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Design of Controllers PD, PI &PID for Speed Control of DC Motor Using IGBT Based Chopper

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ABSTRACT

This paper presents a novel approach for determination of optimum values of Kp, Ki and Kd for design of controllers such as PD, PI & PID for enhancement of performance parameters of Permanent Magnet Direct Current (PMDC) Motor drives using IGBT based chopper in MATLAB/SIMULINK toolbox environments. The effectiveness of proposed novel approach has been presented so that the better performance parameters of PMDC motor drives are achieved in closed loop as compared to in open loop systems. This work is very useful for researchers, scientists, engineers and industrial persons.

Index Terms - Optimization of Kp, Ki and Kd for Controller design, PMDC motor modeling, IGBT based chopper

INTRODUCTION

Developments of high performance motor drives are very essential for industrial applications. A high performance motor drive system must have good dynamic speed command tracking and load regulating response. DC drives, because of their simplicity, ease of application, reliability and favourable cost have long been a backbone of industrial applications. DC drives are less complex as compared to AC drives systems. DC drives are normally less expensive for low horse power ratings. DC motors provide excellent control of speed for acceleration and deceleration. The power supply of a DC motor connects directly to the field of the motor which allows for precise voltage control, and is necessary for speed and torque control applications [1]-[5].

AC drives with this capability would be more complex and expensive. Properly applied brush and maintenance of commutator is minimal. DC motors are capable of providing starting and accelerating torques in excess of 400% of rated. D.C motors have long been the primary means of electric traction. They are also used for mobile equipment such as golf carts, quarry and mining applications. DC motors are conveniently portable and well fit to special applications, like industrial equipment and machineries that are not easily run from remote power sources [6]-[8].

The closed-loop controllers are very common means of keeping motor speed at the required "set-point" under varying load conditions. It is also able to keep the speed at the set-point value where for example, the set-point is ramping up or down at a defined rate. PI, PD and PID controllers are the speed controllers most commonly used to obtain the desired speed in any drive. There are various methods of setting optimum control parameters in these controllers to achieve the desired response. In Trial and error method, the parameters are adjusted by watching system responses [9]-[13].

PROBLEM FORMULATION

The mathematical modeling of PMDC motor with IGBT based chopper and PD, PI and PID controllers are as follows.

A. PMDC Motor

The schematic diagram of PMDC motor is shown in Fig.1.

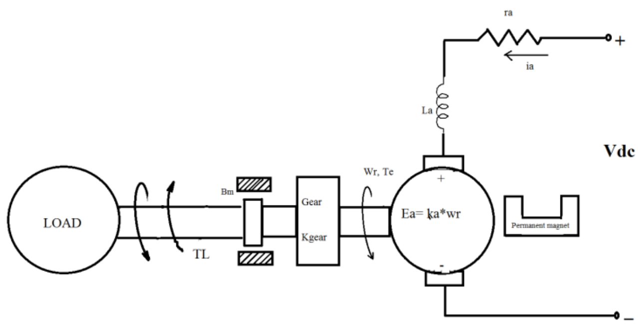


Fig.1. Schematic Diagram of DC motor

To find the transfer function for the block diagram of the open system a differential equation to describe the system dynamics. Kirchhoff's voltage law is used to map the armature circuitry dynamics of the motor.

$$V = I_a r_a + L_a \frac{dI_a}{dt} + K_a \omega_r \qquad (1) \qquad (V_{dc} = V)$$

$$\frac{dI_a}{dt} = \frac{1}{L_a}\left(-I_a r_a - K_a \omega_r + V\right) \qquad (2)$$

The electromagnetic torque developed by PM dc motor:

$$T_e = K_a I_a \qquad (3)$$

The viscous friction torque:

$$B_m * \omega_r \qquad (4)$$

The load is denoted as T_L, using Newton's second law:

$$T_e - T_v - T_L = J\frac{d\omega}{dt} \qquad (5)$$

$$K_a I_a - B_m \times \omega_r - T_L = J\frac{d\omega}{dt} \qquad (6)$$

Taking Laplace transforms of equations (1) and (2), we get

$$I_a(s) = \frac{V}{sL_a} - \frac{I_a(s) r_a}{sL_a} - \frac{K_a \omega_r}{sL_a} \tag{7}$$

and $$\omega_r(s) = \frac{1}{Js}\left(K_a I_a - B_m \omega_r - T_L\right) \tag{8}$$

From the transfer function, the block diagram of PMDC Motor is made in Simulink toolbox [14]-[15].

B. Simulink Model of Modeled PMDC Motor

The Simulink model of PMDC motor is shown in Fig. 2.

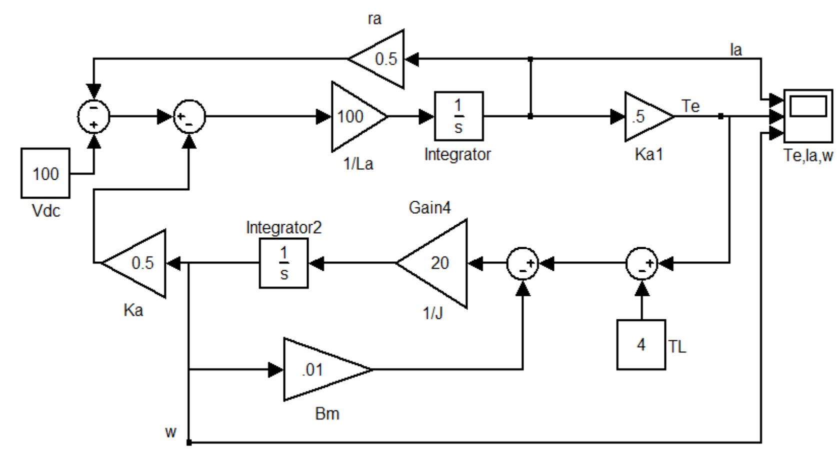


Fig.2. Simulink model of Permanent-Magnet DC Motor

The Characteristic curve of speed-time, motor torque-time and armature current-time for a PMDC Motor is shown in Fig.3.

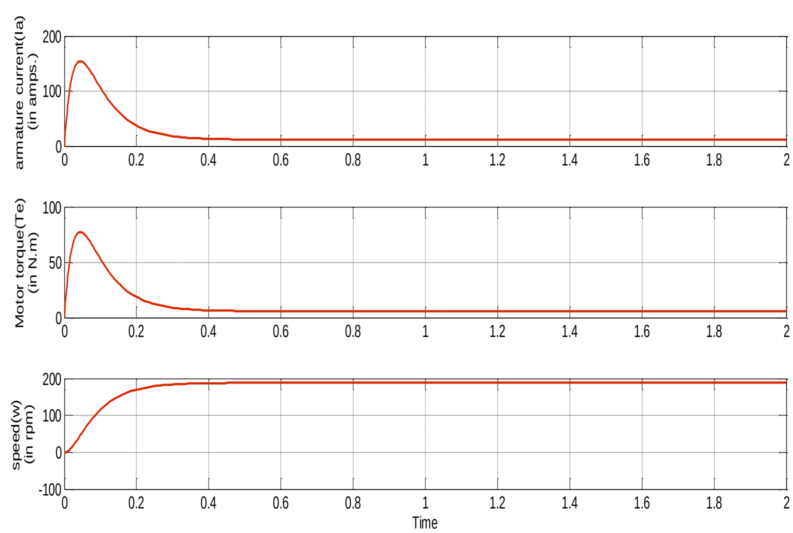


Fig.3. Characteristic curve of speed-time, motor torque-time and armature current-time for a PMDC Motor

C. Chopper Circuit Employing IGBT as a Switch

The basic chopper circuit consists of a switch, diode, inductor connected in parallel. The ON and OFF of switch varies the output voltage across load terminals connected in series with the inductor which smoothens the ripple in the output dc current waveform. MOSFET, BJT, thyristors can be used as switch but IGBT is used due to its several advantages over these power electronic devices.

The basic chopper circuit employing IGBT as a switch is explained:

D. First Quadrant Chopper

The circuit diagram of first quadrant chopper is shown in Fig.4.

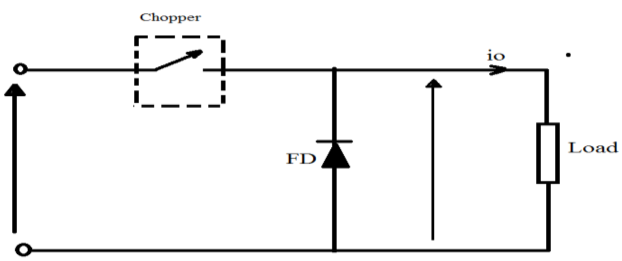


Fig.4. First quadrant Chopper

As we can see from the above figure when chopper CH1 is on, $V_o = V_s$ and current i_o flows in the arrow direction shown. When CH1 is off, $V_o = 0$ but i_o in the load continues flowing in the same direction through freewheeling diode FD. It is thus seen that the average values of both load voltage and current, i.e. V_o and I_o are always positive: this fact is shown by the hatched area in the first quadrant of V_o-I_o plane. The power flow in type – A chopper is always from the source to the load. This chopper is also called step-down chopper as average output voltage V_o is always less than the input dc voltage V_s.

E. Steady State Time Domain Analysis of Chopper

The determination of load current expression is useful for knowing current profile over period time T, the current ripple and whether the current is continuous or discontinuous.

For R-L-E type load, E is the load voltage which may be a dc motor or battery. When CH1 is on, the equivalent circuit is shown in fig.7. For this mode of operation, the differential equation governing its performance is

$$V_S = Ri + L\frac{di}{dt} + E \qquad (9)$$

$$0 \le t \le T_{ON}$$

When CH1 is off, the load current continues flowing through the freewheeling diode and the equivalent circuit is shown in fig.. For this circuit the differential equation is

$$0 = Ri + L\frac{di}{dt} + E \tag{10}$$

For $T_{on} \le t \le T$

Solution of equations and can be obtained by Laplace transform:

$$RI(s) + L[sI(s) - I_{mn}] = \frac{V_s - E}{s} \tag{11}$$

Fig.5 and 6 shows the waveform for continuous and discontinuous load current respectively.

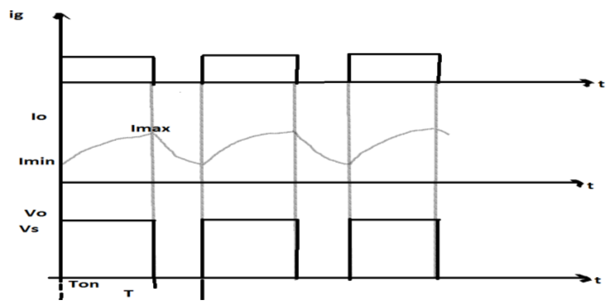


Fig.5. Continuous load current

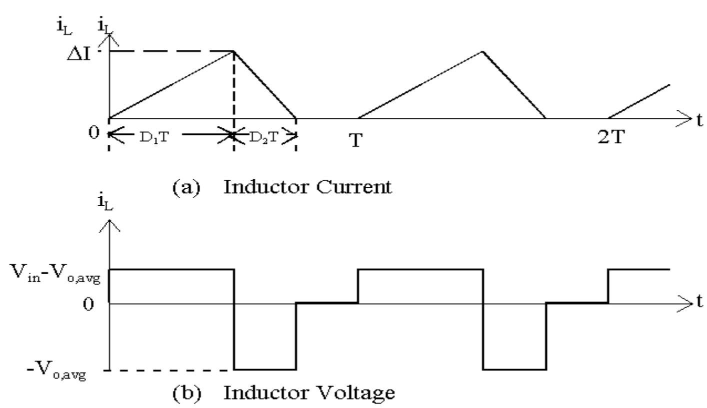
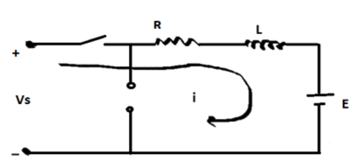


Fig.6. Discontinuous load current



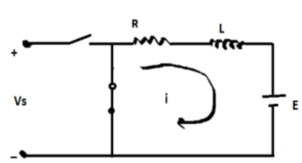


Fig.7. With CH1 ON

Fig.8. With CH1 OFF

$$RI(s)+L[sI(s)-I_{mx}]=\frac{-E}{s} \tag{12}$$

From equation (11),

$$I(s)=\frac{V_s-E}{s(R+sL)}+\frac{L.I_{mn}}{R+Ls} \tag{13}$$

Laplace inverse of the above expression is

$$i(t)=\frac{V_s-E}{R}\left(1-e^{-\frac{R}{L}t}\right)+I_{mn}e^{-\frac{R}{L}t} \tag{14}$$

For $0\le t\le T_{ON}$

Similarly the time domain expression for current from equation (12)

$$i(t')=-\frac{E}{R}\left(1-e^{-\frac{R}{L}t'}\right)+I_{mx}e^{-\frac{R}{L}t'} \tag{15}$$

For $T_{on}<t\le T$

Where t'= $t-T_{on}$, so that when

$t=T_{on}$, t'=0

And for $t=T, t'=T-T_{On}=T_{off}$.

In eqn. (15), at $t=T_{on}, i(t)=I_{mx}$

$$\therefore I_{mx}=\frac{V_s-E}{R}\left(1-e^{-\frac{T_{on}}{T_a}}\right)+I_{mn}e^{-\frac{T_{on}}{T_a}} \tag{16}$$

In above equation, at $t'=T_{off}=T-T_{on}, i(t')=I_{mn}$

$$I_{mn}=-\frac{E}{R}\left(1-e^{-(T-T_{On}/T_a)}\right)+I_{mx}.e^{-(T-T_{On}/T_a)} \tag{17}$$

Where $T_a=\frac{L}{R}$

on solving the equations (16) and (17), we get

$$I_{mx} = \frac{V_s}{R}\left(\frac{1-e^{-\frac{T_{on}}{Ta}}}{1-e^{-\frac{T}{T_a}}}\right) - \frac{E}{R} \tag{18}$$

$$I_{mn} = \frac{V_s}{R}\left(\frac{e^{\frac{T_{on}}{T_a}}-1}{e^{\frac{T}{T_a}}-1}\right) - \frac{E}{R} \tag{19}$$

In case CH1 conducts continuously, then $T_{on} = T$ and from values of maximum and minimum values of current.

$$I_{mx} = I_{mn} = \frac{V_S - E}{R}. \tag{20}$$

The difference of maximum and minimum currents will appear as the ripple in output current when chopper is operating in discontinuous mode [16]-[17].

F. Merits/Demerits of IGBT over other switching devices

- Possess high input impedance.
- Low on-state voltage drop, on-state resistance and losses with increase in temperature.
- Can be designed for high voltage ratings.
- Switching frequency is very high.

G. Speed Controllers

1)Proportional + Integral (PI) controllers were developed because of the desirable property that system with open loop transfer function of type 1 or above have zero steady state error with respect to step input.
In time domain-

$$\frac{Y(t)}{E(t)} = K_p e(t) + K_i \int e(t)dt$$

Taking Laplace transform of above function $$\frac{Y(s)}{E(s)} = K_p + \frac{K_i}{s}$$

The block diagram of PI controller is shown in Fig. 9.

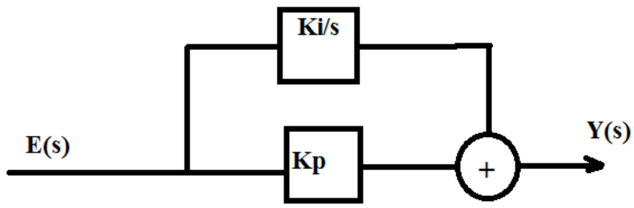


Fig.9. Block diagram of PI controller

2) Proportional + Derivative (PD) controllers are used to reduce the maximum overshoot in the overall time response of the system.

$$\frac{Y(t)}{E(t)} = K_p e(t) + K_d \frac{de(t)}{dt}$$

Taking Laplace of above function:

$$\frac{Y(s)}{E(s)} = K_P + sK_d$$

The block diagram of PD controller is shown in Fig. 10.

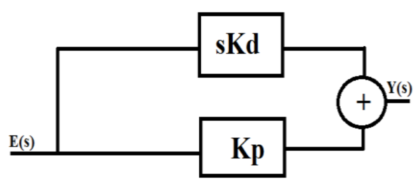


Fig.10. Block diagram of PD controller

3) PID controller will correct the error between the output and the desired input or set point by calculating and give an output of correction that will adjust the process accordingly.

A PID controller has the general form:

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{de}{dt}$$

Taking laplace of above equation

AXAD

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

The block diagram of PID controller is shown in Fig. 11.

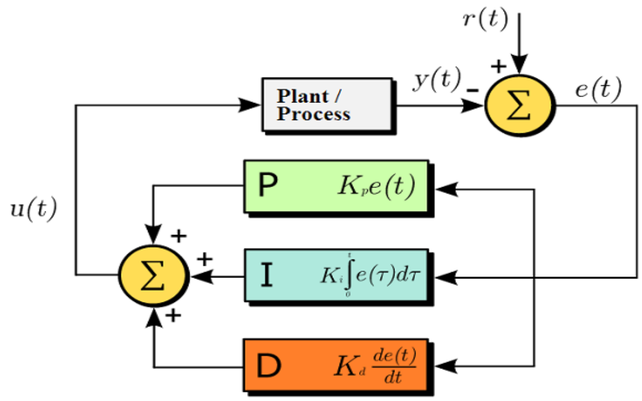


Fig.11. Block diagram of PID controller

Table 1 shows the effect of K_p, K_i and K_d on system output response.

Table 1 Effect of K_p, K_i and K_d on system output response.

CL Response	Rise time	Overshoot	Settling time	s-s Error
K_p	Decrease	Increase	Small change	Decrease
K_i	Decrease	Increase	Increase	Eliminated
K_d	Small Change	Decrease	Decrease	Small Change

H. Current Controller

When the machine is made to run from zero speed to a high speed then motor has to go to specified speed. But due to electromechanical time constant motor will take some time to speed up. But the speed controller used for controlling speed acts very fast. Speed feedback is zero initially. So this will result in full controller output and hence converter will give maximum voltage. So a very large current flow at starting time because back EMF is zero at that time which sometime exceeds the motor maximum current limit and can damage the motor windings. Hence there is a need to control current in motor armature. To solve the above problem we can employ a current controller which will take care of motor rated current limit. The applied voltage will now not depend on the speed error only but also on the current error. We should ensure that voltage is applied in such a way that machine during positive and negative torque, does not draw more than the rated current. So, an inner current loop hence current controller is required [18]-[19].

I. Block Diagram of Complete PMDC Motor Drive System

The block diagram of complete pmdc motor drive system is shown in Fig. 12.

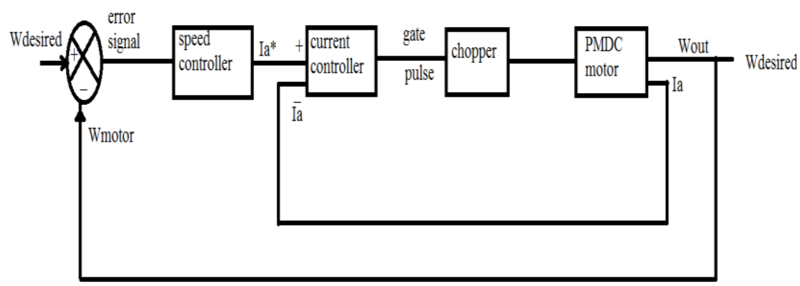


Fig.12. Block Diagram of a Complete Drive System

II. SIMULATION and RESULTS

A. Open Loop Speed Control of PMDC Motor Drives

In the Simulink mode the duty ratio α is set 70% in the pulse generator and time period of each pulse is set 10^{-3} sec. Fig.13. Shows the simulink model for open loop speed control of PMDC Motor drives.

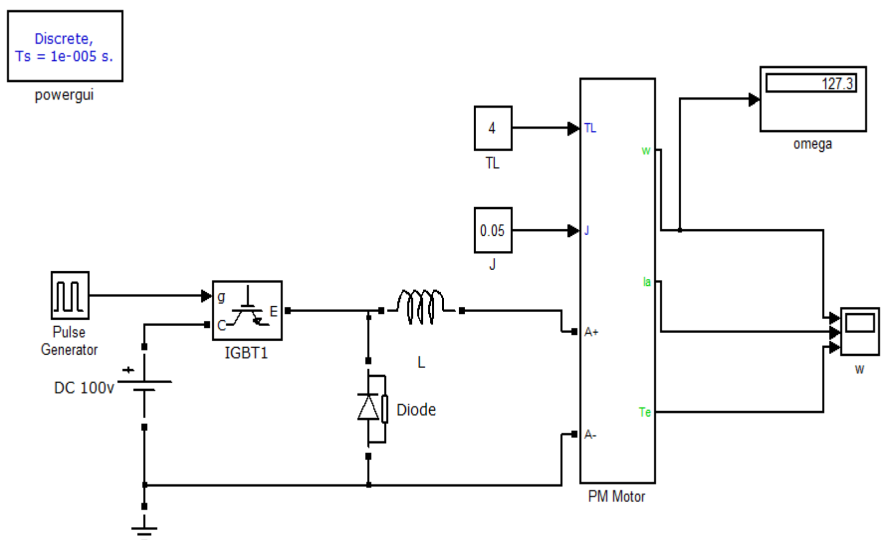


Fig.13. Simulink model for open loop speed control of PMDC Motor

Fig.14. shows the output waveform of closed loop control of PMDC motor drives.

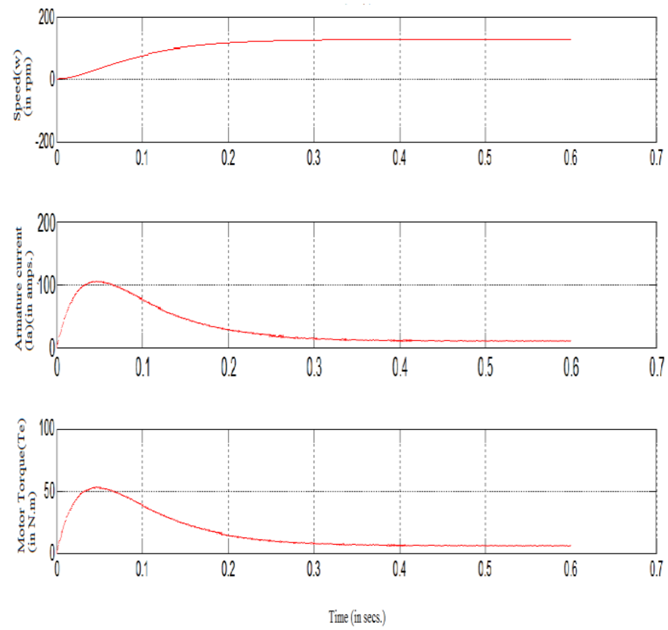


Fig.14. Output waveform of closed loop control of pmdc motor

In the output waveform speed is 127.2 rpm. The output speed can be controlled by varying the duty ratio α of chopper.

B. Closed Loop Speed Control

1) With PD controller

Fig. 15. Shows the Simulink model for closed loop speed control of PMDC Motor drive using PD controller.

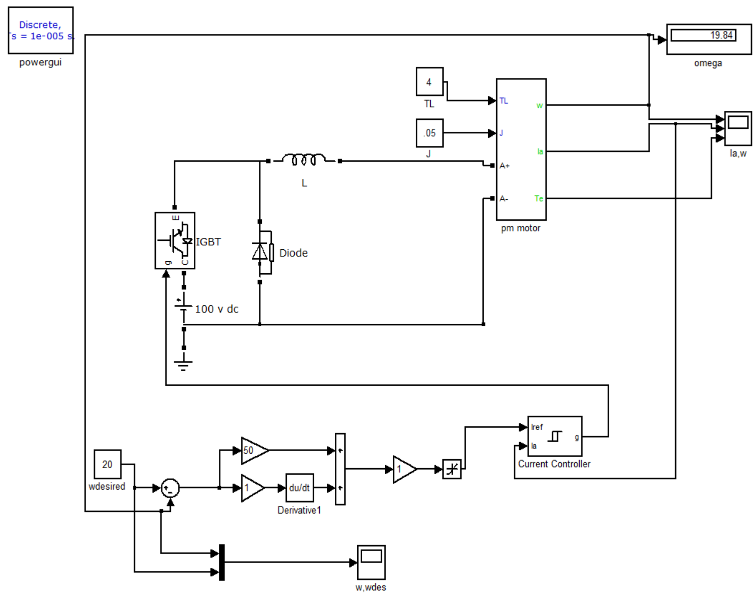


Fig. 15. Simulink model for closed loop speed control of PMDC Motor drives using PD controller

Fig.16 shows the output waveform of closed loop speed control of PMDC Motor using PD controller.

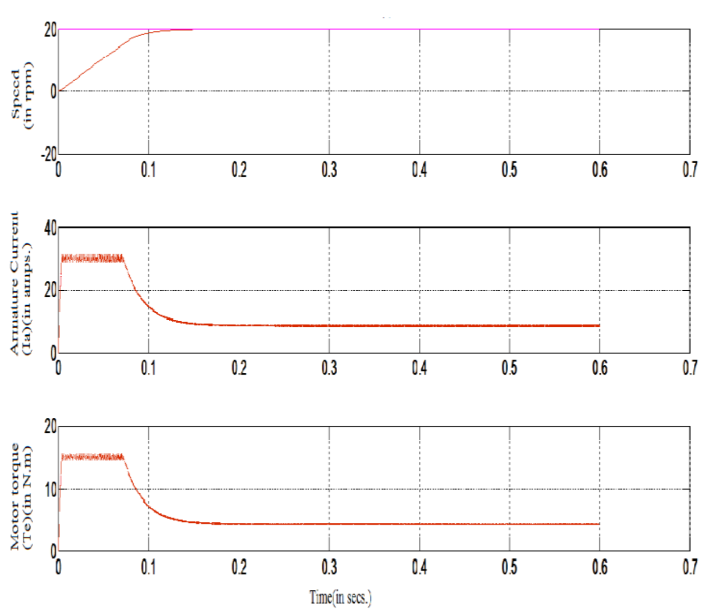


Fig.16 Output waveform of closed loop speed control of PMDC Motor using PD controller

2) With PI controller

The simulink model for closed loop speed control of PMDC motor using PI controller is shown in Fig. 17.

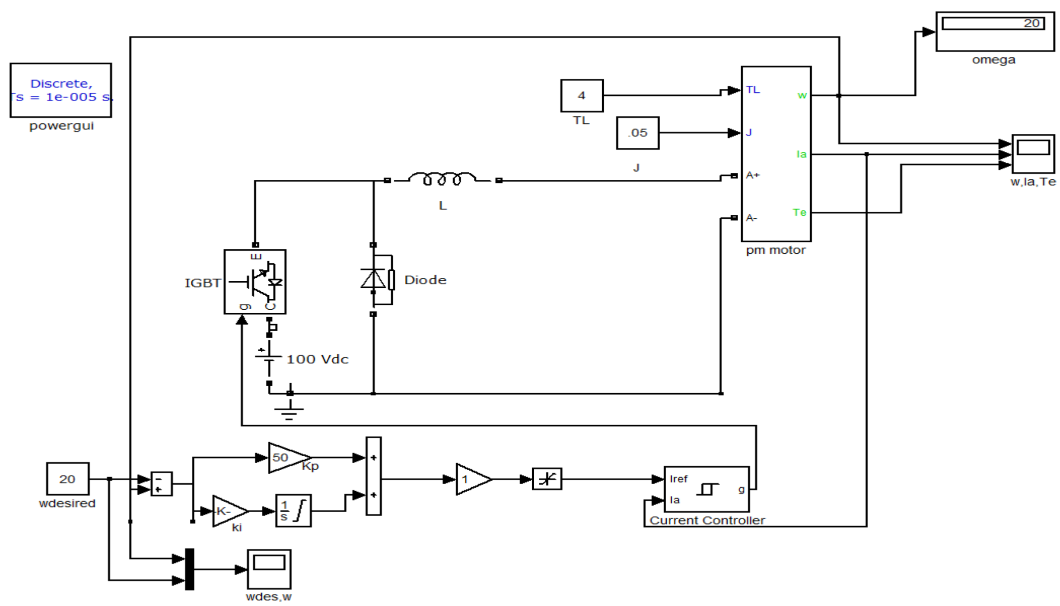


Fig. 17 Simulink model for closed loop speed control of PMDC motor using PI controller

Fig.17 shows the output waveform of closed loop speed control of PMDC motor using PI controller.

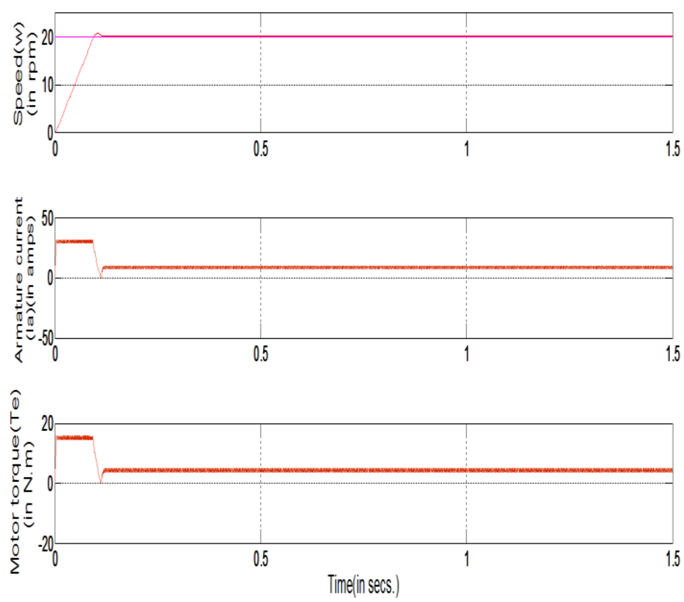


Fig.17 Output waveform of closed loop speed control of PMDC motor using PI controller

3) With PID controller

Fig. 18 shows the simulink model for closed loop speed control of PMDC motor using PID controller.

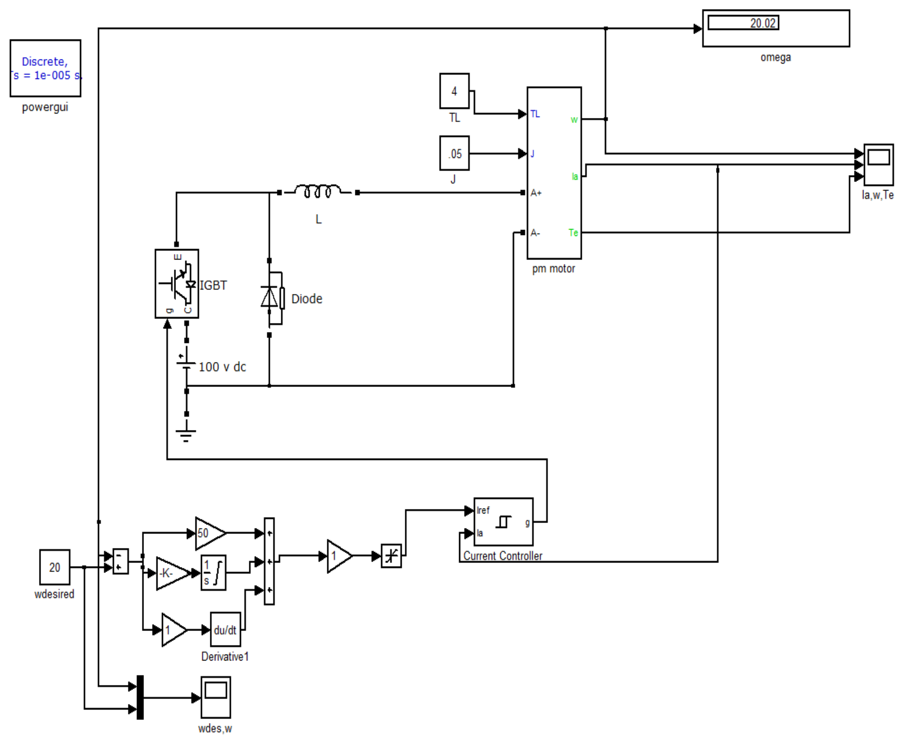


Fig. 18 Simulink model for closed loop speed control of PMDC motor using PID controller

Fig. 19 shows the output waveform of closed loop speed control of PMDC motor using PID controller.

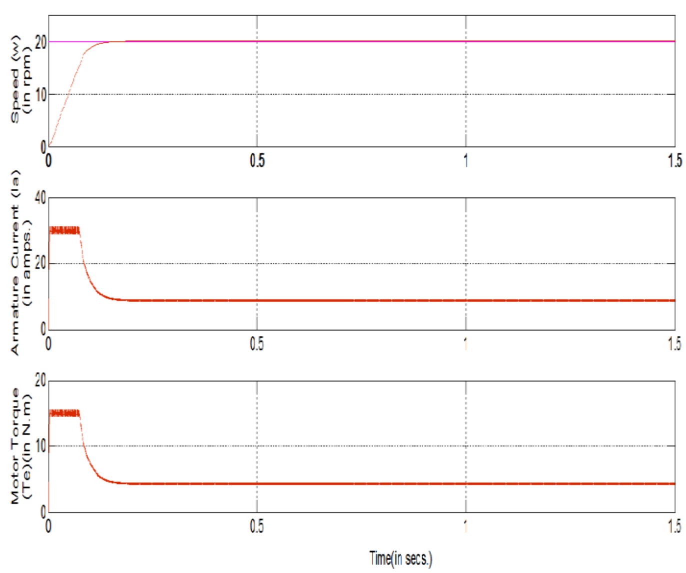


Fig. 19 Output waveform of closed loop speed control of PMDC motor using PID controller.

Table 2 shows the analysis of results obtained from closed loop speed control of PMDC motor drive using PD, PI and PID controllers.

Table 2 Analysis of results obtained from closed loop speed control of PMDC motor drive using PD, PI and PID controllers.

Performance Parameters / Controller Used	**Steady state error (e_{ss})**	**Maximum overshoot (M_p)**	**Settling Time (T_S)**	**Overall output stability**
With PI controller	0.003	0.886	0.449	better
With PD controller	0.12	0	0.292	better
With PID controller	0.016	0.018	0.646	Best

C. A novel approach for obtaining the optimal values of K_p, K_i and K_d for Controller design for enhancement of performance of PMDC motor drives

The tuning of PI, PD and PID controllers is done by trial and error method. In this method firstly, K_i and K_d are set to zero. Then, the Kp is increased until the output of the loop oscillates, after obtaining optimum K_p value K_i is increased until any offset is corrected in sufficient time for the process. However, too much K_i will cause instability. Finally, K_d is increased, until the loop is acceptably quick to reach its reference after a load disturbance. However, too much K_d also will cause excessive response and overshoot. The optimum values of these controllers will be employed in speed controller to control the speed of motor.

In simulation, a large no of speed controllers are used to control separate drives and each controller has different performance parameters. The parameter for which the output response is most desirable is set as the optimized value of controller. Fig.20 shows the simulink diagram for obtaining the optimum values of K_p, K_i and K_d

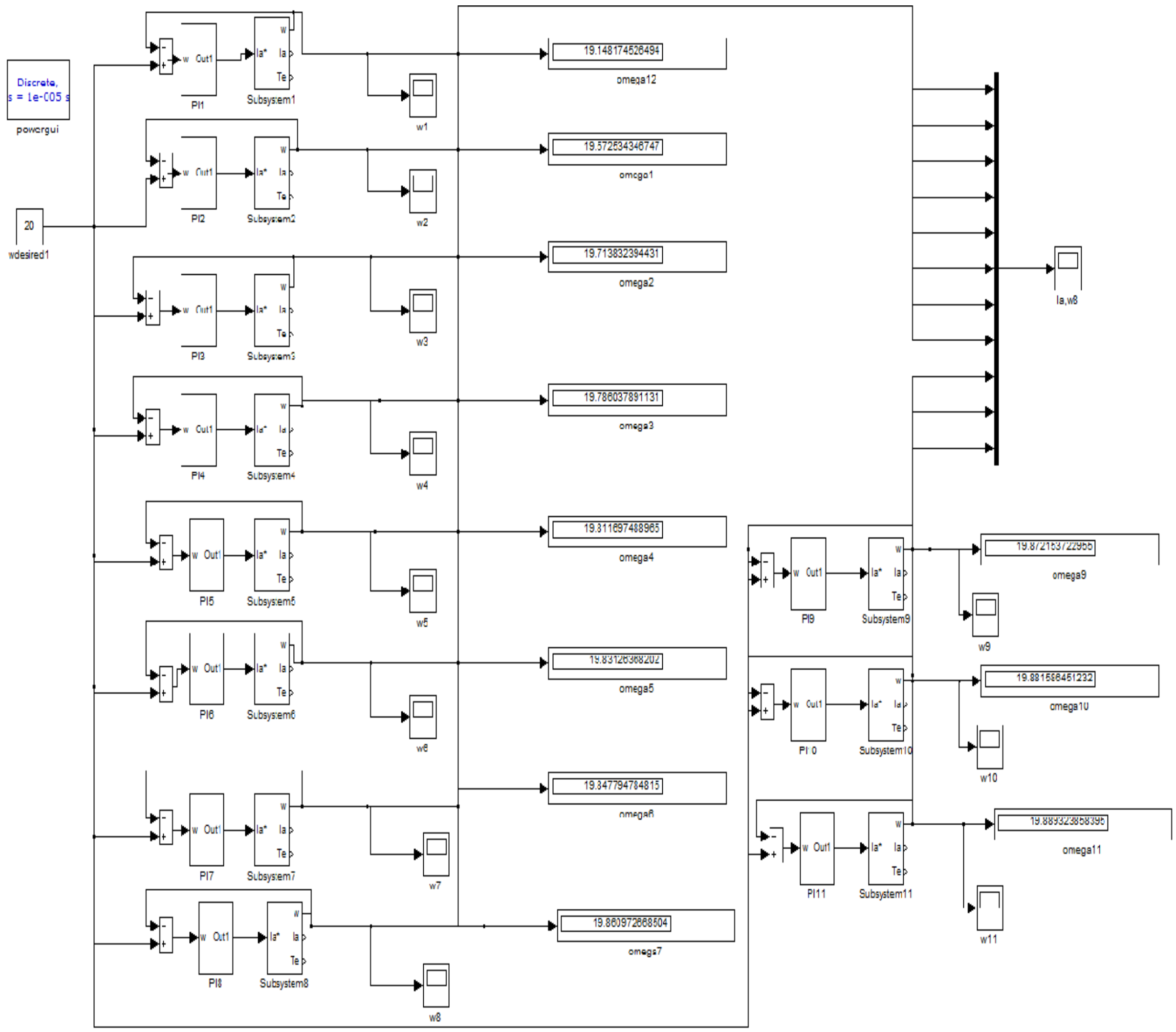


Fig.20 Simulink diagram for obtaining the optimum values of K_p, K_i and K_d.

1) Optimization of K_p

Fig. 21 shows the speed -time curve for optimization of K_p

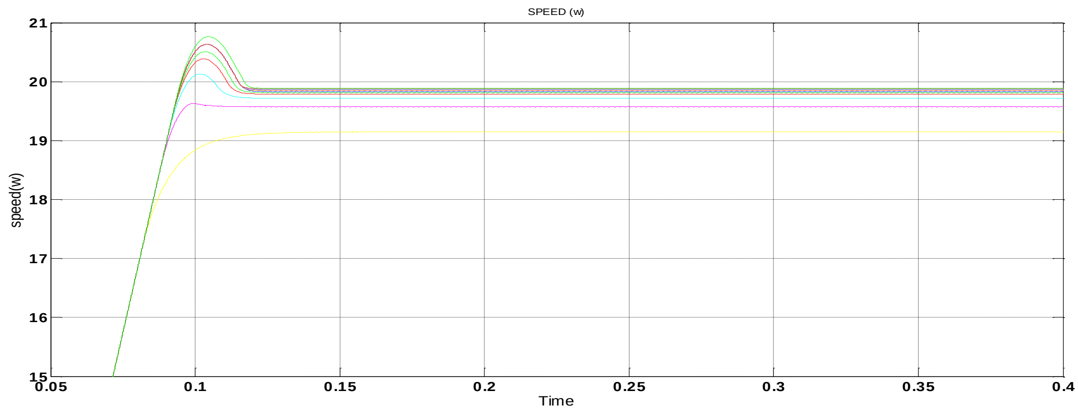


Fig. 21 Speed -time curve for optimization of K_p

K_p	e_{ss}		M_p	T_s
	% e_{SS}	magnitude e_{ss}		
10	4.3	0.86	0	0.177
20	2.15	0.43	-0.37	0.1475
30	1.45	0.29	0.13	0.1400
40	1.1	0.22	0.28	0.135
45	0.95	0.19	0.51	0.135
50	.85	0.17	0.635	0.129
55	.8	0.16	0.637	0.127
60	.7	0.14	0.638	0.123
65	**.65**	**0.13**	**0.633**	**0.123**
70	.6	0.12	0.634	0.1225
75	.6	0.12	0.762	0.1255

2) Optimization of K_i

Fig. 21 shows the speed -time curve for optimization of K_i

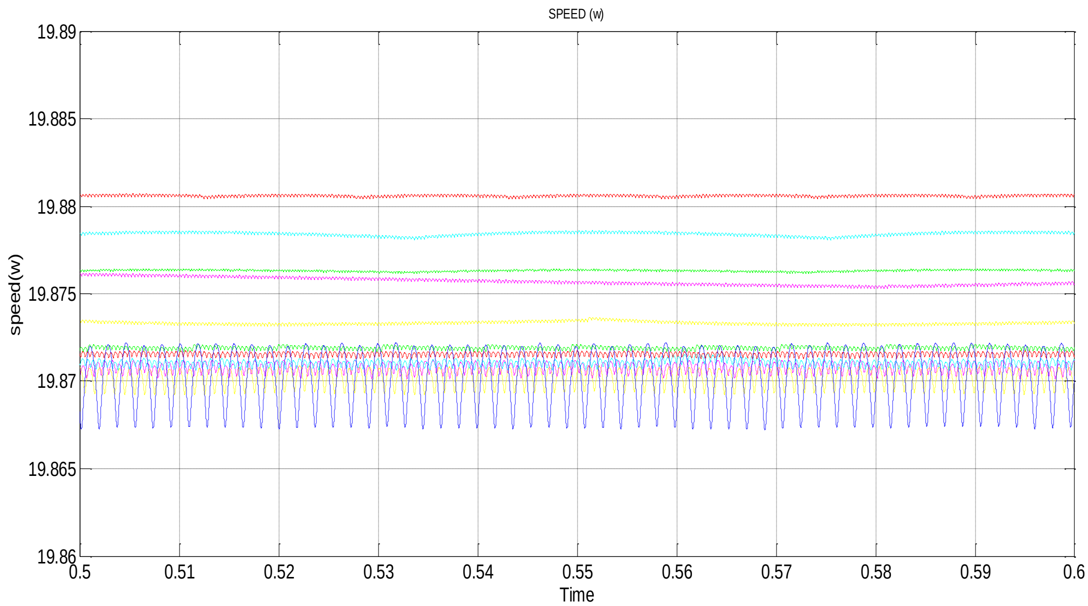


Fig. 21 Speed-time curve for optimization of K_i

3) Optimization of K_d

Fig. 22 shows speed-time curve for optimization of K_d

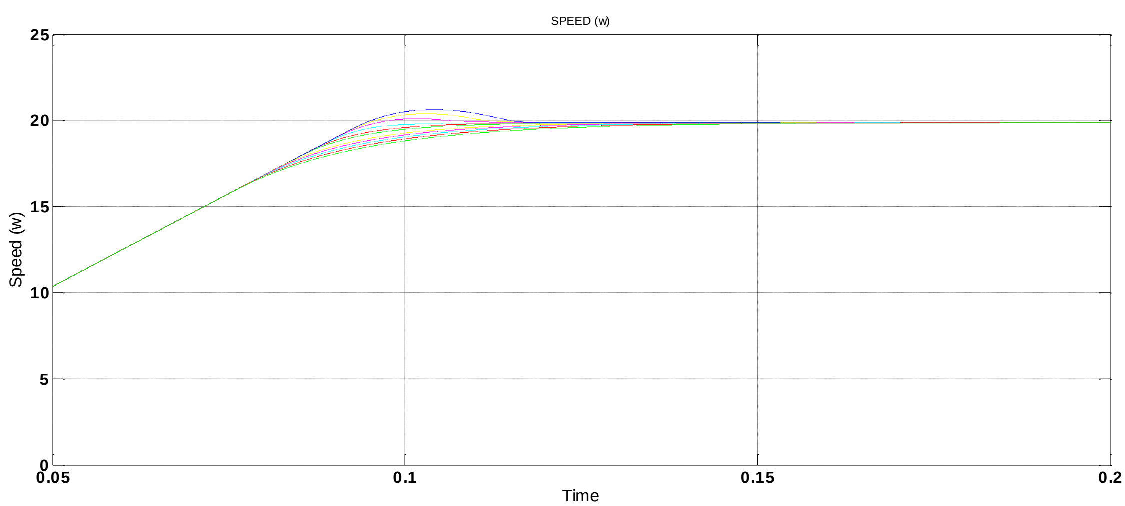


Fig. 22 Speed-time curve for optimization of K_d

Table 2. shows the Optimization of K_p (K_i=0 and K_d=0).

Table 2. Optimization of K_p (K_i=0 and K_d=0)

Table 3. shows the optimization of K_i and K_d by taking K_p=65(optimized value)

Table3. Optimization of K_i and K_d (K_p=65(optimized value))

K_i	**e_{ss}**		**M_p**	**T_s**	**K_d**	**e_{ss}**		T_s
						$\%e_{ss}$	**$\lvert e_{ss}\rvert$**	
6	0.210	-0.042	0.84	0.45	0.1	.650	-0.130	0.36
6.5	0.170	-0.034	0.86	0.47	0.2	.650	-0.130	0.33
7	0.140	-0.028	0.884	0.49	0.3	.650	-0.130	0.33
7.5	0.100	-0.020	0.886	0.5	0.4	.695	-0.139	0.30
8	0.050	-0.011	0.886	0.51	0.5	.695	-0.139	.30
8.5	0.020	-0.004	0.886	0.53	0.6	0.690	-0.138	.29
9	**0.015**	**0.003**	**0.886**	0.536	0.7	0.685	-0.137	.29
9.5	0.050	0.010	0.886	0.541	0.8	.675	-0.135	.27
10	0.075	0.015	0.886	0.556	0.9	.660	-0.132	.26
10.5	0.105	0.021	0.886	0.563	**1.0**	**.600**	**-0.120**	.232
11	0.130	0.026	0.886	0.59	1.1	.615	-0.123	.253

Therefore the optimized values of Kp, Kd and Ki are 65, 9 and 1.0 respectively.

CONCLUSIONS AND FUTURE SCOPE

The analysis of the results obtained from closed loop control and open loop control operation of drive concludes that:

- Closed Loop control of DC drive is far more efficient than open loop speed control and any desired speed below maximum speed of motor can be achieved.
- If we require a DC drive with an improved overall time response then PID controller would be the best choice for the drive.
- If, however the desired speed is our prime consideration in any application of DC drive then PI controller would be the first choice.

The future scope of this work is isn that it can be also used for AC drives such as three phase induction motor and three phase synchronous motor drives in similar fashion.

ACKNOWLEDGEMENT

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APPENDIX

SPECIFICATIONS OF PMDC MOTOR

Parameters of PMDC motor	Its Values
DC source voltage (V_{dc})	100V
Armature resistance (r_a)	0.5 Ω
Armature inductance (L_a)	100 mH
Torque constant (K_a)	0.5 V.s/rad
Rated Motor speed (w)	188rpm
Load torque (T_L)	4N.m
Viscous friction torque Constant (B_m)	0.01 N.m.s
Inertia constant (J)	0.05 Kg. m^2