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Simulation and Experimental Analysis of Permanent Magnet Synchronous Motor Drive System with Field Oriented Control for Building System Prototype

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ABSTRACT: In this work, the simulation of a field oriented controlled PM motor drive system for building system prototype application is developed using Simulink. The simulation circuit will include all realistic components of the drive system. This enables the calculation of currents and voltages in different parts of the inverter and motor under transient and steady conditions. The losses in different parts can be calculated facilitating the design of the inverter.

KEYWORDS*:* Field oriented control, building system prototype, PI controller, permanent magnet motors.

I. INTRODUCTION

A permanent magnet synchronous motor (PMSM) is a motor that uses permanent magnets to produce the air gap magnetic field rather than using electromagnets. These motors have significant advantages, attracting the interest of researchers and industry for use in many applications.
PM motors are broadly classified by the direction of the field flux. The first field flux classification is radial field motor meaning that the flux is along the radius of the motor. The second is axial field motor meaning that the flux is perpendicular to the radius of the motor.
Radial field flux is most commonly used in motors and axial field flux have become a topic of interest for study and used in a few applications.

*Permanent magnet motor radial field motor*s

In PM motors, the magnets can be placed in two different ways on the rotor.

Depending on the placement they are called either as surface permanent magnet motor or interior permanent magnet motor. Surface mounted PM motors have a surface mounted permanent magnet rotor. Each of the PM is mounted on the surface of the rotor, making it easy to build, and specially skewed poles are easily magnetized on this surface mounted type to minimize cogging torque. This configuration is used for low speed applications because of the limitation that the magnets will fly apart during high-speed operations. These motors are considered to have small saliency, thus having practically equal inductances in both axes. The permeability of the permanent magnet is almost that of the air, thus the magnetic material becoming an extension of the air gap. For a surface permanent magnet motor $L_d = L_q$

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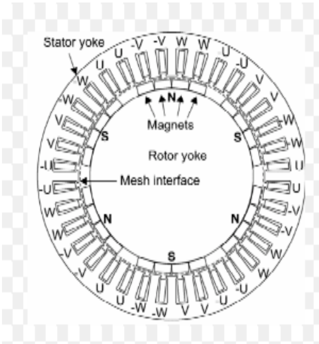

Fig. 1. Surface magnet permanent motors

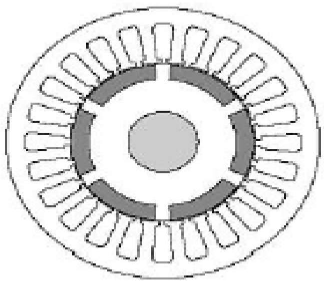

Fig. 2. Interior permanent magnet motors

Each permanent magnet is mounted inside the rotor. It is not as common as the surface mounted type but it is a good candidate for high-speed operation. There is inductance variation for this type of rotor because the permanent magnet part is equivalent to air in the magnetic circuit calculation. These motors are considered to have saliency with q axis inductance greater than the d axis inductance
($L_q>L_d$)

II. MATHEMATICAL MODELLING OF PMSM

In a permanent magnet synchronous motor the inductances vary as a function of rotor position i.e. the rotor angle. The emf of the PMSM is given by

$$W_e = \frac{P}{2} W_m \quad (1)$$

The position of the rotor is given by

$$\theta = \frac{P}{2} \theta_m \quad (2)$$

Where θ is the electrical angle and θ_m is the mechanical angle

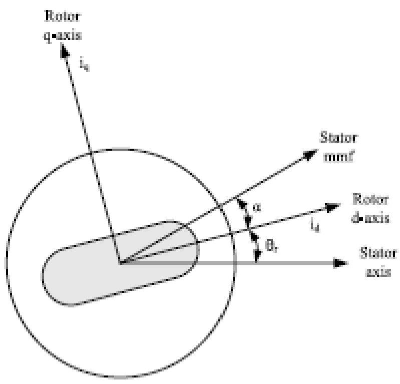

Fig. 3. Motor axis

Detailed modelling of PM motor drive system is required for proper simulation of the system. The d-q model has been developed on rotor reference frame as shown in figure 3. At any time t, the rotating rotor d-axis makes and angle θ_r with the fixed stator phase axis androtating stator mmf makes an angle α with the rotor d-axis. Stator mmf rotates at the same speed as that of the rotor.

The inductances and flux linkages is given by

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$$\varphi_s = L_{ss} i_s + L_{sr} i_r \quad (3)$$
$$\varphi_r = L_{rs} i_s + L_{rr} i_r \quad (4)$$

The rotor voltages and the stator voltages on the rotor reference frame is given by

$$\frac{d\varphi}{dt} = -Ri - V \quad (5)$$
$$\frac{dy}{dx} = -R_s i_s - V_s \quad (6)$$

The total torque developed in the machine is given by

$$J\frac{dW_m}{dt} = T_m - T_e \quad (7)$$

T_m is the torque of the prime mover.
T_e is electromagnetic torque.

As the inductances keep changing with the rotor position and fluxes and currents are also dependent on the rotor position the parks and Clarks transformation are made use of to convert the linear time variant system to an linear time invariant system

$$f_a = C_p(\theta) f_d \quad (8)$$
$$f_b = C_p(\theta) f_q (9)$$
$$f_c = C_p(\theta) f_0 \quad (10)$$

Where c_p is dependent on θ

$$C_p = \begin{bmatrix} K_d \cos\theta & K_q \sin\theta & K_0 \\ K_d \cos(\theta - \frac{2\pi}{3}) & K_q \sin(\theta - \frac{2\pi}{3}) & K_0 \\ K_d \cos(\theta + \frac{2\pi}{3}) & K_q \sin(\theta + \frac{2\pi}{3}) & K_0 \end{bmatrix}$$

At steady state the rotor currents become constant and balanced sinusoidal

$$C\_p^{-1} = \begin{bmatrix} K_1 \cos\theta & K_1 \cos\theta - \frac{2\pi}{3} & K_1 \cos(\theta + \frac{2\pi}{3}) \\ K_2 \sin\theta & K_2 \sin(\theta - \frac{2\pi}{3}) & K_2 (\sin\theta + \frac{2\pi}{3}) \\ K_3 & K_3 & K_3 \end{bmatrix}$$

Where
$K_1 = \frac{2}{3K_d}, K_2 = \frac{2}{3K_q}, K_{23} = \frac{2}{3K_0}$ such that $K_d, K_q, K_0 \neq 0$

Obtaining the mutual and the self-inductances due to coil on each of the rotor axis having the damper windings q, h, k,and g on direct and quadrature axis respectively.

Stator flux linkages given by,

$$\frac{-d\varphi}{dt} - \omega\frac{K_q}{K_d}\Psi_d - R_a i_d = V_d$$
$$\frac{-d\varphi}{dt} - \omega\frac{K_d}{K_q}\varphi_q - R_a i_q = V_q$$
$$\frac{-d\varphi}{dt} - R_a i_0 = V_0$$

Rotor flux linkage equations given by,

$$\frac{d\varphi_f}{dt} + R_f i_f = V_f$$
$$\frac{d\varphi_h}{dt} + R_h i_h = 0$$

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$$\frac{d\varphi_g}{dt} + R_g i_g = 0$$
$$\frac{d\varphi_k}{dt} + R_k i_k = 0$$

Obtaining the entire torque developed by the PMSM is given by,

$$T_e = \frac{3}{2} K_q K_d \{ i_q \left[\varphi_d - \left(L_d - \frac{3}{2} L_{aa2} i_d \right) \right] - i_d \left[\varphi_q - \left(L_q - \frac{3}{2} L_{aa2} i_q \right) \right] \} \quad (11)$$

$$T_e = \frac{3}{2} K_d K_q [\varphi_d i_q - \varphi_q i_d] \quad (12)$$

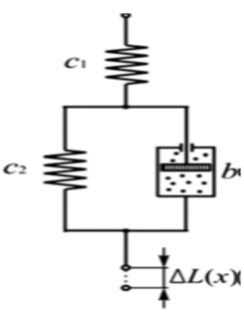
Where,

$$\varphi_d = L_d i_d + M_{df} i_f \quad (13)$$
$$\varphi_q = L_q i_q \quad (14)$$

Mutual inductance of the field and the a-axis is given by M_{df}

III. MODELLING OF BUILDING SYSTEM PROTOTYPE (ELEVATOR)

The elevator is used to transport people from one position to another in high rise buildings. The elevator is modeled considering all the realistic constraints.



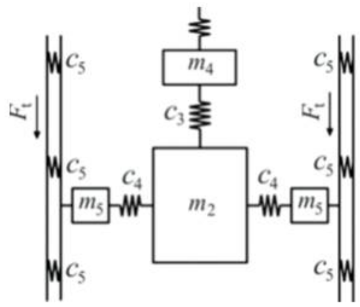


Fig.4. Hooks modelFig. 5. Newton's model

As rope exhibits two basic characteristics one is the stiffness and the other one is the elasticity with the damping. The Newton's model is considered,

Fig. 6 shows the realistic model of the elevator with all the parameter values assumed to design the elevator model.

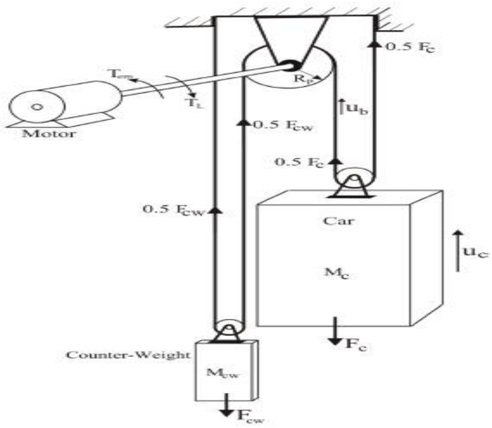


Fig. 6. Elevator model

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The torque equation of the elevator is given by,

$$T_{em} = J_m \frac{dW_m}{dx} + B * W_m + T_L \qquad (15)$$

Where, T_{em} is electromagnetic torque, J_m is motor inertia and T_L is the load torque.
The load torque on the motor shaft running down the pulley is given by,

$$T_L = R_p * F_L + J_p \frac{dw_m}{dt} + Bw_m \qquad (16)$$

Where, R_p is pulley radius, F_L is the force exerted by motor pulley

In order to obtain the overall working of the elevator the motion of the elevator has to be considered in two directions. One direction is when the elevator is moving upwards and the other direction is when the elevator is moving downwards.

$$F_L = \frac{1}{2}[g*(M_c - M_{cw}) + M_c \frac{du_c}{dt}] \qquad (17)$$

Where, g is gravitational constant, M_c is elevator car mass, M_{cw} is elevator counter weight.
The belt is running at a speed of U_b of the motor drive pulley.

$$u_b = 2u_c$$

Where, u_b is motor speed.

$$u_c = \frac{1}{2} u_b$$

$$u_c = \frac{1}{2} R_p * W_m$$

Obtaining the power of car moving upward,

$$P_{mc} = M_c * g * u_c$$

Obtaining the pulling belt mechanical power,

$$P_{mb} = \frac{1}{2} M_c * g * u_b$$

$$P_{mb} = \frac{1}{2} M_c * g * 2u_c$$

$$P_{mb} = P_{mc}$$

Equating the power of the moving car and mechanical belt and obtaining the force,

$$F_{lg} = \frac{1}{2} * g * (M_c - M_{cw})$$

$$J_c = \frac{1}{2} * M_c * \frac{du_c}{dt}$$

$$F_L = F_{lg} + J_c$$

Assuming that the belt is flexible when moving upward and hence predicting that torque is unaffected due to these disturbances in the system.

$$T_L = \frac{1}{2} * R_p * g * (M_c - M_{cw}) + \frac{1}{4} {R_P}^2 * M_c * \frac{dW_m}{dt} + J_p \frac{dW_m}{dt} + BW_m$$

The load torque when the elevator is moving downwards is given by,

$$T_L = -\frac{1}{2} * R_p * g * (M_{cw} - M_c) + \frac{1}{4} {R_P}^2 * M_{cw} * \frac{dW_m}{dt} + J_p \frac{dW_m}{dt} + BW_m \qquad (18)$$

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$(M_c - M_{cw})$is load given to the elevator i.e. is the difference of mass of the car and the mass of the counter weight.

$$T_{em} = J_m \frac{dw_m}{dt} + Bw_m + \frac{1}{2} * R_p * g * (M_c - M_{cw}) + \frac{1}{4} {R_P}^2 * M_c * \frac{dW_m}{dt} + J_p \frac{dW_m}{dt}$$

$$T_{em} = (J_m + \frac{1}{4} {R_P}^2 * M_c + J_p) \frac{dW_m}{dt} + Bw_m + \frac{1}{2} * R_p * g * (M_c - M_{cw})$$

Where,

$$J_{eq} = J_m + \frac{1}{4} {R_P}^2 * M_c + J_p$$

$$T_{lg} = \frac{1}{2} * R_p * g * (M_c - M_{cw})$$

IV. FIELD ORIENTED CONTROL OF PMSM

FOC control mainly involves converting the quantities from rotor reference frame to stationary reference frame and then converting the three phase to two phase orthogonal system.

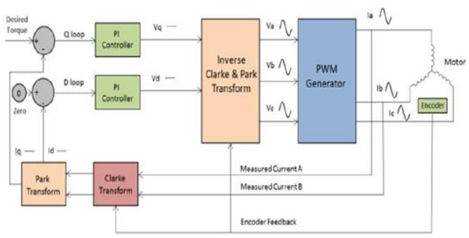

Fig. 7.FOC Technique

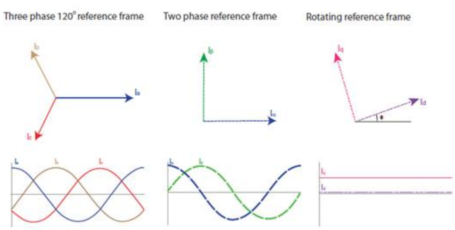

Fig. 8. FOC Transformations

Clarke's transformations:

1. $I_\alpha = I_a$
2. $I_\beta = (I_a + 2I_b)/\sqrt{3}$
3. $I_a + I_b + I_c = 0$

Park's transformation:

1. $I_d = I_\alpha \cos\theta + I_\beta \sin\theta$
2. $I_q = I_\beta \cos\theta - I_\alpha \sin\theta$

Inverse Park's transformation:

1. $V_\alpha = V_d \cos\theta - V_q \sin\theta$
2. $V_\beta = V_q \cos\theta + V_d \sin\theta$

Inverse Clarke's transformation:

1. $V_a = V_\alpha$
2. $V_b = (-V_\alpha + \sqrt{3}V_\beta)/2$
3. $V_c = (-V_\alpha - \sqrt{3}V_\beta)/2$

V.SIMULATION AND RESULTS

A. Three phase voltage source inverter

- $V_{DC} = 30V$
- Switching frequency=5khz

PWM generation:

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- Time values= [0 1/5000/4 3/5000/4 1/5000]
- Output voltage amplitude of the triangular wave= [0 -30 30 0]

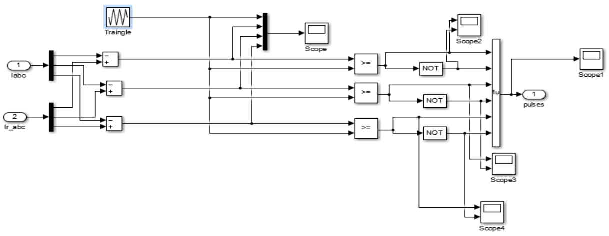

Fig. 9.PWM pulse generation

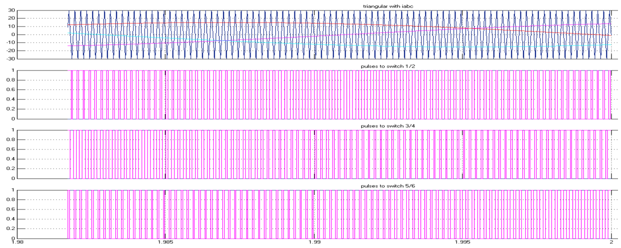

Fig. 10. Pulses to inverter

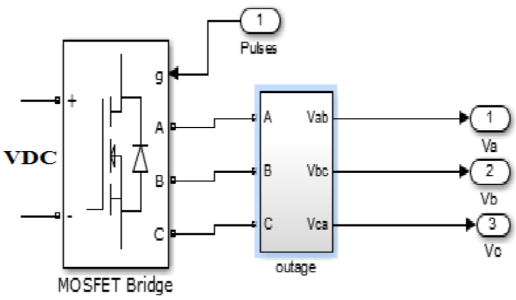

Fig. 11. Inverter model

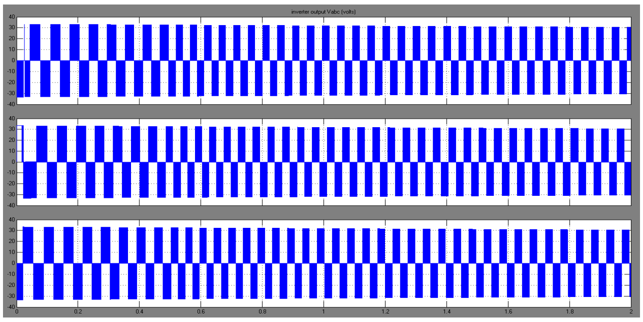

Fig. 12. Inverter output

A. ELEVATOR LOAD CALCULATIONS

J (inertia) = 0.0234 kg/m^2.
B (friction co-efficient) = 0.004
R_p (Radius of pulley) = 0.025m
g (gravitational constant) = 9.8
M_{cw} (Mass of the counter weight) = 100 Kg
M_c=M_{cw} +Load (mass of the car) =150 Kg

$$T_L = \frac{1}{2} * 0.025 * 9.8 * (150 - 100) + \frac{1}{4} * 0.0025^2 * 150 * \frac{1200\pi}{30} + 0.0234 * \frac{1200\pi}{30}$$

T_L=4.8 Nm

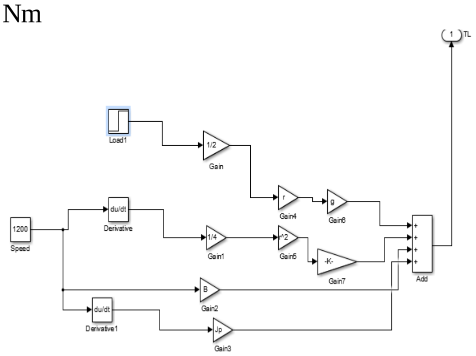

Fig. 13. Elevator Simulink model(upward)

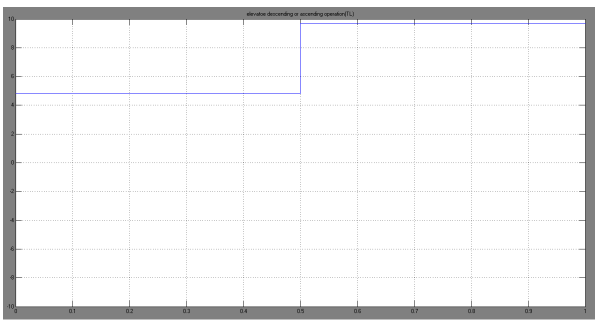

Fig. 13. Elevator output torque

$$T_L = -[\frac{1}{2} * 0.025 * 9.8 * (150 - 100) + \frac{1}{4} * 0.0025^2 * 150 * \frac{1200\pi}{30} + 0.0234 * \frac{1200\pi}{30}]$$

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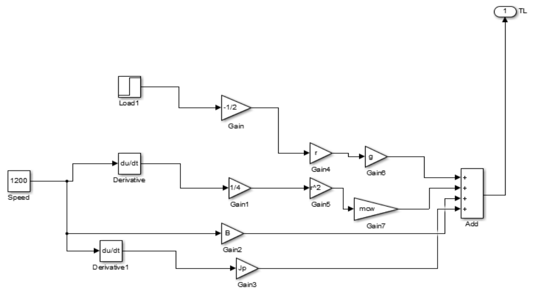

Fig. 14.Elevator Simulink model(downward)

$T_L = -4.8Nm$

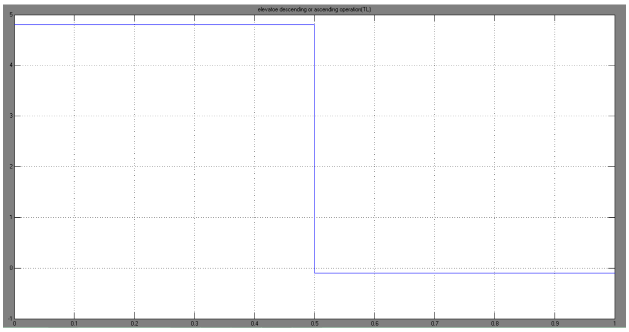

Fig. 15.Elevator torque output

B. FIELD ORIENTED CONTROL CALCULATIONS

Table.1. Details of PI controllerTable.2.Values given to the PI controller

PARAMETER	UNIT	VALUE	DESCRIPTION
f_s	HZ	5000	Switching frequency
V_{dc}	V	30	DC bus voltage
K_{pd}	-	-	Proportional constant of d-axis current regulator
K_{id}	-	-	Integral constant of d-axis current regulator
K_{pq}	-	-	Proportional constant of q-axis current regulator
K_{iq}	-	-	Integral constant of q-axis current regulator
$K_{p\omega}$	-	-	Proportional constant of speed regulator
$K_{i\omega}$	-	-	Integral constant of speed regulator

PARAMETER	UNIT	VALUE	DESCRIPTION
R_s	Type equation here.	7.1	Stator resistance
L_d	H	30e-3	Direct axis inductance
L_q	H	30e-3	Quadrature axis inductance
P	-	6	poles
φ_m	Vs	0.12	Permanent magnet flux
B	Ns/m	0.002	Viscous coefficient
J	Kgm^2	5.8e-4	inertia

- $\alpha_{current} = \frac{2\pi f_s}{10}$; $\alpha_{current} = \frac{2\pi * 5000}{10} = 1000\pi$
- $\alpha_{speed} = \frac{\alpha_{current}}{10} = 100\pi$
- $K_{pd} = \alpha_{current} * L_d = 1000\pi * 30 * 10^{-3} = 94.24$
- $K_{id} = \alpha_{current} * R_S = 1000\pi * 7.1 = 22305.307$
- $K_{pq} = \alpha_{current} * L_q = 1000\pi * 30 * 10^{-3} = 94.24$
- $K_{iq} = \alpha_{current} * R_S = 1000\pi * 7.1 = 22305.307$
- $K_{p\omega} = \alpha_{speed} * J = 100\pi * 0.002 = 0.6283185$
- $K_{i\omega} = \alpha_{speed} * B = 100\pi * 5.8 * 10^{-4} = 1.822123$

C. PMSM CALCULATIONS

Clarke's transformations:

- $I_\alpha = I_a; I_a = 4A$
- $I_\beta = (I_a + 2I_b)/\sqrt{3}$; $I_\beta = (4 + 2 * 4)/\sqrt{3} = 6.9A$
- $I_a + I_b + I_c = 0$

Park's transformation:

$$I_d = I_\alpha \cos\theta + I_\beta \sin\theta$$

Assuming $I_d = 0; I_\alpha \cos\theta = -I_\beta \sin\theta$; $\frac{I_\alpha}{I_\beta} = \tan\theta$

4/6.9=tan θ; θ=30°

$$I_q = I_\beta \cos\theta - I_\alpha \sin\theta$$

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$$I_q = 6.9\cos 30° - 4\sin 30° = 3.975\text{A}$$

Inverse Park's transformation:

$$V_\alpha = V_d \cos\theta - V_q \sin\theta$$
$$V_\beta = V_q \cos\theta + V_d \sin\theta$$

Inverse Clarke's transformation:

$$V_a = V_\alpha$$
$$V_b = (-V_\alpha + \sqrt{3}V_\beta)/2$$
$$V_c = (-V_\alpha - \sqrt{3}V_\beta)/2$$

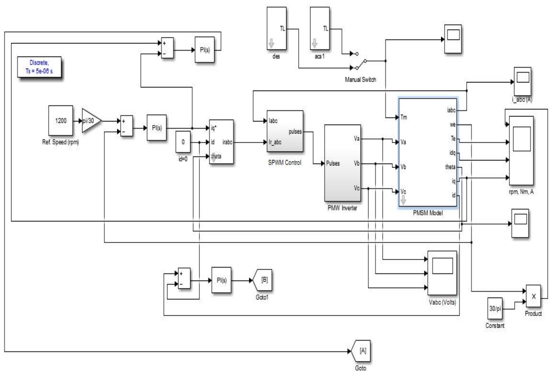

Fig. 16. Simulink model of the PMSM drive

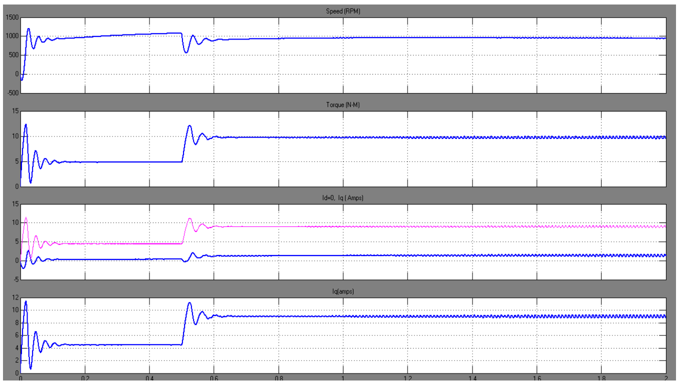

Fig. 17. Output torque, speed, current in q and d axis

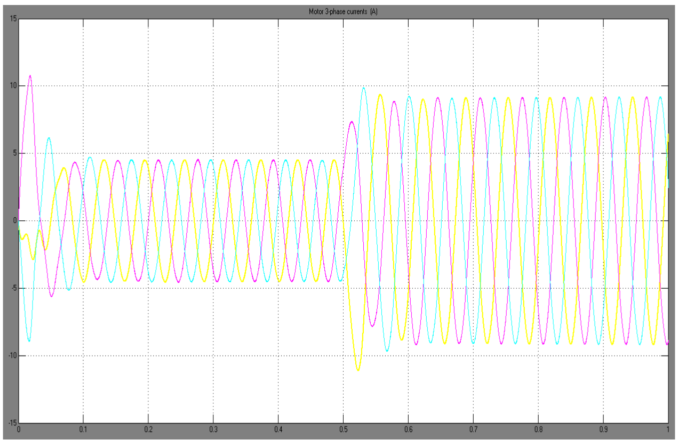

Fig. 18. Stator three phase currents

VI.CONCLUSION

The field oriented control of PMSM Simulink model is developed. The torque ripple is high. The smooth operation of PMSM is quite tedious. The above given model can be further improved by including a fuzzy logic algorithm for a better performance of the machine model. The temperature rise in the machine also adds to the performance of the model. The stator resistance can be further varied to obtain the optimum results.

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