

Performance Control of PMSM Drives Using a Self-tuning PID

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Abstract-In this paper a self-tuning PID controller based on generalized minimum variance method is applied to the permanent-magnet synchronous motors (PMSM) speed control system. The proposed method has approximate minimum variance properties, and can guarantee the stability of the close-loop system by pole-assignment, which is based on the discrete-time mechanical equation and dynamic model of the q-axis current control loop of the PMSM drive system. The complete vector control scheme using the self-tuning PID is implemented in real-time based on a digital signal processor (DSP) for a surface PMSM. Comparing conventional PID regulator, the proposed self-tuning regulator makes the speed control of the PMSM drive more robustness and high performance. Experiments are carried out at low and high speeds, results verified the efficacy of the proposed method.

I. INTRODUCTION

The PMSM have several advantages over the induction motors: high efficient, high power density, high performance in wide range speed and so on. PMSM drive with the vector control has been widely and successfully applied to servo tasks. However, vector control PMSM drive with conventional controllers has difficulty dealing with dynamic speed tracking, parameter variations and load vibration. With the conventional PID regulator, the parameters variation and nonlinearities of the PMSM deteriorate control performance in dynamic process, cause torque and speed pulsation, which limits the PMSM drive as a high precision servo.

Many auto-tuning control methods have been reported to solve above mention problem. In this paper a self-tuning PID controller is proposed, which is based on generalized minimum variance and pole assignment [1]-[4]. The control scheme is suitable to be used in systems with unknown or slowly time-varying parameters, such as PMSM stator resistance, load initial and so on.

This paper presents design method of the self-tuning PID regulator, the regulator is designed to achieve zero steady state error, minimum overshoot and minimum settling time. This method can guarantee both robust control and stability of close-loop system at the same time, which is the special feature over existing control strategies for PMSM drives. To verify the design of the self-tuning PID controller, a experimental system is implemented. The dynamic performance has been studied under load changes and parameter variations of the PMSM drive system. The

experimental results are provided to demonstrate the effectiveness of the proposed method.

II. MATHEMATIC MODEL OF A PMSM DRIVE

The voltage equation of the nonlinear dynamic d-q model of the PMSM at the rotor-flux rotating reference frame is described as follows:

$$\left. \begin{aligned} u_d &= Ri_d + L_d \frac{di_d}{dt} - \omega L_q i_q \\ u_q &= Ri_q + L_q \frac{di_q}{dt} + \omega L_d i_d + \omega \psi_r \end{aligned} \right\} \quad (1)$$

The electro-mechanical torque is

$$T_e = P[\psi_r i_q + (L_d - L_q) i_d i_q] \quad (2)$$

For a surface PMSM, $L_d = L_q$, rotor magnetic linkage is a constant, so (2) can be rewritten as:

$$T_e = k_T i_q \quad (3)$$

The mechanical equation of the PMSM drive is described as:

$$J \frac{d\omega}{dt} = P(T_e - T_L - \beta \frac{\omega}{P}) \quad (4)$$

where u_d , u_q , i_d , i_q are the stator voltages and currents, respectively. R is the stator resistance. L_d and L_q are the d-q axis stator inductances, respectively. ω , J and β are the electrical rotor speed, the inertia and the friction coefficient of the motor, respectively. ψ_r is the rotor flux. T_e and T_L are the electromagnetic torque and the load torque, respectively. k_T is the torque coefficient. P is the pole pairs.

Using rotor magnetic field orientation control strategy and voltage feed-forward decoupling method, we can get a complete decoupling d-q axis currents control. As shown in Fig.1, the electro-mechanical torque can be controlled directly by q-axis current reference according to (3).

For a typical digital signal processor based PWM inverter, the time delay of current control loop equal one sampling interval, the dynamic process of q-axis current loop can be described approximately in discrete-time form:

$$i_q(t) = q^{-1}[(1 + \frac{L_q}{RT_s}) + \frac{L_q}{RT_s} q^{-1}] i_{qref}(t) \quad (5)$$

where q^{-1} is the backward shift operator.

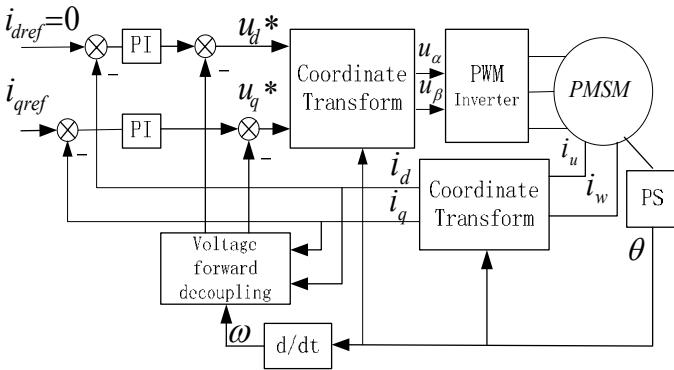


Fig.1. Current loops of PMSM drive

Rewrite (4) in discrete-time form:

$$(J + T_s \beta - Jq^{-1})\omega(t) = PT_s T_e(t) - PT_s T_L(t) \quad (6)$$

Substituting (3), (5) into (6), yields next equation:

$$\begin{aligned} & (J + T_s \lambda - Jq^{-1})\omega(t) \\ &= q^{-1}PT_s k_T [(1 + \frac{L_q}{RT_s}) + \frac{L_q}{RT_s}q^{-1}]i_{qref}(t) - PT_s T_L(t) \end{aligned} \quad (7)$$

(7) describes transfer function of PMSM drive using vector control in discrete-time.

III. GENERALIZED MINIMUM VARIANCE SELF-TUNING PID DESIGN

In this section the design procedures of the self-tuning PID controller based on generalized minimum variance are developed. For that we choose the rotating speed as a output signal $y(t)$, the q-axis current reference as a control signal $u(t)$, and the load with some coefficient as a uncorrelated random noise $\xi(t)$, (7) can be rewritten into a standard discrete form[5][6]:

$$A(q^{-1})y(t) = q^{-1}B(q^{-1})u(t) + C(q^{-1})\xi(t) \quad (8)$$

where $A(q^{-1}), B(q^{-1})$ and $C(q^{-1})$ is polynomials of the form:

$$\left. \begin{aligned} A(q^{-1}) &= 1 + a_1 q^{-1} + \dots + a_{n_a} q^{-n_a} \\ &\cong 1 + (\frac{-J}{J + T_s \beta})q^{-1} \\ B(q^{-1}) &= b_0 + b_1 q^{-1} + \dots + b_{n_b} q^{-n_b} \\ &\cong \frac{PT_s k_T (1 + \frac{L_q}{RT_s})}{J + T_s \beta} + \frac{PT_s k_T L_q}{RT_s (J + T_s \beta)} q^{-1} \\ C(q^{-1}) &= 1 + c_1 q^{-1} + \dots + c_{n_c} q^{-n_c} \cong 1 \end{aligned} \right\} \quad (9)$$

According to the generalized minimum variance method, we can construct a new output, form of which as below:

$$x(t) = \frac{\Gamma_n}{\Gamma_d} y(t) - \psi y_r(t-1) + \Lambda u(t-1) \quad (10)$$

Then we choose a cost function:

$$\begin{aligned} J &= E \{x^2(t+1)\} \\ &= E \left\{ \left[\frac{\Gamma_n}{\Gamma_d} y(t+1) - \psi y_r(t) + \Lambda u(t) \right]^2 \right\} \end{aligned} \quad (11)$$

The optimum control law minimizing the cost function is given by the following equation:

$$u(t) = \frac{C(q^{-1})\psi y_r(t) - E(q^{-1})y(t)/\Gamma_d}{D(q^{-1})B(q^{-1}) + C(q^{-1})\Lambda} \quad (12)$$

Where $D(q^{-1})$ and $E(q^{-1})$ are obtained by solving the following Diophantine equation:

$$\frac{C(q^{-1})\Gamma_n}{A(q^{-1})\Gamma_d} = D(q^{-1}) + \frac{q^{-1}E(q^{-1})}{A(q^{-1})\Gamma_d} \quad (13)$$

The control scheme of the speed loop is shown in Fig. 2. As shown in Fig.2, we will use the actual speed of PMSM and the q-axis current i_q to estimate parameters, which are needed in speed regulator. At the same time, we must guarantee stability of the control system, for that the characteristic equation of the close-loop can be written as below:

$$\Gamma_d \Lambda A(q^{-1}) + \Gamma_n B(q^{-1}) = 0 \quad (14)$$

By theory stability, parameters $\Gamma_d, \Gamma_n, \Lambda$ must be chosen to make all roots of the characteristic equation locate at left part of complex plane.

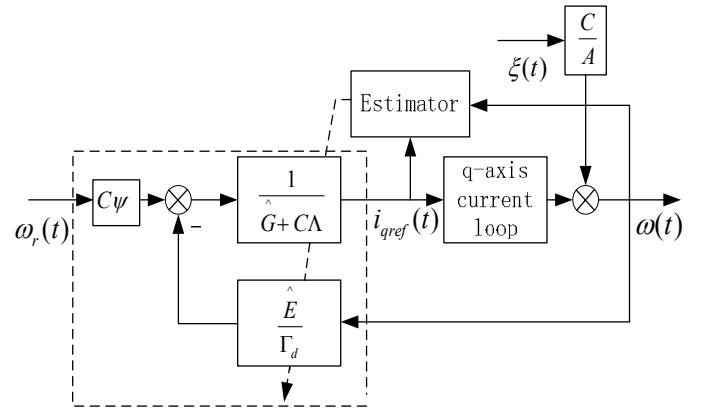


Fig.2. Speed loop based on generalized minimum variance method

To choose parameters $\Gamma_d, \Gamma_n, \Lambda$, another condition is to make the steady-state error of the output rotor speed minimum, which is described as[5]:

$$\begin{aligned}
e_s &= \lim_{\substack{t \rightarrow \infty \\ q \rightarrow 1}} [y(t) - y_r(t)] \\
&= \lim_{\substack{t \rightarrow \infty \\ q \rightarrow 1}} \left[\frac{q^{-1} \Gamma_d B(q^{-1}) \psi}{\Gamma_d \Lambda A(q^{-1}) + \Gamma_n B(q^{-1})} y_r(t) - y_r(t) \right] \quad (15) \\
&= \frac{\Gamma_d B(1) \psi - \Gamma_d \Lambda A(1) - \Gamma_n B(1)}{\Gamma_d \Lambda A(1) + \Gamma_n B(1)} y_r(\infty)
\end{aligned}$$

For a high performance servo system, the steady-state error of the rotating speed is desired to be zero:

$$\Gamma_d B(1) \psi - \Gamma_d \Lambda A(1) - \Gamma_n B(1) = 0 \quad (16)$$

In order to avoid the influence of the parameters variation, we will use the least square method to estimate the coefficients of the unknown polynomials in (12). For convenience we define next variables:

$$\left. \begin{array}{l} z(t) = \frac{\Gamma_n}{\Gamma_d} y(t) \\ v(t) = \frac{y(t)}{\Gamma_d} \\ G(q^{-1}) = D(q^{-1})B(q^{-1}) \end{array} \right\} \quad (17)$$

By (10), we get next equation:

$$\begin{aligned}
z(t+1) &= E(q^{-1})v(t) + G(q^{-1})u(t) + D(q^{-1})\xi(t+1) \\
&= \phi^T(t)\theta + D(q^{-1})\xi(t+1)
\end{aligned} \quad (18)$$

Where

$$\begin{aligned}
\phi^T(t) &= [v(t), v(t-1), \\
&\dots, v(t-n_e), u(t), u(t-1), \dots, u(t-n_g)]
\end{aligned}$$

$$\theta = [e_0, e_1, \dots, e_{n_e}, g_0, g_1, \dots, g_{n_g}]^T$$

According to the least square method, the parameters estimation can be calculated by next form:

$$\hat{\theta}(t) = \hat{\theta}(t-1) + K(t)[z(t) - \hat{z}(t)] \quad (19)$$

where $\hat{z}(t) = \phi^T(t-1) \hat{\theta}(t-1)$ and $K(t)$ is a gain matrix.

By (18)(19) can be seen that the unknown parameters of $E(q^{-1})$ and $G(q^{-1})$ can be estimated by of the q-axis current and rotor speed of the PMSM.

In order to improve the robustness of system, we propose a self-tuning digital PID controller to replace the speed controller based on generalized minimum variance, scheme of speed loop using the PID controller is shown in Fig.3. the control law can be described as:

$$\begin{aligned}
\Delta u(t) &= K_p[e(t) - e(t-1) + \frac{T_s}{T_i} e(t)] \\
&+ \frac{K_p T_d}{T_s}[e(t) - 2e(t-1) + e(t-2)] \\
&= L(q^{-1})y_r(t) - L(q^{-1})y(t) \\
&\approx L(1)y_r(t) - L(q^{-1})y(t)
\end{aligned} \quad (20)$$

where

$$\begin{aligned}
L(q^{-1}) &= l_0 + l_1 q^{-1} + l_2 q^{-2} \\
&= K_p \left(1 + \frac{T_s}{T_i} + \frac{T_d}{T_s} \right) + K_p \left(-1 - \frac{2T_d}{T_s} \right) q^{-1} + K_p \frac{T_d}{T_s} q^{-2}
\end{aligned}$$

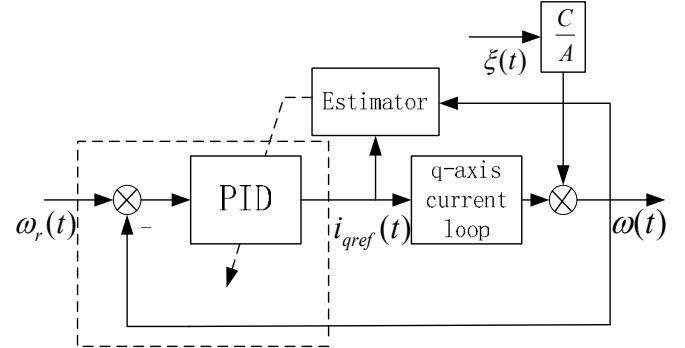


Fig.3. Speed loop based on auto-tuning PID control

Next, we define a coefficient as:

$$\gamma = \frac{1 - q^{-1}}{G(q^{-1}) + \Lambda} \quad (21)$$

Substituting (21) into (12) yields the control law of the generalized minimum variance method:

$$\Delta u(t) = \gamma [\psi \hat{y}_r(t) - \hat{E}(q^{-1}) \hat{y}(t) / \Gamma_d] \quad (22)$$

Based on (20) and (22), the PID parameters can be designed by certainty equivalency principle as below:

$$\left. \begin{array}{l} L(1) = \gamma \psi \\ L(q^{-1}) = \gamma \hat{E}(q^{-1}) / \Gamma_d \end{array} \right\} \quad (23)$$

The PID parameters and ψ can be calculated by following equations:

$$\left. \begin{array}{l} \psi \cong \hat{e}_0 + \hat{e}_1 + \hat{e}_2 \\ K_p \cong -\gamma (\hat{e}_1 + 2 \hat{e}_2) \\ T_d \cong \frac{-\hat{e}_2}{\hat{e}_1 + 2 \hat{e}_2} T_s \\ T_i \cong \frac{-\hat{e}_1 + 2 \hat{e}_2}{\hat{e}_0 + \hat{e}_1 + \hat{e}_2} T_s \end{array} \right\} \quad (24)$$

Parameters $\Gamma_d, \Gamma_n, \Lambda, \gamma$ can be obtained by solving

conditions (9),(16) and (21). At the same time those parameters must guarantee stability of the close loop and make the steady-state error of the rotating speed minimum, by solving the characteristic equation (14) and condition (16).

IV. EXPERIMENTAL RESULTS

The control system is realized based on a digital signal processor (DSP). The PMSM is fed by a voltage source inverter using intelligent power modules (IPM). The parameters of the PMSM are given in Table I.

TABLE I

PARAMETERS OF THE EXPERIMENTAL MOTOR

Rated power	200W
Rated torque	0.64Nm
Rated phase current	1.44A
Maximum phase current	3.69A
Rated speed	2000r/min
Number of pole pairs	4
R	15.42Ω
L	30.08mH
J	$0.138 \times 10^{-4} \text{ kgm}^2$

The control system is composed of:

1. Fixed point DSP TMS320 F2812
2. Mitsubishi PM20CSJ060 IPM
3. A 12-bit A/D converter
4. Two current hall sensors
5. A 2500 lines pulse encoder

All the control calculations are carried out at sample intervals of 0.1ms by using a DSP. The carrier frequency of PWM in the IPM is set at 10 kHz. In experiments the speed control performance of the self-tuning PID controller are compared with that of the conventional PID controller.

The initial parameters of the self-tuning PID and the conventional PID are designed by II type module optimum method, they are set as follows:

$$K_p = 0.01229$$

$$T_d = 0.0081$$

$$T_i = 0.0056$$

The experiments are carried out for a unloaded PMSM and for a PMSM under variant load torque and inertia, speed reference n_{ref} changes from a low value 250rpm to a high value 1000rpm periodically. The results include the q-axis current, reference and actual rotor speed. Fig.4-7 show the dynamic responses of the unloaded PMSM with conventional PID and with the self-tuning PID. Fig.8-11 show the dynamic responses of the PMSM under variant load torque and 2 times increased inertia with conventional PID and with the self-tuning PID.

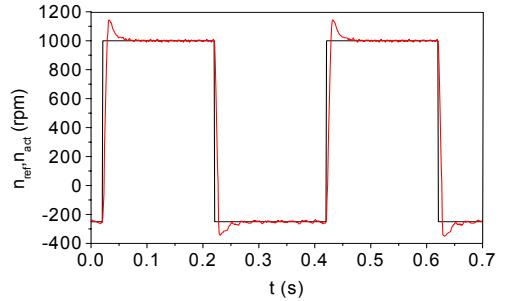


Fig.4.The speed reference and speed response with conventional PID controller for unloaded PMSM

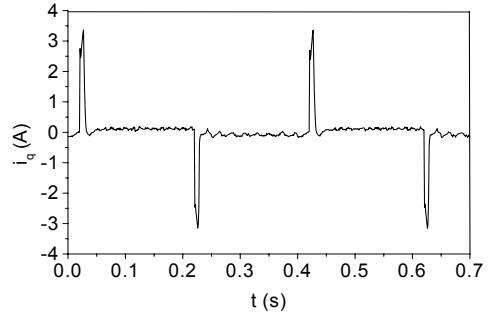


Fig.5. The speed q-axis current response with conventional PID controller for unloaded PMSM

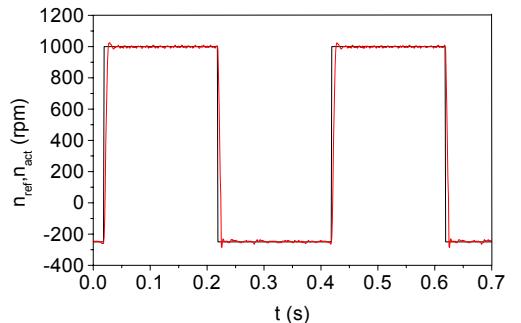


Fig.6. The speed reference and speed response with the self-tuning PID controller for unloaded PMSM

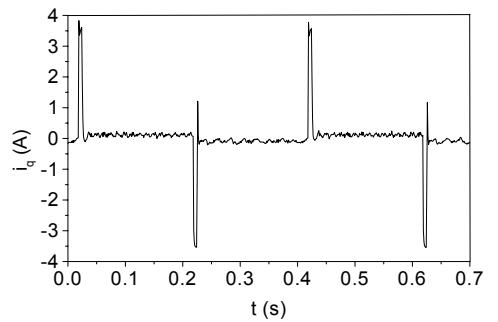


Fig.7. The q-axis current response with the self-tuning PID controller for unloaded PMSM

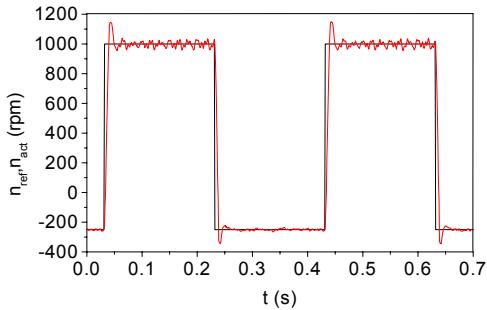


Fig.8. The speed reference and speed response with conventional PID controller under variant load torque and 2 times increased inertia J

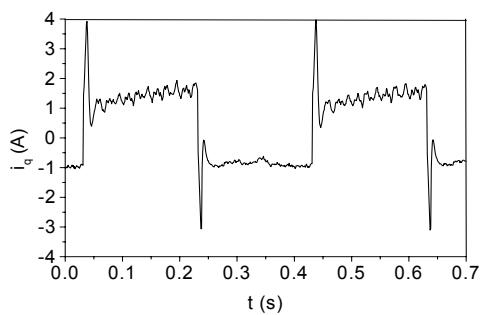


Fig.9. The q-axis current response with conventional PID controller under variant load torque and 2 times increased inertia J

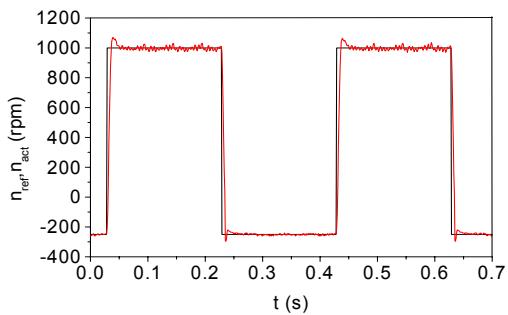


Fig.10. The speed reference and speed response with the self-tuning PID controller under variant load torque and 2 times increased inertia J

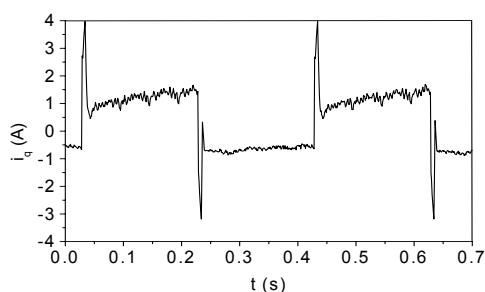


Fig.11. The q-axis current response with the self-tuning PID controller under variant load torque and 2 times increased inertia J

Comparing the waveforms of Fig.4-7, it can be seen that the dynamic speed control performance of the PMSM with self-tuning PID controller is better than that with conventional PID controller, overshoot and average error of the speed response in proposed method are considerably decreased. Comparing the waveforms of Fig.8-11, it can be seen that the system with self-tuning PID controller has more robustness against parameters vibration, such as load torque, speed reference and inertia.

V. CONCLUSIONS

In this paper a self-tuning PID controller is proposed for PMSM speed control. This method is based on generalized minimum variance. In this method coefficients of the PMSM drive transfer polynomials can be estimated by using the least square method, then the PID parameters can be designed by certainty equivalency principle by using generalized minimum variance method. Stability of the control loop is guaranteed by pole-assignment. Experiments are carried out at low and high speeds, results verified the efficacy of the proposed method: as compare with conventional PID regulator, the proposed method makes the speed control of the PMSM drive high performance and more robustness against parameters variation.

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