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Effect of PID Controller on Direct Current Motor Speed Control Performance under Varying Load Torque Disturbance

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ABSTRACT

The MATLAB/Simulink model of DC motor speed control with varying load torque disturbance has been studied. Simulation was initially conducted without a controller considering unit step input and the transient response time domain performance characteristics of the uncompensated system were found to be remarkable but the desired speed was not tracked. The response speed was found to reach 1.649 rad/sec, which was well above the reference speed (1.0 rad/sec) by 64.9%. The introduction of load torque at 4 seconds further increased the magnitude of the motor speed response from 1.649 rad/sec to 3.008 rad/sec, which is 82.4% increment. With 300 rad/sec reference speed, simulation was conducted without PID controller and the resulting response was 494.6 rad/sec which was 64.9% increment. Thereafter, a load torque from 0 to 10 Nm is introduced at 4 seconds into the DC motor control loop and the response showed that the magnitude of the response motor is increased to 508.2 rad/sec, whicj is undesirable. A Proportional integral derivative (PID) controller plus pre-filter was introduced to DC motor speed control loop to compensate for the performance of the system. The step response showed that with the PID plus pre-filter circuit, the desired motor speed was tracked with remarkable time domain performance characteristics. With the introduction of unit load torque at 4 seconds, the step response of the PID controlled DC motor speed changed and tracked the desired speed with just 1% (0.01) deviation. Simulations were further performed with PID controller by setting the reference speed at 300 rad/sec without and with load torque varied from 0 to 10 Nm introduced into the control loop. The response was the same as the desired motor speed but increased to 300.1 rad/sec which is just 0.03% increment from the desired speed. Generally, the simulation tests conducted showed that the designed real PID controller plus pre-filter actually provided better speed response performance for DC motor control by offering precise tracking and robustness under varying load torque disturbance.

Keywords: *Direct current; Load torque; PID controller; Motor.*

1.0 Introduction

There has been an extensive use of direct current (DC) motors in industrial control applications. A DC motor is one of the first machines designed to convert electrical power into mechanical power [1][2]. DC motors are very much deployed in speed and position control system. In industrial application, DC motors are used in feedback control systems, and are called DC-servomotors [3-6]. The aspect of the DC motor application in feedback control system includes such areas like in robotics, computer disk drives, printers, aircraft flight control systems, machining process, flexible manufacturing process, automatic steering control and so on [7]. When compared with alternating current (AC) drive, DC motor drives are simple and less economical [8].

As far as industrial process automation is concern, the feedback control loop using DC motor is very important in achieving the desired set point and improved system performance. Nevertheless, the response of this feedback system is slow. Hence, to achieve fast system response, several control techniques have been proposed and implemented in various DC-servomotors. The essential function of control schemes in electrical machines include accurate and fast tracking of set point speed with reduced peak overshoot with little or no steady state error [8].

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Many control methods used in for the automation of industrial drives, the proportional integral derivative controller has been the most deployed. This can be attributed to its simplicity and easy implementation. The PID controller uses the proportional integral and derivative computing law to adjust the error signal arising from the difference between the desired value and measured value [9]. In DC-servomotor, PID control algorithm is used to meet desired torque-speed characteristics. Nonetheless, the optimization and tuning of the gains of PID controller is time consuming and not easy, largely due to changing load conditions, alterations in system parameter, or in unusual operating modes and so on.

In this paper, the speed control performance of separately excited DC motor under changing load condition is examined through simulations. A model of the DC motor was implemented in Simulink environment and MATLAB/Simulink simulation analysis is carried out under considering varying load disturbance. A PID controller plus pre-filter circuit at the input was integrated into the DC motor feedback control loop.

2.0 Operation of DC Motor

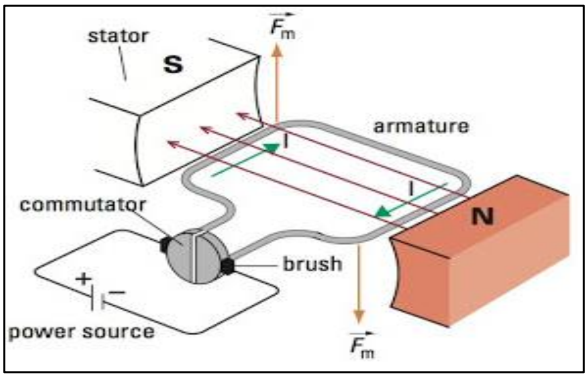
The purpose of Direct current (DC) motor is to convert electrical power into mechanical power. The DC motor uses the effect of electric current flowing through a conductor in a magnetic field to produce torque that causes it to rotate. That is the working principle is based on current-carrying in a magnetic field. This requires two magnets placed side by side with opposing polarity and an electric winding that acts as an electromagnet. The torque required to cause the motor to rotate is produced due to the repulsive and attractive electromagnetic force of the magnets. In actual fact, DC motor consists of a set of windings called armature windings, inside a set of permanent magnets called the stator [10]. Application of voltage to the windings brings about a torque in the armature thereby resulting to motion.

The basic principle of DC motor is shown in Fig. 1. The figure shows that the DC motor is divided into two parts namely, the rotor and the stator. The rotor is the rotating part that is represented by the armature while the stator is the non-rotating part represented by two opposite (North, N and South, S) poles of magnet. The commutator is a segmented metal ring used to change the direction of DC current that is applied to the current-carrying conductor within the rotor. An electrical contact is maintained by the commutator with its external DC electrical power source employing carbon brushes. As shown in Fig. 1, the stator is represented by the magnetic N-S poles and the direction of the current flowing through the armature conductor. The magnetic force acts to turn the conductor of the armature towards the left and the right and given as-

$$\vec{F}_m = \vec{B} \times I\vec{L} \qquad \ldots(1)$$

where $\vec{F}_m$ is the magnetic force vector also called Lorentz force vector in Newton (N), $\vec{B}$ is the magnetic flux density in Weber per square (Wb/m^2), I is the current in ampere (A), and L is the length of the conductor in meter (m).

Fig. 1: Principle of DC Motor [11]



There are basically three types of DC motor, and are usually classified based on two common criteria namely, their characteristics and the connection of their exciting windings or circuits [10]. Hence, in accordance to this, the DC motor can be of any of these three types: shunt, series and compound motors. For shunt DC motor, there is only one exciting winding that is connected across (or in parallel) to the terminals of the armature such that the different current flow through the field winding and the armature. The series DC motor has only one exciting winding connected in series with the armature and so the same current passes through the field and the armature. In the compound type, the motor has both a shunt winding and a series winding on each pole.

Direct current motors provide variable speed control mechanism and are usually much more adaptable speed drives [2][10] than the AC motors which always run at full speed. That is the AC motors are associated with a constant speed rotating field. For this reason, many industrial applications require DC motors for speed control process.

The relationship between the speed of DC motor and the armature voltage is mathematically defined by [12]:

$$\omega = \frac{V_a - I_a R_a}{K\phi} \qquad \ldots(2)$$

Where, ω, V_a, I_a, R_a, K, ϕ are the motor speed in rad/sec, the armature voltage (back emf), the armature current, armature resistance, a constant, and the field magnetic flux per pole.

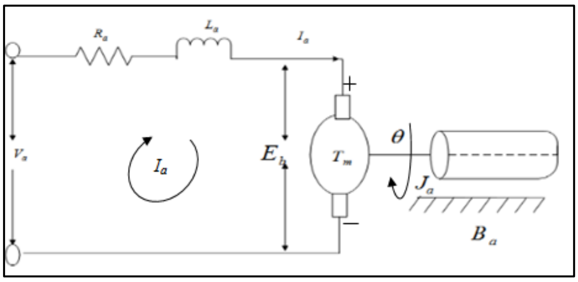
Basically, there are three approaches to controlling the speed of DC motor –armature voltage speed control, field flux speed control and voltage control. The armature voltage control is the most commonly used method. In this paper, the consideration is on the use of armature voltage control.

3.0 Methodology

3.1 DC Motor Dynamic

This section deals with the mathematical representation of an armature controlled DC motor as shown in Fig. 2. The dynamic model of the DC motor can be considered in two parts: electrical component and mechanical component.

Fig. 2: Armature Controlled DC Motor Circuit



The definition of the parameters in Fig. 2 is given as follows: V_a = Applied armature voltage (V), R_a = Resistance of the armature (Ω), L_a = Inductance of the armature (H), I_a = Armature current (A), E_b = Back emf (V), T_m = Developed motor torque (Nm), θ = Angular displacement of motor shaft (rad), J_a = Motor inertia constant (Kgm^2), B_a = Motor dampening coefficient (Nms/rad).

DC motor diagram in Fig. 2 consists of two main parts, which are the electrical components and the mechanical components. The applied voltage to the armature of the motor changes without altering the voltage applied to the field in armature controlled separately excited DC motor. Kirchhoff's Voltage Law (KVL) and the law of dynamic (rotational) motion are applied in to the DC motor model and the following equations are obtained.

$$V_a(t) = R_a I_a(t) + L_a \frac{dI_a(t)}{dt} + E_b(t) \qquad \ldots(3)$$

$$E_b(t) = K_B \omega_m(t) = K_B \frac{d\theta(t)}{dt} \qquad \ldots(4)$$

$$T_m(t) = K_T I_a(t) \qquad \ldots(5)$$

Where, $\omega_m(t)$ = the angular velocity

Putting the expression in Eq. (4) into Eq. (3) gives:

$$V_a(t) = L_a \frac{dI_a(t)}{dt} + R_{aI_a}(t) + K_B \frac{d\theta(t)}{dt} \qquad \ldots(6)$$

The torque equation is given by:

$$J_a \frac{d^2\theta(t)}{dt} + B_a \frac{d\theta(t)}{dt} = K_T I_a(t) \qquad \ldots(7)$$

Application of Laplace transformation to (6) and (7) and assuming zero initial conditions gives:

$$V_a(s) = L_a s I_a(s) + R_a I_a(s) + K_B s\theta(s) \qquad \ldots(8)$$

$$J_a s^2 \theta(s) + B_a \theta(s) = K_T I_a(s) \qquad \ldots(9)$$

The current is made subject in (8) and (9), then equating both gives:

$$\frac{V_a(s) - K_B s\theta(s)}{R_a + L_a s} = \frac{J_a s^2 \theta(s) + B_a s\theta(s)}{K_T} \qquad \ldots(10)$$

The ratio of the output (angular position), θ(s) to the input voltage, $V_a(s)$ is given by:

$$\frac{\theta(s)}{V_a(s)} = \frac{K_T}{s\left[(R_a + L_a s)(J_a s + B_a) + K_T K_B\right]} \qquad \ldots(11)$$

The block model of the DC motor dynamic is shown in Fig.3.

The transfer function from reference input voltage to the angular velocity as shown in Fig. 3 (assuming disturbance is zero) is given by:

$$\frac{\omega(s)}{V_a(s)} = \frac{K_T}{\left[(R_a + L_a s)(J_a s + B_a) + K_T K_B\right]} \qquad \ldots(12)$$

The transfer function expressions given by (11) and (12) are only applicable to the electrical-rotational motion analysis of the DC motor and the concern of this paper is on Eq. (12) which deals with the speed control. The next section will focus on the simulation and analysis of DC motor whose specifications are 3hp, 125V, and 1500rpm, while the parameters are $R_a = 0.6\Omega$, $I_a = 6mH$, $J = 0.093kgm$ $K_T = 0.7274$, $K_B = 0.6$, and $B_a = 0.008Nmrad^{-1}s^{-1}$ [10].

3.2 Controller design and system configuration

In this study a real PID controller is designed to enhance the performance of DC motor speed control. Real PID controller is obtained by filtering the derivative action of the ideal PID controller with a filter coefficient N [13], and it is given by:

$$C(s) = K_p + \frac{K_i}{s} + K_d s\left(\frac{N}{s+N}\right) \qquad \ldots(13)$$

where K_p, K_i, and K_d are the proportional, integral, and derivative gains of PID controller. The parameters of the designed real PID controller are:

Fig. 3: Block Diagram of Dynamic Model of DC Motor

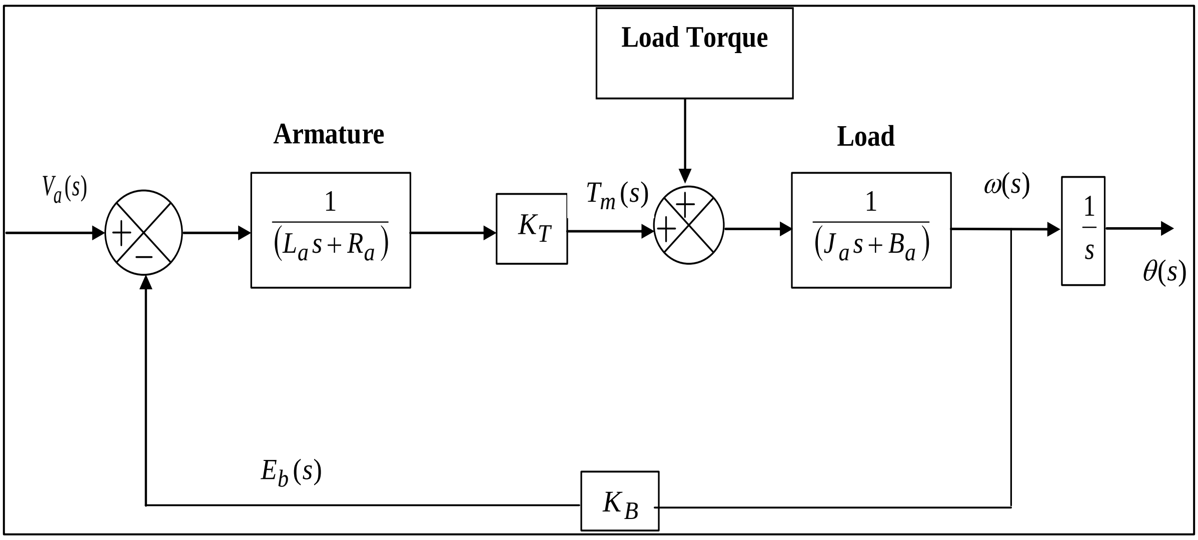
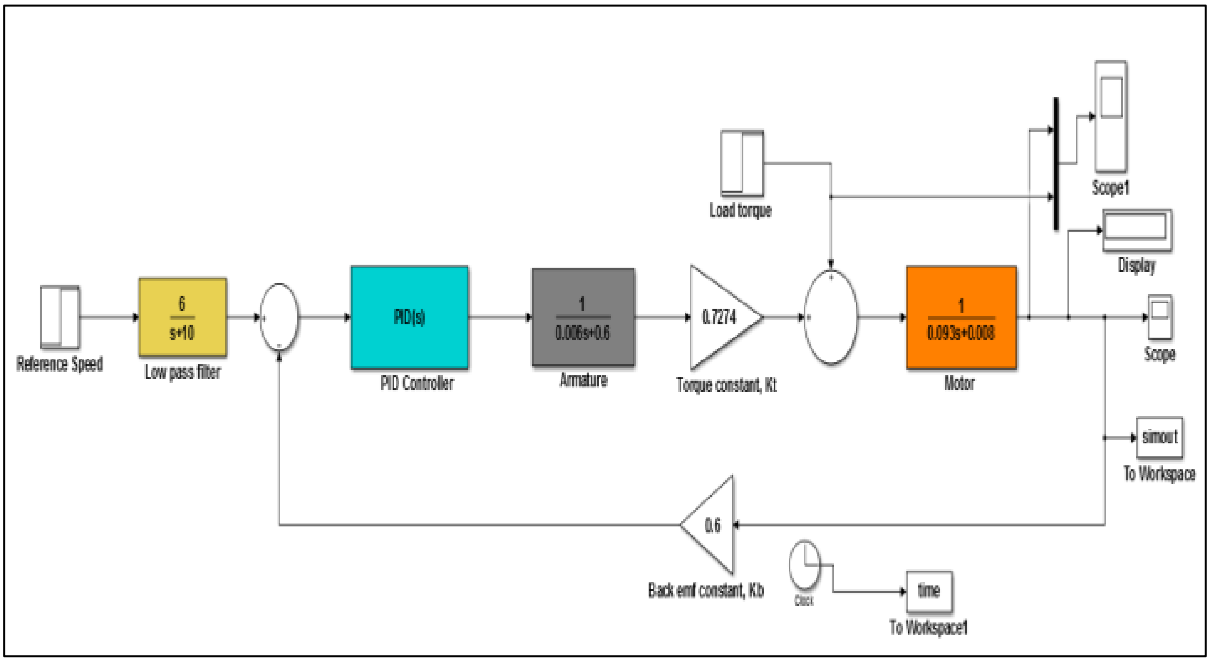


Fig. 4: System Configuration



$K_p = 0.08,\ K_i = 2.30,\ K_d = 1.80,$ and $N = 1.$ Substituting these values into Eq. (13) gives:

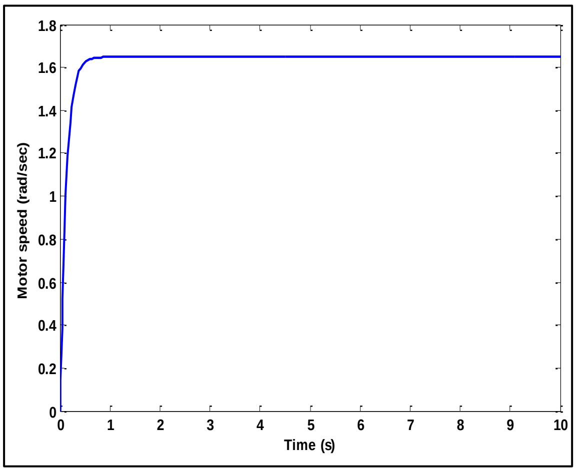
$$C(s) = \frac{0.08s + 2.3 + 1.8s^2}{s(s+1)} \qquad \ldots(14)$$

A forward path pre-filter or low pass filter (LPF) is added together with the PID to enhance the performance of the DC servomotor. The Simulink model of the system is shown in Fig. 4.

4.0 Results and Discussion

In this section, the results of the simulations of the designed speed control system modeled and implemented in MATLAB/Simulink. The Simulation results are presented as follows. First, a step response test was conducted on the system model without PID controller as shown in Fig. 5.

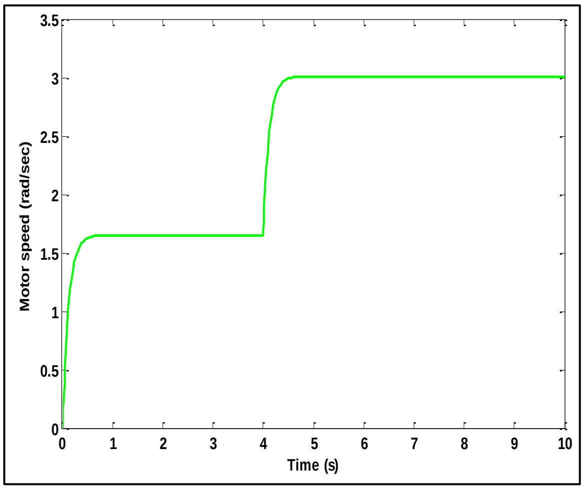
Fig. 5: Step Response of Motor Speed to Unit Input (Without PID)



The response speed was found to reach 1.649 rad/sec, which is well above the reference speed (1.0 rad/sec) by 64.9%. The time domain performance parameters in terms of rise time, peak time, peak percentage overshoot, and settling time are: 0.2572 second, 2.3144 seconds, 0.0061%, and 0.4655 seconds respectively. Simulation was again conducted with unit step input and a step load torque, and the response is shown in Fig. 6.

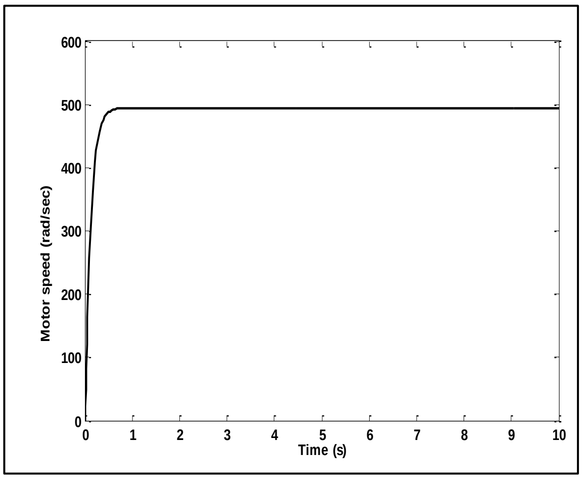
The result as shown in Fig. 6, indicate that the introduction of load torque at 4 seconds increases the magnitude of the motor speed response from 1.649 rad/sec to 3.008 rad/sec, which is 82.4% increment. The resulting rise time is 4.1419 seconds, peak time is 6.3893 seconds, peak percentage overshoot 0.0042, and settling time 4.3621 seconds.

Fig. 6: Step Response Due to Unit Load Torque (Without PID)



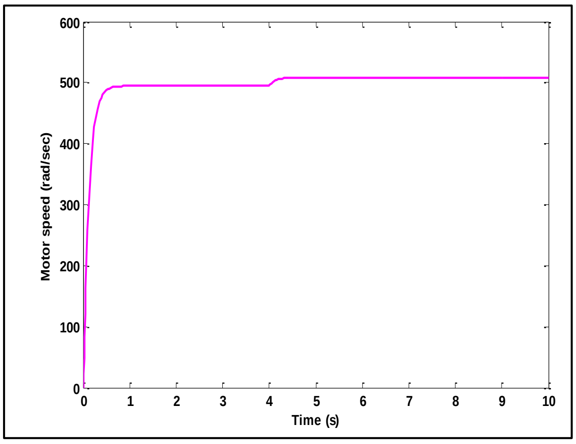
With 300 rad/sec reference speed, simulation is conducted without PID controller and the resulting response plot is shown in Fig. 7.

Fig. 7: Response Speed at Reference Speed of 300 rad/sec (without PID)



The time domain characteristics of system performance response at 300 rad/sec without PID are: rise time of 0.2567 second, peak time of 9.5434 seconds, overshoots of 0.0071%, and settling time of 0.4648 seconds. The plot shows that the response is 494.6 rad/sec which is 64.9% increment. Next, a load torque from 0 to 10 Nm is introduced at 4 seconds into the DC motor control loop and the response plot as shown in Fig. 8 indicates that the magnitude of the response motor is increased to 508.2 rad/sec with rise time of 0.2885 second, peak time 7.2171 seconds, overshoot of 0.0063%, and settling time of 4.0352 seconds. The increment in motor speed from the desired speed due to load torque is by 69.4%.

Fig. 8: Response Speed at Reference Speed of 300 rad/sec Under Load Toque (without PID)



Thereafter, a PID controller plus pre-filter circuit was added and the second simulation test was carried out. The result obtained is shown in Fig. 9. The response plot shows that with the PID plus pre-filter circuit, the motor speed was able to track and reached the reference speed, while achieving a rise time of 0.2553 seconds, peak time of 1.1256 seconds, peak percentage overshoot of 3.7158%, and settling time of 2.2533 seconds.

Fig. 9: Step Response of Motor Speed to Unit Input (with PID)

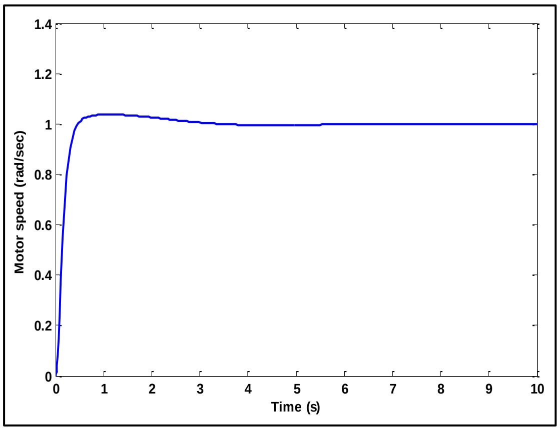
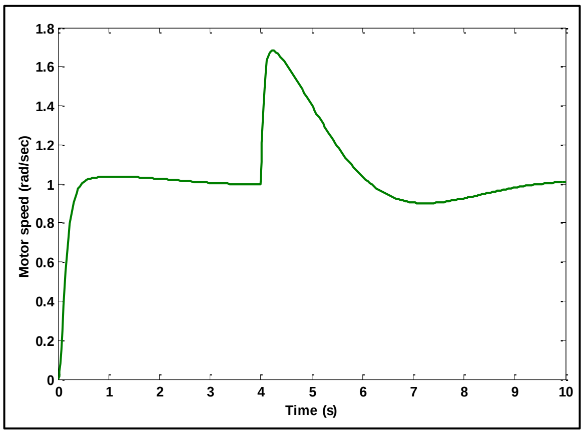


Fig. 10: Step Response Due to Unit Load Torque (with PID)



With the introduction of unit load torque at 4 seconds, the response of the PID controlled DC motor speed changes and provides the following performance parameter: rise time of 0.2621 seconds, peak time of 4.2130 seconds, Overshoot of 66.7044%, and settling time of 9.2102 as shown in Fig. 10. The motor speed response settles finally at 1.01 rad/sec, which is just 1% deviation from the reference speed.

Fig. 11: Response Speed at Reference Speed of 300 rad/sec (with PID)

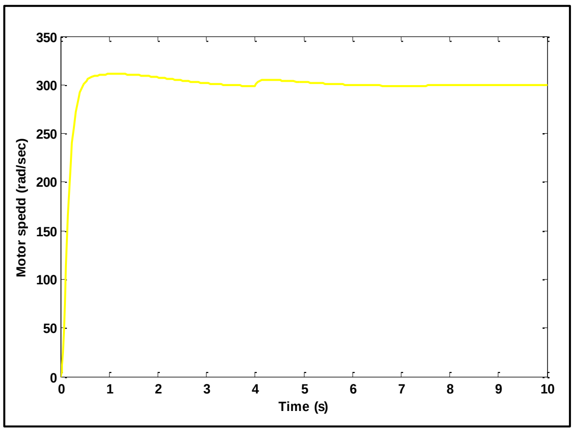


Fig. 12: Response Speed at Reference Speed of 300 rad/sec Under Load Toque (with PID)

Finally, simulations are further performed with PID controller by setting the reference speed at 300 rad/sec without and with load torque varied from 0 to 10 Nm introduced into the control loop as shown in Fig. 11 and 12.

From Fig. 11, the characteristics performance of the motor speed response is: rise time of 0.2544 second, peak time of 1.0976 seconds, overshoot of 3.8331%, and settling time of 2.2529 seconds. The final value is the same as the desired motor speed. For Figure 12, with load torque introduced, the rise time is 0.2556 second, peak time 1.1265 seconds, overshoot of 3.6810%, and settling time of 2.2379 seconds. The Final value is 300.1 which is just 0.03% increment from the desired speed. This is very much insignificant.

5.0 Conclusions

This paper has studied the modelling and simulation of speed control of DC motor under varying load torque disturbance. An armature controlled DC motor was developed in MATLAB/Simulink environment. The analysis and performance evaluation of the developed DC motor speed control system without and with a controller showed the effectiveness of the developed model. In addition, the results of the study indicated that the integration of the real PID into the DC motor speed control provided perfect tracking and maintaining of the desired speed.

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