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Comparison of Adaptive PID controller and PSO tuned PID controller for PMSM Drives

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Abstract—*This paper put forward an advanced approach of speed control of permanent magnet synchronous motor (PMSM) drives using adaptive PID speed control technique.The proposed speed controllerconsists of two control terms, a PID control term and a supervisory control term. Supervisory term is designed to guarantee the system stability. Unlike conventional PID controllers, the proposed adaptive PID controller includesadaptive tuning laws to online adjust the PID control gains based on the gradient descent method, making it adaptively deal with any system parameter uncertainties.The paper also presents an advanced approach of speed control of PMSM drive using Particle Swarm Optimization (PSO) technique. The PSO technique is used to optimize the parameters of PID controller. Comparison between speed control of PMSM using adaptive PID controller and speed control of PMSM using PSO technique is carried out.Simulation results prove that adaptive PID controller is superior to PID controller tuned using PSO technique. The simulation is carried out using Matlab/Simulink software.*

Keywords—*Permanent magnet synchronous motor(PMSM); speedcontroller; adaptive control; proportional-integral-derivative(PID)control; particle swarm optimization(PSO).*

I. INTRODUCTION

Permanent magnet synchronous motors(PMSM) are ac motors which use permanent magnets embedded on the rotor instead of using electromagnets in order to develop the air gap magnetic field. At synchronous speed, permanent magnets on the rotor poles get magnetically locked with rotating magnetic field. Since rotor windings are replaced by permanent magnets, these motors have several advantages such as high efficiency, high power density, elimination of copper loss, fast dynamic response, robustness and electrical stability [1], [2]. Due to these significant advantages, these motor have enormous industrial applicationswhich include PMSMs are used in hybrid electric vehicles, electric vehicles, industrial drives, elevators, escalators, computer peripheral devices and robotics etc.

Since PMSM system is a nonlinear multivariable system, it is very difficult to control its operation and its performance is mostly affected by parameter variations during its operation [3], [4]. The speed control of PMSM is usually done using PI or PID controllers. The proportional-integral derivative(PID)controller is widely used to control the PMSM systems in industrial applications due to its simplicity, high reliability and effectiveness [5].A big disadvantage of traditional PID controller is its sensitivity to the system uncertainties. Therefore performance of PID controller can be seriously degraded under parameter variations.These problems can be overcome using adaptive PID speed control scheme for permanent magnet synchronous motor drives [6].

In this paper, a simple adaptive PID control algorithm for PMSM drives is proposed. The proposed adaptive PID control algorithm is a combination of simplicity and effectiveness of conventional PID control and automatic adjustment capability of the adaptive control. The adaptive PID controller make uses the adaptive tuning laws which are designedto online adjust the control gains by using the supervisory gradient descent method. Consequently, when the motor parameters change,the PID gains are automatically tuned to attain their optimal values. As a result, the proposed control system achieves a good regulation performance which includes faster dynamic response and smaller steady-state error even under system parameter uncertainties.

Particleswarm optimization (PSO)is an optimization technique which can beused to optimize the PID parameters,using which PID parameters can be selected automatically. The PSO algorithm is a population-based stochastic approach for solving optimization problems [7],[8]. It is widely used in many applications such as fuzzy control systems, robot control, power electronics, power systems, and image processing, etc.[9]. The technique is simple and easier to implement because it does not use the gradient of the problem being optimized and another advantage is that there are only fewer parameters to be adjusted in PSO algorithm.In this paper, PID controller tuned using PSO algorithm for PMSM drive is also presented.

The paper is organized as follows. PMSM drive model in the *d-q* reference frame is presented in section II. Section III explains about Particle Swarm Optimization. The in depth explanation of adaptive PID controller is given in section IV. Results are discussed in section V and section VI is conclusion.

II. MATHEMATICAL MODELING OF PMSM DRIVE

A. Field oriented control(foc)

In ac machines, the stator and rotor fields are notorthogonal to each other. The only current that can be controlled is the stator current. Field oriented control is the technique used to achieve the decoupled control of torque and flux by transforming the stator current quantities from stationary reference frame to torque and flux prducing current components in rotating reference frame called *d-q* reference frame. The equations of PMSM are developed in *d-q* reference frame. The block diagram of field oriented control is shown below:

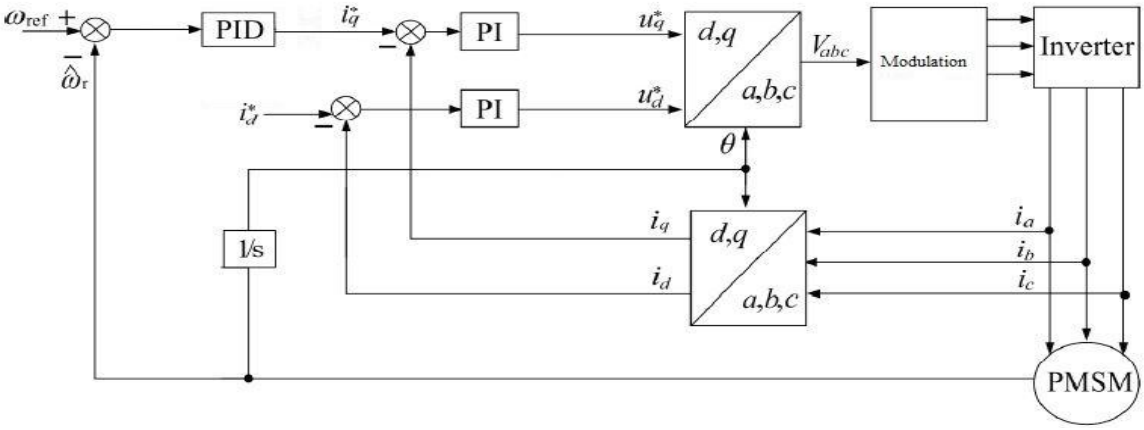

Fig. 1. Field oriented control of PMSM drive system

B. Mathematical model of PMSM drive using FOC

The figure below presents an equivalent circuit of PMSM in d-q axis which is to be used in both dynamic equations of PMSM, and static characteristics.

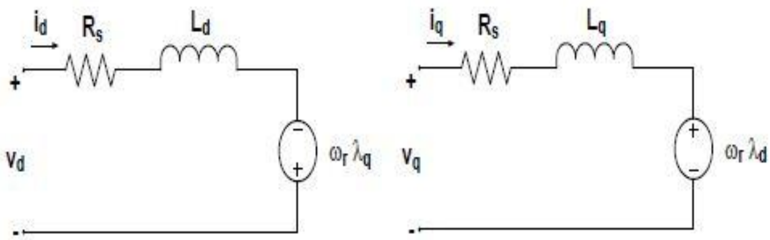

Fig. 2. Equivalent circuit of PMSM in *d-q* reference frame

The mathematical model of PMSM and wound rotor synchronous motor is similar because the stator of the PMSM and the wound rotor synchronous motor are similar [10].The model of PMSM without damper winding has been developed using the given assumptions:

1. Saturation is neglected.
2. The induced EMF is sinusoidal.
3. Eddy currents and hysteresis losses are negligible.
4. There are no field current dynamics.
5. There is no cage on the rotor.

Taking into consideration these assumption, equations in PMSM in *d-q* synchronously rotating reference frame are as follows [11], [12]:

$$V_d = R_s i_d + \rho\lambda_d - \omega_r\lambda_q$$
$$V_q = R_s i_q + \rho\lambda_q - \omega_r\lambda_d \qquad (1)$$

The flux linkage equation in *d-q* reference frame can be written as,

$$\lambda_d = L_d i_d + \lambda_{af}$$
$$\lambda_q = L_q i_q \qquad (2)$$

The above equation can be rearranged in the following form:

$$\rho i_d = (V_d - R_s i_d + \omega_r L_q i_q)/L_d$$
$$\rho i_q = (V_q - R_s i_q - \omega_r L_d i_d - \omega r\lambda_{af})/L_q \qquad (3)$$

Where id, iq are the d, q axis stator currents, Vd and Vq are the d, q axis voltages, Ld and Lq are the d, q axis inductances, R is the stator winding resistance per phase. λ_d and λ_q are the d, q axis stator flux linkages, λ_{af} is flux linkage due to rotor PMs linking the stator and ωr is electrical rotor speed. ρ is the derivative operator used.

The electro mechanical torque is given by:

$$Te=(3/2)(P/2)[\lambda_{af}iq-(Ld-Lq)idiq] \quad (4)$$

The equation of motor dynamics is given by :

$$Te=T_L+B\omega_m+J\rho\omega_m \quad (5)$$

The above equation can be modified as following:

$$\rho\omega_m=(Te-T_L-B\omega_m)/J \quad (6)$$

Where TL is the load torque, P is the number of poles, B is the damping co-efficient, J is the moment of inertia and ωm is the rotor mechanical speed.

However, this model is only the *d-q* model of PMSM. As the supply voltage to the PMSM will always be in the three phase stationary reference frame, the voltages in the three phase stationary reference frame must be transformed into two phase synchronously rotating reference frame by vector transformation [13].

The equations in *d-q* reference frame is obtained from stationary three phase reference frame using Park transformation.

$$V_q=2/3[V_a\cos\theta+V_b\cos(\theta-2\pi/3)+V_c\cos(\theta+2\pi/3)]$$
$$V_d=2/3[V_a\sin\theta+V_b\sin(\theta-2\pi/3)+V_c\sin(\theta+2\pi/3)] \quad [7]$$

The equations in stationary three phase reference frame are obtained from *d-q* reference frame using inverse Park transformation.

$$Va=Vq\cos\theta+Vd\sin\theta$$
$$Vb=Vq\cos(\theta-2\pi/3)+Vd\sin(\theta-2\pi/3)$$
$$Vc=Vq\cos(\theta+2\pi/3)+Vd\sin(\theta+2\pi/3) \quad [8]$$

III. PARTICLE SWARM OPTIMIZATION

Particle swarm optimization (PSO) solves a problem by having a population (swarm) of candidate solutions called particles and these particles move around in search space according to simple mathematical formula based on particles' position and velocity [14]. The movements of the particles are guided by their own best known position in the search-space as well as the entire swarm's best known position. When better positions are being discovered then these will then come to guide the movements of the swarm. The process is repeated and a satisfactory solution will be found out at the end.

A. Basic PSO algorithm

Step 1:Initialization

For each particle $i= 1, 2……N$

1. Initialize the particle's position with a uniformly distribution as $X_i(0)\sim U(L, U)$, where L and U represent the lower and upper bounds of the search space
2. Initialize Pbest to its initial position: $Pbest(i,0)= X_i(0)$.
3. Initialize Gbest to the minimal value of the swarm: $Gbest(0) = \arg\min f[X_i(0)]$.
4. Initialize velocity V_i.

Step 2. Repeat until a termination condition is reached.

For each particle i= 1….N

1. Pick random numbers: r_1 and $r_2 \sim U(0,1)$
2. Update particle's velocity.
3. Update particle's position.
4. If $f[X_i(k)] < f[Pbest_i(k)]$, then
   a. Update the best known position of the particle i: $Pbest_i(k)= X_i(k)$
   b. If $f[X_i(k)] < f[Gbest(k)]$, update the swarm's best known position : $Gbest(k) = X_i(k)$
5. $k \leftarrow k+1;$

Step 3: Output $Gbest(k)$ contains the best found solution.

In each iteration, each particle is updated using two 'best' values. They are:

1. Best solution (fitness value) a particle has achieved so far, personal best, *Pbest*.
2. Best solution obtained so far by any particle in the population, global best, *Gbest*.

Particles update themselves using these above 'best' values [15]. Two major parameters used for calculation are particle velocity and position; both are updated after each iteration and solution moves ahead towards best possible results. New position is created according to previous velocity, personal best and global best.

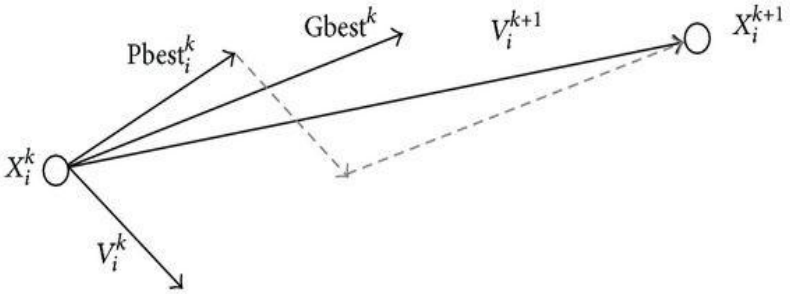

Fig. 3. Concept of Particle Swarm Optimization

The velocity *V* and position *P*of particles are updated using the following equations:

$$V_i^{k+1} = wv_i^k + c_1 r_1 (Pbest_i^k - X_i^k) + c_2 r_2 (Gbest - X_i^k)$$
$$X_i^{k+1} = X_i^k + V_i^{k+1} \qquad (9)$$

where w is the inertia weight used to balance the global exploration and local exploitation, r_1 and r_2 are uniformly distributed random variables within range [0 ,1], and $c_1$and c_2 are positive constant parameters called "acceleration coefficients."

B. Fitness function used

A fitness function is usedas a single figure of meritto summarizehow close a given solution is to achieve the specified aims.In this paper, the fitness function used is the integral square error (ISE). It is the measure of the system performance, calculated by integrating the square of the system error over a fixed interval of time. The PSO algorithm minimizes the integral square error of speed response of the PMSM drive:

$$ISE = \int_0^t e^2 dt \qquad (10)$$

The objective of the optimization problem is to minimize the above cost function. So the optimization problem aims at minimizing the weighted sum of the square error of the speed response of the system.

C. PSO programming block diagram

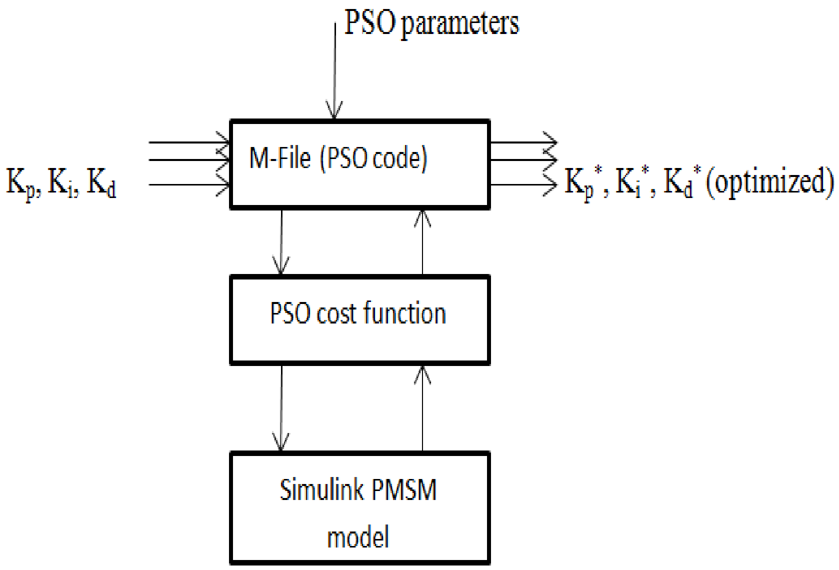

Fig. 4. PSO programming block diagram

IV. PROPOSED ADAPTIVE PID CONTROLLER

The traditional PID controller with the offline-tunedcontrol gains can give a good control performance only if the motorparameters are precisely known. But the fact is that the systemparameters gradually change during its operating time; as a result,after a long running time, the control performance canbe seriously degraded if changed system parameters are notupdated properly. To overcome this problem, adaptive tuning laws are designed for automatic adjustment of the control gains.The control gains, denoted asK_{1P}, K_{2P}, K_{1I}, K_{2I} and K_{1D} are adjusted to the optimum values based on thesupervisory gradient descent method. The proposed adaptive PID controller is designed to have the form given below:

$$V_{dq} = u_{PID} + u_S \quad (11)$$

whereu_{PID} is the PID control term which containing the adaptive tuning laws, $u_S$is the supervisory control term which guarantees system stability.

The controller is designed to have two control terms, a PID term and a supervisory term.The first control term, PID control term which includes adaptive tuning laws based on the gradient descent method is employed to automatically adjust the control gains, and the second one, the supervisory control term is to guarantee the system stability. Therefore, it can adaptively deal with any system parameter uncertainties at any time. The proposed scheme is simple and easy to implement, andalso make possiblean accurate and fast speed tracking.

u_{PID}in(11) is defined as the following:

$$u_{PID}=\begin{bmatrix} u_{1PID} \\ u_{2PID} \end{bmatrix} = \begin{bmatrix} -K_{1P}\omega_e - K_{1I}\int_0^t \omega_e dt - K_{1D}\dfrac{d\omega_e}{dt} \\ -K_{2P}i_d - K_{2I}\int_0^t i_d dt \end{bmatrix} \quad (12)$$

where(K_{1P}, K_{2P}),(K_{1I}, K_{2I}) and (K_{1D})are proportional gains, integral gains, and derivative gain respectively of the PID control term. ω_e is the speed error of the system and β is the rotor acceleration.

To derive the adaptive tuning laws for the PID control gains (12), the supervisory gradient descent method is used. The gradient descent search algorithm is found out in the direction opposite to the energy flow, and the convergence properties of the PID control gains can also be found out. Thus, the adaptation laws for the above control gainsK_{1P}, K_{2P}, K_{1I}, K_{2I} and K_{1D} can be obtained based on the supervisory gradient method as shown below:

$$\dot{K}_{1P} = -\gamma_{1P}\frac{\partial V_1}{\partial K_{1P}} = -\gamma_{1P}\frac{\partial V_1}{\partial u_{1PID}}\frac{\partial u_{1PID}}{\partial K_{1P}} = -\gamma_{1P}s_1\omega_e$$

$$\dot{K}_{1I} = -\gamma_{1I}\frac{\partial V_1}{\partial K_{1I}} = -\gamma_{1I}\frac{\partial V_1}{\partial u_{1PID}}\frac{\partial u_{1PID}}{\partial K_{1I}} = -\gamma_{1I}s_1\int_0^t \omega_e dt$$

$$\dot{K}_{1D} = -\gamma_{1D}\frac{\partial V_1}{\partial K_{1D}} = -\gamma_{1D}\frac{\partial V_1}{\partial u_{1PID}}\frac{\partial u_{1PID}}{\partial K_{1D}} = -\gamma_{1D}s_1\beta$$

$$\dot{K}_{2P} = -\gamma_{2P}\frac{\partial V_1}{\partial K_{2P}} = -\gamma_{2P}\frac{\partial V_1}{\partial u_{2PID}}\frac{\partial u_{2PID}}{\partial K_{2P}} = -\gamma_{2P}s_2 i_d$$

$$\dot{K}_{2I} = -\gamma_{2I}\frac{\partial V_1}{\partial K_{2I}} = -\gamma_{2I}\frac{\partial V_1}{\partial u_{2PID}}\frac{\partial u_{2PID}}{\partial K_{2I}} =$$

$$-\gamma_{2I}s_2\int_0^t i_d dt \quad (13)$$

Where $\gamma_{1P}, \gamma_{1I}, \gamma_{1D}, \gamma_{2P}, \gamma_{2I}$ are positive learning rates.

A. *Supervisory control term*

To derive the proper adaptation laws, a new tracking error vector based on the reduced-order sliding mode dynamics is defined as the following:

$$s(t)=\begin{bmatrix} s_1(t) \\ s_2(t) \end{bmatrix} = \begin{bmatrix} \lambda\omega_e + \beta + k\int_0^t \omega_e dt \\ i_d \end{bmatrix} \quad (14)$$

whereλ is a positive control parameter.

The integral term added to the sliding manifold makes the linear sliding surface nonlinear and also equations in (13) developed used gradient descent method converge more faster than in the case without using integral term .

The supervisory control term (11) is essential to regain the dynamic errors to the predetermined bounded region and assuring the stability of the system.Let $\varepsilon = [$□□□□$]^T$; □□□and □□ denote the approximation errors and they are assumed to be bounded by $0 \le |\varepsilon_1| \le \delta_1$ and $0 \le |\varepsilon_2| \le \delta_2$, where δ_1 and δ_2 are positive constants.
Therefore the supervisory control term can be designed as

$$u_s = \begin{bmatrix} -\delta_1.\mathrm{sgn}(s_1) \\ -\delta_2.\mathrm{sgn}(s_2) \end{bmatrix} \qquad (15)$$

Thus the designed controller is a combination of PID controller with adaptation laws(13) to automatically adjust the control gain and supervisory control term (15) to guarantee system stability as shown in (11).

V. RESULTS AND ANALYSIS

A. Results

The responses developed using adaptive PID speed controller is shown below:

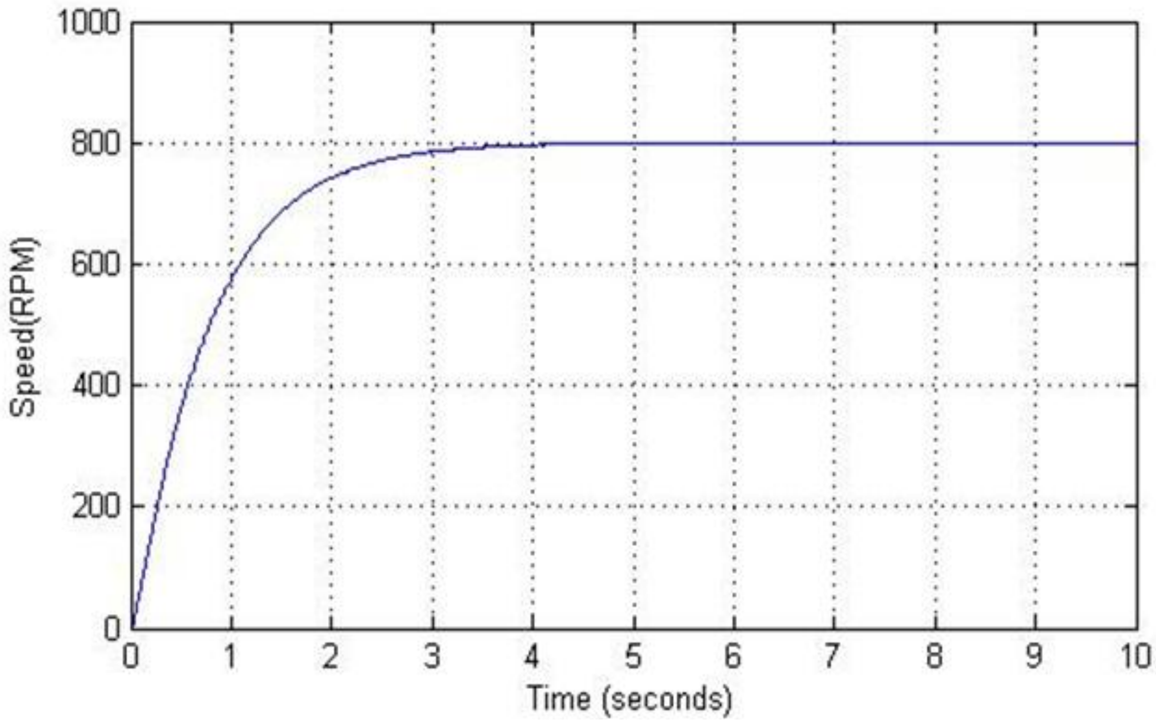

Fig. 5. Speed response of PMSM using adaptive PID speed controller

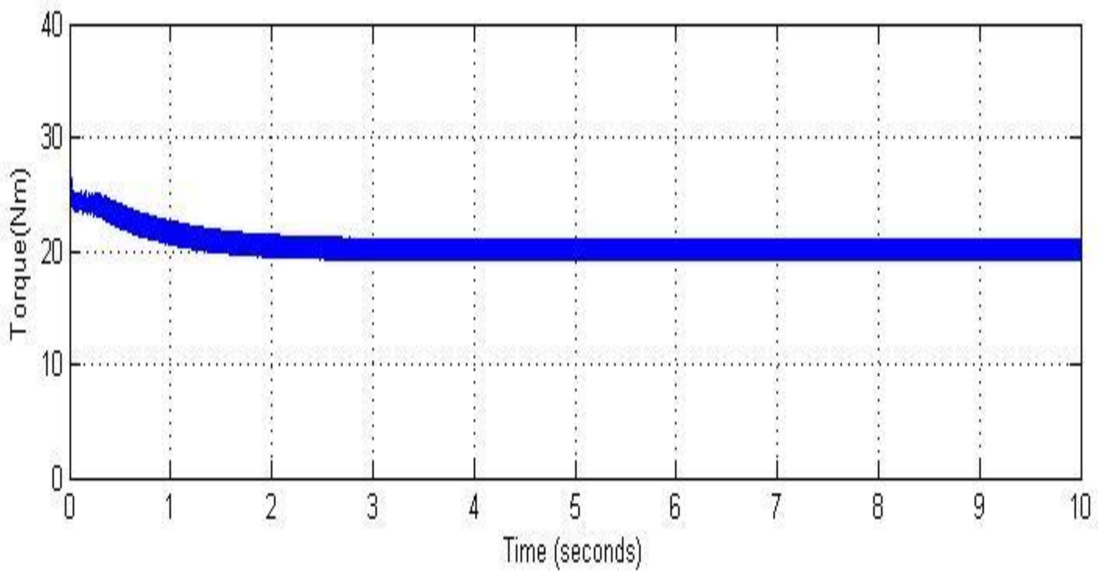

Fig. 6. Torque developed in the case of adaptive PID speed controller

The responses developed using PID controller tuned using PSO are shown below:

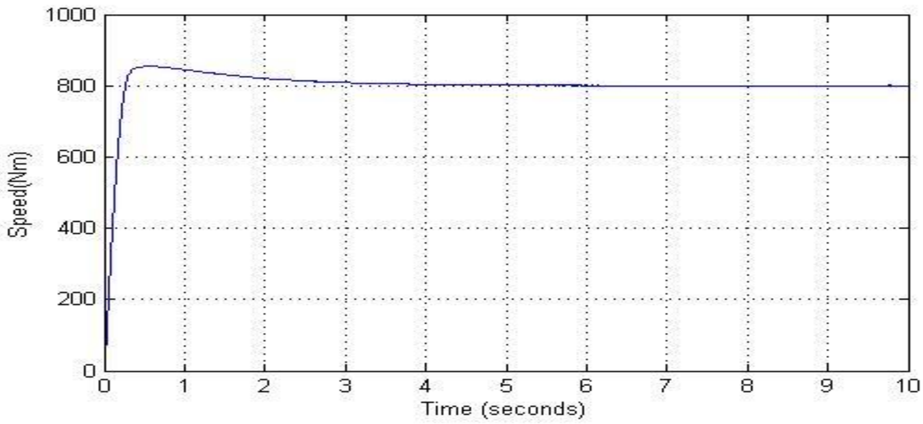

Fig. 7. Speed response of PMSM using PID speed controller tuned using PSO

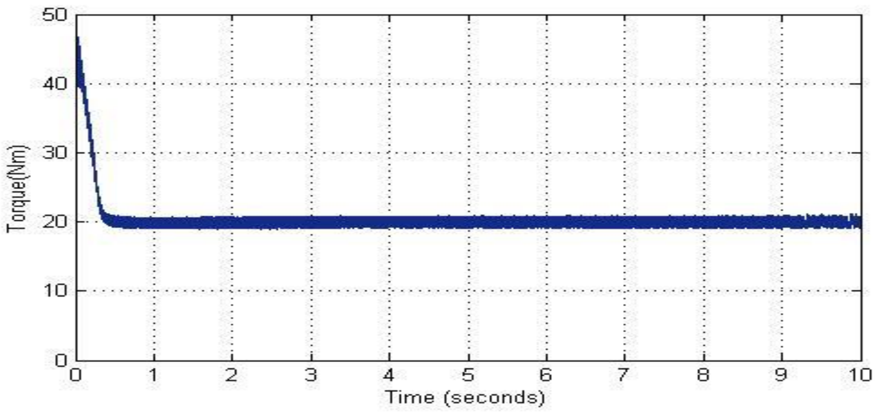

Fig. 8. Torque developed in the case of adaptive PID speed controller

B. Analysis

Considering the above responses, the effectiveness of both the controllers can be analyzed. A comparison between speed developed using both methods is carried out in table I. From the table it can be summarized, when applying adaptive PID controller method, it gives no overshoot and steady state error, but it takes a longer rise time. Table II summarizes that peak overshoot in torque response can be reduced using adaptive PID controller.

TABLE I: COMPARISON OFSPEED RESPONSES OF THE PMSM DRIVE USING ADAPTIVE PID SPEED CONTROLLER AND PSO TUNED PID SPEED CONTROLLER

Motor speed response	Adaptive PID speed controller	PID speed controller tuned using PSO
Steady state error (RPM)	0	0
Peak overshoot (%)	0	54
Settling time (s)	4	6
Rise time (s)	1.77	0.214

TABLE II: COMPARISON OF TORQUE RESPONSES OF THE PMSM DRIVE USING ADAPTIVE PID SPEED CONTROLLER AND PSO TUNED PID SPEED CONTROLLER

Motor torque response	Adaptive PID speed controller	PID speed controller tuned using PSO
Steady state error (RPM)	0	0
Peak overshoot (%)	9	26.5
Settling time (s)	2	0.4
Rise time (s)	0.006	0.002

VI. CONCLUSION

In this paper, two speed control methods for PMSM are explained. One is speed control of PMSM using adaptive PID control method and other is speed control using PID controller tuned using particle swarm optimization (PSO)technique. Simulation results show that adaptive PID controller is superior to the one tuned using PSO technique. The results show that speed response using adaptive PID speed controller has no overshoot and steady state error. The electromagnetic torque developed in this case is much better than that developed using PID speed controller tuned using PSO.

APPENDIX

TABLE 2: PARAMETERS OF PMSM

Motor parameters	Values
Stator resistance, R_s	1.25 Ω
d axis inductance, L_d	0.0025 H
q axis inductance, L_q	0.006 H
Viscous friction coefficient, B	0N.m.s/rad
Equivalent inertia, J	0.05kg.m^2
Magnetic flux, l_{af}	0.199 V.s/rad
No of poles, p	4

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