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Brief Analysis and Field Oriented Control of Permanent Magnet Synchronous Motor Drive

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Abstract

Permanent magnet synchronous motors (PMSM) have several advantages over dc motor and induction motors. The development of ASIC and advanced VLSI technologies compact size and high efficiency of PMSM made it a suitable for applications where cost of drive is justified by high performance. PMSM drive is usually used in application where high precision and high performance is compulsory. In this paper a brief analysis of PMSM including magnetic materials used for permanent magnet, classification of PM motors, mathematical modelling and control is discussed. Field oriented control (FOC) of PMSM is presented to achieve the performance of PMSM similar to dc machine for adjustable speed drive application. By using FOC torque and speed of motor can controlled separately. The performance of PMSM drive with FOC is implemented and verified through simulations. Simulation results presented for various reference speed and load torque values.

Keywords - Mathematical model, PI controller, SVM, PMSM, Vector Control.

Introduction

PMSM is being increasingly used because of their advantages over other machines, which include compactness, high efficiency, and well developed drives (Rahman *et al*., 1996; Rahman *et al*., 1980). For many decades, dc motors, particularly separately excited dc motors, have been used extensively for variable speed and high performance drive systems, because it can be controlled in a simple way due to the decoupled nature of its field and armature (Slemon *et al*., 1989). However, the dc motor has some disadvantages, which include limited range of speed operation, lack of overload capability, robustness, frequent maintenance requirement as well as high cost due to brush-gear, and commutators and power loss in the field circuit. Due to these drawbacks of dc motors, researchers have developed ac motors such as induction and synchronous motors to use for high performance variable speed drives, where robustness and maintenance free operations are the main concern (Slemon *et al*., 1989). The advantages of PMSM over dc motor are as follows.

- Less audible noise
- Longer life
- Spark less (no fire hazard)

- Higher speed
- Higher power density and smaller size
- Better heat transfer

The ac motors are suitable for constant speed operation, but due to recent development of power electronic devices, very large scale integrated (VLSI) technologies and efficient use of microprocessors, ac motors can also be used for variable speed drives. The ac motors can be used for high performance drive systems using closed loop vector control techniques(Rahman *et al*., 1996). Among the ac motors, induction motors (IM) have been widely used and considered as a workhorse in the industry because of their good efficiency, low cost, reliability and ruggedness (Rahman *et al*., 1980; Tesla *et al*., 1888; Slemon *et al*., 1989). However, there are some limitations of the induction motor. One of the limitations is that it always runs at a lagging power factor because the rotor field voltage is induced from the stator side(Krause *et al*., 2002). Another limitation is that the IM drive system is not highly efficient due to slip power loss. As the IM runs at a speed always less than the synchronous speed, the control of these motors is very complex (Vas *et al*., 1998). Moreover, the real time implementation of these motor drives needs accurate estimation of motor parameters and sophisticated modeling with complex control circuitry. The advantages of PMSM over IM are as follows.

- Higher efficiency
- Higher power factor
- Higher power density for lower than 10 kW applications, resulting in smaller size
- Better heat transfer

Due to the above mentioned limitations, researchers have looked into the synchronous motors for easier control in high performance variable speed drives (Rahman *et al*., 1996; Tesla *et al*., 1888; Bolognani *et al*., 2001; Rahman *et al*.,1979; Erdelyi *et al*.,1996; Schiferl *et al*.,1990). The advantages of synchronous motors over the induction motors which are as follows 1) as the synchronous motor runs at synchronous speed, its control is less complex 2) no slip power loss. However, the conventional wire wound excited synchronous motors have some drawbacks such as the requirement of extra power supply, slip ring and brush gears at the rotor side to supply the dc field excitation (Hancock *et al*., 1974). Due to the limitations of the conventional wire-wound synchronous motors, more recently different kinds of special motors have been developed. Among them, the permanent magnet (PM) motor is becoming popular due to some of its advantageous features, which include high torque to current ratio as well as high power to weight ratio, high efficiency, low noise and robustness. Unlike in the wire-wound synchronous motor, the excitation is provided by the permanent magnets in a PM synchronous motor. Thus, there is no need for any extra power supply or field windings. Hence, the cost is reduced and the power loss due to the excitation windings is eliminated.

Permanent magnets are the vital components of PM machines. Characteristics of permanent magnet materials provide a basis for appreciating the potential and limitation of PM machines (Rahman *et al*., 1985). The advantages of PM machines recently make them highly attractive candidates for "Direct Drive" applications, such as hybrid electrical vehicles (HEV) or electrical vehicles (EV) and washing machines. Various types of electric motors have been investigated for use in a Hybrid Electric Vehicles (HEV) system in the fields of output power, maximum speed, efficiency, manufacturing cost, and durability.

The popularity of PMSMs comes from their features: High efficiency, High torque to inertia ratio, High torque to volume ratio, High air gap flux density, High power factor, High acceleration and deceleration rates, Lower maintenance cost, Simplicity and ruggedness, Compact structure, Linear response in the effective input voltage.

A Permanent Magnet Synchronous Motor is a motor that uses permanent magnets to produce the air gap magnetic field rather than using electromagnets. These motors have significant advantages, attracting the interest of researchers and industry for use in many applications. The development in high energy permanent magnets like NdBFe PMSM is becoming more popular in adjustable speed drive applications.

Permanent Magnet Materials

The properties of the permanent magnet material will affect directly the performance of the motor and proper knowledge is required for the selection of the materials and for understanding PM motors (Rahman *et al*.,1980 ; Rahman *et al*., 1979; Parker *et al*., 1962). Table 1 shows the properties of some permanent magnet materials. B_r is residual flux density and H_c is the coercive force.

Table 1: Properties of permanent magnets

Material	B_r (T)	H_c (kA/m)	BHmax W (kJ/m^3)	Remark
Alnico	1.280	51	44	Brittle and hard to machine
Ferrites	0.385	235	28	Brittle and hard to machine
Mn-Al-C	0.560	239	61	Ductile, machinable
$SmCO_5$	0.87	637	146	Brittle and hard to machine
$Nd_{15}B_8Fe_{17}$	1.23	881	290	Machinable, 150°C limit

The earliest manufactured magnet materials were hardened steel. Magnets made from steel were easily magnetized. However, they could hold very low energy and it was easy to demagnetize. In recent years other magnet materials such as Aluminium Nickel and Cobalt alloys (ALNICO), Strontium Ferrite or Barium Ferrite (Ferrite), Samarium Cobalt (First generation rare earth magnet) (SmCo) and Neodymium Iron-Boron (Second generation rare earth magnet) (NdFeB) have been developed and used for making permanent magnets.

The rare earth magnets are categorized into two classes: Samarium Cobalt (SmCo) magnets and Neodymium Iron Boride (NdFeB) magnets. SmCo magnets have higher flux density levels but they are very expensive. NdFeB magnets are the most common rare earth magnets used in motors these days.

The PMSM rotate because of the magnetic attraction between the rotor and the stator poles. When the rotor poles are facing stator poles of the opposite polarity, a strong magnetic attraction is set up between them. The mutual attraction locks the rotor and the stator poles together and the rotor is literally yanked into step with the revolving stator magnetic field. At no-load conditions, rotor poles are directly opposite to the stator poles and their axes coincide. At load conditions the rotor poles lag behind the stator poles, but the rotor continues to turn at synchronous speed, the mechanical angle "θ" between the poles increases progressively as we increase the load.

Classification of PM Motors

Based on the different aspects PM motors can be classified in manner as shown in fig.1. They are classified on the basis of position and orientation of magnet, rotor cage winding, use of sensors and control strategies.

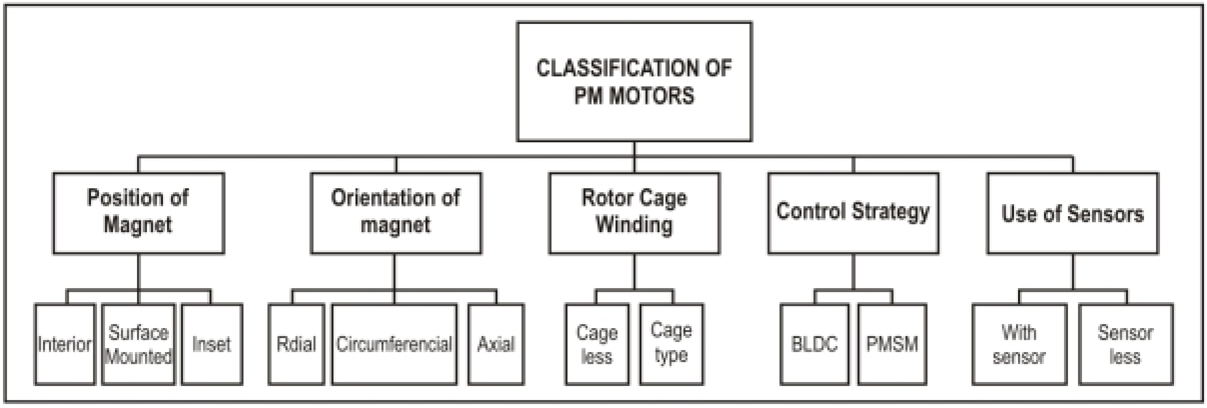
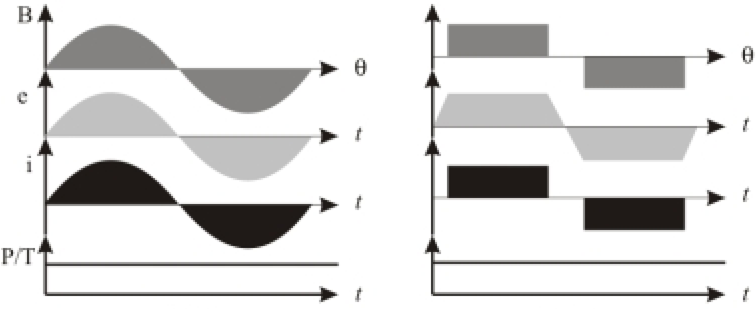


Figure 1: Classification of PM Motors

Each type of motors in above classification is having their own merits and demerits. Some of them which are commonly used are discussed here in detail. As classified above Based on the control strategy PM motors are classified as PMSM and BLDC. Figure 2 shows the flux, emf and current waveforms of PMSM and BLDC.



PMSM BLDC

Figure 2: Waveforms of PMSM and BLDC

Table 2: Comparison of PMSM and BLDC

PMSM	**BLDC**
Synchronous machine	Synchronous machine
Fed with sinusoidal currents	Fed with direct currents
Sinusoidal BEMF	Trapezoidal BEMF
Continuous stator flux position variation	Stator Flux position commutation each 60 degrees
Possible to have three phases ON at the same time	Only two phases ON at the same time

Depending on the placement of magnet they are called either as surface permanent magnet motor or interior permanent magnet motor. Surface mounted PM motors have a surface mounted permanent magnet rotor. Each of the PM is mounted on the surface of the rotor, making it easy to build, and specially skewed poles are easily magnetized on this surface mounted type to minimize cogging torque (Schiferl *et al.*,1990). This configuration is used for low speed applications because of the limitation that the magnets will be detached apart during high-speed operations. These motors are considered to have small saliency, thus having practically equal inductances in both axes .The permeability of the permanent magnet is almost that of the air, thus the magnetic material becoming an extension of the air gap. For a surface permanent magnet motor $L_d = L_q$. The rotor has an iron core that may be solid or may be made of punched laminations for simplicity in manufacturing. Thin permanent magnets are mounted on the surface of this core using adhesives. Figure. 3 (a) shows the placement of the magnet.

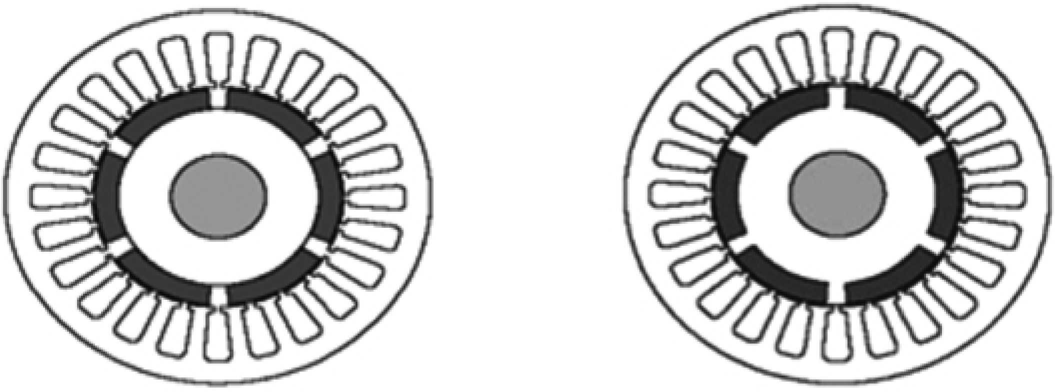


Figure 3: (a) Surface Permanent Magnet Motor (b) Interior Permanent Magnet Motor

Table 3: Comparison of surface and interior permanent magnet motor

Surface permanent magnet motor	**Interior Permanent Magnet Motor**
Salient	Non-salient
Direct and quadrature axis inductance are nearly equal	Variation in direct and quadrature axis inductance
Large air-gap	Small air-gap
Small saliency ratio	Large saliency ratio

Interior PM Motors have interior mounted permanent magnet rotor as shown in Fig. 3(b). Each permanent magnet is mounted inside the rotor. It is not as common as the surface mounted type but it is a good candidate for high-speed operation. There is inductance variation for this type of rotor because the permanent magnet part is equivalent to air in the magnetic circuit calculation. These motors are considered to have saliency with q axis inductance greater than the d axis inductance ($L_q > L_d$). For 3−5 kW, the values for the q-axis inductances were 10−20 % higher than the values in the d-direction. Table. 3 shows the properties of surface and interior permanent magnet synchronous motor.

Mathematical Modeling of PMSM

Detailed modelling of PM motor drive system is required for proper simulation of the system. The d-q model has been developed on rotor reference frame (Slemon *et al.*, 1989) as shown in Figure 4. 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.

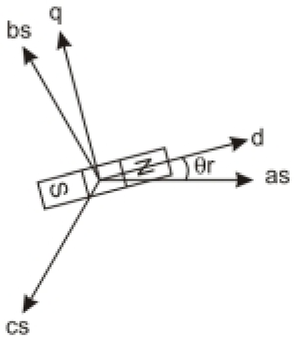


Figure 4: Motor Axis

The model of PMSM without damper winding has been developed on rotor reference frame using the following assumptions (Vas *et al*., 1998)

- Stator winding produce sinusoidal mmf distribution. Space harmonics in air-gaps are neglected.
- Stator winding produce sinusoidal mmf distribution. Space harmonics in air-gaps are neglected.
- Air -gap reluctance has a constant component as well as a sinusoidally varying component.
- Balanced three-phase supply voltage is considered
- Saturation is neglected although it can be taken into account by parameter changes.
- The back emf is sinusoidal.
- Eddy currents and hysteresis losses are negligible.

The stator flux-linkage equations are given by:

The equations of the permanent-magnet synchronous machine are (Vas *et al*., 1998).

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} . \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \lambda_a \\ \lambda_b \\ \lambda_c \end{bmatrix} \qquad \text{... (1)}$$

where va, vb, vc, and ia, ib, ic, and λa, λb, λc, are the stator phase voltages, currents, and flux linkages,respectively, and Rs, is the stator phase resistance. The flux linkages are further defined as

$$\begin{bmatrix} \lambda_a \\ \lambda_b \\ \lambda_c \end{bmatrix} = \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{cc} \end{bmatrix} . \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \lambda_{pm} \begin{bmatrix} \cos(\theta_r) \\ \cos\left(\theta_r - \frac{2\pi}{3}\right) \\ \cos\left(\theta_r + \frac{2\pi}{3}\right) \end{bmatrix} \qquad \text{... (2)}$$

Where θ_r is the rotor electrical angle, and λ_{pm} is a coefficient and defined as

$$\lambda_{pm} = \frac{60 \cdot V_{peak}/K_{rpm}}{\sqrt{3} \cdot \pi \cdot P \cdot 1000} \qquad \text{... (3)}$$

V_{peak} / K_{rpm} is line to line back emf constant in V / K_{rpm} (mechanical speed), and P is number of ploles.

The stator self and mutual inductances are rotor position dependent and are defined as

$$L_{aa} = L_{sl} + L_0 + L_2 \cdot cos(2\theta_r) \qquad \text{... (4)}$$

$$L_{bb} = L_{sl} + L_0 + L_2 \cdot cos\left(2\theta_r + \frac{2\pi}{3}\right) \qquad \text{... (5)}$$

$$L_{bb} = L_{sl} + L_0 + L_2 \cdot cos\left(2\theta_r - \frac{2\pi}{3}\right) \qquad \text{... (6)}$$

$$L_{ab} = L_{ba} = -\frac{L_0}{2} + L_0 + L_2 \cdot cos\left(2\theta_r - \frac{2\pi}{3}\right) \qquad \text{... (7)}$$

$$L_{ac} = L_{ca} = -\frac{L_0}{2} + L_0 + L_2 \cdot cos\left(2\theta_r + \frac{2\pi}{3}\right) \qquad \text{... (8)}$$

$$L_{bc} = L_{cb} = -\frac{L_0}{2} + L_0 + L_2 \cdot cos(2\theta_r) \qquad \text{... (9)}$$

Where L_{sl} is stator leakage inductance. L_0 and L_2 are the magnetizing inductance components of stator winding.

The developed torque can be expressed as

$$T_{em} = \frac{P}{2} \cdot L_2 \cdot [i_a \quad i_b \quad i_c] \cdot \begin{bmatrix} sin(2\theta_r) & sin\left(2\theta_r - \frac{2\pi}{3}\right) & sin\left(2\theta_r + \frac{2\pi}{3}\right) \\ sin\left(2\theta_r - \frac{2\pi}{3}\right) & sin\left(2\theta_r + \frac{2\pi}{3}\right) & sin(2\theta_r) \\ sin\left(2\theta_r + \frac{2\pi}{3}\right) & sin(2\theta_r) & sin\left(2\theta_r - \frac{2\pi}{3}\right) \end{bmatrix} \cdot \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} - \frac{P}{2} \cdot \lambda_{pm} \cdot [i_a \quad i_b \quad i_c] \cdot \begin{bmatrix} \sin(\theta_r) \\ \sin\left(\theta_r - \frac{2\pi}{3}\right) \\ \sin\left(\theta_r + \frac{2\pi}{3}\right) \end{bmatrix} \qquad \text{... (10)}$$

The d-axis and q-axis inductances are associated with above inductances are as follows

$$L_d = L_{sl} + \frac{3}{2}L_0 + \frac{3}{2}L_2 \qquad \text{... (11)}$$

$$L_q = L_{sl} + \frac{3}{2}L_0 - \frac{3}{2}L_2 \qquad \text{... (12)}$$

Using d-q transformation the voltage equations of PM machine in rotor reference frame are as follows

$$v_d = R_s \cdot i_d + \frac{d\lambda_d}{dt} - \omega_e\lambda_q \qquad \text{... (13)}$$

$$v_q = R_s \cdot i_q + \frac{d\lambda_q}{dt} + \omega_e\lambda_d \qquad \text{... (14)}$$

Where $\lambda_d = L_d \cdot i_d + \lambda_m$ and $\lambda_d = L_q \cdot i_q$ and stator flux linkage

$$\lambda_s = \sqrt{{\lambda_d}^2 + {\lambda_q}^2} \qquad \text{... (15)}$$

The equivalent circuit of PMSM based on above voltage equation is shown in fig 1.

The mechanical equations are given as

$$J \cdot \frac{d\omega_m}{dt} = T_{em} - B \cdot \omega_m - T_{laod} \qquad \text{... (16)}$$

$$\frac{d\theta_r}{dt} = \frac{P}{2} \cdot \omega_m \qquad \text{... (17)}$$

Where B is a coefficient and Tlaod is toad torque. The coefficient B is calculated from moment of inertia J and mechanical time constant τ_{mech} as

$$B = \frac{J}{\tau_{mech}} \qquad \text{... (18)}$$

Total input power to machine in terms of abc variable is

$$Power = v_a i_a + v_b i_b + v_c i_c \qquad \text{... (19)}$$

Power in terms of d, q variables

$$Power = \frac{3}{2}\left(v_d i_d + v_q i_q\right) \qquad \text{... (20)}$$

Then speed and torque generated by motor is are calculated as

$$T_e = P.\frac{3}{4}\left[i_q \lambda_m + i_d i_q\left(L_d - L_q\right)\right] \qquad \text{... (21)}$$

$$\omega_e = \frac{T_e - T_{load}}{J_s + B}.\left(\frac{P}{2}\right) \qquad \text{... (22)}$$

$$\theta = \int \omega_e \qquad \text{... (23)}$$

Transformations used in vector control are given as (Bose *et al*., 1988)

$$\begin{bmatrix} V_q \\ V_d \\ V_o \end{bmatrix} = \frac{2}{3}\begin{bmatrix} cos\theta_r & cos(\theta_r - 120) & cos(\theta_r + 120) \\ sin\theta_r & sin(\theta_r - 120) & sin(\theta_r + 120) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \qquad \text{... (24)}$$

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} cos\theta_r & sin\theta_r & 1 \\ cos(\theta_r - 120) & sin(\theta_r - 120) & 1 \\ cos(\theta_r + 120) & sin(\theta_r + 120) & 1 \end{bmatrix}\begin{bmatrix} V_q \\ V_d \\ V_o \end{bmatrix} \qquad \text{... (25)}$$

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 currents to dqo variables by using Parks transformation.

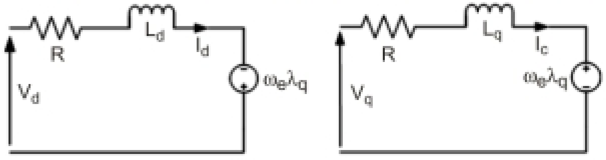
Converting the phase voltages variables V_{abc} to V_{dqo} variables in rotor reference frame the following equations are obtained

$$\begin{bmatrix} V_q \\ V_d \\ V_o \end{bmatrix} = \frac{2}{3}\begin{bmatrix} cos\theta_r & cos(\theta_r - 120) & cos(\theta_r + 120) \\ sin\theta_r & sin(\theta_r - 120) & sin(\theta_r + 120) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \qquad \text{... (26)}$$

Convert V_{dqo} to V_{abc}

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} cos\theta_r & sin\theta_r & 1 \\ cos(\theta_r - 120) & sin(\theta_r - 120) & 1 \\ cos(\theta_r + 120) & sin(\theta_r + 120) & 1 \end{bmatrix}\begin{bmatrix} V_q \\ V_d \\ V_o \end{bmatrix} \qquad \text{... (27)}$$

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. Based on the above voltage equations of PMSM in terms of dq variables equivalent circuit is obtained as shown on figure 5.



(a) d-axis equivalent circuit (b) q-axis equivalent circuit

Figure 5: Permanent Magnet Motor Equivalent Circuits without Damper Windings

PMSM Drive System

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 Fig. 6.

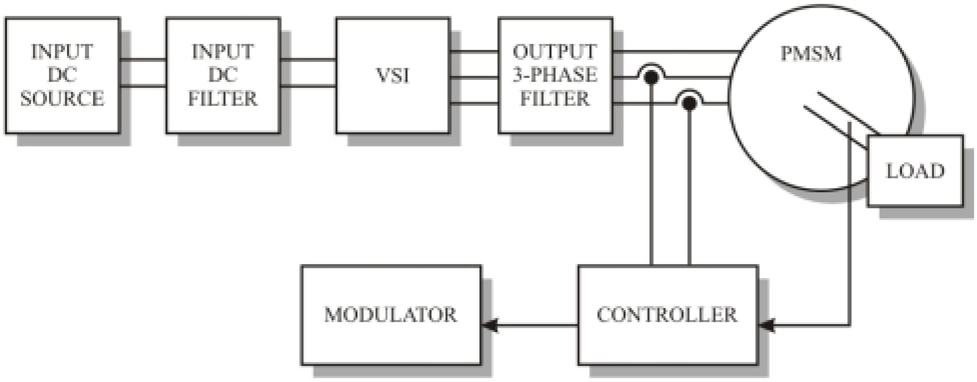


Figure 6: PMSM Drive System

PMSM

It is a motor that uses permanent magnets to produce the air gap magnetic field. The most commonly used magnetic materials are rare earth magnets such as NdFeB, SmCo, Strontium Ferrite or Barium ferrite etc.

Inverter

The stator windings of the motor are fed by an inverter that generates a variable frequency variable voltage.

Position sensor

Instead of controlling the inverter frequency independently, the frequency and phase of the output wave are controlled using a position sensor. These are mainly used for determining the position of the rotor. The most commonly used position sensors are encoders and resolvers. Depending on the application and performance desired by the motor a position sensor with the required accuracy can be selected.

Control unit

The control input and the rotor position signal is given to the controller and depending upon both the signals it will generate the output which is given to the inverter.

Control of PM motors is performed using field oriented control for the operation of synchronous motor as a DC motor. The stator windings of the motor are fed by an inverter that generates a variable frequency variable voltage. Instead of controlling the inverter frequency independently, the frequency and phase of the output wave are controlled using a position sensor (Rahman *et al*.,1996; Rahman *et al*., 1979; Jian-Xin *et al*., 2004; Pillay *et al*., 1989).

In order for the motor to behave like DC motor, the control needs knowledge of the position of the instantaneous rotor flux or rotor position of permanent magnet motor. This needs a resolver or an absolute optical encoder. Knowing the position, the three phase currents can be calculated. Its calculation using the current matrix depends on the control desired. Some control options are constant torque and flux weakening (Bolognani *et al*., 2001). These options are based in the physical limitation of the motor and the inverter. The limit is established by the rated speed of the motor, at which speed the constant torque operation finishes and the flux weakening starts as shown in Fig. 7.

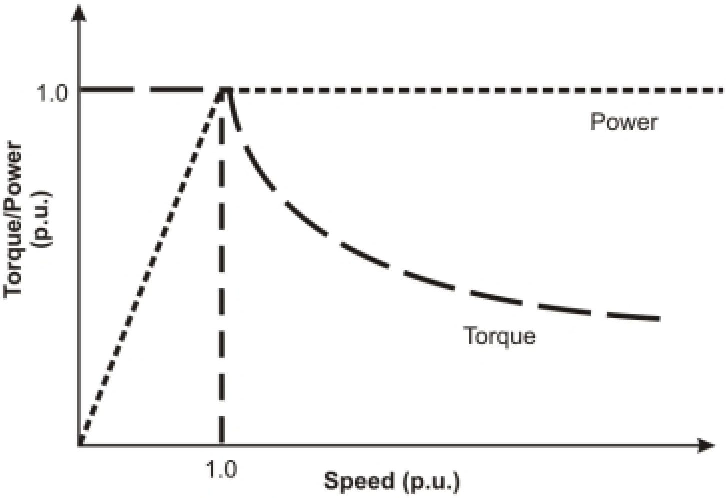


Figure 7: Steady State Torque versus Speed

Operation of permanent magnet synchronous motors requires position sensors in the rotor shaft when operated without damper winding. The need of knowing the rotor position requires the development of devices for position measurement. There are four main devices for the measurement of position, the potentiometer, linear variable differential transformer, optical encoder and resolvers. The ones most commonly used for motors are encoders and revolvers. Depending on the application and performance desired by the motor a position sensor with the required accuracy can be selected (Bose *et al*.,2002).

Position revolver also called rotary transformers works on the transformer principle as shown in figure 8. The primary winding is placed on the rotor and depending upon the rotor shaft angle the induced voltage at the two secondary windings of the transformer shifted by 90° would be different. The position can be calculated using the two voltages.

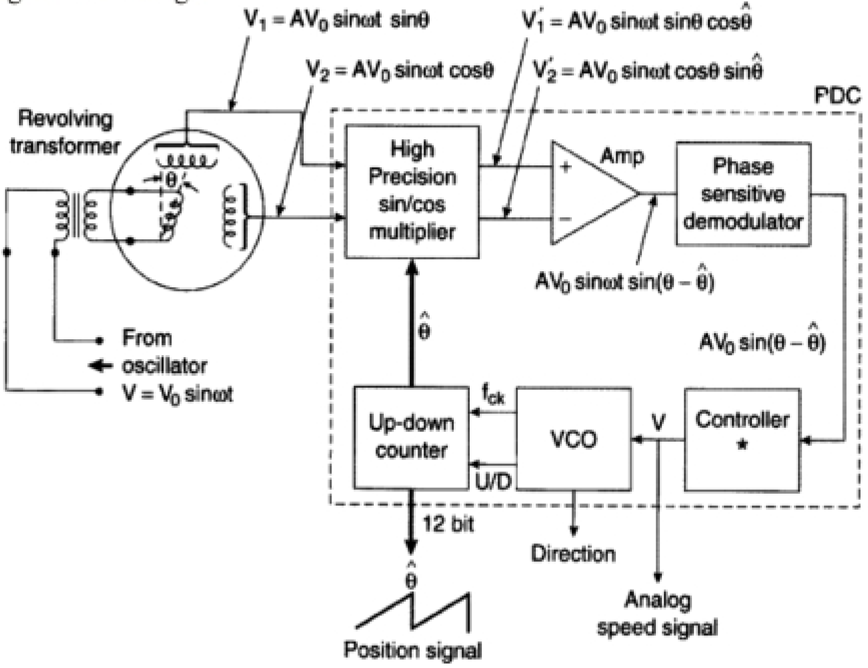


Figure 8: Analog Resolver With decoder

The resolver is basically a rotary transformer with one rotating reference winding (V_{ref}) and two stator windings. The reference winding is fixed on the rotor, and therefore, it rotates jointly with the shaft passing the output windings (Kaewjindam *et al*., 2006). Two stator windings are placed in quadrature (shifted by 90°) with one another and generate the sine and cosine voltages (V_{sin} , V_{cos}) respectively. Both windings will be further referred to as output windings. In consequence of the excitement applied on the reference winding V_{ref} and along with the angular movement of the motor shaft θ, the respective voltages are generated by resolver output windings V_{sin} , V_{cos}. The frequency of the generated voltages is identical to the reference voltage and their amplitudes vary according to the sine and cosine of the shaft angle θ. Considering that one of the output windings is aligned with the reference winding, then it is generated full voltage on that output winding and zero voltage on the other output winding and vice versa.

Field Orientated Control of PMSM

The vector or field-oriented control technique brought on a renaissance in modern high-performance control of ac drives (Vas *et al*., 1998; Bose *et al*., 1988; Qian *et al*., 1993; Rodriguez *et al*., 2004). This control method has found wide acceptance in applications such as paper mills, textile mills, steel rolling mills, machine tools, servos, and robotics. The Field Orientated Control (FOC) consists of controlling the stator currents represented by a vector. This control is based on projections which transform a three phase time and speed dependent system into a two co-ordinate (d and q co-ordinates) time invariant system. These projections lead to a structure similar to that of a DC machine control. Field orientated controlled machines need two constants as input references: the torque component (aligned with the q co-ordinate) and the flux components (aligned with d co-ordinate). As Field Orientated Control is simply based on projections the control structure handles instantaneous electrical quantities. This makes the control accurate in every working operation (steady state and transient) and independent of the limited bandwidth mathematical model.

The previous currents obtained are the stator currents that must be transformed to the rotor reference frame with the rotor speed ω_r , using Park's transformation. The q and d axis currents are constants in the rotor reference frames since α is a constant for a given load torque. The q axis current is distinctly equivalent to the armature current of the DC machine; the d axis current is field current, but not in its entirety. It is only a partial field current; the other part is contributed by the equivalent current source representing the permanent magnet field. For this reason the q axis current is called the torque producing component of the stator current and the d axis current is called the flux producing component of the stator current.

With vector or decoupling control, the dynamics of ac drives is similar to that of dc drives, and with current control, the conventional stability limit of ac machine does not arise. This is indeed a remarkable accomplishment. At present, significant R&D efforts have been focused on parameter identification techniques (Vas *et al*., 1998; Kadjoudj *et al*., 2004; Hyunbae *et al*., 2003; Qiu *et al*., 2004). The so-called slip gain tuning in order to have decoupling between the rotor flux and torque component of current has been attempted by reactive power balancing, injecting a pseudo-random binary sequence, Kalman filter estimation (Peroutka *et al*., 2005; Anbang *et al*., 2009; Ciabattoni *et al*., 2011; Bolognani *et al*., 2003; Bolognani *et al*., 2001), and MRAC (Wu *et al*., 2009) balancing of reactive power, torque, and voltages. While the on-line controller tuning (Kshirsagar *et al*., 2006) with initial parameters is not difficult, tracking of controller parameters with machine parameters during system operation is always a challenge. Recently, a hybrid or universal vector control method has been suggested (Yen-Shin *et al*., 2003) , where the indirect vector control operates in the lower speed range and is switched to parameter-independent direct vector control in the higher speed range. It should be mentioned here that, the vector control can be applied to both induction and synchronous machines and, in fact can be applied to the general AC system for independent active and reactive power control (Vas *et al*., 1998; Qian *et al*., 1993; Tairov *et al*., 2007; Song *et al*., 2005). The basic idea of the vector control algorithm is to decompose a stator current into a magnetic field-generating component and a torque-generating component. After decomposition both components can be separately controlled like dc machine. By using the Vector control, the performance of the ac machine can be made similar to that of a separately excited DC motor by the orientation of the stator MMF or current vector in relation to the rotor flux to achieve a desired objective as shown in figure 9.

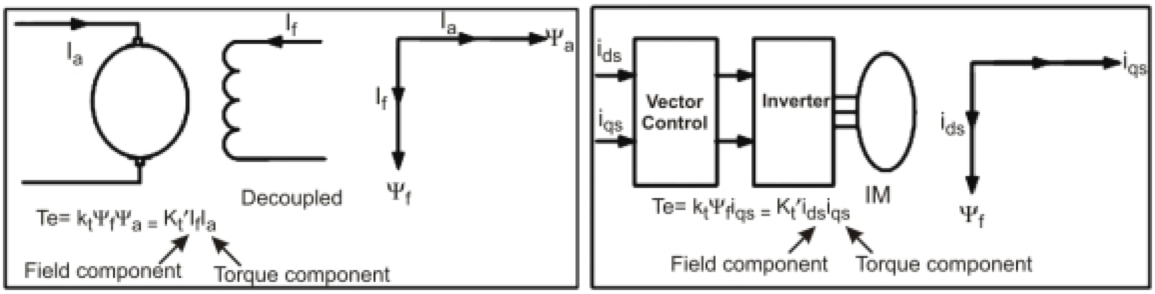


Figure 9: (a) Separately Excited Dc Motor (b) Vector Controlled Ac Motor

In vector control we are making the i_a and i_f which are responsible for producing the fluxes of Ψ_a and Ψ_f orthogonal to each other. But due to the inherent coupling effect the ac machine cannot give such fast response. In order to exhibit the DC machine characteristics, the machine is controlled in the synchronously rotating reference frame (d^e-q^e), where the sinusoidal machine variables appear as DC quantities in the steady state.

Scalar control is based on relationships valid in steady state. It is simple but due to the inherent coupling effect (i.e., torque and flux are proportional to the voltage or current and frequency) gives sluggish response and the system can be easily prone to instability. In this only magnitude and frequency of voltage, current, etc are controlled. Scalar control (Wei *et al*., 2005) is used where several motors are driven in parallel by the same inverter. In order to overcome these problems we are going for vector control.

The vector control processing block diagram is shown in fig.10. As shown in block diagram first three phase quantities have to be converted to two phase using clarke transformation, and then quantities are converted into dq variables. The control process is implemented here in dq reference frame, because in dq reference frame quantities are independent and can be controlled separately, which is the basic purpose of vector control. Then after electrical quantities are again converted back to three phase to feed power to three-phase PMSM. Here as shown in diagram the electrical quantities may voltage or current.

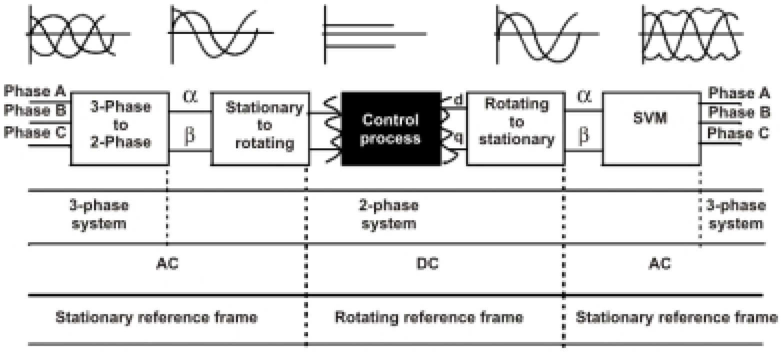


Figure 10: Block diagram of vector control processing

The basic purpose of implementing vector control to PMSM is to get the performance similar to dc machine. The stator current is first decomposed into two components flux and torque producing components (Kadjoudj *et al*., 2004). Two controllers are used for d-axis and q-axis current control and one controller for speed control. Speed controller takes speed error as input and generates q-axis current reference. The voltage reference for d-axis and q-axis are generated by two current controllers.

Results and Discussion

The Vector controlled PMSM drive is simulated in MATLAB/SIMULINK, and performance is investigated. The block diagram of drive system is shown in fig.11.

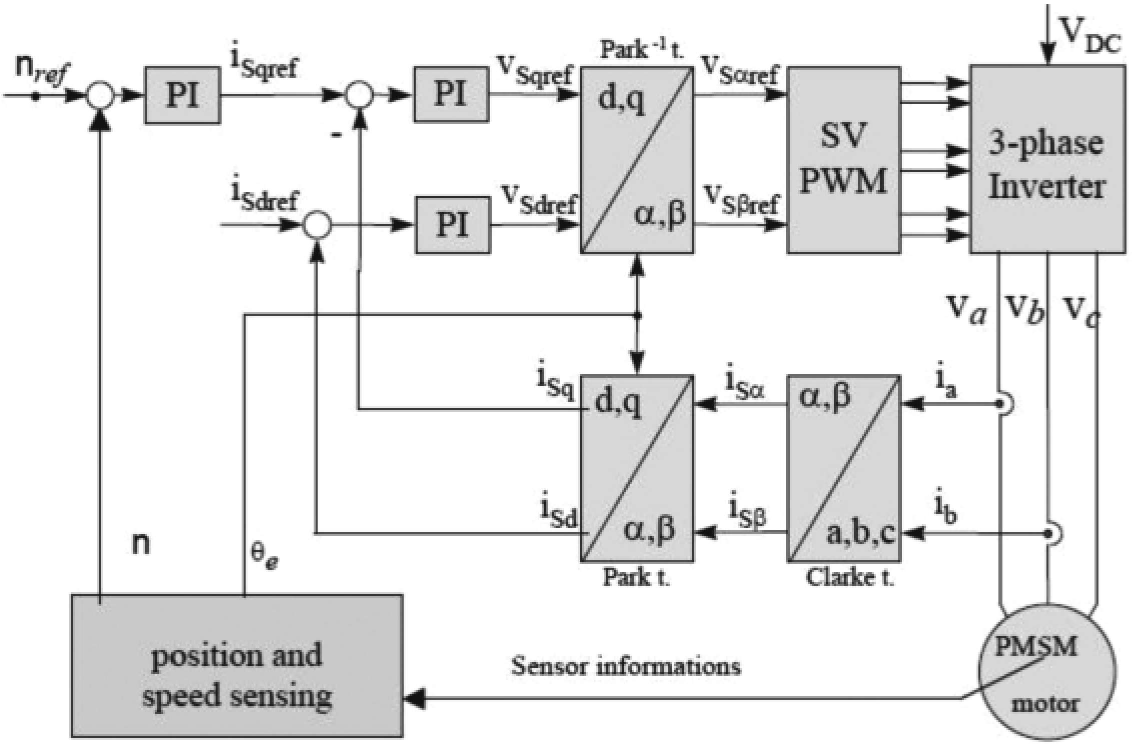


Figure 11: Block diagram for vector controlled PMSM

Space vector PWM inverter is used to feed three-power to motor. As shown in block diagram three PI controllers (two in current loops and one in speed loop) are used to regulate the speed and torque of PMSM. These PI controllers are appropriately tuned to achieve a good performance of drive.

Fig. 12 shows three-phase stator currents of PMSM when the load torque applied to motor is changed from 0-10-15-10 Nm. As the load on motor is changing, the stator current is changing accordingly. The top portion of fig.12 shows the zoomed view of stator currents which are sinusoidal. Fig.13 shows the electromagnetic torque generated by PMSM as step-change (0Nm at 0 sec, 10Nm at 0.5 sec, 15Nm at 1 sec and 10Nm at 1.5 sec) in load torque applied to motor. The vector control of PMSM makes instantaneous control of currents a load changes. Two current controllers are used in this drive system. The q-axis current is directly related to torque applied to motor, and d-axis current reference is kept zero in this case to optimize the torque generated per ampere. Figure 14 shows the speed of motor as the speed reference to drive is changed 700rad/sec at 0, 400rad/sec at 0.5, and again 700rad/sec at 1.0 sec. It is clear from fig. 14 that speed of motor is following the reference speed.

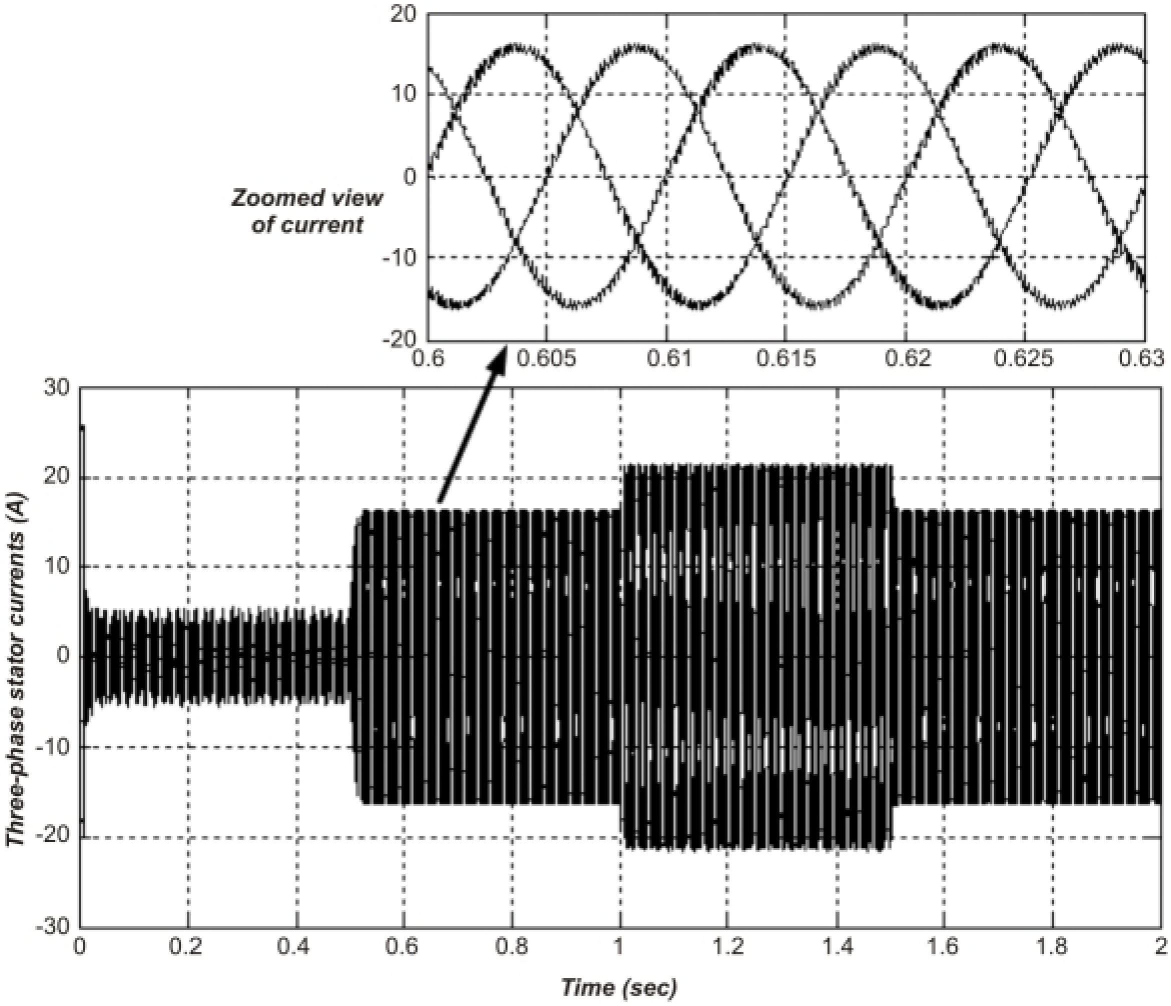


Figure 12: Three-phase stator currents of PMSM

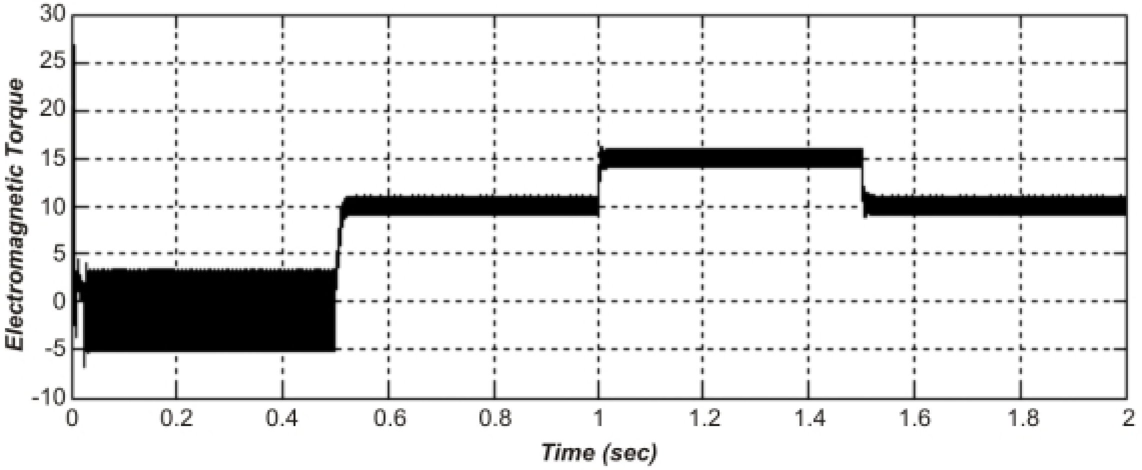


Figure 13: Electromagnetic Torque generated by PMSM with step change in load torque 0-10-15-10 Nm.

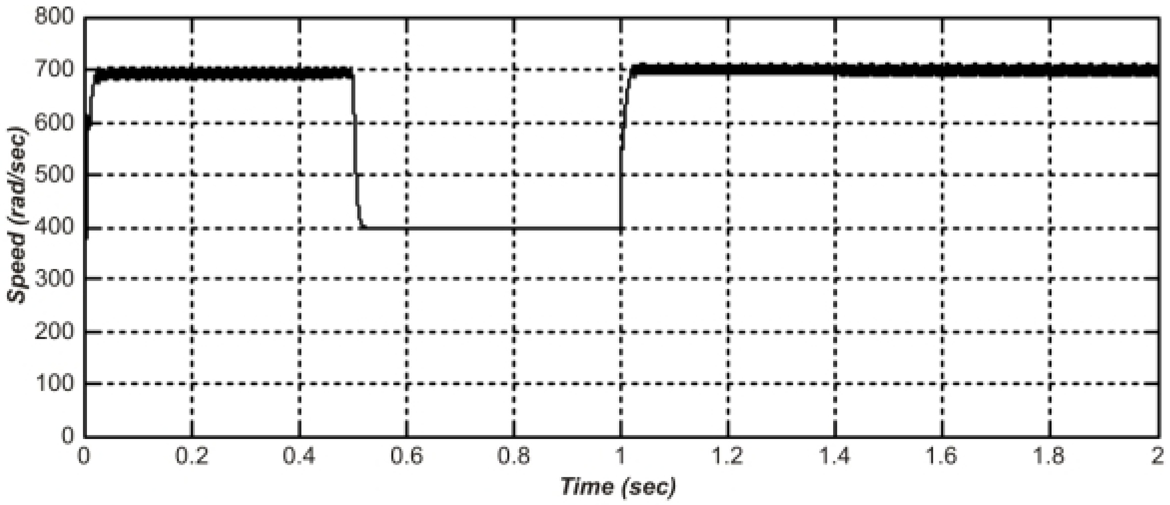


Figure 14: Speed of PMSM with step change in reference speed 700-400-700 rad/sec

Conclusion

In this paper a comprehensive analysis, modeling, operation and control of permanent magnet synchronous motor is presented. The superiority of PMSM over dc motor; which was a most suitable option for adjustable speed drives in last few decades, and over induction motor; which is the work horse for the industries and domestic appliances. Comparison with other types of motor is also discussed. Mathematical modeling and control of PMSM is described in detail. Further the vector control scheme for PMSM drive is described and implemented. To investigate the performance of vector controlled PMSM drive under various operating conditions extensive simulation is carried out to validate theoretical analysis. Three PI controllers are used in complete drive system. In scalar control when speed of motor is changed toque generated by motor is also changed, same way when load torque is changed, the speed of motor is automatically changed. The results presented here show the advantage of vector control scheme as discussed in previous sections. Speed and torque of a vector controlled PMSM drive are controlled separately like the dc machine which is not possible with scalar control.

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