

# Simulation of Speed Controlled Switched Reluctance Motor Drive System using MATLAB Simulink

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**Abstract**— For Switched Reluctance Motor drive, design of controller i.e. current controller and speed controller is very essential. This paper represent the speed controlled drive of SRM, with the design of controller, where the speed is controlled in outer loop of the drive and current is controlled in inner loop. And the drive is simulated in MATLAB Simulink, R2014a with a condition of applying load in different time and the output response of the motor is observed for different load condition.

**Keywords**— SRM, Speed control, Controller, Current controller, Speed controller, Simulation.

## INTRODUCTION

Characteristic of Switched Reluctance Motor is similar to dc series motor, but the close loop control of the two is remotely connected. So there is no scope for development of an analogous controller. In the SRM [5], the per phase inductance varies mainly rotor position and also some what with exciting current. Current control lies at the heart of any motor drive's control and side by side speed control is a major issue.

The voltage and torque equations of an SRM are linearised the rated current and speed. The dynamic voltage and torque equations are

$$V = R_s + \frac{d\varphi(\theta, i)}{dt} \dots\dots\dots(1)$$

$$T_e(\theta, i) - T_l = J \frac{d\omega}{dt} + B\omega_m \dots\dots\dots(2)$$

Where,

- V= Applied phase voltage
- R<sub>s</sub>= Phase resistance
- i= Phase current
- φ(θ, i)= Flux linkage
- T<sub>e</sub>(θ, i)= Developed torque
- T<sub>l</sub>= Load torque
- J= Moment of inertia of the SRM
- ω<sub>m</sub>= Angular speed of motor
- B= Friction of co-efficient

And once again, φ(θ, i) = L(θ, i)i .....(3)

From the upper equation we get,

$$\begin{aligned} V &= R_s + \frac{d[L(\theta, i) * i]}{dt} \\ &= R_s i + L(\theta, i) \frac{di}{dt} + i \frac{dL(\theta, i)}{dt} \\ &= R_s i + L(\theta, i) \frac{di}{dt} + i \frac{dL(\theta, i)}{dt} * \frac{d\theta}{dt} \\ &= R_s i + L(\theta, i) \frac{di}{dt} + \omega_m i \frac{dL(\theta, i)}{dt} \dots\dots\dots(4) \end{aligned}$$

Where,  $\omega_m = \frac{d\theta}{dt}$  And the three terms in the right hand side represent the resistive voltage drop, inductive voltage drop, and back emf respectively, which are similar to a separately excited dc motor.

And the develop torque,

$$T_e = \frac{1}{2} i^2 \frac{dL(\theta, i)}{dt} \dots\dots\dots(5)$$

**SMALL SIGNAL MODEL OF THE MOTOR**

In the plant described by equation (2), (4) and (5), the states are rotor speed, and the phase current. Equation (4) is evidently non-linear in these states. To design a controller employing linear control theory a linearized model of the plant [4] is developed bellow.

For the sake of simplicity, the following assumptions have been made.

1. The inductance  $L(\theta, i)$  is constant w.r.t. position. It is taken the mean value between the aligned inductance and unaligned inductance.
2. The derivative of the inductance w.r.t. rotor position,  $\frac{dL(\theta, i)}{d\theta}$ , is constant.

Perturbing the system around a steady state operating point with small signals, the new system states and inputs are,

$$\begin{aligned} i &= i_0 + \partial i \\ \omega_m &= \omega_{m0} + \partial \omega_m \\ v &= v_0 + \partial v \\ T &= T_{10} + \partial T_1 \end{aligned}$$

Where the extra subscript 0 indicates steady-state values of the states and inputs, and the small signals are indicated by  $\partial$ . Due to small perturbation around the steady-state point, the equation (4) becomes,

$$\begin{aligned} v_0 + \partial v &= R_s(i_0 + \partial i) + L(\theta, i) \frac{d(i_0 + \partial i)}{dt} + (i_0 + \partial i)(\omega_{m0} + \partial \omega_m) \frac{dL(\theta, i)}{d\theta} \\ \partial v &= R_s \partial i + L(\theta, i) \frac{d(\partial i)}{dt} + (i_0 \partial \omega_m + \partial i \omega_{m0}) \frac{dL(\theta, i)}{d\theta} \\ \frac{d(\partial i)}{dt} &= \frac{1}{L} (-R_s - \frac{dL}{d\theta} * \omega_{m0}) \partial i - \frac{1}{L} \frac{dL}{d\theta} i_0 (\partial \omega_m) + \frac{\partial v}{L} \end{aligned}$$

Defining,

$$\begin{aligned} R_{eq} &= R_s + \frac{dL}{d\theta} * \omega_{m0} \\ K_b &= \frac{dL}{d\theta} i_0 \end{aligned}$$

$$\frac{d(\partial i)}{dt} = -\frac{R_{eq}}{L} \partial i - \frac{1}{L} K_b (\partial \omega_m) + \frac{\partial v}{L} \dots\dots\dots(6)$$

Now due to perturbation, equation (2) becomes,

$$\begin{aligned} \frac{1}{2} (i_0 + \partial i)^2 \frac{dL}{d\theta} - (T_0 + \partial T_1) &= J \frac{d(\partial \omega_{m0} + \partial \omega_m)}{dt} + B(\omega_{m0} + \partial \omega_m) \\ \frac{d(\partial \omega_m)}{dt} &= \frac{1}{J} K_b (\partial i) - \frac{B}{J} \partial \omega_m - \frac{\partial T_1}{J} \dots\dots\dots(7) \end{aligned}$$

Taking Laplace transform of equation (6) and (7) and rearranging we get,

$$\partial I(s) = -\frac{K_b}{L(s + \frac{R_{eq}}{L})} \partial \omega_m(s) + \frac{1}{L(s + \frac{R_{eq}}{L})} \partial v(s) \dots\dots\dots(8)$$

And,  $J(s + \frac{B}{J}) \partial\omega_m(s) = K_b * \partial I(s) - \partial T_1(s) \dots\dots\dots(9)$

The above two equations are implemented through the block diagram given in Fig. 1,

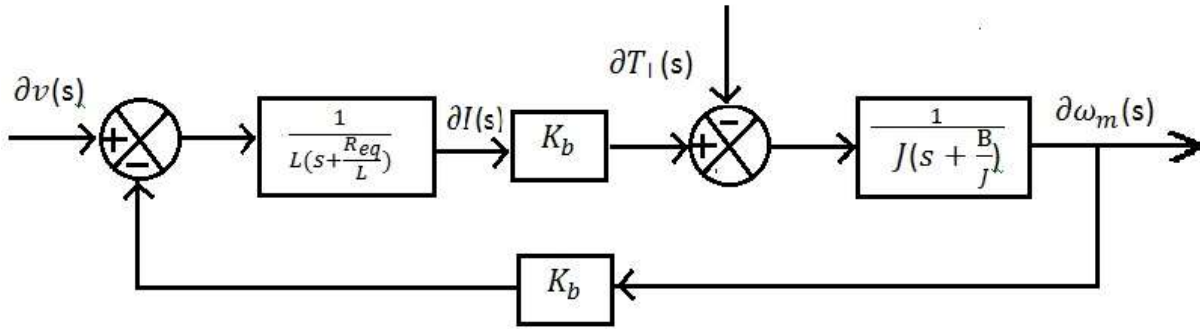


Fig. 1 Block diagram of small signal model

Assuming the load to be frictional the load torque is treated as an integral component of the system and not as a disturbance. Then equation (8) and (9) becomes,

$$\partial I(s) = \frac{\partial V(s) - K_b \partial\omega_m(s)}{R_{eq} + sL} \dots\dots\dots(10)$$

$$\partial\omega_m(s) = \frac{K_b}{B + sJ} \partial I(s) \dots\dots\dots(11)$$

From equation (10) and (11),

$$\frac{\partial I(s)}{\partial V(s)} = \frac{1 + s \frac{J}{B}}{\left( R_{eq} + \frac{K_b^2}{B} \right) + s \left( L + \frac{R_{eq}J}{B} \right) + s^2 \frac{LJ}{B}}$$

And,

$$\frac{\partial I(s)}{\partial V(s)} = \frac{K_1(1 + sT_m)}{(1 + sT_1)(1 + sT_2)} \dots\dots\dots(12)$$

Where,

$$K_1 = \frac{B}{K_b^2 + R_{eq}B}$$

$$T_m = \frac{J}{B}$$

$$-\frac{1}{T_1}, -\frac{1}{T_2} = \frac{1}{2} \left[ \frac{B}{J} + \frac{R_{eq}}{L} \right] \pm \sqrt{\frac{1}{4} \left( \frac{B}{J} + \frac{R_{eq}}{L} \right)^2 - \frac{K_b^2 + R_{eq}B}{JL}}$$

In absence of load torque, the simplified block diagram has been shown in the Fig. 2.

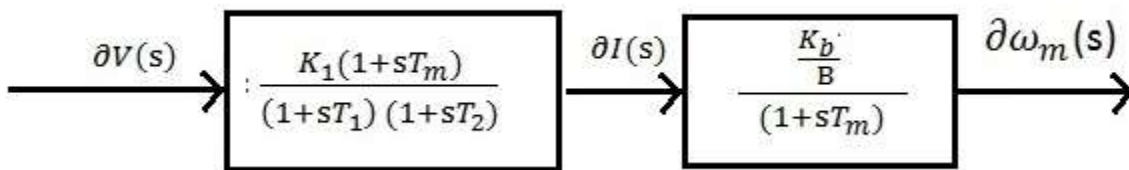


Fig. 2 Block diagram of SRM without considering load

**Design of current controller and Speed controller:**

The complete scheme of speed controlled SRM system [4] with two Proportional Integral (PI) controllers is shown here.

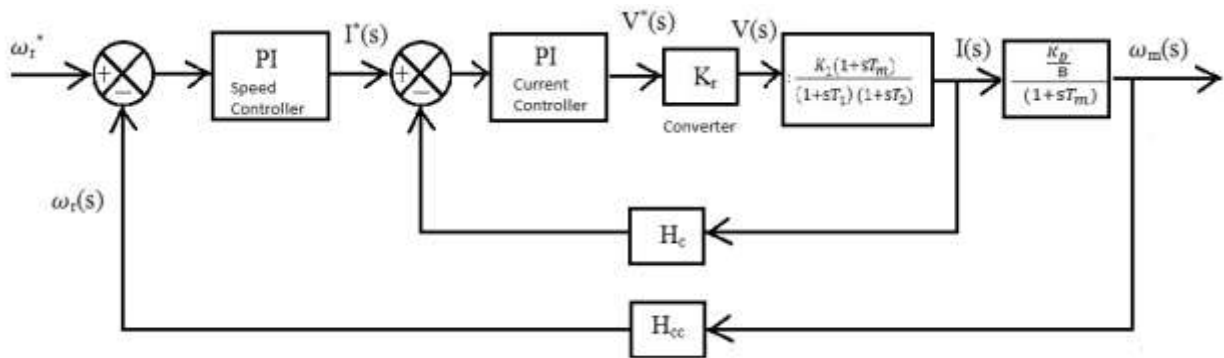


Fig.3 Block diagram of speed controlled SRM model

In this case, rotor speed is compared with the reference speed and the output is fed to the PI speed controller and the output of the speed controller is again compared with the feed-back current signal, and the comparator output is again fed to the current controller of PI type. The current controller sends the output to the converter block as a command signal of the power converter. The converter output drives the machine to provide our desired speed.

**DESIGN OF CURRENT CONTROLLER**

The current loop is given below. The Proportional-Integral controller [1][2][4] is used as the current controller and has the transfer function,

$$\frac{K_c (1 + sT_c)}{sT_c}$$

After the Proportional-Integral controller there is a converter block for feeding the SRM. It is represented by a simple gain block and hence the time delay of the converter block is neglected.

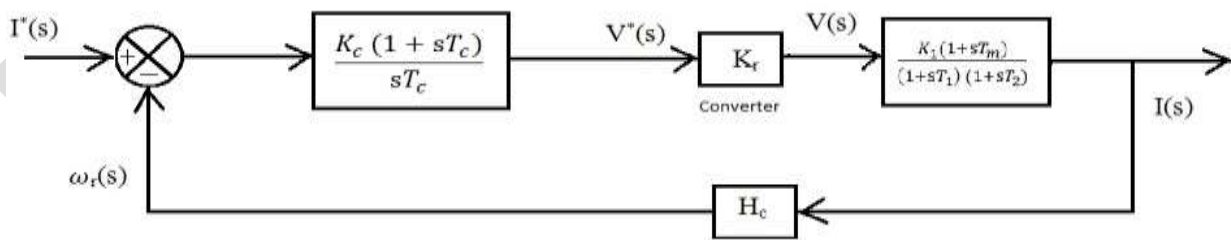


Fig. 4 Block diagram of current loop

From the above block diagram,

$$\frac{I^*(s)}{I(s)} = \frac{K_c K_r K_t T_m (1+sT_c)}{T_c T_1 T_2 \left( s^2 + \frac{T_1 + T_2 + K_c K_1 K_r T_m H_c}{T_1 T_2} s + \frac{T_c + K_1 K_c K_r T_m H_c}{T_c T_2 T_1} \right)}$$

The close loop characteristic equation is given below,

$$s^2 + \frac{T_1 + T_2 + K_c K_1 K_r T_m H_c}{T_1 T_2} s + \frac{T_c + K_1 K_c K_r T_m H_c}{T_c T_2 T_1} = 0 \dots\dots\dots(13)$$

By comparing the equation (13) with the close loop characteristic equation of a standard second order system with a natural frequency of oscillation,  $\omega_n$ , and damping ratio,  $\aleph$ ,

$$s^2 + 2 \aleph \omega_n s + \omega_n^2 = 0 \dots\dots\dots(14)$$

Now we get,

$$2 \aleph \omega_n = \frac{T_1 + T_2 + K_c K_1 K_r T_m H_c}{T_1 T_2}$$

$$\text{And } \omega_n^2 = \frac{T_c + K_1 K_c K_r T_m H_c}{T_c T_2 T_1}$$

Now for a given natural frequency and damping ratio,

$$K_c = \frac{2 \aleph T_1 T_2 \omega_n - T_1 - T_2}{K_1 K_r T_m H_c}$$

$$T_c = \frac{K_1 K_c K_r T_m H_c}{T_2 T_1 \omega_n^2 - 1}$$

Let,  $\aleph = 0.7$  and  $\omega_n = 1000\text{rad/sec}$

$$K_c = 68$$

$$T_c = 0.0008$$

Now the current loop for the system has been simulated in MATLAB Simulink considering the above data. The values are changed a little bit for better performance.

$$K_c = 74$$

$$T_c = 0.00076$$

**DESIGN OF SPEED CONTROLLER**

To design the speed controller for the SRM model the following assumption have been made:

1. Current loop gain is taken as unity [4].
2. Current loop time constant is neglected compared to speed loop time constant.
3. The delay due to the speed feedback is neglected.

As the speed feedback loop time constant is neglected, the closed loop system for the speed loop becomes second order and the block diagram of this is given in fig.5.

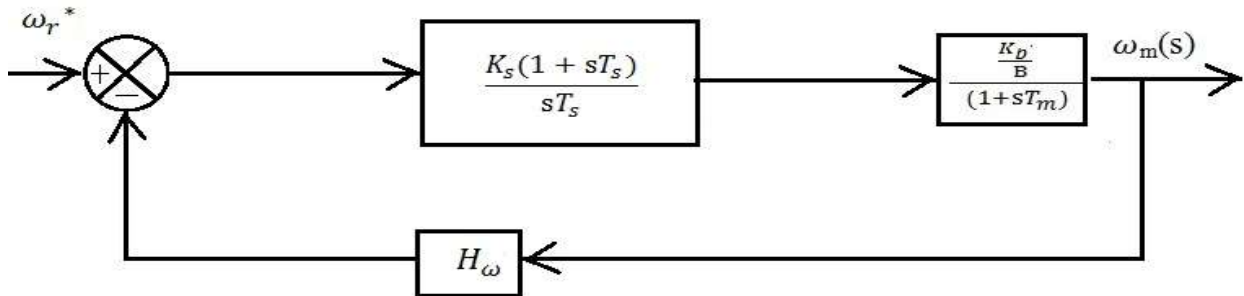


Fig. 5 Block diagram of speed loop

The Proportional-Integral controller used for the speed controller has the transfer function:

$$\frac{K_s(1 + sT_s)}{sT_s}$$

From the block diagram,

$$\frac{\omega_m(s)}{\omega_r^*(s)} = \frac{K_s K_b (1 + sT_s)}{BT_s T_m \left( s^2 + \frac{1}{T_m} \left( 1 + \frac{K_s K_b H_\omega}{B} \right) s + \frac{K_s K_b H_\omega}{BT_s T_m} \right)}$$

The close loop characteristic equation is given as,

$$s^2 + \frac{1}{T_m} \left( 1 + \frac{K_s K_b H_\omega}{B} \right) s + \frac{K_s K_b H_\omega}{BT_s T_m} = 0 \dots\dots\dots(15)$$

Comparing the equation (15) with the close loop characteristic equation of a standard second order system, equation (14) we get,

$$2 \zeta \omega_n = \frac{1}{T_m} \left( 1 + \frac{K_s K_b H_\omega}{B} \right)$$

And,

$$\omega_n^2 = \frac{K_s K_b H_\omega}{BT_s T_m}$$

Now for a given natural frequency and damping ratio,

$$K_s = \frac{B (2 \zeta \omega_n T_m - 1)}{K_b H_\omega}$$

$$T_s = \frac{K_s K_b H_\omega}{BT_m \omega_n^2}$$

Let,  $\zeta = 0.7$  and  $\omega_n = 200$ rad/sec

$$K_s = 5$$

$$T_s = 0.7$$

After that the whole system considering the speed loop and current loop is simulated in MATLAB Simulink. For getting the better performance, value of the above two constant have been changed little bit,

$$K_s = 2.6$$

$$T_s = 0.8$$

## SIMULATION AND RESULT

The simulation has been done in MATLAB Simulink, version R2014a. In this simulation, a speed controlled SRM drive has been designed, where two controller is used one is speed controller and the other is current controller and the controller values, which are calculated previously are used here.

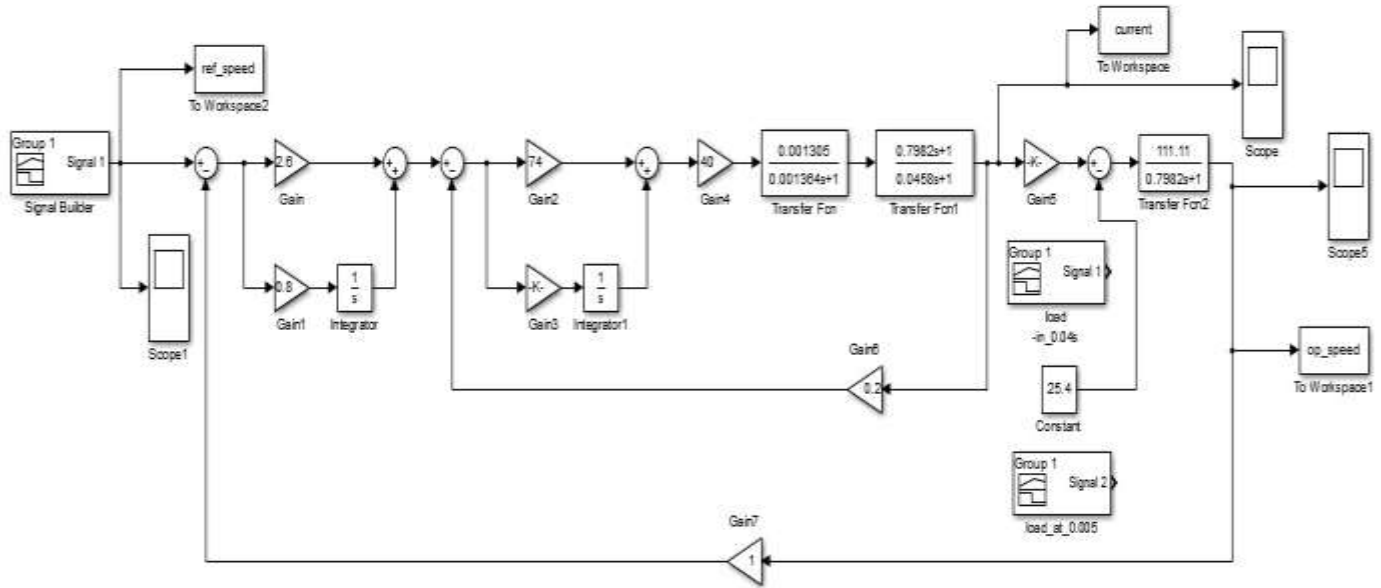


Fig.6 Control circuit developed in Simulink

The reference input is angular speed, 157 rad/sec. The input is taken as initially ramped in nature and after 0.01 sec, it becomes steady ref. input at 157 rad/sec, which is shown in Fig. 7

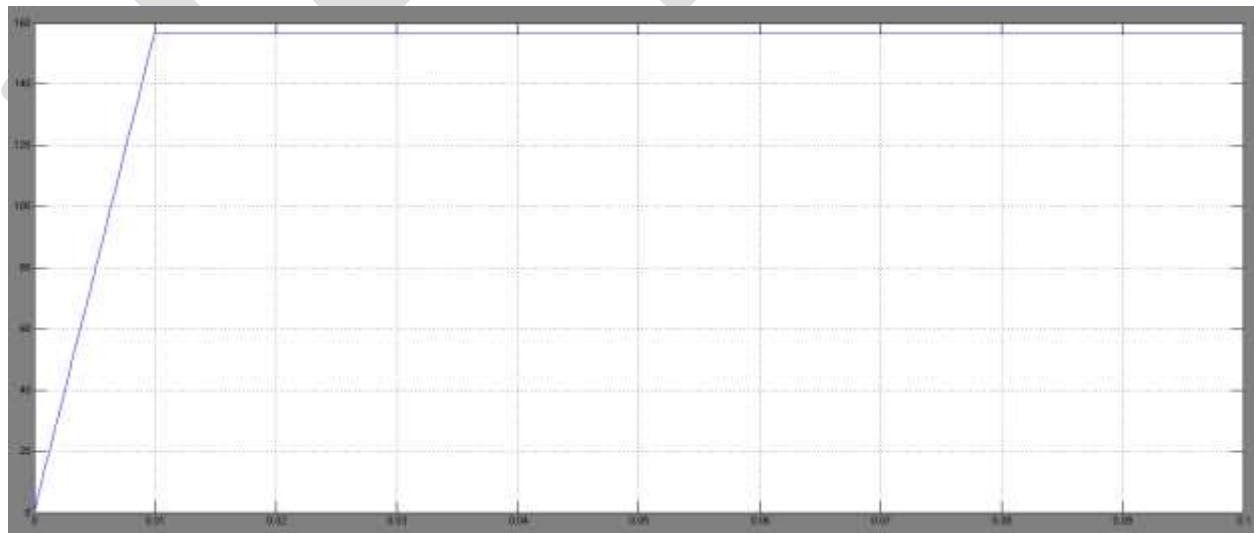


Fig.7 Ref. speed input

Now the Fig. 8 shows the no load current vs. time plot, the max current is about 45 Amp during the starting at  $t=0.001$ sec, here the current provide only no-load rotational losses. Fig. 9 shows the output speed waveform of the SRM at no load condition.

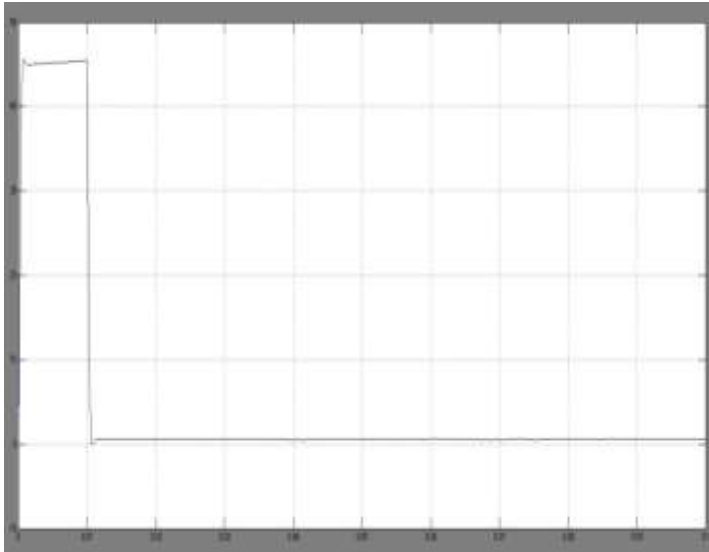


Fig. 8 Current at no load

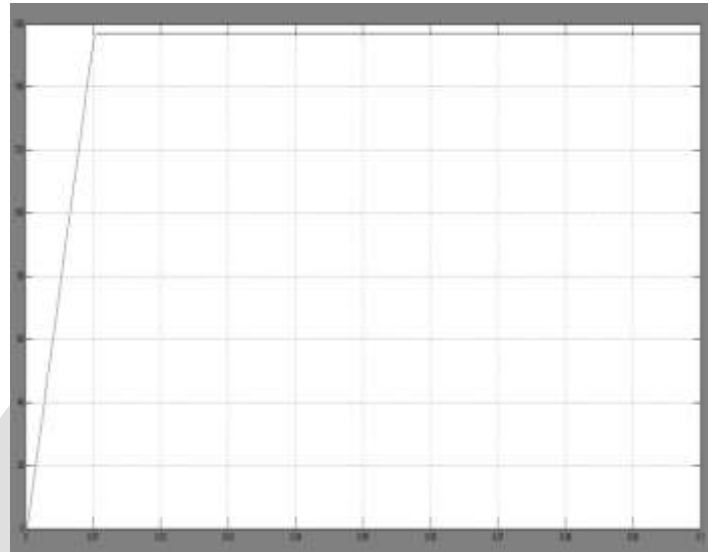


Fig. 9 Output speed at no load

Fig. 10 shows the current vs. time plot for the load of 25.4 Nm, which is subjected at  $t=0$  sec. Fig. 11 shows the output speed waveform for the load of 25.4 Nm at  $t=0$  sec.

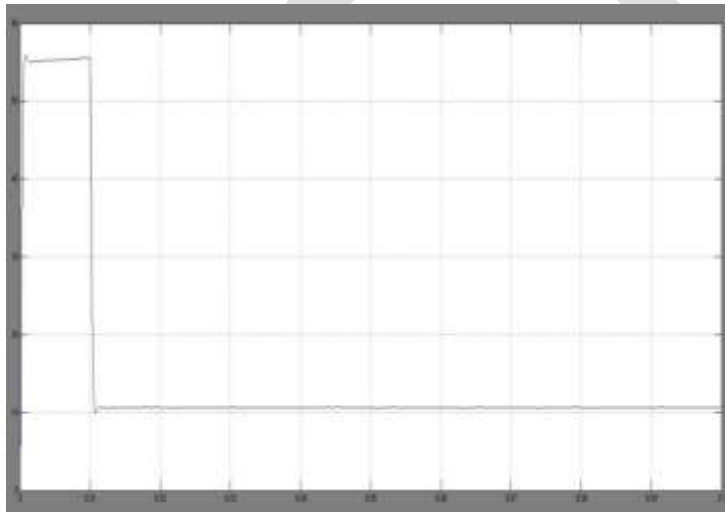


Fig. 10 Current at load applied at starting

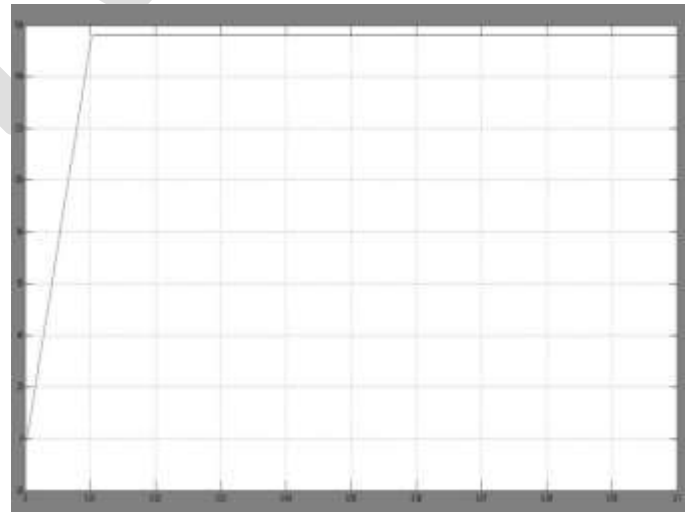


Fig.11 Output speed at load in starting

Fig. 12 shows the current vs. time plot for the load of 25.4 Nm, which is applied at  $t=0.005$  sec and the current changes 45Amp to 55 Amp at the time of load applying. Fig. 13 shows the output speed waveform for the load of 25.4 Nm at  $t=0.005$  sec.



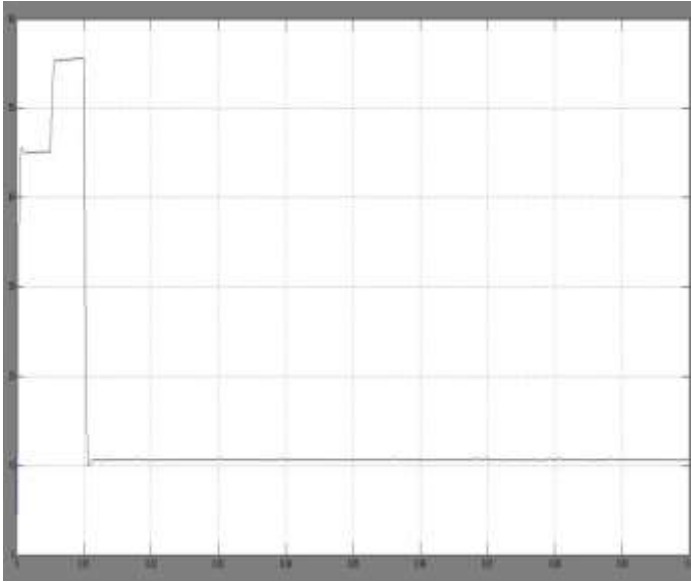


Fig. 12 Current at load applied at  $t=0.005\text{sec}$

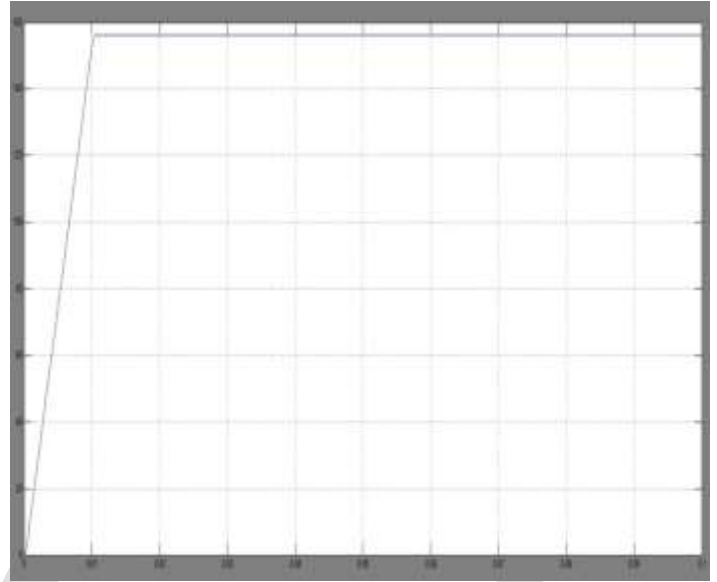


Fig.13 Output speed at load applied in  $t=0.005\text{ sec}$

Fig. 14 shows the current vs. time plot for the load of 25.4 Nm, which is applied at  $t=0.04\text{ sec}$  and the current changes 1.2Amp to 11.2 Amp at the time of load applying. Fig. 15 shows the output speed waveform for the load of 25.4 Nm at  $t=0.04\text{ sec}$ .



Fig. 14 Current at load applied at  $t=0.04\text{sec}$

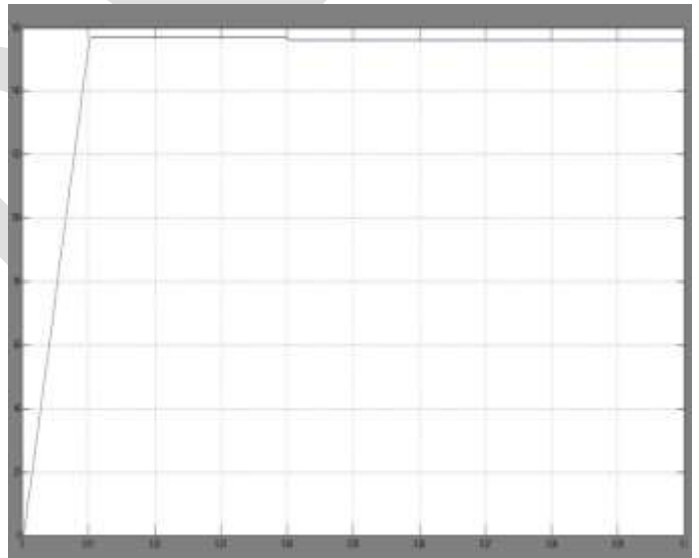


Fig.15 Output speed at load applied in  $t=0.04\text{ sec}$

## CONCLUSION

In the simulation circuit, the calculated controller parameter values give the desired output response (speed-time waveform), which is more or less same to our reference input values. And in different load condition the system output always remains the same, which is the common criterion of a speed controlled drive.

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