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SIMULATION OF FIELD ORIENTED CONTROL OF PERMANENT MAGNET SYNCHRONOUS MOTOR

Yashvi Narendrasinh Parmar[1],

[1]PG student, Electrical Engineering, Sarvajanik College of Engineering & Technology, Surat

Abstract —*Field oriented control (FOC) of permanent magnet synchronous motor (PMSM) is one of the widely used methods for the speed control of the motor. The Field Oriented Control is an external device that regulates and controls the performance of Permanent Magnet Synchronous Motor. A PMSM drive system based on FOC is designed, simulated and implemented. The whole drive system is simulated in Matlab/Simulink based on the mathematical model of the system devices including PMSM and inverter. Permanent magnet synchronous motors are widely used in low and mid power applications such as computer peripheral equipments, robotics, adjustable speed drives and electric vehicles.*

Keywords*-FOC (Field oriented control), PMSM (Permanent magnet synchronous motor), Drive system, SPWM (Sinusoidal pulse width modulation), rotor reference frame.*

I. INTRODUCTION

PMSM is an AC motor that uses permanent magnet as the rotor excitation. It has the highest power density and efficiency among all types of motors due to the use of permanent magnets. It requires no excitation and commutation circuit, therefore the maintenance for the excitation circuit and copper loss on the rotor are eliminated. The elimination of rotor winding copper loss can improve the efficiency.

1.1. PMSM drive system

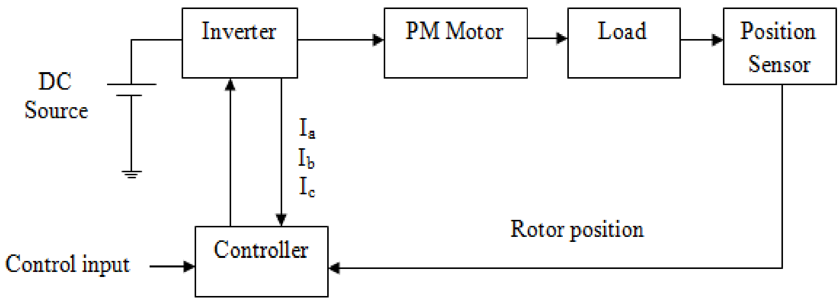


Figure 1. Drive system [4]

The motor drive consists of four main components, the PM motor, inverter, control unit and the position sensor. The components are connected as shown in Figure 1. Permanent magnet synchronous motor (PMSM) is a motor that uses permanent magnets to produce the air gap magnetic field rather than using electromagnets. Operation of permanent magnet synchronous motors requires position sensors in the rotor shaft when operated without damper winding. There are four main devices for the measurement of position, the potentiometer, linear variable differential transformer, optical encoder and resolvers. The motor is fed form a voltage source inverter with current control. The control is performed by regulating the flow of current through the stator of the motor. [4]

1.2 Detailed Modeling of PMSM

The d-q model has been developed on rotor reference frame as shown in Figure 2. At any time t, the rotating rotor d-axis makes and angle θ_r with the fixed stator phase axis and rotating stator mmf makes an angle α with the rotor d-axis. Stator mmf rotates at the same speed as that of the rotor.

The model of PMSM without damper winding has been developed on rotor reference frame using the following assumptions:

1) Saturation is neglected.
2) The induced EMF is sinusoidal.
3) Eddy currents and hysteresis losses are negligible.

4) There are no field current dynamics.

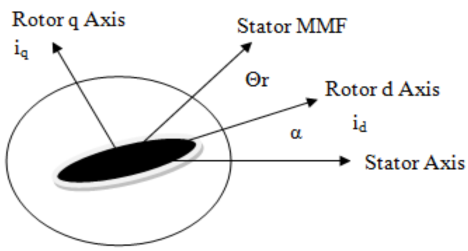


Figure 2. Axis representation of motor [5]

Voltage equations are given by:

$$V_q = R_q i_q + \omega_r L_d + p\lambda_q \quad (1)$$

$$V_d = R_d i_d - \omega_r L_q + p\lambda_d \quad (2)$$

Flux Linkages are given by:

$$\lambda_q = L_q i_q \quad (3)$$

$$\lambda_d = L_d i_d + \lambda_m \quad (4)$$

Substituting Eq. (3) and (4) into Eq. (1) and (2),

$$\begin{bmatrix} V_q \\ V_d \end{bmatrix} = \begin{bmatrix} R_s + pL_q & \omega_r \lambda_d \\ -\omega_r \lambda_q & R_s + pL_d \end{bmatrix} \begin{bmatrix} i_q \\ i_d \end{bmatrix} + \begin{bmatrix} \omega_r \lambda_m \\ p\lambda_m \end{bmatrix} \quad (5)$$

Power equation is given by,

$$P_i = \frac{3}{2} (V_q i_q + V_d i_d) \quad (6)$$

The developed torque of motor is given by,

$$T_e = \left(\frac{3}{2}\right)\left(\frac{p}{2}\right)(\lambda_d i_q - \lambda_q i_d) \quad (7)$$

Equation for motor dynamics is,

$$(T_e - T_l) = \left(\frac{p}{2}\right)(J\dot{\omega}_m + B\omega_m) \quad (8)$$

Solving for the rotor mechanical speed,

$$\omega_m = \int \left(\frac{(T_e - T_l - B\omega_m)}{J}\right) dt \quad (9)$$

$$\omega_m = \omega_r \frac{2}{p} \quad (10)$$

In the above equations ω_r is the rotor electrical speed where as ω_m is the rotor mechanical speed. [1]

1.3 Field Oriented Control of PMSM

Field oriented control of PMSM is one important variation of vector control methods. The aim of the FOC method is to control the magnetic field and torque by controlling the d and q components of the stator currents or consequently the fluxes. The main advantages of this technique are the fast response and the little torque ripple. Figure 3 shows basic structure of vector control algorithm.

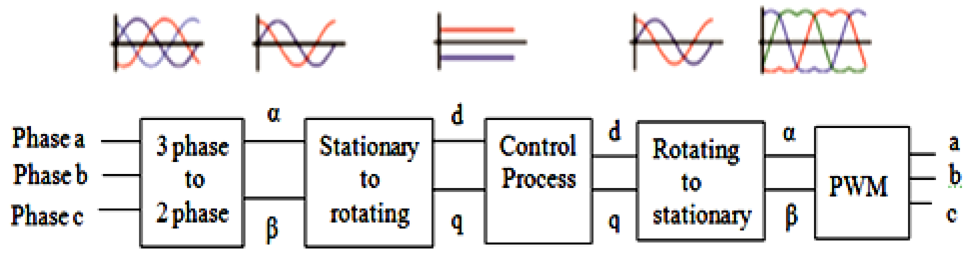


Figure 3. Basic structure of vector control algorithm [3]

1. Measure the motor current.
2. Transform them into two phase system (*α, β*) using Clarke transformation.
3. Calculate rotor flux space vector magnitude and phase angle.
4. Transform stator currents into d,q reference frame using park transformation.
5. The stator current torque (i_{sq}) and flux (i_{sd}) producing components are controlled separately by the controllers.
6. The output stator voltage space- vector is transformed back from the d,q-coordinate system into the two- phase system fixed with the stator by inverse Park transformation.
7. Using the space vector modulation, the output three-phase voltage is generated.

The vector control of the PM synchronous motor is derived from its dynamic model.

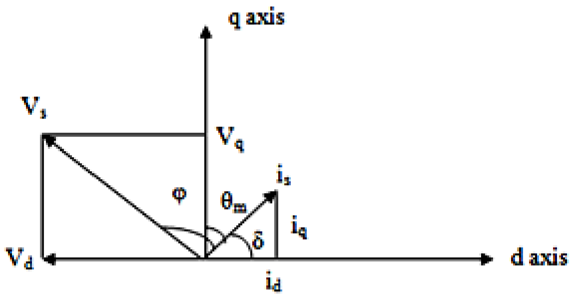


Figure 4. Phasor diagram of PMSM [6]

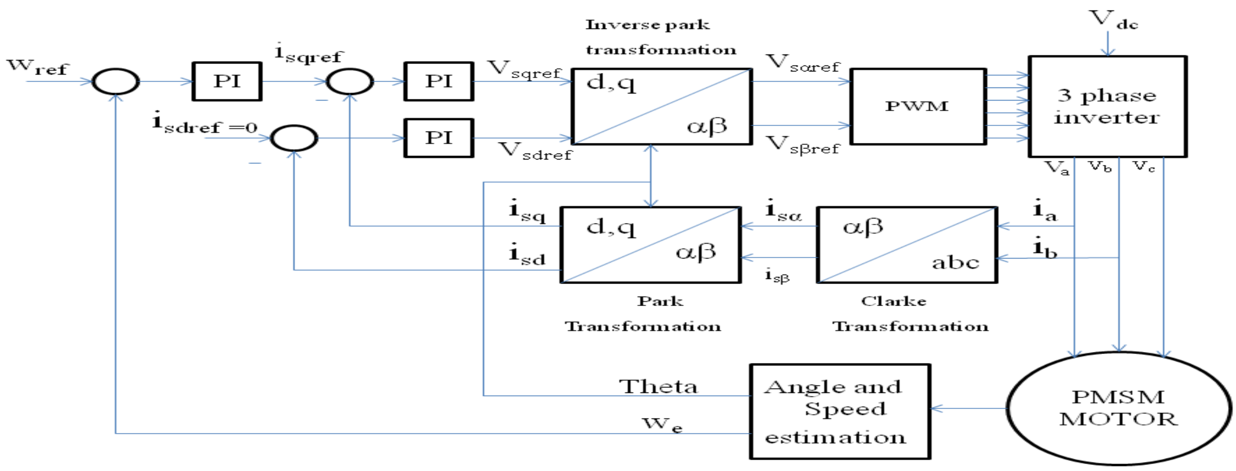


Figure 5. Block Diagram of field oriented control of PMSM [3]

Phasor diagram is shown in Figure 4.The block diagram of field oriented vector control system is shown in Figure 5. Considering the currents as inputs, the three currents are:

$$i_a = i_s \sin \omega_r t + \delta \quad (11)$$
$$i_b = i_s \sin \omega_r t + \delta - \frac{2\pi}{3} \quad (12)$$
$$i_c = i_s \sin \omega_r t + \delta + \frac{2\pi}{3} \quad (13)$$

Where α is the angle between the rotor field and stator current Phasor, ω_r is the electrical rotor speed.
Rotor field is travelling at a speed of ω_r rad/sec , hence the q and d axes stator currents in the rotor reference frame for a balanced 3 phase operation are given by,

$$\begin{bmatrix} i_{qs}{}^{r} \\ i_{ds}{}^{r} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\omega_r t & \cos\left(\omega_r t - \frac{2\pi}{3}\right) & \cos\left(\omega_r t + \frac{2\pi}{3}\right) \\ \sin\omega_r t & \sin\left(\omega_r t - \frac{2\pi}{3}\right) & \sin\left(\omega_r t + \frac{2\pi}{3}\right) \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (14)$$

Substituting the equations from (11) to (13) into (14) gives stator currents in rotor reference frames:

$$\begin{bmatrix} i_{qs}{}^{r} \\ i_{ds}{}^{r} \end{bmatrix} = i_s \begin{bmatrix} \sin\delta \\ \cos\delta \end{bmatrix} \quad (15)$$

i_q = Torque-producing component of stator current = i_T
i_d = Flux – producing component of stator current = i_f

1.4 Constant torque operation

This is performed by making the torque producing current i_q equal to the supply current Im. That results in selecting the angle δ to be 90 ° degrees according to Eq. (15). By making the i_d current equal to zero the torque equation can be rewritten as,

$$T_e = K i_T \text{, Where } k = \frac{3}{2}\frac{P}{2}\lambda_m \quad (16)$$

II. SIMULATION OF FIELD ORIENTED CONTROL OF PMSM USING SINEPWM

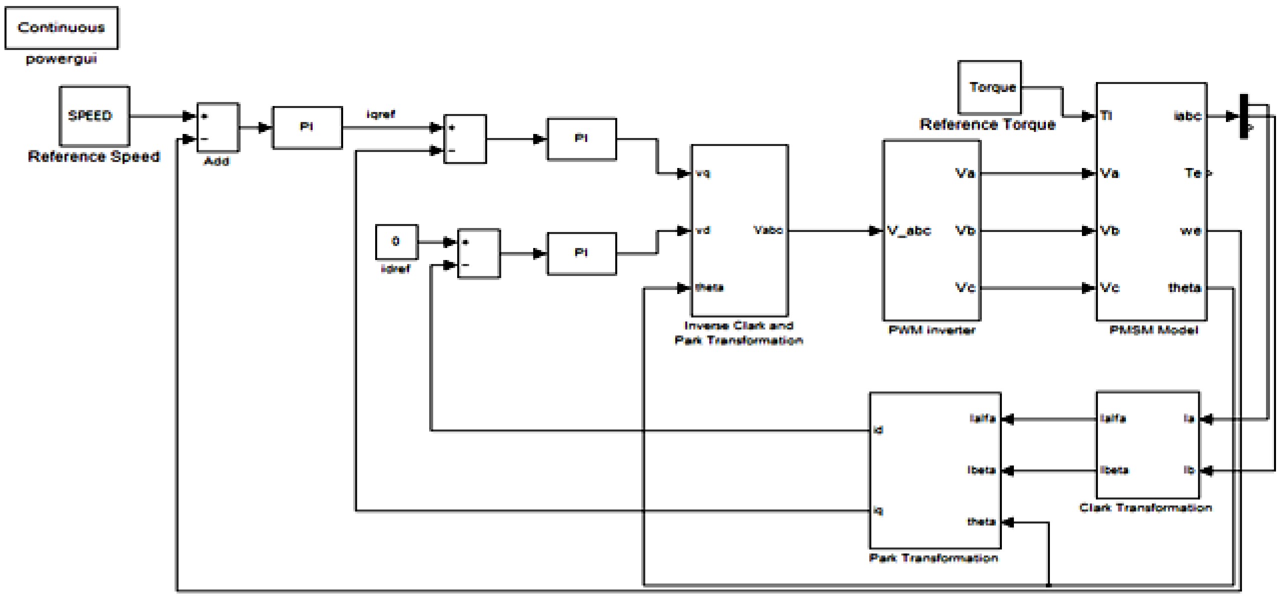


Figure 6. Simulation Block of FOC of PMSM using MATLAB

In Figure 6, simulink model of FOC control of PMSM drive is shown. This is done using MATLAB/ SIMULINK. Different Case studies are taken for this simulation which proves that drive is flexible. Table 2 shows Parameters of PMSM which is used in this simulation. Sinusoidal Pulse Width Modulation (SPWM) technique has been used for controlling the inverter as it can be directly controlled the inverter output voltage and output frequency according to the sine functions. In SPWM technique three sine waves and a high frequency triangular carrier wave are used to generate PWM signal. Generally, three sinusoidal waves are used for three phase inverter. The sinusoidal waves are called reference signal and they have 120 phase difference with each other. The frequency of these sinusoidal waves is chosen based on the required inverter output frequency (50 Hz). The carrier triangular wave is usually a high frequency (in several KHz) wave. The switching signal is generated by comparing the sinusoidal waves with the triangular wave.

2.1 PMSM Model

Table 1. PMSM Parameters

Sr. No.	Parameter	Value	Sr. No.	Parameter	Value
1.	DC voltage	36 V	6.	Stator resistance	0.75 Ω
2.	Magnetic flux linkage	0.0203 V.	7.	Inertia	0.00176 $Kg.M^2$
3.	Poles	4	8.	0.00038 N.M.S/ rad	0.00038 N.M.S/ rad
4.	q-axis inductance	2.475 mH	9.	Rated speed	4000 RPM
5.	d-axis inductance	2.475 mH	10.	Rated Torque	0.32 N.m

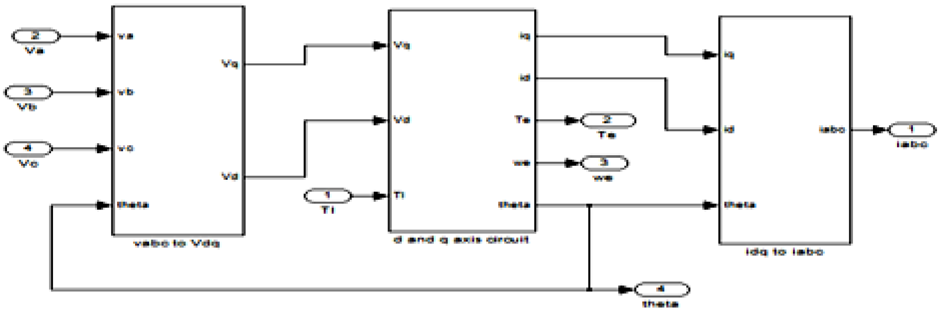


Figure 7. Mathematical Model of PMSM

2.2 Simulation Results

Case 1: Constant Speed and Constant Torque

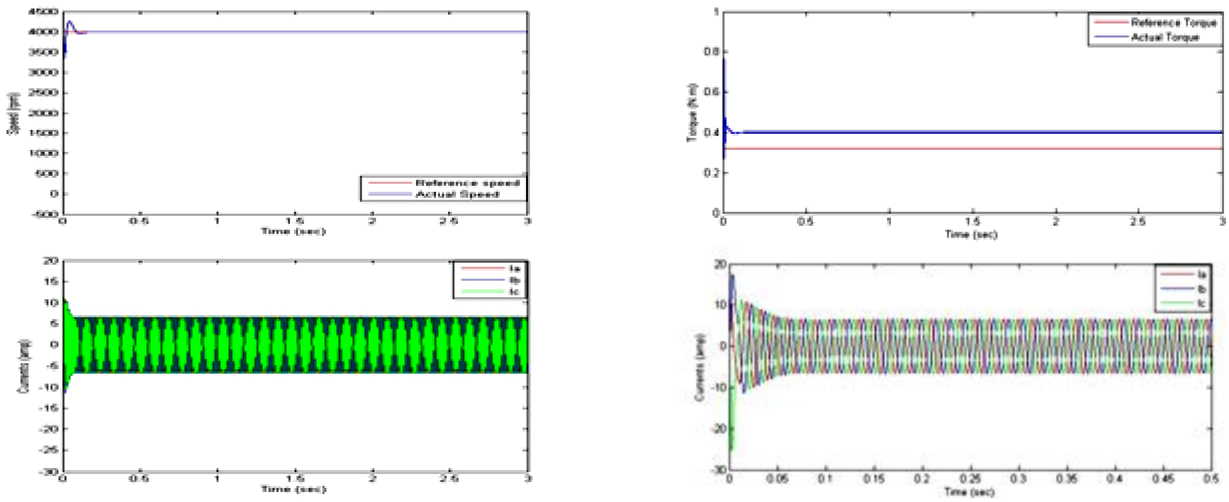


Figure 8. Simulation results for constant speed and torque

Here, Reference Speed is set at 4000 Rpm. Steady state Speed is achieved at 10 ms. The electrical Torque rises to 0.8 N.m, when the motor starts and steady at around 20 ms when motor reaches the set speed. Initial current is high and decreases as steady state speed is achieved. At starting current is non-sinusoidal. Current is sinusoidal when set speed is achieved.

Case 2: Variable Speeds and Constant Torque

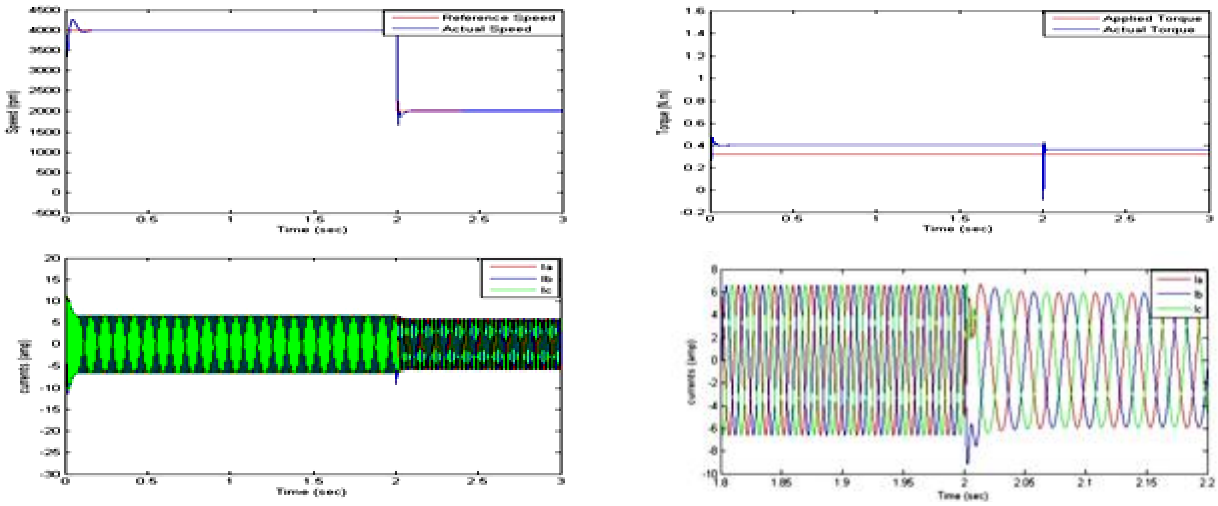


Figure 9. Simulation results for variable speeds and constant torque

In this case, Variable speeds are taken. Reference Speed is set to 4000 Rpm for 2 sec and after 2 sec it is set to 2000 Rpm. According to reference speed Actual Electrical Speed is also varied. In this case, applied torque is constant. But, speed is decreased from 4000 RPM to 2000 RPM. At 2 sec. So, due to this reason electrical torque is also decreased and becomes negative at 2 sec .If speed is increased from 4000 RPM to 6000 RPM then electrical torque rises at 2 sec. In first figure, current in 0 to 3 sec. interval is shown. At 2 sec, there is change in current waveform because speed is varied at that point .In 0 to 2 sec., speed is 4000 RPM. And in 2 to 3 sec. speed is decreased to 2000 RPM.So that, current completes more number of cycles in 0 to 2 intervals and less number of cycles in 2 to 3 interval.

Case 3: Constant Speed and Variable Torques

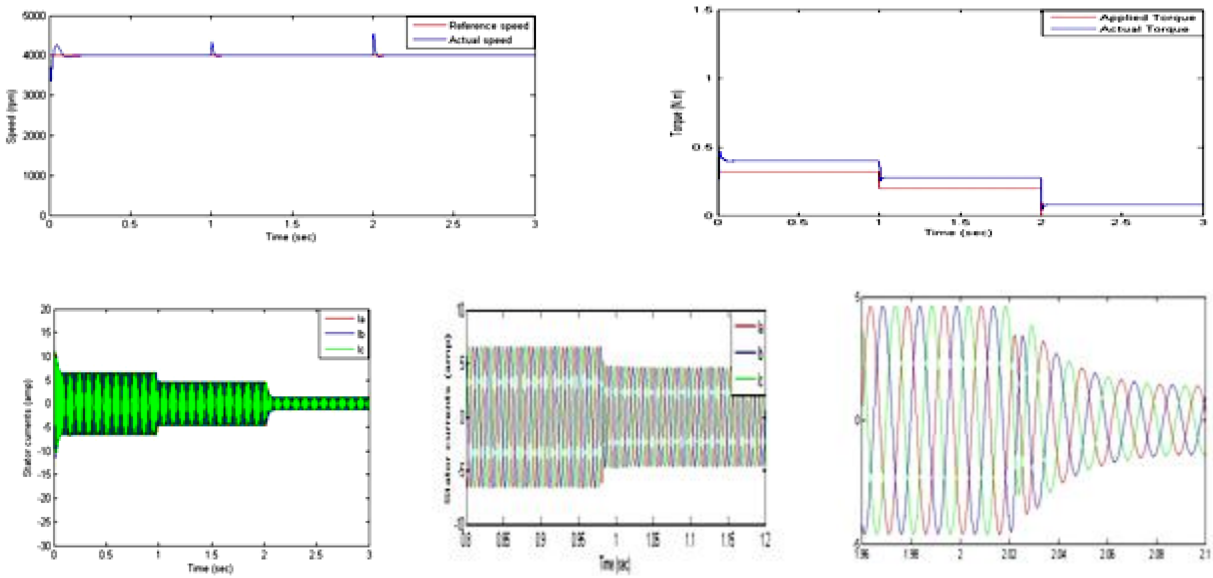
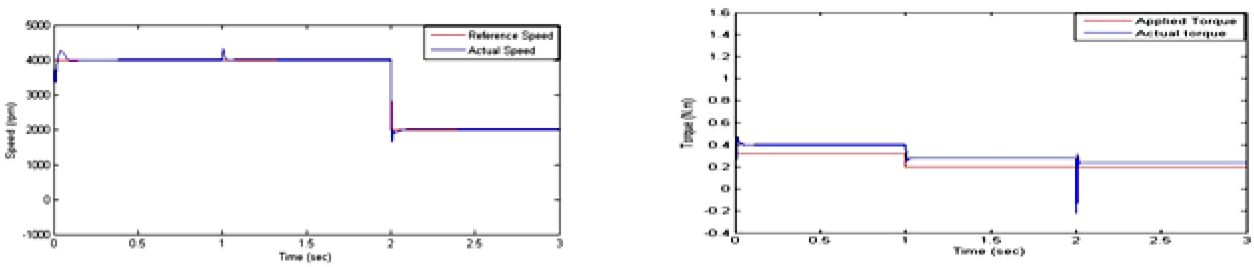


Figure 10. Simulation results for constant speed and variable torques

In this case, reference speed is set to 4000 Rpm and Load torque is varied at 2 sec. So, there is change in actual speed curve at 2 sec. Here, Initially Load torque is taken 0.32 N.m. Load torque is changed at t=1 sec. which is 0.2 N.m also it is changed at t=2 sec which is 0 N.m. According to applied Torque, Electrical torque is also changed as shown in fig.5.9. At 1 sec and 2 sec., as torque is varied current waveform is also changed in magnitude. If torque decreases, then current magnitude also decreases.

Case 4: Variable Speeds and Variable Torques



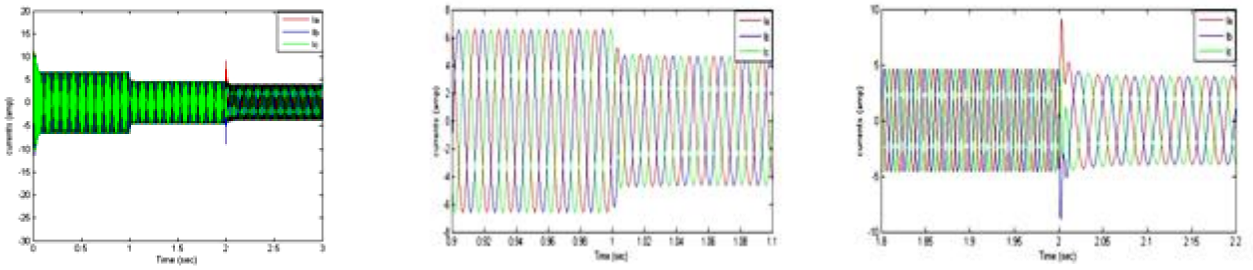


Figure 11. Simulation results for variable speeds and torques

Here, speed is varied at 2 sec. from 4000 to 2000 RPM. According to which actual speed curve is also changed. But, there is change in actual speed at 1 sec. Because load torque is changed at that point and then settles. Applied torque is shown here, which is 0.32 N.m for 1 sec and 0.2 N.m for 1 to 3 sec. According to it, Electrical torque is changed. But Variation in torque is also observed at 2 sec. Because Speed is decreased at that point . First figure shows whole interval of currents. In second figure interval 0.9 to 1.1 sec is shown which shows effect of variation of torque at t=1 sec. on current waveform. In third figure interval 1.8 to 2.2 sec is shown which shows effect of variation of speed at 2 sec.

III. CONCLUSION

By observing above cases, conclusion is that Model of PMSM and FOC are flexible and give accurate results. Either speed or torque is changed; output is also varied as per reference given. Response of drive was found by this analysis. By changing q-component of current and d-component of current, Torque and Flux of PMSM are controlled respectively.

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