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Analysis and Design of Permanent Magnet Synchronous Motor (PMSM) Control with Advanced Vector Control Technique

VenkataRamana G[1], Dr. K Suneeta[2]

[1]*Ph.D Scholar, Dept. of EEE, JJTU, India*
[2]*Professor, Dept. of EEE, JBIET, India*

ABSTRACT

Permanent magnet synchronous motors (PMSM) are highly used in traction purpose due to these motors are light weight, compact in size and highly efficient when compared with other motors. We will get good performance in railways also. This article will represent detail modeling of state feedback controller (SFB) to control the parameters of PMSM using vector control method including complete modeling of PMSM drive in simulink environment. Sensors are completely eliminated by using The observer. The observer is designed for estimating anyone of the state variable if the other state variable is known thus eliminating the need to sense both speed and current .the state feedback is designed in such a away that which will provide that zero steady state error. For observation purpose a PI controller has been designed and the results of control actions have been compared and observed that these controllers are robust than PI controllers in case of both the operations like normal, overloading .In this article we have designed and simulated the mathematical model of PMSM synchronous motor and designed the state feedback control system using pole placement method and PI controller using bode plot method for speed control of PMSM. The controller hence designed is found to be satisfactory and robust over wide range of operating condition and parameter variations.

Keywords— Motor, Permanent Magnet Synchronous Motor, State Feedback Control Observer, Vector Control.

I INTRODUCTION

Permanent magnet (PM) synchronous motors are mainly used for applications like low power, mid power applications such as computer peripheral devices, robotics adjustable speed drives and electrical vehicles .As the growth of motor in market has been drastically the need for simulation of tools for understanding for motor characteristics becomes necessary and this has been increase in market due to its wide range of applications. The main important feature PMSM is its high efficiency which is given by ratio of its output with losses .There is no rotor current which can be called field current also unlike induction motors thus there are no losses in PMSM and also the copper losses half to that of induction motors hence these PMSM are used industries ,servo drives and in traction motor systems.

Different authors had performed the modeling and simulation of such drives. In paper [1] the authors have shown the equivalent electric circuit models for PMSM and also compared the computed parameters with the measured parameters. Authors of paper [2] observed that interior permanent magnet (IPM) synchronous motors have special features for adjusting their speed during operation which makes them unique from other classes off AC motors. Paper [8] has presented the comparison between different types of synchronous motors and induction motors. In 2002 authors of paper [10] have described the vector-control of interior permanent-magnet synchronous motor drive which are very good in energy optimization and in its efficiency. In 2004 author of the paper [11] presented a modular control approach to a permanent-magnet synchronous motor (PMSM) through speed control. In this work, the vector control of permanent magnet synchronous motor has been established with the help of state feedback controller that will not only remove the use of sensors but also make the system more efficient and also economical. The effect of overloading is shown and the behavior of SFB and PI controller is also analyzed.

II STATE SPACE MODEL OF PMSM

The permanent magnet synchronous machine has the ability to operate in both motor mode as well as in generation mode depending upon the applied mechanical torque (Positive for motor and negative for generator). The second order state space model is used to represent the electrical and mechanical parts of an machine and thus a proper detailed modeling of PM motor drive system is required for the perfect simulation of the system. Fig. 1 shows the development of the d-q model which is implied on rotor reference frame. At an instant the rotor which is rotating i.e d-axis makes an angle 0r with the stator which is fixed phase axis and rotating stator mmf makes an angle with the rotor d-axis. Stator mmf rotates at the speed same as that of the rotor.

The model of PMSM has been developed on rotor reference frame using the following assumptions:

a) Neglecting the saturation.
b) Assuming the induced EMF is sinusoidal in nature.
c) Eddy currents and hysteresis losses are negligible.
d) Field current dynamics are not present.

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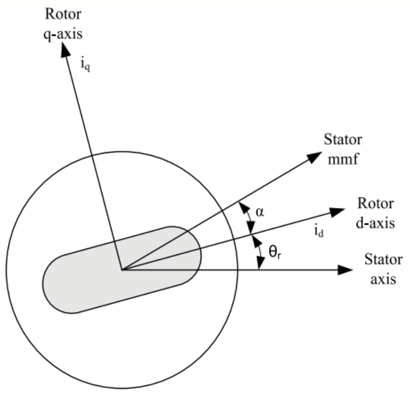

Fig. 1 Motor Axis [11]

Voltage equations are given by:

$$V_q = R_s i_q + \omega_r \lambda_d + \rho\lambda_q \text{.................................}(1)$$

$$V_d = R_s i_d - \omega_r \lambda_d + \rho\lambda_d \text{.................................}(2)$$

Flux Linkages are given by:

$$\lambda_q = L_q i_q \text{...}(3)$$

$$\lambda_d = L_d i_d + \lambda_f \text{..}(4)$$

Substituting Equations (3) and (4) in equations (1) and (2) and rearranging them in matrix format we get:

$$\begin{pmatrix} V_q \\ V_d \end{pmatrix} = \begin{pmatrix} R_s + \rho L_q & \omega_r L_d \\ -\omega_r L_q & R_s + \rho L_d \end{pmatrix} \begin{pmatrix} i_q \\ i_d \end{pmatrix} = \begin{pmatrix} \omega_r \lambda_f \\ \rho \lambda_f \end{pmatrix} \text{....}(5)$$

The torque equation is given by:

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)(\lambda_d i_q - \lambda_q i_d) \text{........................}(6)$$

$$T_e = T_L + B\omega_m + J\frac{d\omega_m}{dt} \text{...........................}(7)$$

Using the above parameters the model of PMSM has been developed in matlab simulink thus by giving an voltage input of 220V (Rated Voltage) at an speed of 158 rad/sec . The fig. 2 shows the rated output speed.

Table 1

Permanent Magnet Synchronous Motor Parameters

Symbol	Name	Value
V_{LL}	Rated Voltage	220V
Pout	Output Power	800W
P	No. of Poles	4
m_m	Rated Speed	1500 rpm, 158rad/sec

R_s	Stator Resistance	4.8fi
Z_f	PM Flux linkage	0.272Wbturns
L_q	q-axis Inductance	30mH
L_d	d-axis Inductance	65mH
I_s	Rated Current	3A
J	Motor Inertia	0.000180 kg m^2

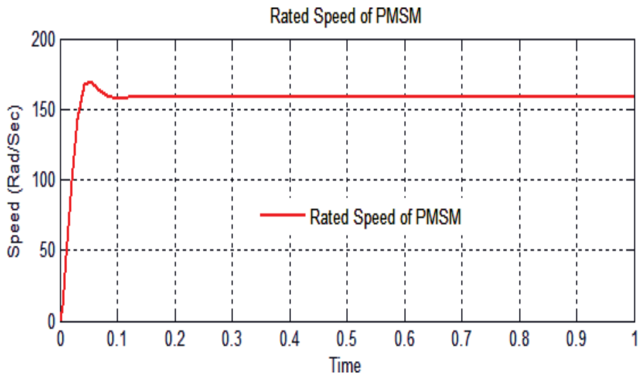

Fig. 2 Rated Speed of PMSM

III SYNCHRONOUS ROTATING FRAME (D-Q AXIS)

Vector control approach is the commonly used method for speed control of three-phase induction motor and synchronous motor. The control is done by first transforming the 3 phase parameters to dq0 reference frames. The general idea of the vector control technique is to control the flux producing component which is nothing but (direct axis current) and the torque-producing component (Quadrature axis current) in a decoupled manner so that the change in one component does not affect the other component.

The equation to transform abc components to dq0 components is given as [12]:

$$\begin{bmatrix} i_q \\ i_d \\ i_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos(\theta-120) & \cos(\theta+120) \\ \sin\theta & \sin(\theta-120) & \sin(\theta+120) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \text{.....(8)}$$

The inverse transformation becomes

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos(\theta-120) & \sin(\theta-120) & 1 \\ \cos(\theta+120) & \sin(\theta+120) & 1 \end{bmatrix} \begin{bmatrix} i_q \\ i_d \\ i_0 \end{bmatrix} \text{........(9)}$$

Fig. 3 shows the block diagram of a three phase PLL [13], where the 3 phase voltage is represented as

V_{abc} which needs to be transformed into DC components using coordinate transformation abc-dq0 and by setting V_d* to zero by which the PLL gets locked. The loop filter PI is a low pass filter (LPF). The LPF sends the DC controlled signal to voltage controlled oscillator (VCO) which acts as an integrator. The output of the controller is nothing but the frequency which is integrated to obtain the phase angle of the converter (0).

As from the equations it can be deduced that in order to transform any vector from stationary reference frame into synchronously rotating *d–q-0* reference frame, the quantities sin (0) and cos (0) are needed. These are the components of a synchronously revolving unit vector. These quantities should have the same frequency as that of the system voltage.

Fig. 3 shows the block diagram of a three phase PLL [13], where the 3 phase voltage is represented as V_{abc} which is need to be transformed into DC components using coordinate transformation abc-dq0 and by setting V_d* to zero the PLL gets locked. The loop filter PI is a low pass filter (LPF). The LPF gives the DC controlled signal to voltage controlled oscillator (VCO) which acts as an integrator. The output of the controller is the frequency of that is integrated to obtain the phase angle of the converter (0).

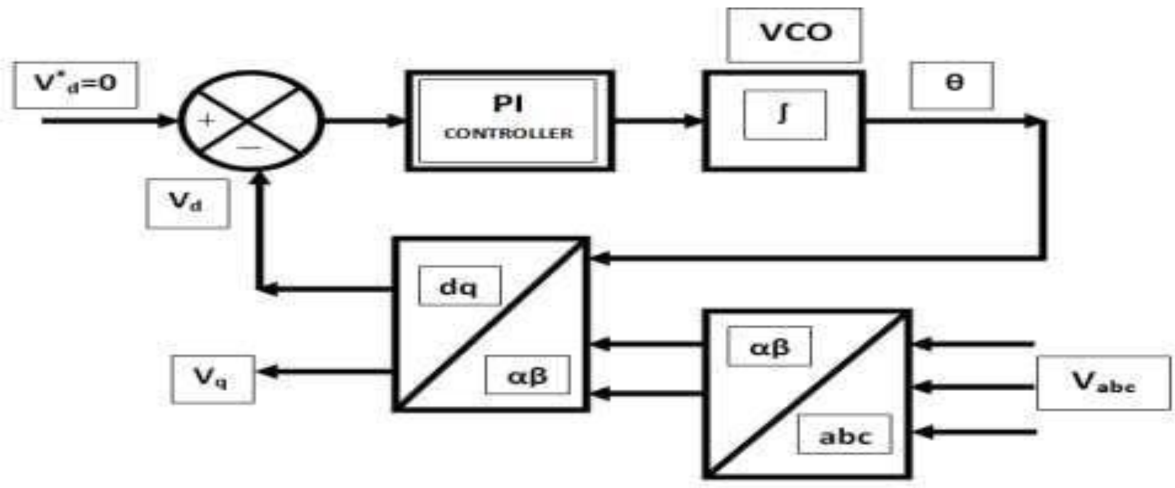

Fig. 3 Structure of three phase d-q PLL

IV STATE FEEDBACK CONTROLLER DESIGN

A controller can be in the form of hardware or software program that manages, control and directs the flow of data between two systems. In computing the design of controllers that can be cards, microchips , processors or separate hardware devices which controls the peripheral devices and surrounding systems. In a general sense, a controller can be thought of interfacing between two systems that manages the communications between them.

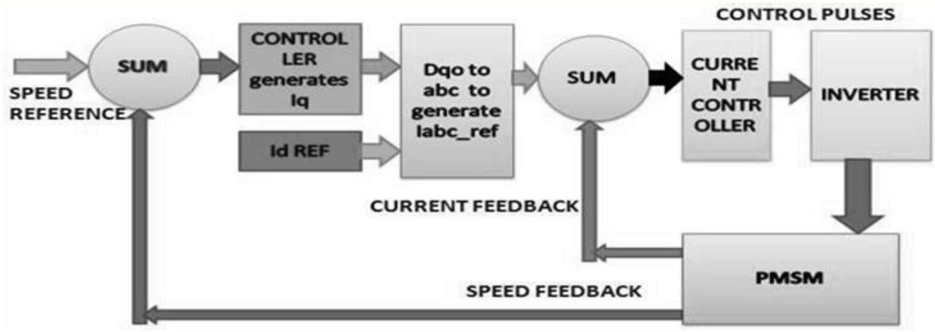

Fig. 4 Complete Control Scheme of PMSM

Full state feedback (FSF), or pole placement [14], is a method that is used in feedback control system. In this method the closed-loop poles of a plant are placed in pre-determined locations in the s-plane which corresponds to the Eigen values of the system and hence controls the characteristic response of the system. The system needs to be controlled in order to implement the above mentioned method.

If the closed-loop input-output transfer function can be represented by a state space equation

$$x' = Ax + Bu \text{ .... } (10)$$

$$y = Cx + Du \text{ .... } (11)$$

Then the poles of the system are the roots of the characteristic equation given by

$$\det[sI - (A - BK)] \text{ .... } (12)$$

Full state feedback is utilized by commanding the input vector u. Considering an input which is proportional (in the matrix sense) to the state vector,

U=-Kx…………………. (13)

Substituting this into the state space equations above,

$$x' = (A - BK)x \text{ .... } (14)$$

$$y = (C - DK)x \text{ .... } (15)$$

The roots of the FSF system are given by the characteristic equation,

$$\det[sI - (A - BK)] \text{ .... } (16).$$

The comparison of the terms of this equation with those of the desired characteristic equation gives the values of the feedback matrix K which will force the closed-loop Eigen values to the pole locations specified by the desired characteristic equation.

V PROPORTIONAL AND INTEGRAL CONTROL

In general the control action can be imagined as something like if the error between the measured output is negative, then multiply it by some scale factor generally known as gain and set the output drive to the desired level. This technique is also known as "proportional control". But the increase in gain makes the system unstable and hence this method is not completely successful. So an improvement is required in the model by which there is an provision for the correction in the output which will keep on adding or subtracting a small amount to the output until the system reaches Stability. This approach is basically based on the techniques of integration of the error which constitutes a “PI (proportional-integral) controller”. The proportional component acts as a fast acting corrector which will produce a change in the output as quickly as the error increases. The integral action takes is own time to act but it has the capability to make the steady-state speed error zero.

5.1 Design of Controllers Using Bode Diagram

To meet the required specifications of the system the open loop bode plot is first obtained and then it is shaped into the desired specifying values which is required with the help of controllers. To obtain the bode diagram of a system the specifications of the system is transformed into phase and gain margins along with the knowledge of steady- state errors. The advantage of this classical design method over the state feedback method is nothing but the whole system and its responses on the controllers can be easily represented graphically. This is not the case with state space form, where as it only deals with the Eigen values, poles and zeros, i.e., with numbers.

VI ANALYSIS OF SPEED CONTROL RESULT OF SFB AND PI CONTROLLER

With the given parameters of PMSM in Table I, a PI and a SFB controller is designed to control the speed of PMSM at desired level. The gains of PI controller has been designed using Bode Plot where as the gains of SFB is obtained by pole placement method. The fig. 5 shows the output of PMSM using both PI and SFB controller. The results are shown for input of 130 rad/sec and 100 rad/sec speed respectively. A load torque of 2 N-m is applied after 1sec of simulation and the effect of the load torque is hereafter shown. Also after application of overloading torque of 10 N-m, the effect on speed for reference input of 130 rad/sec speed, is shown in fig. 6, which represents for both the controllers. The comparison shows that the steady state error in PI controller is more than that of the SFB after applying the load torque for both rated and over loading cases.

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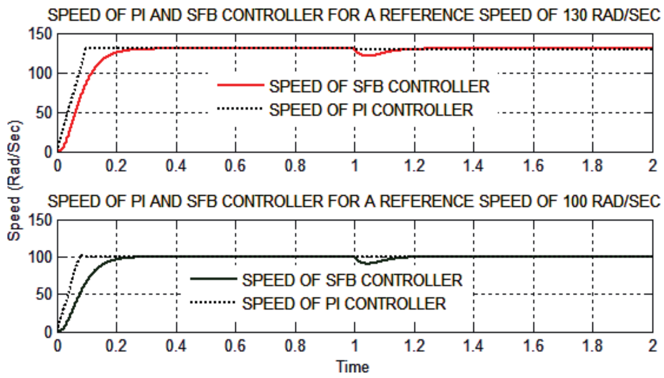

Fig. 5 Speed Response of PMSM after incorporating controller

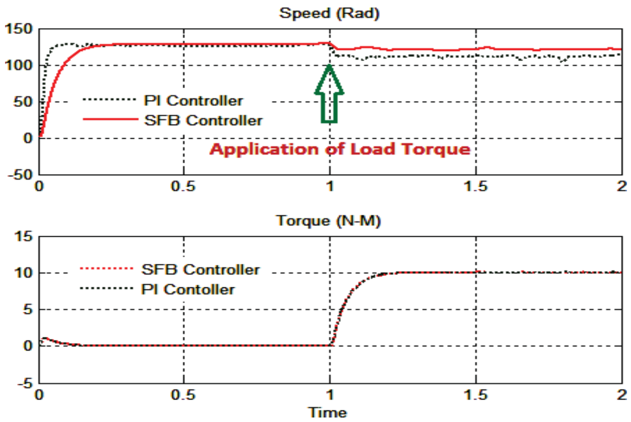

Fig**. 6 Speed Response of PMSM after applying the condition of overloads**

The detailed comparison between SFB and PI controller is listed in Table 2.

Table 2

Comparison between SFB and PI controller

S. NO	PROPERTIES	PI CONTROLLER	SFB CONTROLLER
1	STEADY STATE ERROR	0% (INTIALLY) 1.2% (After Applying Rated Load Torque)	0% (INTIALLY) 0% (After Applying Rated Load Torque)
2	RISE TIME	0.07 SEC	0.24 SEC
3	OVERSHOOT	0.5%	0%
4	SETTELING TIME	0.2 SEC	0 SEC
5	STEADY STATE ERROR (after overloading)	15.38%	7.6%

In controller designing while tuning the PI controller, the plant is modeled without its physical limitation. The Output magnitude limiters are not at all present in the linear PI controllers, and therefore, which ultimately results in large values of output which can damage the real system as a result of large control action. For instance, an inrush of excessive current and voltage can damage the PMSM along with the power electronic converters. In order to protect PMSMs, the output current and voltage values are limited with the help of a saturator and consequently the outer loop speed of PI controller accumulates error, producing a big overshooting of the speed which could even destabilize the system. This phenomenon is called wind up. To avoid this wind up, anti windup scheme are incorporated in the PI control system. Anti-windup scheme used in the conventional speed control scheme are nonlinear in nature. The linear controller designed for this nonlinear system will give satisfactory performance in a small neighborhood of the operating point around which the nonlinear plant has been linearised. This scheme gives a satisfactory performance within the saturation limit where the plant is linear. This is one of the limitations of using PI controller.

Unlike PI controller state feedback controller tuning does not have any wind up phenomenon and thus it is free from nonlinearity of anti windup scheme and hence providing better control over its wide operating area.

VII DESIGN OF OBSERVER

Controller design depends upon the availability of control variables which takes the feedback through adjustable gains. This access is generally been provided by the help of sensors or special measurement devices. Sometimes due to unavailability of equipments , cost and also accuracy of measurement, sensors are not being used. In that case state variable can be estimated using observer.

According to Luenberger, the full-state observer for the system

$$\dot{x} = Ax + Bu \quad (17)$$

$$y = Cx \quad (18)$$

is given by

$$\dot{\hat{x}} = A\hat{x} + Bu + L(y - C\hat{x}) \quad (19)$$

Where $\hat{x}$ denotes the estimate of the state x. The matrix L is the observer gain matrix and is to be determined as part of the observer design procedure. The observer is depicted in Fig. 9. The observer has two inputs, u and y, and one output $\hat{x}$.

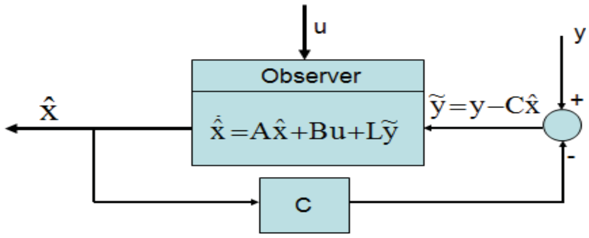

Fig. 7 The Observer Overview

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The goal of the observer is to provide an estimate $\hat{x}$ so that $\hat{x} \rightarrow x$ as t → œ. $x(t_0)$ is not known precisely; therefore, Initial estimate $\hat{x}(t_0)$ is provided to the observer. The observer estimation error is define as:

$$e(t) = x(t) - \hat{x}(t) \ldots\ldots\ldots\ldots\ldots\ldots \quad (20)$$

The observer design should produce an observer with the property that e(t) → 0 as t → œ. One of the main of systems theory is that if the system is completely observable, L is finded so that the tracking error is asymptotically stable, as desired. Taking the time-derivative of the estimation error in the error equation yields

$$\dot{e} = \dot{x} - \dot{\hat{x}} \ldots\ldots\ldots\ldots\ldots\ldots \quad (21)$$

and using the system model and the observer, the obtained equations are:

$$\dot{e} = Ax + Bu - A\hat{x} - Bu - L(y - C\hat{x}) \ldots\ldots\ldots \quad (22)$$

or

$$\dot{e}(t) = [A - LC]e(t) \ldots\ldots\ldots\ldots\ldots\ldots (23)$$

e(t) → 0 as t→ œ for any initial tracking error $e(t_0)$ if the characteristic equation

$$\det[ZI - (A - LC)] = 0 \ldots\ldots\ldots\ldots\ldots\ldots (24)$$

has all its roots in the left half-plane. Therefore, the observer designs the process to reduce finding the matrix L such that the roots of the characteristic equation lie in the left half- of plane. This can always be accomplished if the system is completely observable i.e. if the observability matrix, P_O, has full rank.

Fig. 8 shows the speed control of PMSM after the speed is being estimated via the observer. The speed control is shown for both SFB and PI controller.

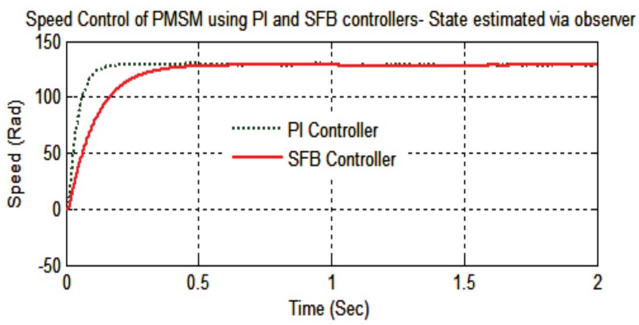

Fig.8 State estimated via Observer and Speed control

VIII CONCLUSION

In this paper, we have designed and simulated the mathematical model of PM synchronous motor in MATLAB/ SIMULINK and designed the state feedback control system using pole placement method and PI controller using bode plot method, for speed control of PMSM. The vector control scheme is incorporated for decoupled control of flux and torque producing components. An observer is also designed to eliminate the need of sensors. The simulation results of State feedback controller are compared with that of the PI controller with anti wind up scheme. The advantages of SFB over PI controller have also been discussed. The SFB controller designed is found to be satisfactory and robust over wide range of operating condition and parameter variations for both normal and overloading.

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