Research Journal of Applied Sciences, Engineering and Technology 5(18): 4576-4583, 2013
DOI:10.19026/rjaset.5.4377
ISSN: 2040-7459; e-ISSN: 2040-7467

Submitted: December 31, 2012 Accepted: January 31, 2013 Published: May 05, 2013

Research Article

Swarming Speed Control for DC Permanent Magnet Motor Drive via Pulse Width Modulation Technique and DC/DC Converter

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Abstract: This study presents an approach for the speed control of a permanent magnet DC motor drive via Pulse Width Modulation (PWM) technique and a DC/DC converter. The Particle Swarm Optimization (PSO) technique is used to minimize a time domain objective function and obtain the optimal controller parameters. The performance of the proposed technique has been evaluated using various types of disturbances including load torque variations. Simulation results illustrate clearly the robustness of the controller and validity of the design technique for controlling the speed of permanent magnet motors.

Keywords: DC/DC Converter, particle swarm optimization, permanent magnet DC motor, PI controller, pulse width modulation

INTRODUCTION

Speed control of DC motor could be achieved using mechanical or electrical techniques. In the past, speed controls of DC drives were mostly mechanical and required large size hardware to implement. The development has launched these drives back to a position of formidable relevance, which were hitherto predicted to give way to AC drives. Some important applications are: rolling mills, paper mills, mine winders, hoists, machine tools, traction, printing presses, textile mills, excavators and cranes. Fractional horsepower DC drives are widely employed as servo means for positioning and tracking (Dubey, 1989). Controlled rectifiers provide a variable DC voltage from a fixed DC voltage. Due to their ability to supply a continuously variable DC voltage, controlled rectifier and DC choppers made a revolution in modern industrial equipment and variable speed drives (Rashid, 2003). Adjustable speed drives may be operated over a wide range by controlling armature or field excitation.

In last few years, many researchers have posed techniques for speed control of DC motors. The use of chopper in collaboration to PC for speed control of DC motor is elucidated in Mksc *et al*. (2001). Software was developed, fed into a PC and consequently, commands were given to the chopper via the computer for control of motor speed. The use of standalone micro controller for the speed control of DC motor is discussed in Chiasson (1994). The operation of the system can be summarized as: the drive form rectified voltage; it consists of chopper driven by a PWM signal generated from a microcontroller unit. The motor voltage control is achieved by measuring the rectified main voltage with the analog to-digital converter present other microcontroller and adjusting the PWM signal duty cycle accordingly. Another system that uses a microprocessor is reported in Khoei (1996). The microprocessors compute the actual speed of the motor by sensing the terminal voltage and the current, it then compares the actual speed of the motor with the reference speed and generates a suitable control signal which is fed into the triggering unit. This unit drives an H-Bridge Power MOSFET amplifier, which in turn supplies a PWM voltage to the DC motor. Development of hardware and software of the closed loop DC motor speed control system have been explained and illustrated in Dewangan *et al*. (2012). The realization of the speed control by using PWM and a windows application programmed with C# language is designed in Meha *et al*. (2011). The separately excited DC motor fed by a chopper and controlled by intelligent controller is demonstrated in Kumar *et al*. (2004). It has been reported that the Fuzzy Logic Controller (FLC) controls the duty cycle of the chopper, there by the voltage fed to the motor for regulating the speed. However, the experimental setup has improved the performance over PI controller. It is seen that the separately excited DC

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drive has low starting torque which limits its applications. The DC series motor drive fed by a single phase controlled rectifier and controlled by intelligent controller is introduced in Yousef and Khalil (1995). It has been concluded that the FLC provides better control over the classical PI controller which has improved the performance. It is also reported that the settling time and maximum overshoot can be reduced but AC to DC converter fed drive introduces unwanted harmonic ripples in the output. The DC series motor drive fed by a single phase full-bridge converter controlled by intelligent controller is reported in Tan (2001). It has been reported that the motor performance was simulated for different controllers like Simplify Fuzzy Logic model (SFL), PI type Fuzzy controller (FPI) and classical PI controller. The simulation result shows that the SFI provides superior performance over other controllers. On the other hand, it is found from the analysis that only the speed error has been taken as fuzzy input. The performance of the two inputs with five membership function FLC controlled DC-DC converter fed DC series motor and separately excited motor is discussed in Muruganandam and Madheswaran (2009a). FLC for closed loop control of DC drive fed by DC-DC converter (Chopper) is designed and presented in Muruganandam and Madheswaran (2009b). Swarming optimization techniques have attracted attention in recent years. Swarming strategies in bird flocking and fish schooling are used in the Particle Swarm Optimization (PSO) and introduced in Kennedy and Eberhart (1995) for designing multiply PSS and defining the location of PSS (Abido, 2002; Panda and Padhy, 2008; Mostafa *et al*., 2012).

This study proposes a new control technique called a swarming controller to control the speed of DC permanent magnet motor. The design problem of the proposed controller is formulated as an optimization problem and PSO is employed to search for optimal controller parameters. A time domain objective function representing the error between reference speed and actual one is optimized for different load torque. The drive system has the characteristics of precise, fast, effective speed reference tracking with minimum overshoot/undershoot and minimal steady state error.

PROPOSED SYSTEM

The system under study consists of PWM drive system, DC-DC converter, swarm speed controller and permanent magnet DC motor with variable load torque. Figure 1 and 2 show the block diagram and Matlab/Simulink of the proposed system. The system consists of two loops. The first one is the swarm speed control loop and the second is ON/OFF current control loop. The speed control loop is designed using PSO.

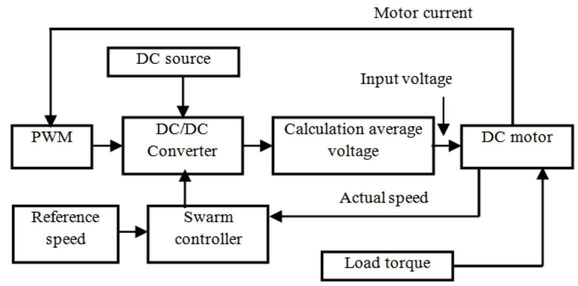


Fig. 1: Block diagram for DC motor control system.

The speed error signal is obtained by comparing between the reference speed and the actual one. The output of the swarm controller is denoted as duty cycle. The overall system construction is illustrated in Fig. 1.

DC permanent magnet motor construction: The permanent magnet DC machines offer a number of useful benefits in industrial applications. The space required for the permanent magnets may be less than that required for the field winding and thus permanent-magnet machines may be smaller and in some case cheaper, than their externally excited counterparts. The proposed system can be simulated with proper mathematic modeling. The equations of permanent magnet DC motor are shown as follow:

$$\frac{di_a(t)}{dt} = \frac{V_t(t)}{L_a} - \frac{R_a}{L_a} i_a(t) - \frac{K_t}{L_a}\omega_r(t) \tag{1}$$

$$\frac{d\omega_r(t)}{dt} = \frac{K_t}{J} i_a\ (t) - \frac{f}{J}\omega_r(t) - \frac{T_L}{J} - \frac{B}{J} \tag{2}$$

where,

i_a = The motor current
V_t = The motor terminal voltage
R_a, L_a = The armature resistance and inductance
ω_r = The motor angular speed
J = The moment of inertia
T_L = The load torque
f = The friction coefficient
K_v = The field constant
B = The damping constant (losses torque)

The specification of permanent magnet DC motor under study is shown in appendix.

DC-DC Converter: The DC-DC converter switch can be a Power Transistor, SCR, GTO and IGBT, Power MOSFET or similar switching device. In order to get high switching frequency (up to 100 KHz) the Power MOSFET may be taken as a switching device. Normally on state drop in the switch is small and it is neglected (Khan and Primer, 1998). When the gate

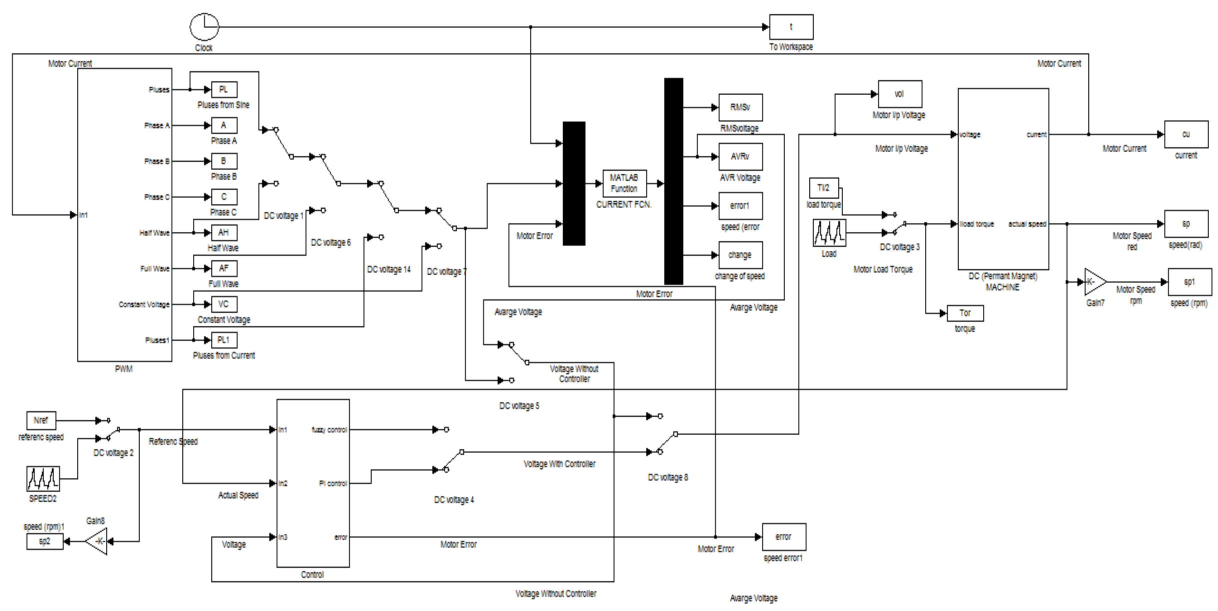


Fig. 2: Simulink of DC motor with PWM drive and DC/DC converter

pulse is applied the device is turned on. During the period the input supply connects with the load. When the gate pulse is removed the device is turned off and the load disconnected from the input supply.

The model equation for DC-DC converter is given by:

$$V_o = \delta * V_s \tag{3}$$

$$\delta = \frac{T_{on}}{T} \tag{4}$$

$$T = T_{on} + T_{off} \tag{5}$$

where,

V_o = The output voltage
V_s = The input voltage
T_{on} = The on time
T_{off} = The off time
δ = The duty cycle ratio

PWM Drive: In the PWM switching at a constant frequency controls the state (on or off) which is generated by comparing the control signal level (motor current feedback) with a repetitive waveform as shown in Fig. 3. The control signal generally is obtained by amplifying the error signal. The frequency of the repetitive wave form with a constant peak, which is shown as saw tooth, establishes the switching frequency. This frequency is kept constant in a PWM control and is chosen to be in a few KHz to a few hundred KHz range. When the amplified error signal, which varies very slowly with time relative to the switching frequency, is greater than the saw tooth waveform, the switch control signal becomes high, causing the switch to turn on. Otherwise, the switch is turn off.

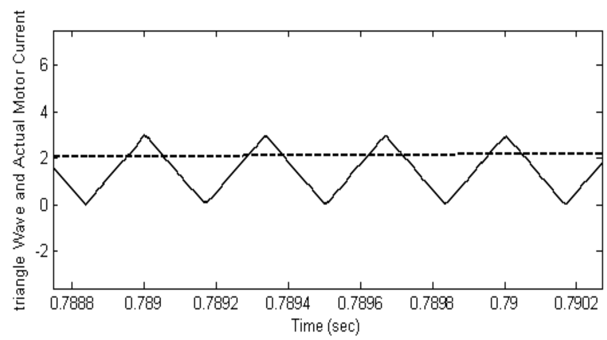


Fig. 3: Comparator signals for PWM

OBJECTIVE FUNCTION

A performance index can be defined by the Integral of Time multiply Absolute Error (ITAE). Accordingly, the objective function J is set to be:

$$J = \int_0^{\infty} t(|e|)dt \tag{6}$$

where,

$$e = w_{reference} - w_{actual}$$

Based on this objective function J optimization problem can be stated as: Minimize J subjected to:

$$K_p^{\min} \le K_P \le K_p^{max} \;,\; K_i^{\min} \le K_i \le K_i^{max} \quad (7)$$

This study focuses on optimal tuning of PI controller for speed tracking of DC permanent magnet motor using PSO algorithm. The aim of the optimization is to search for the optimum controller parameters setting that minimize the difference between reference speed and actual one. On the other hand, in this study the goal is designing a low-order controller for easy implementation for speed control of DC permanent magnet motor.

OVERVIEW OF PSO

The PSO method is a member of wide category of Swarm Intelligence methods for solving the optimization problems. It is a population based search algorithm where each individual is referred to as particle and represents a candidate solution. Each particle in PSO flies through the search space with an adaptable velocity that is dynamically modified according to its own flying experience and also the flying experience of the other particles. In PSO each particles strive to improve themselves by imitating traits from their successful peers. Further, each particle has a memory and hence it is capable of remembering the best position in the search space ever visited by it. The position corresponding to the best fitness is known as pbest and the overall best out of all the particles in the population is called gbest (Kennedy and Eberhart, 1995; Abido, 2002)

The features of the searching procedure can be summarized as follows (Panda and Padhy, 2008):

- Initial positions of pbest and gbest are different. However, using the different direction of pbest and gbest, all agents gradually get close to the global optimum.
- The modified value of the agent position is continuous and the method can be applied to the continuous problem. However, the method can be applied to the discrete problem using grids for XY position and its velocity.
- There are no inconsistency in searching procedures even if continuous and discrete state variables are utilized with continuous axes and grids for XY positions and velocities. Namely, the method can be applied to mixed integer nonlinear optimization problems with continuous and discrete state variables naturally and easily.
- The above concept is explained using only XY axis (2 dimensional spaces). However, the method can be easily applied to n dimensional problem. The modified velocity and position of each particle can be calculated using the current velocity and the distance from the $pbest_{j,g}$ to $gbest_g$ as shown in the following formulas (Mostafa *et al*., 2012):

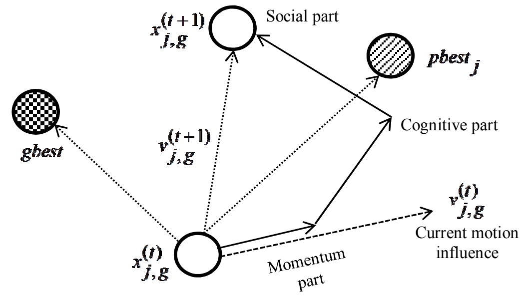


Fig. 4: Deception of velocity and position updates in PSO

$$v_{j,g}^{(t+1)} = w * v_{j,g}^{(t)} + c_1 * r_1(\,) * (pbest_{j,g} - x_{j,g}^{(t)}) + c_2 * r_2(\,) * (gbest_g - x_{j,g}^{(t)})$$

$$x_{j,g}^{(t+1)} = x_{j,g}^{(t)} + v_{j,g}^{(t+1)})$$

with $j = 1, 2, \ldots, n$ and $g = 1, 2, \ldots, m$

where,

n = Number of particles in a group
m = Number of members in a particle
t = Number of iterations (generations)
$v^{(t)}_{j,g}$ = Velocity of particle j at iteration t, with $v_g^{\min} \le v_{j,g}^{(t)} \le v_g^{\max}$
w = Inertia weight factor
c_1, c_2 = Cognitive and social acceleration factors respectively
r_1, r_2 = Random numbers uniformly distributed in the range (0, 1)
$x(t)_{j,g}$ = Current position of j at iteration t
$pbest_j$ = pbest of particle j
$gbest$ = gbest of the group

The *j*-th particle in the swarm is represented by a *g* dimensional vector $x_j = (x_{j,1}, x_{j,2}, \ldots x_{j,g})$ and its rate of position change (velocity) is denoted by another *g* dimensional vector $v_j = (v_{j,1}, v_{j,2}, \ldots v_{j,g})$. The best previous position of the *j*-th particle is represented as p $best_j = pbest_{j,1}, pbest_{j,2}, \ldots, pbest_{j,g}$. The index of best particle among all of the particles in the group is represented by the $gbest_g$.

In PSO, each particle moves in the search space with a velocity according to its own previous best solution and its group's previous best solution. The velocity update in a PSO consists of three parts; namely momentum, cognitive and social parts. The balance among these parts determines the performance of a PSO algorithm. The parameters c_1 and c_2 determine the relative pull of pbest and gbest and the parameters r_1 and r_2 help in stochastically varying these pulls.

In the above equations, superscripts denote the iteration number. Figure 4 shows the velocity and position updates of a particle for a two-dimensional

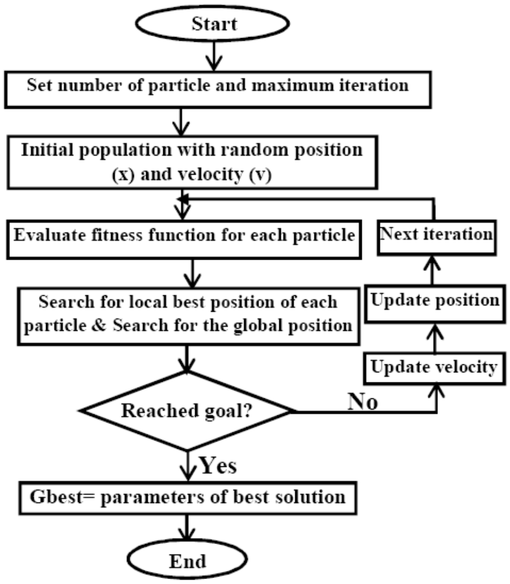


Fig. 5: Flow chart of PSO algorithm

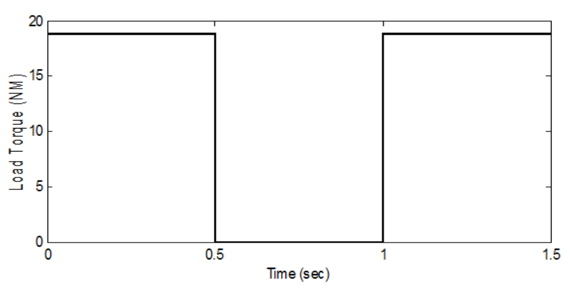


Fig. 6: The step change of load torque

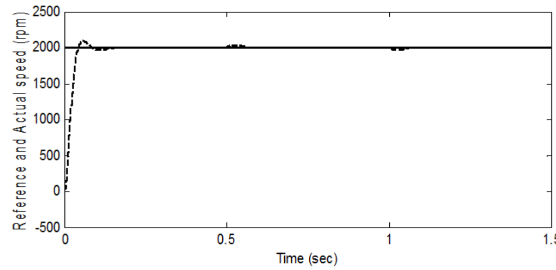
parameter space. The computational flow chart of PSO algorithm is shown in Fig. 5. The parameters of PSO are shown in appendix.

RESULTS AND SIMULATIONS

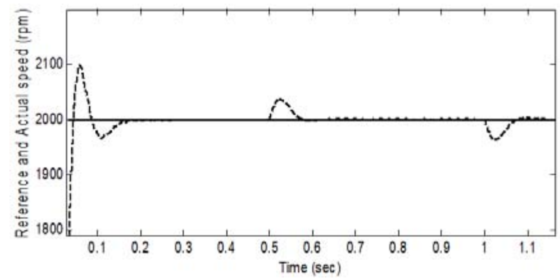
In this section different comparative cases are examined to show the effectiveness of the proposed swarm speed controller and the input voltage of motor. Also, the dynamic operation of motor is discussed.

Effect of controller on dynamic operation: Figure 6 shows the step change of load torque. The speed response due to step change of load torque is shown in Fig. 7a and the zoom for actual motor speed and the reference speed is shown in Fig. 7b. The actual speed tracks the reference speed with minimum overshoot and minimum settling time. The overshoot and settling time are approximately 0.05% and 0.12 sec respectively. Moreover, the speed response is very fast for step change of load torque. The parameters of proposed swarm PI controller are $K_p = 0.0127$ and $K_i = 0.7935$.

No swarming controller and input voltage ≠ average value: Figure 8 shows the variation of the load



(a)



(b)

Fig. 7 (a) The motor actual and reference speed; (b) The zoom for motor actual and reference speed

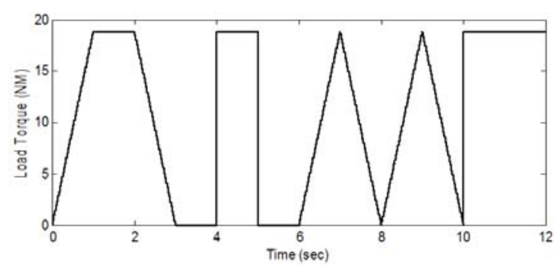


Fig. 8: The high disturbance load torque

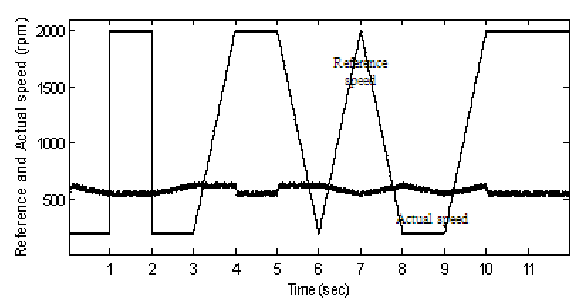
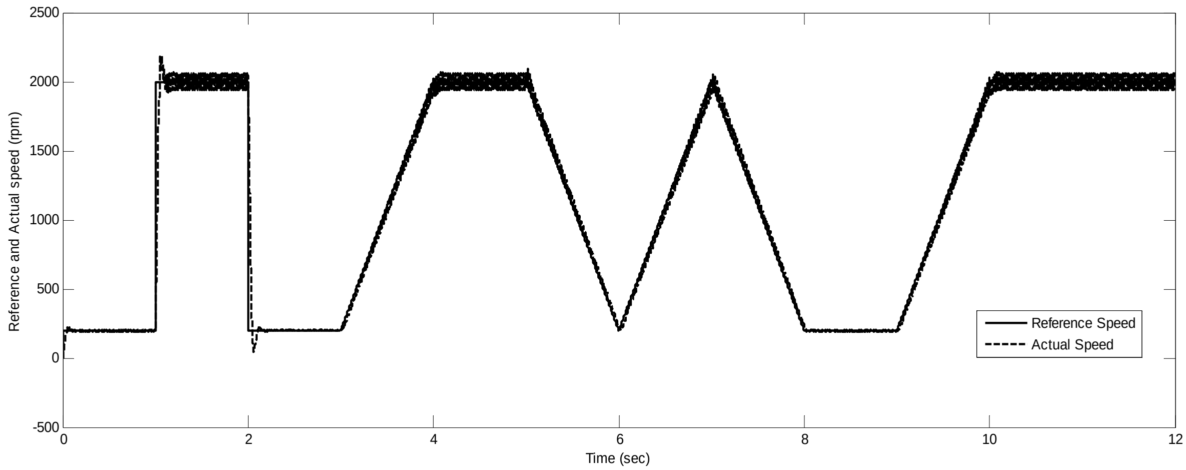


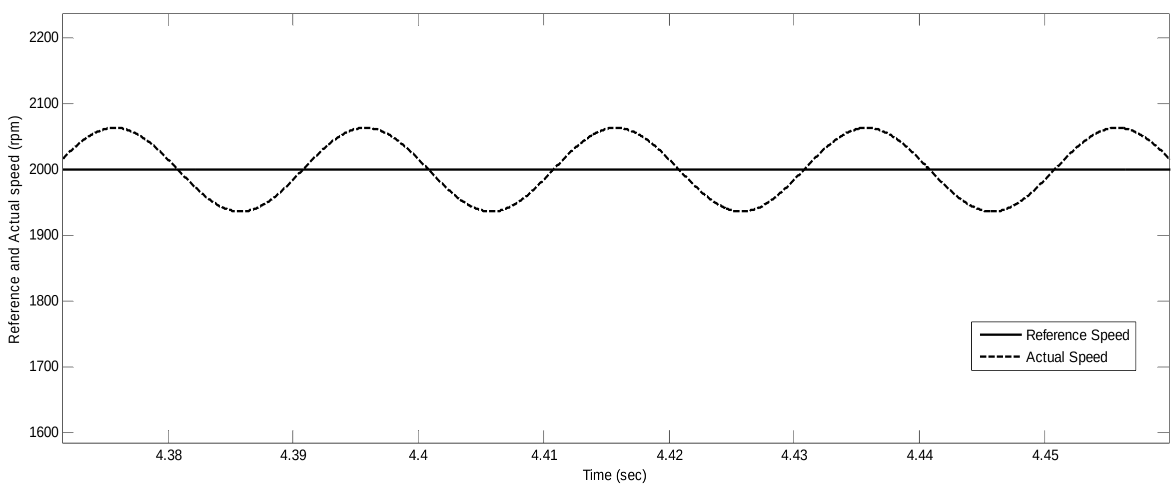
Fig. 9: The motor actual and the reference speed

torque as a disturbance. The effect of absence of swarming speed controller and the input voltage of the motor isn't the average value of the output DC/DC converter is shown in Fig. 9. It is clear that, there is a large difference between actual and reference speed.

Swarming controller and input voltage ≠ average value: A comparison between the actual and reference



(a)



(b)

Fig. 10: (a) The actual and reference speed of DC motor; (b) The zoom of actual and reference speed

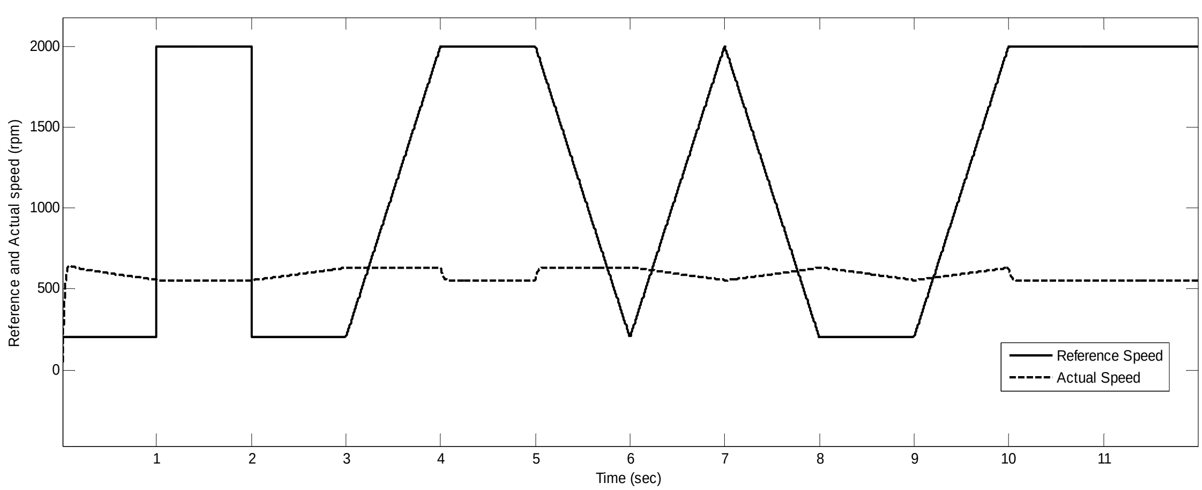


Fig. 11: The actual and reference speed

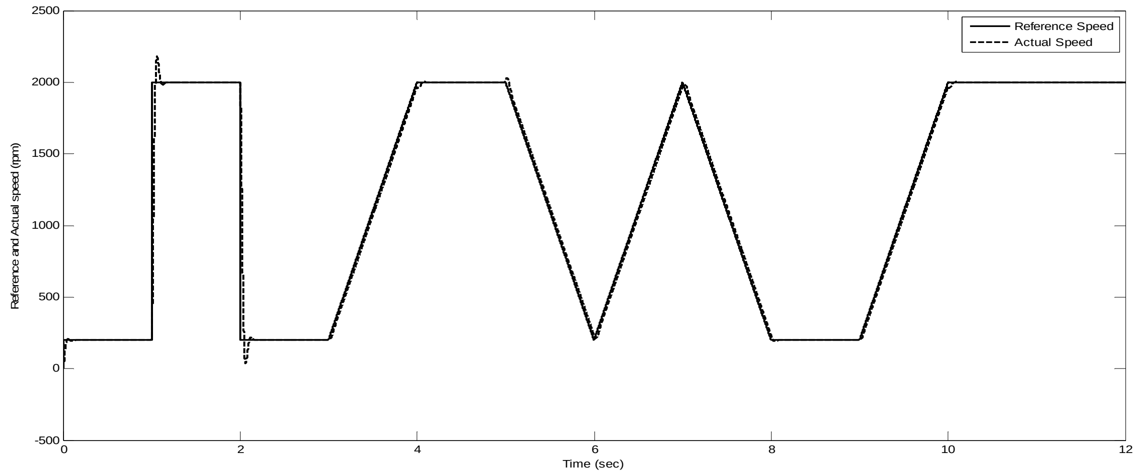


Fig. 12: The actual and reference speed of DC motor

speed when the input voltage of the motor isn't the average value of the DC/DC converter and applying swarming speed controller is shown in Fig. 10a. Moreover, the zoom for actual motor speed and the reference speed is shown in Fig. 10b. From these figures, the actual speed tracks the reference speed at every step. On the other hand, the actual speed suffers from high oscillations around steady state value. Also, it is critically damped response.

No swarming controller and input voltage = average value: Figure 11 shows the response of speed without swarming controller and the input voltage of the motor is the average value of the output DC/DC converter. From this figure, it is found the actual speed isn't tracking the reference speed. On the other hand, this response is a little best when compared with the response in Fig. 9.

Swarming controller and input voltage = average value: The effect of applying the proposed swarming controller and taking the input voltage equals to average value of the output DC/DC converter is shown in Fig. 12. It is clear from this figure, that the actual speed tracks the reference speed. Moreover, the actual speed reaches steady state value at every step of reference speed. Also, the oscillations of speed response have been damped quickly.

CONCLUSION

In this study, a novel method of speed controller of DC permanent magnet motor is proposed via PSO and DC/DC converter. The design problem of the proposed controllers is formulated as an optimization problem and PSO is employed to search for optimal parameters of PI controller. By minimizing the time domain objective function, in which the difference between the reference and actual speed are involved; speed control of DC permanent magnet motor is improved. The system is tested for the change in the input voltage for DC permanent magnet motor with the presence of swarm controller. Also, the dynamic starting operation of motor is discussed. Simulation results have shown that, the effectiveness of the proposed swarming controller and taking the average value of input voltage in providing good speed tracking over a wide range of load torque.

APPENDIX

(a): The specification of permanent magnet DC motor used for simulation is given in the following table.

DC motor parameters	Value
Motor rating	2.5HP
Motor rated voltage	240 V
Motor rated current	10 A
Inertia constant J	0.068 Kg-m^2
Damping constant B	0.001 N.m.Sec./rad
Armature resistance R	1.43 Ω
Armature inductance L	0.0104 H
Motor Speed	1200 rpm
Armature torque constant Kt	1.8 A. H/rad
Full load torque	18.85 N.m

(b): PSO parameters: c_1, c_2 =2.0, ω=0.9.

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