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Research paper

Optimization of PI Controller Gain for Simplified Vector Control on PMSM Using Genetic Algorithm

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Abstract : This paper proposes the used of genetic algorithm for optimizing PI controller and describes the dynamic modeling simulation for the permanent magnet synchronous motor driven by simplified vector control with the aid of MATLAB-Simulink environment. Furthermore, three kinds of error criterion minimization, integral absolute error, integral square error, and integral time absolute error, are used as objective function in the genetic algorithm. The modeling procedures and simulation results are described and presented in this paper. Computer simulation results indicate that the genetic algorithm was able to optimize the PI controller and gives good control performance of the system. Moreover, simplified vector control on permanent magnet synchronous motor does not need to regulate the direct axis component current. This makes simplified vector control of the permanent magnet synchronous motor very useful for some special applications that need simple control structure and low cost performance.

Key Words : Genetic Algorithm, Permanent Magnet Synchronous Motor, Simplified Vector Control, Integral Absolute Error, Integral Square Error, Integral Time Absolute Error

1. Introduction

Permanent Magnet Synchronous Motors(PMSMs) are used in many applications that required fast and accurate torque or speed response in the servo system owing to the vector control methods. Field Oriented Control(FOC) is one representative method of the vector control types to drive the PMSM motor. Many researches about conventional FOC combined with various controller types for PMSM have been proposed. Artificial Neural Network(ANN) FOC can obtain desired performance without an exact model[1)]. However, ANN structural uncertainties may cause system instability. Fuzzy Logic Controller(FLC) can also obtain good performance with decent robustness, however it strongly depends on designers' experiences. Moreover, FOC requires complicated coordinate transformations in spite of its good control performances. Therefore, simplified vector control based on FOC, without massive coordinate transformations, is used to control the PMSM in this paper. PI controllers are used in FOC method as the current and speed regulator. PI controller allows the system to achieve very high performances when it was tuned optimally. However, it is difficult to find the optimal gain

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values without exact motor model including motor parameters. Furthermore, using conventional method is very complicated and needs tremendous calculations in determining the appropriate gain.

Recently, Genetic Algorithm(GA) is being used in many optimization problems which could not be solved by conventional solving techniques. The use of GA technique for determining controller parameter is practical due to their fast convergence and reasonable accuracy without experiencing complicated mathematical calculation. The benefit of GA is analyzing the output directly, which is needed to be optimized, instead of analyzing the system parameter. The GA method is able to solve complicated control system structure, such as PMSM vector control that uses three PI controllers on the system. Moreover, the GA is not only able to optimize the PI controller, but also able to satisfy the control performance of the system as the design specification.

This paper reports the application of the GA on the PMSM simplified vector control simulation and compares the results obtained from various error criterion minimization. Three kinds of error criterion minimization: Integral Absolute Error(IAE), Integral Square Error(ISE), and Integral Time Absolute Error(ITAE) are used as the objective functions for the GA optimization. Computer simulation results implemented under MATLAB-Simulink environment indicate that the GA is able to optimize the three PI controllers gain simultaneously and able to satisfy design specifications for PMSM simplified vector control.

2. Dynamic modeling and simplified vector control of PMSM

2.1 Dynamic modeling of PMSM

The mathematical modeling of the PMSM in the synchronous rotating frame can be represented in dq model. Superscript r defines the parameter in synchronous rotating frame. The stator voltage equations in the synchronous rotating frame can be carried out as follows[6)]:

$$v_{ds}^r = R_s i_{ds}^r + L_d \frac{d}{dt} i_{ds}^r - \omega_r L_q i_{qs}^r \tag{1}$$

$$v_{qs}^r = R_s i_{qs}^r + L_q \frac{d}{dt} i_{qs}^r + \omega_r L_d i_{ds}^r + \omega_r \lambda_m \tag{2}$$

where v_{ds}^r, v_{qs}^r, i_{ds}^r, and i_{qs}^r are the stator voltages and currents. R_s, L_d, and L_q are the stator resistance and inductance in direct axis and quadrature axis. ω_r and λ_m represent rotor angular speed and flux linkage generated by the rotor permanent magnet respectively.

The instantaneous electromagnetic torque T_e is given as equation (3), and it is finally derived as equation (4) considering that the direct axis current is set to be zero in PMSM.

$$T_e = \frac{3}{2}\frac{P}{2}\left\{\lambda_m i_{qs}^r + \left(L_d - L_q\right) i_{ds}^r i_{qs}^r\right\} \tag{3}$$

$$T_e = \frac{3}{2}\frac{P}{2}\lambda_m i_{qs}^r \tag{4}$$

The relation between inertia and motor speed is:

$$T_e = J_m\left(\frac{2}{P}\right)\frac{d}{dt}\omega_r + \beta_m\left(\frac{2}{P}\right)\omega_r + T_L \tag{5}$$

where J_m, β_m, P, and T_L are motor inertia, friction coefficient, the number of pole, and load torque respectively.

2.2 Simplified vector control of PMSM

In FOC, PMSM is supplied by three phase ac voltage(abc-phase) which will be transformed into two phase ac voltage($\alpha\beta$-phase) by the usage of Clarke transformation matrix. Park transformation is needed to transform two phase ac voltage($\alpha\beta$-phase) into 2 phase dc voltage (dq-phase). In FOC, not only used two transformation processes, but also applied the inverse from both transformation for the main control and feedback process. The transformation process is massive and takes a lot of memory in the computing process.

In simplified vector control(SVC), the coordinate transformation is remarkably reduced. The SVC concept can be derived from both inverse Clarke and Park transformations combination which is shown on equation (6) and reduced into equation (7) when i_{ds}^{r} is set to be zero[7].

$$\begin{bmatrix} a \\ b \\ c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta_r & -\sin\theta_r \\ \cos\left(\theta_r - \frac{2\pi}{3}\right) & -\sin\left(\theta_r - \frac{2\pi}{3}\right) \\ \cos\left(\theta_r - \frac{4\pi}{3}\right) & -\sin\left(\theta_r - \frac{4\pi}{3}\right) \end{bmatrix} \begin{bmatrix} d \\ q \end{bmatrix} \quad (6)$$

$$\begin{bmatrix} a \\ b \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} -\sin\theta_r \\ -\sin\left(\theta_r - \frac{2\pi}{3}\right) \end{bmatrix} [q] \quad (7)$$

Where θ_r is the rotor angular position.

Fig. 1 shows the PMSM simplified vector control block diagram. The PI controller gain is tuned by using GA.

3. GA and design of PI controllers

3.1 Genetic algorithm

Basically, GA has three main operators: selection, crossover, and mutation. The application of these three operators allows the algorithm to create new individuals which may be better than their parents. This algorithm is repeated for many generations until acquire individuals that represent the optimal solution of the given problems.

Types of selection operator are roulette, tournament, top percent, and best selection. Crossover occurs during evolution according to a user-definable crossover probability, which usually modeled as a fixed value. Mutation occurs during evolution according to a certain mutation probability. Although the mutation operator is the only mechanism for directly generating new schema, the mutation probability should generally be set to a fairly low value. The following is the general types of mutation: flip bit, boundary, non-uniform, uniform, and Gaussian.

3.2 Design of PI controllers by genetic algorithm

GA optimization technique is proposed in this paper to find optimal gains for three PI controllers which are applied into the PMSM simplified vector control. The individuals are the parameter gains of three PI controllers those are selected in certain interval number. This group of individuals is called a population. Each individual will be processed into the controllers and the response will be checked from the objective function fitness value. The gains(individuals) are updated by GA three main operators for each generation until

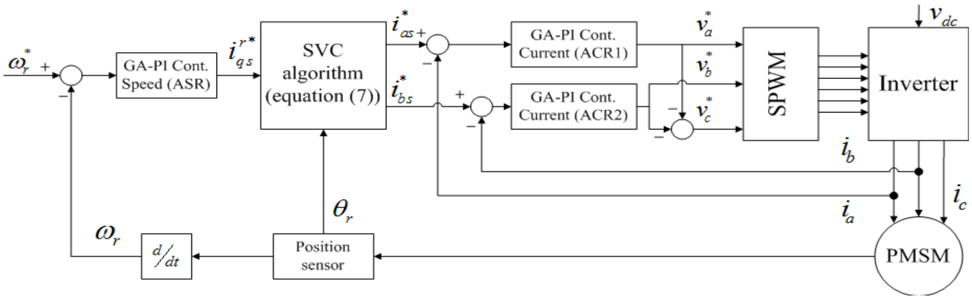


Fig. 1 Block diagram of simplified vector control for PMSM with GA-PI controller

reach optimal value from the objective function. IAE, ITAE, and ISE are used as the objective function for the GA optimization and those mathematical representations are described in equation (8) to equation (10).

$$IAE = \int_0^T |r(t) - y(t)| dt \tag{8}$$

$$ITAE = \int_0^T t.|r(t) - y(t)| dt \tag{9}$$

$$ISE = \int_0^T [r(t) - y(t)]^2 dt \tag{10}$$

Where $r(t)$ and $y(t)$ are reference input, and measured variable. The operation of PI controllers tuned by using GA is explained as following steps:

Initialize a population of K_p and K_i for three controllers. Define the objective function shown in equation (8) to equation (10) in the GA program. Population size is decided by the designer.

Set the initial population as the first generation. In the end of the first generation, select the individuals which have minimum fitness value of the objective function and make this individual as the parents for next generations. The roulette wheel method is used for the selection method in this step which expressed in equation (11).

$$p_i = \frac{F_i}{\left(\sum_{j=1}^{n} F_j\right)} \tag{11}$$

Where p_i is the probability of the individual i being selected. F_i is the fitness value for the individual i. n is population size. F_j is the total fitness value from the population.

Reproduction is applied to the next step. Crossover and mutation are applied in the reproduction process.

a. Crossover is the process of finding solutions of individuals to the objective function. Arithmetic crossover is used in the process and expressed in equation (12).

$$o_i = \alpha P_i + (1 + \alpha) P_{i+1} \tag{12}$$

Where o_i is offspring number i. P_i is parent number i. α is the crossover probability $(0 \le \alpha \le 1)$.

b. Mutation takes a secondary role in reproduction. Flip bit mutation is used in this process. The mutation operator simply inverts the value of the chosen gene.

The process is repeated until reach maximum generation or the GA find the optimal gain from the optimal fitness value.

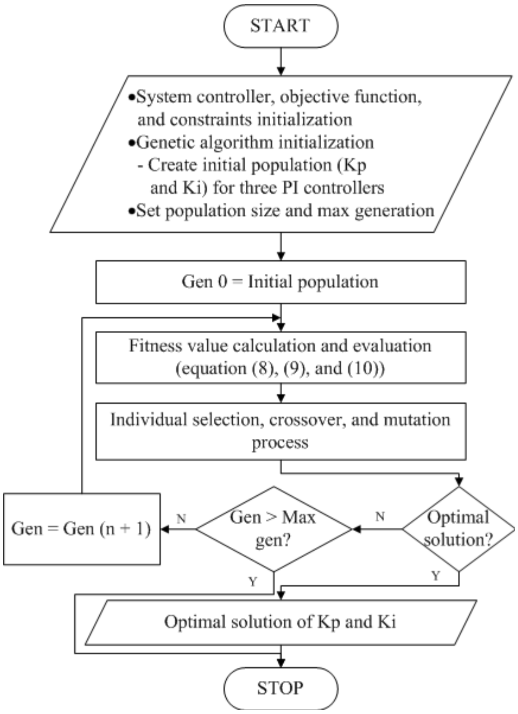


Fig. 2 Flowchart of PI gain tuned by GA

Fig. 2 shows the flowchart of the PI controllers tuned by GA technique. 100 generations are set as the maximum generation parameter for the GA.

Different population sizes are chosen in the process and analyzed to investigate its adequate size that generates good result based on the minimization of the objective function. Table 1 shows the detail parameters of the GA that used in the optimization process. The PMSM parameters and design specifications of the PMSM simplified vector control are described on Table 2 and Table 3 respectively. These design requirements are set as the constraints and processed simultaneously in the GA program.

Table 1 Parameters of genetic algorithm

Parameter	Value
Number of optimization parameter	6
Population size	20, 40, 60, 80
Selection method	Roulette wheel selection
Crossover method	Arithmetic crossover
Crossover probability	0.8
Mutation method	Flip bit mutation
Mutation probability	0.01
Number of constraint	4
Maximum generation	100

Table 2 Parameters of PMSM for simulation

Parameter (symbol)	Value (unit)
Rated power	1.1 (kW)
Rated torque	3 (N.m)
Rated speed (n)	3000 (rpm)
Stator resistance (R_s)	2.875 (Ω)
Stator d, q inductance (L_d, L_q)	8.5e-3 (H)
Flux linkage (λ_m)	0.175 (Wb)
Moment of inertia (J_m)	0.8e-3 (kg.m^2)
Friction coefficient (β_m)	0.001 (N.m.s/rad)
Number of pole (P)	4

Table 3 Design specifications of the system

Specification	Value
Percent overshoot (po)	< 1%
Rise time (t_r)	< 0.05s
Settling time (t_s)	< 0.06s
Error at 0.5s ($e_{0.5s}\%$)	< 1%

4. Simulation and results

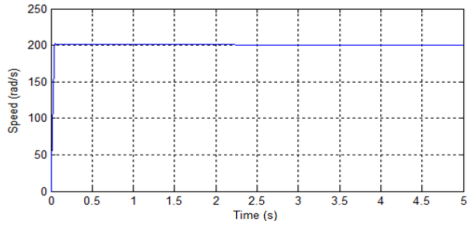
GA optimization for PMSM simplified vector control is simulated and analyzed in this chapter. Various population sizes are applied in the GA

Table 4 Comparisons of dynamic response characteristics according to population size variations

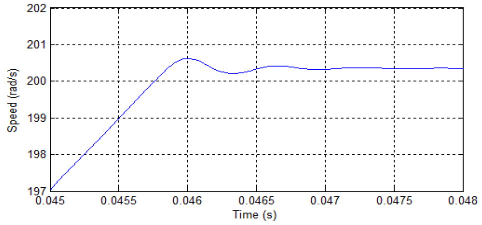
Error criterion	Population size	$po(\%)$	t_r(s)	t_s(s)	$e_{0.5s}(\%)$
IAE	20	0.2743	0.0334	0.041	0.9751
	40	0.5572	0.0369	0.0454	1.1246
	60	0.3341	0.0385	0.0475	0.8538
	80	0.3341	0.0385	0.0475	0.8663
ITAE	20	0.2519	0.0336	0.0413	0.8081
	40	0.3487	0.0343	0.0421	0.883
	60	0.28	0.364	0.0447	0.7347
	80	0.3023	0.0358	0.044	0.7827
ISE	20	0.4672	0.033	0.0406	0.9767
	40	0.5247	0.0348	0.0428	1.0796
	60	0.3526	0.0347	0.0427	0.8836
	80	0.4539	0.035	0.043	1.004

tuning technique to find out its appropriate size that generates good gains which have optimal performance on the system. System performance is analyzed from the speed response of the system.

Simulation run-time is 5s and 1N.m load torque is applied to the system. The reference speed is set as 200rad/s. In the simulation process, the controllers and PMSM motor are assumed in ideal conditions without disturbances and uncertainties. Table 4 shows the dynamic response characteristic comparisons from several population size variations.



(a) Speed response during 5 seconds



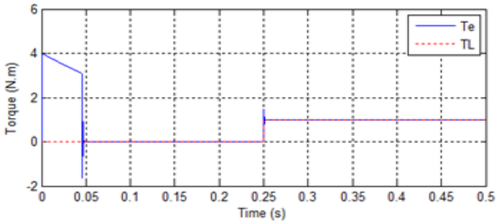
(b) Magnification of the transient speed response

Fig. 3 Simulated speed response (ω_r)

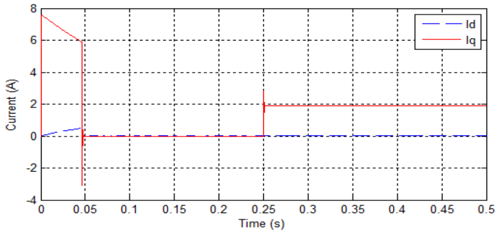
From Table 4, generally, almost all dynamic response characteristic of the system tuned by GA tuning technique was satisfying the design specifications of the system. However, the optimization results for IAE with population size of 40, ISE with population size of 40, and ISE with population size of 80 were unsatisfying the specifications. GA with ITAE as the objective function and with the population size of 60 was given the best result compare with the other population size. This GA results give smallest percent overshoot and error at 0.5s. The dynamic response of the system tuned by GA with ITAE as the objective function and with the population size of 60 is represented hereafter and the PI gain optimization result is shown in Table 5.

Table 5 Optimization results of PI gain for ITAE with population size 60

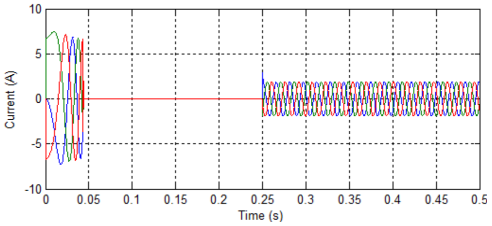
Gain	Controller		
	ASR	ACR 1	ACR 2
K_p	47.32	39.45	39.44
K_i	19.73	29.37	37.73



(a) Torque response



(b) Current response in dq coordinate



(c) Current response in abc coordinate

Fig. 4 Simulation results of torque and current

Fig. 3 shows the speed response of the PMSM simplified vector control. Fig. 3(a) shows the speed performance is not having a steady-state error after 5s for the PMSM simplified vector control which applying PI controllers on the system. Fig. 3(b) is used to analyze the speed response characteristic in transient time. From Fig. 3(b), it is clear that the speed response was following the reference with 0.0447s settling time. The controller was able to keep the speed in constant even though 1N.m load torque was applied at 0.25s. It is found that the speed response of the system which used GA-PI controller has small error(0.73%) in 0.5s and able to obtain quick and accurate speed response.

Fig. 4(a) shows the torque response of the PMSM simplified vector control when the speed reference was given as 200rad/s. From the figure it can be explained that the motor torque was giving a good response. The motor starts under no load torque and 1N.m load torque applied at 0.25s afterwards. The response shows that the electromagnetic torque of the PMSM can follow the 1N.m load torque precisely. Fig. 4(b) shows the dq current responses of the system. It is clear that the current was giving a good result. The current controller was able to make the d current component zero condition and the q current component stepwise increase to cope with load torque.

From the simulation results, the GA technique was able to decide three PI controllers gain simultaneously. Furthermore, the PMSM simplified vector control with GA-PI controllers were giving good control performance and satisfying the design specification. The GA technique was making the gain decision simpler and more efficient without involving complex calculation.

5. Conclusion

In this paper, genetic algorithm technique was proposed to optimize the PI controller on PMSM simplified vector control. Three kinds of error criterion minimization: IAE, ISE, and ITAE were used as the objective function for the GA optimization. Based on the computer simulations, the GA technique was able to decide the three controllers gain simultaneously. Furthermore, the GA optimization which adopted ITAE as its objective function and with population size of 60 was given the best performance compared with other criterion. By using this GA technique, not only finding the optimal PI gain was simpler and more efficient, but also it can assure the system performance result was satisfying the design specifications. Moreover, simplified vector control on PMSM does not need to regulate the direct axis(d component) current. This makes simplified vector control on PMSM very useful for applications that need simple control structure and low cost performance.

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