Abstract

Objectives: This paper proposes the state estimation of Permanent Magnet Synchronous Motor (PMSM) by designing and comparing two non-linear observers such as reduced order and full order observers. Methods: Control system design for an inverter fed PMSM drive can be carried out using conventional two loop structure; which are outer speed loop and inner current loop. Conventional control system design uses the classical transfer function approach for Single-Input Single Output (SISO) systems. Proportional plus Integral (PI) controllers were designed for individual control loops. The PI controller transient response is slow, which can be improved through state feedback by using pole placement technique. The State Feedback Controller (SFC) of a PMSM drive requires all the state information. In PMSM, damper winding currents are usually inaccessible and need to be estimated using an observer. Findings: A non-linear reduced order observer is designed in order to estimate the damper winding currents of PMSM where as to estimate both damper winding and stator winding currents a non-linear full order observer is proposed. The performances of two observers for the drive system are verified and compared through the extensive simulations using MATLAB/SIMULINK implementation. Applications: Generally the states of the drive system are estimated using sensors, resulting the cost and complexity of the drive system increases. Also the estimated states are inaccurate due to parameter imperfections. So in order to overcome these problems, one can design a non-linear reduced/full order observer.

Keywords: Full Order Observer, Permanent Magnet Synchronous Motor, Reduced Order Observer, Rotor Reference Frame, State Feedback Controller

1. Introduction

Due to recent advancement in power electronic converters, microprocessor technology and permanent magnet materials, induction and synchronous machines are very popular in drive technology. Synchronous motors, such as PMSM can be worked like a dc machine, when it is controlled by using power electronics together with a pole position sensor. In PMSM, both phase voltage and current are sinusoidal and peak value of the current is also low. In Induction Motor (IM) for a given current rating some of the current is utilized for magnetization, but in PMSM there is absence of magnetizing current due to permanent magnets on rotor. So with a given current less torque is produced in IM compared to PMSM. From this, the PMSM has higher output, high power

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density and improved power factor with same physical dimensions and current rating compared to IM. PMSM is nothing but synchronous machine but the field excitation is provided by permanent magnets provided on the rotor. Due to this, there is no excitation voltage source, field winding, collecting rings and brushes, resulting in improving efficiency when compared to other machines. By considering various features such as good dynamic performance, easy controllability, high torque to inertia ratio, high efficiency and improved power factor; PMSM drives\(^2\) are used in robotics, machine tools, pumps, ventilators, compressors etc.

In this paper, a PMSM along with damper windings is considered. The damper windings are used in order to damp out the natural frequency of oscillations due to small disturbances like transients, harmonics etc. The damper windings produce opposing fields during the time of disturbances. This opposing field is generated by damper winding currents and these are immeasurable. Due to this importance of damper windings, the damper winding currents must be known. These currents are not directly accessible with sensors. So in order to overcome this, an observer\(^3\) is designed to estimate these currents. The observer can be defined as a dynamic system which estimate the entire state of the system from the observation of system input and output parameters. Commonly, two observers such as reduced and full order observers\(^4\) are used to estimate the currents or states from the system. In reduced order observer\(^5\), minimum number of states i.e., damper winding currents only estimated, whereas in full order observer\(^6\), all the states such as both damper winding currents and stator winding currents are estimated. To control PMSM, position and speed information are much needed, so that an encoder is used.

This paper presents, the design and stability analysis of PMSM drive. In order to get stability and control, a state feedback controller\(^7\) is designed, which requires the knowledge of all the states. So, the currents which are estimated from the observer are fed back to the state feedback controller. In the implementation of state feedback controller, a linear state feedback control law is applied and stability is obtained using a pole placement technique. In addition to this, with respect to reference current specification the zero steady state error is achieved using an Integral of Output Error (IOE) approach\(^8\).

### 2. Modeling of PMSM

For high performance drive application, the design of control system requires mathematical model\(^9\) of the machine. To develop mathematical model of PMSM, the actual machine in abc reference frame\(^10\) is converted into d-q axis representation. By using mathematical modelling, the complexity of calculations is reduced while analyzing the system performance of any machine. Also the time variant inductances are treated as time invariant inductances and the sinusoidal quantities are represented as dc quantities. The schematic diagram of PMSM with damper windings is as shown in Figure 1. Using rotor reference frame, the model of PMSM with damper winding has been developed in d-q axis representation.

![Figure 1. Permanent magnet synchronous machine.](image)

The voltage equations of PMSM in rotor reference frame are

\[
\begin{align*}
\dot{v}_{qi} & = r_{qi} i_{qi} + l_{aq} i_{q} p_{si} + l_{pi} i_{pi} + \omega l_{qi} i_{q} + \omega l_{pi} i_{p} \\
\dot{v}_{di} & = r_{di} i_{di} + l_{dq} i_{dq} p_{si} + \omega l_{di} i_{q} - \omega l_{dq} i_{p} \\
\dot{v}_{qi} & = r_{qi} i_{qi} + l_{aq} i_{q} p_{si} + l_{pi} i_{pi} + \omega l_{qi} i_{q} - \omega l_{pi} i_{p} \\
\dot{v}_{di} & = r_{di} i_{di} + l_{dq} i_{dq} p_{si} - \omega l_{di} i_{q} + \omega l_{dq} i_{p}
\end{align*}
\]

In the matrix form, Equations (1) to (4) are represented as

\[
\begin{bmatrix}
\dot{v}_{qi} \\
\dot{v}_{di} \\
\dot{v}_{qi} \\
\dot{v}_{di}
\end{bmatrix} =
\begin{bmatrix}
r_{qi} & l_{aq} p_{si} & l_{pi} & \omega l_{qi} \\
-\omega l_{qi} & r_{di} & l_{dq} p_{si} & -\omega l_{di} \\
l_{aq} & 0 & r_{qi} & l_{pi} \\
0 & l_{dq} & 0 & r_{di} p_{si} + l_{dq} p_{si}
\end{bmatrix}
\begin{bmatrix}
i_{qi} \\
i_{di} \\
i_{qi} \\
i_{di}
\end{bmatrix} =
\begin{bmatrix}
r_{qi} & \omega l_{di} & 0 & 0 \\
-\omega l_{di} & r_{qi} & -\omega l_{qi} & 0 \\
r_{qi} & 0 & r_{qi} & 0 \\
0 & r_{qi} & 0 & 0
\end{bmatrix}
\begin{bmatrix}
0 & l_{pi} & 0 & l_{pi} \\
0 & l_{pi} & 0 & l_{pi} \\
0 & l_{pi} & 0 & l_{pi} \\
0 & l_{pi} & 0 & l_{pi}
\end{bmatrix}
\begin{bmatrix}
i_{qi} \\
i_{di} \\
i_{qi} \\
i_{di}
\end{bmatrix} =
\begin{bmatrix}
r_{qi} & \omega l_{di} & 0 & 0 \\
-\omega l_{di} & r_{qi} & -\omega l_{qi} & 0 \\
r_{qi} & 0 & r_{qi} & 0 \\
0 & r_{qi} & 0 & 0
\end{bmatrix}
\begin{bmatrix}
l_{pi} \\
l_{pi} \\
l_{pi} \\
l_{pi}
\end{bmatrix}
\]

The developed electric torque is,
\[ T_e = \frac{3}{2} P \left[ (l_{sd} - l_{sq})i_{sd}i_{qr} + l_{sq}i_{sd}i_{dr} - l_{sd}i_{sd}i_{dr} \right] \]  \hspace{1cm} (7)

And the torque balance equation for no. of poles, \( P = 4 \)
\[ p\omega_r = \frac{2}{J} \left[ T_e - \frac{B\omega_r}{2} \right] \]  \hspace{1cm} (8)

Hence by using system and torque equations one can model PMSM motor.

### 3. Design of a Non-Linear Observer

The state estimation for controlling system performance plays an important role in drive system. Numbers of methods\(^\text{13}\) are available in literature in order to estimate the states of a drive system. Out of all these, observers are very useful to augment or replace the sensors from the control system. In the design of control system, an observer is a sub-system, which estimates the states of the system by measurements of the output and control variables. These observed signals are more accurate, less expensive and reliable compared to sensed signals. In order to estimate the states of a PMSM two observers such as reduced order and full order observers are used. In PMSM two states such as damper winding currents are inaccessible and can be estimated using reduced order observer\(^\text{14–16}\). The full order observer\(^\text{17,18}\) estimates all the states of PMSM such as damper winding as well as stator winding currents.

#### Case (i): Design of Reduced Order Observer

The state and output equations of the system can be written in state space form as,
\[
\dot{x} = Ax + Bu
\]  \hspace{1cm} (9)
\[
y = Cx
\]  \hspace{1cm} (10)

In designing of reduced order observer, ‘q’ is the rank of ‘C’ matrix, and \( q \leq r \), where ‘r’ represents no. of outputs and no. of states are represented by ‘n’, which resulting that ‘q’ no. of states are only accessible and remaining (n-q) no. of states are to be estimated.

A new vector, \( \zeta \) of dimension ‘n’ can be taken as,
\[
\zeta = Lx
\]  \hspace{1cm} (11)

Where, ‘L’ is a transformation matrix and ‘x’ is of 4×1 vector as it is associated with \( i_{qs}, i_{ds}, i_{qr}, \) and \( i_{dr} \) vectors, and ‘\( \zeta \)’ is of 2×1 order i.e., \( i_{qs} \) and \( i_{dr} \); therefore the dimension of ‘L’ will be 2×4. The maximum no. of linearly independent rows of matrix ‘C’ can be comprised by matrix ‘C’ and the corresponding output be ‘y’.

\[
\therefore \ y = \dot{C}x
\]  \hspace{1cm} (12)

Where, \( y \) is of 2×1 order as it deals with the terms \( i_{qs} \) and \( i_{dr} \). The matrix ‘\( \dot{C} \)’ is of order 4×1 so, the dimension of ‘\( \dot{C} \)’ is of 2×4. Then, the Equations (12) and (11) can be combined as,
\[
\begin{bmatrix}
y \\
\dot{\zeta}
\end{bmatrix} =
\begin{bmatrix}
C \\
L
\end{bmatrix}
x
\]  \hspace{1cm} (13)

Now the \( \hat{x} \) (i.e., estimated states) becomes
\[
\dot{\hat{x}} = \begin{bmatrix}
C^{-1} y \\
L
\end{bmatrix} \begin{bmatrix}
y \\
\dot{\zeta}
\end{bmatrix}
\]  \hspace{1cm} (14)

Where, \( \hat{x} \) is an estimation of ‘x’ and \( \hat{\zeta} \) is an estimation of ‘\( \zeta \)’. So, in order to estimate states of the system (\( \hat{x} \)) \( \hat{\zeta} \) must be known.

An observer is a dynamical system, which can be represented by the inputs and outputs of the actual system as given by
\[
\dot{\zeta} = D\zeta + Gu + Fy
\]  \hspace{1cm} (15)

Where, D = observer system matrix, G = input (control) matrix and F = input (output) matrix.

Here, F to be chosen as
\[
F = F_1 + (\omega_d - \omega_{ds})F_2
\]  \hspace{1cm} (16)

Introducing non-linearity at the input of the observer, the matrix \( F_2 \) is chosen such that the observer error dynamics are linearized. So \( F_2 \) is given as
\[
F_2 = L(A^{-1})F_3
\]  \hspace{1cm} (17)

Where \( \omega_{ds} \) is a design constant, which can be taken as the average operating speed, so that the magnitude of the non-linear term remains small. Therefore, \( F_3 \) is taken as
\[
F_3 = \begin{bmatrix}
0 & -I_{ds} \\
I_{qs} & 0 \\
0 & 0 \\
0 & 0
\end{bmatrix}
\]  \hspace{1cm} (18)

Differentiating Equation (11) and using the Equations (9) and (14), the error in the estimation of \( \zeta \) can be obtained as,
\[
\dot{\hat{\zeta}} = D\hat{\zeta} - [LA_d - F_1C - DL + (\omega_r - \omega_d)(LA_d - F_1C)] \hat{x}
\]

For precise estimation of  \( \zeta \)
\[
\hat{\zeta} \rightarrow 0 \text{ or } \hat{\zeta} \rightarrow \zeta, \text{ as } t \rightarrow \infty
\]

The effect of  \( u \) in Equation (19) is eliminated by choosing
\[
G = LB
\]

Substituting Equations (16) and (20) in Equation (19) and rearranging,
\[
\dot{\hat{\zeta}} = D(\hat{\zeta} - \zeta) - [LA_d - F_1C - DL + (\omega_r - \omega_d)(LA_d - F_1C)] \hat{x}
\]

For the error estimation of  \( \zeta \),  \( \hat{\zeta} = \hat{\zeta} - \hat{\zeta} \) to decay,

(i) \( L(A_d - A_d^{-1}F_1C) = 0 \)  \hspace{1cm} (22)

(ii) \( LA_d - F_1C - DL = 0 \)  \hspace{1cm} (23)

(iii) The matrix D should be a stable with the restriction that
\[
\{\lambda_k\}_D \neq \{\lambda_k\}_A
\]

The above conditions are used to find matrices D, L and F.

To satisfy condition (i), a matrix L is chosen as,
\[
L = \begin{bmatrix}
  l_{11} & l_{12} & l_{13} & l_{14} \\
  l_{21} & l_{22} & l_{23} & l_{24}
\end{bmatrix}
\]

Now by solving the equations from conditions (i) and (ii) the matrices F and D can be determined, where
\[
F_1 = \begin{bmatrix}
  f_{11} & f_{12} \\
  f_{21} & f_{22}
\end{bmatrix}
\]
\[
D = \begin{bmatrix}
  d_{11} & d_{12} \\
  d_{21} & d_{22}
\end{bmatrix}
\]

Case (ii): Design of Full Order Observer

In designing of full order observer the procedure is same as that of the reduced order observer\(^{19}\) with following changes is adopted. While designing of full order observer\(^{20}\) all the states of PMSM are to be considered in the estimation process. So, the state space representation of the system is directly taken as,
\[
\dot{x} = Ax + Bu
\]
\[
y = Cx
\]
\[
\zeta = Lx
\]

Now the above Equations (29) and (30) can be combined as
\[
\begin{bmatrix}
  \dot{\hat{\zeta}} \\
  \hat{\zeta}
\end{bmatrix} = \begin{bmatrix}
  C \\
  L
\end{bmatrix} \hat{x}
\]

Now the  \( \hat{x} \) (i.e., estimated states) becomes
\[
\dot{\hat{x}} = \begin{bmatrix}
  C^{-1} \dot{y} \\
  L
\end{bmatrix}
\]

An observer is a dynamical system can be represented by
\[
\hat{\zeta} = D\hat{\zeta} + Gu + Fy
\]

Here, \( F \) to be chosen as
\[
F = F_1 + (\omega_r - \omega_d)F_2
\]
\[
F_2 = L(A_d^{-1})F_1 \text{ and } F_3 = \begin{bmatrix}
  0 & -I_d \\
  I_d & 0 \\
  0 & 0
\end{bmatrix}
\]

The error in the estimate of  \( \zeta \) can be obtained as
\[
\hat{\zeta} = \hat{\zeta} - \hat{\zeta} = D(\hat{\zeta} - \zeta) - [LA_d - F_1C - DL + (\omega_r - \omega_d)(LA_d - F_1C)] \hat{x}
\]

For precise estimation of  \( \zeta \)
\[
\hat{\zeta} \rightarrow 0 \text{ or } \hat{\zeta} \rightarrow \zeta, \text{ as } t \rightarrow \infty
\]

\[
\hat{\zeta} = D\hat{\zeta} - [LA_d - F_1C - DL + (\omega_r - \omega_d)(LA_d - F_1C)] \hat{x}
\]

For the error estimation of  \( \zeta \),  \( \hat{\zeta} = \hat{\zeta} - \hat{\zeta} \) to decay,

(i) \( L(A_d^{-1} - A_d^{-1}F_1C) = 0 \)  \hspace{1cm} (37)

(ii) \( LA_d - F_1C - DL = 0 \)  \hspace{1cm} (38)

(iii) The matrix D should be a stable with the restriction that
\[
\{\lambda_k\}_D \neq \{\lambda_k\}_A
\]

The above conditions are used to find matrices D, L and F.
To satisfy condition (i), a matrix \( L \) is chosen as, \[
L = \begin{bmatrix}
  l_{11} & l_{12} & l_{13} & l_{14} \\
  l_{21} & l_{22} & l_{23} & l_{24} \\
  l_{31} & l_{32} & l_{33} & l_{34} \\
  l_{41} & l_{42} & l_{43} & l_{44}
\end{bmatrix}
\] (40)

Now by solving the equations from conditions (i) and (ii) the \( F \) and \( D \) matrices can be determined, where \[
F = \begin{bmatrix}
  f_{11} & f_{12} \\
  f_{21} & f_{22} \\
  f_{31} & f_{32} \\
  f_{41} & f_{42}
\end{bmatrix}
\] (41)
\[
D = \begin{bmatrix}
  d_{11} & d_{12} & d_{13} & d_{14} \\
  d_{21} & d_{22} & d_{23} & d_{24} \\
  d_{31} & d_{32} & d_{33} & d_{34} \\
  d_{41} & d_{42} & d_{43} & d_{44}
\end{bmatrix}
\] (42)

### 4. Design of the Control System

The proposed control system is represented in the conventional two loop structure as shown in Figure 2. The two loops are named as one is outer speed loop and second one is inner current loop. The inner current loop for current control of SPWM inverter fed PMSM drive consists of a state feedback controller along non-linear reduced/full order observer. The outer speed loop consisting of PI controller as speed controller, which generates torque reference \( T_e^* \) from which the reference currents are generated. The gain constants of PI controller are designed as follows:
\[
T_e^* = K_p e + K_i \int_0^t e dt
\] (43)

Where, \( e = \omega_e - \omega_r \) = speed error \( \omega_e \) is reference speed, \( \omega_r \) is actual speed, \( K_p \) is proportional constant, \( K_i \) is integral constant. These gain constants can be obtained as
\[
K_i = \frac{\omega_r^2}{2}
\] (45)
\[
K_p = J \xi \omega_n - \frac{\beta}{2}
\] (46)

Where, \( \xi = \) desired value of damping ratio, and \( \omega_n = \) desired value of natural frequency.

Assigning proper values of \( \xi \) and \( \omega_n \), using the machine parameters of \( J \) and \( \beta \), \( K_p \) and \( K_i \) values are computed.

In design of state feedback controller, the linear feedback control law is applied with a gain matrix of \( K \). In addition, a pole placement technique is used in order stabilize the system. For this purpose, the poles or eigen values of closed loop system are placed at the desired locations in negative half of the S-plane. Now Partitioning \( K \) into \( K_s \) and \( K_i \), multiplied with the regulator model, the control signal \( u \) in terms of state vector and the integral of the differences of output and reference vectors is given as

![Figure 2. Block-diagram of proposed control system.](image-url)
Integrating and simplifying, the control law come out as
\[ u = K_b x + K_a \int_0^t (y - y_1) dt \]  
(48)

From the above equation, it is concluded that the Integral of Output Error (IOE) feedback makes the controller as robust from the modelling imperfections and step like disturbances.

5. Results and Discussions

The simulation results in Figure 3 and Figure 4 shows that, taking the estimated states such as d-q axes damper winding currents (i_{dq}^{d} and i_{dq}^{q}) as zero, the initial currents are only affected as damper currents exist only under transient condition and goes to zero at steady state. The transient response of these currents is oscillatory nature and very close to that with the actual states since the observer converges very fast. The other estimated states such as stator d-q currents (i_{ds}^{q} and i_{ds}^{d}) are nearly similar to the actual states. Comparison of non-linear reduced and full order observers is as shown in Figure 5.

6. Conclusion

For implementing sophisticated control schemes of a PMSM drive the state feedback strategy is usually employed. To apply state feedback controller, the knowledge of all the state information is required. For estimating the states of PMSM a non-linear reduced/full order observer is designed. With the reduced order observer only the inaccessible states are estimated and the remaining states are sensed from the sensors. But with the full order observer, all states are estimated with fair amount of accuracy, and concluded that the full order observer is more reliable than reduced order observer. While in design, the full order observer is very sensitive to system disturbances when compared to reduced order observer. The mathematical calculations are complex in full order observer as system states increases.

Table 1. Machine ratings of PMSM

| Motor specification | Value       |
|---------------------|-------------|
| Voltage rating      | 400V        |
| Current rating      | 2.17A       |
| Power rating        | 1.2/1.5kW   |
| Speed               | 1500rpm     |
| Number of poles     | 04          |
| Power factor        | 0.8/1.0     |
| Viscous coefficient | 0.0048N-m/sec/rad |
| Moment of Inertia   | 0.048 kg-m^2 |
Figure 4. Performance of non-linear reduced order observer with actual and estimated states.

Figure 5. Comparison of non-linear reduced and full order observers.
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