CLOSED LOOP SPEED CONTROL OF SEDC MOTOR USING THREE PHASE FULLY CONTROLLED BRIDGE RECTIFIER WITH INNER CURRENT LOOP

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ABSTRACT

The speed control of separately excited DC [SEDC] motors by PI and PID controller is widely used in industry application. This paper describes the designing of a closed loop model of the SEDC drive for controlling speed below the rated speed. The mathematical modelling of closed loop speed control of SEDC motor using three phase fully controlled rectifier is done. In this paper, the design of PI speed controller using modulus hugging approach for closed loop speed control of dc motor using three phase fully controlled rectifier is presented. After that the Simulink model of rectifier fed SEDC motor is made in Matlab. The results are obtained for reference speed which is rated or below the rated speed of motor. The speed of the motor is obtained at pre-set value [ref. Speed]. When the load is increase, speed of the motor is decrease. But by closed loop control of motor, the speed of the motor is settled at reference speed.

KEYWORDS: *Fully controlled rectifier as a Converter, Modulus Hugging Approach, PI- Controller, SEDC Motor, and Simulink.*

I. INTRODUCTION

The speed of separately excited DC [SEDC] motor can be controlled below the rated speed by using controlled rectifier as a converter. The controlled rectifier firing circuit receives signals from the controllers and then controlled rectifier gives variable voltage to the armature of the dc motor for achieve required speed. There are two control loops, first one for controlling current and another one for control of speed. Proportional-Integral [PI] type controllers are used, which removes the delay and provides fast control. [1][8]. In this paper initially mathematical analysis of SEDC motor is performed followed by designing of current and speed controllers. Then modulus hugging approach is used to design speed controller. Finally simulation model is developed to obtain the results.

II. EQUIVALENT CIRCUIT OF SEDC MOTOR AND EQUATIONS

The equivalent circuit of SEDC motor is given as:

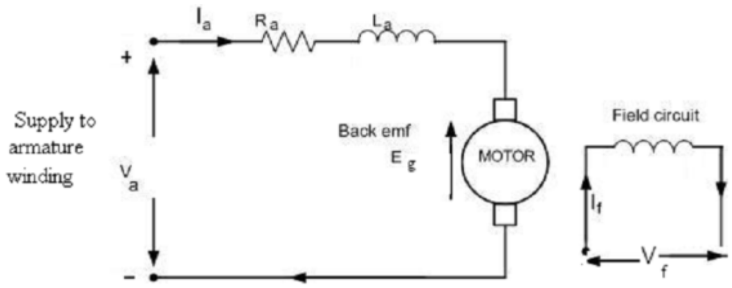

Figure 1. Equivalent circuit of SEDC motor.

Where: Va is the armature voltage in volts.
: Ia is the armature current in amps.
: Ra is the armature resistance in ohms.
: La is the armature inductance in henrys.
: E_b is the back emf in volts.
: V_f and I_f is the field voltage and current respectively.

The armature voltage equation is given as:

$$V_a = Ia\, R_a + L_a\, d\, Ia/dt + E_b \tag{2.1}$$

The developed torque is given as:

$$T_d = J\, d\omega / dt + B\omega + T_L \tag{2.2}$$

Where:

- Td is the developed torque in the motor in Nm.
- TL is the load torque in Nm.
- J is the moment of inertia in Kg/m^2.
- B is the friction coefficient of the motor.
- ω is the angular velocity of motor in rad/sec.

Let assume that B=0, then
The developed torque is given as:

$$T_d = J\, d\omega / dt + T_L \tag{2.3}$$

The back emf of the motor will be:

$$E_b = K\, \phi\, \omega \tag{2.4}$$

Where: K is the back emf constant in volt-sec/rad.
The developed torque is also given as:

$$T_d = K\, \phi\, Ia \tag{2.5}$$

After taking the Laplace Transform of above equations and the simplified equations:
The armature current is obtained as:

$$Ia(S) = (V_a - E_b) / R_a\, (1+T_aS) \tag{2.6}$$

The Speed of the motor is obtained as:

$$\omega(S) = (T_d - T_L) / JS \tag{2.7}$$

After simplified above equations the speed of dc motor is given by equation:

$$\omega(s) = \frac{1}{TmS}\left[\frac{RaIa}{Km} - \frac{RaT_L}{Km^2}\right] \tag{2.8}$$

The equivalent circuit of SEDC motor is given as:

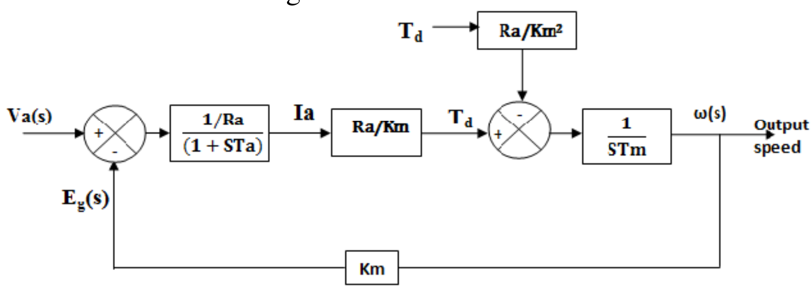

Figure2. Block model of SEDC motor.

III. REPRESENTATION OF THREE PHASE FULLY CONTROLLED RECTIFIER

Let the converter is a three phase fully controlled converter for a typical firing angle α = 60.

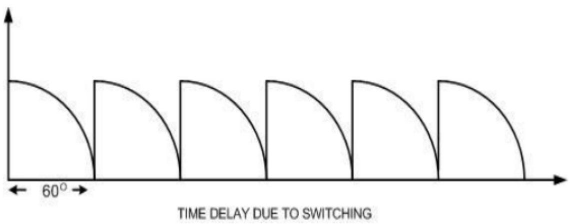

Figure 3. Output of three phase controlled rectifier.

Ripple will be six times the fundamental frequency. So the duration of each ripple will be 60 Degree.
Let for 50 Hz supply:
For 360 degrees, Time period T = (1/50) = 0.02 s.
For 60 degree, t = (0.02 * 60)/360 = 3.3 ms.
A change in converter firing angle occurs after every 60 degree. It's not instantaneous. That means a delay of 3.3 ms. It can have a maximum delay of 3.3 ms or a minimum of zero.
So, let us take an average Tr = (3.3 ms + 0)/2 = 1.7 ms.

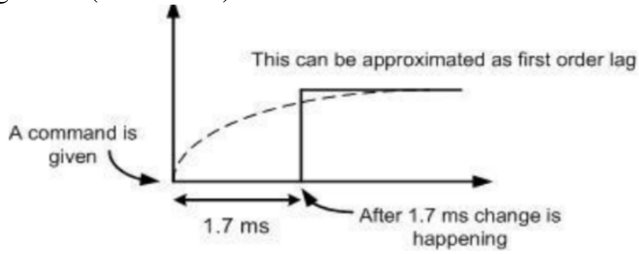

Figure 4. Ripples with 60 degree duration for 50 Hz waveform.

So, converter can be represented as a first order delay with a gain. So, converter can be represented as first order lag with some gain Kt.

$$\frac{Kt}{1 + STt}$$

IV. CONTROLLERS DESIGN

The controllers used in closed loop system to provide a very easy control and common technique of keeping motor speed at desired set point by continuously control of motor input. If the loads will increases then speed of the motor will decrease and the error will be negative. To compensate the speed, motor controller output should be increase and vice-versa. [3]

4.1. Designing of current controller:

We need to design of current controller because at the time of starting, back emf is zero (due to zero speed) that is during starting period large current flows through the motor.

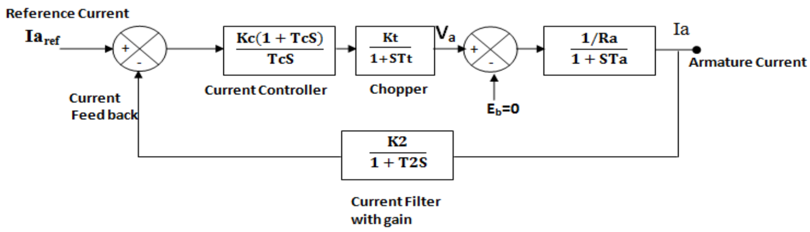

Figure 5. Block model of current controller design.

Transfer function of above block model is given as:

$$\frac{Ia(s)}{Iaref(s)} = \frac{KtKc(1 + STc)(1 + ST2)}{RaTcS(1 + STt)(1 + STa)(1 + ST2) + KtKcK2(1 + STc)} \quad (4.1)$$

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. Therefore the response will be much faster. So Tc=Ta. [3][9]
Put the value in above equation (4.1), we get

$$\frac{Ia(s)}{Iaref(s)} = \frac{Ko\ (1 + ST2)}{\delta\, S^2 + S + KoK2} \quad (4.2)$$

Where δ=Tt+T2 and $Ko = \frac{KcKt}{TaRa}$

The standard Characteristic Equation is given as: $S^2+2\varepsilon\omega_n S+\omega_n^2$ =S2+S/δ+K2Ko/δ.

Here ω=√K2Ko/δ and ε = ½[√1/δK2Ko].

Since, it is a second order system. So, to get a proper response ϵ should be 0.707. [2]

Then $Kc = \frac{RaTa}{2\delta KtK2}$

The value of Kc and Ko put in equation (4.2) then we get:

$$\frac{Ia(s)}{Iaref(s)} = \frac{1/K2}{1+2\delta S} \tag{4.3}$$

4.2. Designing of speed controller:

The block model of speed controller design is given below:

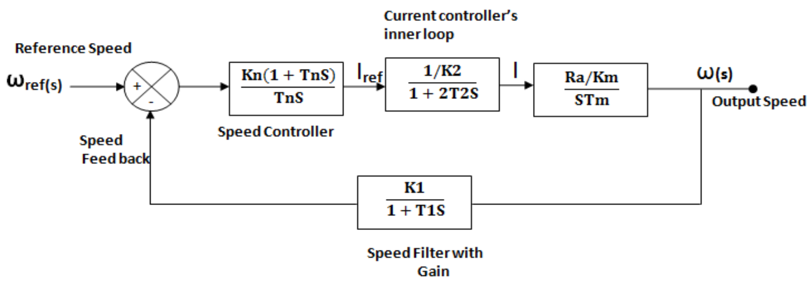

Figure 6. Block model of Speed controller design.

Transfer function of above block model is given as:

$$\frac{\omega(s)}{\omega ref(s)} = \frac{KnRa(1+STn)(1+ST1)}{TnK2KmTmS^2(1+2\delta S)(1+T1S)+KnRaK1(1+TnS)} \tag{4.4}$$

To cancels the largest time constant of the transfer function so Tn= 2δ then,
Transfer function of above block model is given as:

$$\frac{\omega(s)}{\omega ref(s)} = \frac{KnRa(1+ST1)}{TnK2KmTmS^2(1+T1S)+KnRaK1} \tag{4.5}$$

In above transfer function, the S term is absent. So that damping constant (ε) will be zero. Due to this the system will be oscillatory and unstable. To optimize this we must get transfer function whose gain is close to unity. For this purpose the MODULUS HUGGING APPROCH is used. [2][3][5]

V. MODULUS HUGGING APPROACH FOR OPTIMIZATION OF SPEED CONTROLLER TRANSFER FUNCTION

The process of making output close to input variable so as to obtain unity gain for wide range of frequency is termed as Modulus Hugging approach. [3]

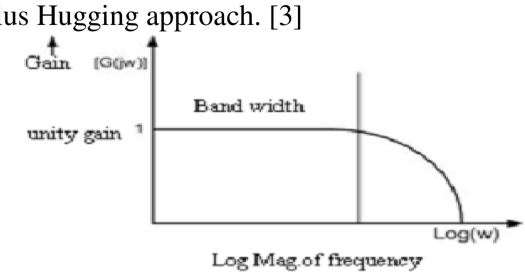

Figure 7. Gain Vs frequency.

Considering equation (4.4):

$$\frac{\omega(s)}{\omega ref(s)} = \frac{KnRa(1 + STn)(1 + ST1)}{TnK2KmTmS^2(1 + 2\delta S)(1 + T1S) + KnRaK1(1 + TnS)}$$

Here $(1 + 2\delta S)(1 + ST1) \cong 1 + S(2\delta + T1) + 2\delta T1S^2$

Where, T1 and δ are smaller time constants. So their product can be approximated to zero. So that

$$(1 + 2\delta S)(1 + ST1) \cong (1 + SP)$$

Where P = (2δ+T1) and $Ko = \frac{KnRa}{K2Km}$

Then transfer function of speed block model is as:

$$\frac{\omega(s)}{\omega ref(s)} = \frac{Ko(1 + TnS)(1 + ST1)}{TnTmS^2(1 + PS) + KoK1(1 + TnS)} \quad (5.1)$$

In above $(1 + ST1)(1 + STn)$ are cancelled by using filter.

Taking a standard third order system:

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

For low frequency $b_o = a_o$ and $b_1 = a_1$.

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

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

So $a_1^2 = 2a_o a_2$ and $a_2^2 = 2a_1 a_3$ (5.2)

Now, from optimization condition in (5.2), we get-

$Tm = \frac{KoK1Tn}{2}$, Tn=4P, $Kn = \frac{K2KmTm}{2RaK1P}$

Now putting the value of Tn and Tm in equation (5.1) then-

$$\frac{\omega(s)}{\omega ref(s)} = \frac{1/K1}{8P^3S^3 + 8P^2S^2 + 4PS + 1} \quad (5.3)$$

VI. CALCULATION OF CONTROLLERS' PARAMETER

A separately excited DC motor with name plate ratings of 300KW, 460V (DC), 52.3 rad/sec is used in all Simulation. Following parameter values are associated with it.

- Moment of Inertia, J = 84 Kg-m.
- Back EMF Constant = 8.5 Volt-sec/rad.
- Rated Current = 690 A.
- Maximum Current Limit = 1200 A.
- Resistance of Armature, Ra = 0.02342 ohm.
- Armature Inductance, La = 0.7026 mH.
- Speed Feedback Filter Time Constant [3], T1 = 25 ms.
- Current Filter Time Constant [3], T2 = 3.5ms.

6.1 The Speed controller parameters are calculated as, by using formulas:

K1=10/52.3=0.191, Kn=6.12, Tn=141.6×10^{-3}sec.

6.2 The Current controller parameters are calculated as, by using formulas:

K2=10/1200=8.33×10^{-3}, Kc=0.1762.

6.3 The three phase controlled rectifier parameters are calculated as:

Kt=460/10=46[3], Tt=1.7×10^{-3}sec.

VII. SIMULINK MODEL OF CLOSED LOOP SPEED CONTROL OF SEDC MOTOR USING CONTROLLED RECTIFIER

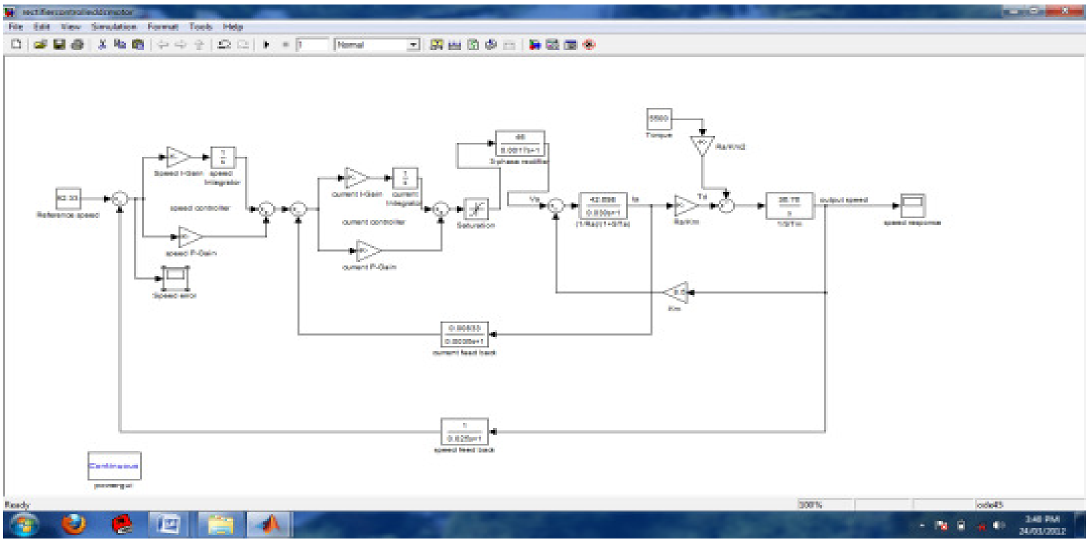

Figure 8. Simulink model of closed loop speed control of SEDC Motor.

VIII. SIMULATION RESULTS

The simulation results of different speed and load torque:

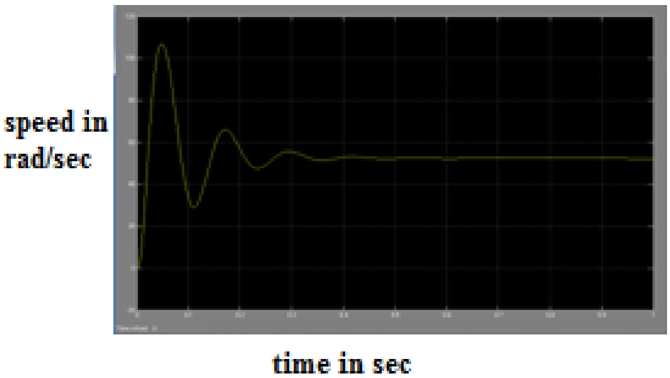

Figure 9. Speed response at rated speed and rated load torque:

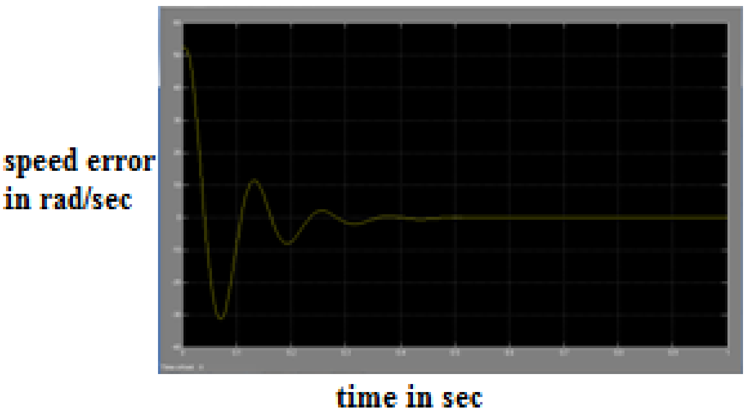

Figure 10. Error in speed response at rated speed and rated load torque:

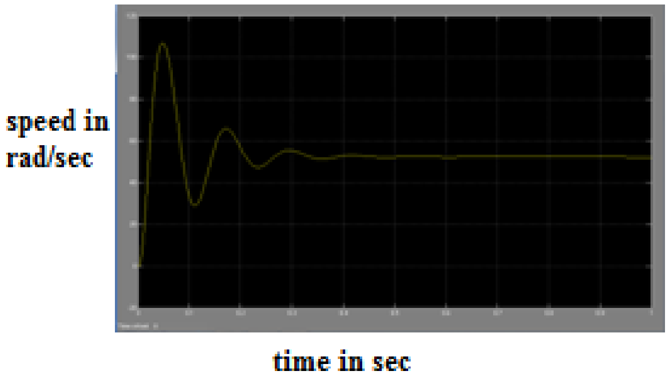

Figure 11. Speed response at rated speed at half of rated load torque:

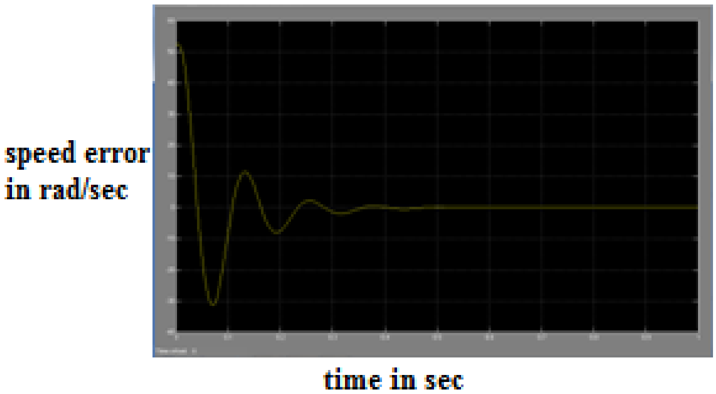

Figure 12. Error in speed response at rated speed and at half of rated load torque:

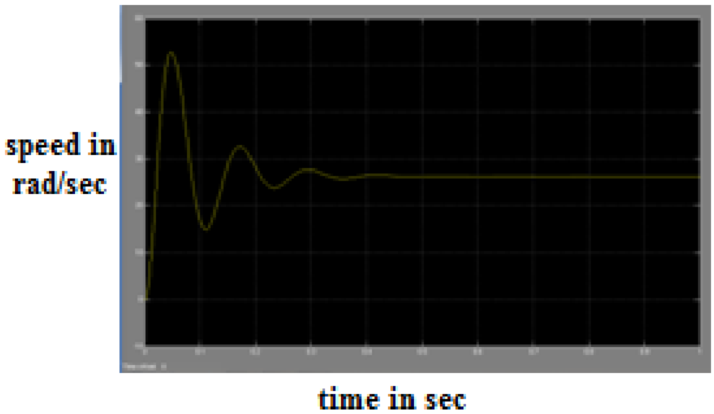

Figure 13. Speed response at half of rated speed and at rated load torque:

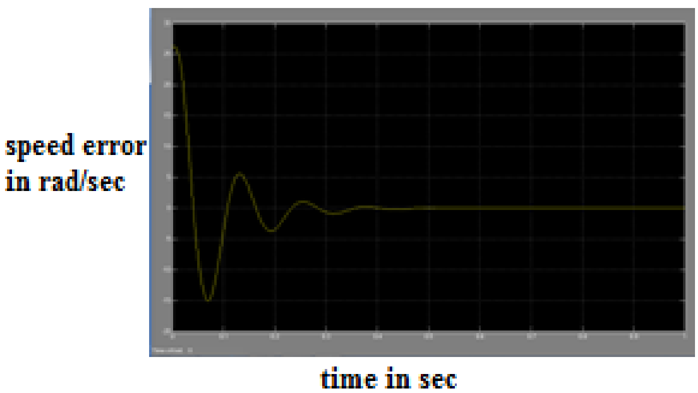

Figure 14. Error in speed response at half of rated speed and rated load torque:

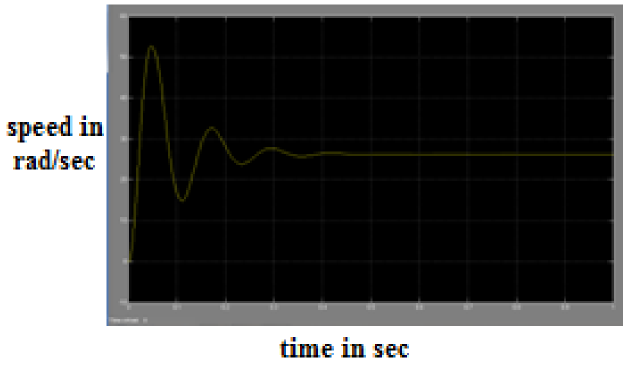

Figure 15. Speed response at half of rated speed and half of rated load torque:

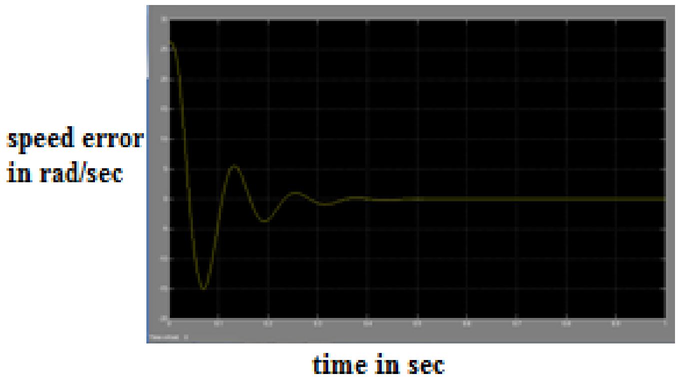

Figure 16. Error in speed response at half of rated speed and half of rated load torque:

IX. CONCLUSION

This paper presents mathematical modelling of closed loop speed control of dc motor using three phase controlled rectifier. For stable operation of SEDC motor, the designing of speed controller is done using Modulus hugging approach. By this approach the gain of system becomes unity. The simulation results are obtained after designing of closed loop system. From the simulation result we observed that the speed of SEDC motor is constant at the reference speed which is rated or below the rated speed of motor and also observed that the speed error is set to be zero. The system's response shows the fast rise time, fast setting time as well as fast recovering time.

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