Comparison of Speed control of PMSM with PI, PID& Adaptive PID Controllers

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***Abstract**— This paper proposes a speed control scheme for permanent magnet synchronous motor (PMSM) drives using different control methods. The proposed controllers are PI, PID & Adaptive PID controller. The adaptive PID controller consist of three control terms namely, a decoupling term which is employed to compensate for nonlinear factors then the PID term is made to automatically adjust the control gains and the last one is supervisory term, designed to guarantee the system stability. It is an online tuning method, So it can adaptively deal with any system parameter uncertainties in reality. To confirm, which is the effective speed control technique, all the control techniques are simulated in MATLAB/ Simulink environment and the performance is compared .Finally it is validated that the adaptive PID controller has the advantages of robustness, easy implementation and adequate performance in the face of uncertainties.*

Key words: Adaptive control, Proportional-integral-derivative (PID) controls, Permanent magnet synchronous motor (PMSM).

1. INTRODUCTION

Compared with other forms of machines permanent magnet synchronous motor (PMSM) are widely used because of its better dynamic performance, higher efficiency, smaller size, easy maintenance and so on. Now a days permanent magnet synchronous motor (PMSM) are extensively applied in home appliances as well as industrial applications such as wind generation systems, industrial robots, electric vehicles, air conditioners, washing machines, national defense, agriculture and daily life. The PMSM is not easy to control because of its nonlinearity. In the run time parameter variations are highly affected by the performance of PMSM [1]. So the design of PMSM must contain a high-performance controller which has a simple algorithm, fast response, high accuracy, and robustness against the motor parameter and load torque variations.

The proportional-integral (PI) & proportional-integral derivative (PID) controller are widely adopted to control the PMSM systems due to its simplicity, effectiveness, and clear functionality [10]. However the traditional PID controller is sensitive to the system uncertainties. Thus, the control performance of the conventional PID method can seriously degraded under parameter variations. The offline-tuning rules, such as a hybrid control system, which contains a fuzzy controller in the transient and a PI controller in the steady state and the fuzzy rules are employed for tuning the PI gains which have a lack the adaptability to deal with the time-varying system uncertainties An adaptive PI controller has online-tuning rules because it does not require the exact knowledge of any motor parameter

Recently, various advanced control methods are available for the control of the PMSM systems, such as fuzzy logic control (FLC), neutral network control (NNC), sliding mode control (SMC) adaptive control, etc. The FLC [5] is used because of its fuzzy reasoning capacity. However, the number of the fuzzy rules increases, the control accuracy increases but the control algorithm can be complex. The SMC have great properties such as robustness to external load disturbances and fast dynamic response so it is popularly used in the speed control of PMSM [9]. But it also subject to the parameter variations and chattering problems.

The adaptive control is an interesting method for the PMSM drives because it can deal with the motor parameter and load torque variations. Here only the stator inductances and load torque variations are considered and neglect stator resistance, moment of inertia, viscous friction coefficient, etc. Moreover, the adaptive control algorithm does not guarantee the convergence condition of the system error.

By combining the simplicity and effectiveness of the conventional PID control and the automatic adjustment capability of the adaptive control, proposes a simple adaptive PID control algorithm for the PMSM drives. The adaptive PID controllers consist of adaptive tuning laws which are designed to online adjust the control gains using the supervisory gradient descent method. Therefore, when the motor parameters change the PID gains are automatically adjusted to attain the optimal values. So the proposed control system achieves a good regulation performance such as fast dynamic response and small steady-state error even under system parameter uncertainties. The stability analysis of the adaptive control strategy found by Lyapunov stability theories.

The organization of the rest of this paper can be summarized as follows. The key points while the design of Adaptive PID controller method is explained in Section 3. Different combinations of parameters from different control methods are taken and compared in this section. Conclusion based on the simulink work is given in Section 5.

2. SYSTEM MODEL DESCRIPTION

The modeling of PMSM drive system is required for proper simulation of the system. The d-q model has been developed on rotor reference frame. At any time t, the rotating rotor d-axis makes and angle θr with the fixed stator phase axis and rotating stator mmf makes an angle α with the rotor d-axis. Stator mmf rotates at the same speed as that of the rotor.

Voltage equations in rotor reference frame is given by,

$$V_q = R_q i_q + \frac{d\lambda_q}{dt} + \omega_r \lambda_d$$
$$V_d = R_d i_d + \frac{d\lambda_d}{dt} - \omega_r \lambda_q \quad (1)$$

Where λ_d and λ_q are the flux linkages. The electromagnetic torque developed is given by,

$$T_e = \frac{3}{2}\frac{p}{2}(\varphi_m i_q + (L_q - L_d) i_d i_q) \quad (2)$$

From the above equations the dq frame model is formed by

$$\frac{di_d}{dt} = \frac{v_d}{L_q} - \frac{R}{L_d} i_d + \omega_r \frac{L_q}{L_d} i_q \quad (3)$$
$$\frac{di_q}{dt} = \frac{v_q}{L_q} - \frac{R}{L_q} i_q - \omega_r \frac{L_d}{L_q} i_d - \omega_r \frac{\varphi_m}{L_q}$$
$$\frac{d\omega_r}{dt} = \frac{3p\,\varphi_m}{2J} i_q + \frac{3p}{2J}(L_q - L_d)\, i_d i_q - \frac{\beta}{J}\omega_r - \frac{T_L}{J}$$

Where i_d , i_q are direct and quadrature axis current, L_d , L_q are direct and quadrature axis inductances, R is the stator resistance and P number of magnetic pole pairs. The system parameters $k_1 - k_6$ are depend on the values of R_s, L_q, J,B, and ψ_m. Then

$$k_1 = \frac{3}{2J}\frac{p}{4}\varphi_m \qquad k_4 = \frac{R_s}{L_q}$$
$$k_2 = \frac{B}{J} \qquad k_5 = \frac{\varphi_m}{L_q} \quad (4)$$
$$k_3 = \frac{p}{2J} \qquad k_6 = \frac{1}{L_q}$$

Then, the PMSM drive system model is rewritten as

$$\frac{di_d}{dt} = k_1 V_d - k_4 i_d + \omega_r i_q$$
$$\frac{d\omega_r}{dt} = k_1 i_q - k_2 \omega_r - k_3 T_L \quad (5)$$
$$\frac{di_q}{dt} = k_6 V_q - k_4 i_q - \omega_r i_d - \omega_r k_5$$

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2.1 Conventional PID with Decouping Term

The speed error and rotor acceleration are define as

$$\omega_e = \omega - \omega_d$$
$$\beta = \dot{\omega} = k_1 i_q - k_5 \omega - k_3 T_L \quad (6)$$

where ωd is the desired speed.From the above equations , the dynamics equation derived as

$$\dot{\omega}_e = \dot{\omega} - \dot{\omega}_d \quad (7)$$
$$\dot{\beta} = k_1 (-k_4 i_q - k_5 \omega + k_6 V_q - \omega i_d) - k_2 \dot{\omega} - k_3 \dot{T}_L$$
$$\dot{i}_d = -k_4 i_d + k_6 V_d + \omega i_q$$

In practical applications, supposed that the derivatives of ω_d and T_L can be neglected because of the desired speed and the load torque vary slowly in the sampling period. Then, the system model (1) is,

$$\dot{\omega}_e = \beta$$
$$\dot{\beta} = -k_2 \beta - k_1 k_4 i_{qs} - k_1 k_5 \omega - k_1 \omega i_{ds} + k_1 k_6 V_{qs} \quad (8)$$
$$\dot{i}_{ds} = -k_4 i_{ds} + \omega i_{qs} + k_6 V_{ds}$$

Then, the second-order system as follows,

$$\ddot{\omega}_e + \lambda \dot{\omega}_e = -k_2 \beta - k_1 k_4 i_{qs} - k_1 k_5 \omega - k_1 \omega i_{ds} + \lambda \beta + k_1 k_6 V_{qs}$$
$$\dot{i}_{ds} = -k_4 i_{ds} + \omega i_{qs} + k_6 V_{ds} \quad (9)$$

where λ is the positive control parameter.

Based on the basic theory of the feedback linearization control, the decoupling control term

$$u_f = [u_{1f} \quad u_{2f}]^T$$

where

$$u_{1f} = (k_1 k_4 i_{qs} + k_1 k_5 \omega + k_1 \omega i_{ds} + (k_2 - \lambda)\beta)/(k_1 k_6) \quad (10)$$
$$u_{2f} = (k_4 i_{ds} - \omega i_{qs})/k_6$$

From (9) and (10), the dynamic error system can be formulated as follows

$$\ddot{\omega}_e = \lambda \dot{\omega}_e + k_1 k_6 (V_{qs} - u_{1f}) \qquad (11)$$
$$\dot{i}_{ds} = k_6 (V_{ds} - u_{2f})$$

Then, the conventional PID controller is the form

$$V_{dqs} = \begin{bmatrix} k_1 k_6 V_{qs} \\ k_6 V_{ds} \end{bmatrix} = B \begin{bmatrix} V_{qs} \\ V_{ds} \end{bmatrix} = u_f + u_{PID} \qquad (12)$$

where B=diag[k_1k_6,k_6], Uf is the decoupling control term to compensate for the nonlinear factors, and U_{PID} is the PID control term

$$u_{PID} = \begin{bmatrix} u_{1PID} \\ u_{2PID} \end{bmatrix} = \begin{bmatrix} -k_{1P}\omega_e - k_{1I}\int_0^t \omega_e dt - k_{1D} D \frac{d\omega_e}{dt} \\ -k_{2P} i_{dse} - k_{2I} \int_0^t i_{dse} dt \end{bmatrix} \qquad (13)$$
$$= EK$$

Where (K_{1P}, K_{2P}), (K_{1I}, K_{2I}), and (K_{1D}) are the proportional gains, integral gains, and derivative gain of the PID control term, respectively. The state and gain matrices are given as

$$E = \begin{bmatrix} \int_0^t \omega_e dt & \omega_e & \beta & 0 & 0 \\ 0 & 0 & 0 & \int_0^t i_{ds} dt & i_{ds} \end{bmatrix} \qquad (14)$$
$$k = \begin{bmatrix} -k_{1I} & -k_{1P} & -k_{1D} & -k_{2I} & -k_{2P} \end{bmatrix}^T$$

3. ADAPTIVE PID CONTROLLER DESIGN

The adaptive regulator is used in about the same way as a conventional PID, i.e. the purpose is to keep a measured value as close as possible to a given set point. The adaptive regulator has, however, a much more advanced internal structure and it is capable to change its own behaviour if the process changes. Therefore, the adaptive regulator is considerably more accurate in controlling an industrial process. A truly adaptive controller is capable of learning from previous events to improve future performance.

The conventional PID controller with the offline-tuned control gains can give a good control performance if the motor parameters (k1 to k6) are known.If the system parameters gradually change during operating time, the control performance can be seriously degraded, but the system parameters are not updated. Adaptive tuning laws for auto adjustment of the control gains are introduced to overcome this challenge. The supervisory gradient descent method is used for the proper adjustment of control gains. The proposed adaptive PID controller is the form,

$$V_{dqs} = u_f + u_{PID} - u_{PID0} + u_s \qquad (15)$$

where u_f is the decoupling control term which compensates for the nonlinear factors , u_{PID} is the PID control term which includes the adaptive tuning laws, u_S is the supervisory control term which guarantees the system stability, and u_{PID0} = EK_0 is a constant coefficient matrix.

For getting proper adaptation laws, a new tracking error vector based on the reduced-order sliding mode dynamics is defined as,

$$s(t)=\begin{bmatrix} s_1(t) \\ s_2(t) \end{bmatrix}=\begin{bmatrix} \lambda\,\omega_e+\beta \\ i_{ds} \end{bmatrix} \quad (16)$$

Based on SMC method, the sliding condition is deduced according to the Lyapunov stability theory. Commonly, the Lyapunov function for the SMC is given by

$$V_1 = s^T S/2 \quad (17)$$

Then, the sliding condition can be obtained from the Lyapunov stability theory as

$$\dot{V}_1(t)=s^t\dot{s}\angle 0$$

The sliding condition guarantees that s→0 as t→∞. The adaptation laws for the control gains are the in the form,

$$\begin{aligned}
\dot{K}_{1P} &= -\gamma_{1P}\frac{\partial V_1}{\partial K_{1P}} = -\gamma_{1P}\frac{\partial V_1}{\partial_{U1PID}}\frac{\partial_{U1PID}}{\partial K_{1P}} = -\gamma_{1P}{}^{P}s_1\omega_e \\
\dot{K}_{1I} &= -\gamma_{1I}\frac{\partial V_1}{\partial K_{1I}} = -\gamma_{1I}s_1\int_0^t \omega_e \\
\dot{K}_{1D} &= -\gamma_{1D}\frac{\partial V_1}{\partial K_{1D}} = -\gamma_{1D}s_1\beta \\
\dot{K}_{2P} &= -\gamma_{2P}\frac{\partial V_1}{\partial K_{2D}} = -\gamma_{2P}{}^{P}s_2 i_{ds} \\
\dot{K}_{2I} &= -\gamma_{2I}\frac{\partial V_1}{\partial K_{2I}} = -\gamma_{2I}s_2\int_0^t i_{ds}
\end{aligned} \quad (18)$$

Where γ1P , γ1I , γ1D , γ2P , and γ2I are the positive learning rates. The adaptive tuning laws can be expressed in the following vector form

$$\dot{K} = \Phi E^T S$$

where Φ= diag (γ1P , γ1I , γ1D , γ2P , γ2I).

The supervisory control term in (21) is necessary for pulling back the dynamic errors to the predetermined bounded region and guaranteeing the system stability. Assume that there exists an optimal PID control term

$$U^*_{PID} = U_{PID0} + \varepsilon \quad (19)$$

Where $K^* = \begin{bmatrix} K^*_{1I} & K^*_{1P} & K^*_{1D} & K^*_{2I} & K^*_{2P} \end{bmatrix}^T$ is the optimal gain matrix and $\varepsilon = \begin{bmatrix} \varepsilon_1 \varepsilon_2 \end{bmatrix}^T$ are the approximation errors and they are assumed to be bounded by 0 ≤ |ε1| ≤ δ1 and 0 ≤ |ε2| ≤ δ2 in which δ1 and δ2 are the positive constants.

Then, the supervisory control term is designed as,

$$u_s = \begin{bmatrix} -\delta_1.\text{sgn}(s_1) \\ -\delta_2.\text{sgn}(s_2) \end{bmatrix} \quad (20)$$

The desired controller is obtained by combining the decoupling control term , PID control term with the adaptation laws , and supervisory control term as,

$$V_{dqs} = u_f + u_{PID} + u_s \quad (21)$$

4.SIMULATION RESULTS

Simulations have been carried out for the speed control of PMSM with PI, PID &Adaptive PID controllers. The motor parameters used for simulation are given in table 1. first section discuss about the speed control of pmsm with PI controller.The simulation block is shown in Fig 1. The desired speed is choosen as 251.3 rad per seconds.

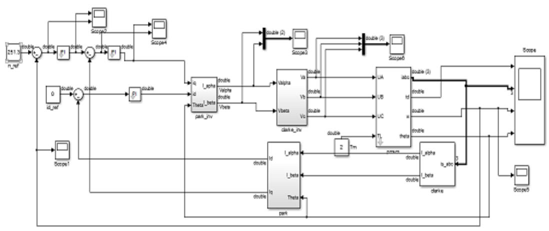

Fig-1: Simulink model of PMSM with PI Controller

Table -1:PMSM Parameters

Parameters	Values
P_{rated}	750W
Vrated	220V
Irated	4.3A
Trated	2.4Nm
N	8
Rs	0.43 ohm
Ls	3.2mH
φ_m	0.085V-s/rad
J	0.0018kg-m2
B	0.0002 N-m-s/rad

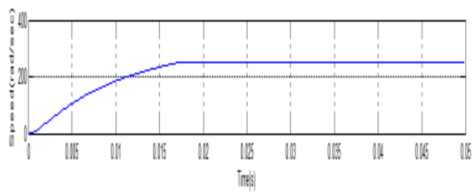

Chart-1:Simulation result of PMSM with PI Controller

It can be observed that the motor speed settles down at the reference value of 251.3 rad/sec in 20.670 ms with a small oscillation or overshoot. From the plot for the output of the speed controller it is observed that there exist sudden spikes and dips around the instant when the motor speed has reached its reference value. The maximum peak overshoot is about 251.016.

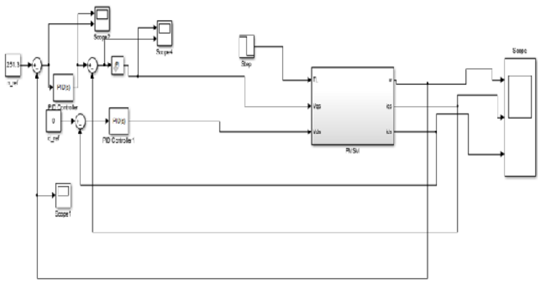

Fig-2: Simulink model of PMSM with PID Controller

Then discuss about the speed control of pmsm with PID controller.The simulation block is shown in Fig 2. Here also the desired speed is choosen as 251.3 rad per seconds.The simulation result is shown in Chart 2. It can be observed that the motor speed settles down at the reference value of 251.3 rad/sec in 20.003 ms with a small overshoot.Here the settiling time is increased due to the noise in the derivative controller part. The maximum peak overshoot is about 253.249.

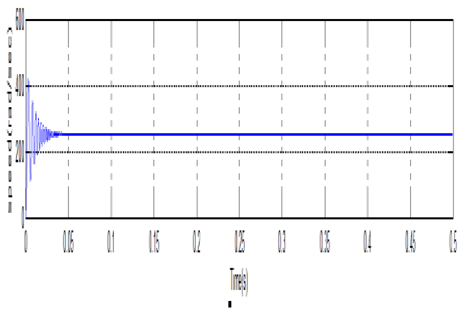

Chart-2: Simulation result of PMSM with PID Controller

Last section discuss about the speed control of pmsm with Adaptive PID controller. It consists of three control terms namely a decoupling term, a PID term, and a supervisory term.The simulation block is shown in Fig 3.

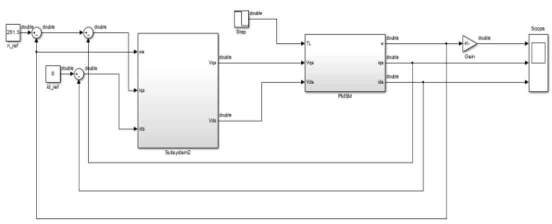

Fig-3: Simulink model of PMSM with PI Controller

By utilizing the online-tuning rules (18), the control gains are automatically adjusted as the system parameters. Therefore, the adaptive PID controller can overcome the disadvantage of all offline-tuning methods [4] and it can exhibit the good performance even if the system parameter vary.The Chart 3 shows the simulation result of speed response of PMSM with adaptve PID controler.It is observedthat setting time is 8.937 msec for the the reference speed of 251.3 rad/sec.From the graph overshoot is 274.216. Chart 1.2 &3 show the experimental results of thePI, the conventional PID control method and Adaptive PID control method In Fig. 6, the rotor speed can be accurately tracked to the desired valuee. It can be seen in Chart 2 that the conventional controller tracks the rotor speed with a considerable steady-state error . Chart 1 shows that settiling time is less than in PI than PID. An the adaptive PID control scheme exhibits the faster dynamic behavior than the conventional control methods From the above result, the Adaptive PID Controller method has better response compared to other two methods

Table-2: Comparison of Motor Parameters

Control methods	Peak overshoot	Settling time(ms)	Rise time(ms)
PI Controller	251.016	20.670	12.290
PID Controller	253.249	20.003	23.865
Adaptive PID Controller	274.216	8.937	5.735

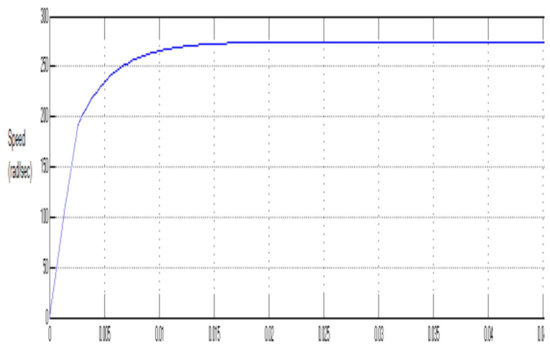

Chart-3:Simulation result of PMSM with Adaptive PID Controller

5.CONCLUSION

This paper proposes, the speed control scheme for permanent magnet synchronous motor (PMSM) drives using different control methods. The proposed control algorithm was simple and easy to implement in the practical applications. For comparison purpose, the PI & PID controller was tested at the same conditions. From the experimental results it is clear that the adaptive PID controller method gives better performance compared to the other two control techniques.

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