Fuzzy PID Controller Using Adaptive Weighted PSO for Permanent Magnet Synchronous Motor Drives

Ming Yang, Xingcheng Wang
School of Information Science and Technology, Dalian Maritime University
Dalian, China
E-mail: m.y_dl@hotmail.com

Abstract—A optimization method of self-tuning fuzzy PID controller for permanent magnet synchronous motor (PMSM) is presented in this paper. The proposed controller is developed for speed control of the PMSM using in vehicle. The design of self-tuning fuzzy PID controller is a complex task due to a large number of parameters and rule bases. In this paper, the parameters of membership functions and rule bases of fuzzy logic controller are optimized by adaptive weighted particle swarm optimization (PSO), which is an efficient and simple tool for multi-objective and multi-dimensional problem. The proposed controller is verified by simulation, the result showing robust and good dynamic response.

Keywords- self-tuning fuzzy PID controller; adaptive weighted particle swarm optimization; permanent magnet synchronous motor; particle swarm optimization; fuzzy controller

I. INTRODUCTION

The modern power electronics, magnetic material technology developing, permanent magnet synchronous motor (PMSM) drives have been used widely in traction drives, electrically powered air compressor drives in vehicles, high torque servomotor, and hydraulic pump drives, because of its high torque to current ratio, large power to weight ratio, high efficiency, high power factor and robustness [1]. In order to achieve high performance, the vector control of the PMSM has been employed, and applications of advanced control theories and techniques have further improved the performance of PMSM drives.

Self-tuning fuzzy PID controller has the advantages of fuzzy logic and proportional-integral-derivative (PID) controllers, which is shown to be a versatile for control of nonlinear system with good accuracy and fast dynamic response. The controller is also able to tolerate many poor selections or inadequate implementations of the controller which would make most conventional controllers unstable, while design of the controller is not an easy task for engineers, because of a large number of parameters and rule bases [2].

Particle Swarm Optimization (PSO) is presented by Kennedy in 1995, which is an evolutionary computation technique [4]. The algorithm is derived from the social psychological theory and has been shown robust for solving problems featuring nonlinearity, multiple optima, and high dimensionality. The algorithm is used in optimization of controller parameters, and the scaling factors of fuzzy logic controller are optimized by PSO in [5]. Adaptive weighted PSO improves the searching capability of PSO via the adaptive inertia weight and acceleration factor [7]. In this paper, the parameters of membership functions and rule bases of the fuzzy logic controller (FLC) are optimized by adaptive weighted PSO.

II. MODEL OF PMSM DRIVE

The mathematical model of PMSM drive can be represented by the following equations in a synchronously rotating rotator d-q reference frame as [8, 9]

\[
\begin{align*}
V_d &= \left[ R_s + pL_d - n_p \omega_r L_q \right] i_d + \left[ 0 \right] \\
V_q &= \left[ n_p \omega_p L_d \right] i_q + \left[ n_p \omega_r \psi_f \right]
\end{align*}
\]

(1)

\[
T_e = T_L + J_m p \omega_r + B_m \omega_r
\]

(2)

\[
T_e = \frac{3n_p}{2} \left[ \psi_f i_q + (L_d - L_q)i_d i_q \right]
\]

(3)

where \( v_d \) and \( v_q \) are the d- and q-axes stator voltages, respectively; \( i_d \) and \( i_q \) are the d- and q-axes currents, respectively; \( R_{s} \) is the resistance per phase; \( L_d \) and \( L_q \) are the d- and q-axes stator inductances, respectively; \( T_{e} \) and \( T_{L} \) are the electromagnetic and load torques, respectively; \( J_{m} \) is the moment of inertia of the motor; \( B_{m} \) is the friction coefficient of the motor; \( n_{p} \) is the number of pole pairs; \( \omega_{r} \) is the rotor mechanical speed; \( p \) is the differential operator \( (d/dt) \); and \( \psi_{f} \) is the permanent magnet flux linkage. The parameters of PMSM drive can be obtained by parameter identification.

III. CONTROL PRINCIPLE

The self-tuning fuzzy PID controller with vector control is used to control the PMSM drive in this paper, and the structure of PMSM drive is shown as Fig. 1. The \( \omega_{r} \) and \( \omega_{m} \) are the setting rotor mechanical speed and actual speed, respectively; \( i_q \) and \( i_d \) are the q- and d-axes reference currents, respectively; \( i_{q*} \), \( i_{d*} \), and \( i_{r*} \) are A, B, and C phases reference currents, respectively. Hysteresis current controller, which is an instantaneous feedback current controller, generates the gate pulses, according the error of three-phase reference currents and three-phase actual currents. The \( i_q \) is given by self-tuning fuzzy PID controller, and at same time,
\( i_d^* \) is zero. The actual currents continually track the reference currents with the current controller, and the equations of PMSM drive are simplified as following equations

\[
p_{i_d} = \frac{1}{Lq} \left( v_i - R_i q - n_p \alpha_i \psi_f \right)
\]

\( \psi \) is zero. The actual currents continually track the reference currents with the current controller, and the equations of PMSM drive are simplified as following equations

\[
v_d = -n_p \alpha_i L_i q
\]

\[
T_e = T_L + J_m p \omega + B_m \omega
\]

\[
T_e = \frac{3n_p}{2} (\psi_f i_q)
\]

To improve the reaching capability of PSO algorithm, adaptive weighted PSO has been proposed. The acceleration factor \( \alpha \) in (8) is represented as follows

\[
\alpha = \alpha_0 + \frac{t}{N_f}
\]

where \( N_f \) denotes the number of iterations, \( t \) represents the current generation, and suggested range for \( \alpha_0 \) is [0.5,1]. The inertia weight is changed at every generation via the following formula

\[
w = w_0 + r_j (1 - w_0)
\]

where \( w_0 \) is positive constant in [0,1], and the suggested range for \( w_0 \) is [0.5,1]; \( r_j \) is a random function in the range of [0,1].

V.  OPTIMIZATION OF CONTROLLERE

A. SELF-TUNING FUZZY PID CONTROLLER

The field of fuzzy controller applications has expanded including many industrial control applications, and significant research work has supported the development of fuzzy controllers, since Mandani introduced the controller using compositional rule of inference that has been proposed by Zedeh. The self-tuning PID controller, as an important type of fuzzy PID controller, is proposed [10]. The structure of the controller is shown as Fig. 2. Self-tuning fuzzy controller consists of general PID and parameter self-tuning fuzzy inference part. Error \( e \) and error change \( e_c \) are taken as controller inputs. FLC is utilized for tuning of the parameters of general PID at any time according to \( e \), \( e_c \). General PID controller can be described as follows

\[
u = K_p e + K_i \int e dt + K_d e_c
\]

where \( e \), and \( e_c \) denote system error, error change respectively. \( K_p \), \( K_i \), \( K_d \) are proportion coefficient, integral coefficient and differential coefficient respectively. The increased \( K_p \) enhance the response speed of system, but the over much of \( K_p \) will result in instability of the closed system; \( K_i \) can remove steady error of system; \( K_d \) can improve dynamic performance of system.

B.  OPTIZATION PRINCIPLE

The performance of self-tuning fuzzy PID controller is determined by FLC. Adjusting the membership functions
and rule bases of fuzzy controller is the key task of controller design. The optimal FLC makes $K_p$, $K_i$, $K_d$ of the general PID controller attain appropriate values, and the system gains robust, fast response, and fine dynamic performance. The optimization of membership functions and rule bases of FLC using adaptive weighted PSO is represented in this paper. The input variables error, error change are defined as $e_1$, $e_2$, respectively, and the output $K_p$, $K_i$, $K_d$ of PID controller are defined as $\{K_p\}$, $\{K_i\}$, $\{K_d\}$, respectively. The membership functions for error are shown as fig. 3.

![Fig. 3. Membership functions for error](image)

The universe of discourse for $e$ is the range of $[-1, 1]$, and $f(x(1))$, $f(x(1)+x(2))$, $f(x(1)+x(2)+x(3))$ are the parameters of the membership functions. The parameters of membership functions for $\{e_1\}$, $\{K_p\}$, $\{K_i\}$, $\{K_d\}$ is defined as follows

$$f(x(j-2)), f(x(j-1)+x(j-2)), f(x(j-2)+x(j-1)+x(j))$$

where $j = 1, 2, 3, 4, 5$ represent parameters for $\{e_1\}$, $\{K_p\}$, $\{K_i\}$, and $\{K_d\}$, respectively. The function $f(x)$ is defined as follows

$$f(x) = \begin{cases} x_1(3j) + x_2(3j-1) + x_3(3j-2) \\ x_1(3j-2), x_2(3j-1), x_3(3j) \in [0, 1] \end{cases}$$

The function $f(x)$ makes parameters of membership functions and the universe of discourse for the input and output in the range of $[-1, 1]$.

The parameters $K_p$, $K_i$, and $K_d$ are determined by the rules as follows

Rule k: if $e$ is $A_k$ and $e_1$ is $B_l$, then $K_p$ is $x_{(3k+13)}$, $K_i$ is $x_{(3k+14)}$, and $K_d$ is $x_{(3k+15)}$

$$k = 1, 2, \cdots, m$$

where $m$ is the number of fuzzy rules, and for the controller, the number of fuzzy rules is 49: $A_k$, $B_l$, $x_{(3k+13)}$, $x_{(3k+14)}$, and $x_{(3k+15)}$ are the $k$th fuzzy sets of the input and output variables used in fuzzy rules. The fuzzy term set is $\{\text{NB}, \text{NM}, \text{NS}, \text{ZO}, \text{PS}, \text{PM}, \text{PB}\}$. NB, NM NS, ZO, PS, PM, PB can be represented as 1, 2, 3, 4, 5, 6, 7, respectively, so $x_{(3k+13)}$, $x_{(3k+14)}$, and $x_{(3k+15)}$ are integral numbers in the range of $[1, 7]$.

In adaptive weighted PSO, $x_{(3j)}$, $x_{(3j-1)}$, and $x_{(3j-2)}$ are the previous 15 dimensions of particles, and $x_{(3k+13)}$, $x_{(3k+14)}$, $x_{(3k+15)}$ are the following 147 dimensions of particles. The particles consist of the two parts which represent parameters of membership functions and rules.

C. Optimization Procedure

The swarm has 162-dimension particles, and the following 147 dimensions of $x_i$ are the integral numbers in the range of $[1, 7]$. The procedure of optimization using adaptive weighted PSO is described as

- Initialize the particles.
- Generate the FLC using (13-15).
- Evaluate the fitness for each particle. The integral of time multiplied by absolute error (ITAE) is used as fitness function, and the ITAE can be defined as

$$\int_0^T |e(t)| dt$$

- Update $x_{pbest}$ and $x_{gbest}$

$$x_{pbest} = x_i \quad \text{If } f_i < f_{pbest}$$

$$x_{gbest} = x_i \quad \text{If } f_i < f_{gbest}$$

- Generate $r_1$, $r_2$, and $a$, $w$ using (10) (11)
- Update velocity $v_i$ and position $x_i$ using (8) (9).
- If attain the maximum iteration, exit, and otherwise go to iterate.

VI. SIMULATION RESULTS

Model of PMSM drive is built, which is described as fig.1. The similar structure is used in actual system for vehicle, and nominal parameters of the simulated PMSM are listed in Table I.

<table>
<thead>
<tr>
<th>PMSM parameters</th>
<th>Nominal values (unit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power</td>
<td>40 (kW)</td>
</tr>
<tr>
<td>Rated voltage</td>
<td>380 (V)</td>
</tr>
<tr>
<td>Rated current</td>
<td>70 (A)</td>
</tr>
<tr>
<td>Pole pairs P</td>
<td>4</td>
</tr>
<tr>
<td>d-axis inductance $L_d$</td>
<td>1.25 (mH)</td>
</tr>
<tr>
<td>q-axis inductance $L_q$</td>
<td>1.25 (mH)</td>
</tr>
<tr>
<td>Stator resistance $R_s$</td>
<td>0.02 (Ω)</td>
</tr>
<tr>
<td>Motor inertia $J_m$</td>
<td>0.089 (kg. m²)</td>
</tr>
<tr>
<td>Friction coefficient $B_m$</td>
<td>0.005 (N.m.sec/rad)</td>
</tr>
<tr>
<td>Magnetic flux constant $\psi_f$</td>
<td>0.381 (V/sec/rad)</td>
</tr>
</tbody>
</table>

In adaptive weighted PSO, the number of iteration is 50, and the size of population is 20. Fig. 4 shows the speed response of self-tuning fuzzy PID controller using the proposed optimization algorithm and without optimization for a step change under a step load torque of 6 Nm. In the figure, it can be seen that the performance of optimal controller is better than the performance of controller without
optimization. Fig. 5 and Fig.6 show optimal electromagnetic torque and optimal stator phase current, respectively.

![Graph](image1)

**Fig. 4.** Speed response of self-tuning fuzzy PID controller using adaptive weighted PSO and without optimization for a step change in load torque

![Graph](image2)

**Fig. 5.** Electromagnetic torque of self-tuning fuzzy PID controller using adaptive weighted PSO for a step change in load torque

![Graph](image3)

**Fig. 6.** Phase current of self-tuning fuzzy PID controller using adaptive weighted PSO for a step in load torque

VII. CONCLUSION

Optimization of self-tuning fuzzy PID controller based on adaptive weighted PSO is proposed for speed controller of PMSM, in this paper. The algorithm has searched parameters of membership functions and rules for the system. The simulation results prove the controller using the proposed algorithm owns high performance.

REFERENCES


