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Electro-Mechanical Modeling of Separately Excited DC Motor & Performance Improvement using different Industrial Controllers with Active Circuit Realization

A.F.M. Sajidul Qadir [1*]
[1] Department of Electrical, Electronic & Communication Engineering, Military Institute of Science & Technology, Mirpur Cantonment, Dhaka-1216, BANGLADESH

ABSTRACT
In this paper, Mathematical Modelling of a reference Separately excited DC motor has been done & Transfer Function has been derived with simulated result. Later Parameter Identification has been carried out to find the suitable design criteria for testing different controllers (P, PI, PD, PID controllers) with the machine. As it turned out to be a stable system (as per Routh–Hurwitz Stability Criterion), different controllers has been used to evaluate the Step response of Open loop & Closed loop system with simulated result. Controller tuning has been done to find the best result for controlling speed of the machine. Settling time, % Overshoot, Steady-State error & Rise time has been calculated for all the controllers. Later active RC realization of the best fitted controller has been done using Ideal PID Control Algorithm.

Keywords: Mathematical Modeling; DC Machine; Industrial Controller; Parameter Estimation; Transfer Function; Active Circuit Realization

1. Introduction

Separately excited DC motors have been widely used prime movers in many industrial applications such as electric vehicles, steel rolling mills, electric cranes, and robotic manipulators due to precise, wide, simple, and continuous control characteristics. The widely used traditional way of controlling low power DC motor is rheostatic armature control. Due to non-linearity properties, implementation of traditional control system is tedious and inefficient. The controllability, cheapness, higher efficiency and higher current carrying capabilities of static power converters brought a major change in the performance of electrical drives. The desired torque-speed characteristics can be achieved by the use of conventional proportional-integral-derivative (PID) controllers. The purpose behind this work is to deeply investigate the performance of DC machine and hence tuning the speed using the suitable controller & deriving physical realization of the system.

2. Modeling Approach of SEDM

The DC motor is basically a torque transducer. The torque developed in the motor shaft is directly proportional to the field flux & armature current. For modeling any physical active element, Transfer function of it needed to be derived which represents the mathematical form of the physical element. When an idealized physical system's Mathematical model is tested for various input conditions and tuned accordingly with controllers, the result represents the dynamic behaviour of the system. Since SEDM is extensively used in control system, for analytical purpose, it is necessary to establish mathematical models for control application of it. [1] After that suitable design criteria will be established in consistent with the particular machine parameter. It is assumed that the motor has magnetic linearity, thus the basic motor equations are:

$$T = K_f I_f I_a = K_m I_a \tag{1}$$

$$e_a=K_f I_f \omega_m=K_m\omega_m \tag{2}$$

Where $K_m = K_f I_f$ is a constant, which is also ratio $\frac{e_a}{e_m}$. The Laplace transformation of Eq.(1) and Eq.(2) are:

$$T(S)=K_m I_a(S) \tag{3}$$

$$E_a=K_m\omega_m(S) \tag{4}$$

In the physical system, a switch is positioned after armature resistance (**R_a**) and the switch be closed at **t=0** as because for Transfer Function, all initial conditions must be zero. After the switch is closed:

$$V = e_a + R_a I_a + L_a \frac{dI_a}{dt} \tag{5}$$

From Eq.(2) and Eq.(5):

$$V = K_m \omega_m + R_a I_a + L_a \frac{dI_a}{dt} \tag{6}$$

As the necessary differential equation is obtained which is required to derive Transfer Function of the reference system, Laplace transform of the equations can now be obtained. It is independent of input excitation and shows the relationship between input and output of the system. Laplace transform of Eq.(6) for initial zero condition is:

$$V(S)=K_m\omega_m(S)+R_aI_a(S)+L_a(S)I_a(S) \tag{8}$$

$$V(S)=K_m\omega_m(S)+ I_a(S)\, R_a\,(1+S\tau_a) \tag{9}$$

* Corresponding Author. Tel.: +88-01922268656
E-mail Address: sajid.kaist@gmail.com

Where $\tau_a = \frac{L_a}{R_a}$ is the electrical time constant of the armature. The dynamic equation for the mechanical system is:

$$T = J\frac{d\omega_m}{dt} + B\omega_m + T_L \qquad (10)$$

The term $\mathbf{B\omega_m}$ represents the rotational loss torque of the system. The Laplace transform of Equation of Voltage is:

$$T(S)=J(S)\omega_m(S)+B\omega_m(S)+T_L(S) \qquad (11)$$

From Eq.(3) and Eq.(11) :

$$\omega_m(S) = T(S) - \frac{T_L(S)}{B\{1+S\tau_m\}} = \frac{K_m I_a(S) T_L(S)}{B\{1+S\tau_m\}} \qquad (12)$$

Where $\tau_m = \frac{J}{B}$ is the mechanical time constant of the system. From Eq.(4) and Eq. (9):

$$I_a(S) = V - \frac{E_a(S)}{R_a(1+S\tau_a)} = V(S) - \frac{K_m\omega_m(S)}{R_a(1+S\tau_a)} \qquad (13)$$

Taking Laplace transform, the transfer function from the input voltage **V(S)** to the output angular velocity **ω(S)** directly follows:

$$\frac{\omega(S)}{V(S)} = \frac{K}{(R+LS)(JS+B)+K^2}$$

This is the desired transfer function of the SEDM which represents the ratio of system's input condition to the output. A block diagram representation of the Equation is as follows:

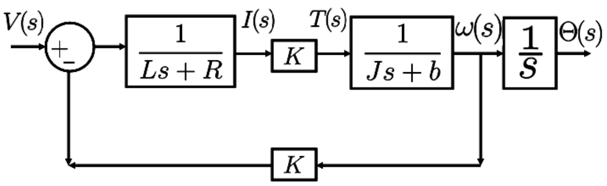

Fig.1 Block diagram representation of Transfer Function

2.1 Parameter Identification

Before any consideration of the above transfer function, the value of the parameters (**J, B, K, R, L**) must be known which is very important for the proper application of the DC Motor. [2] There are many methods of parameter identification. Some widely practiced methods are:

1. Gradient Algorithm
2. Stochastic State Estimation (Using Kalman Filter)
3. Least Square Algorithm

In these methods, Kalman filter can be used as an observer which helps to reduce the % of error. Using the 3rd method, parameters can be estimated even from open loop transfer function. Considering the table of specification of the reference Separately Excited DC motor provided by the manufacturer, the following values have been taken for the design purpose using the method described above. These values will be used in designing the desired system with recommended speed control. [3]

Table 1 Physical Parameters of SEDM

Moment of inertia of the rotor (J_m)	0.007 kg.m^2
Damping ratio of the mechanical system (b_m)	0.02 Nms
Electromotive force constant ($K=K_e=K_t$)	0. 1 Nm/Amp
Electric resistance (R)	1 Ω
Electric inductance (L)	0.1 H

Since the most basic requirement of a motor is that it should rotate at the desired speed, the steady-state error of the motor speed better be less than 1%. The other performance requirement is that the motor must accelerate to its steady-state speed as soon as it turns on. In this case, considering the full load speed 1500r/min, desired settling time is of 1 second. Since a speed faster than the reference may damage the equipment, an overshoot of less than 2% is desired. If the reference input (**r**) is simulate by a unit step input, then with a **1 rad/sec** step input the motor speed output should have:

- Settling time less than 0.2 seconds
- Overshoot less than 2%
- Steady-state error less than 1%
- Rise Time less than 0.2 second

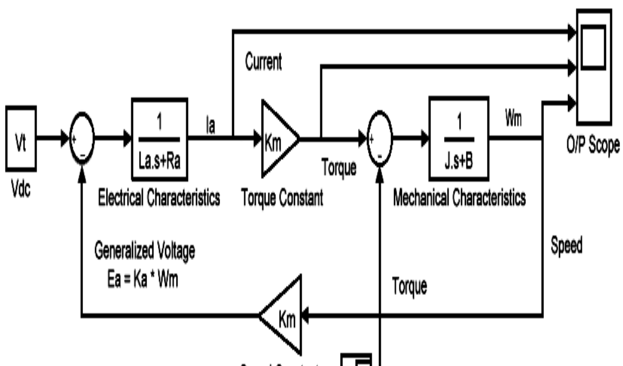

Fig.2 Simulink representation of the SEDM TF

With all the required specifications of the DC motor, a model of the system has been developed using SIMULINK. The system has been modeled using the characteristics transfer function of the electrical and mechanical parameters of the motor. The Electro-Mechanical model is obtained only after deriving the differential equations and Transfer function of all the components of the system. Fig.2 shows the DC motor input armature voltage (**V_t**) summed with the internal EMF. The result is then fed into the electrical characteristics transfer function block to produce the armature current (**I_a**). It is then pass through a torque constant to produce torque. This is then summed with a torque load, giving an output torque which is then fed into the mechanical characteristics transfer function block. The output is the rotor speed (**W_m**), which is fed back into the speed constant providing the constant EMF.

3. Controller Selection & Performance Improvement

To test the reference model, two performance measures have been chosen to use. These measures are widely used in analyzing the performance of the controller and also next generation Fuzzy-PID. They are:

1. *Transient Response:* One of the most important characteristics of control system is their transient response. The transient response is the response of a system as a function of time. It can be described in terms of two factors:

A. The swiftness of response, as represented by the rise-time (T_r).

B. The closeness of response to the desired response, as represented by the overshoot (O_s) and settling-time (T_s).

2. *Robustness:* A robust controller is capable of dealing with significant parameter variation provided that it's steady state error [$e(\infty)$] will be negligible. Examining the machines performance with different parameter values showing negligible steady state error usually assesses controller robustness.

Before testing any controller for the reference system, open-loop and close-loop response of the transfer function has to be measured for finding out the level of the parameters which has to be improved. So open-loop and close-loop response of the reference system has been measured followed simulation of by Proportional (P), Proportional Integral (PI) and Proportional Integral derivative (PID) controllers.

3.1 Step Response for Open Loop Control

As derived earlier, the transfer function of the SEDM for open loop control system is:

$$\frac{\omega}{V} = \frac{K}{(JS + B)(LS + R) + K^2}$$

Using the electrical & mechanical parameters that have been defined in Table 1, the modified transfer function is:

$$\frac{\omega}{V} = \frac{0.1}{(0.007S+0.02)(0.1S+1)+0.01}$$

$$\text{Or } \frac{\omega}{V} = \frac{0.1}{0.0007S^2+0.009S+0.03}$$

$$\text{Or } \frac{\omega}{V} = \frac{1}{0.007S^2+0.09S+0.3} \quad (14)$$

After running the necessary code (M-file) in Matlab, the step response has been generated as Fig.(3). The DC gain of the plant transfer function is 1/0.3, so 3.333 is the final value of the output to a unit step input. This corresponds to the steady-state error 0.2308, quite a high value. Furthermore, the rise time is about 0.513 second, and the settling time is 0.866 seconds. So, a controller has to be selected & tuned properly that will reduce the rise time, reduce the settling time, and eliminates the steady-state error.

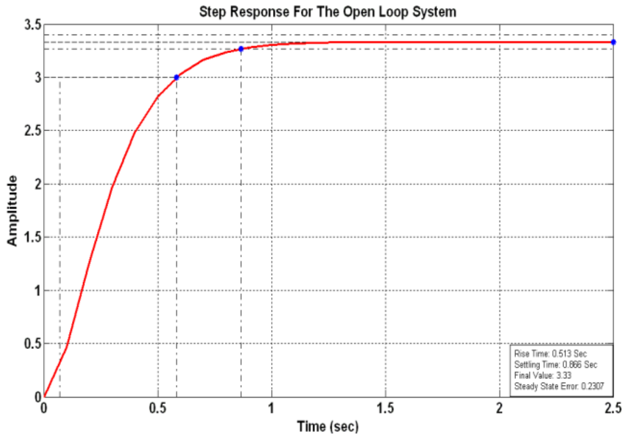

Fig.3 Open-loop step response of the transfer function

3.1.1 Checking System Stability

Stability of a system indicates it's usability. As the characteristic equation of open loop TF of the SEDM is algebraic in nature, Routh-Hurwitz stability criteria can be used to measure system's stability. The open loop TF is as derived earlier in Eq.(14):

$$\frac{\omega}{V} = \frac{1}{0.007S^2 + 0.09S + 0.3}$$

Using Routh-Hurwitz theory, if the system prevails to be stable, than different controllers can be used to modify the transfer function to satisfy the design criteria.

Table 2 Routh-Hurwitz Table

S^2	0.007	0.03	0
S^1	0.09	0	0
S^0	0.0027	0	0

Here it can be seen that the system is stable, because there is no sign change in first column of the Routh table and all terms are positive. As the system turns out stable, different types of controller can be used with the machine to check performance.

3.2 Close-Loop Response

Close loop control improves machine performance by increasing the speed of response and improving on speed regulation. The step response plotted in Fig.3 shows a sluggish response of speed and current with time. The Closed Loop Speed Control presents an enhanced control method. To validate it, different controllers will be tested in close loop control system to improve the overall speed regulation by decreasing the rise time, settling time and overshot. Based on the DC motor speed response measurement under a constant voltage input, important motor parameters such as the electrical time constant, the mechanical time constant, and the friction can be estimated.

3.3 Effects of Different Control Gain

There are 3 different conventional control gain namely K_p, K_i, K_d. They have varied effect on the system. They can be used alone or together. Using together is advisable because demerits of one type will be compensated by other one. So to eliminate huge oscillation, sluggish rise time and much delayed steady state final value, the combination of these controllers can be used. The feedback device that has been used is a Tachometer. Tachometer is a kind of sensor which is electromechanical devices that converts mechanical energy into electrical energy. [4]

3.3.1 Proportional Controller

K_p is termed as the proportional gain. After many trial & error, a suitable value has been taken for proportional gain. It is known that proportional controller decreases Rise Time, increases overshoot and decreases Steady-State error. It also has small effect on Settling Time. Considering all these effect, value of K_p has been taken.

$$K_p = 1$$

The close loop transfer function of the above system with a proportional controller is:

$$\frac{\omega}{V} = \frac{1 \times K_p}{0.007S^2 + 0.09S + (0.3 + K_p)}$$

$$\text{Or } \frac{\omega}{V} = \frac{1}{0.007S^2 + 0.09S + 1.3} \tag{15}$$

After running the necessary code in Matlab (M-file), the response has been generated as follows:

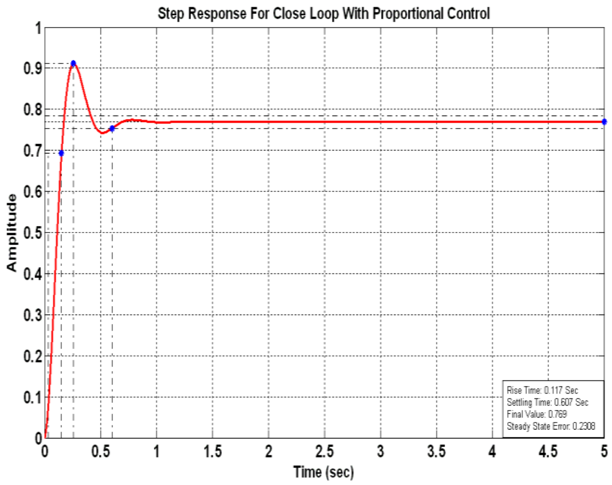

Fig.4 Close loop step response with Proportional Controller

So using Proportional controller, rise time is 0.117 seconds, settling time 0.607 seconds, Steady state error 0.2308 with a minor overshoot. The above plot shows that the proportional controller reduced rise time, increased the overshoot, and decreased the settling time by small amount. But the steady state error remained unchanged. Derivative controller decreases overshoot and settling time. So a combination of Proportional & Derivative controller has been used together to offset the effects.

3.3.2 Proportional Derivative (PD) Controller

K_d is termed as the derivative gain. The gain of proportional controller will remain same. The new derivative gain K_d has been taken as 5 after trial and error. All the values have been taken on expert guess.

$$K_p = 1, \qquad K_d = 5$$

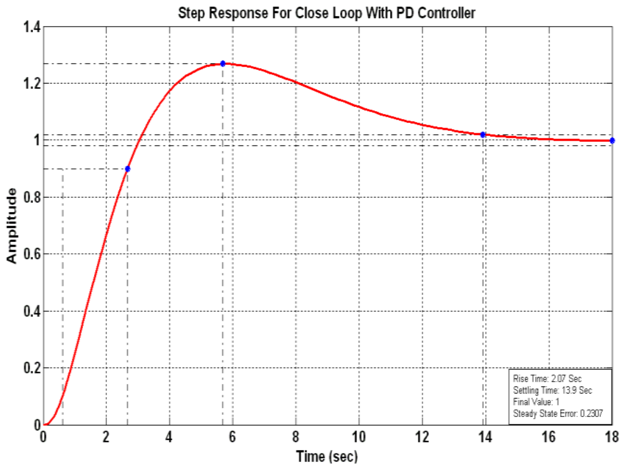

Fig.5 Close loop step response with PD Controller

The close loop transfer function of the above system with a PD controller is:

$$\frac{\omega}{V} = \frac{K_d S + K_p}{0.007S^2 + (0.09 + K_d)S + (0.3 + K_p)}$$

$$\text{Or } \frac{\omega}{V} = \frac{5S + 1}{0.007S^2 + 5.09S + 1.3} \tag{16}$$

The derivative term reduces overshoot and settling time and has little effect on rise time and steady state error. After running the necessary code in Matlab (M-file), the response has been generated as above. So using PD controller, rise time is 2.07 seconds, settling time 13.9 seconds, Steady state error 0.2307 with a minor overshoot. The above plot shows that the PD controller increased rise time, increased the overshoot, and increased the settling time by huge amount. But the steady state error remained unchanged. So it is observed that PD controller has worst effect on the system. Now PI controller will be examined because they both decreases the rise time and eliminate the steady state error.

3.3.3 Proportional Integral (PI) Controller

It introduces a pole and a zero to the overall system. It is better than the previous Controllers. The gain of proportional controller will remain same. The new integral gain K_i has been taken as 8 after trial and error. All the values have been taken on expert guess.

$$K_p = 1, \qquad K_i = 8$$

The close loop transfer function of the above system with a PD controller is:

$$\frac{\omega}{V} = \frac{K_p S + K_i}{0.007S^3 + 0.09S^2 + (0.3 + K_p)S + K_i}$$

$$\text{Or } \frac{\omega}{V} = \frac{S+8}{0.007S^3 + 0.09S^2 + 1.3S + 8} \qquad (17)$$

The proportional and integral both term reduces the rise time and eliminates the steady state error, but it increases overshoot. After running the necessary code in Matlab, the response has been generated.

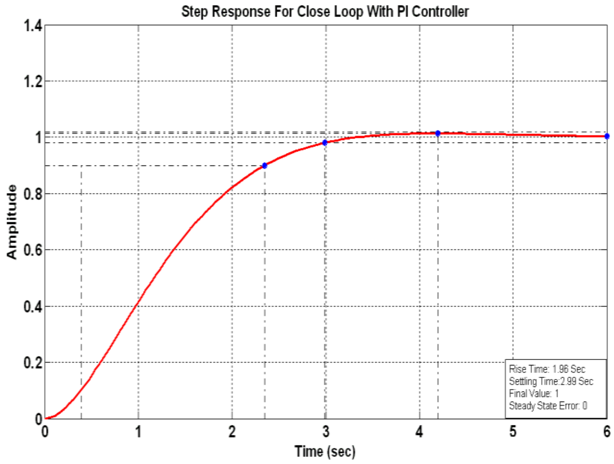

Fig.6 Close loop step response with PI Controller

It is observed from the graph that rise time is 1.96 seconds, settling time is 2.99 seconds. Steady state error is 0(zero). PI controller has much better effect on the system as it has decreased the settling time & rise time. More importantly, it eliminates the steady state error to zero. Also the system has negligible overshoot. Yet the system with PI is still far off from the design requirement.

3.3.4 Proportional Integral Derivative (PID) Controller

Two zeroes and a pole at origin is introduced by this controller. Proper selection of controller gains (K_p, K_i & K_d) improves stability and response of the overall system. The gain of proportional & integral controller will remain same. The new derivative gain K_d has been taken the same as that of PD control mechanism. All the values have been taken on expert guess.

$$K_p = 1, \qquad K_d = 5, \qquad K_i = 8$$

The close loop transfer function of the above system with a PD controller is:

$$\frac{\omega}{V} = \frac{K_d S^2 + K_p S + K_i}{0.007S^3 + (0.09 + K_d)S^2 + (0.3 + K_p)S + K_i}$$

$$\text{Or } \frac{\omega}{V} = \frac{5S^2 + S + 8}{0.007S^3 + 5.09S^2 + 1.3S + 8} \qquad (18)$$

PID controller brings the best of the entire available controller. The proportional and integral controller decreases the rise time & eliminate the steady state error while the derivative controller decreases the overshoot and settling time which is increased by P & I gain. After running the necessary code in Matlab, the response has been generated as follows:

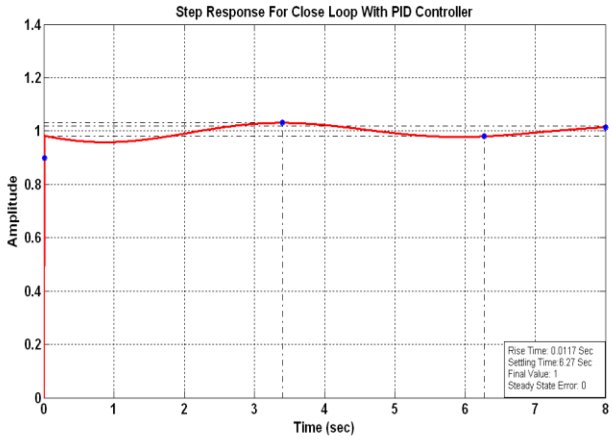

Fig.7 Close loop step response with PID Controller

From the graph, it is observed that rise time is 0.0117 seconds, settling time is 6.27 seconds, steady state error is 0 (zero). There are some very small scale oscillation or ripple in the system which increased the settling time of the system. So proper tuning of the gain is necessary.

3.4 Tuning the PID Controller

There exist many methods to tune PID controllers. Some common methods are listed used in the industry are: [5]

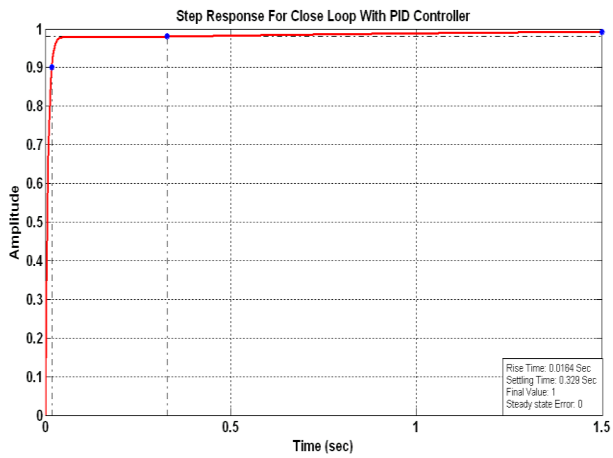

Fig.8 Close loop step response with Tuned PID

1. Ziegler–Nichols method
2. Skogestad's method
3. Good Gain method
4. Cohen-Coon method

As it is possible to take the proposed system of the paper offline, that's why 3rd method has been followed. Among these methods, 3rd method need no prior knowledge of the system & is easier of the methods mentioned.

As seen from the Fig.8, settling time decreased a lot if the gain values are taken as below:

$$K_p = 10, \qquad K_d = 1, \qquad K_i = 8$$

K_p & K_d is increased to decrease the rise time and overshoot. The Matlab code shows the graph as Fig.8. From the figure it is observed that rise time is 0.0164 seconds, settling time is 0.329 seconds, steady state error is 0(zero). Furthermore there is no overshoot. So these gain combination can meet the design requirement almost satisfactorily. The figure gives almost perfect system condition with very fast rise time, very fast settling time, zero steady state error with zero overshoot. So this particular combination of gain values gives near perfect system response with all the responses very fast and no overshoot, no steady state error. From above experimental data & figures, it can be concluded that perfectly tuned PID controller best suites the proposed design criteria to control the speed of separately excited DC Motor & hence improve the performance of the machine.

3.5 Calculation of Steady State Error, Rise Time & Settling Time

For a unity feedback system without any controller attached to it, the steady state error response is:

$$e_{step}(\infty) = \frac{1}{1+lim_{S\to 0}\, G(S)} \tag{19}$$

From Fig.3, T_r =0.513 sec, T_s = 0.866 sec. So for the reference SEDM, the steady state error is:

$$e_{step}(\infty) = \frac{1}{1+3.333} = 0.2308$$

For a unity feedback system with different controllers attached to it after checking the stability, the steady state error response is:

$$e(\infty) = lim_{S\to 0}\{1 - T(S)\} \tag{20}$$

For Proportional Controller from Eq.(15):

$$T(S) = \frac{1}{0.007S^2+0.09S+1.3}$$

$$e(\infty) = lim_{S\to 0}\{1 - T(S)\} = 1 - 0.76923 = 0.2308$$

From Fig.4 of Step response of Proportional controller, T_r = 0.117 sec, T_s = 0.607 sec.

For PD Controller from Eq.(16):

$$T(S) = \frac{5S+1}{0.007S^2+5.09S+1.3}$$

$$e(\infty) = lim_{S\to 0}\{1 - T(s)\} = 1 - 0.76923 = 0.2308$$

From Fig.5 of Step response of PD controller, T_r = 2.07 sec, T_s = 13.9 sec.

For PI Controller from Eq.(16):

$$T(S) = \frac{S+8}{0.007S^3+0.09S^2+1.3S+8}$$

$$e(\infty) = lim_{S\to 0}\{1 - T(S)\} = 1 - 1 = 0$$

From Fig.6 of Step response of PI controller, T_r = 2.07 sec, T_s = 13.9 sec.

For PID Controller from Eq.(17):

$$T(S) = \frac{5S^2+S+8}{0.007S^3+5.09S^2+1.3S+8}$$

$$e(\infty) = lim_{S\to 0}\{1 - T(S)\} = 1 - 1 = 0$$

From Fig.7 of Step response of PID controller, T_r = 0.0117 sec, T_s = 6.27 sec.

4. Active Circuit Realization

PID (proportional Integral Derivative) control is one of the earlier control strategies. Its early implementation was in pneumatic devices, followed by vacuum and solid state analog electronics, before arriving at today's digital implementation of microprocessors. Since many process plants controlled by PID controllers have similar dynamics it has been found possible to set satisfactory controller parameters from less plant information than a complete mathematical model. These techniques came about because of the desire to adjust controller parameters in situ with a minimum of effort, and also because of the possible difficulty and poor cost benefit of obtaining mathematical models. The goal is to design a PID controller with the tuned gains found earlier with active circuits. This can also be termed as 'Physical Realization' of the controller.

4.1 Different Methods of Physical Realization

There are many methods of physically realizing a controller or compensator. Two general way of implementing controllers are:

1. Analog Implementation
2. Digital Implementation

Analog implementation is preferred over digital implementation when the system considered is not necessarily to be very fast in response such as responsive of µsec limit. Also digital implementation needs complex circuitry which is costly. That's why analog implementation has been preferred in this work. Analog implementation can be done in 3 ways: [6]

1. Parallel PID Algorithm
2. Series PID Algorithm
3. Ideal PID Algorithm

In Ideal PID Algorithm, a simple inverting amplifier is used to implement PID controller. Its response and tenability is slower than the other two algorithms but because of cost effectiveness, 3rd method has been chosen for the work. The classical implementation of PID controller or the active circuit realization of the controllers contains several active elements to realize the transfer function. For instance, parallel structures using Operational Amplifiers (Op-Amp) requires 5 amplifiers: Differentiator, P, I, D Op-amp and adder. At least 3 operational amplifiers are needed to implement a PID controller:

1. Integral - Need one Op-amp to perform integration of input signal.
2. Derivative - Need one Op-amp to perform derivative of input signal.
3. Proportional - Need one Op-amp to provide proportional gain.

Utilizing Operational amplifier, all the conventional industrial controller as well as compensators can be realized.

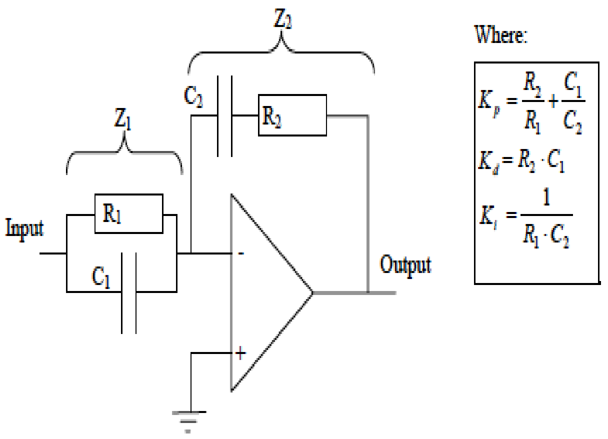

Fig.9 Ideal PID Implementation

The transfer function of the inverting amplifier is:

$$T = -\frac{Z_2}{Z_1} = \frac{V_0(S)}{V_i(S)} \tag{21}$$

By judicious choice of $\mathbf{Z_1(s)}$ and $\mathbf{Z_2(s)}$, the circuit of Fig.9 can be used as a building block to implement PID controller. Using Eq.(21) and the Fig.9, it can be shown that:

$$\frac{V_{out}}{V_{in}} = -\left[\left(\frac{R_2}{R_1} + \frac{C_1}{C_2}\right) + S.C_1.R_2 + \frac{1}{R_1 C_2}.\frac{1}{S}\right] \tag{22}$$

Above Eq.(22) corresponds to a PID controller. The transfer function of the PID controller is found as:

$$G(S) = K_p + K_d S + \frac{K_i}{S} = \frac{K_d S^2 + K_p S + K_i}{S} \tag{23}$$

By putting the desired gains, a function of S will be formed. From Fig.8, if gain of PID controllers if taken as follows:

$$K_p = 10, \quad K_d = 1, \quad K_i = 8$$

Than the transfer function of the PID controllers will be as follows:

$$G(S) = \frac{K_d S^2 + K_p S + K_i}{S} = S + 10 + \frac{8}{S} \tag{24}$$

Comparing the PID controller of Fig.9 with Eq.(24), the following three relationships were obtained:

Proportional Gain, $K_p = \frac{R_2}{R_1} + \frac{C_1}{C_2} = 10$

Derivative Gain, $K_d = R_2 C_1 = 1$

Integral Gain, $K_i = \frac{1}{R_1 C_2} = 8$

Since there are 4 unknowns (R_1, R_2, C_1, C_2) and 3 equations, practical value of any one parameter is chosen arbitrarily. If $C_2 = 0.3$ µF than remaining values are found as below by solving the equations using Quadratic Formula.

$R_1 = 416.67$ KΩ

$R_2 = 365.4$ KΩ

$C_2 = 2.74$ µF

Using these values, the complete circuit is simulated in PSPICE. [7] Using PSPICE, PID implementation has been done by operational amplifier which is the basis of Ideal PID Algorithm. Fig.10 is PSPICE schematics of active RC realization of PID controller of the reference system.

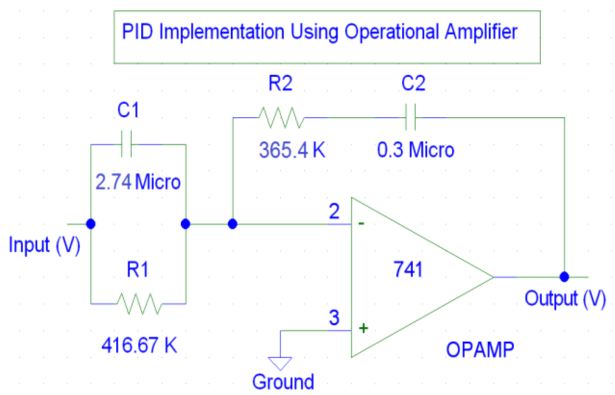

Fig.10 PSPICE Schematics of PID controller using Ideal PID Algorithm

5. Conclusion

In this paper, a novel approach has been adopted to model a Separately Excited DC Motor with mathematical differential equation to test it with different industrial controller and later to derive active

RC realization. Transfer function has been derived from the basic machine equations. Suitable electrical and mechanical parameters have been calculated to perfectly represent the DC Motor that has been used throughout the work. Finally specific design criteria have been set up to the best interest of the machine application. A Simulink representation has been done and added to check and validate the initial parameters which have been taken in modeling the machine's mathematical equivalence. Later, the open loop step response has been calculated to find the best suitable conventional controller for use with the machine and the system has been proved to be stable through Routh-Hurwitz method. After that, different controllers have been used with the system and it is observed that properly tuned PID controller is the best controller to get sharp and quick response from the system. $\mathbf{T_r}$, $\mathbf{T_s}$, Steady State Error and % overshoot for different configuration have been measured. Finally, the tuned PID controller has been designed using 'Ideal PID Algorithm' which uses operational amplifier as a building to physically realize the system. The Schematics have been drawn based on the values of the active circuits (Resistance, Capacitance) calculated by the Ideal PID Algorithm method. With the value of the feedback voltage known, a transient analysis can be done. This PID controller is fully compatible with the reference machine that has been used in the work.

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