taguchi Method is smaller than scheduled setting speed: 0.02 sec. In addition, overshoot is also smaller than the setting speed, while settling time is more obvious in the case of lower speed (50 rpm).

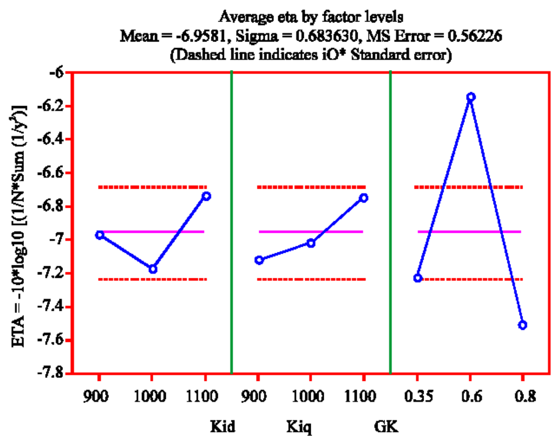

Fig. 6: Comparison diagram of SN ratio of Taguchi method SN

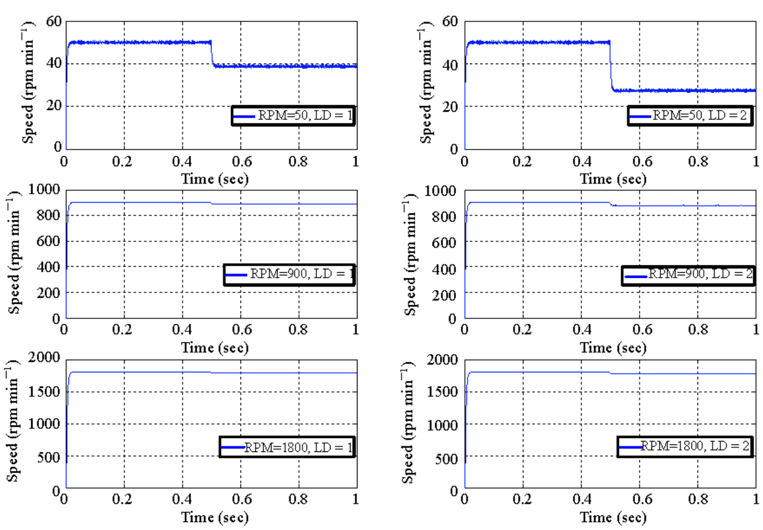

Fig. 7: Results of Taguchi Method: Kid = 1100, Kiq = 1100, Gk = 0.6; simulation response diagram of motor speed, with 0.5 sec instantaneous loading of 1.0 and 2.0 Nt-m and speed command of 50, 900, 1800 rpm

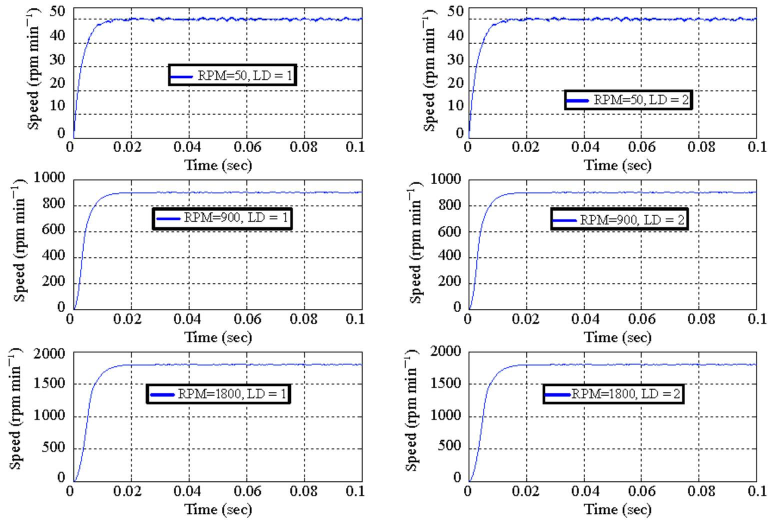

Fig. 8: Kid = 1100, Kiq = 1100, Gk = 0.6; simulation response diagram of motor speed, with full-distance loading of 1.0 and 2.0 Nt-m and speed command of 50, 900, 1800 rpm

OPTIMIZATION OF PARAMETERS OF PMSM

By using Taguchi Method, this study found that, at Kid = 1100, Kiq = 1100, Gk = 0.6, the important factors to PMSM overall output quality characteristics Kid, Kiq and Gk ensure reliable output quality (QI = 0.527) with minimum variance. Of which, Gk has the strongest influence upon PMSM. To obtain an optimal parameterization, this study made optimization analysis with Gk factor. GA is a function-related optimization tool most commonly used to resolve the problem of solution space and calculate global optimal solution. So, it is a method of searching target function limit. Though GA is a random search mode, it often searches and amends space to generate reasonable solutions according to cumulative information of every generation of population. During optimization process of GA, possible solution chromosome is composed of genes. In general, every gene is represented by a series of binary strings, which complete the evolution through Selection, Crossover and Mutation. Firstly, GA enables encoding of variables and then expresses the search space in the form of encoding. Population Size represents the number of every generation of chromosome. In the case of excessively small size, GA will be converged too quickly, often leading to poorer solution owing to insufficient information of population. Fitness function in GA process, also called target function, is used to decide the degree of fitness of a chromosome under an environmental condition, namely, measuring the performance of every chromosome. The fitness function of this study is expressed by Eq. (16):

$$\text{Fitness} = 100 * (10 + \text{QI}) \tag{16}$$

Population size of chromosomes is often fixed, but the percentage of fitter chromosome is increased by reproduction. This paper used 100 groups of chromosome, which were reproduced by common Roulette Wheel Method. So, the percentage of fitter chromosome dictates the probability of selection. With Two-point Crossover method, two crossover points are selected randomly from all selected binary strings and all strings between two crossover points are exchanged. In general, the crossover ratio will affect the survival probability of mothers in next generation. A higher crossover ratio means a lower survival probability and higher birth rate. The crossover ratio is set as 0.8. When applied to a particular problem, GA only requires two elements: (1) an encoding of candidate structures (solutions) and (2) a method of evaluating the relative performance of candidate solutions. A simple GA procedure was introduced as follows (Hung and Huang, 2006):

```
Produce an initial population of individuals
    evaluate the fitness of all individuals
    while termination condition not met do
    select fitter individuals for reproduction
    recombine between individuals
    mutate individuals
    evaluate the fitness of the modified individuals
    generate a new population
End while
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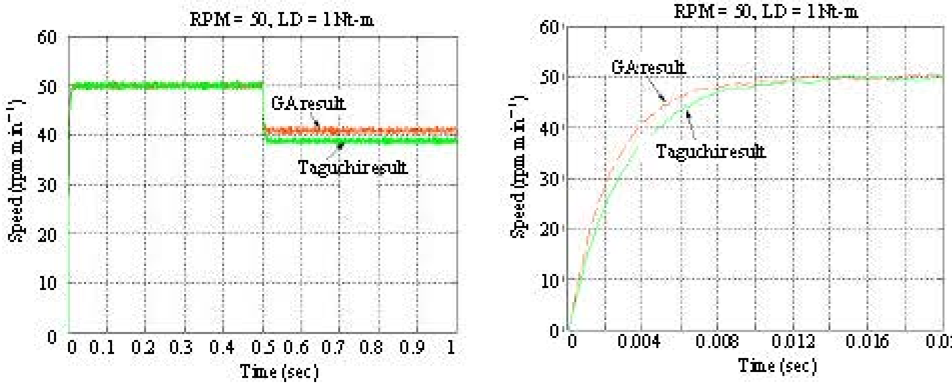

Fig. 9 (a): Motor speed simulation response diagram of GA and Taguchi, with 0.5 sec instantaneous loading of 1 Nt-m and speed command of 50 rpm
(b): Motor speed simulation response diagram of GA and Taguchi, with full-distance loading of 1 Nt-m and speed command of 50 rpm

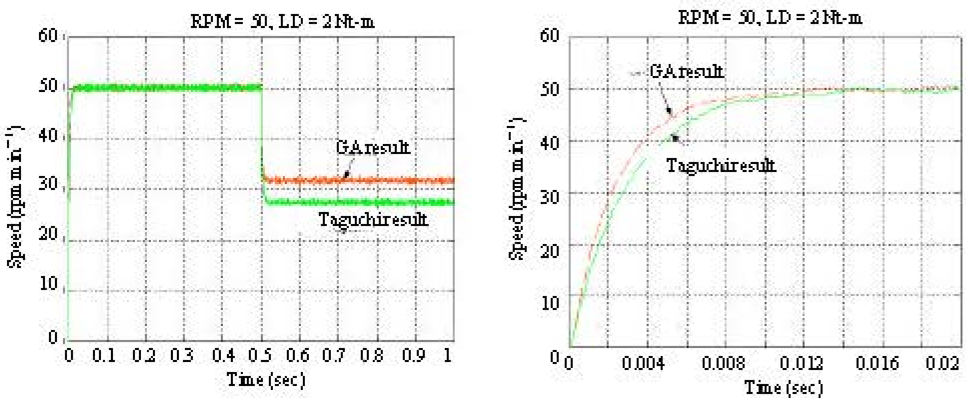

Fig. 10 (a): Motor speed simulation response diagram of GA and Taguchi, with 0.5 sec instantaneous loading of 2 Nt-m and speed command of 50 rpm
(b): Motor speed simulation response diagram of GA and Taguchi, with full-distance loading of 2 Nt-m and speed command of 50 rpm

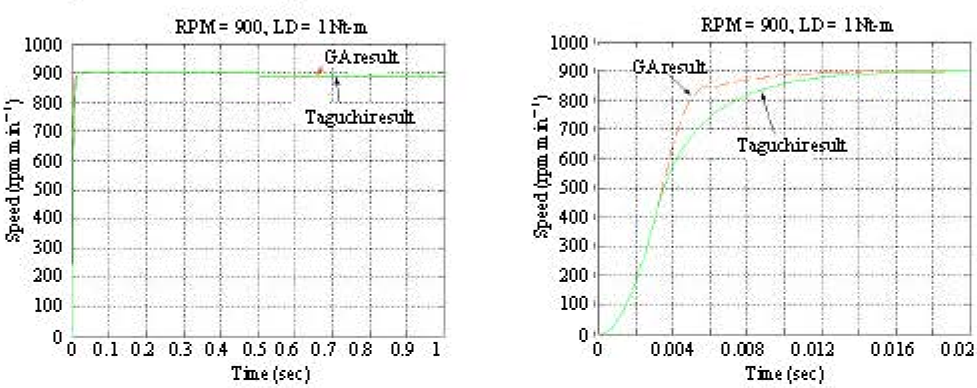

Fig. 11 (a): Motor speed simulation response diagram of GA and Taguchi, with 0.5 sec instantaneous loading of 1 Nt-m and speed command of 900 rpm
(b): Motor speed simulation response diagram of GA and Taguchi, with full-distance loading of 1 Nt-m and speed command of 900 rpm

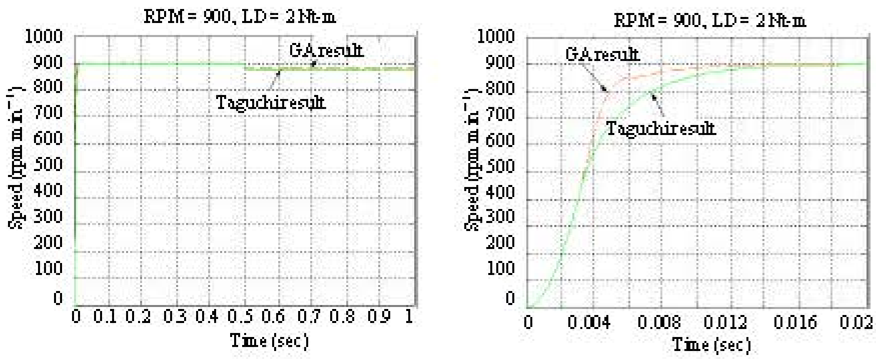

Fig. 12 (a): Motor speed simulation response diagram of GA and Taguchi, with 0.5 sec instantaneous loading of 2 Nt-m and speed command of 900 rpm
(b): Motor speed simulation response diagram of GA and Taguchi, with full-distance loading of 2 Nt-m and speed command of 900 rpm

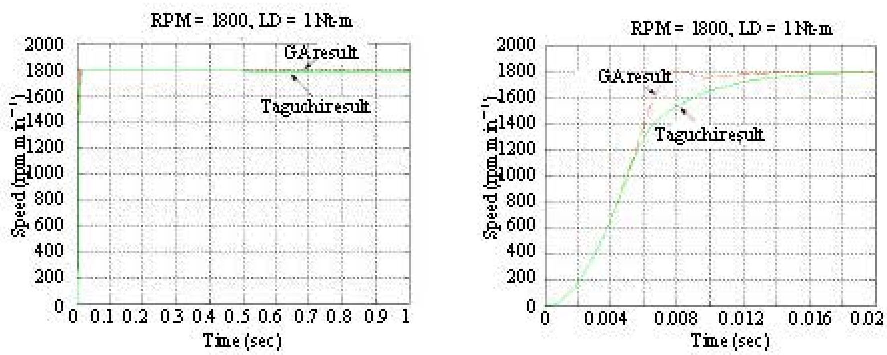

Fig. 13 (a): Motor speed simulation response diagram of GA and Taguchi, with 0.5 sec instantaneous loading of 1 Nt-m and speed command of 1800 rpm
(b): Motor speed simulation response diagram of GA and Taguchi, with full-distance loading of 1 Nt-m and speed command of 1800 rpm

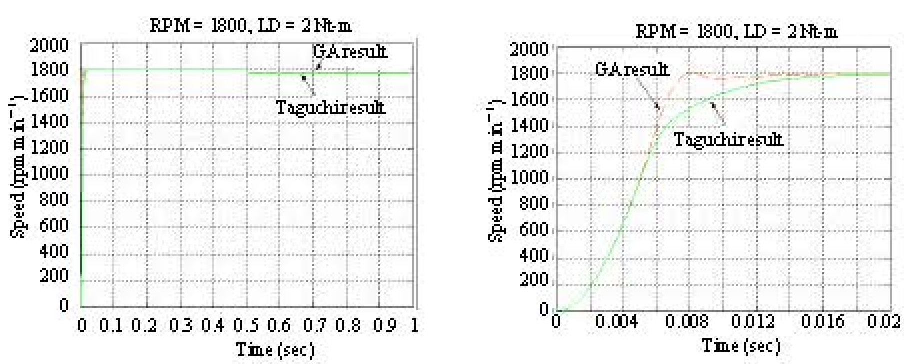

Fig. 14 (a): Motor speed simulation response diagram of GA and Taguchi, with 0.5 sec instantaneous loading of 2Nt-m and speed command of 1800 rpm
(b): Motor speed simulation response diagram of GA and Taguchi, with full-distance loading of 2Nt-m and speed command of 1800 rpm

Hundred generations are set according to above-specified GA. By using the analytical model of PMSM fuzzy controller parameters and output quality characteristics, GA searches optimum fitness function. Under different rotational speed of GA, if Kid = 1100, Kiq = 1100, Gk = 0.585, QI = 0.53161, the design results with Taguchi method at QI = 0.527 have good simulation response results. Fig. 9-14 depict the speed simulation response of GA and Taguchi under different speed-load conditions. Of which, Fig. 9-14a depict the comparative speed simulation response of GA and Taguchi at 0.0~1.0 sec; Fig. 9-14b depict the comparative speed simulation response of GA and Taguchi at 0.00~0.02. The simulation results from Fig. 9-14 suggests that, under low speed (50 rpm), medium speed (900 rpm) and high speed (1800 rpm), the overall quality output simulation response (overshoot, rise time and settling time) of GA at 1.0 and 2.0 Nt-m is better than the simulation response of Taguchi, especially for rise time within 0.015 sec.

CONCLUSIONS

This study attempted to design a controller based on the fuzzy theory, such that the controller could select proper rules according to the state error between system and feedback. It then sets up an analytical model with PMSM controller parameters, combines three STB quality characteristic (η_{OH}, η_{RT} and η_{SR}) into an overall Quality Index (QI) based on TOPSIS method and computes optimum parameters of motor using GA method to achieve a high-performance PMSM controller system based on Taguchi experimental results. So that a robust PMSM speed control system can be developed through PC-Based motor controller. The PC-based simulation and experimental results showed that the FLC in this study presents excellent speed control and robustness against PMSM parameter or load change. The simulation results showed that under low speed (50 rpm), medium speed (900 rpm) and high speed (1800 rpm), the overall quality output simulation responses (overshoot, rise time and settling time) of GA at 1.0 and 2.0 Nt-m are better than those of Taguchi, especially for rise time within 0.015 sec.

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