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Optimization of Output Performance of Model Reference Adaptive Control for Permanent Magnetic Synchronous Motor

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Abstract: The aim of this research is to discuss how to optimize Model Reference Adaptive Control (MRAC) for a Permanent Magnet Synchronous Motor (PMSM). With the help of MRAC that can overcome the influence of change of motor parameters and load, PMSM is characterized by good response and robustness. Generally speaking, PMSM controller has a long-proven infrastructure without complex computation, of which the Small-the-Better (STB) output features of PMSM include: Overshoot, Rise Time and Settling Time. In previous designs of controllers, only individual quality characteristics were considered without overall output planning of multi-quality characteristics. By combining quality characteristics into a single quality characteristic index through Desirability Function, this paper strives for optimization of parameters using Genetic Algorithm (GA), thereby improving the robustness and output performance of PMSM speed control. By using directly the stator current and speed signals in the control structure, a system integrating hardware and software was developed through PC-based motor controller. The results from simulation and experiment show that, under different rotational speeds with or without load, the adaptive control policy could offer better Multi-response performance.

Key words: PMSM, MRAC, small-the-better, multi-quality, desirability function, genetic algorithm

INTRODUCTION

AC motors are categorized into two types, synchronous motor and induction motor. The class of synchronous motors is further comprised of PMSM and wound synchronous motors. Since the rotor of PMSM is made of magnetic materials, PMSM has a lower moment of inertia than an induction motor, indicating a higher response speed under the same load torque. While a single smaller inverter is only required under the same output power, PMSM has an improved performance without the problem of temperature rise and loss of rotor due to absence of excitation current. Therefore, PMSM has been widely applied to high-performance Servo drive systems.

In recent years, Vector Control theory (Senjyu *et al*., 1996; Santisteban and Stephan, 2001) is well-proven in Permanent Magnet Synchronous Motor (PMSM), so Fuzzy Proportional-Integral (PI) controllers are widely applied thanks to simple construction and good performance (Cerruto *et al*., 1997; Kazemian, 2005). However, PI controllers shall be adjusted according to the running state and load torque likely varies in this context. So, traditional PI controllers cannot achieve good output performance under a wide range of operating conditions. To this end, an adaptive controller enables PMSM to obtain good speed control since it can overcome the influence of changes of motor parameters or load. In fact, Model Reference Adaptive Control (MRAC) is a perfect adaptive control method (Islam *et al*., 1990; Lin and Liaw, 1993; Astron and Wittenmark, 1995; Tsai and Tzou, 1997; Kao *et al*., 1997), since it can be treated as an adaptive servo system. If the desired output performance specifications are represented by model reference, the parameters of controller could be adjusted through the output of model reference and output error of actual system. In such a case, the output response of PMSM is forced to track the output response of model reference, irrespective of the change of motor parameters or load. Using the method of MRAC and stabilization theory of Lyapunov, an adaptive speed controller of PMSM is designed in such a manner that actual output response of

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PMSM is insensitive to the change of motor parameters and load. So, inferior speed control of traditional PI controllers could be improved. Generally speaking, PMSM controller has a long-proven infrastructure without complex computation, of which the Small-the-Better (STB) output features of PMSM include: Overshoot, Rise Time and Settling Time. In previous designs of controllers, only individual quality characteristics were considered without overall output planning of multi-quality characteristics (Dolinar *et al*., 1991; Salvatore and Stasi, 1994; Sozer *et al*., 1997; Perng *et al*., 2000). To provide a further insight into the overall output performance of PMSM, this study employed Desirability Function (Wu, 2005) to integrate three quality characteristics (Overshoot, Rise Time and Settling Time) into a single quality indicator. Then, the parameters of adaptive speed controller of PMSM were optimized with Genetic Algorithm (GA), thereby achieving the objective of improving speed control and robustness design of PMSM.

MATHEMATICAL MODELS OF PMSM

The permanent magnet synchronous motor (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:

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

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

Equation 1 is rearranged into:

$$P\begin{bmatrix} i_{da} \\ i_{qa} \end{bmatrix} = \begin{bmatrix} -\frac{R_a}{L_a} & \omega_{re} \\ -\omega_{re} & -\frac{R_a}{L_a} \end{bmatrix} \begin{bmatrix} i_{da} \\ i_{qa} \end{bmatrix} + \frac{1}{L_a}\begin{bmatrix} v_{da} \\ v_{qa} \end{bmatrix} - \frac{1}{L_a}\begin{bmatrix} 0 \\ e_{qa} \end{bmatrix} \quad (2)$$

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

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

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.

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

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 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.

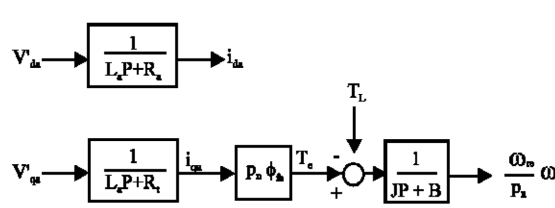

Fig. 1: Block diagram of PMSM with noninterference control

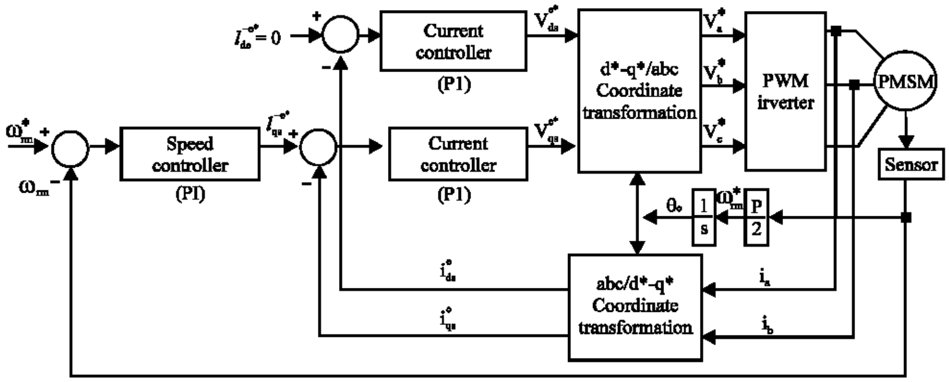

Fig. 2: Vector control framework of PMSM

MODEL REFERENCE ADAPTIVE CONTROL (MRAC)

MRAC system comprises a Model Reference, a Plant, an adjustable controller and an adjustment mechanism (adaptive control rule), with the infrastructure shown in Fig. 3.

Assuming the devices and models are expressed separately with First-Order Differential Equation:

$$\text{Plant}: \dot{x}_p = -a_p(t)x_p + b_p(t)u \tag{7}$$

$$\text{Model}: \dot{x}_m = -a_m x_m + b_m r \tag{8}$$

where, x_m represents the output signal of Model Reference, r represents the input reference signal and the values of a_m and b_m are selected according to the desired output response. In general, $a_m>0$, $b_m>0$ and $a_p(t)$, $b_p(t)$ are time-varying parameters of devices.

It is clearly observed from Fig. 3 that, the MRAC system is actually based on original plant feedback control system, along with the Model Reference and an adjustment mechanism (adaptive control rule) for automatic adjustment of control parameters. The parameters of Model Reference can be permanently stored into computer memory, with the output response x_m (the signal of rotational speed) expressed as the desired output performance specification. According to the actual output of closed-loop system and output error of Model Reference, the adjustment mechanism is used to regulate the control parameters to ensure that the output response of system can meet the performance requirements and also make the controlled system insensitive to the changes of its parameters. So, MRAC is a convenient control method for plant control systems with inherent disturbance.

The parameters of PMSM are difficult to regulate for a MRAC system with PMSM as a plant. So, an adjustable

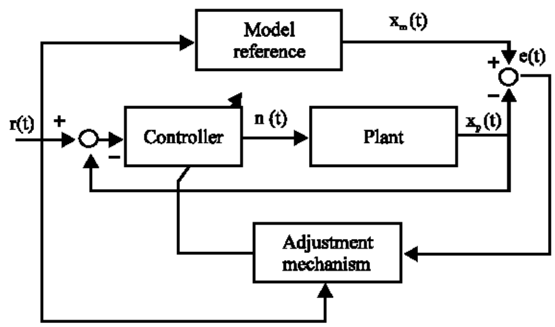

Fig. 3: MRAC system infrastructure

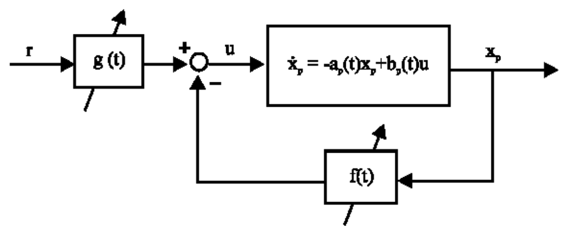

Fig. 4: Structural diagram of first-order adjustment system

controller must be provided to ensure that the controlled output of PMSM corresponds to the output response of Model Reference. It is assumed that adjustable feedforward controller g(t) and feedback controller f(t) is separately mounted into the feedforward and feedback paths of controlled vector control PMSM system, an adjustment system is shaped as shown in Fig. 4, wherein r is input reference signal. The following state equation of an adjustment system could be deducted form Fig. 4:

$$\dot{x}_p = -[a_p(t) + b_p(t)f(t)]x_p + b_p(t)g(t)r \tag{9}$$

The purpose of MRAC is to make the adjustment system's dynamic output response to the reference input command r correspond to that of Model Reference. It is found from Eq. 8 and 9 that, the gain f(t) and g(t) of controller in Eq. 9 shall be regulated to:

$$a_p(t)+b_p(t)f(t)\rightarrow a_m \quad (10)$$

$$b_p(t)g(t)\rightarrow b_m \quad (11)$$

In other words, output x_p of controlled system will be the same of output x_m of Model Reference. It is assumed that, due to temperature rise and wear of plants, most of MRAC systems have a parameter drift process, which is much slower than the response speed of Model Reference and plant as well as the regulation process of controller. Thus, during the regulation process of control parameters f(t) and g(t), $a_p(t)$ and $b_p(t)$ are treated as constants for a simplified design. The state equation of adjustment system can thus be rewritten from Eq. 9 into:

$$\dot{x}_p=-[a_p+b_pf(t)]x_p+b_pg(t)r \quad (12)$$

Let the error of output state between Model Reference and adjustment system as e(t), namely:

$$e(t)=x_m(t)-x_p \quad (13)$$

By subtracting Eq. 8 from Eq. 12, the following differential equation for error state could be obtained:

$$\dot{e}=-a_me-[a_m-a_p-b_pf(t)]x_p+[b_m-b_pg(t)]r \quad (14)$$

Where, let:

$$\phi(t)=a_m-a_p-b_pf(t) \quad (15)$$

$$\psi(t)=b_m-b_pg(t) \quad (16)$$

$\phi(t)$ and $\psi(t)$ represent the error of Model Reference parameters and plant parameters. Thus, Eq. 14 can be rewritten as:

$$\dot{e}=-a_me-\phi x_p+\psi r \quad (17)$$

It can be seen from Eq. 17 that, parameter error $\phi(t)$, $\psi(t)$ and output state error e must meet the above-specified differential equation for error state. To make the differential equation for error state more stable, an adaptive control rule shall be designed to regulate the control parameters f(t) and g(t), such that the output of controlled system could satisfy the output performance of model reference. In this paper, Lyapunov stabilization theory is used to ensure the stability of control system. And adaptive control rule is planned using Lyapunov stabilization theory (Åstron and Wittenmark, 1995). Three error variables, i.e., e, ϕ and ψ are contained in the above-specified differential equation for error state. So, the stability analysis of entire error system shall cover e, ϕ and ψ. According to Lyapunov stabilization theory, the following secondary Lyapunov function is selected:

$$V(e,\phi,\psi)=\frac{1}{2}\left[b_pe^2+\frac{1}{\lambda_1}\phi^2+\frac{1}{\lambda_2}\psi^2\right] \quad (18)$$

where, $\lambda_1>0$, $\lambda_2>0$. As the parameter of controlled system $b_p>0$, $V(e,\phi,\psi)>0$ if e, ϕ and ψ are not equal to 0. Then, the derived function of time can be obtained from Eq. 18:

$$\dot{V}(e,\phi,\psi)=b_pe\dot{e}+\frac{1}{\lambda_1}\phi\dot{\phi}+\frac{1}{\lambda_2}\psi\dot{\psi} \quad (19)$$

If substituting Eq. 14 into Eq. 19:

$$\dot{V}(e,\phi,\psi)=-b_pa_me^2+\phi\left[\frac{1}{\lambda_1}\dot{\phi}-b_pe\omega_{rm}\right]+\psi\left[\frac{1}{\lambda_2}\dot{\psi}+b_per\right] \quad (20)$$

Let:

$$\dot{\phi}=\lambda_1b_pe\omega_{rm} \quad (21)$$

$$\dot{\psi}=-\lambda_2b_per \quad (22)$$

Equation 22 is then simplified as:

$$\dot{V}(e,\phi,\psi)=-b_pa_me^2\leq 0 \quad (\because b_p>0, a_m>0) \quad (23)$$

$\dot{V}(e,\phi,\psi)\leq 0$. Thus, it shall be possible to maintain a stable control system by following the adaptive control rule in Eq. 21 and 22 and Lyapunov stabilization theory. Since control gains f(t) and g(t), not $\phi(t)$ and $\psi(t)$, are adjustable parameters in actual MRAC system, the adaptive control rule of f(t) and g(t) could be derived from Eq. 15, 16, 21 and 22:

$$\dot{f}(t)=-\lambda_1e(t)x_p(t) \quad (24)$$

$$\dot{g}(t)=\lambda_2e(t)r(t) \quad (25)$$

Thus, a stable system could be guaranteed if the adaptive control rule in Eq. 24 and 25 is observed based on Lyapunov stabilization theory, namely, consistent output of the system and Model Reference could be achieved if $t\rightarrow\infty$ and $e(t)\rightarrow 0$. According to the adaptive control rule in Eq. 24 and 25, the infrastructure of MRAC system for vector control PMSM is shown in Fig. 5.

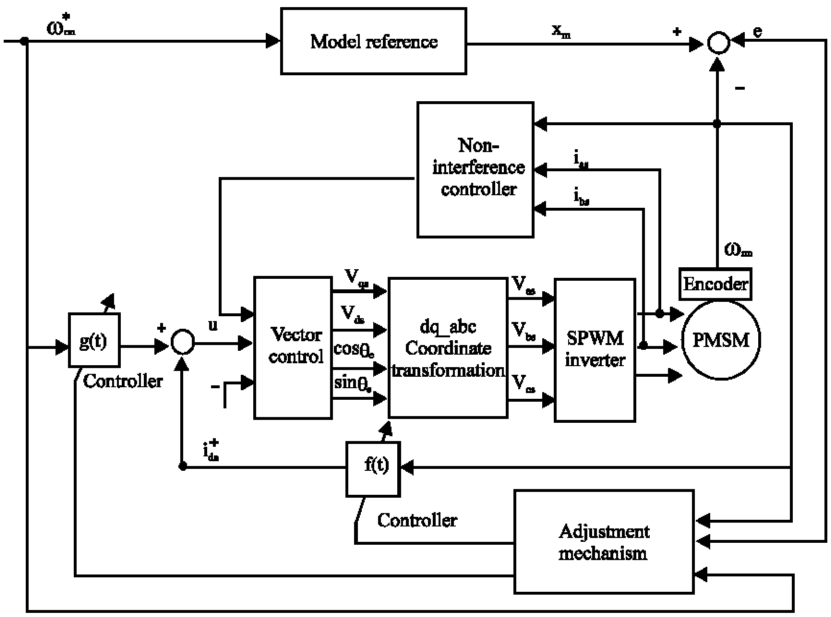

Fig. 5: Infrastructure of MRAC for PMSM

DESIRABILITY FUNCTION

As mentioned earlier, the output response of PMSM shall comprise Maximum overshoot M_o, rise time R_t and settling time S_t, of which M_o is often used to measure the relative stability of control system and represented by the percentage of specific order response value:

$$M_o = \frac{y_{max} - y_{ss}}{y_{ss}} \times 100\% \quad (26)$$

where, y_{max} is maximum specific order response value, y_{ss} is stable value of specific order response. In addition, R_t is generally the period when the specific order response value increases from 10-90%. The performance characteristic index S_t is maintained within the 2% when the specific order response is reduced. It is clearly seen that the smaller performance response characteristics represent more stable output quality of PMSM. In other words, the quality of PMSM is characterized by Small-the-Better of multi-qualitye. In previous designs 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. In 1965, Harrington developed a mathematic conversion method with desirability function, which was used to resolve the multi-quality problem by converting it into single response. The Individual Desirability d was defined using Eq. 27:

$$d(z_i) = \left(-\left| \frac{2z_i - (USL + LSL)}{USL - LSL} \right| \right)^n \quad (27)$$

where, d represents desirability function, z_i represents i-th actual response, USL and LSL represents separately upper and lower limit of quality specifications and n is called Deviation Importance. Then Overall Desirability (D) is obtained from average of individual desirability, thus converting optimum parameter into maximum overall desirability. According to desirability function concept designed by Harrington, the response value shifts within the tolerance far away from Midpoint of specification; this design, however, is not suitable for practical applications. For this reason, Wu (2005) made a rectification, with the Smaller-the-Better desirability function as:

$$d(z_i) = \begin{cases} 0 & , USL < y \\ \left(\left| \frac{z_i - USL}{T - USL} \right| \right)^n & \ldots, T \le y \le USL \end{cases} \quad (28)$$

where, T represents the target value of quality characteristic, n is set depending upon the characteristics of individual response. A bigger value means a quicker slow-down of desirability when it is far away from T. To obtain optimum output response of PMSM, the quality response output $d_{slt}(s,l,t = 1, 2, 3)$ of PMSM is given with different load conditions: without load, semi-load (1.2 Nt-m) and 3/4 load (1.8 Nt-m) under low, middle and high speed (300, 900 and 1800 rpm). Twenty seven quality response items ($d_{111} \sim d_{333}$), target (T) of quality response,

Table 1: Desirability function of quality characteristics under different speed/load conditions

Speed (rpm)	Load conditions	Quality response/ s/t	$d_{slt}(z)_{max}$ T	d(T)	$d_{slt}(z)_{min}$ USL	d(USL)
300	Without load	M_o/111	0	1	2.0%	0
		R_t/112	0	1	0.1	0
		S_t/113	0	1	0.4	0
	Semi-load (1.2 Nt-m)	M_o/121	0	1	2.0%	0
		R_t/122	0	1	0.1	0
		S_t/123	0	1	0.4	0
	3/4 load (1.8 Nt-m)	M_o/131	0	1	2.0%	0
		R_t/132	0	1	0.1	0
		S_t/133	0	1	0.4	0
900	Without load	M_o/211	0	1	2.0%	0
		R_t/212	0	1	0.1	0
		S_t/213	0	1	0.25	0
	Semi-load (1.2 Nt-m)	M_o/221	0	1	2.0%	0
		R_t/222	0	1	0.1	0
		S_t/223	0	1	0.25	0
	3/4 load (1.8 Nt-m)	M_o/231	0	1	2.0%	0
		R_t/232	0	1	0.1	0
		S_t/233	0	1	0.25	0
1800	Without load	M_o/311	0	1	2.0%	0
		R_t/312	0	1	0.1	0
		S_t/313	0	1	0.4	0
	Semi-load (1.2 Nt-m)	M_o/321	0	1	2.0%	0
		R_t/322	0	1	0.1	0
		S_t/323	0	1	0.25	0
	3/4 load (1.8 Nt-m)	M_o/331	0	1	2.0%	0
		R_t/332	0	1	0.1	0
		S_t/333	0	1	0.25	0

upper limit (USL) and desirability $d_{slt}(z)$ are listed in Table 1. In this study, let n = 1, T = 0, USL is set properly as the upper limit according to speed and load conditions. USL is set as 0.4 sec under low speed and reduced to 0.25 sec under middle and high speed. The desirability of quality response $0 \le d_{slt}(z) \le 1$ is shown in Table 1 and $d_{slt}(z) = d_{slt}(T) = d_{slt}(z)_{max} = 1$ in the case of z = t, or otherwise z = USL $d_{slt}(z) = d_{slt}(z)_{min} = 0$. In addition, $d_{sl2} = 0.1$ for R_t in Table 1. All d_{slt} are converted by Eq. 29 into single-response overall desirability D, $0 \le D \le 1$. A bigger D indicates better speed response and robustness of PMSM.

$$D = \left(\prod_{s,l,t=1}^{3} d_{slt} \right)^{s*l*t} \qquad (29)$$

PARAMETERIZATION AND SIMULATION

Parameter control in MRAC is a crucial factor to design the robust response of PMSM. The parameters of PMSM are shown in Table 2.

Based upon MRAC of PMSM as discussed in section 3, parameters λ_1 and λ_2 in Eq. 24 and 25 are taken as control variables. And overall quality desirability D in Eq. 29 is taken as an output variable. Finally, GA is used to find optimum parameters λ_1, λ_2 and desirability D,

Table 2: Parameters of PMSM

Rating torque	2.39 N m	Armature resistance	3.27 Ω
Rating output	750 W	Armature inductance	0.0102 H
Electrical time constant	3.12 ms	Pole pair number	4
Torque constant	7.92 kgf.cm/A	Moment of inertia	0.002432 kg m^2

enabling to design an optimal MRAC parameter control model. This helps to improve the robustness of PMSM under different speed and load conditions, in addition to the consistency of output between PMSM and Model Reference.

Genetic Algorithms (GA), proposed by Holland (1992) has a solution process similar to biological evolution. That's to say, the survival pressure and threats represent the adaptive function of target issues, which could guide the searching for a solution. After continuous evolution, a highly adaptive value could be maintained as the solution. Every chromosome in GA represents a possible solution. Firstly, possible solutions of fixed quantity may be generated during searching process, of which every possible solution is an individual for the solution space. Genes are generally represented by binary strings. The evolution process of population within the solution space is finished through Selection, Crossover and Mutation. GA evaluates each of those solutions and decides on a fitness level for each solution set (Goldberg, 1989; Holland, 1992). In GA optimization, the factors involved are the size of initial population, the crossover probability and the mutation probability. The optimal plasma cleaning parameter design through the procedures of executing GA is simplified as follows.

Step 1: Encoding: GA permits encoding of the variables for the searching space. The MRAC parameters: λ_1 and λ_2 will vary within a known range and encoding as a binary string. We use 10 bit encoding which resulted in a 20 bit chromosome for each parameter. Figure 6 show the encoding and mapping of two parameters.

Step 2: Creation of a random initial population: Set the GA's operating conditions: the generation size was set to 500, the size of the initial population was set to 100, the crossover and mutation probabilities were set to 0.75 and 0.03, respectively.

Step 3: Scoring each member of the current population by computing the individual's fitness value. The GA algorithm meeting a given fitness function is expressed as:

Step 4: Selection of members: The members of the new population are selected based on their fitness. Elite

Table 3: Desirability value searched by GA

GA's 30 runs	Desirability value (D)
D_{max}	0.99399
D_{min}	0.93260
Average	0.98152
Std.	0.00271

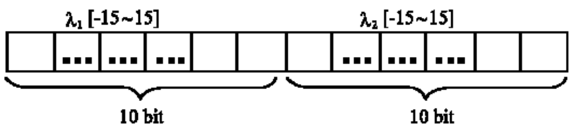

Fig. 6: Encoding λ_1 and λ_2 using a 20 bit string

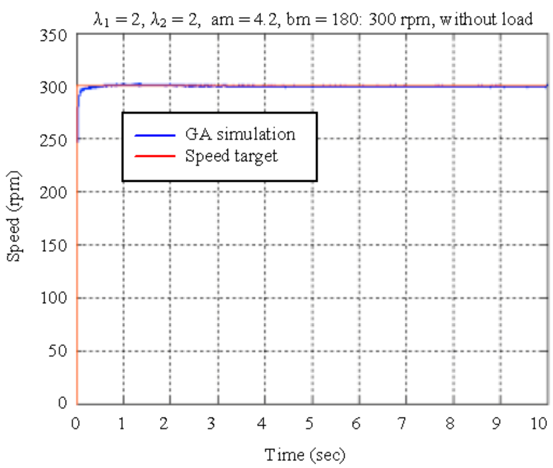

Fig. 7: Speed simulation response diagram of unloading motor under speed command of 300 rpm

children are the individuals in the current generation with lower fitness values. Roulette wheel selection is employed in this algorithm. These individuals automatically survive to the next generation.

Step 5: Crossover and mutation: Production of children from their parents. Dependent on the crossover rate, crossover of the bits from each chosen chromosome occurs at a random position, where there is an interchange between the two parts. Proceed through the chosen chromosome bits and flip them in dependence to the mutation rate. Replace the current population with the children, to form the next generation.

Step 6: Step 3, 4, 5 are repeated until a stopping criteria is met.

After 30 calculations with GA, the maximum desirability is 0.99399, as shown in Table 3. The optimum parameter is: $\lambda_1 = 2$ and $\lambda_2 = 2$, D = 0.979. To validate the feasibility of the aforementioned MRAC method,

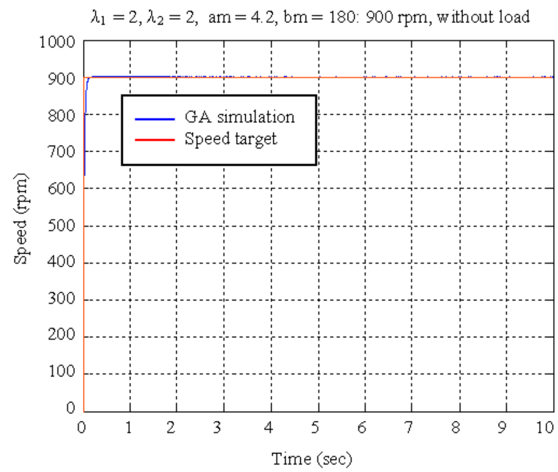

Fig. 8: Speed simulation response diagram of unloading motor under speed command of 900 rpm

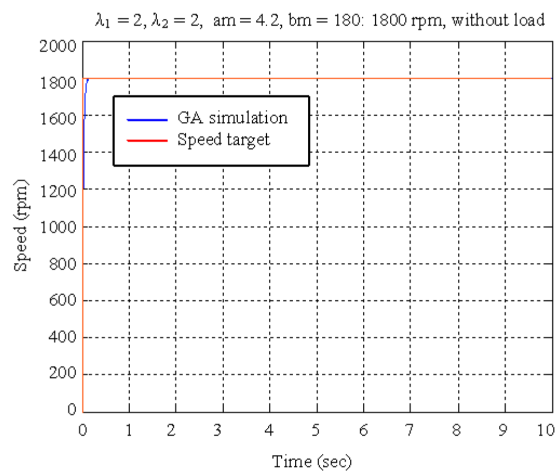

Fig. 9: Speed simulation response diagram of unloading motor under speed command of 1800 rpm

Matlab/Simalink software was used according to the control structure in Fig. 6. Optimum parameters λ_1, λ_2 obtained from GA were taken as control objects and PC-based simulation was made when input command r is 300, 900 and 1800 rpm, with the results shown in Fig. 7-15.

While GA method is used to find optimum MRAC parameters λ_1, λ_2 and desirability value D of PMSM, an optimal MRAC parameter control model is designed. The response simulation from Fig. 7-15 shows that, under any speed-load conditions, PMSM is proved to have stronger robustness in addition to the consistency of output between PMSM system and Model Reference.

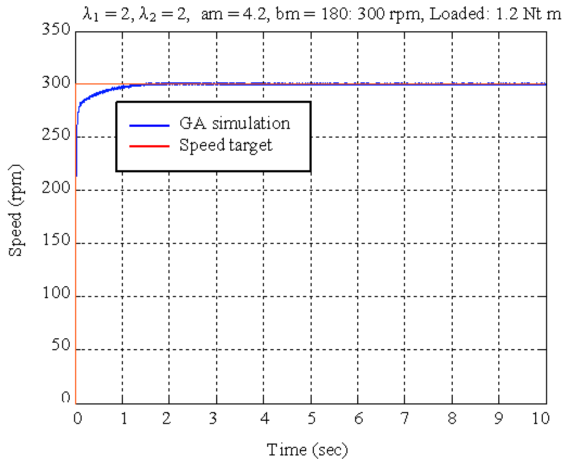

Fig. 10: Speed simulation response diagram of semi-load (1.2 Nt m) motor under speed command of 300 rpm

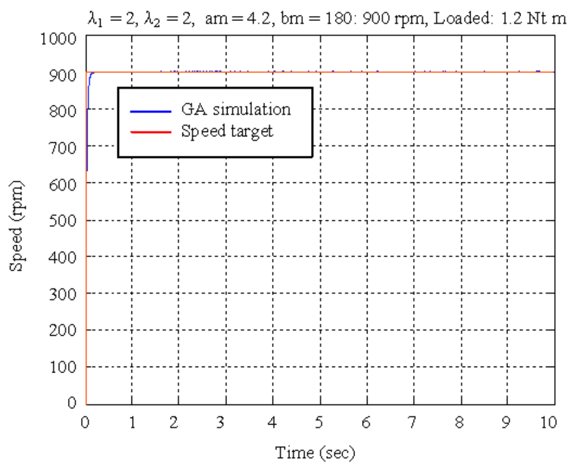

Fig. 11: Speed simulation response diagram of semi-load (1.2 Nt m) motor under speed command of 900 rpm

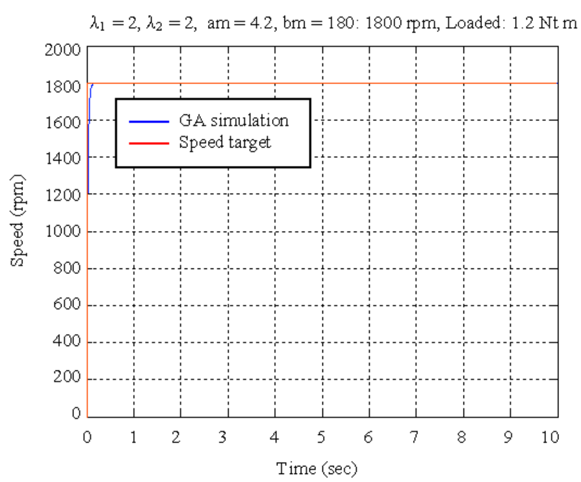

Fig. 12: Speed simulation response diagram of semi-load (1.2 Nt m) motor under speed command of 1800 rpm

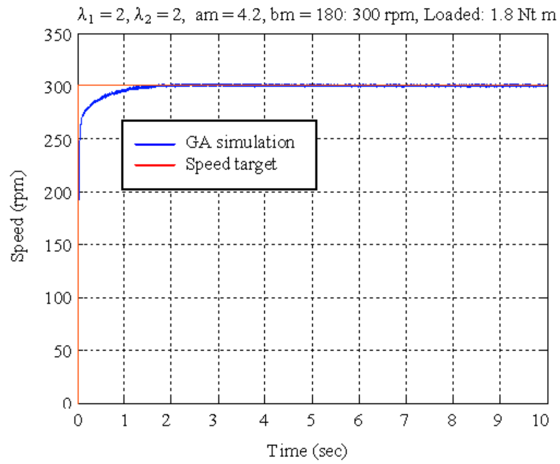

Fig. 13: Speed simulation response diagram of 3/4 load (1.8 Nt m) motor under speed command of 300 rpm

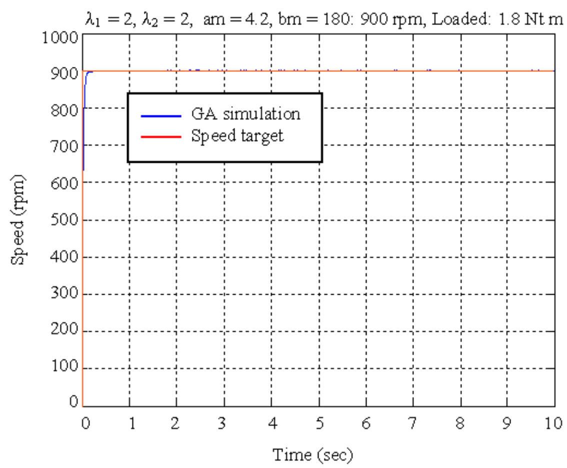

Fig. 14: Speed simulation response diagram of 3/4 load (1.8 Nt m) motor under speed command of 900 rpm

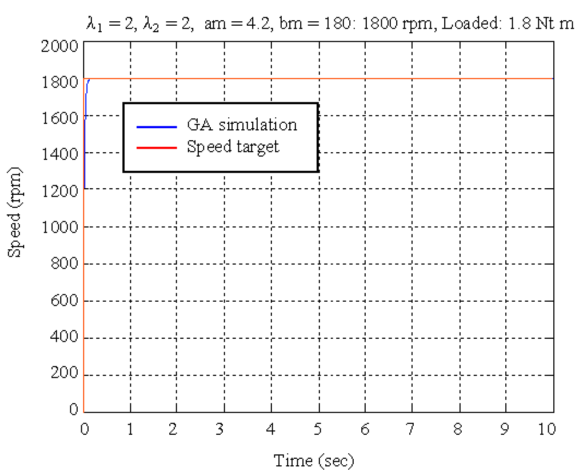

Fig. 15: Speed simulation response diagram of 3/4 load (1.8 Nt m) motor under speed command of 1800 rpm

EXPERIMENTAL SYSTEMS AND RESULTS

Introduction to infrastructure of experimental system: Signals were previously processed through analog devices. With recent rapid development of digital systems, there is a growing trend of signal processing with much quicker computers or special-purpose digital processors. In such cases, this paper enables PC-based control of PMSM in order to obtain more stable operating performance within a shorter sampling period. As shown in Fig. 16, the control system of PMSM mainly comprises: (1) PC processor; (2) motor control interface card; (3) inverter power drive circuit.

Experimental results: To validate the feasibility of the aforementioned MRAC method, a system integrating hardware and software is developed through PC-based motor controller. And, optimum parameters λ_1, λ_2 obtained from GA are taken as control objects. The field test is made when input command r is 300, 900 and 1800 rpm, with the simulation and actual response results compared in Fig. 17-25.

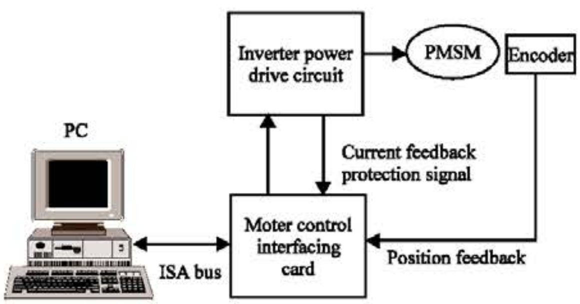

Fig. 16: PMSM drive control system

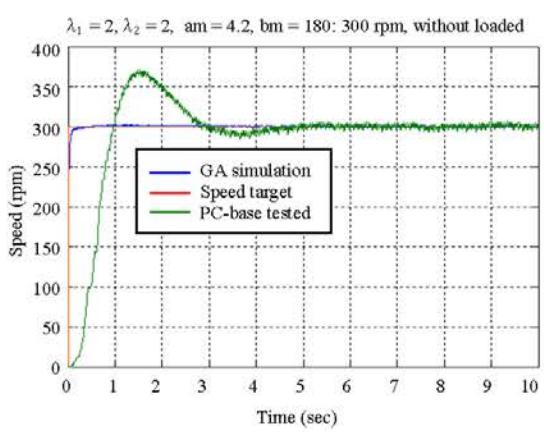

Fig. 17: Comparison diagram of speed simulation and actual response for unloading motor under speed command of 300 rpm

While GA is used to search optimum MRAC parameters λ_1, λ_2 of PMSM, the actual response diagram and simulation response diagrams are compared and analyzed. Figure 17, 20 and 23 show the comparison of simulation and test results in the case of low-speed unloading, semi-load (1.2 N m) and 3/4 load (1.8 Nm). But, overshoot and delay are observed due to the following reasons:

- Floating-point calculating ability and control program of PC are impossible to realize optimum calculation time.
- Initial angle of rotor may affect seriously the performance of PMSM drive system, so high priority of concern shall be paid to calibration of the rotor's initial angle.

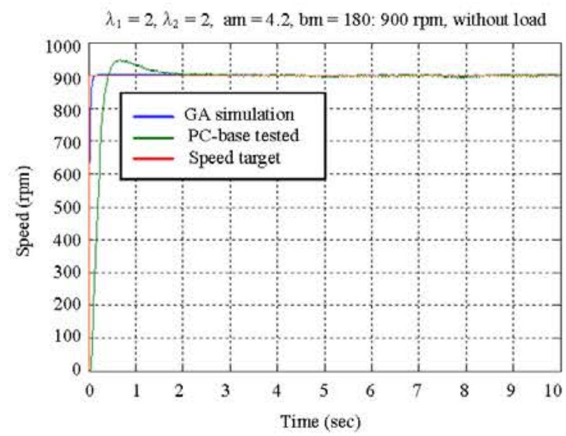

Fig. 18: Comparison diagram of speed simulation and actual response for unloading motor under speed command of 900 rpm

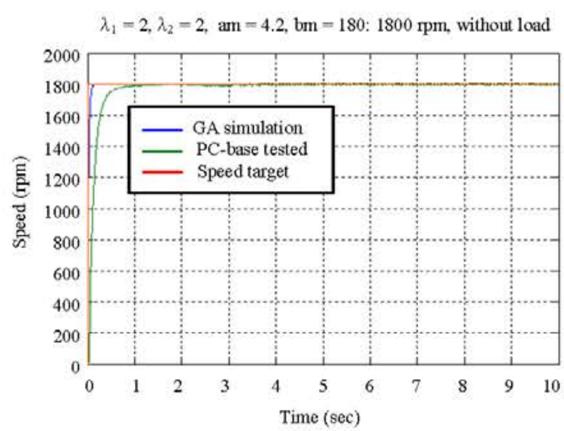

Fig. 19: Comparison diagram of speed simulation and actual response for unloading motor under speed command of 1800 rpm

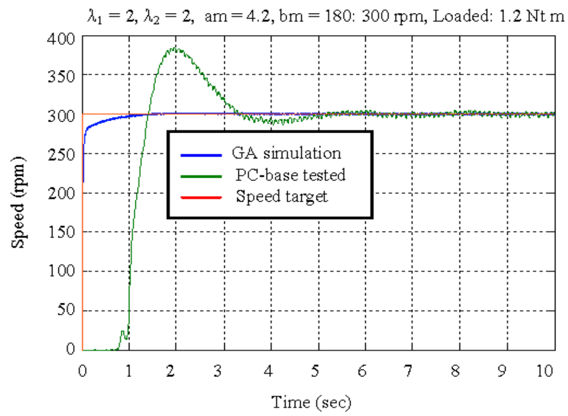

Fig. 20: Comparison diagram of speed simulation and actual response for semi-load (1.2 Nt-m) motor under speed command of 300 rpm

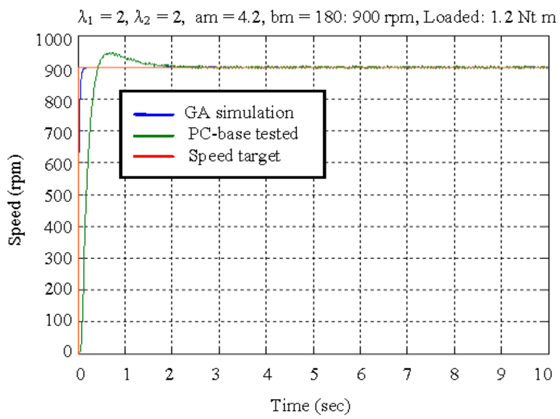

Fig. 21: Comparison diagram of speed simulation and actual response for semi-load (1.2 Nt-m) motor under speed command of 900 rpm

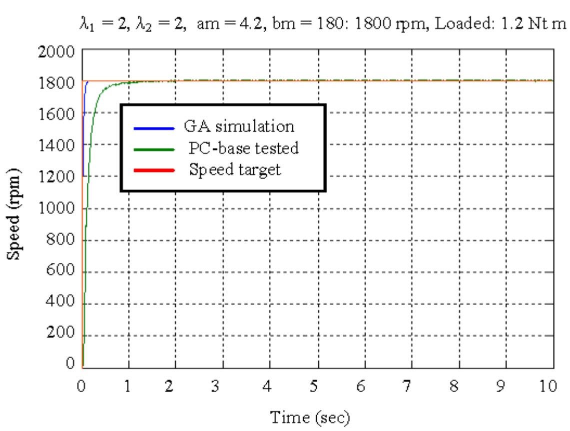

Fig. 22: Comparison diagram of speed simulation and actual response for semi-load (1.2 Nt-m) motor under speed command of 1800 rpm

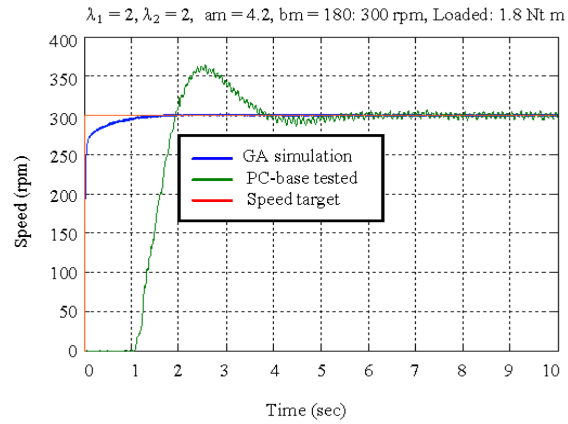

Fig. 23: Comparison diagram of speed simulation and actual response for 3/4 load (1.8 Nt-m) motor under speed command of 300 rpm

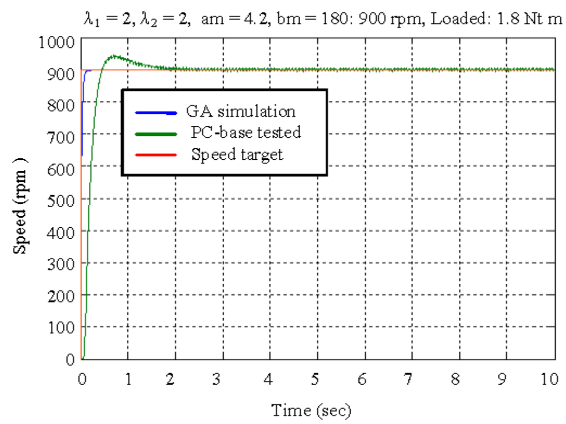

Fig. 24: Comparison diagram of speed simulation and actual response for 3/4 load (1.8 Nt-m) motor under speed command of 900 rpm

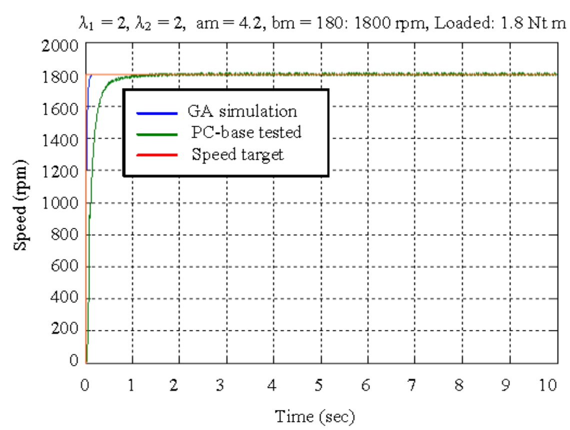

Fig. 25: Comparison diagram of speed simulation and actual response for 3/4 load (1.8 Nt-m) motor under speed command of 1800 rpm

But, the phenomenon in low speed occurred in Fig. 18, 19, 21, 22, 24 and 25 have been improved considerably in middle speed (900 rpm), high speed (1800 rpm) and different loads. It is proved that MRAC in this paper presents excellent speed control and robustness against PMSM parameter or load change. The experimental results in low speed are acceptable despite of limited deviation from the ideal simulation results. To improve overshoot and delay during low-speed operation, one solution is to improve the digital signal processor in cooperation with calibration of the initial angle.

CONCLUSIONS

This study has developed a design method for adaptive speed controller (MRAC) of PMSM. And, an adaptive control rule is designed with Lyapunov stabilization theory such that the control parameters could be regulated properly to be suitable for a PMSM speed control system according to the output state error of the system and Model Reference. By taking overall output quality of PMSM into account based on the Desirability Function, it is possible to design optimum MRAC parameters with GA, thereby serving the purpose of improved speed control and robustness design of PMSM. A PMSM speed control system with hardware and software can be developed through PC-Based motor controller. The PC-based simulation and experimental results show that, MRAC in this study presents excellent speed control and robustness against the PMSM parameter or load change.

On a whole, this study takes the overall output quality of multi-response characteristic of controller into consideration while designing synchronous motor and integrates the multi-response characteristic through desirability function to achieve the single quality characteristic index. Then it uses GA to design the optimal parameter standards for λ_1 and λ_2 in order to enhance the stability and output quality of the speed control of synchronous motor. The optimal parameters λ_1 and λ_2 obtained from GA are applied in the simulation result control comparison and actual testing of the adaptive speed control of PMSM reference model and conventional PI controller. The results indicate that the adaptive speed control of parameter design model of multi-response characteristic proposed in this study could increase the tracing and regulating abilities of high, medium and low rational speeds of the motor. In other words, the results can contribute to the parameters or load interference of synchronous motor. Therefore, the adaptive control strategy proposed herein can generate better speed response result.

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