

# Design of Speed and Current Controllers Based on Online Particle Swarm Optimization Method for IPMSM Drives

Zhengqiang SONG<sup>1</sup>, Huiling YANG<sup>1</sup>

<sup>1</sup>Yangzhou Polytechnic College, China

**Abstract.** In this paper, a novel online particle swarm optimization method is proposed to design speed and current controllers of vector controlled interior permanent magnet synchronous motor drives considering stator resistance variation. In the proposed drive system, the space vector modulation technique is employed to generate the switching signals for a two-level voltage-source inverter. The nonlinearity of the inverter is also taken into account due to the dead-time, threshold and voltage drop of the switching devices in order to simulate the system in the practical condition. Speed and PI current controller gains are optimized with PSO online, that means single iteration optimization computation can be completed within single sample time. In addition, the fitness function is changed according to the system dynamic and steady states. The proposed optimization algorithm is compared with conventional PI control method in the condition of step speed change and stator resistance variation, showing that the proposed online optimization method has better robustness and dynamic characteristics compared with conventional PI controller design.

Key words: PMSM, Online PSO, Parameters Variation

## 1 Introduction

Proportional-integral (PI) control technique has been widely used in high performance field orientation controlled IPMSM drives. However, fixed PI gains have to be designed based on a precise mathematical model of the drive for guaranteeing certain control performance. It is unavoidable that the uncertainties are caused by parametric variations such as flux linkage or stator resistance and unstructured dynamics in a practical IPMSM drives [1, 2].

Thus, to obtain a high dynamic performance for an IPMSM drive, current controllers should be optimized together with speed controller at the same time, because the current controller influences directly the drive dynamics.

There are numerous researches on the applications of computational intelligence techniques to controller parameters design for PMSM [3-4]. Among these, Particle Swarm Optimization [4], first introduced by Kennedy and Eberhart in 1995, is one of the modern heuristic algorithms. Because of its simplicity and computational efficiency, PSO has been widely used to solve a broad range of optimization problems, such as adaptive tuning of controller gains and parameters identification. However, there still exist some problems/limitations with this method on the optimization of controller gains. Firstly, the PSO optimization applications in designing controller gains for PMSM rely on offline precise calculations of responses of PMSM using mathematical model [3]. It

makes optimization effectiveness rely on the fixed PMSM model excessively. Secondly, the online PSO for PMSM controller optimization, however only applied to the speed controller gains without considering current controller optimization. It is difficult to achieve high dynamics and robustness for PMSM drive system. Thirdly, much effort has been made on real-time PSO application in parameters identification, and results show effectiveness because parameters of PMSM are changed slowly [3]. This should be incorporated with the optimization process online.

In this paper, a discrete simulation model of IPMSM is set up firstly considering dead-time of inverter to present a real-time simulation condition. Then by measuring speed and current, an online PSO method is applied to design speed and current PI controller parameters for PMSM drives. To achieve good dynamic and steady states performance, different fitness function has been adopted. Numerical simulation test has been carried out with a step speed reference, while the stator resistance is varying. Simulation results show that this online optimization method is model free and has better robustness and faster optimization ability.

## 2 Real-Time Simulation Model Of Ipmsm Drive

The IPMSM model in the rotor reference frame is

$$\begin{bmatrix} u_{d(t)} \\ u_{q(t)} \end{bmatrix} = \begin{bmatrix} R_s & 0 \\ 0 & R_s \end{bmatrix} \begin{bmatrix} i_{d(t)} \\ i_{q(t)} \end{bmatrix} + \begin{bmatrix} p & -\omega_{re(t)} \\ \omega_{re(t)} & p \end{bmatrix} \begin{bmatrix} \phi_{d(t)} \\ \phi_{q(t)} \end{bmatrix} \quad (1)$$

<sup>a</sup> Corresponding author: songyang@alumni.sjtu.edu.cn

$$\phi_{d(t)} = L_d i_{d(t)} + \phi_f \quad (2)$$

$$\phi_{q(t)} = L_q i_{q(t)} \quad (3)$$

$$T_{em(t)} = \frac{3}{2} P_n \cdot (\phi_{d(t)} \cdot i_{q(t)} - \phi_{q(t)} \cdot i_{d(t)}) \quad (4)$$

$$T_{em(t)} - T_{L(t)} = \frac{J}{P_n} \frac{d\omega_{re(t)}}{dt} \quad (5)$$

where  $u_{d(t)}$ ,  $u_{q(t)}$ ,  $i_{d(t)}$ ,  $i_{q(t)}$ ,  $L_d$ ,  $L_q$ ,  $\phi_{d(t)}$  and  $\phi_{q(t)}$  are the stator voltages, stator currents, inductances and flux linkages on  $dq$ -axis respectively;  $\phi_f$  is permanent flux;  $p = \frac{d}{dt}$  is the differentiation operator;  $P_n$  is the

number of pole pair;  $\omega_{re(t)}$  is rotor velocity electrical;  $T_{em(t)}$  is generated torque;  $T_{L(t)}$  is load torque.

The  $d$ - and  $q$ -axis current controllers are PI whose transfer functions are  $k_{id}(1+\tau_{id}s)/s$  and  $k_{iq}(1+\tau_{iq}s)/s$ , respectively. The reference of  $q$ -axis current  $i_q^{ref}$  is provided by the speed controller ( $k_{s\_p} + k_{s\_i} \cdot \frac{1}{s}$ ). A low-

pass filter is applied to the measured speed and a rate limitation is applied to the speed reference signal. They are used to reduce the overshoot and settling associated with step commands, while retaining a fast disturbance rejection. The online PSO scheme is implemented with a S-Function. The input variables of the S-Function are references and feedback values of  $q$  axis current and rotor speed respectively, the output variables are gains of the  $q$  axis current and speed PI controllers respectively.

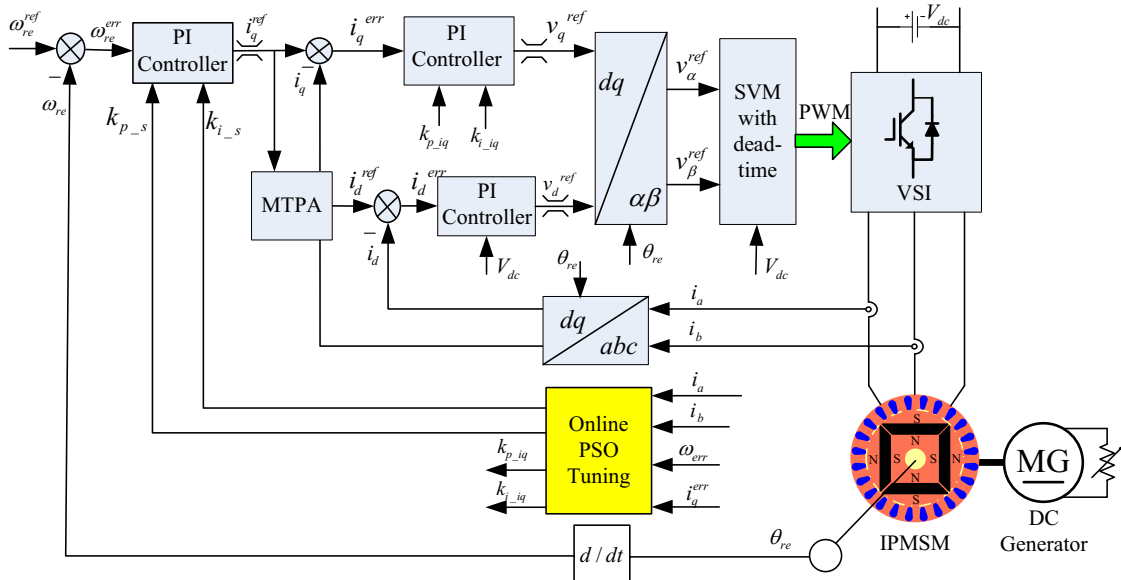


Fig.1. Block diagram of a vector-controlled PMSM drive based on PSO controller

### 3 Online PSO for Controller Gains Tuning

#### 3.1. Basic principle of the PSO algorithm

Particle swarm optimization algorithm is an evolutionary computation technique developed by Kennedy and Eberhart in 1995. It finds global optimum solution in search space through the interactions of individuals in a swarm of particles. Similar to other evolutionary algorithms, the PSO algorithm firstly produces initial swarm of particles in search space. Each particle represents a candidate solution to the problem and it has its own position  $X$  and velocity  $V$ . Each row in the position matrix  $X$  shows each particle's position, through which we can acquire the evaluation value of the particle. At each iteration, each particle memorizes and follows the tracks of its personal best ( $Pbest$ ) and the global best position ( $Gbest$ ) vectors to update the velocity matrix  $V$ .

Known these two best positions, particles can change velocities and positions using the following rules:

$$v_{j,g}^{(t+1)} = w \cdot v_{j,g}^{(t)} + c_1 \cdot r_1 \cdot (pbest_{j,g}^{(t)} - x_{j,g}^{(t)}) + c_2 \cdot r_2 \cdot (gbest_g^{(t)} - x_{j,g}^{(t)}) \quad (6)$$

$$X^{(t+1)} = X^{(t)} + V^{(t)} \quad (7)$$

where  $j=1, 2, \dots, m$ ;  $g=1, 2, \dots, n$ . The superscripts  $t$  and  $t+1$  denote the time index of the current and the next iterations respectively. The parameters  $c_1$  and  $c_2$  are called acceleration constant which adjust the maximum step of the particle flight towards  $Pbest$  and  $Gbest$  position. Usually, parameters  $c_1$  and  $c_2$  are equal to 2,  $r_1$  and  $r_2$  are uniformly distributed random numbers in the interval  $(0, 1)$ . Parameter  $w$  is inertia weight factor that usually decreases linearly from 0.9 to 0.4 in

according to (8) over the course of the run. In this way, the algorithm can easily escape from local optimal solution in the early iteration stage as well as speed the convergence in the later iteration stage, and increase the reliability of finding the global optimal solution.

$$w^{(t)} = w_{\max} - t \cdot (w_{\max} - w_{\min}) / \text{iter}_{\max} \quad (8)$$

where  $w_{\max}$  and  $w_{\min}$  are the maximum and minimum values of  $w$ , and  $\text{iter}_{\max}$  is the maximum iteration times.

In order to reduce the likelihood of particles leaving the search space, the value of each dimension of the velocity  $v_{j,g}^{(t)}$  is clamped to the interval  $[-v_g^{\max}, v_g^{\max}]$ . The value of  $v_g^{\max}$  is usually chosen to be

$$v_g^{\max} = k \cdot x_g^{\max}, \quad 0.1 \leq k \leq 0.5 \quad (9)$$

where  $x_g^{\max}$  is the upper bound of search region in the  $g$ -th dimension.

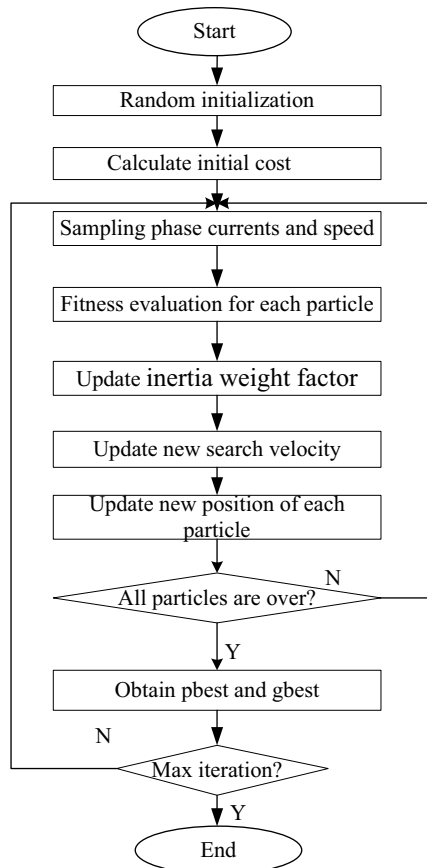


Fig.2 Online PSO flow frame within one sampling time

### 3.2 Definition of the Evaluation Function

To optimize the overall response of the motor drive, the fitness function is a weighted sum of several performance index based on measurements of the speed and currents outputs. It is shown in (10):

$$F(k_{p1}, k_{p2}, k_{i1}, k_{i2}) = \sum_{i=1}^3 (a_i \cdot f_i) \quad (10)$$

$$f_1 = (\omega_{re}(k) - \omega_{re}(k-1))^2 \quad (11)$$

$$f_2 = (\omega_{re}(k) - \omega_{re}^{ref})^2 \quad (12)$$

$$f_3 = ((i_a(k) - i_a^{ref}(k))^2 + (i_b(k) - i_b^{ref}(k))^2 + (i_c(k) - i_c^{ref}(k))^2) \quad (13)$$

and  $a_i$  represent positive weights, and  $f_i$  are three performance indices defined in the following:

- 1)  $f_1$ , speed transient response index
- 2)  $f_2$ , speed steady index
- 3)  $f_3$ , current reference oscillations for constant speed reference.

$\omega_{re}, i_a, i_b, i_c$  are speed and phase current measurement values, respectively, from IPMSM output;  $\omega_{re}^{ref}, i_a^{ref}, i_b^{ref}, i_c^{ref}$  are speed and phase current references; when IPMSM is in transient state,  $a_i = [0.6, 0.1, 0.3]$ , when IPMSM nearly reach steady state,  $a_i = [0.1, 0.6, 0.3]$ .

## 4 Simulation Results

The block diagram of the drive system used for the simulation is shown in Fig.1 The flow chart of online PSO of controllers is shown in Fig. 2. The simulation model includes the encoder, sensor and control input nonlinearities. The controllers are in discrete time with the Euler method, to make the simulation to mimic the real experiment closely. The controller sampling time is chosen as 100  $\mu\text{sec}$ , which is the same as the controller sampling time of real experiment.

IPMSM parameters are presented in TABLE I, and resistance can be changed from 5.8 to 7.8 for testing the robustness of proposed method. Initial swarm size of particles is 30, and each particle has four variables ( $k_{p_{iq}}, k_{i_{iq}}, k_{p_s}, k_{i_s}$ ) representing its position vectors in search space. After 30 iterations, the results of  $G_{best}$  would be updated as optimized outputs.

TABLE I: PARAMETERS of IPMSM

Phase resistance, $R_s$	5.8-7.8 $\Omega$
d-axis inductance $L_d$	0.0448H
q-axis inductance $L_q$	0.1027H
Rated voltage	230V
Moment of inertia	0.001329 $\text{kg} \cdot \text{m}^2$
Rated speed	4000 $\text{rpm}$
Permanent magnet flux	0.533 $\text{wb}$
Pole pair	2

Fig.3 shows the change of fitness value of PSO for IPMSM drives and its decline rate is very fast. In order to test the proposed method in this paper, two

different controllers were applied on IPMSM drive, and comparison results between conventional PI controllers and online PSO-PI controllers for IPMSM drives are presented in Fig.4 and Fig.5. Where (a) is  $i_d$  current response curve; (b) is  $i_q$  current response curve; (c) is speed response curve; (d) is torque response curve; (e) are three phase current curves. These results clearly show the effectiveness of the PSO method proposed in this paper.

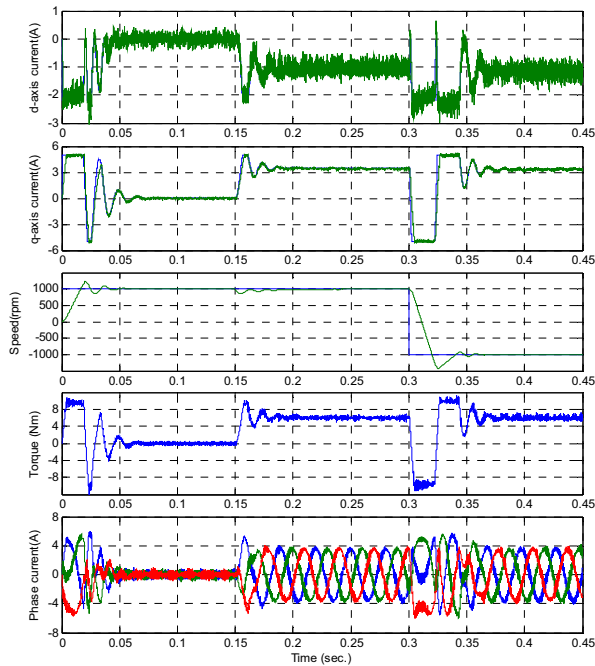


Fig.4 Results of IPMSM drive with conventional PI controllers

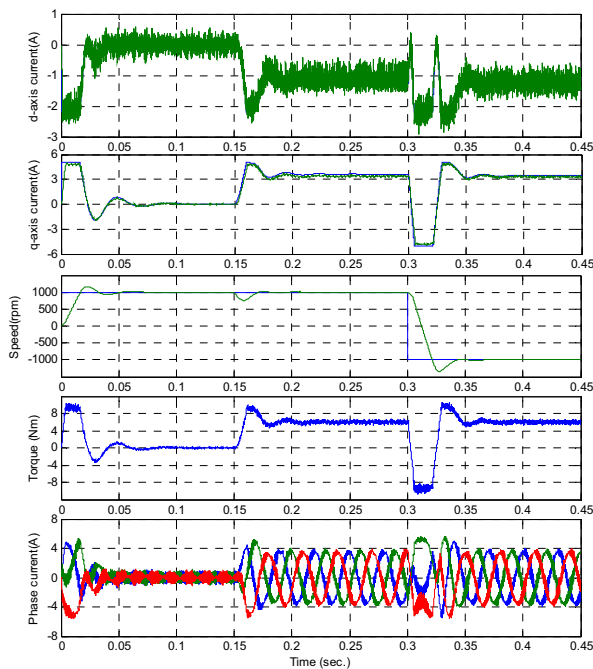


Fig.5 Results of IPMSM drive with online PSO-PI controllers

## 5 Conclusion

In this paper, a novel online particle swarm optimization method is proposed to design speed and current PI controllers of vector controlled interior permanent magnet synchronous motor drives, taking into account stator resistance variation. The speed and current controllers are optimized online as PSO update is carried out in each sampling cycle for the position and velocity of particle which represent the performance of the controllers. Furthermore, optimization process does not rely on the preciseness of IPMSM model excessively, because when stator resistance changes within 15%, IPMSM drive system still has a good dynamic and robustness. In addition, the dynamic and steady-state performance of the drive system has been improved by optimization of speed and current controller at the same time.

## References

1. Shin-Hung Chang, Shin-Hung Chang, "Self-tuning gains of PI controllers for current control in PMSM," *IEEE 5th Conference on Industrial Electronics and Applications*, pp.1282-1286, (2010)
2. Muhammed Fazlur Rahman, Md. Enamul Haque, "Problems associated with the direct torque control of an Interior permanent-magnet synchronous motor drive and their remedies," *IEEE Trans. on industrial electronics*, vol.51, no. 4, pp. 799-808, 2004.
3. Wenxin Liu, Li Liu, Il-Yop Chung, David A. Cartes, "Real-time particle swarm optimization based parameter identification applied to permanent magnet synchronous machine," *Elsevier, Applied Soft Computing*, pp. 2556–2564, 2011.
4. Kennedy J, Eberhart RC. "Particle swarm optimization," in *Proceedings of International Conference on Neural Network (ICNN)*, Vol. 4, pp. 1942–1948 Perth, Australia 1995.