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Vector Control of PMSM Drive with Hysteresis Current Controller

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Abstract - This paper presents an advanced simulation model of Permanent Magnet Synchronous Motor (PMSM). The vector control scheme of a PMSM drive has been implemented using the developed simulation model. In the developed model, speed and torque as well as the voltages and currents of voltage source inverters components can be effectively monitored and analyzed. The developed simulation model has been implemented using Matlab and the dynamic response of PMSM drive has been analyzed for constant speed, varying torque and variable speed constant torque operation. Also, the simulation results have been presented. The simulation results of the developed model have been validated with the circuit simulation using the PMSM block available in the Matlab/Simulink library. Therefore, it can be expected that the developed simulation model can be an easy to design tool for the design and development of PMSM drives for different control algorithms and topological variations with reduced computation time and memory size.

Keywords - PMSM drive, vector control, closed loop, constant torque angle control, Reference frame theory.

I. INTRODUCTION

In recent years, many DC drives were replaced by brushless AC drives. PMSM gained much attention and has become the most used drive in machine tool servos and modern speed control applications. The inherent advantages of the machine include high efficiency, high power factor, high power density, easy maintenance, fast dynamic response. PMSM replaces Induction motor (IM) and Synchronous motor (SM) in several applications due to its higher efficiency, high power density and high torque to inertia ratio [1]. Rotor of PMSM is made up of permanent magnet so there is no need of supplying magnetizing current through stator to produce airgap flux. SM requires dc excitation on the rotor, which is supplied by brushes and slip rings; it leads to rotor losses and requires regular maintenance [2]. In PMSM rapid torque build up required by, variable speed and fast dynamic response drives, could be achieved by stator current control technique.

PMSM is a topic of interest for last twenty years. Vector control technique is one of the most common closed loop control technique used in a PMSM drive. Vector control eliminates oscillating flux, torque responses in inverter fed induction motor and synchronous motor drives. This method has further classification, which includes constant torque angle control, Unity power factor control, constant mutual air gap flux-linkages control, optimum-torque-per-ampere control and flux-weakening control. The choice of these methods depends on mainly on the type of application and the load characteristics. Hence, it is always essential to perform a simulation study prior to designing a PMSM drive for choosing the appropriate control algorithm for a particular application. The mathematical model of PMSM as such has been well established in literature [2] and [3]. Incorporation of PMSM model along with the inverter model and load characteristics is essential to represent a complete drive system. Such a simulation model has been reported for a BLDC drive [4]. Also the modeling of complete PMSM drive is reported in [2]. This paper proposes a system simulation model for a complete PMSM drive based on the mathematical model of an inverter fed PMSM implemented using MATLAB\Simulink, which could be used for simulating various control algorithms. In the developed model, speed and torque as well as the voltages and currents of voltage source inverters components can be effectively monitored and analyzed. In this paper, section II discusses about mathematical modeling of PMSM. Section III discusses about the developed simulation model of PMSM drive system. The simulation results of the developed model validated with the circuit simulation model has been presented in section IV.

With introduction of permanent magnets to replace the electromagnetic poles with windings requiring an electric energy supply source resulted in compact dc machines. Likewise in synchronous machines, the conventional electromagnetic field poles in the rotor are replaced by the PM poles and by doing so the slip rings and brush assembly are dispensed. With the advent of switching power transistor and silicon controlled rectifier devices the replacement of the mechanical commutator with an electronic commutator in the form of an inverter was achieved. These two developments contributed to the development of PMSMs and brushless dc machines. The armature of the dc machine need not be on the rotor if the mechanical commutator is replaced by its electronic version. Therefore, the armature of the machine can be on the stator enabling better cooling and allowing higher voltages to be achieved as significant clearance space is available for insulation in the stator. The excitation field that used to be on the stator is transferred to the rotor with the PM poles.

Based on arrangement of permanent magnets on the rotor there are many types of PMSMs like surface-mounted PMSM, surface-inset PMSM, interior PMSM, Line-start PMSM. The permanent magnet motors classified based on type of back emf induced. Permanent magnet synchronous motor has sinusoidal back emf and Brushless DC motors have trapezoidal back emf. The silent features of PMSM motor are:

- Due to low inertia used in servo applications.
- High torque density.
- High reliability (no brush wear), even at very
- High achievable speeds.
- High efficiency.
- Low EMI.

II. MODELING OF PMSM

The dynamic model of the permanent magnet synchronous machine is derived using a two-phase motor in direct and quadrature axes. This approach is done to obtain conceptual simplicity of modeling. The rotor has no windings, only magnets. The magnets are modeled as a current source or a flux linkage source, concentrating all its flux linkages along only one axis. Constant inductance for windings is obtained by a transformation to the rotor by replacing the stator windings with a fictitious set of d-q windings rotating at the electrical speed of the rotor.

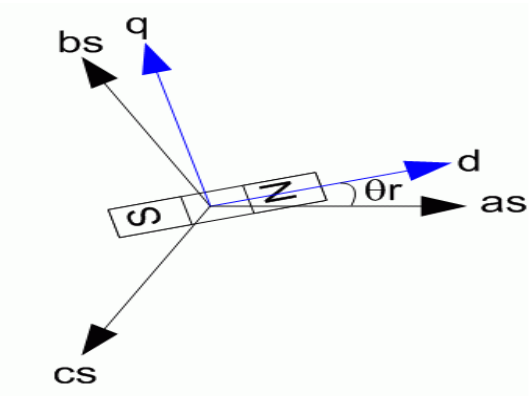

Figure 1. A two phase PSMS

The transformation from the two-phase to the three-phase variables of voltages, currents, or flux linkages is derived. From the obtained current and flux linkages electromagnetic torque is derived. The differential equations describing the PMSM are nonlinear

The windings d,q axis are displaced in space by 90 electrical degrees and the rotor winding is at an angle θr from the stator d-axis winding. It is assumed that the q-axis leads the d-axis to a counter clockwise direction of rotation of the rotor. A pair of poles is assumed for this figure, but it is applicable with slight modification for any number of pairs of poles. Note that θr is the electrical rotor position at any instant obtained by multiplying the mechanical rotor position by pairs of electrical poles. The d- and q-axes stator voltages are derived as the sum of the resistive voltage drops and the derivative of the flux linkages in the respective windings as below.

$$V_{qs} = R_s i_{qs} + i_{qs} p L_{qq} + L_{qq} p i_{qs} + L_{qd} p i_{ds} + i_{ds}\, p\, L_{qd} + \lambda_{af}\, p \sin\theta r \quad \text{(i)}$$
$$V_{ds} = R_s\, i_{ds} + i_{qs} p L_{qd} + L_{qd} p i_{qs} + L_{dd} p i_{ds} + i_{ds}\, p\, L_{dd} + \lambda_{af}\, p \cos\theta r \quad \text{(ii)}$$

Where, p = differential operator(d/dt)
V_{qs} and V_{ds} are the voltages in the q- and d-axes windings
i_{qs} and i_{ds} are the q- and d-axes stator currents R_s is the stator resistance
λ_{qs} and λ_{ds} are the stator q- and d-axes stator flux linkages
L_{qq} and L_{dd} are the self-inductances of the q and d-axes windings
θr is the instantaneous rotor position
λ_{af} is the rotor flux linkages that link the stator

The rotor type is surface mounted in which the inductances are equal, the self inductances and mutual inductance of windings is found, and rearranging the terms the motor equations are obtained I stator reference as

$$\begin{bmatrix} V_{qs} \\ V_{ds} \end{bmatrix} = R_s \begin{bmatrix} i_{qs} \\ i_{ds} \end{bmatrix} + \begin{bmatrix} L1 & 0 \\ 0 & L2 \end{bmatrix} d/_{dt} \begin{bmatrix} i_{qs} \\ i_{ds} \end{bmatrix} + \lambda_{af} W_r \begin{bmatrix} cos\theta_r \\ -sin\theta_r \end{bmatrix} \quad \text{(iii)}$$

The equations reveal that inductances are rotor position dependent. So, the rotor position dependency is eliminated by transformation

III. TRANSFORMATION TO ROTOR REFERENCE FRAMES

The rotor field position determines the induced emf and affects the dynamic system. So by viewing the entire system from the rotor, i.e., rotating reference frames, the system inductance matrix (equ.iii) becomes independent of the rotor position, thus leading to the simplification and compactness of the system equations. Reference frames rotating at the speed of the rotor is referred to as rotor reference frames. The relationship between the stationary reference frames denoted by d_s and q_s axes and the rotor reference frames denoted by d_r and q_r axes. Transformation to obtain constant inductances is achieved by replacing the actual stator and its windings with a fictitious stator having windings on the q_r and d_r –axes. The fictitious stator will have the same number of turns for each phase as the actual stator phase windings and should produce the equivalent mmf. The actual stator mmf in any axis (say q or d) is the product the number of turns and current in the respective axis winding. The mmf produced by the fictitious stator windings on the q- and d-axes is same as actual stator mmf. Similarly, the same procedure is repeated for the d axis of the actual stator winding. This leads to a cancellation of the number of turns on both sides of the q- and d-axes stator mmf equations, resulting in a relationship between the actual and fictitious stator currents. The relationship between the currents in the stationary reference frames and the rotor reference frames currents is written as.

$$i_q d_s = [T]\, i^r_q d_s \quad \text{(iv)}$$

and similarly voltage relation is given as

$$v_q d_s = [T]\, v^r_q d_s \quad \text{(v)}$$

Where T is transition matrix

$$T = \begin{bmatrix} cos\theta_r & sin\theta_r \\ -sin\theta_r & cos\theta_r \end{bmatrix} \quad \text{(vi)}$$

The PMSM model in rotor reference frames is obtained as

$$\begin{bmatrix} v^r_{qs} \\ v^r_{ds} \end{bmatrix} = \begin{bmatrix} R_s + L_q P & W_r L_d \\ -W_r L_q & R_s + L_d P \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \end{bmatrix} + \begin{bmatrix} W_r \lambda_{af} \\ 0 \end{bmatrix} \quad \text{(vii)}$$

Where, Wr is the rotor speed in electrical radians per second.

The equations that are derived is for a two-phase PMSM but PMSMs with three phases are prevalent in industrial applications. A dynamic model for the three-phase PMSM is derived from the two phase machine by the equivalence between the three and two phases is established. The equivalence is based on the equality of the mmf produced in the two-phase and three-phase windings and on equal current magnitudes. Assuming that each of the three-phase windings has $T1$ turns per phase, and equal current magnitudes, the two-phase windings will have $3T1/2$ turns per phase for mmf equity. The d and q-axes mmfs are found by resolving the mmfs of the three phases along the d- and q-axes. Then three phase to two phase transformation (abc to dq0).

Electromagnetic Torque can be derived as below. The dynamic equations of the PMSM can be written as

$$V = [R]\, i + [L]\, p\, i + [G]\, w_r\, i \quad \text{(viii)}$$

By pre multiplying equation (viii) by the transpose of the current vector, the instantaneous input power is

$$P_i = i^t V = i^t [R]\, i + i^t [L]\, p\, i + i^t [G]\, w_r\, i \quad \text{(ix)}$$

Where, $[R]$ Matrix consists of resistive elements
$[L]$ Matrix consists of the coefficients of the derivative operator p
$[G]$ Matrix has elements that are the coefficients of the electrical rotor speed, θ_r

The term $i^t[R]i$ gives stator and rotor resistive losses. The term $i^t[L]$ pi denotes the rate of change of stored magnetic energy. The air gap power, is given by the term $i^t[G]w_r i$. The air gap power is the product of the mechanical rotor speed and air gap or electromagnetic torque. Hence, the air gap torque, *T*e, is derived from the terms involving the rotor speed, w_m, in mechanical rad/s, as

$$W_m T_e = P_a = i^t[G]\, i\, w_r$$
$$= i^t\,[G]\, i\, [P/2]\, w_m \qquad (x)$$

Where, P is the number of poles.

Cancelling speed on both sides of the equation leads to an electromagnetic torque that is

$$T_e = (P/2)\, i^t[G]\, i \qquad (xi)$$

Substituting [*G*] in Equ.(xi), the electromagnetic torque is obtained as

$$T_e = (3/2)(P/2)[\lambda_{af} + (L_d - L_q) i^r_{dr}]\, i^r_{qr} \text{ (N.m)} \qquad (xii)$$

IV. SIMULATION OF VECTOR CONTROL

The block diagram of simulation is as below

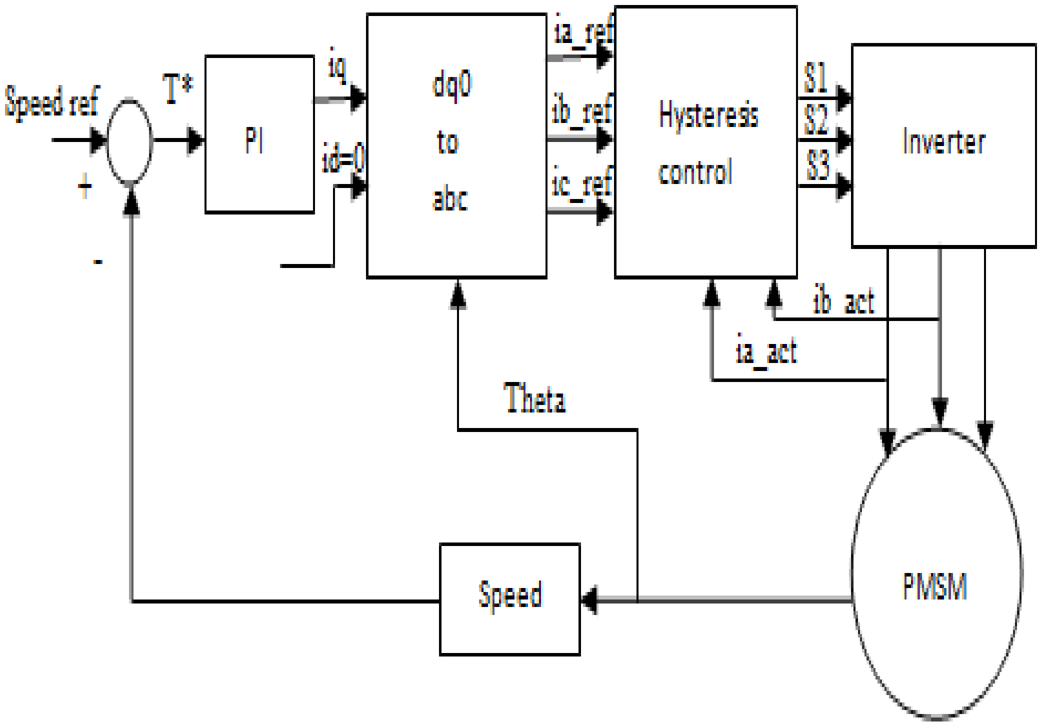

Figure 2. Block diagram of closed loop speed control of PMSM

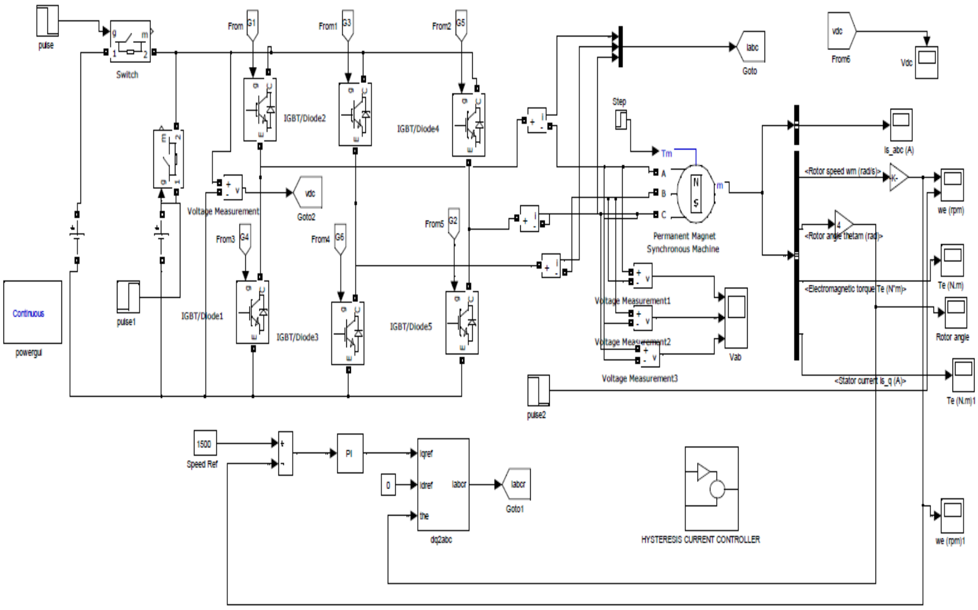

Figure 3. Simulation of Vector Control of PMSM

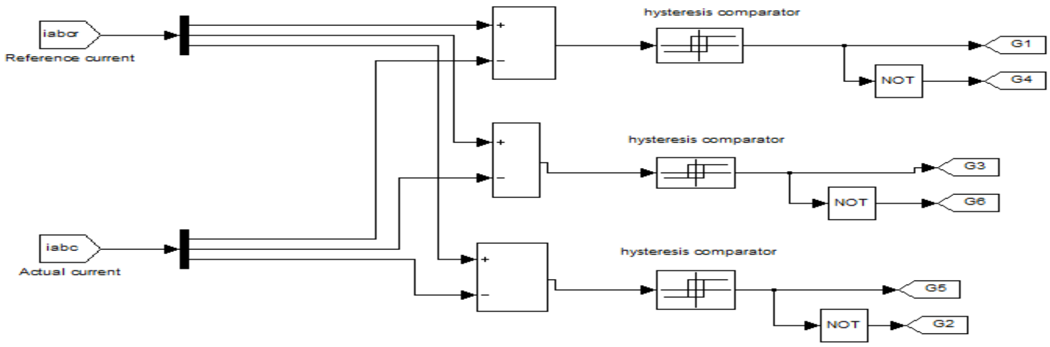

Figure 4. Subsystem of hysteresis current controller

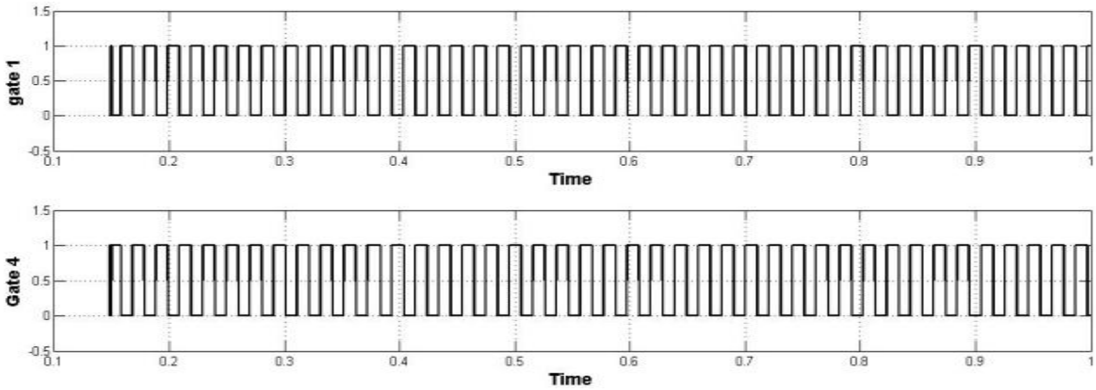

Figure 5. Gate pulses

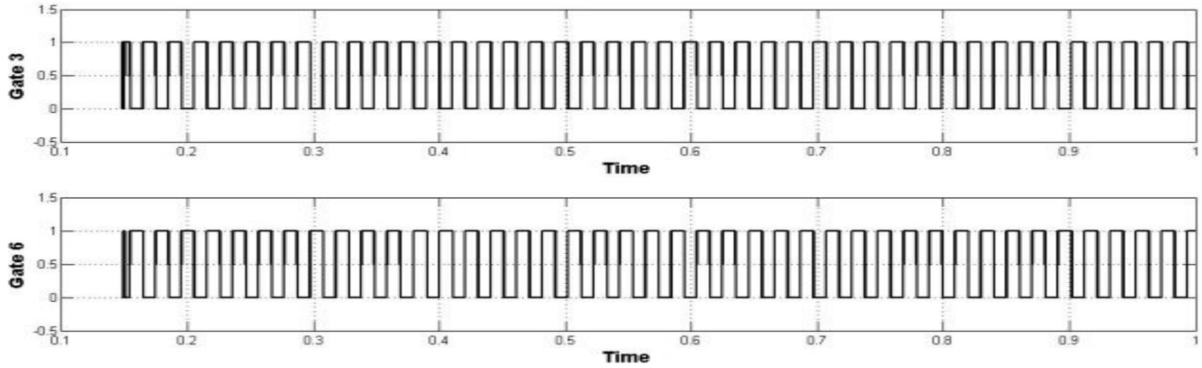

Figure 6. Gate pulses

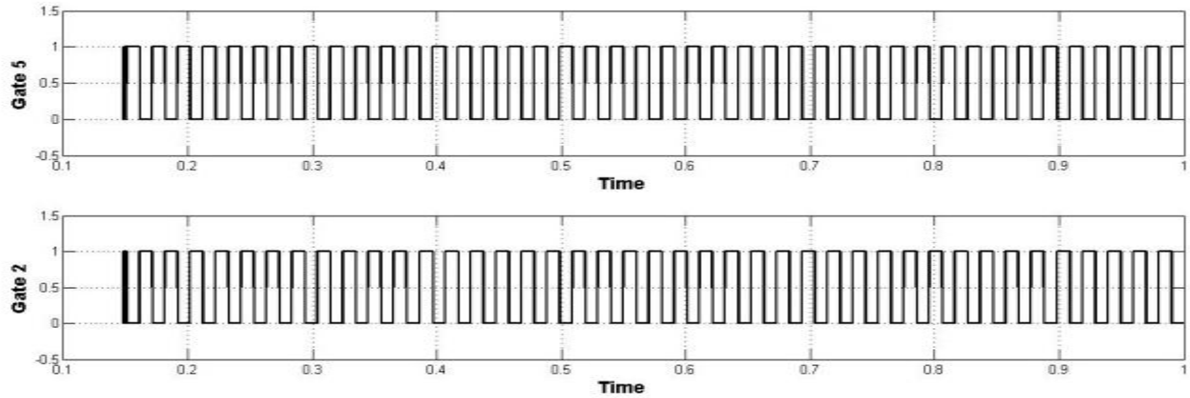

Figure 7. Gate pulses

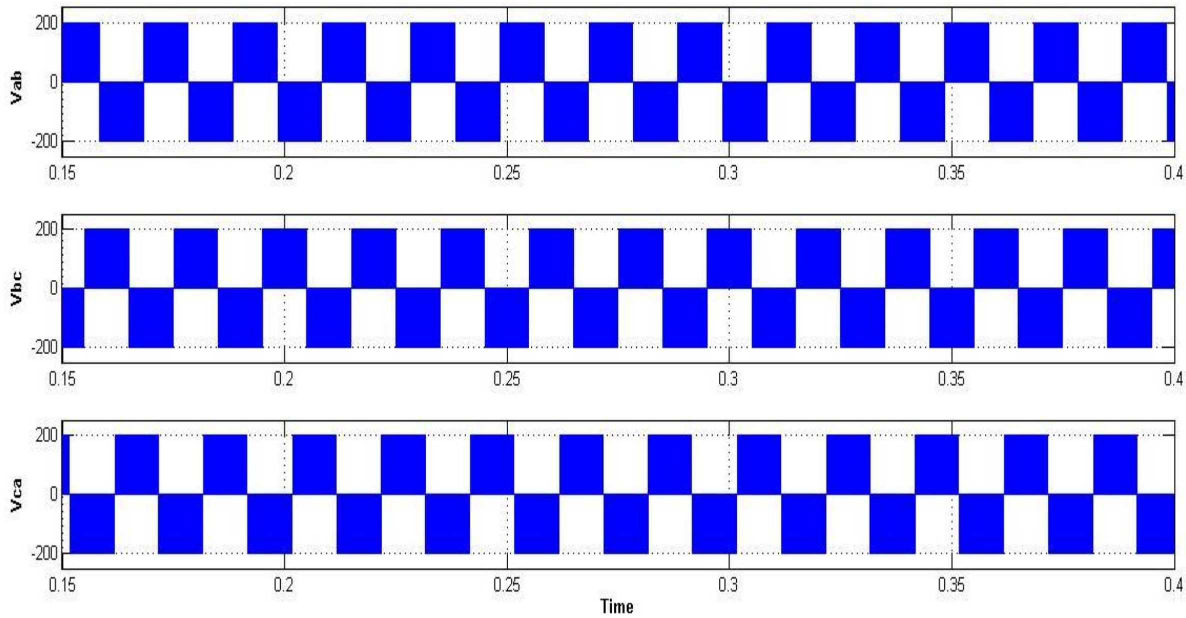

Figure 8. Phase Voltage

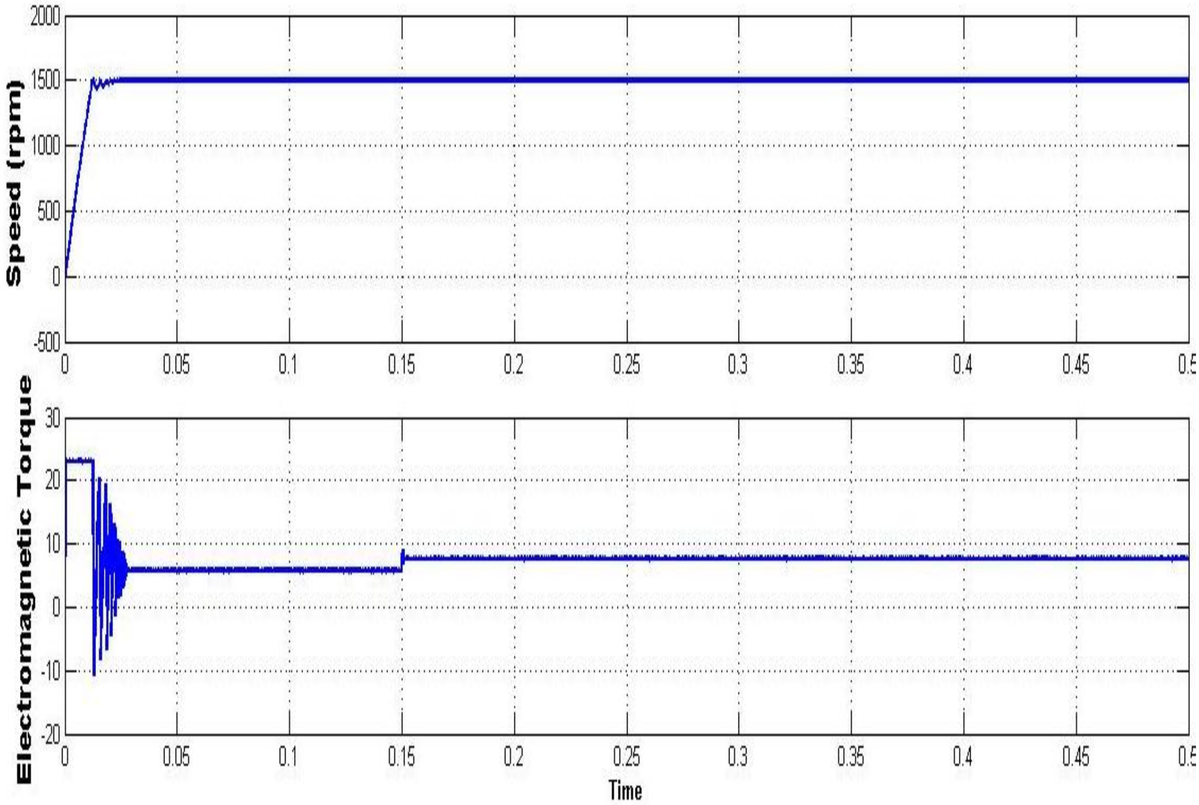

Figure 9. Speed and Electromagnetic Torque

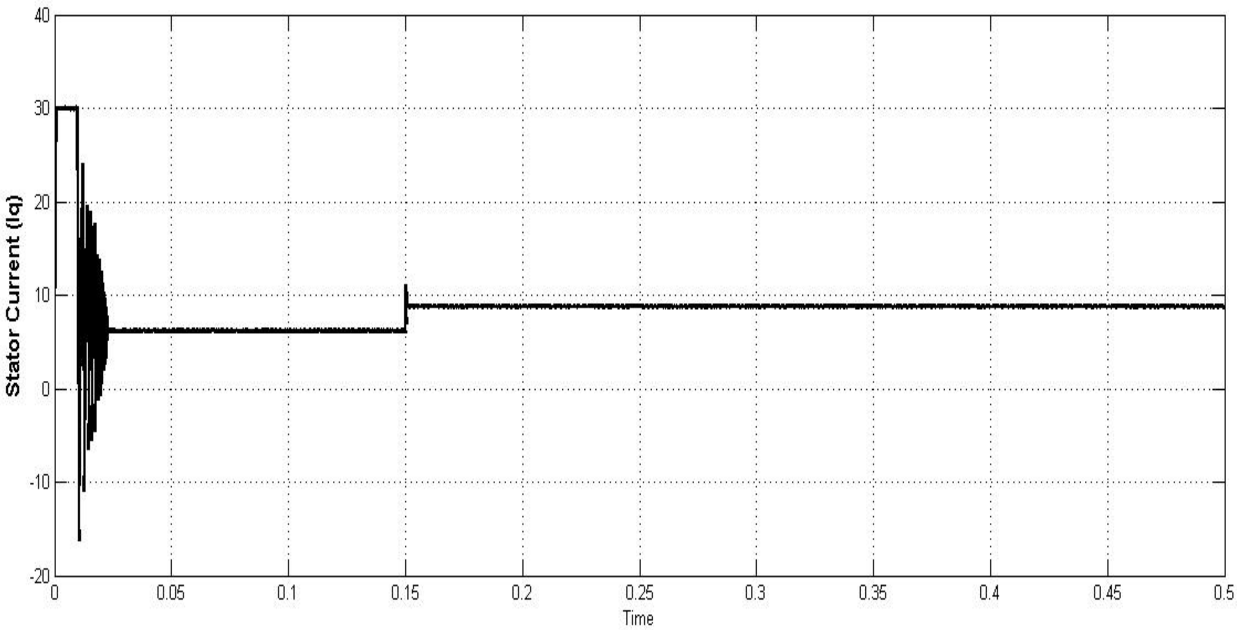

Figure 10. Quadrature axis Stator Current

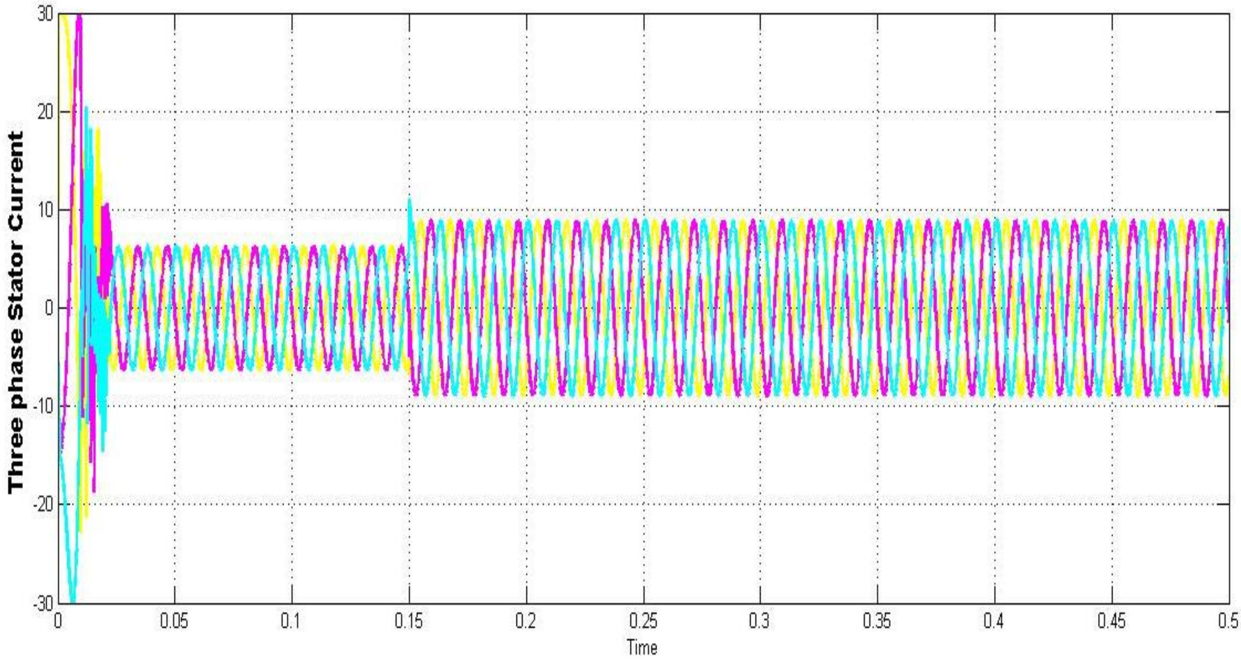

Figure 11. Three Phase Stator Current

For constant speed operation, the reference speed is set 1500 rpm. The simulation results of the developed model and the circuit simulation model respectively which includes, speed and torque response along the change in dc voltage. An advanced simulation model of closed loop PMSM drive system has been developed by utilizing the mathematical model of PMSM and hysteresis controlled three phase VSI inverter. The developed system simulation model has been validated by circuit simulation model of the same scheme which shows the accuracy of the developed model. This developed model can be well utilized in the design and development of closed loop PMSM drives system for experimenting with different control algorithms and topological variations but with a much reduced computational time and memory size.

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