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Performance Comparison of PI and IP Controller in Speed Control of DC Motor

Saleh Ebn Sharif[1] and Anamika Bose[2]

[1,2]Department of Electrical and Electronic Engineering,
Bangladesh University of Engineering and Technology, Dhaka, Bangladesh
[2]Department of Electrical Engineering, West Bengal University of Technology, Calcutta, India
Saleh.electrical07@gmail.com

ABSTRACT

Nowadays, DC motor plays important role due to its ability to control torque & flux independently and the speed control of DC motor is an important issue to the engineers. In this paper, the speed control methodology of DC motor has been discussed and to control precisely the performance of PI and IP controller have been studied. Though, PI controller is used in speed control purpose widely due to its simplicity but it has some disadvantages, for example, high starting overshoot, high sensitivity and slow response in sudden disturbance. To overcome this disturbance IP controller is proposed and studied. The performance of these two controllers has been studied in various simulation conditions in MATLAB/SIMULINK. After comparison, IP controller shows better performance in terms of overshoot and steady state error.

Key words: PI controller, IP controller, DC motor, Speed control, Overshoot, Settling time

INTRODUCTION

Nicola Tesla first developed the poly-phase induction motor in 1886 and by 1890 the simple three-phase motor had been developed. Currently, the main types of electric motors are still the same, DC, Alternating Current (AC) asynchronous and synchronous, all based on Oersted, Faraday and Tesla's theories developed and discovered more than a hundred years ago. An electric drive performs the conversion of electrical energy to mechanical energy or vice-versa. Electric drives may run at constant speed or at variable speed. Both DC and AC motors have been extensively used in control systems but each has its own characteristics [1]. DC motor drives, because of their simplicity, ease of application, high reliabilities, flexibilities and favourable cost have long been a backbone of industrial applications where speed control of motor are required. Therefore, the control of the speed of a DC motor is an important issue and has been studied since the early decades in the last century [1-2]. The most commonly used controller for the speed control of the DC motors is conventional PI controller.

Conventional PI controllers have several important features. The reason is that the conventional PI controller is easy to implement either by hardware or by software. Furthermore, it has the ability to eliminate steady state offset trough integral action and it can anticipate the changes through derivative action. In addition to this, traditional PI controllers have very simple control structure and inexpensive cost [9]. In spite of the major features of the classical PI controller, it has some disadvantages. This makes the use of traditional PI controller a poor choice for industrial variable speed drive applications where higher dynamic control performance with little overshoot and high efficiency is required. However, the PI controller has some disadvantages such as the high starting overshoot in speed, the sensitivity to controller gains and sluggish response due to sudden change in load torque disturbance. So, the relatively IP controller is proposed to overcome the disadvantages of the PI controller [3].

The main objectives of this paper is to formulate the complete mathematical model and state space representation of the separately excited DC motor and study and understand PI and IP controllers to control the speed of the separately excited DC motor. Then evaluate the performance of the speed control of the separately excited DC motor using two controllers and compare the performance of the PI and IP controllers via simulation results using MATLAB/SIMULINK software.

SEPARATELY EXCITED DC MOTOR

The schematic circuit diagram of the separately excited DC motor is illustrated in following Figure 1. When the armature of a DC machine rotates in the stator field, a voltage is induced in the armature winding. In a DC motor, it is called counter EMF or back EMF. In either case, the level of this voltage can be calculated using Faraday's Law, which states that a voltage is induced. The field and armature circuits are totally separate. The field current is supplied from a secondary source [1-2].

A DC Motor works on the principle that whenever a current carrying conductor is placed in a magnetic field, it experiences a force. The magnitude is given by equation 1.

$$F = B.I.L \tag{1}$$

Where: F = Force in Newton's, B = Flux density in Web/ m^2, I = Current in amperes flowing through the conductor, L = Length of the conductor in meters.

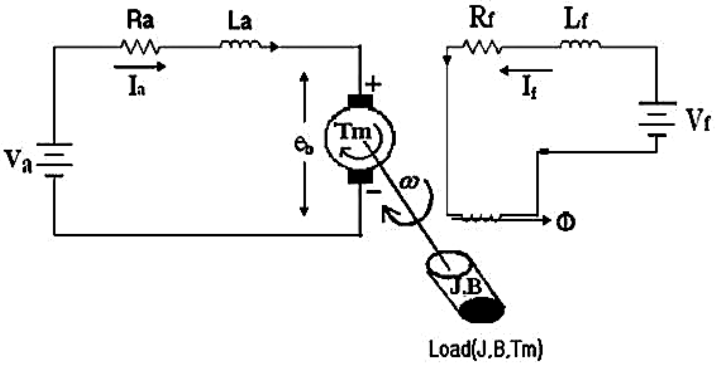


Fig.1 Separately excited DC motor

Speed Control of DC Motors

Speed control of a motor refers to the intentional change of the motor speed to a value needed for performing the required work. Many applications require the speed of a motor to be varied over a wide range. One of the most attractive features of DC motors in comparison with AC motors is the ease with which their speed can be varied. Based on the operating parameters, the speed of DC motors governed by the equation:

$$\omega = \frac{V_a - R_a I_a}{\emptyset K_b} \tag{2}$$

On the right hand side of the Equation (2) there are three operating parameters, namely, the voltage applied to the armature circuit (V_a), the voltage drops in the armature circuit (I_a R_a) and the useful flux per pole (Φ). From this equation, it is evident that the speed can be varied by using any of the following methods [1- 2].

- By varying the resistance (R_a) in the armature circuit. This is known as armature control method.
- By varying the flux per pole (Φ). This is known as flux control method.
- By varying the applied voltage (V_a). This is known as voltage control method

Armature Resistance Control Method

Armature resistance control provides a means of obtaining reduced speed by insertion external series resistance in the armature circuit. It can be used with series, shunt, and compound DC motors. For the last two types of DC motor, the series resistor must be connected between the shunt field and the armature, not between the line and the motor. It is a common method of speed control for series motors. Depending upon the value of the series resistance, the speed may vary significantly with the load, since the speed depends on the voltage drop in this resistance and hence on the armature current demanded by the load. A significant disadvantage of this method of speed control is that the power loss in the external resistor is large, especially when the speed is greatly reduced [1-2].

Flux Control Method

Another approach to control the speed of a DC motor involves the control of the field current, which in turn controls the flux in the motor. The field current in a shunt DC motor can be controlled by inserting an external resistor in series with the field winding. Because the field current is a very small fraction of the total current intake of a shunt DC motor, the power dissipated by the external resistor is relatively small. Therefore, the flux control method is economically better than the armature resistance control method. To control the flux in a series DC motor, a field diverter resistor can be connected in parallel with the series field winding. If all the coils in a series field winding are connected in series, we can also change the flux in a series motor by connecting the coils in parallel.

The addition of a resistance in series with the shunt field winding or in parallel with the series field winding causes the field current and thereby the flux in the motor to decrease. Since the speed of a motor is inversely proportional to its flux, a decrease in its flux results in an increase in its speed. Thus, the flux control method makes a motor operate at a speed higher than its rated speed. As the torque developed by a shunt DC motor is proportional to the product of the armature current and the flux per pole, a decrease in the flux must be accompanied by a corresponding increase in the armature current for the motor to deliver the same torque. This method of speed control is, therefore, not satisfactory for compound DC motors, because any decrease in the flux produced by the shunt field winding is offset by an increase in the flux produced by the series field winding owing to an increase in the armature current [1- 2].

Armature Voltage Control Method

This method is usually applicable to the separately excited DC motors. In the armature voltage control method, the voltage applied to the armature circuit is varied without changing the voltage applied to the field circuit of the motor. So, the motor must be separately excited to use armature voltage control. The advantage of this method is that it has a wide range of speed control from zero up to the rated speed. However, it is quite expensive. Therefore, this method of speed control is employed for large size motors where efficiency is of great importance [1-2].

MATHEMATICAL MODEL OF THE SEPARATELY EXCITED DC MOTOR

The general system description refers to a mathematical expression that appropriately relates the physical system quantities to the system components. This mathematical relation constitutes the mathematical model of the system. A system in operation involves the following three elements: the system's input (or excitation), the system itself, and the system's output (or response). The mathematical model of a system is a mathematical relation which relates the input, the system, and the output. This relation must be such as to guarantee that one can determine the system's output for any given input. From the above definition it follows that the mathematical model is not just any relation, but a very special relation, which offers the capability of system analysis, i.e., the capability to determine the system's response under any excitation. Furthermore, the foregoing definition reveals the basic motivation for determining mathematical models. This motivation is to have available appropriate tools that will facilitate the system analysis. It is well known that in order to analyze a system, it must have available its mathematical model. It should be also noted that the mathematical model is useful for other purposes, as for example to study the system's stability and other properties, to improve the system's performance by applying control techniques [2]. There are several types of mathematical models have been proposed for the description of system. The most popular ones are the following:

(1) The differential equations (2) The transfer function and (3) The state equations.

In this project the state space equations are used. The state space equation is description in time domain which may be applied to very wide category of systems, such as linear and nonlinear system. The term state of a system refers to the past, present, and future of the system. Usually, a system is described by a finite number of state variables [2].

Model of the Separately Excited DC Motor

Direct current motors are widely used for industrial and domestic applications. The control of the speed of a DC motor with high accuracy is required. There are two main ways of controlling a DC motor: The first one named armature control consists of maintaining the stator magnetic fluxconstant, and varying the armature current. Its main advantage is a good torque at high speeds and its disadvantage is high energy losses. The second way is called field control, and has a constant voltage to set up the armature current, while a variable voltage applied to the stator induces a variable magnetic flux. Its advantages are energy efficiency, inexpensive controllers and its disadvantages are a torque that decreases at high speeds. In this project, the separately excited DC motor model is chosen according to his good electrical and mechanical performances more than other DC motor models. The electric circuit of the separately excited DC motor is shown in Figure 1. The main objective is to control the speed of the separately excited DC motor by armature voltage control [1-2]. From Figure 1, the dynamics of a separately excited DC motor may be expressed as [2]:

$$Va = R_a I_a + \frac{di_a}{dt} + E_b$$

$$Va = R_a I_a + \frac{di_a}{dt} + E_b + K_b\,\omega \tag{3}$$

$$T = K_T\, i_a = J\,\frac{d\,\omega}{dt} + B\omega \tag{4}$$

Where V_a is the input terminal voltage (armature voltage) in volt, E_b is the motor back EMF in volt, R_a is the armature resistance in ohm, L_a is the armature inductance in H, Kb is the back EMF constant in Vs/rad, is represents angular speed in rad/s, i_a is the armature current in A, J is the moment of inertia of the motor in kgm^2/s^2, T is the motor torque in Nm, B is the viscous friction coefficient in Nms/rad, and KT is the torque factor constant in Nm/A.

State Space Equations

Equation (3) and Equation (4) are rearranged to obtain:

$$\frac{di_a}{dt} = -\frac{R_a}{L_a} i_a - \frac{K_b}{L_a} \omega + \frac{V_b}{L_a} \tag{5}$$

$$\frac{d\omega}{dt} = -\frac{K_T}{J} i_a - \frac{B}{J} \omega \tag{6}$$

In the state space model of a separately excited DC motor, the Equation (3.3) and Equation (3.4) can be expressed by choosing the angular speed (ω) and armature current (i_a) as state variables and the armature voltage (V_a) as an input. The output is chosen to be the angular speed [2].

$$\begin{vmatrix} \frac{di_a}{dt} \\ \frac{d\omega}{dt} \end{vmatrix} = \begin{vmatrix} i_a \\ \omega \end{vmatrix} = \begin{vmatrix} \frac{-R_a}{L_a} & \frac{-K_b}{L_a} \\ \frac{K_T}{J} & \frac{-B}{J} \end{vmatrix} \begin{vmatrix} i_a \\ \omega \end{vmatrix} + \begin{vmatrix} 0 \\ \frac{1}{L_a} \end{vmatrix} V_a \tag{7}$$

$$y = [0 \quad 1] \left[{i_a \atop \omega} \right] \tag{8}$$

The physical and functional parameters of the separately excited DC motor used for simulation testing are given in Table -1.

Table -1 Parameter of the Separately Excited DC Motor

Parameter	Description	Value
R_a	Armature resistance	1Ω
L_a	Armature inductance	0.05 H
J	Moment of inertia	0.01 kgm^2/s^2
B	Viscous friction coefficient	0.00003 Nms
K_T	Torque constant	0.023 Nm/A
K_b	Back EMF constant	0.023 Vs/rad

PI AND IP CONTROLLER

PI Controller Background

The conventional PI controller remains the most popular design approach used in industrial applications due to its simplicity and reliability for the control of first and second order plants, and even high order plants with well-defined conditions. A well-tuned PI controller is capable in achieving an excellent performance. However, the PI controller has some disadvantages such as the high starting overshoot in speed, the sensitivity to controller gains and sluggish response due to sudden change in load torque disturbance. Fig. 2 shows the block diagram configuration of the conventional PI controller [3, 9].

Where it can be seen that in a PI controller the error e(t) is used to generate the proportional and integral action with the resulted signals weighted and summed to form the control signal u(t) applied to the plant model. The differential equation of a conventional PI controller is:

$$u(t) = K_p e(t) + K_I \int e(t)dt$$

Where K_P is the proportional gain and K_I is the integral gain. The transfer function of a classical PI controller is expressed as follows:

$$G_{PI}(s) = U(s) / E(s) = K_P + K_I / S$$

The effects of each gain controllers KP and KI on a closed-loop system are summarized as shown in Table -2.

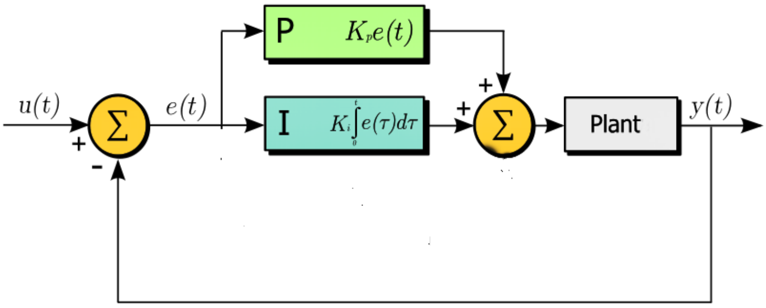


Fig. 2 Block diagram of PI controller

Table -2 PI Controller Characteristic Parameters

Close Loop Response	**Rise Time (T_r)**	**Overshoot (M_p) %**	**Settling Time (T_s) sec**	**Steady State Error (e_{ss})**
K_p	Decrease	Increase	Small change	Decrease
K_I	Decrease	Increase	Increase	Eliminate

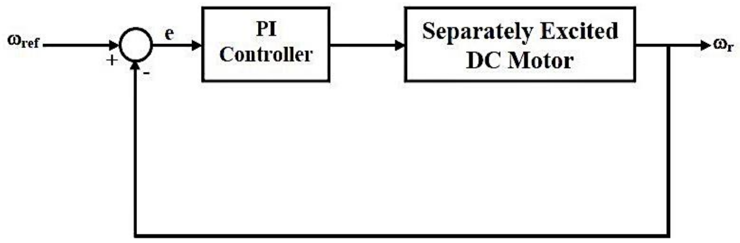


Fig. 3 Simplified block diagram of speed control of DC motor using PI controller

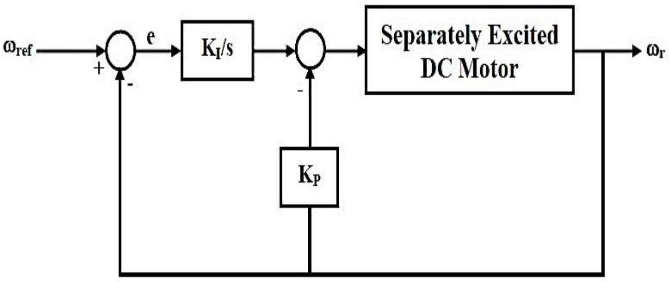


Fig. 4 Block diagram of DC motor speed control using IP controller

Note that these correlations may not be exactly accurate, because KP and KI are dependent of each other. In fact, changing one of these variables can change the effect of the other two. For this reason, the table should only use as a reference when we are determining the values of KP and KI. To improve the dynamic performance for transient state and avoid overshoot, the speed control is confided to an integral plus proportional controller [3]. The IP controller is considered the major contribution in this study. A simplified block diagram of the speed control of the separately excited DC motor using the PI controller is shown in Fig. 3 [4].

IP Controller Background

Takahashi, Harashima and Kondo suggested a new method of control calledIP controller as a trial to solve the main problems of PI controller [6]. Figure 4 shows IP controller along with the separately excited DC motor, where the proportional term is moved to the feedback path and it acts like feedback compensation [4, 7].

PI and IP Controllers Tuning

Tuning the PI and IP controller is adjusting of its parameter gains KP and KI to the optimum values for the desired control response. There is according various method for loop tuning, the traditional manual method for loop tuning is used in this paper [3].

DESIGN AND SIMULATION

A comparative study of PI and IP control scheme for the separately excited DC motor has been done here. Two simulation tests for the separately excited DC motor were carried out using both IP controller and conventional PI controller. Simulation tests are based on the facts that whether the IP controller is better than the conventional PI controller or not.

MATLAB/ SIMULINK Model for DC Motor

MATLAB is a simple and flexible programming environment for a wide range of problems such as signal processing, optimization, linear programming and control systems. The basic MATLAB software package can be extended by using add-on toolboxes such as: fuzzy logic toolbox andcontrol toolbox. With the complexity of medium-size to large-size nonlinear models, it may be more efficient to use a set of differential equations written in an m-file. These m-files will be accessed by SIMULINK through the S-Function block. Thus, this method mixes the advantages of an m-file with the graphical links to other SIMULINK blocks. The state space equations (3) and (4) can be written into MATLAB/SIMULINK by using S-Function block. This file will be saved as an m-file. It contains the protocol in which SIMULINK can access information from MATLAB as shown in Fig. 5.

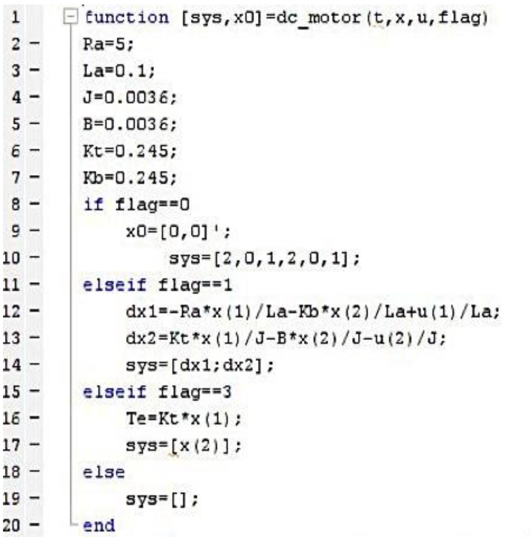
The first line specifies the S-Function name (here dc-motor), input and output arguments. The input and output arguments are classification as follows [5]:

(a) Input Arguments

- t is the time variable.
- x is the column-vector of state variables.
- u is the column-vector of input variables (whose value will come from other SIMULINK blocks).
- Flag is indicator of which group of information and/or a calculation is being requested by SIMULINK. There are many types of flags; here we described their flags as shown in Table 3.

Table -3 Three Type of Flags

Flag	Data Request
0	Initialization: a) Setup of input/output vector sizes and other setup modes b) Specification/ calculation of initial conditions for the state variables
1	Derivatives Equation Updating: a) Calculation involving input vectors b) Calculation of the derivatives
3	Output calculations: Evaluating output variables as a function of the elements of the state vector (and in some case, also the elements of the input vector)



```
function [sys,x0]=dc_motor(t,x,u,flag)
Ra=5;
La=0.1;
J=0.0036;
B=0.0036;
Kt=0.245;
Kb=0.245;
if flag==0
    x0=[0,0]';
        sys=[2,0,1,2,0,1];
elseif flag==1
    dx1=-Ra*x(1)/La-Kb*x(2)/La+u(1)/La;
    dx2=Kt*x(1)/J-B*x(2)/J-u(2)/J;
    sys=[dx1;dx2];
elseif flag==3
    Te=Kt*x(1);
    sys=[x(2)];
else
    sys=[];
end
```

Fig. 5 S function block

Table -3Three Type of Flags

Flag	Data Request
0	Initialization: a) Setup of input/output vector sizes and other setup modes b) Specification/ calculation of initial conditions for the state variables
1	Derivatives Equation Updating: a) Calculation involving input vectors b) Calculation of the derivatives
3	Output calculations: Evaluating output variables as a function of the elements of the state vector (and in some case, also the elements of the input vector)

Table -4 Type of sys

Flag	Operation
If flag =0	Sys = [a, b, c, d, e, f, g] Where: a is number of continuous time states b is number of discrete time states c is number of outputs d is number of the inputs e = 0 (required to be 0, not currently used) f = 0 (no) or 1 (yes) for direct algebraic feed through of inputto output. (This is relevant only if during flag=3, the outputvariables depend algebraically on the input variables) g is number of sample times. (for continuous process, we setthis equal to 1)
If flag = 1	sys =a column vector of the derivatives of the state variables
If flag = 3	sys = a column vector of the output variables

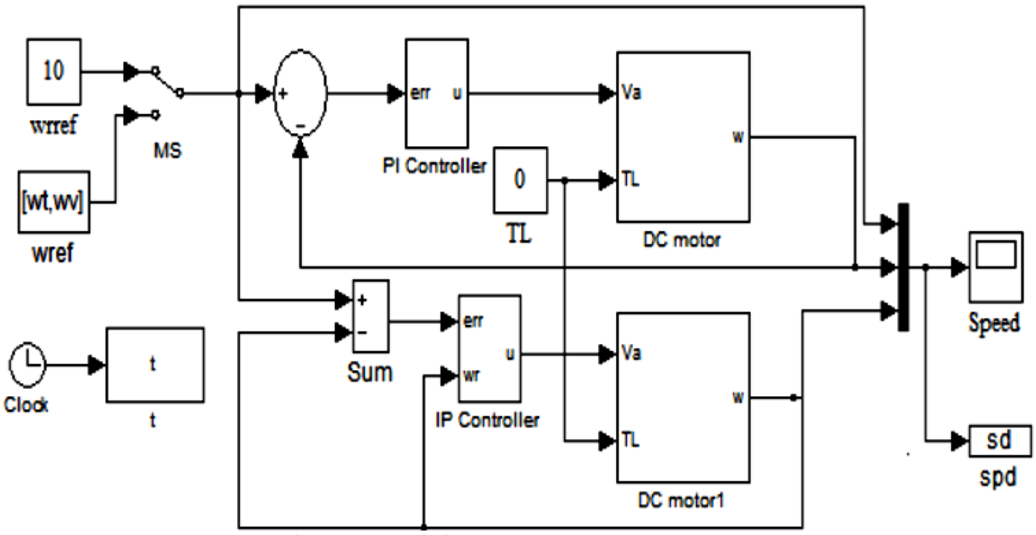


Fig. 5 SIMULINK model of speed control of the separately excited DC motor using PI and IP controller

(b) Output arguments

- Sys is the main vector of results requested by SIMULINK. Depending on the flag sent by SIMULINK, this vector will hold different information as shown in Table -4.
- x_0 is column vector of initial conditions.

The MATLAB/SIMULINK overall model of system under study with conventional PI controller and IP controller is shown in Fig. 5.

RESULT AND DISCUSSION

Constant Speed Command

To test the performance of the speed control of the separately excited DC motor at a constant speed, the separately excited DC motor is started up from standstill to trace the speed command of 10 rad/sec. Figure 6 gives the speed responses of the separately excited DC motor drive with IP controller and ordinary PI controller. In terms of the speed control trajectories shown in Figure 6, two controllers have a similar performance in term of fast tracking of the desired speed. Also, steady state error with both controllers is almost zero. However, in Figure 6 it can be easily observed that the speed response of the separately excited DC motor with IP controller shows no sign of overshoot as observed with classical PI controller thus reducing the settling time. However, the rise time for traditional PI controller is shorter than for IP controller.

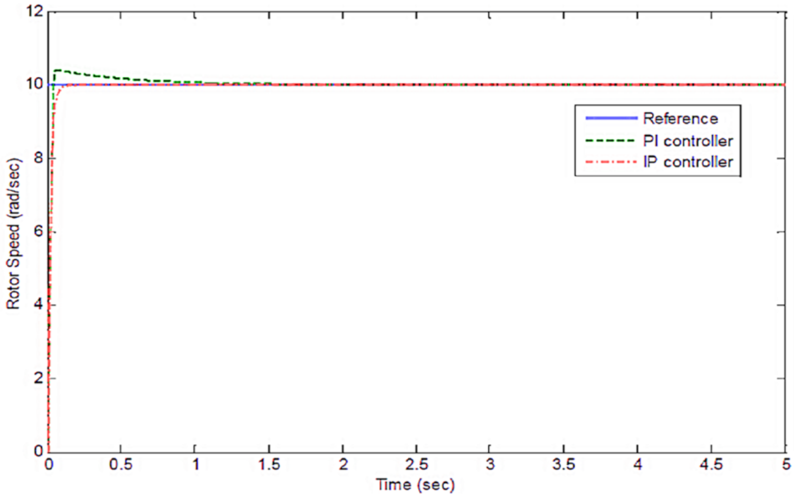


Fig 6 Simulation result at constant speed

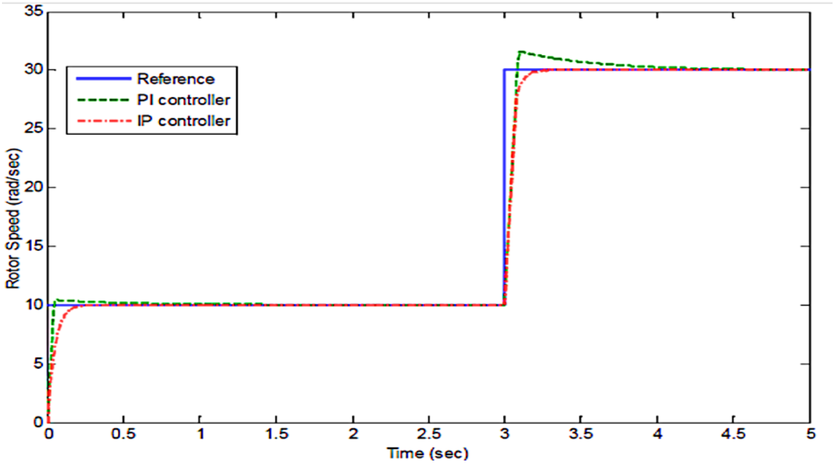


Fig. 7 Simulation result at variable speed

Variable speed command

In this case, the separately excited DC motor is tested under variable speed command. The simulation is performed for 5 seconds. The speed command is 10 rad/sec for the first three seconds then followed by 30 rad/sec for the last two seconds. Figure 7 shows the speed response for a stepped speed reference for IP and standard PI controllers. It can be seen that there is a very good accordance between real speed and reference speed. However, from Figure 7 it is clear that IP controller provided optimum performance in terms of overshoot and settling time. Only rise time remained to be good for conventional PI controller.

CONCLUSION

The control of the speed of a DC motor is an important issue and has been studied since the early decades in the last century. DC motors are generally controlled by conventional PI controller. In spite of the major features of the classical PI controller, it has some disadvantages such as the high starting overshoot in speed, the sensitivity to controller gains and the sluggish response due to sudden change in load torque disturbance. Thus, the relatively IP controller is proposed to solve some disadvantages of the conventional PI controller and achieve accurate control performance of speed control of a DC motor. A series of simulation results have been conducted in order to evaluate the performances of the two controllers using MATLAB/SIMULINK software package. From the comparative simulation results, one can conclude that the two controllers demonstrate nearly the same performances. However, it is observed that IP controller provide important advantages over the traditional PI controller like limiting the overshoot in speed, thus the starting current overshoot can be reduced. In addition, the settling time for IP controller is shorter than for conventional PI controller. The results of this project open some interesting and challenging problems of great importance. We point out some of the possible future research directions to be followed; it would be useful to further compare between IP controller, fuzzy logic control. It also would be useful to further compare between IP controller and neural network schemes for speed control of DC motor.

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