Modeling and Analysis of Closed Loop PMSM Drive System

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Abstract

This paper presents a simulation model of Permanent Magnet Synchronous Motor (PMSM). A high voltage boost converter with a smooth 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 analysed for constant varied speed. 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; Smooth Control; Modeling; Closed Loop; Variable Speed, High Boost Converter.

I. Introduction

Earlier many DC drives were replaced by brushless AC drives. But now a day's PMSM has become the most used drive in machine tool servos and modern speed control applications. PMSM machine has high advantages like high efficiency, high power factor, high power density, easy maintenance, fast dynamic response In some cases due higher efficiency, high power density and high torque to inertia ratio PMSM replaces Induction motor (IM) and Synchronous motor (SM). Since PMSM rotor is made up of permanent magnet so there is no need of supplying magnetizing current through stator to produce air gap flux. DC excitation on the rotor, which is supplied by brushes and slip rings is required for SM which leads to rotor losses and requires regular maintenance. The variable speed and fast dynamic response drives in PMSM could be achieved by stator current control technique.

Since twenty years PMSM topic is quite interesting. One of the most common closed loop control technique used in a PMSM drive is Vector control technique. This Vector control techniques eliminates oscillating flux, torque responses in inverter fed induction motor and synchronous motor drives. This technique has different classification which includes as constant torque angle control, Unity power factor control, constant mutual air gap flux-linkages control, optimum-torque-per-ampere control and flux-weakening control. Mainly this depends on the type of application and the load characteristics.

An Appropriate control algorithm is necessary to perform a particular application for PMSM drive. To represent a complete drive system Incorporation of PMSM model along with the inverter model and load characteristics is essential. The simulation model for a complete PMSM drive is based on the mathematical model of an inverter fed PMSM is implemented using MATLAB\Simulink which can be
used for stimulating algorithms. Speed, torque, voltages and currents ofvoltage source inverters are the components that can be effectively monitored and analyzed.

II. Boost Converter
PROPOSED CONVERTER TOPOLOGY AND OPERATION ANALYSIS:
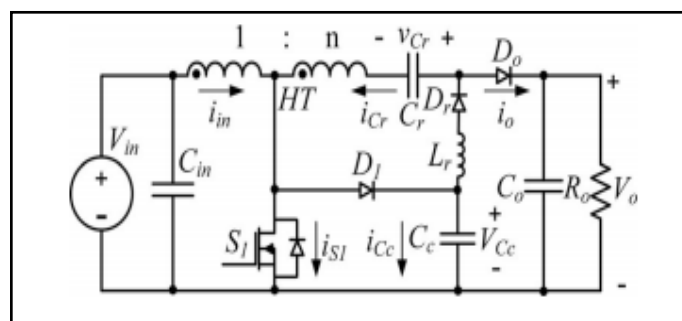
Proposed high step-up dc–dc converter with hybrid transformer

In this circuit diagram of the proposed converter.C_T is the input capacitor; H_T is the hybrid transformer with the turns ratio 1:n; S_1 is the active MOSFET switch; D_1 is the clamping diode, which provides a current path for the leakage inductance of the hybrid transformer when S_1 is OFF, C_c captures the leakage energy from the hybrid transformer and transfers it to the resonant capacitor C_r by means of a resonant circuit composed of C_c , C_r , L_r , and D_r; L_r is a resonant inductor, which operates in the resonant mode; and D_r is a diode used to provide an unidirectional current flow path for the operation of the resonant portion of the circuit. C_r is a resonant capacitor, which operates in the hybrid mode by having a resonant charge and linear discharge. The turn-on ofD_r is determined by the state of the active switch S_1. D_o is the output diode similar to the traditional coupled-inductor boost converter and Co is the output capacitor. R_o is the equivalent resistive load.

III. Closed Loop Speed Control of PMSM

Vector Control scheme for closed loop PMSM drive shown in Fig. The constant torque method of vector control scheme has been considered for analysis. In this method, the angle between the rotor field and stator current phasor is known as torque angle and is maintained at 90^0 so that flux is kept constant, then the torque is controlled by the stator current magnitude [1]. The machine, speed and position feedback, speed and current controllers, and inverter constitute the PMSM drive. The error between the reference and actual speed has given as the input to the speed controller, which generates the torque reference and is proportional to K_{iq}.

IV. Mathematical Model of PMSM

The Mathematical model of PMSM existing is represented in the following .The stator of the PMSM and the wound rotor synchronous motor are similar. The permanent magnets used in the PMSM are of a modern rare-earth variety with high resistivity, so induced currents in rotor are negligible. In addition, there is no difference between the back EMF produced by a permanent magnet and that produced by an excited coil. Hence the mathematical model of a PMSM is similar to that of the wound rotor SM. The rotor reference frame is chosen because the position of the rotor magnets determines the instantaneous induced emfs and subsequently the stator currents and torque of the machine independently of the stator voltages and currents. The following assumptions are considered in the derivation.

- Saturation and parameter changes are neglected
- Stator windings are balanced with the induced EMF is sinusoidal
- Eddy current and hysteresis losses are negligible
- There are no field current dynamics
- There is no cage on the rotor

The equivalent circuits of PMSM in d, q axes in rotor reference frame are shown in fig 1 and fig 2 respectively.
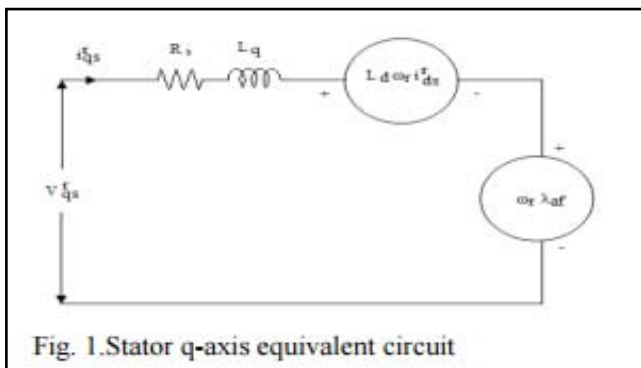

Fig. 1.Stator q-axis equivalent circuit

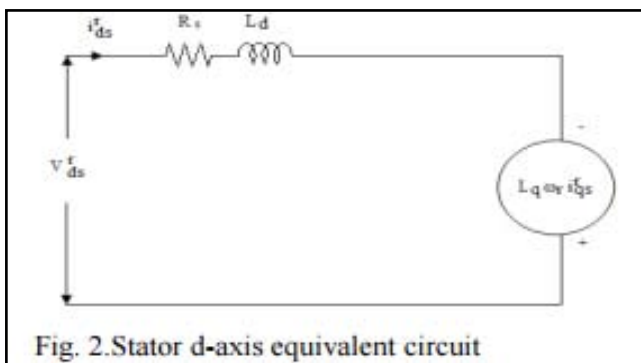

Fig. 2.Stator d-axis equivalent circuit

With these assumptions, the stator voltage d-q equations of the PMSM in the rotor reference frame are given by equations (1) and (2).

$$V_{qs} = R_s i_{qs} + p\lambda_{qs} + \omega_{ds} \tag{1}$$

$$V^r_{ds} = R_s i^r_{ds} + p\lambda^r_{ds} - \omega^r_{qs} \tag{2}$$

The stator flux linkages is given by equations (3) to(5)

$$\lambda^r_{qs} = L_q i^r_{qs} \tag{3}$$

$$\lambda^r_{ds} = L_d i^r_{ds} + L_m i_{fr} \tag{4}$$

$$L_m i_{fr} = \lambda_{af} \tag{5}$$

V^r_{qs} and V^r_{ds} are the d,q axes voltages,i^r_{qs} and i^r_{ds} are the d, q axes

stator currents in rotor reference frame, L_d and Lq are the d, q axis inductances and λ_d and λq are the d, q axis stator flux linkages in rotor reference frame, while Rs and ω_r are the stator resistance andinverterfrequency, respectively. λ_{af} is the flux linkage due to the rotormagnets linkingthestator.

Equations (6) and (7) is obtained by substitutingequations (3) to (5) in (1) and(2)

$$V^r_{qs} = R_s i^r_{qs} + p(L_q i^r_{qs}) + \omega_r(L_d i^r_{ds} + \lambda_{af}) \tag{6}$$

$$V_{ds} - R_s i^r_{ds} + P(L_d i^r_{ds}) - \omega r(L_q i^r_{qs}) \tag{7}$$

Equations (8) and (9) is obtained by rearranging equations (6) and (7) in matrixform

$$\begin{bmatrix} Vrqs \\ vrds \end{bmatrix} = \begin{bmatrix} Rs + pLq & \omega rLd \\ -\omega rLq & Rs + pLd \end{bmatrix} \begin{bmatrix} irqs \\ irds \end{bmatrix} + \begin{bmatrix} \omega r\lambda af \\ 0 \end{bmatrix} \tag{8}$$

The electromagnetic torque developed by the motor is given by equation (9)

$$T = \frac{3}{2}\frac{P}{2}\{\lambda^r_{ds} i^r_{qs} - \lambda^r_{qs} i_{rds}\} \tag{9}$$

The three phase stator voltage equations is given by equations (10) to (12)

$$V_{as} = V_m \sin\omega t \tag{10}$$

$$V_{bs} = V_m \sin (\omega t - 2\pi/3) \tag{11}$$

$$V_{cs} = V_m \sin (\omega t - 2\pi/3) \tag{12}$$

V_{as}, V_{bs}, V_{cs} are a-phase, b-phase and c-phase stator voltages respectively. V_m is the peak value of the stator voltage. ω is the synchronous speed in rad/sec. The stator voltages in the 'abc' axes V_{abc} is transferred to the d, q axes V_{qd0} by using park's transformation.

$$V_{qdos} = K_s V_{abcs} \tag{13}$$

The transformation matrix K_S is given by equation(14)

$$K_s = \frac{2}{3}\begin{bmatrix} cos\theta & cos\left(\theta - \frac{2\pi}{3}\right) & cos(\theta + 2\pi/3) \\ sin\theta & sin\left(\theta - \frac{2\pi}{3}\right) & sin(\theta + 2\pi/3) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \tag{14}$$

$$\begin{bmatrix} Vqs \\ Vds \\ vos \end{bmatrix} = \frac{2}{3}\begin{bmatrix} Cos\theta & cos(\theta - 2\pi/3) & cos(\theta + 2\pi/3) \\ sin\theta & sin(\theta - 2\pi/3) & sin(\theta + 2\pi/3) \\ 1/2 & 1/2 & 1/2 \end{bmatrix}\begin{bmatrix} Vas \\ Vbs \\ vcs \end{bmatrix} \tag{15}$$

θ is the rotor angle. Transformation of variables from stationary to synchronously rotating reference frame are given by equations (16) and (17)

$$V^e_{qs} = V_{qs}\cos\theta_c + V_{ds}\sin\theta_c \qquad (16)$$

$$V^e_{ds} = V_{ds}\cos\theta_e - V_{qs}\sin\theta_e \qquad (17)$$

The stator current equations in synchronously rotating reference frame are given by equations (18) and (19).

$$i^e_{qs} = \int \frac{\overline{veqs}}{Lq}_{Veds} - \frac{\omega e}{rs}\frac{\lambda af}{Lq} - \frac{Rs}{Lq}i^e_{qs} - \omega e i^e_{ds}\frac{Ld}{Lq} (18)$$

$$i^e_{ds} = \int \overline{Ld} - \overline{Lq}i^e_{ds} - \omega e i^e_{qs}\overline{Ld} (19)$$

V^e_{qs}, V^e_{ds} and i^e_{qs}, i^e_{ds} are q-axis and d-axis voltage and current in synchronously rotating reference frame respectively.

The expression for electromagnetic torque developed by the motor in terms of inductances and current are given by equation (20) as

$$T = 3/2\ P/2\ \{\lambda_{af}i^e_{qs} + (L_d - L_q)i^e_{qs}i^e_{ds}\} \qquad (20)$$

This equation relating the load torque and the electromagnetic torque is given by the equation (21)

$$T_e = T_L + B\omega_m + J\ (d_{\omega}m)/dt \qquad (21)$$

P is the number of pole pairs, T_L is the torque is damped coefficient, ωm is the rotor speed, and J is moment of inertia.

Rotor mechanical speed is given by equation (22)

$$\omega m = T\int Te - Tl - B\omega m \qquad (22)$$

Rotor electrical Speed ωe is given by equation (23)

$$\omega_{e = P/2}\omega_m \qquad (23)$$

Rotor angle θm is given by equation (24)

$$\theta_{m=}\int \omega_m \qquad (24)$$

angle between the rotor field and the stator current phasor is known as torque angle and is maintained at 90 0 so flux is kept constant, then the torque is controlled by the stator current magnitude(1). The machine, speed and position feedback, speed and current controllers and inverter constitute the PMSM drive. The error between the reference and actual speed has given as the input to the speed controller, which generates the torque reference and is proportional to $k_t i_q$.

The equation (20) by substituting id=0, equation (25) and (26) is obtained.

$$T = K_t i^e_{qs} \qquad (25)$$

$$K_t = \frac{3}{2}\frac{P}{2}\lambda_{af} \qquad (26)$$

The stator current i_{dqo} in dq-axis is transformed to 'abc' axis by inverse Parks Transformation given by equation

$$i_{abcs} = k^{-1}s_{iqd0s} \qquad (27)$$

$$K^{-1}_{s=}\frac{2}{3}\begin{bmatrix} cos\theta & sin\theta & 1/2 \\ \cos\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta - \frac{2\pi}{3}\right) & 1/2 \\ \cos\left(\theta + \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) & 1/2 \end{bmatrix}(28)$$

The reference current ias, ibs and ics are generated by substituting equation (28) in equation (27).

In the constant air gap flux mode of operation.kt is constant upto base speed and is equal to unity. Hence, the torque reference is directly proportional to iq, which is transformed to 'abc' axes by using inverse park's transformation given by equation (27). The 'dq0 to abc' transformation block shown in fig gives the stator reference current ia, ib and icin'abc' axes which is compared with the actual current and the current error is given to a hysteresis controller. The hysteresis current controller generates triggering pulses to the inverter in such a way that the actual current follows the reference current.
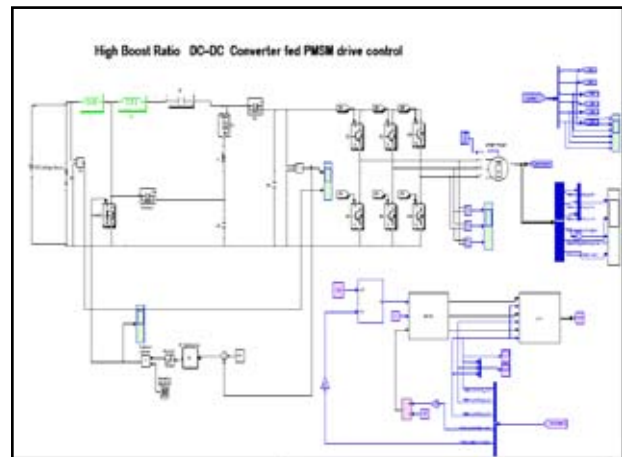
Block Diagram

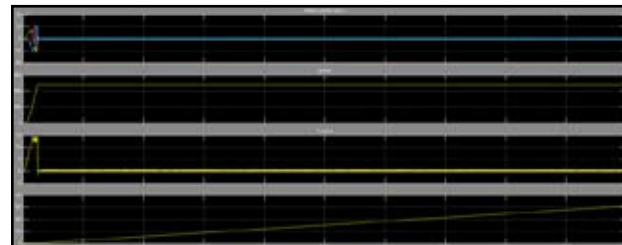Fig. 2: High boost dc dc converter with PMSM Control.
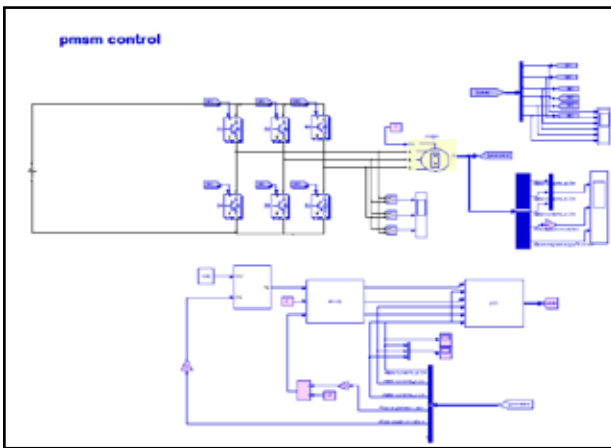

Fig.3 : Response of PMSM Control
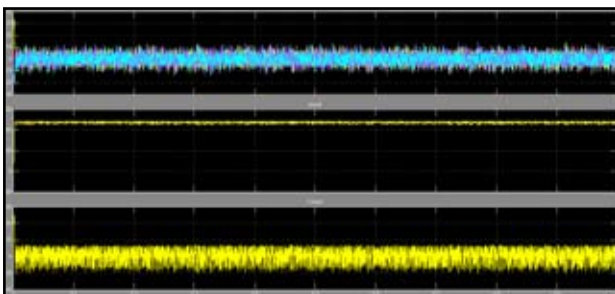
Fig. 4 :Speed control of PMSM

Fig.5 : Response of PMSM without High boost converter.

V. Conclusion

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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