Performance Analysis and Simulation of Inverter-fed A Permanent Magnet Synchronous Motor Drive

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ABSTRACT

The purpose of this work was to research, design, simulate and implement the detailed modeling of a permanent magnet synchronous motor drive system. As a result of this comprehensive analysis, the Field Oriented Controller was selected as the most feasible design option. The performance of this control algorithm was thoroughly tested using the dynamic system modeling package Simulink. This enables the calculation electrical quantities in different parts of the inverter and motor under transient and steady conditions. The losses in different parts are calculated, facilitating the design of the inverter. A closed loop control system with a Proportional Integral (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 Pulse Width Modulation (PWM) control schemes associated with current controllers has been made in terms of harmonic spectrum and total harmonic distortion. Simulation results are given for different speeds of operation.

INTRODUCTION

In recent years, Permanent Magnet Synchronous Motors (PMSM) are increasing applied in several areas such as traction, automobiles, robotics and aerospace technology (A. B. Dehkordi, 2005). Accurate digital simulation tools are necessary to evaluate their field performance particularly when they are driven with solid state drives connected to larger electrical networks. One of the areas of interest is the design of controllers for these motor drives. In many applications the physical controls must be designed and tuned for best performance. If the simulation of the motor and drive can be implemented in real time, it becomes possible to interface the physical manufacturer-built controller (not its model) and protection equipment to the simulation using appropriate converters. Traditionally transient simulation programs use the dq0based modeling method to model different types of machines and the machines are interfaced to the network. The machine is modeled as a set of time-variant mutual inductances. Themachines are compared in the transient and steady states situations.

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.

It is now recognized that the two high-performance control strategies for PMSM are field-oriented control (FOC) and direct torque control (DTC). They have been invented respectively in the 70’s and in the 80’s. These control strategies are different on the operation principle but their objectives are the same. They aim both to control effectively the motor torque and flux in order to force the motor to accurately track the command trajectory regardless of the machine and load parameter variation or any extraneous disturbances. Both control strategies have been successfully implemented in industrial products. The supporters of field-oriented control
and direct torque control claim the superiority of their strategy versus the other. Up to now, the question has not been clearly answered. (M. S. Merzoug, and F. Naceri, 2008).

PMSM with FOC emulates the separately excited DC motor. In this method of control, the stator current can be decoupled into flux and torque current components. They can be controlled separately. In four quadrants with keeping magnetic circuit linear, under perfect field orientation, with constant flux operation, applying the principles operation of the FOC, the linear relation can be described the motor torque. However, the control performance of PMSM drive is still influenced by uncertainties, which usually are composed of unpredictable plant parameter variations, external load disturbances and nonlinear dynamics of the plant and harmonics in both motor and inverter. These problems shaped difficult in getting robust control. (Hamdy and Hakim, 2012)

1.1 Previous work:

(Onge, C in 1998) explained the need for powerful computation tools to solve complex models of motor drives. Among the different simulation tools available for dynamic simulation he had chosen MATLAB/SIMULINK® as the platform for his work because of the short learning curve required to start using it, its wide distribution, and its general-purpose nature.

(Domenico Casadei in 2002) Using Field-oriented control and direct torque control for induction motors torque control. This paper is aimed to give a contribution for a detailed comparison between the two control techniques, emphasizing advantages and disadvantages. The performance of the two control schemes is evaluated in terms of torque and current ripple, and transient response to step variations of the torque command. The analysis has been carried out on the basis of the results obtained by numerical simulations, where secondary effects introduced by hardware implementation are not present.

( demo circuit 2005) Simulink PM Synchronous Motor Drive used the AC6 block of SimPower Systems library. It modeled a permanent magnet synchronous motor drive with a braking chopper. The PM synchronous motor was fed by a PWM voltage source inverter, which was built using a Universal Bridge Block. The speed control loop used a PI regulator to produce the flux and torque references for the vector control block. The vector control block computed the three reference motor line currents corresponding to the flux and torque references and then fed the motor with these currents using a three-phase current regulator. Motor current, speed, and torque signals were available at the output of the block.

Several papers have been published on FOC and DTC in the last 30 years, but only few of them was aimed to emphasize differences, advantages and disadvantages. The name direct torque control is derived by the fact that, on the basis of the errors between the reference and the estimated

(M. S. Merzoug, and F. Naceri, 2008) presents a comparative study on two most popular control strategies for Permanent Magnet Synchronous Motor (PMSM) drives: field-oriented control (FOC) and direct torque control (DTC). The comparison is based on various criteria including basic control characteristics, dynamic performance, and implementation complexity. The study is done by simulation using the Simulink Power System Blockset that allows a complete representation of the power section (inverter and PMSM) and the control system. The simulation and evaluation of both control strategies are performed using actual parameters of Permanent Magnet Synchronous Motor fed by an IGBT PWM inverter.

(Hamdy M S, S.M.EL. Hakim, in 2012) presents adaptive hysteresis current controller to control the inverter. It is used to reduce the ripple, total harmonic distortion and improvement the switching frequency through design of PI current controller. The performance of the drive system due to improvement in the hysteresis current controller is simulated through the matlab/simulink. The modified hysteresis current controller is compared to conventional hysteresis controller under steady state and transient conditions with fixed load, sudden applied and sudden removal load to show the effectiveness of this modification.

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 electrical quantities 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 different speeds of operation.

1.2 The PMSM Model:

A. Structure of the Permanent Magnet Machine: The cross-sectional layout of a surface mounted permanent magnet motor is shown in Figure 1.
Fig. 1: Structure of the permanent magnet synchronous machine

The stator carries a three-phase winding, which produces a near sinusoidal distribution of magneto motive force based on the value of the stator current. The magnets are mounted on the surface of the motor core. They have the same role as the field winding in a synchronous machine except their magnetic field is constant and there is no control on it. In this work, Permanent Magnet Synchronous Machine (PMSM) block assumes a linear magnetic circuit with no saturation of the stator and rotor iron. This assumption can be made because of the large air gap usually found in permanent magnet synchronous machines.

B. Equivalent dq0 model of the PM machine:

The dq0 equivalent circuit of the PM machine shown in Fig. 2 is similar to the one for the synchronous machine; it has the armature resistance \( R_s \), d and q axis leakage and mutual inductances \( L_s \), \( L_{md} \) and \( L_{mq} \).

The rotor magnet can be considered as a loop of constant current source, \( i_m \), located at the stator direct axis. Any change in the magnetic flux of the rotor magnet will cause an induced electromagnetic force, resulting in a circulating current in the magnet. Essentially, resistance \( R_m \) connected across the direct-axis magnetization inductance \( L_{md} \) shows this effect. There is no leakage inductance in the field. The permeability of the magnet material is almost unity so the air gap inductance seen by the stator is the same in direct and quadrature axes and also no saturation will happen inside the machine. Fig. 3 shows the demagnetization curve of the magnet that can be divided into three regions by three lines, called no load, rated-load, and excessive-load lines. (A. B. Dehkordi, 2005)
We always try to not enter the excessive load region; otherwise the magnet is in danger of being damaged. The equations for the dq model of the Permanent Magnet Synchronous Machine are (P.M. Anderson and A.A. Fouad, 1994)

\[
\begin{align*}
\frac{d\Psi_d}{dt} &= V_d - R_i d - \alpha \Psi_d \\
\frac{d\Psi_f}{dt} &= -R_m i_m - R_m i_f \\
\frac{d\Psi_q}{dt} &= V_q - R_q i_q + \alpha \Psi_q
\end{align*}
\]  

(1)

The magnet is modeled by a current source \(i_m\) parallel to the resistance \(R_m\). This part of the circuit can be modeled as a Thevenin equivalent circuit, so that the direct axis equivalent circuit of the machine will be the circuit shown in Fig. 4.

\[
\begin{bmatrix}
\Psi_d \\
\Psi_f \\
\Psi_q
\end{bmatrix} = 
\begin{bmatrix}
L_s + L_m & L_m & 0 \\
L_m & L_m & 0 \\
0 & 0 & L_s + L_m
\end{bmatrix}
\begin{bmatrix}
i_d \\
i_f \\
i_q
\end{bmatrix}
\]  

(2)

The mechanical Torque equation is

\[
T_e = T_L + B_0 \omega_m + J \left\{ \frac{d \omega_m}{dt} \right\}
\]

(4)

Solving for the rotor mechanical speed form equation (4)
\[ \omega_m = \int \left( \frac{T_e - TL - B \omega_m}{J} \right) dt \]  
\[ \omega_m = \omega_r \]  

In the above equations \(\omega_r\) is the rotor electrical speed where as \(\omega_m\) is the rotor mechanical speed.

### 3.1.1 Parks Transformation and Dynamic d q Modeling:

The dynamic d q modeling is used for the study of motor during transient and steady state. It is done by converting the three phase voltages and currents to d q o variables by using Parks transformation. Converting the phase voltages variables \(v_{abc}\) to \(v_{dqo}\) variables in rotor reference frame and visa versa the following equations are obtained which are the same transformation matrix for the currents. (B. K. Bose, 2002.)

\[
\begin{pmatrix}
v_q \\
v_d \\
v_o
\end{pmatrix} = \frac{2}{3}
\begin{pmatrix}
\cos \theta & \cos \left( \theta - \frac{2\pi}{3} \right) & \cos \left( \theta - \frac{4\pi}{3} \right) \\
\sin \theta & \sin \left( \theta - \frac{2\pi}{3} \right) & \sin \left( \theta - \frac{4\pi}{3} \right)
\end{pmatrix}
\begin{pmatrix}
v_a \\
v_b \\
v_c
\end{pmatrix}
\]

\[ (7) \]

\[
\begin{pmatrix}
v_a \\
v_b \\
v_c
\end{pmatrix} = \frac{1}{2}
\begin{pmatrix}
\cos \theta & \sin \theta & 1 \\
\cos \left( \theta - \frac{2\pi}{3} \right) & \sin \left( \theta - \frac{2\pi}{3} \right) & 1 \\
\cos \left( \theta - \frac{4\pi}{3} \right) & \sin \left( \theta - \frac{4\pi}{3} \right) & 1
\end{pmatrix}
\begin{pmatrix}
v_q \\
v_d \\
v_o
\end{pmatrix}
\]

\[ (8) \]

### 2.2 PMSM Motor Drives:

Power electronic devices known as motor drives are used to operate AC motors at frequencies other than that of the supply. These consist of two main sections, a controller to set the operating frequency and a three phase inverter to generate the required sinusoidal three phase system from a DC voltage. 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.

### 2.3 Three Phase Voltage Source Inverter:

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. Current controllers are used to generate gate signals for the inverter. Proper selection of the inverter devices and selection of the control technique will guarantee the efficacy of the drive. The most common three phase inverter topology is that of a switch mode voltage source inverter. This generates an AC voltage from a DC voltage source when a Pulse Width Modulated waveform is used to switch the MOSFETs in each of the three converter legs. Although the power flow through the device is reversible, it is called an inverter because the predominant power flow is from the DC bus to the three phase AC motor load. Bi-directional power flow is an important feature for motor drives as it allows regenerative breaking i.e. the kinetic energy of the motor and its load is recovered and returned to the grid when the motor slows down. In an AC grid connected motor drive, a second converter is required between the drive and the utility grid, which acts as a rectifier during the motoring mode and an inverter during the breaking mode. An additional benefit is unity power factor (sinusoidal) current flows to or from the grid. In an electric vehicle application, the energy for the DC bus is supplied directly from the batteries, or primary energy source. (B. K. Bose, 1987) and (B. K. Bose, 1992.)

### 3. Pulse Width Modulation:

Although the basic MOSFET circuitry for an inverter may seem simple, accurately switching these devices provides a number of challenges for the power electronics engineer. The devices list with their respective power switching capabilities are shown in table 3.1 MOSFETs and IGBTs are preferred by industry because of the MOS gating permits high power gain and control advantages. MOSFET is considered a universal power device for low power and highswitching speed applications. The power devices when used in motor drives applications require an inductive motor current path provided by antiparallel diodes when the switch is turned off. Inverters with antiparallel diodes are shown in figure 4.

Table 3.1: Devices Power and Switching Capabilities

<table>
<thead>
<tr>
<th>Device</th>
<th>Power Capability</th>
<th>Switching Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>BJT</td>
<td>Medium Medium</td>
<td></td>
</tr>
<tr>
<td>GTO</td>
<td>High Low</td>
<td></td>
</tr>
<tr>
<td>IGBT</td>
<td>Medium Medium</td>
<td></td>
</tr>
<tr>
<td>MOSFET</td>
<td>Low High</td>
<td></td>
</tr>
<tr>
<td>THYRISTOR</td>
<td>High Low</td>
<td></td>
</tr>
</tbody>
</table>
The most common switching technique is called Pulse Width Modulation (PWM) which involves applying voltages to the gates of the six MOSFETS at different times for varying durations to produce the desired output waveform. In Figure 4, $T_a$ to $T_c$ represents the six MOSFETS. Each switching leg may consist of more than two MOSFETs in order to reduce switching losses by paralleling the on resistance.

![Fig.4:Basic Three Phase Voltage Source Inverter.](image)

In the following equations the control signals are represented by logic values that are equal to 1 when the MOSFET is on and 0 when it is off. In PM motor control when the upper MOSFET is switched on i.e. $a,b,c$ is 1 the corresponding lower MOSFET is switched off i.e. $a',b',c' = 0$. Using complementary signals to drive the upper and lower MOSFETS prevents vertical conduction providing that the control signals don’t overlap. From the states of $a,b,c$ the phase voltages connected to the motor winding can be calculated using the following matrix representation:

### 3.1 Sine-Triangle PWM of Three Phase Inverters:

One commonly used PWM scheme is called carrier based modulation. This uses a carrier frequency usually between 10 to 20 kHz to produce positive and negative pulses of varying frequency and varying width [B.K. Bose 1992]. The pulse widths and spacing’s are arranged so that their weighted average produces a sine wave. Increasing the number of pulse per half cycle reduces the frequency of the output sine wave whilst, increasing the pulse widths increases the amplitude.

In sine-triangle PWM a triangular carrier waveform of frequency $f_s$ shown in figure 5 establishes the inverter switching frequency. This is compared with three sinusoidal control voltages that comprise the three phase system. The output of the comparators produces the switching scheme used to turn particular inverter MOSFETS on or off. These three control voltages have the same frequency as the desired output sine wave which, is commonly referred to as the modulating frequency, $f_1$. The modulation ratio is equal to $mf = f_1/f_s$.

One limitation of the sine triangle method is that it only allows for a limited modulation index, so it doesn’t fully use the DC bus. The modulation index can be increased by using distorted wave forms that contain only triple harmonics. These form zero sequence systems where the harmonics cancel out resulting in no iron losses.( K Rajashekara, A Kawamura, 1996)

![Fig.5:Single Phase Sine-Triangle Modulation](image)

### 4. A Field Oriented Controller Block Diagram:

The key component of the FOC strategy is the Clarke and Park transform blocks. As can be seen in Figure 6 these map the three phase stator currents onto a direct and quadrature rotating reference frame that is aligned with the rotor flux. This decouples the torque and flux producing components of the stator currents allowing the PM motor to be controlled in much the same was as a separately excited DC machine. The d-axis component of the stator current is related to the rotor flux magnitude via the torque is related to the q axis component of the stator current. The PI regulator compares the speed set point with the measured mechanical speed of the rotor and produces the stator current quadrature axis reference, isqref. The stator current direct axis reference isidref is usually kept constant at the value required to produce the nominal rotor flux.(H. L. Huy, 1999). To operate the
motor above its nominal speed a technique known as Field Weakening is used to reduce the rotor flux. Field Weakening is a technique used to operate a motor above its nominal speed. This requires precise control over rotor flux which makes it an ideal candidate for use with FOC. At and below the rated speed the rotor flux is maintained at its nominal value to achieve the maximum level of torque production. Above nominal speed the back EMF generated by the motor is large enough given DC bus limitations to limit the phase currents. This causes magnetic saturation and heat dissipation that reduces torque production and drive efficiency. By reducing the rotor flux the high efficiency operating range of the drive can be extended beyond the nominal speed. This approach is called Field Weakening and allows the motor speed to be quadrupled under certain operating conditions. The reference currents are compared with the measured stator currents.

Fig. 6: System configuration of field-oriented PMSM

4. Simulation and Result:
SIMULINK® is a toolbox extension of the MATLAB program. It is a program for simulating dynamic systems [C.-m. Ong, 1998]. Simulink has the advantages of being capable of complex dynamic system simulations, graphical environment with visual real-time programming and broad selection of tool boxes [R. E. Araujo, A. V. Leite, and D. S. Freitas, 1997]. The simulation environment of Simulink has a high flexibility and expandability which allows the possibility of development of a set of functions for a detailed analysis of the electrical drive. Its graphical interface allows selection of functional blocks, their placement on a worksheet, selection of their functional parameters interactively, and description of signal flow by connecting their data lines using a mouse device. System blocks are constructed of lower level blocks grouped into a single maskable block. Simulink simulates analogue systems and discrete digital systems.

The PMSM motor drive simulation was built in several steps like abc phase transformation to dqo variables, the PM synchronous motor is fed by a PWM voltage source inverter, which is built using a Universal Bridge Block. The speed control loop uses a PI regulator to produce the flux and torque references for the vector
control block. The vector control block computes the three reference motor line currents corresponding to the
flux and torque references and then feeds the motor with these currents using a three-phase current regulator.
Calculation torque and speed, and control circuit. Using all the drive system blocks, the complete system block
has been developed as shown in figure 7.

Set the simulation parameters as follows:

- Type: Fixed-step
- Integrator type: Runge-Kutta, ode4
- Sample time: 5e-6 (set automatically by the Model properties)
- Stop time: 0.2

Run the simulation to observe the motor's torque, speed, and currents.

A. Starting of the machine at load:

Figure 8 illustrates the simulation results of technical command FOC hysteresis, where to apply a torque
load equal to 5N.m at t = 0s with a reference speed equal to 1000 rpm. It is noted that the FOC hysteresis
presents a peak torque at startup, and a torque of quick response due to application of the load which allows the
rapid rejection of the disturbance. At speed, we can see that the FOC has a medium dynamic without overshoot,
start-up, and the response time are reduced. For the answer stator flux, it reaches its reference value with
overrun at startup. The torque climbs to nearly 35 N.m when the motor starts and stabilizes rapidly when the
motor reaches the reference value. The controller reacts rapidly and increases the DC voltage from rectifier
circuit to produce the required electric torque.

B. Test of Reference Speed Change:

To test the robustness of technical command at speed variation of the Machine, it introduced a change in
record speed reference 3000 rpm to 1000 rpm at time t=0.1s with a torque load equal to 3 N.m. In Figure 9, we
can say that the continuation in speed is normally and without overrun for technical commands (FOC). It notes
that the FOC hysteresis presents a peak torque.

C. Test for Load Change:

Figure 10 represents speed, torque and stator current of the machine in case of load torque change, at a level
of speed equal to 3000 rpm. At the moment t = 0.1s applies a load torque equal to 5N.m, then at t = 0.15s
applying a load torque equal to 0N.m, we find that the torque responds instantly, and that its speed reaches
reference after a small deformation reaches its reference after a small deformity in the case of FOC. Observe the
saw tooth shape of the currents waveforms. This is caused by the six-step controller, which applies a constant
voltage value during 120 electrical degrees to the motor. The initial current is high and decreases during the
acceleration to the nominal speed. When the nominal torque is applied, the stator current increases to maintain
the nominal speed. The saw tooth waveform is also observed in the electromotive torque signal Te. However,
the motor's inertia prevents this noise from appearing in the motor's speed waveform.

Harmonic contents in phase currents are determined using Fast Fourier Transform (FFT). The results are
given below PWM mode of current control. These results are obtained using Simulink FFT tool of Powergui
to display the frequency spectrum current waveforms and THD content. IEEE Standard 519-1992 provides a
guideline for the acceptable levels of voltage distortion to loads (including motors). A broad recommendation is
to establish the voltage distortion monitoring limits at 5% THD and at 3% for any particular harmonic
frequency. Figure 11 shows the phase current waveform with PWM control and the corresponding harmonic
spectrum. The value of THD is 0.13%.
Fig. 7: Entire Simulink Model For PMSM with FOC Controller

Fig. 8: Response of PMSM in case of starting with 5 N.m load.
Fig. 9: Regulation of reference speed between 3000 rpm-1000 rpm with 3 N.m l
Fig. 10: Response at the variation of torque load
Conclusion:
In this paper, main characteristics of field-oriented control scheme for PMSM drives are studied by simulation with a view to highlighting the advantages and disadvantages of this approach. It is difficult to clearly state on the superiority of FOC versus other method because of the balance of the merits of the schemes. We can conclude that the vector order it better adapted (load variation). The initial current is high and decreases during the acceleration to the nominal speed. When the nominal torque is applied, the stator current increases to maintain the nominal speed. The saw tooth waveform is also observed in the electromotive torque signal \( T_e \). However, the motor's inertia prevents this noise from appearing in the motor's speed waveform. A speed controller has been designed successfully for closed loop operation of the PMSM drive system so that the motor runs at the commanded or reference speed. The simulated system has a fast response with practically zero steady state error thus validating the design method of the speed controller.

Good simulation results have been obtained from the model with two-time step. To simulate a digital controller device, the control system has two different sampling times:

- Speed controller sampling time
- FOC sampling time

The speed controller sampling time has to be a multiple of the FOC sampling time. The latter sampling time has to be a multiple of the simulation time step. The average-value inverter allows the use of bigger simulation time steps since it does not generate small time constants (due to the RC snubbers) inherent to the detailed converter. For an FOC sampling time of 60 µs, good simulation results have been obtained for a simulation time step of 60 µs. This time step can, of course, not be higher than the FOC time step.

REFERENCES


Matlab-Works-Support, "PM Synchronous Motor Drive."