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LabVIEW Based Speed Control of DC Motor using Modulus Hugging Approach

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Abstract

The speed control of separately excited DC motors by PI and PID controller is widely used in industry. A design of controller by applying a several method in analyzing controlled parameter to tune parameter in order to obtain the best process response. A design of PI and PID controller by Modulus Hugging Approach are presented in this paper for testing the performance of controllers in command following control and in disturbance rejection control. From simulation results with LABVIEW, it was found that the controller was fast response and stable, and the effect of disturbance is fast rejected.

Keywords: Modulus Hugging Approach, PI-PID Controller, Real Time, LabVIEW, DC Motor.

1. Introduction

The speed of separately excited DC motor can be controlled from below and up to rated speed using chopper as a converter. The chopper firing circuit receives signal from controller and then chopper gives variable voltage to the armature of the motor for achieving desired speed. There are two control loops, one for controlling current and another for speed. The controller used is Proportional-Integral type which removes the delay and provides fast control. Modelling of separately excited DC motor is done. The complete layout of DC drive mechanism is obtained. The designing of current and speed controller is carried out. The optimization of speed controller is done using modulus hugging approach, in order to get stable and fast control of DC motor. After obtaining the complete model of DC drive system, the model is simulated using LABVIEW. The simulation of DC motor drive is done and analyzed under varying speed and varying load torque conditions like rated speed and load torque, half the rated load torque and speed, step speed and load torque and stair case load torque and speed.

A controller designed by SO (Symmetrical Optimum) for the optimization of a control loop, we begin by considering the transfer function of the closed loop system as shown in Fig. 1. The dynamic performance of a control system is good if the controlled variable very rapidly reaches the value required by the command variable in terms of the frequency characteristic; this means a frequency range as wide as possible over which the modulus lies very near to 1 i.e. a wide bandwidth. At the instant of the input step, the controlled variable cannot correspond to the command variable, but very rapidly after, when lower frequencies come into effect, the modulus of the frequency characteristic comes very close to 1. Then the error between the command variable and the controlled variable rapidly becomes zero [5]. For the optimization of a control loop, we begin by considering the transfer function of the closed loop. This function dependent on the command variable, is

$$F\omega(s)=\frac{X(s)}{\omega(s)}=\frac{F_O(s)}{1+F_O(s)} \tag{1}$$

where $F_o(s)$ is the transfer function of the open loop system .

The transfer function for the closed control loop relative to the command variable shows two characteristics. In terms of frequency response, they are

$$F\omega(s)=\frac{b_0}{a_0+sa_1+s^2a_2} \tag{2}$$

$$F\omega(s)=\frac{b_0+sb_1}{a_0+sa_1+s^2a_2+s^3a_3} \tag{3}$$

The equation follows from the transfer function for the open loop. Thus we have $b_0=a_0$, real and imaginary parts can be obtained from equation (2) and then the modulus is obtained as follows

$$\left|F\omega(\omega)\right|=\sqrt{\frac{a_0^2}{a_0^2+\omega^2(a_1^2-2a_0a_2)+\omega^4a_2^2}} \tag{4}$$

If this modulus is to approach 1 at low frequency, the term in parentheses must become zero, a_1^2-$2a_0a_2$=0. This gives the first optimization equation for the design of the controller

$$a_1^2=2a_0a_2 \tag{5}$$

Similarly, the modulus for equation (3) is obtained as

$$\left|F\omega(\omega)\right|=\sqrt{\frac{a_0^2+\omega^2a_1^2}{a_0^2+\omega^2(a_1^2-2a_0a_2)+\omega^4(a_2^2-2a_1a_3)+\omega^6a_3^3}} \tag{6}$$

For modulus hugging, the expressions in parentheses in the denominator must be zero. Thus the following two equations are obtained

$$a_1^2=2a_0a_2 \tag{7}$$

$$a_2^2=2a_1a_3 \tag{8}$$

If equations (5), (7) and (8) are satisfied, then equation (2) becomes to

$$\left|F\omega(\omega)\right|=\sqrt{\frac{1}{1+\omega^4(a_2/a_0)^2}} \tag{9}$$

And equation (3) becomes to

$$\left|F\omega(\omega)\right|=\sqrt{\frac{1+\omega^2(a_1/a_0)^2}{1+\omega^6(a_3/a_0)^2}} \tag{10}$$

2. Controller Design

The controller used in a closed loop provides a very easy and common technique of keeping motor speed at any desired set-point speed under changing load conditions. This controller can also be used to keep the speed at the set-point value when, the set-point is ramping up or down at a defined rate. For example, if the error speed is negative, this means the motor is running slow so that the controller output should be increased and vice-versa [1].

2.1. Deciding the Type of Controller

The control action can be imagined at first sight as something simple like if the error speed is negative, then multiply it by some scale factor generally known as gain and set the output drive to the desired level. But this approach is only partially successful due to the following reason: if the motor is at the set-point speed under no load there is no error speed so the motor free runs. If a load is applied, the motor slows down and a positive error speed is observed. Then the output increases by a proportional amount to try and restore the desired speed. However, when the motor speed recovers, the error reduces drastically and so does the drive level. The result is that the motor speed will stabilize at a speed below the set-point speed at which the load is balanced by the product of error speed and the gain. This basic technique discussed above is known as "proportional control" and it has limited use as it can never force the motor to run exactly at the set-point speed [15].

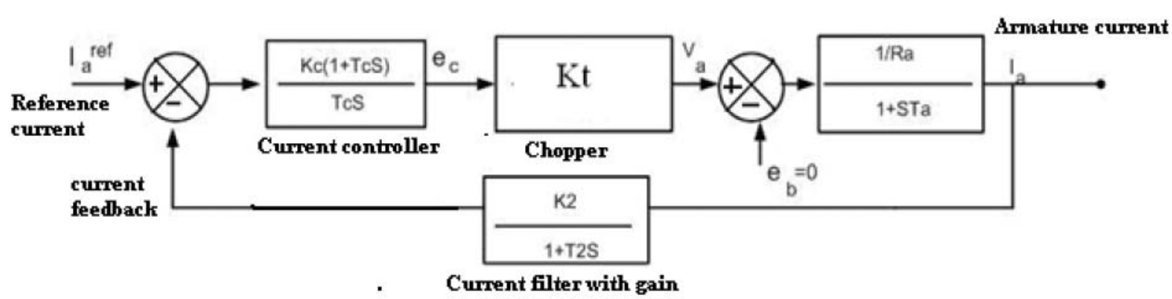
2.2. Importance of Current Controller in a DC Drives System

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 E_c 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 V_a will now not dependent on the speed error only but also on the current error. We should ensure that V_a 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.

2.3. Current Controller Design

We need to design current controller for the extreme condition when back emf is zero that is during starting period because at that time large current flows through the machine.

Figure 1: Block Model for Current Controller Design



Transfer function of the above model:

$$\frac{I_a(s)}{I_a(s)(ref)} = \frac{\{[K_c(1+TS_c)/T_cS](K_t)[(1/R_a)/(1+ST_a)\}}{\{1+[K_c(1+T_cS)/T_cS)]K_t[(1/R_a)/(1+ST_a)][K_2/(1+T_2S)]\}} \tag{11}$$

Here, *Tc* (Current Controller Parameter) can be varied as when required. *Tc* should be chosen such that it cancels the largest time constant in the transfer function in order to reduce order of the system [1, 2, 3]. Now, the response will be much faster. So, let us assume

$T_c = T_a$

Now, putting this value in equation (11)

$$\frac{I_a(s)}{I_a(s)(ref)} = \frac{\{K_c(K_t/T_aR_a)(1+T_2S\ )\}}{\{S(1+T_2S+(K_cK_tK_2)/T_a\ R_a\}} \tag{12}$$

Let,

$$K_0 = \frac{K_cK_t}{T_aR_a}$$

$$\frac{I_a(s)}{I_a(s)(ref)} = \frac{K_0(1+T_2S)}{S^2T_2+S+K_0K_2} \tag{13}$$

Where T_2 corresponds filter lag. Dividing T_2 on R.H.S:

$$\frac{I_a(s)}{I_a(s)(ref)} = \frac{\{(K_0/T_2)(1+T_2S)\}}{[S^2+S/T_2+K_0K_2/T_2]} \tag{14}$$

Characteristic Equation

$$S^2 = (s/T_2)+(K_0K_2/T_2) \approx S^2+2\varepsilon\omega+\omega^2$$

Here, $\omega = \frac{\sqrt{(K_0K_2)}}{T_2}$

$$\varepsilon = \frac{1}{2T\omega} = \frac{1}{2\sqrt{(T_2K_2K_0)}}$$

Since, it is a second order system.

So, to get a proper response ϵ should be 0.707 [4] [6].

So,

$$\frac{1}{\sqrt{2}} = \frac{1}{2\sqrt{(T_2K_2K_0)}}$$

$$K_0 = \frac{1}{2K_2T_2} = \frac{K_cK_t}{R_aT_a}$$

$$K_c = \frac{R_aT_a}{2K_tK_2T_2}$$

Here,

$$K_0 = \frac{K_cK_t}{R_aT_a} = \frac{1}{2K_2T_2}$$

$$\Rightarrow K_0K_2 = \frac{1}{2T_2}$$

Now, from equation (13) $\frac{I_a(s)}{I_a(s)(ref)} = \frac{\{(1/K_2)(1+T_2S)\}}{[2S^2T_2^{\ 2}+2ST_2+1]}$ (15)

We can see that the zero in the above equation may result in an overshoot. Therefore, we will use a time lag filter to cancel its effect. The current loop time constant is much higher than filter time constant [7, 8, 9]. Hence a small delay will not affect much

$$\left\{\frac{I_a(s)}{I_a(s)(ref)}\right\}(1+T_2S) = \frac{\{(1/K_2)(1+T_2S)\}}{[2S^2T_2^{\ 2}+2ST_2+1]}$$

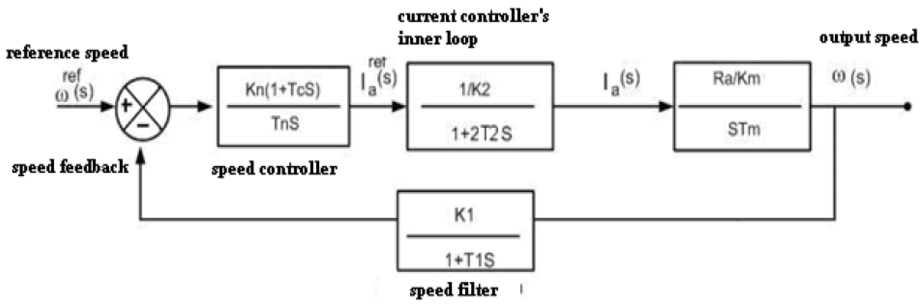
Hence

$$\frac{I_a(s)}{I_a(s)(ref)} = \frac{(1/K_2)}{(2S^2T_2^{\ 2}2ST_2+1)}$$

2.4. Speed Controller Design

The block model for speed controller design is shown in Fig. 2[10].

Figure 2: Block model for Speed Controller design



Now, converting the block model in transfer function, we will get:

$$\frac{\omega(s)}{\omega(s)(ref)}=\frac{(K_n/K_2)(R_a/K_mT_mT_n)\{(1+T_nS)/(1+2T_2S)S^2\}}{\{1+(K_nR_a/K_2K_mT_mT_n)(1+T_nS/(1+2T_2S)S^2)(K_1/(1+T_1S)\}} \tag{16}$$

Here, we have the option to Tn such that it cancels the largest time constant of the transfer function [1]. So, $T_n = 2T_2$

Hence, equation (16) will be written as:

$$\frac{\omega(s)}{\omega(s)(ref)}=\frac{(K_nR_a/K_2K_mT_mT_n)(1+T_1S)}{\{K_2K_mT_mS^2)(1+T_1S)+K_nR_aK_1\}}$$

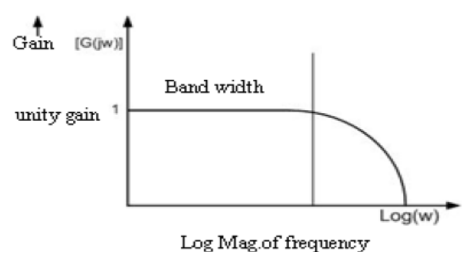
Ideally, $\omega(s)=\dfrac{1}{S(S^2+\alpha s+\beta)}$

The damping constant is zero in above transfer function because of absence of S term, which results in oscillatory and unstable system. To optimize this we must get transfer function whose gain is close to unity [1] [4] [6].

2.5. Modulus Hugging Approach for Optimization of Speed Controller Transfer Function

If the variable to be controlled rapidly reaches the desired value then dynamic performance of the control system is considered as good. For any frequency variation within bandwidth of the input variable, the output should follow the input variable instantaneously for achieving unity gain.

Figure 3: Gain Vs Frequency Waveform



The process of making output close to input variable so as to obtain unity gain for wide frequency range is termed as Modulus Hugging [1]. Considering equation (16):

$$\frac{\omega(s)}{\omega(s)(ref)}=\frac{\{(K_nR_a)(1+T_nS)(1+T_1S)\}}{\{S^2T_mT_nK_2K_m(1+2T_2S)(1+T_1S)+(K_nR_aK_1)(1+T_nS)\}}$$

Here,

$$(1+2T_2S)(1+T_nS)=1+T_1S+2T_2S+2T_2T_1S^2$$
$$\approx 1+S(2T_2+T_1)+2T_2T_1S^2$$
$$\approx 1+S(2T_2+T_1)$$

Here, T1 and T2 are smaller time constants. So their product can be approximated to zero.

So, $1+S(2T_2+T_1)=1+\delta S$

Assuming,

$\delta = 2T_2 + T_1$ and $K_0 = (K_n R_a / K_2 K_m)$

Then, $\dfrac{\omega(s)}{\omega(s)(ref)} = \dfrac{\{(K_n R_a / K_2 K_m)(1+T_n S)(1+T_1 S)\}}{\{S^3 T_m T_n \delta + S^2 T_m T_n + (K_0 K_1 T_n) S + K_0 K_1\}}$

The above transfer function is of third order. The terms (1 + T_nS) and (1 + T_1S) in the denominator will be cancelled by using filters [1].

Taking a standard third order system:

$$G(j\omega) = \frac{(b_0 + j\omega b_1)}{[a_0 + j\omega a_1 + (j\omega)^2 a_2 + (j\omega)^3 a_3]}$$

For low frequency b_0=a_0 and b_1=a_1

$$|G(j\omega)| = \frac{(a_0^2 + \omega^2 a_1^2)}{[a_0^2 + \omega^2(a_1^2 - 2a_0 a_2) + \omega^4(a_2^2 - 2a_1 a_3) + \omega^6 a_3^2]^{1/2}}$$

Now, modulus hugging principle, $|G(j\omega)| = 1$ for that coefficients of ω^2 and ω^4 are made equal to zero.

So, $a_1^2 = 2a_0 a_2$ & $a_2^2 = 2a_1 a_3$ (A)

We need to use filters on the ω(s) (ref) side to cancel $(1+T_n S)(1+T_1 S)$ term:

$$\frac{\omega(s)}{\{\omega(s)(ref)(1/(1+T_n S))(1/(1+T_1 S))\}} = \frac{(K_n R_a / K_2 K_m)(1+T_n S)(1+T_1 S)\}}{\{S^3 T_m T_n \delta + S^2 T_m T_n + (K_0 K_1 T_n) S + K_0 K_1\}}$$

Now, from optimization condition in (A), we get

$\Rightarrow (K_0 K_1 T_n)^2 = 2 * K_0 K_1 * T_m T_n$

$\Rightarrow K_0 K_1 T_n = 2T_m$

$\Rightarrow T_m = K_0 K_1 T_n / 2$ (17)

Also, $(T_m T_n)^2 = 2 * T_m T_n \delta K_0 K_1 T_n$

$\Rightarrow T_n = 4\delta = (2T_2 + T_1)$ (18)

$K_n = T_m K_m K_2 / (2 K_1 R_a \delta)$ (19)

Now, putting the values of K_n and K_m in the main transfer function, we get

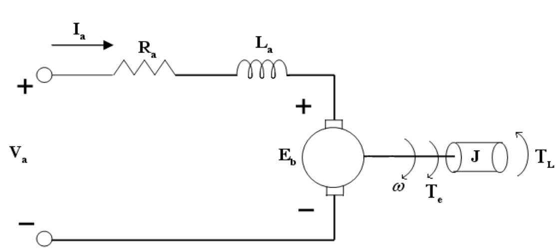
$$\frac{\omega(s)}{\omega(s)(ref)} = \frac{1}{(K_1 + 4\delta K_1 + 8S^2 \delta K_1 + 8S^3 \delta K_1)}$$

3. DC Motor

3.1. Equivalent Circuit of DC Motor

The equivalent circuit of a dc motor armature is based on the fact that the armature winding has a resistance R_a, a self-inductance L_a, and an induced emf. This is shown in Fig. 4. [11-14].

Figure 4: Equivalent circuit of dc motor



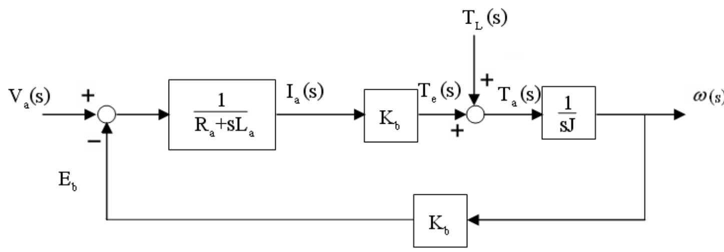
The dc motor will give the following equations

$$I_a(s) = \frac{V_a(s) - K_b\omega(s)}{R_a + sL_a} \tag{20}$$

$$\omega(s) = \frac{K_b I_a(s) - T_L(s)}{B + sJ} \tag{21}$$

B (viscous friction coefficient) was considered very small. The transfer function between angular velocity and torque appears in constant integrator and causes a block diagram of DC motor as in Fig. 5.

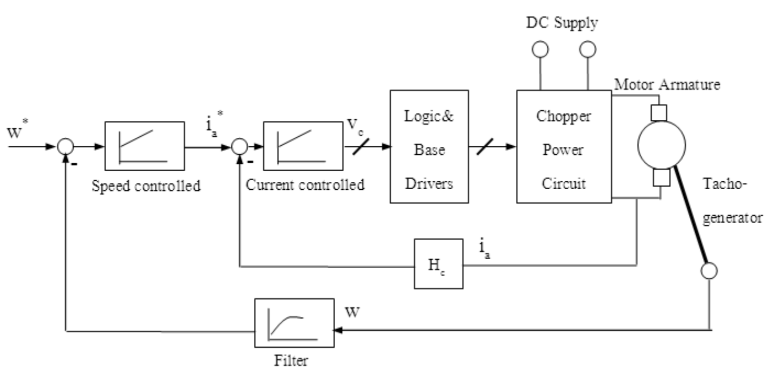
Figure 5: Block diagram of the dc motor



3.2. DC Motor Speed Control

The dc motor speed control consists of a controller, a driver, dc motor, tachogenerator, and low-pass filter with internal current control loop and external speed control loop , showing in Fig. 6.

Figure 6: The dc motor speed control



The driver circuit with the first order delay and a signal gain all can be shown as equation (22).

$$G_r(s) = \frac{K_r}{1 + sT_r} \tag{22}$$

Feedback's transfer function of speed control loop consists of tachogenerator and low-pass filter as equation (23).

$$G_\omega(s) = \frac{K_\omega}{1 + sT_\omega} \tag{23}$$

When K is the gain and T_ω is the time constant.

4. The Simulation Results

A separately excited DC motor with name plate ratings of 2.5 HP, 440V (DC), 55 rad/sec is used in all simulations. Following parameter values are associated with it [16].

Moment of Inertia, J = 85 Kg-m2.
Back EMF Constant = 9 Volt-sec/rad.
Rated Current = 50 A.
Maximum Current Limit = 100 A.
Resistance of Armature, Ra = 0.0241 ohm.
Armature Inductance, La = 0.718 mH.
Speed Feedback Filter Time Constant [1], T1 = 25 ms.
Current Filter Time Constant [1], T2 = 3.5 ms.

4.1. Current Controller Parameter

Current PI type controller is given by:

$$K_c\{(1+T_cS)/T_cS\}$$

Here, $T_c = T_a$ and $K_c = \frac{R_a T_a}{2K_2 K_t T_2}$

$$T_a = \frac{L_a}{R_a} = o.718 * 10^{-3} / 0.0241 = 29.79ms$$

For analog circuit maximum controller output is ± 10 Volts [1]. Therefore, Kt = 440/10 = 44. Also, K2 = 10/1000 = 1/100.

Now, putting value of Ra, Ta, K2, Kt and T2 we get: Kc = 0.233.

4.2. Speed Controller Parameter

Speed PI type controller is given by:

$$K_n\{(1+T_nS)/T_nS\}$$

Here, $T_n = 4\delta = 4(T_1 + 2T_2) = 4(25+7) = 128ms$

Also,

$$K_n = T_m K_m K_2 / (2K_1 R_a \delta)$$

$$K_1 = 10/55 = 0.181$$

$$T_m = JR_a / K_m = 85 * 0.0241/9 = 22.7ms$$

Now, Kn = (22.7*9*1)/ (2*0.181*0.0241*32*100) = 6.15 38

The LabVIEW simulation of the complete simulation is shown in Fig. 7. The hardware in loop simulation for a step input is shown in Fig. 9 and 10.

Figure 7: LabView simulation

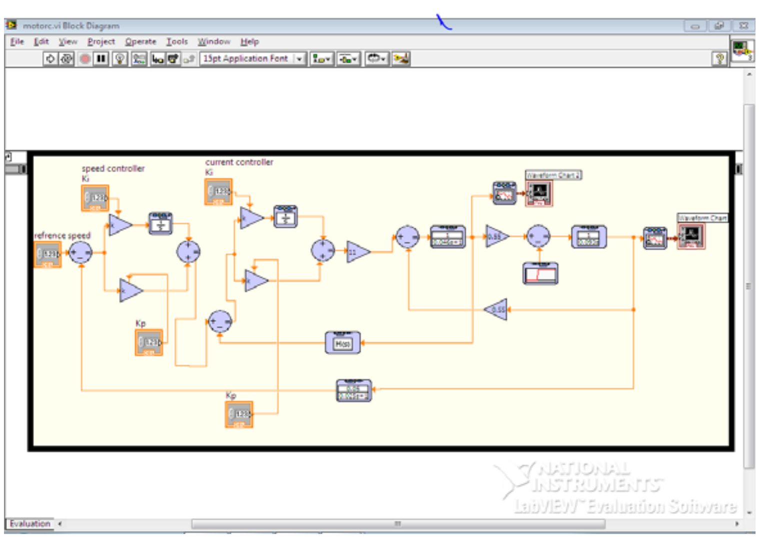


Figure 8: Interfacing of DC Motor with LabVIEW using DAQ CRIO 6293 analog output card

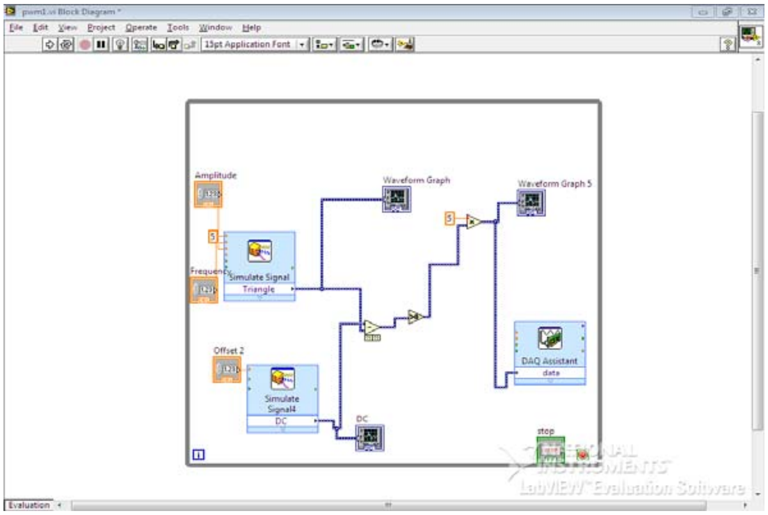


Figure 9: Hardware Setup

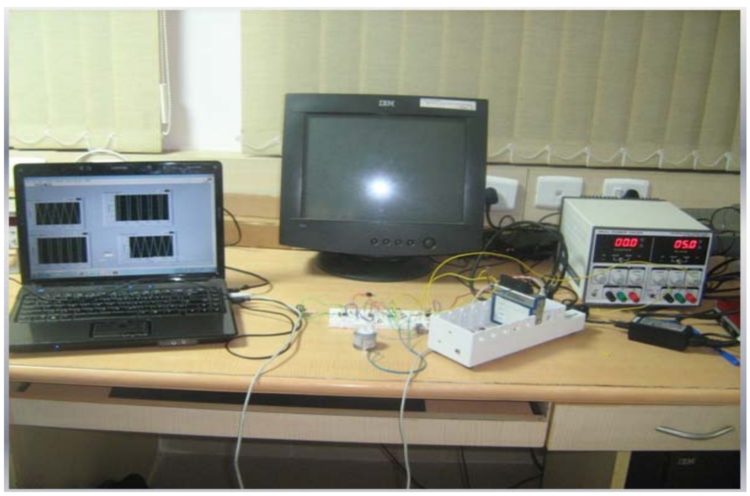
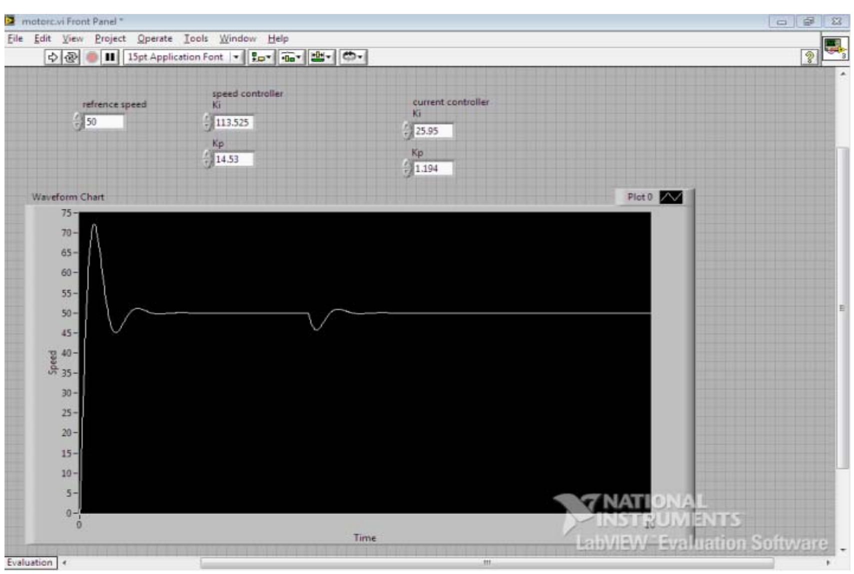


Figure 10: Hardware in loop simulation



5. Conclusion

This paper presents how to design PI and PID controller by Modulus Hugging Approach method, for the system consists of the first order delay and an integrator by using the sum of the smallest time constant (only in case that poles of plant are more than zeros of the controller). From the simulation result with LabView both in command following control and disturbance rejection control, it was found that PI controller could control plants that consist of the first order delay and the integrator element. The system's response shows the fast rise time, fast setting time as well as fast recovering time.

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