

Comperative Performance Analysis of PMSM Drive Using MPSO and ACO Techniques

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ABSTRACT

This work proposes an optimization algorithm to control speed of a permanent magnet synchronous motor (PMSM) during starting and speed reversal of motor, as well as during load disturbance conditions. The objective is to minimize the integral absolute control error of the PMSM shaft speed to achieve fast and accurate speed response under load disturbance and speed reversal conditions. The maximum overshoot, peak time, settling time and rise time of the motor is also minimized to obtain efficient transient speed response. Optimum speed control of PMSM is obtained with the aid of a PID speed controller. Modified Particle Swarm Optimization (MPSO) and Ant Colony Optimization (ACO) techniques has been employed for tuning of the PID speed controller, to determine its gain coefficients (proportional, integral and derivative). Simulation results demonstrate that with use of MPSO and ACO techniques improved control performance of PMSM can be achieved in comparison to the classical Ziegler-Nichols (Z-N) method of PID tuning.

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1. INTRODUCTION

During last two decades, a gradual and noteworthy advancement on Permanent Magnet Synchronous Motor (PMSM) drive front has motivated researchers for Artificial Intelligence (AI) based speed controller designs. PMSM drives have been increasingly applied in a wide variety of industrial and automotive applications. These drives are also used in hybrid electrical vehicles and washing machines due to high power density, improved efficiency, larger torque to inertia ratio and high reliability. The controlling of PMSM drive has undergone remarkable improvements over the passage of time, however, numerous-challenges are yet to be resolved in order to improve the performance of this drive to be practically viable in the current scenario and future commercial applications. As per literature survey, it is found that DC and induction motor drives face various constraints, hence, researchers and manufacturers prefer the PMSM drive over these. Therefore, lot of scope to take initiative is prevalent in this area to design and develop enhanced and compact intelligent PID Speed Controller for PMSM drives [1],[2].

A very effective control system is needed to obtain optimal performance of a PMSM in industry. The Proportional Integral Derivative (PID) controller is one of the traditional controllers which are widely used in many drive system. But it has sluggish response due to sudden change in load torque and the sensitivity to controller gains (K_p , K_i and K_d) [3]-[5]. The control effect of PID depends solely on tuning of PID controller. However, finding optimal gain coefficients is cumbersome because of dynamics involved in motor performance and variation of system parameters with time [5]. Traditionally, 'trial and error' approach was employed to find appropriate gain values but it is complex, time consuming and does not guarantee

optimal solution. Another traditional method is Ziegler-Nichols (Z-N) method which is the most standard method and widely used. But this method is tedious for systems with non-linearities such as PMSM. It provides high overshoot in system response and not suitable to achieve fast dynamic response [6]-[8]. In recent times artificial intelligence (AI) techniques are being adopted for efficient and optimum tuning of PID speed controllers [9]. In this paper, speed of PMSM is controlled with the help of a PID speed controller using AI techniques. The designing of the PID speed controller is treated as an optimization problem, employing MPSO [10]-[17] and Ant Colony Optimization (ACO) [18]-[23] for its solution. In this work tuning of PID controller by using MPSO and ACO technique is implemented to control speed of PMSM.

This chapter is arranged in six sections including the current introductory Section 1. The tuning of PID speed controller using MPSO method is discussed in Section 2. Problem formulation of PID controller that has been used in PMSM drive is discussed in Section 3. The tuning of PID speed controller using ACO method is discussed in Section 4. PMSM simulation model and analytical results are validated in Section 5. Finally, a summary of the paper is concluded in Section 6.

2. METHODOLOGY OF PROPOSED MODIFIED PSO

The Modified PSO technique overcome the demerits of PSO technique [24], it improve the convergence rate and prevent the prematurely condition. When each group is divided, the group which has maximum population at the center is preferred. It shows a particle subgroup as a central subgroup, and the other subgroups are neighborhoods to the central subgroups, it can communicate with other subgroup near to it and other subgroups cannot share the information with each other. By using MPSO technique the information can transmit faster and improving efficiency of the algorithm. Accordingly, the distance of two vectors was obtained by the space position of each particle. The L_{\max} denoted as the maximum distance of any two particles. Meanwhile $\|X_i(k) - X_j(k)\|/L_{\max}$ was also calculated. If the ratio is smaller than a certain value then two particles merge into one group, if the ratio is greater than a certain value then they should be divided from the group. Each particle updates its status according to equation (1),(2) as follows [25]:

$$V_i(k+1) = w(k) V_i(k) + c_1(k) r_1(P_i - X_i(k)) + c_2(k) r_2(P_g - X_i(k)) \quad (1)$$

$$X_i(k+1) = X_i(k) + V_i(k+1) \quad (2)$$

Fitness function is used to evaluate every new position. In MPSO technique, the value of weight w adjust the properly, which prevent algorithm from getting into a local optimization. In the further stage, small one is propitious to accelerate algorithm converge. This way used is illustrated as follows:

$$w(k) = w_{\text{initial}} + (w_{\text{initial}} - w_{\text{final}})(1 - k/K) \quad (3)$$

$$c_1(k) = c_{1\text{initial}} + (c_{1\text{initial}} - c_{1\text{final}})(1 - k/K) \quad (4)$$

$$c_2(k) = c_{2\text{initial}} + (c_{2\text{initial}} - c_{2\text{final}})(1 - k/K) \quad (5)$$

k denotes current iterate time; K denotes max iterate time.

The optimized values of PID controller gains are shown in Table 1. Implemented MPSO-PID controller is described in flowchart as shown in Figure 1.

Table 1. Values of PID gains obtained from MPSO method

Z-N Technique	MPSO Technique
K_p : 0.34584	K_p : 2
K_i : 3.460165	K_i : 3
K_d : 0.008641591	K_d : 0.008

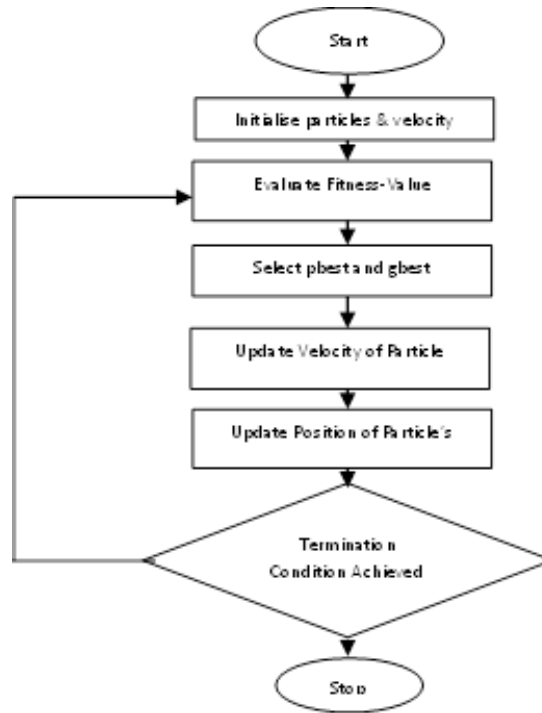


Figure 1. Flowchart of Modified PSO PID Controller

3. PROBLEM FORMULATION

In this section, the basic concept of the PID controller is explained. The block diagram of the PID speed controller employed in the work is illustrated in Figure 2.

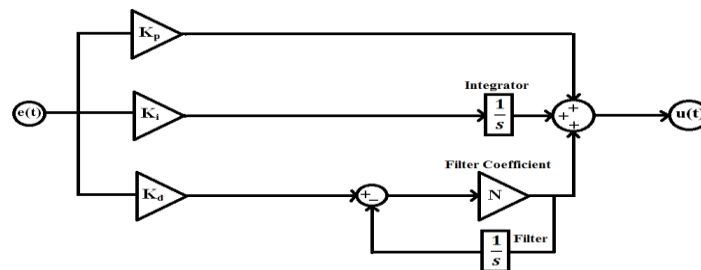


Figure 2. Block diagram representation of PID speed controller

The transfer function of the PID speed controller for a continuous system is described by the equation (6)

$$G_{PID}(s) = K_p + \frac{K_i}{s} + K_d \frac{N}{1+N\frac{1}{s}} \quad (6)$$

where K_p , K_i , K_d are proportional, integral and derivative gains respectively of the PID speed controller and N is constant filter coefficient. The gains K_p , K_i , and K_d are generated by ACO algorithm. The schematic block diagram of PMSM drive with PID speed control system used in transient response analysis and parameter extraction is shown in Figure 3.

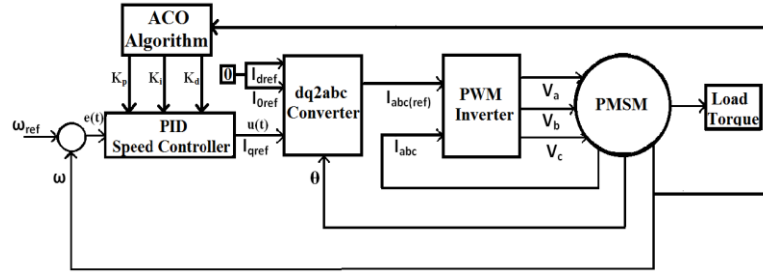


Figure 3. Block Diagram of PMSM with PID Control System

As shown in the Figure 3, the reference speed ω_{ref} is compared with the measured speed ω_r and the error signal is fed to the PID speed controller. This compares the actual and reference speed. The output of the controller is transformed dq to abc transformation. Then, that reference current is fed to the PWM inverter to generate the inverter's command signals. Here the phase current I_{abc} and I_{ref} are given as input. These are compared by using the comparators. The output of the comparators is fed to the motor.

To achieve desired response through control system a cost function is implemented that describes the performance of the system quantitatively. The transient response specifications and performance indices taken into consideration are as follows.

3.1. Maximum Overshoot (Mp)

It is the normalized difference between the maximum speed (ω_{max}) attained by the PMSM and the desired reference speed (ω_{ref}) of the motor i.e.

$$f_m = M_p = \frac{\omega_{max} - \omega_{ref}}{\omega_{max}} \times 100 \% \quad (7)$$

3.2. Peak Time (t_p)

It is the time taken by PMSM to reach the maximum speed (ω_{max}).

$$f_p = t_p \quad (8)$$

3.3. Rise Time (t_r)

It is the time taken by the PMSM to raise its speed from 10% to 90% of the desired reference speed.

$$f_r = t_r \quad (9)$$

3.4. Settling Time (t_s)

It is the time required by PMSM speed to reach and stay within a permissible tolerance band (selected as 0.02%) of the reference speed.

$$f_s = t_s \quad (10)$$

3.5. Integral Absolute Error

It is the integral of the absolute magnitude of the error which is given as:

$$f_{IAE} = IAE = \int_0^{\infty} |e(t)| dt \quad (11)$$

Thus summarizing, the cost function (f) is given as:

$$f = f_m + f_p + f_r + f_s + f_{IAE} \quad (12)$$

The objective is to minimize this function f , to achieve fast and effective speed control of PMSM.

4. ANT COLONY OPTIMIZATION ALGORITHM

ACO is defined as a meta-heuristic algorithm derived from the co-operative foraging behaviour of

real ants [18]. The optimization problem to be solved using ACO algorithm is modeled as a graphical problem. Virtual ants traverse the nodes of this graph in search of a minimum cost path. Each ant individually chooses a rather poor-quality path. Better paths are found by co-operation among the entire ant population [19],[20]. The problem of finding optimized values of K_p , K_i , K_d of the PID speed controller is represented as a graphical problem as shown in Figure 4.

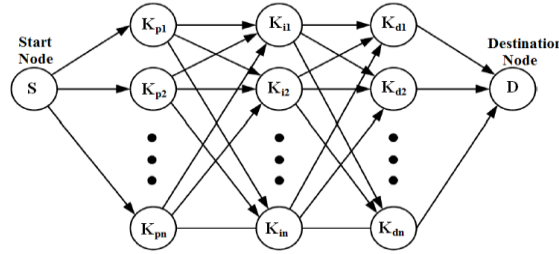


Figure 4. Graphical Representation of ACO for tuning PID Speed Controller

In this graph K_p , K_i , K_d are represented as three different vectors in which each value of the vector acts as a node of the graph. An ant while traversing the graph must choose three nodes, one from each vector. The choice for a node is made by the ant based on a probabilistic function [17],[18] given in equation (13):

$$\rho_{ij} = \frac{[h_{ij}]^\alpha [p_{ij}]^\beta}{\sum_{i \in S} [h_{ij}]^\alpha [p_{ij}]^\beta} \quad (13)$$

h_{ij} : heuristic factor dependent on problem parameters

p_{ij} : pheromone factor determining the amount of pheromone deposited at a node

α : constant determining relative importance of pheromone value at a node

β : constant determining relative importance of heuristic factor at a node

S : set of nodes not yet visited by the ant

One iteration or tour is completed when all the ants have chosen three nodes, one from each vector. An ant while travelling marks its presence on a node by depositing pheromones. Pheromone deposition is a way of communication between the ants. The pheromone levels at a node are updated after each tour so as to differentiate between good and bad paths i.e. paths with low and high cost respectively. In the proposed algorithm, two fold updating of pheromone is implemented. These are called local and global pheromone updating rule. Local pheromone updating is carried after each ant has completed one tour according to equation (14):

$$p(k)_{ij} = p(k-1)_{ij} + \frac{p \cdot p_{pos}}{f} \quad (14)$$

$p(k)_{ij}$: pheromone deposited on path connecting the nodes i and j at the k^{th} tour

p : constant pheromone value

p_{pos} : positive pheromone updating coefficient

C : cost function of the tour traversed by the ant

Global pheromone updating is implemented after completion of a tour by all the ants of the colony. According to this rule the pheromone of the best and worst tours paths are updated as follows:

$$p(k)_{ij} = p(k)_{ij}^\gamma + [p(k)_{ij}^{\text{best}} + p(k)_{ij}^{\text{worst}}] \quad (15)$$

$$p(k)_{ij}^{\text{best}} = p(k)_{ij}^{\text{best}} + \frac{p}{f_{\text{best}}} \quad (16)$$

$$p(k)_{ij}^{\text{worst}} = p(k)_{ij}^{\text{worst}} - \frac{p \cdot p_{\text{neg}}}{f_{\text{worst}}} \quad (17)$$

$p(k)_{ij}^{\text{best}}$: pheromone of nodes chosen in best tour i.e. tour resulting in lowest cost f_{best}

$p(k)_{ij}^{\text{worst}}$: pheromone of nodes chosen in worst tour i.e. tour with highest cost f_{worst}

γ : pheromone evaporation factor to degrade pheromone value with time, allowing ants to forget past history of the tours travelled.

Global pheromone updating is carried out to avoid early convergence due to ants being trapped in local minima, and allowing ants to continue searching in new directions. The ACO algorithm applied to design an optimal PID speed controller for PMSM is as follows (Figure 5):

Step 1: Initialization

Number of ants k in the colony are initialized at the start node. Number of tours m and values of p , p_{pos} , p_{neg} and λ are also set. A gain matrix with three columns one for each of the gain parameter K_p , K_i and K_d is also constructed.

For: number of tours = 1 to m

For: number of ants = 1 to k

Step 2: Choice of nodes

Ants traverse the gain matrix and choose the values of K_p , K_i and K_d with maximum pheromone level according to equation (13).

Step 3: Calculation of cost of tour

Cost of the tour traversed by an ant is calculated according to the cost function given in equation (12).

Step 4: Local pheromone updating

Local pheromone updating is carried out according to equation (14) until maximum ant count has been reached. Steps 2 to 4 are repeated out until maximum ant count is reached.

Step 5: Global pheromone updating

Once maximum ant count is reached, best tour having lowest cost and worst tour having highest cost is chosen. Pheromone of best tour nodes is increased while that of worst tour nodes is decreased according to equations (15)-(17). Steps 2 to 5 are repeated until maximum tour count is reached.

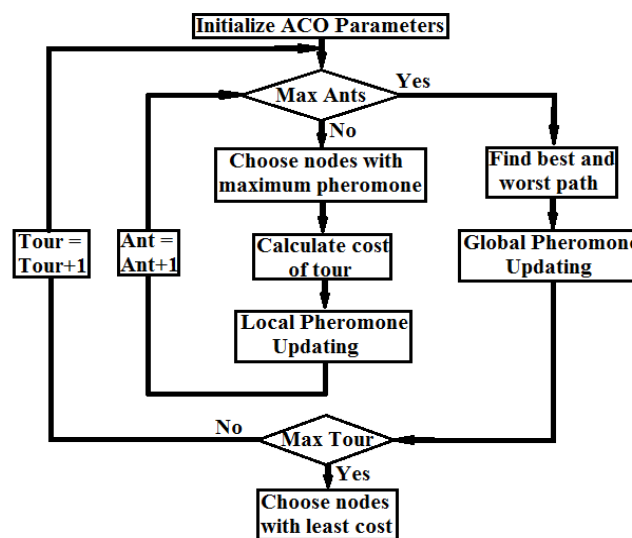


Figure 5. Flowchart for ACO Algorithm

5. MODEL OF PMSM AND RESULTS

The reference speed of the PMSM is chosen as 1000 rpm and step function applied for load torque with simulation time of 0.5 seconds. The values of gain parameters obtained from classical Z-N method, MPSO and ACO method are tabulated in Table 1 and 2. The model for speed control of PMSM is as shown in Figure 6. Matlab R2013a is used for simulation of the model.

Table 2. Values of PID gains obtained from ACO method

Z-N method	ACO method
K_p : 0.34584	K_p : 9.60
K_i : 3.460165	K_i : 0.405
K_d : 0.008641591	K_d : 0.0001

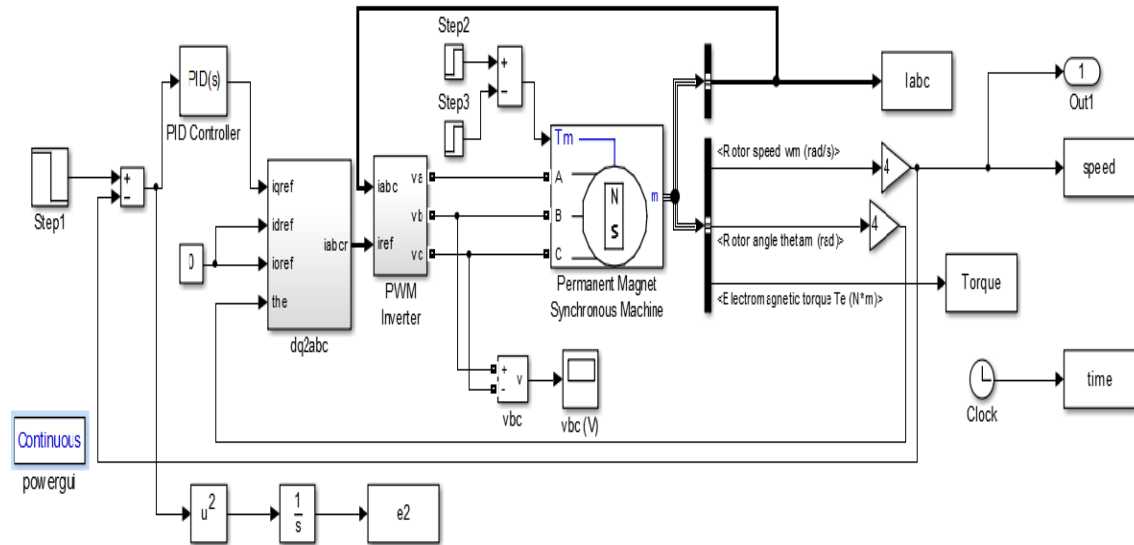


Figure 6. Model of PMSM

The motor speed is compared with reference speed by the comparator and the output is fed to the PID controller. These controllers improve the transient response. The output of controller is fed to the dq to abc transformation by using inverse park's transformation. The inverter circuit is fed by the dq to abc transformation. The output of inverter circuit is fed to PMSM. The output of PMSM is taken with the help of bus-selector. The Rotor speed is fed back to the comparator to achieve the desired speed which is required. The simulation is carried out under the different operating conditions such as starting, braking and load application and removal.

Figures 7-9 illustrates the transient speed response, stator current and electromagnetic torque of the PMSM incorporating a Z-N tuned PID speed controller under starting, speed reversal and load disturbance conditions.

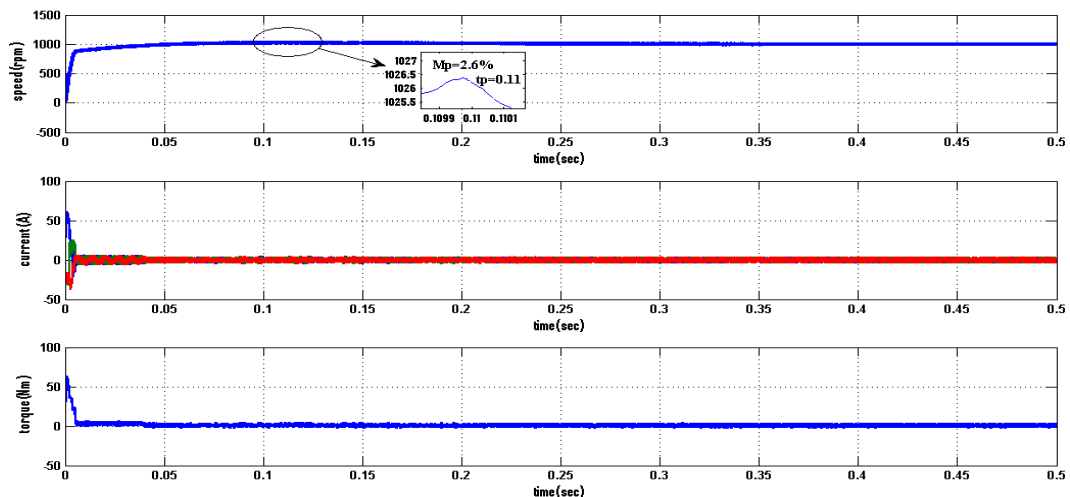


Figure 7. Starting dynamics of PMSM drive using Z-N method

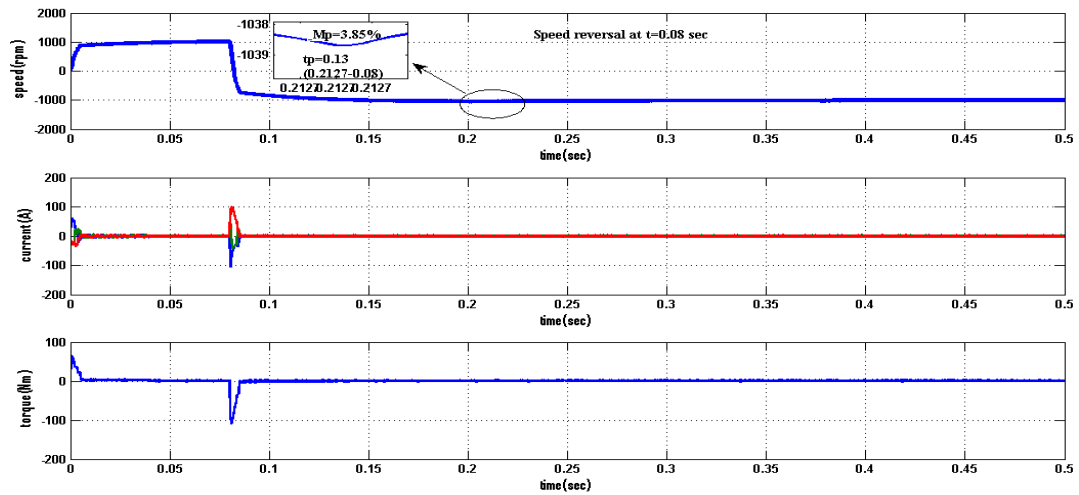


Figure 8. Speed reversal characteristics of PSMM drive using Z-N

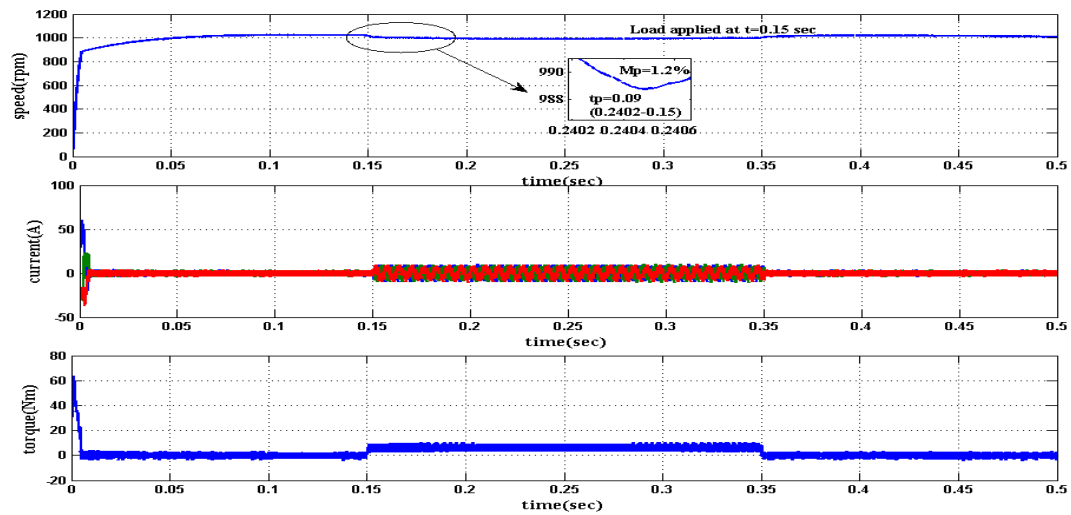


Figure 9. Load application and Load removal characteristics of PSMM drive using Z-N

Figures 10-12 illustrates the transient speed response, stator current and electromagnetic torque of the PMSM incorporating a MPSO tuned PID speed controller under starting, speed reversal and load disturbance conditions.

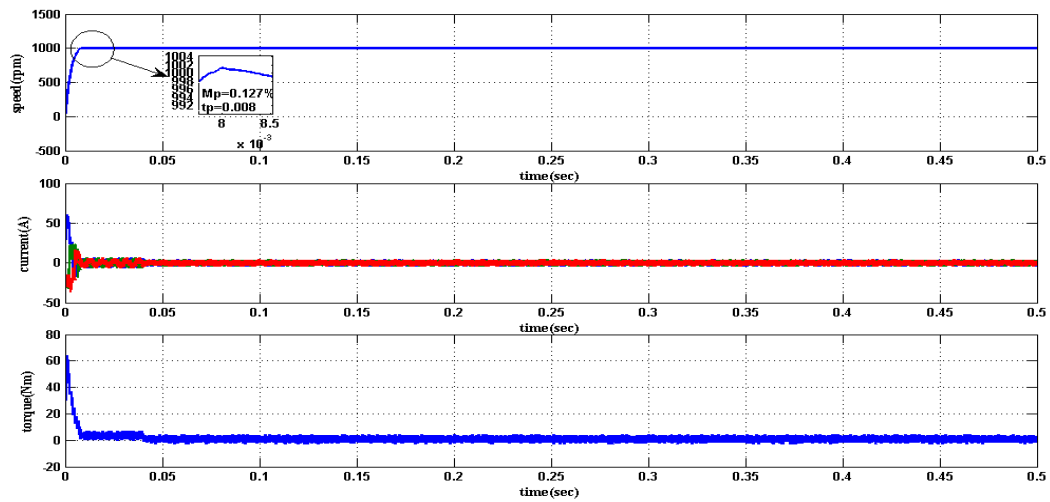


Figure 10. Starting dynamics of PMSM drive using MPSO method

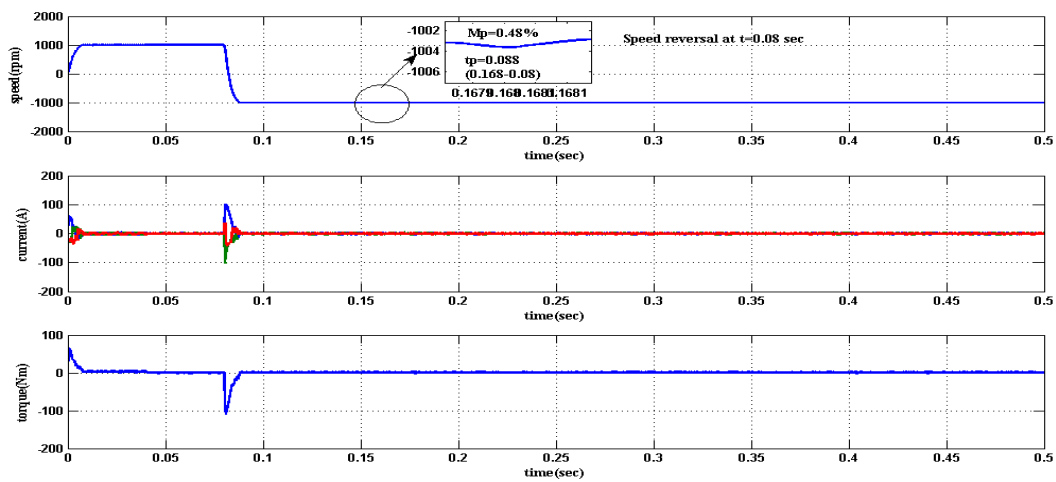


Figure 11. Speed reversal characteristics of PSMM drive using MPSO

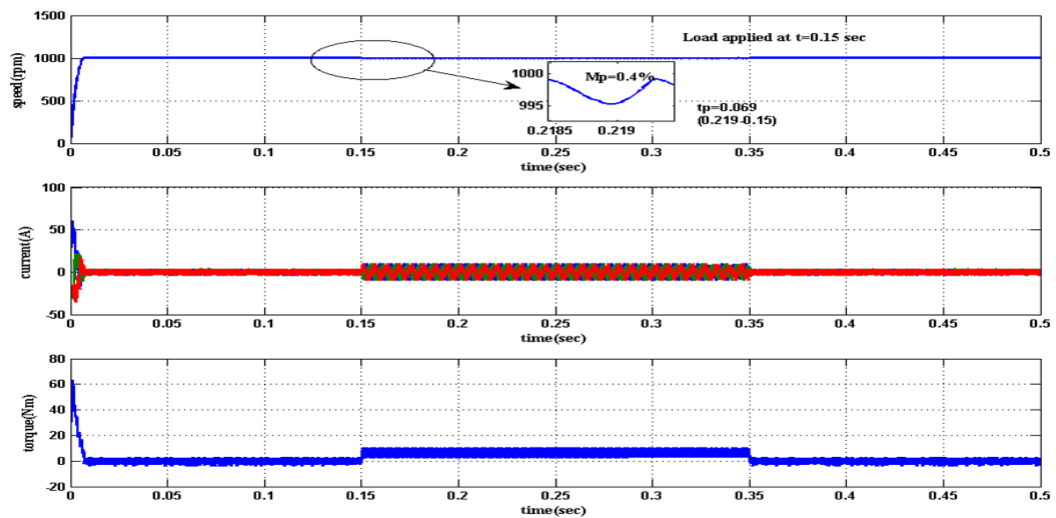


Figure 12. Load application and Load removal characteristics of PSMM drive using MPSO

Figures 13-15 depict the transient speed response, stator current and electromagnetic torque of the PMSM employing an ACO tuned PID speed controller under starting, speed reversal and load disturbance conditions.

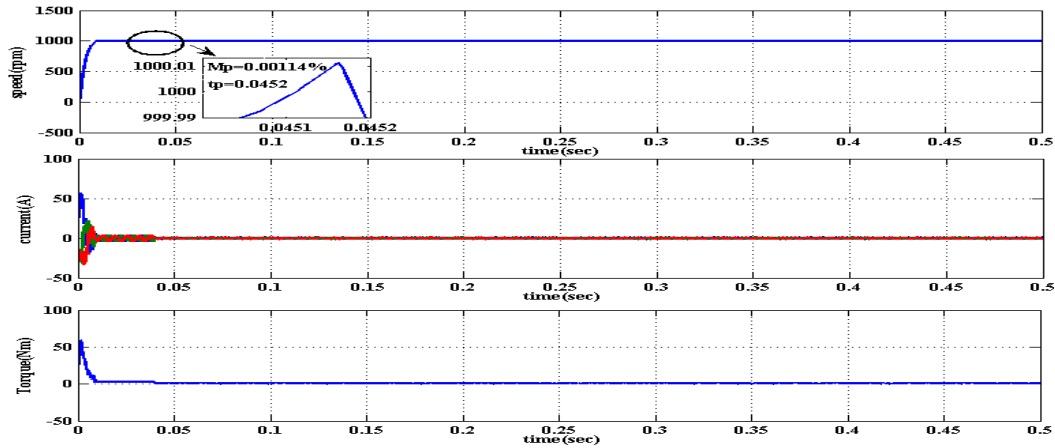


Figure 13. PMSM Step Response with ACO Tuning under Starting Condition

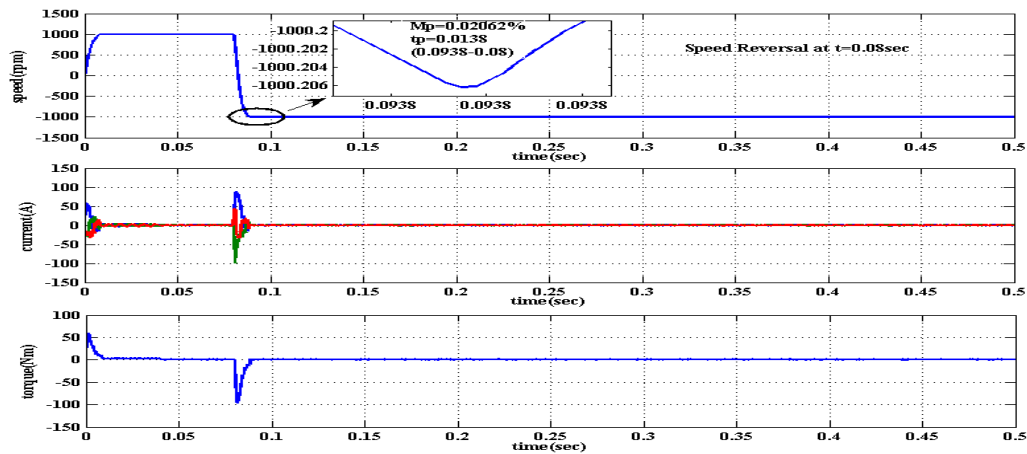


Figure 14. PMSM Step Response with ACO Tuning under Speed Reversal Condition

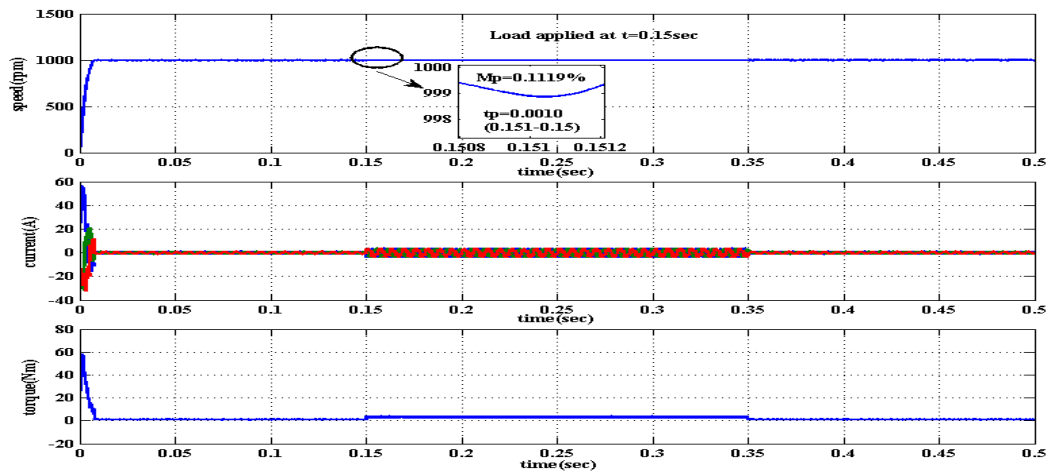


Figure 15. PMSM Step Response with ACO Tuning under Load Disturbance Condition

5.1. Starting Characteristics

The motor is started at no load with 1000 rpm reference speed. The motor try to attain the reference speed of 1000 rpm. At this instant, the torque reaches it's no load value (zero Nm) and the stator winding currents settle down to their normal values. The PMSM drive using AI techniques minimized the overshoot and rise time, peak time and settling time is lower when compared to existing Z-N tuned PID speed controller.

5.2. Speed Reversal Characteristics

The reference speed is reversed at $t = 0.08\text{s}$ to -1000rpm . The rotor speed follows it and tries to attain the reference value. The torque T_{em} also reduces, the speed settles down to its new reference value of -1000 rpm and the torque reverts to the no load value of zero Nm. The current waveforms show a sharp increase in the magnitude with low frequency.

5.3. Load Application and Load Removal

When the load is applied at $t=0.15\text{s}$. The rotor speed ω_m decreases but with the increased stator winding current and torque. When the load is removed at $t=0.35\text{s}$, the AI techniques responds immediately by decreasing the stator winding current and torque. The speed of the motor changes accordingly by settling down to its reference value.

The results presented above that MPSO and ACO algorithm are much more efficient in speed control of PMSM as compared to the classical Z-N method. MPSO and ACO algorithm has sufficiently suppressed the peak overshoot in speed response of PMSM during starting and speed reversal conditions which was dominant in Z-N tuning method. The sudden drop in electromagnetic torque at the time of application of load has also improved considerably.

The summary of extracted parameters from the sets of inset graphs from Figures 7-15, respectively under starting of the motor, speed reversal, load application and load removal conditions are summarized in Table 3. These parameters are analyzed during the various operating conditions of the Z-N method tuned PID speed controller for PMSM drive.

Table 3. Dynamic Response of PMSM Drive using AI techniques and Z-N Method Tuned PID Controller

S. No.	Type of Speed Controller	Motor Characteristics	Rise time $t_r(\text{sec})$	Peak overshoot $M_p(\%)$	Peak time $t_p(\text{sec})$	Settling time $t_s(\text{sec})$	Reference time(sec)
1	Z-N	Starting	0.010	2.6	0.118	0.44	0.0
		Speed Reversal	0.03	3.85	0.13	0.4	0.08
		Load Application	-	1.2	0.09	0.18	0.15
		Load Removal	-	2.1	0.06	0.38	0.35
2	MPSO	Starting	0.007	0.127	0.008	0.0088	0.0
		Speed Reversal	0.087	0.48	0.088	0.44	0.08
		Load Application	-	0.4	0.069	0.12	0.15
		Load Removal	-	1.8	0.02	0.28	0.35
3	ACO	Starting	0.0052	0.00114	0.0452	0.05	0.0
		Speed Reversal	0.0063	0.02062	0.0138	0.02	0.08
		Load Application	-	-0.1119	0.0010	0.0014	0.15
		Load Removal	-	0.00062	0.0010	0.0014	0.35

6. CONCLUSION

The aim of the work was to design a speed controller for PMSM which has been achieved successfully. The PID speed controller designed provides efficient load disturbance and transient response to the motor as is evident from Table 3. The result obtained from MPSO and ACO techniques has been compared with that derived from classical Z-N technique and have proven to be better than it. The most important feature of this work is that online tuning of PID speed controller has been conducted using MPSO and ACO techniques so that any dynamic conditions of the plant can be reflected immediately in the PID gain parameters. PMSM's have found wide application in servo robotics industry. PMSM control strategy employing MPSO and ACO can be of immense help in precision control of robots. Moreover, this analysis has also helped in development of new speed controller under various load conditions and techniques for industry applications.

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APPENDIX

Comperative Performance Analysis of PMSM Drive Using MPSO and ACO Techniques (Deepti Yadav)

Table 4. PMSM Parameters

Variable	Parameter Name	Value	Units
R_s	Stator Winding Resistance	2.875	Ω
L_d	Direct axis inductance	1.53	mH
L_q	Quadrature axis inductance	1.53	mH
λ_{af}	Constant flux linkage of permanent magnets	0.175	Wb or V.s
J	Moment of inertia	0.0008	Kg.m ²
P	No. of pole pairs	4	

Table 5. MPSO Algorithm Parameters

Parameter	Parameter Name	Value
N	No. of generation	200
	Population size	20
w_1	Initial inertial-weight	0.9
w_2	Final inertial-weight	0.2
c_1	Initial cognitive-parameter	0.5
c_2	Final cognitive-parameter	2.5
r_1	Initial social-parameter	0.5
r_2	Final social-parameter	2.5

Table 6. ACO Algorithm Parameters

Parameter	Parameter Name	Value
k	No. of ants	50
m	No. of tour	50
p	Constant pheromone value	0.06
p_{pos}	Positive pheromone coefficient	0.2
p_{neg}	Negative pheromone coefficient	0.3
γ	Evaporation parameter	0.95
α	Constant for pheromone factor	1
β	Constant for heuristic factor	1