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SPEED CONTROL OF PERMANENT MAGNET SYNCHRONOUS MOTOR USING VOLTAGE SOURCE INVERTER

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ABSTRACT

This paper presents the Permanent magnet (PM) synchronous motors are widely used in low and mid power applications such as computer peripheral equipment's, robotics, adjustable speed drives and electric vehicles. The growth in the market of PM motor drives has demanded the need of simulation tools capable of handling motor drive simulations. Simulations have helped the process of developing new systems including motor drives, by reducing cost and time. Simulation tools have the capabilities of performing dynamic simulations of motor drives in a visual environment so as to facilitate the development of new systems. In this work, the simulation of a field oriented controlled PM motor drive system 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. A closed loop control system with a PI controller in the speed loop has been designed to operate in constant torque and flux weakening regions. Implementation has been done in Simulink. A comparative study of hysteresis and PWM control schemes associated with current controllers has been made in terms of harmonic spectrum and total harmonic distortion. Simulation results are given for two speeds of operation, one below rated and another above rated speed.

Keywords: PMSM, VSI, PWM, PI

I . INTRODUCTION

PM motor drives have been a topic of interest for the last twenty years. Different authors have carried out modeling and simulation of such drives. In 1986 Sebastian, T., Slemon, G. R. and Rahman, M. A. [1] reviewed permanent magnet synchronous motor advancements and presented equivalent electric circuit models for such motors and compared computed parameters with measured parameters. Experimental results on laboratory motors were also given. In 1986 Jahns, T.M., Kilian, G.B. and Neumann, T.W. [2] discussed that interior permanent magnet (IPM) synchronous motors possessed special features for adjustable speed operation which distinguished them from other classes of ac machines. They were robust high-power density machines capable of operating at high motor and inverter efficiencies over wide speed ranges, including considerable range of constant power operation. The magnet

cost was minimized by the low magnet weight requirements of the IPM design. The impact of the buried magnet configuration on the motor's electromagnetic characteristics was discussed. The rotor magnetic saliency preferentially increased the quadrature-axis inductance and introduced a reluctance torque term into the IPM

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motor's torque equation. The electrical excitation requirements for the IPM synchronous motor were also discussed. The control of the sinusoidal phase currents in magnitude and phase angle with respect to the rotor orientation provided a means for achieving smooth responsive torque control. A basic feed forward algorithm for executing this type of current vector torque control was discussed, including the implications of current regulator saturation at high speeds. The key results were illustrated using a combination of simulation and prototype IPM drive measurements. In 1988 Pillay and Krishnan, R. [3], presented PM motor drives and classified them into two types such as permanent magnet synchronous motor drives (PMSM) and brushless dc motor (BDCM) drives. The PMSM has a sinusoidal back emf and requires sinusoidal stator currents to produce constant torque while the BDCM has a trapezoidal back emf and requires rectangular stator currents to produce constant torque. The PMSM is very similar to the wound rotor synchronous machine except that the PMSM that is used for servo

applications tends not to have any damper windings and excitation is provided by a permanent magnet instead of a field winding. Hence the d, q model of the PMSM can be derived from the well known model of the synchronous machine with the equations of the damper windings and field current dynamics removed. Equations of the PMSM are derived in rotor reference frame and the equivalent circuit is presented without dampers. The damper windings are not considered because the motor is designed to operate in a drive system with field-oriented control. Because of the nonsinusoidal variation of the mutual inductances between the stator and rotor in the BDCM, it is also shown in this paper that no particular advantage exists in transforming the abc equations of the BCDM to the d, q frame. As an extension of his previous work, Pillay, P. and Krishnan, R. in 1989 [4] presented the permanent magnet synchronous motor (PMSM) which was one of several types of permanent magnet ac motor drives available in the drives industry. The motor had a sinusoidal flux distribution. The application of vector control as well as complete modeling, simulation, and analysis of the drive system were given. State space models of the motor and speed controller and real time models of the inverter switches and vector controller were included. The machine model was derived for the PMSM from the wound rotor synchronous motor. All the equations were derived in rotor reference frame and the equivalent circuit was presented without dampers. The damper windings were not considered because the motor was designed to operate in a drive system with field-oriented control. Performance

differences due to the use of pulse width modulation (PWM) and hysteresis current controllers were examined. Particular attention was paid to the motor torque pulsations and speed response and experimental verification of the drive performance were given. Morimoto, S., Tong, Y., Takeda, Y. and Hirasa, T. in 1994 [5], in their paper aimed to improve efficiency in permanent magnet (PM) synchronous motor drives. The controllable electrical loss which consisted of the copper loss and the iron loss could be minimized by the optimal control of the armature current vector. The control algorithm of current vector minimizing the electrical loss was proposed and the optimal current vector could be decided according to the operating speed and the load conditions. The proposed control algorithm was applied to the experimental PM motor drive system, in which one digital signal processor was employed to execute the control algorithms, and several drive tests were carried out. The operating characteristics controlled by the loss minimization control algorithm were examined in detail by computer simulations and experimental results. The paper in 1997 by Wijenayake, A.H. and Schmidt, P.B. [6], described the development of a two-axis circuit model for permanent magnet synchronous motor (PMSM)

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by taking machine magnetic parameter variations and core loss into account. The circuit model was applied to both surface mounted magnet and interior permanent magnet rotor configurations. A method for on-line parameter identification scheme based on no-load parameters and saturation level, to improve the model, was discussed in detail. Test schemes to measure the equivalent circuit parameters, and to calculate saturation constants which govern the parameter variations were also presented.

II. PERMANENT MAGNET SYNCHRONOUS MOTOR DRIVE SYSTEM

The motor drive consists of four main components, the PM motor, inverter, controlunit and the position sensor. The components are connected as shown in figure 1.1

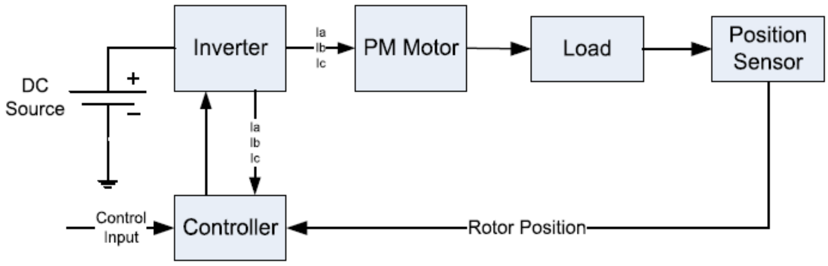

Fig 1.Drive System Schematic

III. CURRENT CONTROL

The power converter in a high-performance motor drive used in motion control essentially functions as a power amplifier, reproducing the low power level control signals generated in the field orientation controller at power levels appropriate for the driven machine. High-performance drives utilize control strategies which develop command signals for the AC machine currents. The basic reason for the selection of current as the controlled variable is the same as for the DC machine; the stator dynamics (effects of stator resistance, stator inductance, and induced EMF) are eliminated. Thus, to the extent that the current regulator functions as an ideal current supply, the order of the system under control is reduced and the complexity of the controller can be significantly simplified.Current regulators for AC drives are complex because an AC current regulator must control both the amplitude and phase of the stator current. The AC drive current regulator forms the inner loop of the overall motion controller. As such, it must have the widest bandwidth in the system and must, by necessity, have zero or nearly zero steady-state error. Both current source inverters (CSI) and voltage source inverters (VSI) can be operated in controlled current modes. The current source inverter is a "natural" current supply and can readily be adapted to controlled current operation. The voltage source inverter requires more complexity in the current regulator but offers much higher bandwidth and elimination of current harmonics as compared to the CSI and is almost exclusively used for motion control applications. Current controllers can be classified into two groups, hysteresis and PWM current controllers.

IV. PWM CURRENT CONTROLLER

PWM current controllers are widely used. The switching frequency is usually kept constant. They are based in the principle of comparing a triangular carrier wave of desire switching frequency and is compared with error of the controlled signal. The error signal comes from the sum of the reference signal generated in the controller and

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the negative of the actual motor current. The comparison will result in a voltage control signal that goes to the gates of the voltage source inverter to generate the desire output. Its control will respond according to the error. If the error command is greater than the triangle waveform, the inverter leg is held switched to the positive polarity (upper switch on). When the error command is less than the triangle waveform, the inverter leg is switched to the negative polarity (lower switch on). This will generate a PWM signal like in figure 3.3. The inverter leg is forced to switch at the frequency of the triangle wave and produces an output voltage proportional to the current error command. The nature of the controlled output current consists of a reproduction of the reference current with high-frequency PWM ripple superimposed.

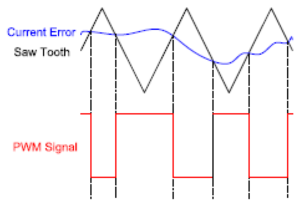

Fig 2. PWM Current Controller

V. MODELLING OF PM DRIVE SYSTEM

This deals with the detailed modeling of a permanent magnet synchronous motor. Field oriented control of the motor in constant torque and flux-weakening regions are discussed. Closed loop control of the motor is developed using a PI controller in the speed loop.

VI. DETAILED MODELING OF PMSM

Detailed modeling 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 4.1. At any time t, the rotating rotor d-axis makes and angle θr 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.

Voltage equations are given by:

$$V_q = R_s i_q + \omega_r \lambda_d + \rho \lambda_q$$

$$V_d = R_s i_d - \omega_r \lambda_q + \rho \lambda_d$$

Flux Linkages are given by

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$$\lambda_q = L_q i_q$$

$$\lambda_d = L_d i_d + \lambda_f$$

Substituting equations

$$V_q = R_s i_q + \omega_r \left(L_d i_d + \lambda_f \right) + \rho L_q i_q$$

$$V_d = R_s i_d - \omega_r L_q i_q + \rho \left(L_d i_d + \lambda_f \right)$$

Arranging equations in matrix form

$$\begin{pmatrix} V_q \\ V_d \end{pmatrix} = \begin{pmatrix} R_s + \rho L_q & \omega_r L_d \\ -\omega_r L_q & R_s + \rho L_d \end{pmatrix} \begin{pmatrix} i_q \\ i_d \end{pmatrix} + \begin{pmatrix} \omega_r \lambda_f \\ \rho \lambda_f \end{pmatrix}$$

The developed torque motor is being given by

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

The Mechanical Torque equation is

$$T_e = T_L + B\omega_m + J\frac{d\omega_m}{dt}$$

Solving for the rotor mechanical speed from equations

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

$$\omega_m = \omega_r \left(\frac{2}{P}\right)$$

In the above equations ωr is the rotor electrical speed where as ωm is the rotor mechanical speed.

VII. EQUIVALENT CIRCUIT OF PERMANENT MAGNET SYNCHRONOUS MOTOR

Equivalent circuits of the motors are used for study and simulation of motors. From the d-q modeling of the motor using the stator voltage equations the equivalent circuit of the motor can be derived. Assuming rotor d axis flux from the permanent magnets is represented by a constant current source as described in the following equation

λ f = Ldmif

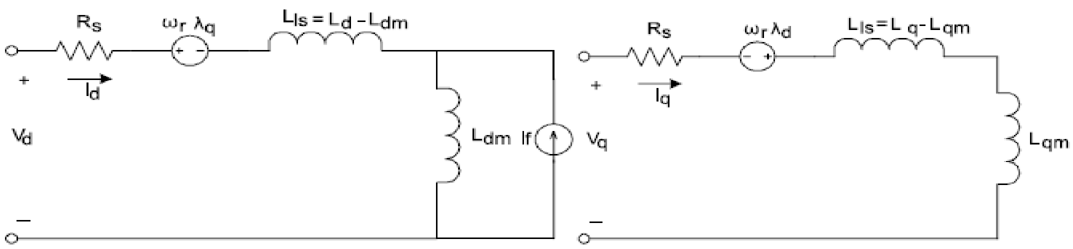

Fig 3. Permanent Magnet Motor Electric Circuit without Damper Windings

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VIII. SPEED CONTROL OF PM MOTOR

Many applications, such as robotics and factory automation, require precise control of speed and position. Speed Control Systems allow one to easily set and adjust the speed of a motor. The control system consists of a speed feedback system, a motor, an inverter, a controller and a speed setting device. A properly designed feedback controller makes the system insensible to disturbance and changes of the parameters. The purpose of a motor speed controller is to take a signal representing the demanded speed, and to drive a motor at that speed. Closed Loop speed control systems have fast response, but become expensive due to the need of feed back components such as speed sensors.

IX. IMPLEMENTATION OF THE SPEED CONTROL LOOP

For a PM motor drive system with a full speed range the system will consist of a motor, an inverter, a controller (constant torque and flux weakening operation, generation of reference currents and PI controller)

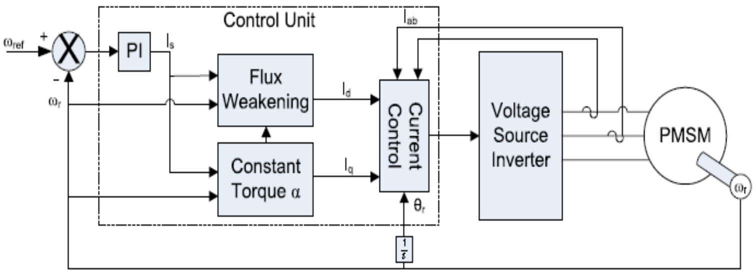

Fig 4. Block Diagram

The operation of the controller must be according to the speed range. For operation up to rated speed it will operate in constant torque region and for speeds above rated speed it will operate in flux-weakening region. In this region the d-axis flux and the developed torque are reduced. The process can be easily understood with the flow diagram .

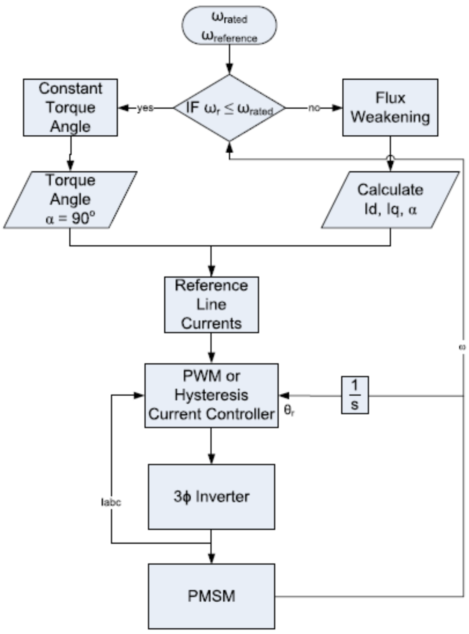

Fig5. System Flow Diagram

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Simulation Model

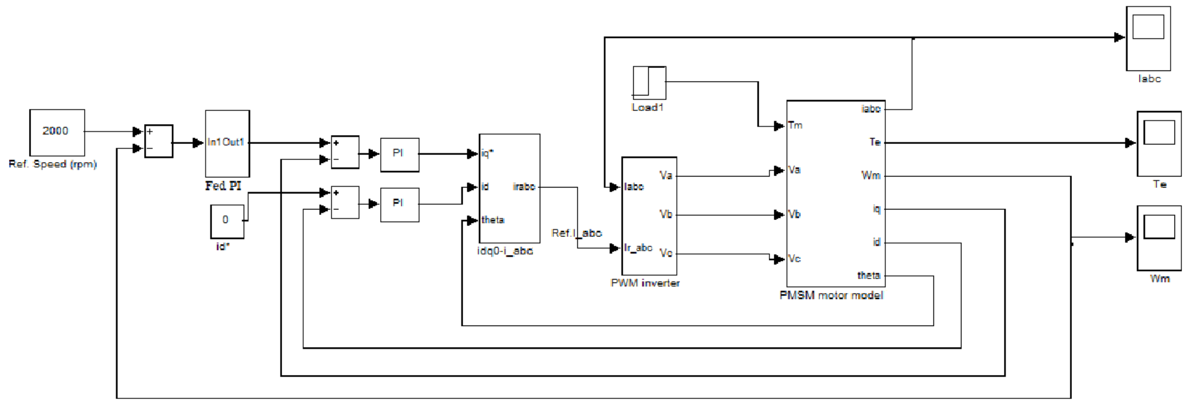

Fig 6. Simulation Model of PMSM Drive System

II.SIMULATION RESULTS

The simulation model of PMSM drive system using Fed PI controller has been developed in MATLAB environment with Simulink. The speed, torque and current responses are observed under various operating conditions such as change in reference speed, step change in load, parameter variations etc., and some of the sample results are presented in this paper. The parameters of PMSM used in this simulation model are,

Stator Resistance Rs = 1.4 ohm

Direct axis inductance Ld = 6.6 mH

Quadrature axis inductance Lq = 3.8 mH

Moment of Inertia J = 0.00176 Kg.m2

Rotor flux linkage _f = 0.1546 Wb

Number of poles P = 6

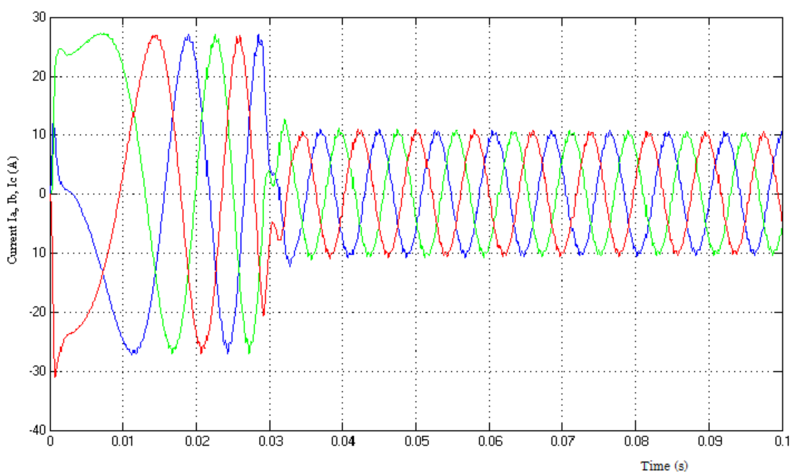

Fig 7. Three Phase Current Waveforms of Fed PI controller

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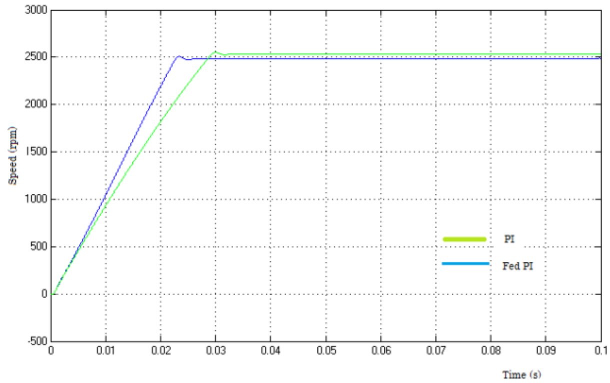

Fig 9. Comparison of Speed for PI and Fed PI controller

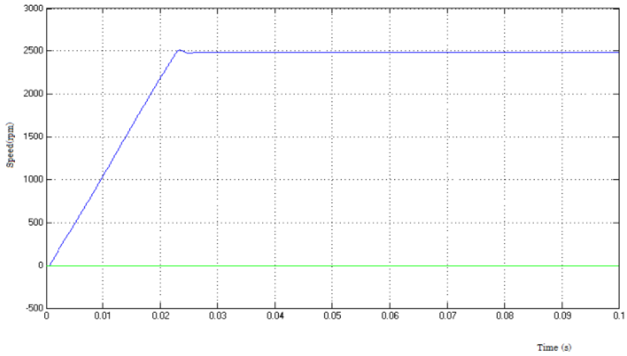

Fig 8. Speed Response of Fed PI controller

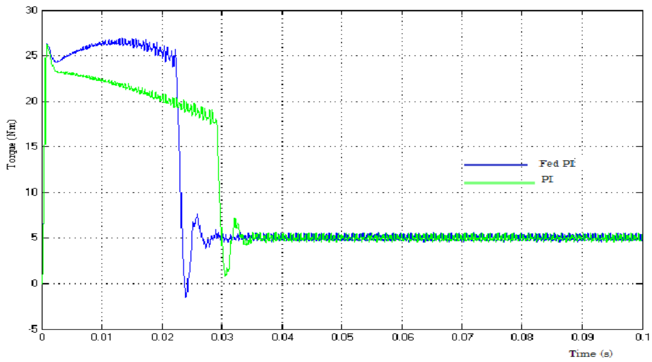

Fig 10. Comparison of Torque for PI and Fed PI controller

III. CONCLUSION

This paper has presented the mathematical modelling for analysis of PMSM drive system and implemented using

MATLAB/Simulink. The proposed Fed PI control technique is implemented to control the PMSM drive system based on current hysteresis PWM. The performance differences due to both conventional PI controller and Fed PI controller are examined for torque, speed and current. The Fed PI controller is used as speed controller in PMSM control system according to the speed error. The simulation results show that Fed PI controller have shorter regulating time and simple structure with quick tracking performance.

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