PI and PID Controller Design and Analysis for DC Shunt Motor Speed Control

Irma Husnaini, Krismadinata, Asnil, Hastuti

Abstract*: *This paper proposes a step by step procedure design and analysis of proportional Integral (PI) and proportional integral derivative (PID) controller. These controllers are employed to control the speed of a DC shunt motor. DC shunt motor Characteristics are modeled in s-function, the speed characteristic of motor is analyzed in open loop condition and closed loop condition without controller and Parameter controlling of PI & PID controller is designed by frequency response analysis. Design, analysis and implementation of PI & PID controller are conducted separately. The performances controllers such as rise time (tr), settling time (ts), steady state error, percent overshoot (%OS), and phase margin are compared to both controllers. Design and analysis of controller are verified by simulation, the results show that PID controller that applied speed control DC shunt motor is better than PI controller.

Keywords: DC shunt motor, PI, PID, frequency response

I. INTRODUCTION

DC motors are ones of electric machinery that convert electrical source to mechanical source. These machines are very flexible, have high reliability, flexibility and low cost. DC motor control can be carried out in a wide range with stable and linear characteristics. The use of DC motors can be found, for example as a mechanical load drive motor or industrial applications. DC shunt motor is a widely utilized type of DC motor which is accomplished of sustaining a fix speed regardless of the load of the motor.

One type of DC motor that is widely employed is a DC shunt motor. This is due to its robust construction, simple design, and reliable. Apart from all these advantages, one of the disadvantages of DC shunt motors is that the speed of the motor and the load torque are relatively difficult to regulate. When there is a change in load, the speed of the DC shunt motor will decrease. Speed control is needed to get a fix speed and recover the performance of the DC shunt motor against load changes. Speed control of motor means running the motor at the desired speed for each variation in load changes or references given to the motor. For a application, the motor must be precisely controlled to provide the desired performance [1-3].

Recently, many controller structures have been proposed to speed controls of DC shunt motor. The conventional controllers PI and PID are employed for control of DC motor speed. The PI and the PID are used because of the simplicity of the speed controls of DC shunt motors. By decreasing the overshoot and shortening the settling time, a PID controller increases a system's transient response [4-6]. Due to their simple constructions and easy control algorithms, PID controllers are commonly used in motor control implementations. Parameters of the controller are usually set using Ziegler-Nichols tuning and the frequency response technique.

In this paper, design and analysis to determinate the control parameters is done by frequency response method to get the most optimal control parameter values therefore it has a fast response and good stability. The steps taken are designing, simulating and analyzing and comparing the performance of both controllers.

II. MODEL OF DC SHUNT MOTOR

DC motors, which have parallel connections between the armature and the field winding, are known as DC shunt motors. The current in a shunt motor will be divided into two portions, namely, the current will flow to the armature winding and field winding. Fig. 1 shows the equivalent circuit for DC shunt motor model. [3][9] [10].

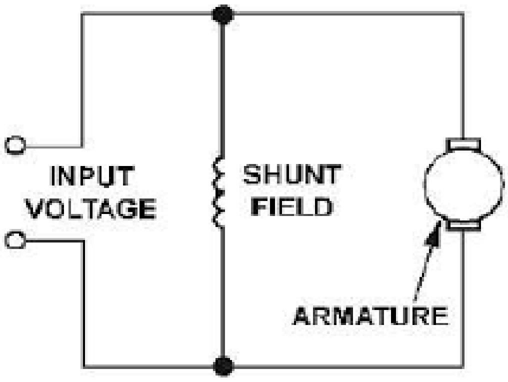

Fig. 1. DC Shunt Motor

The characteristics of DC shunt motor can be modelled in mathematical equations. Equation (1) to (5) show mathematics equation of DC shunt motor in time function. The DC shunt motor has a voltage equation model is as follows [3] [7] [9] [12]

$$V = L\frac{di}{dt} + Ri + e_b \qquad (1)$$

Due to the proportion of the back EMF e_b to the speed ω directly,

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$$e_b = K_b \frac{d\theta}{dt} = K_b \omega \tag{2}$$

Hence,

$$V = L\frac{di}{dt} + R\,i + K_b\frac{d\theta}{dt} \tag{3}$$

The motor torque, T associated to the armature current I by a constant factor K_m as follows:

$$T = K_m i \tag{4}$$

$$T = J\frac{d^2\theta}{dt^2} + b\frac{d\theta}{dt} = K_m i \tag{5}$$

Using the Laplace transform

$$V(s) = LsI(s) + RI\ (s) + K_b s\theta(s) \tag{6}$$

Where (s) is s-function in Laplace operator. The equation (6) can be rearrange in *I(s)* hence

$$I\ (s) = \frac{V(s) - K_b s\theta(s)}{R\ + Ls} \tag{7}$$

$$T(s) = K_m I_a(s)$$

(8)

By substituting equation (7) in equation (8), it is obtained

$$T(s) = K_m\left[\frac{V(s) - K_b s\theta(s)}{R + Ls}\right] \tag{9}$$

$$T(s) = (Js^2 + Bs)\theta(s)$$

(10)

Solve this equation for the angular displacement of shaft producing

$$\theta(s) = \frac{T(s)}{Js^2 + Bs} \tag{11}$$

The transfer function of DC shunt for the angular speed that associated to Va(s) is [9][10].

$$G(s) = \frac{\omega(s)}{V_a(s)}$$

$$G(s) = \frac{K_m}{[L_a Js^2 + (L_a B + R_a J)s + R_a B + K_m K_b]}$$

(12)

Where , R_a is armature winding resistance (ohm) and L_a is armature winding inductance (Henry).

III. CONTROL SYSTEM DESIGN

A. *The PI controller design*

The PI controller is a simple linear control method that is commonly used in varying application. In this controller, proportional K_p gain and integral *Ki* gain are the control parameters. The block diagram PI controller that related to plant system can be shown in Fig. 2. [6] [9] [13].

The input or output relationship with the error feedback for an ideal PI controller,

$$u(t) = K_p e(t) + K_i \int_0^t e(t)dt \tag{13}$$

Where, e(t) = error = Set point (SP) - process variable (PV)

In Fig. 2 shows the PI control block diagram with error compensation system. The error is increased by a gain K_p and the error is integrated by a coefficient Ki. Both of results are added. The Laplace transform of the actuating signal in the PI controller is

$$U(s) = K_p.E(s) + K_i\frac{.E(s)}{s} = \frac{(K_p s + K_i)E(s)}{s} \tag{14}$$

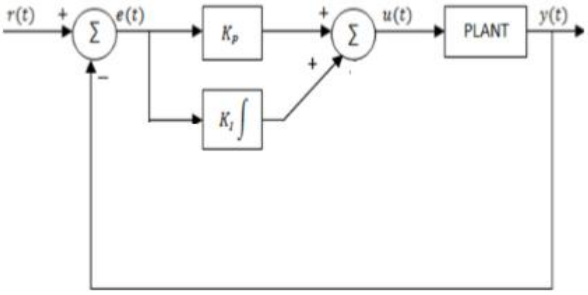

Fig. 2. PID controller block diagram

Let the control be a PI as is given by

$$G(s) = \frac{U(s)}{E(s)} = \frac{K_p s + K_i}{s} \tag{15}$$

Design procedures of PI controller as follows: [6]:

1. Determine the frequency ω_1 where the angle G ($j\omega_w$) is equal to (-180°+ϕ_m°+5^0), with ϕ_m is the desired phase margin.
2. Determine the value
$$K_p = \frac{1}{|G(j\omega_1)H(j\omega_1|} \tag{16}$$
3. Calculate magnitude 0 with the equation
$$\omega_0 = 0{,}1\omega_1 \tag{17}$$
Therefore
$$K_I = \omega_0.K_p \tag{18}$$
4. Substitute of equation (16), (18) to equation (15).

Integral control elements have a weakness in dynamic response, where the arrangement of closed oscillates with amplitude that slowly decreases or even an amplitude that enlarges, usually both of these are undesirable [7].

B. *The PID Controller design*

The PID controller is a linear control system which comprises of proportional, integral and derivative. The combined operation of these three controllers provides process control strategies. The PID controller is PI controller plus derivative element. The derivative gain elements is necessary to avoid the oscillations and overshoot in the response output of plant system. PID controller is the most frequently used controller design algorithm and the most frequently used in the sector. The PID controller offers optimal control dynamics, quick response (short-rise time), including zero steady state error, increased stability and no oscillations.

The error feedback is the deviation of desired value and actual value. The error will be compensated by PID elements. By modifying process control inputs, the controller tries to minimize the error. [5] [6] [13]. The block diagram for PID controller with plant system can be shown in Fig. 3.

The PID Controller Equation can be written as follows [6] [7]:

$$u(t) = K_p \left(e(t) + \frac{1}{T_i} \int_0^t e(t)dt + T_d \frac{de(t)}{dt} \right) \qquad (19)$$

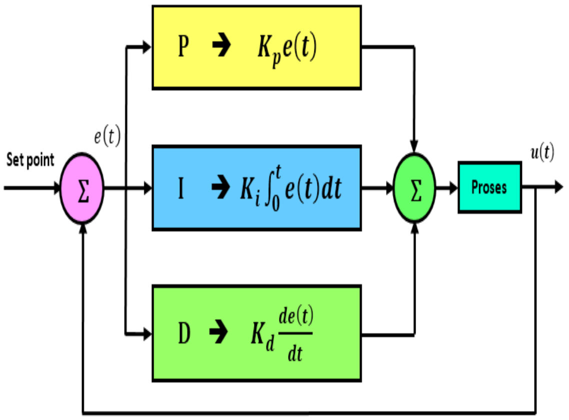

Fig. 3. PID controller block diagram

Taking the Laplace transform ,

$$U(s) = K_p \left(E(s) + \frac{1}{T_i s} E(s) + T_d E(s) \right) \qquad (20)$$

This controller has a transfer function

$$\frac{U(s)}{E(s)} = K_p \left(1 + \frac{1}{T_i s} + T_d \right)$$

(21)

where

$$K_i = \frac{K_P}{T_i},\ K_d = K_p . T_d \qquad (22)$$

Therefore, the PID controller transfer function:

$$\frac{U(s)}{E(s)} = G_c(s) = K_p + \frac{K_i}{s} + K_d s$$

(23)

Where

K_p = proportional gain
T_i = time constant of integral
T_d = time constant of derivative
K_i = integral gain
K_d = derivative gain

There are many methods to design and analysis control system such as the Root Locus, Routh- Hurwitz Criterion and response frequency. In this paper, the frequency response method is employed to design procedure and process of determining the operator parameters, K_p, K_i and K_d to meet the specifications provided. The PID operator designing procedure is as follows [6]:

1. Determine the frequency ω_1 where the phase angle $G(j\omega_w)$ is equal to (-180°+ϕ_m°- $\angle G(j\omega_1)H(j\omega_1))$, with ϕ_m is the desired phase margin.
2. Determine the value of K_p

$$K_p = \frac{Cos\theta}{|G(j\omega_1)H(j\omega_1|} \qquad (24)$$

$$K_d = \left[\frac{\sin\theta}{\omega_1 |G(j\omega_1)| H(j\omega_1)} \right] + \frac{K_I}{\omega_1{}^2}$$

(25)

3. Substitute of equation (24), (25) to equation (23).

The PID controller features are affected by the significant contribution of the three control parameters. The proportional gain (K_p) increases the time response but leads in oscillation and process instability. The integral gain (K_i) is quicker in trying to eliminate steady state errors, but it makes the plant system overshoot. The gain derivatives (K_d) will decrease the overshoot, but slump the transient response and can cause instability. The control parameters must be determined based on the controlled characteristics [5] [7].

There are three common goals of a control design, namely:

- Minimum(zero) Steady state error
- Overshoot (0%, 5% or 10% are common values)
- The output of plant control system generates rising time less than certain limit .

C. *Transient response characteristics*

Control system design specification often includes certain system response time demands. The step responses specifications are specified in the quantity of criteria and are shown in Fig. 4. There are some parameters that must be considered, namely the rise time (t_r), settling time (t_s), maximum overshoot (M_p) and maximum peak time (t_p). The t_r is time the system needs to achieve its new setting nearby. The t_s is time desired for the damped oscillation of the transient to reach and remain within ±2 percent of the steady-state value. The M_p is the percentage maximum of peak value on the response curve that compared to required value. Meanwhile, t_p is time required to reach the maximum excess point [6][7][14].

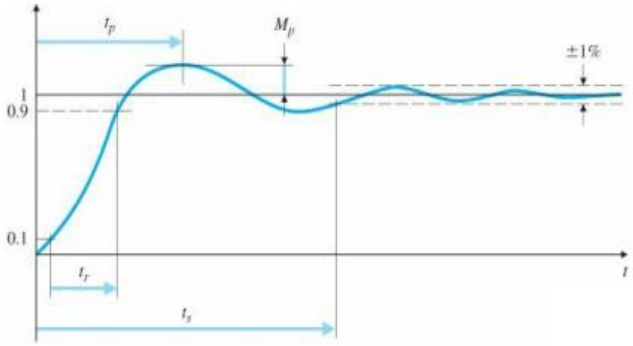

Fig. 4. Unit step response curve

Due to motor DC shunt model and PID controller are second order differential equation, thus design control for second-order systems specifically:

$$s^2 + 2\xi\omega_n s + \omega^2{}_n = 0 \qquad (26)$$

Where the ζ is parameter of damping ratio, and the undamped natural frequency is symbolled by ω_n. For second order- systems with $0 < \zeta < 1$ and $\omega_n > 0$ In Fig. 4 the system step response is illustrated [6]. The damping ratio of the second-order system is therefore between 0.4 and 0.8 for a desirable transient response. Bode diagram can be used to identify the stability of the system.

In Fig. 5 can be shown, for a stable system, the gain margin and phase margin may be positive, and vice versa, the system will become unstable if the gain margin and the phase margin is negative. A control system with a sufficiently stable margin has a phase margin of 45^0 or more, with a gain margin of 8 dB or more.

The phase margin determines the DC shunt switching motor response. Increased phase margin makes the system more stable by reducing oscillation.

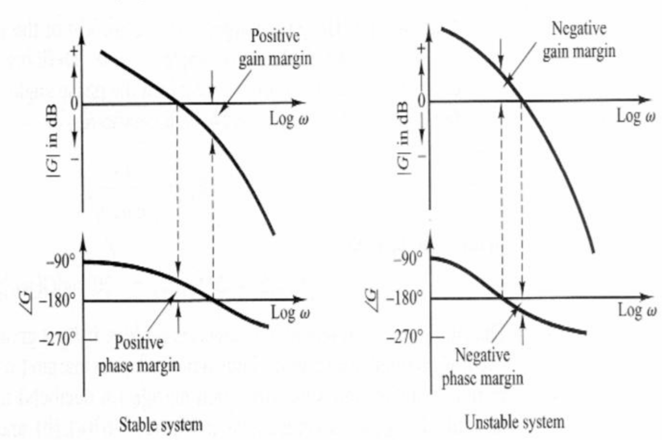

Fig. 5. Bode diagram with for stable and unstable systems

IV. RESULTS AND DISCUSSION

Design and analysis is conducted by using a simulation method. Simulink/Matlab is used to see the controller performance in a graphical form. The following steps are carried out:

- Simulate a DC shunt motor model without speed controller
- Design and simulate PI and PID controllers
- Simulate characteristics of motor model with disturbance
- Analyze and compare the performance both of controllers desired system specifications.

Hence, these criteria can be met, the desired system specifications are determined as follows: Damping factor $\zeta = 0.55$. Overshoot $\leq 10\%$ with Phase margin $= 55^0$. The system has fast rise time, zero steady-state error and fast settling time. In this paper the specifications and parameters of the shunt motor are used (see Table-I) as follows [10]:

Specifications: Power: 2-HP, 1500 rpm, 8.5A, 230 V.

Table-I: Typical Parameter for DC shunt motor

Parameter	Symbol	Typical Value
Power	P	2 HP
Nominal Speed	ω	1500 rpm
Current	I	8.5A
Voltage	V	230 V
Inertia	J	0.022Kg-m^2/rad
Friction	B	0.2x0^{-3} N-m/(rad/sec).
Motor constant	Kb	0.5 volt/(rad/sec),
Resistance of Armature	Ra	0.45 Ω
Inductance of Armature	La	0.035 H

The transfer function for the given parameter is

$$G(s) = \frac{0.5}{0.00077\,s^2 + 0.009907\,s + 0.2501} \qquad (27)$$

The step responses of plant system for the open loop and the closed-loop system are shown in Fig 6 and 7. Based on Fig. 6 to 8 can be analyzed that characteristics motor has been not desired yet. The characteristic motor on open-loop and closed-loop without controller condition can be shown in Table-II.

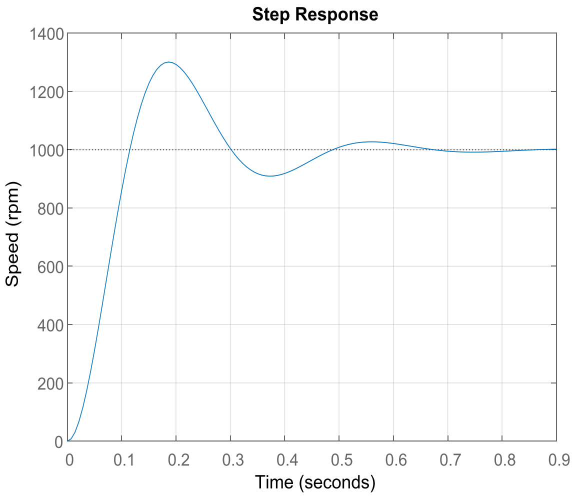

Fig. 6 Output of the open loop system without control

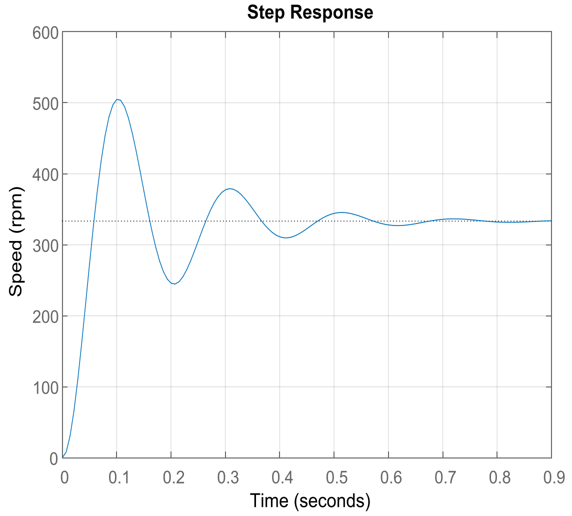

Fig. 7. Output of the closed loop system without control

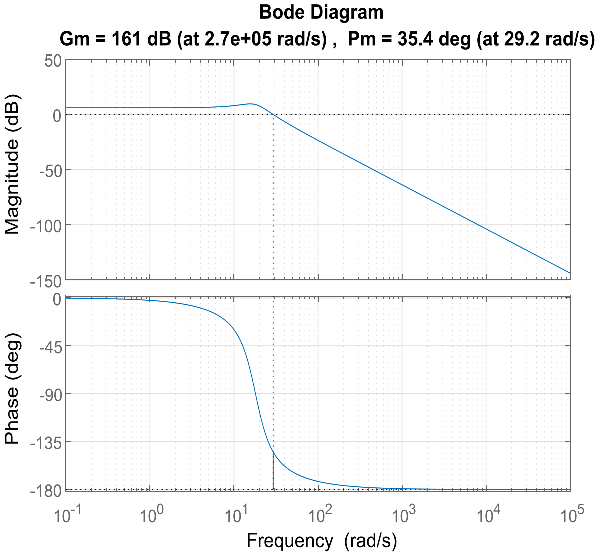

Fig. 8. Frequency response without control

Table-II: Performance motor without a controller

Plant conditions	Open loop	Closed loop
Rise Time (s)	0.0778	0.0389
Percent Overshoot	30.1	51.4
Settling time (s)	0.606	0.549
Steady state error	-	33.4%
Phase margin(degree)	$35,4^0$	

Calculating of the system open loop frequency response shows that this system results in a phase margin of approximately 35.4^0 and a gain margin of approximately 261 dB. Based on the results obtained the system does not meet the desired criteria. The speed produced by a DC shunt motor does not match the reference given where there is large error. A control unit is required to design to eliminate the error of the steady-state system.

A. *PI Controller Design*

The specification of the PI controller design is $\phi_m = 55^o$. Based on the design steps PI controller is obtained:$\angle G(j\omega_w) = (-180° \; 55°+5^0) = -120^0$**.** The results of the system's open loop frequency response to $\angle$-120^0 was obtained ω_1=22 rad/s with $|G(j\omega_1)H(j\omega_1)|$=0.47422149. The control parameters are obtained using equations (16) and (18), respectively. The proportional gain is constant, K_p = 0.5156660, and integral gain is K_i = 1.15005.

In order to get the equation controlling function PI over equation (15),

$$G_c(s) = \frac{0.5156660\,s + 1.15005}{s} \tag{28}$$

The step response for this system is plotted in Fig. 9

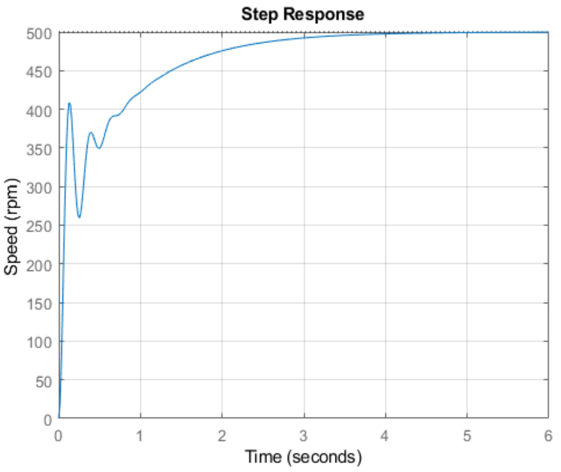

Fig. 9. Speed response of output plant with PI controller

Table-III shows the performance for the closed-loop response of PI controller is obtained

Table-III: The motor performance with PI controller

Performance Measure	Actual Response
Rise Time (s)	1.35
Percent Overshoot	0
Settling time (s)	2.77
Steady state error	0
Phase margin(degree)	53^0

The steady state error is compensated by integral control. The final obtained phase margin for the process PI controller, 53^0 on 22.4rad/sec, which does not satisfy design.

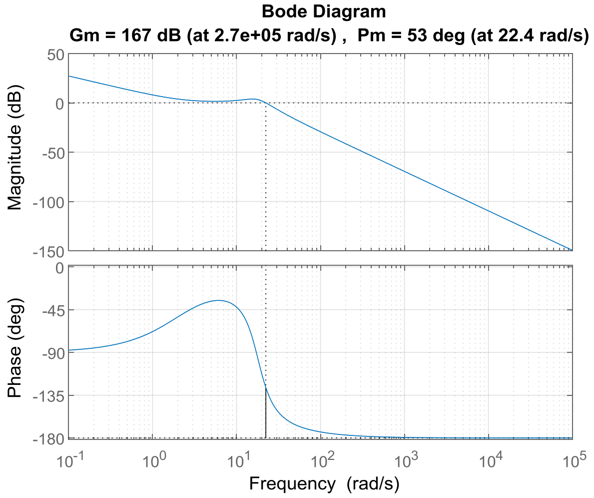

Fig. 10 Frequency response with PI controller

B. *PID Controller Design*

Based on the design steps PID controller is obtained Where, Select margin phase $\phi_m = 55^o$ $\angle G(j\omega_1)H(j\omega_1) = \angle -180^0 + 55^0 = -125^0$. The open loop system in the frequency response is $\angle -125^0$ and ω = 35.01rad/s, therefore $\omega_1$must be chosen greater than ω with the provision of $|G(j\omega_1)H(j\omega_1)|\angle 1$. Based on the terms and conditions of the PID controller design $|G(j\omega_1)H(j\omega_1)|$= 0. 64467.Value K_p, and K_d successively obtained from equation (23) and (24) as follows: K_i= 4.77554, Kp = 1.3640 and Kd= 0.02499. A PID controller with the transfer function

$$G_c(s) = 1.36406 + \frac{4.7754}{s} + 0.02499\,s \tag{29}$$

The step response of output plant system is shown in Fig. 11 and the bode diagram of closed-loop plant system in frequency response is shown in Fig. 12.The motor performance with PID controller can be shown in Table-IV.

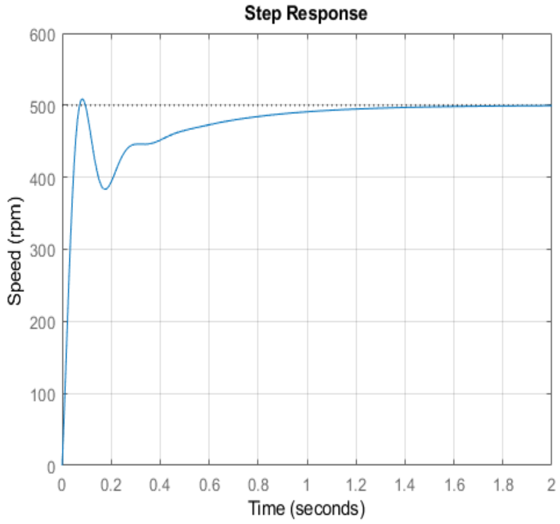

Fig. 11. Speed response with PID controller

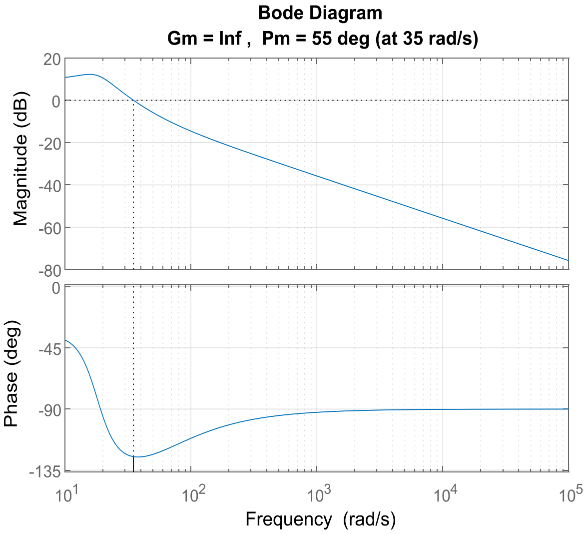

Fig.12. Frequency response with PID controller

Table-IV: The motor performance with PID controller

Performance Measure	Actual Response
Rise Time(s)	0.0492
Percent Overshoot	1.8
Settling time (s)	0.965
Steady state error	0
Phase margin (degree)	55^0

In Fig. 13 can be shown comparison characteristic motor when employing controllers and without controller. The speed motor is set in 500 rpm. A PI controller has lower overshoot than PID controller, however PID controller has faster of rise time than PI controller and faster be stable.

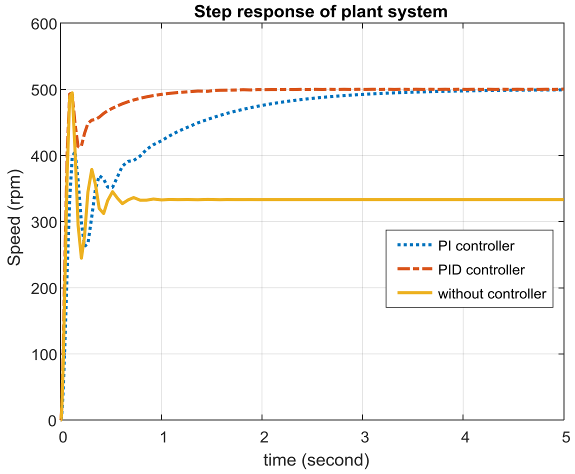

Fig.13. Closed-loop step responses

C. *Effect of Disturbances*

Feedback control systems are used to compensate for disturbances or unwanted input that enter a system. The effect of load on the machines is represented by the disturbance. Fig. 14 show varying disturbance when the plant system has been achieved steady-state after starting. The disturbances are modeled by sudden changes in load on the system that occur every 5 seconds. The motor can maintain the speed although many disturbances. The controllers can recover the speed according to desired value. The effect of disturbances and recovery process the motor can be shown in Fig. 15. In this figure, PID controller has smaller overshoot and faster rise time than PI controller. The PID controller is also faster to achieve steady-state than PI controller.

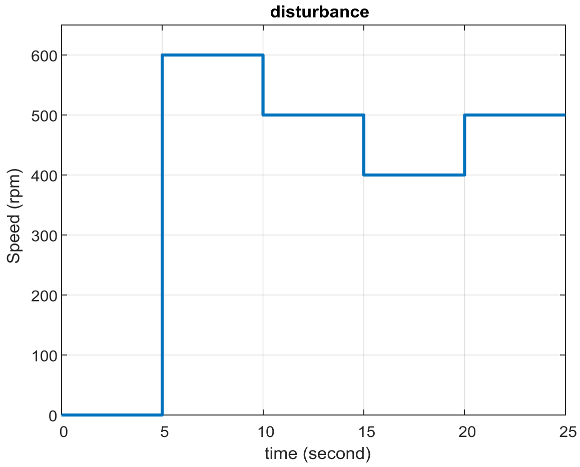

Fig. 14. Varying disturbances on plant system

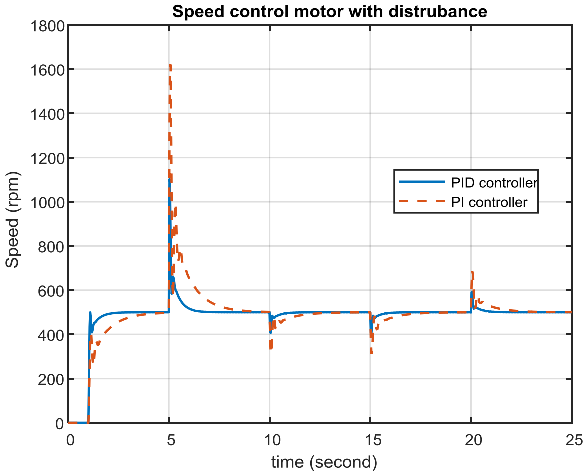

Fig. 15. Recovery process when disturbance

The performance of the PI and the PID compensated system is recorded in Table-III and Table-IV. Both steady-state and transient response have been considered. The transient responses (*ts*, *tr*, %OS) and steady-state error requirements have been met. The generated steady-state error can be decreased by PI and PID controllers, although the phase margin is fewer than that proposed for the PI controller. Meanwhile, the phase margin obtained for the PID controller is in accordance with the desired phase margin (55^0). The PID controller resulting in a system that responds faster. Based on the results obtained the system meet the desired criteria.

V. CONCLUSION

A step by step procedure design of speed control for DC shunt motor was presented. Analysis and comparative from both of controllers were also described. The PID controller makes a control loop responds faster with less overshoot and zero steady state error. DC motor based on proposed controller structure has better performance in reference speed and disturbance. The controller can maintain speed motor on 500 rpm when there is disturbance. The PID controller has lower overshoot and faster achieving steady-state than the PI controller.

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