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ARTICLE

STATE ESTIMATION OF PERMANENT MAGNET SYNCHRONOUS MOTOR DRIVE USING NON-LINEAR FULL ORDER OBSERVER

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ABSTRACT

This paper presents stability analysis, robust control and estimation of damper winding currents for a non-salient pole permanent magnet synchronous motor (PMSM). The proposed work combines State feedback Controller (SFC) with a Non-linear Full order Observer (NFO) based on rotor reference frame model. The inputs to the observer are motor voltages, currents and speed. The proposed observer estimates all the four states such as damper winding currents (i_{dr} & i_{qr}) as well as stator winding currents (i_{ds} & i_{qs}) of PMSM with fair amount of accuracy. In addition to this, a state feedback controller is designed in order to control the system performance. To provide stability, a pole placement technique is used in order to shift all poles to the left half of the s-plane. The speed and position of the rotor are estimated using an encoder. By providing all these, permits the successful design of control system, which is able to maintain stability and robustness in spite of uncertainties in system dynamics and parameter imperfections.

KEY WORDS
Non-linear controller, Non-linear full order observer, Permanent Magnet synchronous Motor, PI controller,

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INTRODUCTION

In drive mechanism, the electrical machine plays a vital role. Nowadays, DC motors are of minor importance, since recent advances in power semiconductor and microprocessor technology increased the relevance of Induction and Electrically Commutated (EC) Motors for electrical drives. The EC motor like PMSM can be controlled by power electronics together with a pole position sensor and works like a DC machine. In Induction Motor (IM), the stator current contains magnetizing as well as torque producing components, whereas in PMSM due to the usage of permanent magnets on rotor magnetizing current component is absent, therefore the stator current provides only torque producing component [1]. Due to this, the PMSM can be operated at high power factor. PMSM drives are used in robotics, machine tools, pumps, ventilators, compressors etc. due to various features like good dynamic performance, easy controllability, high torque to inertia ratio, high efficiency and improved power factor [2].

In this paper, PMSM with damper windings is provided in order to damp out natural frequency of oscillations. The existence of inverse-field under transient conditions is compensated by counteracting magneto motive force of damper currents, but these currents are immeasurable. Due to this, the damper winding currents are to be estimated with fair amount of accuracy. To get stability and control, SFC [3] is designed based on a linear state feedback control [4] law and the closed loop stability is obtained using pole placement technique. In order to implement SFC, the knowledge of all the states is needed. For this purpose a non-linear full order observer [5 - 7] is designed to estimate both accessible and inaccessible states.

MODELING OF PMSM

The advantage of modelling of any machine is to limit the complexity of calculations for machine with non-constant mutual inductances and also it decouples the stator and rotor windings in order to control independently [8] [9]. For modelling of any machine, two kinds of transformation are required i.e., a 3-phase to 2-phase transformation and stationary to arbitrary rotating coordinate system [2]. The transient behaviour of a high-performance vector controlled PMSM drive is obtained using d-q model of the PMSM. The modelling of PMSM is done in rotor reference frame model, since this model is useful to control the switching elements and power on the rotor side.

The modelling equations of PMSM in rotor reference frame are given as below:

$$v_{qs} = r_a i_{qs} + l_{qs} p i_{qs} + l_{aq} p i_{qr} + \omega_r l_{ds} i_{ds} + \omega_r l_{ad} i_{dr} \quad (1)$$

$$v_{ds} = r_a i_{ds} + l_{ds} p i_{ds} + l_{ad} p i_{dr} - \omega_r l_{qs} i_{qs} - \omega_r l_{aq} i_{qr} \quad (2)$$

$$v_{dr} = r_{dr} i_{dr} + l_{dr} p i_{dr} + l_{ad} p i_{ds} \quad (3)$$

$$v_{qr} = r_{qr} i_{qr} + l_{qr} p i_{qr} + l_{aq} p i_{qs} \quad (4)$$

The electrical torque developed is,

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$$T_e = \frac{3}{2}\times\frac{P}{2}\left[(l_{ad}-l_{aq})i_{ds}i_{qs}+l_{ad}i_{qs}i_{dr}-l_{aq}i_{qr}i_{ds}\right] \tag{5}$$

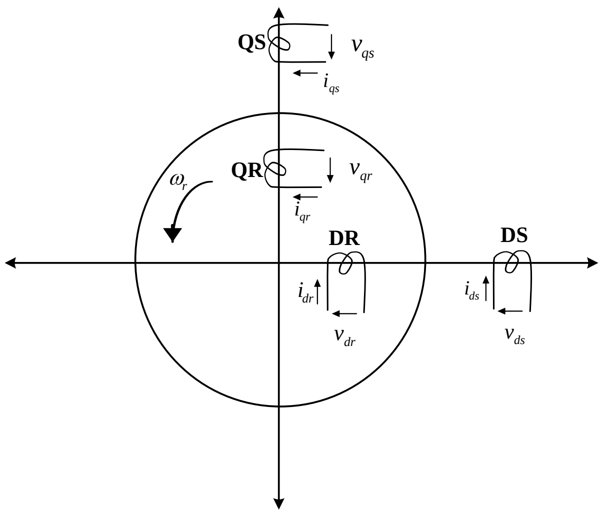

Fig: 1. Schematic of PMSM with damper windings

And the torque balance equation for no. of poles, P=4 is taken as

$$p\omega_r = \frac{2}{J}\left[T_e - T_1 - \frac{B\omega_r}{2}\right] \tag{6}$$

$$\begin{bmatrix} v_{qs}\\ v_{ds}\\ v_{qr}\\ v_{dr}\end{bmatrix} = \begin{bmatrix} r_a + l_{qs}p & \omega_r l_{ds} & l_{aq}p & \omega_r l_{ad}\\ -\omega_r l_{qs} & r_a + l_{ds}p & -\omega_r l_{qs} & l_{ad}p\\ l_{aq}p & 0 & r_{qr}+l_{qr}p & 0\\ 0 & l_{ad}p & 0 & r_{dr}+l_{dr}p\end{bmatrix}\begin{bmatrix} i_{qs}\\ i_{ds}\\ i_{qr}\\ i_{dr}\end{bmatrix} \tag{7}$$

$$\begin{bmatrix} l_{qs} & 0 & l_{aq} & 0\\ 0 & l_{ds} & 0 & l_{ad}\\ l_{aq} & 0 & l_{qr} & 0\\ 0 & l_{ad} & 0 & l_{dr}\end{bmatrix}\begin{bmatrix} pi_{qs}\\ pi_{ds}\\ pi_{qr}\\ pi_{dr}\end{bmatrix} = \begin{bmatrix} r_a & \omega_r l_{ds} & 0 & \omega_r l_{ad}\\ -\omega_r l_{qs} & r_a & -\omega_r l_{aq} & 0\\ 0 & 0 & r_{qr} & 0\\ 0 & 0 & 0 & r_{dr}\end{bmatrix}\begin{bmatrix} i_{qs}\\ i_{ds}\\ i_{qr}\\ i_{dr}\end{bmatrix} + \begin{bmatrix} v_{qs}\\ v_{ds}\\ v_{qr}\\ v_{dr}\end{bmatrix} \tag{8}$$

Thus, above equation can be written in the form of,

$$A_y\dot{x} = A_x x + B_x u \tag{9}$$

or it will be modified as,

$$\dot{x} = Ax + Bu \tag{10}$$

with $A = (A_y^{-1}A_x)$ & $B = (A_y^{-1}B_x)$

Where

$$A_x = \begin{bmatrix} r_a & \omega_r l_{ds} & 0 & \omega_r l_{ad}\\ -\omega_r l_{qs} & r_a & -\omega_r l_{aq} & 0\\ 0 & 0 & r_{qr} & 0\\ 0 & 0 & 0 & r_{dr}\end{bmatrix} \tag{11}$$

$$A_y = \begin{bmatrix} l_{qs} & 0 & l_{aq} & 0\\ 0 & l_{ds} & 0 & l_{ad}\\ l_{aq} & 0 & l_{qr} & 0\\ 0 & l_{ad} & 0 & l_{dr}\end{bmatrix} \tag{12}$$

$$x = \begin{bmatrix} i_{qs} & i_{ds} & i_{qr} & i_{dr}\end{bmatrix}^T \tag{13}$$

$$B_x = \begin{bmatrix} 1 & 0\\ 0 & 1\\ 0 & 0\\ 0 & 0\end{bmatrix} \tag{14}$$

DESIGN OF A NON-LINEAR FULL ORDER OBSERVER

Development of a high performance controller-observer needs an accurate estimation of machine states. So far, numerous methods have been presented [10-14] to estimate the states of synchronous machine. Out of all, observers are desirable, which augment or replace sensors in a control system. An Observer [10] can be defined as an algorithm that produces observed signals from the sensed signals with the knowledge of the control system. These signals are accurate, less expensive and more reliable than sensed signals. In PMSM, four states such as stator and damper winding currents have to be estimated to implement SFC. For this purpose, a NFO [15-17] is designed. The design of NFO is as follows:
The system equations of PMSM in state space form

$$\dot{x} = Ax + Bu \tag{15}$$

$$y = Cx \tag{16}$$

Let a new vector ζ of dimension 'n' (n=no. of states) be defined as,

$$\zeta = Lx \tag{17}$$

where L = transformation matrix and the dimension of 'x' is 4×1 as it associated with i_{qs}, i_{ds}, i_{qr} and i_{dr} vectors, 'ζ' will be 4×1 as it has to estimate all the four states and the dimension of 'L' will be 4×4. Then, the equations (16) and (17) can be combined as,

$$\begin{bmatrix} y \\ \hat{\zeta} \end{bmatrix} = \begin{bmatrix} C \\ L \end{bmatrix} x \tag{18}$$

From the above equation, the estimated states $\hat{x}$ can be written as,

$$\hat{x} = \begin{bmatrix} C \\ L \end{bmatrix}^{-1} \begin{bmatrix} y \\ \hat{\zeta} \end{bmatrix} \tag{19}$$

A full order observer [7] can be represented by,

$$\dot{\hat{\zeta}} = D\hat{\zeta} + Gu + Fy \tag{20}$$

Here, F to be chosen as

$$F = F_1 + (\omega_r - \omega_d)F_2 \tag{21}$$

The nonlinearity of observer can be cancelled by choosing the matrix F_2 as

$$F_2 = L(A_y^{-1})F_3 \tag{22}$$

Here, the design constant ω_d can be chosen as the average operating speed; resulting the non-linear term magnitude remains small. Now, the matrix F_3 is chosen as,

$$F_3 = \begin{bmatrix} 0 & -l_{ds} \\ l_{qs} & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \tag{23}$$

Differentiating equation (17) and using equations (20) and (15), the error in the estimate of ζ can be given as,

$$\dot{\tilde{\zeta}} = \dot{\hat{\zeta}} - \dot{\zeta} = D\hat{\zeta} + (G - LB)u + [F_1C + (\omega_r - \omega_{d2})F_2C - L(A_1 + \omega_{d2}A_2) - (\omega_r - \omega_{d2})LA_2]x \tag{24}$$

For an accurate estimate of ζ

$\tilde{\zeta} \to 0$ or $\hat{\zeta} \to \zeta$, as $t \to \infty$

In the above equation (24), the effect of 'u' can be eliminated by choosing

$$G = LB \tag{25}$$

Substituting equations (21) and (25) in equation (24) and rearranging,

$$\dot{\tilde{\zeta}} = D(\hat{\zeta} - \zeta) - [LA_d - F_1C - DL + (\omega_r - \omega_{d2})L(A_2 - A_y^{-1}F_3C)]x \tag{26}$$

For the error estimation of ζ, $\dot{\tilde{\zeta}} = \dot{\hat{\zeta}} - \dot{\zeta}$ to decay,

(i) $L(A_2 - A_y^{-1}F_3C) = 0$ (27)

(ii) $LA_d - F_1C - DL = 0$ (28)

(iii)D should be a stable matrix such that

$$\{\lambda_i\}_D \neq \{\lambda_i\}_A \tag{29}$$

The matrices D, L and F_1 can selected using the above three conditions. To satisfy condition (i), the matrix L is chosen as

$$L = \begin{bmatrix} l_{11} & l_{12} & l_{13} & l_{14} \\ l_{21} & l_{22} & l_{23} & l_{24} \\ l_{31} & l_{32} & l_{33} & l_{34} \\ l_{41} & l_{42} & l_{43} & l_{44} \end{bmatrix} \tag{30}$$

Where, one possible solution is given as

$$l_{11} = \frac{\Delta_1}{r_a l_{qr}}, \quad l_{12} = \frac{\Delta_2}{\omega_{d2} l_{qs} l_{dr}}, \quad l_{13} = \frac{\Delta_1}{r_a l_{aq}}, \quad l_{14} = \frac{\Delta_2}{\omega_{d2} l_{qs} l_{ad}}$$

$$l_{21} = \frac{\Delta_1}{\omega_{d2} l_{ds} l_{qr}}, \quad l_{22} = \frac{\Delta_2}{r_a l_{dr}}, \quad l_{23} = \frac{\Delta_1}{\omega_{d2} l_{aq} l_{ds}}, \quad l_{24} = \frac{\Delta_2}{r_a l_{ad}}$$

$$l_{31} = \frac{\Delta_1}{r_{qr} l_{aq} l_{qs} l_{qr}}, \quad l_{32} = \frac{\Delta_2}{\omega_{d2} l_{aq} l_{dr}}, \quad l_{33} = \frac{\Delta_1}{r_{qr} l_{aq}^2 l_{qs}}, \quad l_{34} = \frac{\Delta_2}{\omega_{d2} l_{aq} l_{ad}}$$

$$l_{41} = \frac{\Delta_1}{\omega_{d2} l_{ad} l_{qr}}, \quad l_{42} = \frac{\Delta_2}{r_{dr} l_{ad} l_{ds} l_{dr}}, \quad l_{43} = \frac{\Delta_1}{\omega_{d2} l_{ad} l_{aq}}, \quad l_{44} = \frac{\Delta_2}{r_{dr} l_{ad}^2 l_{ds}}$$

with

$$\Delta_1 = l_{qs} l_{qr} - (l_{aq})^2$$

$$\Delta_2 = -(l_{ad})^2 (l_{ds} + l_{dr} - 2 l_{ad})$$

To find the matrices F_1 and D, we can solve the simultaneous equations from conditions (i) and (ii), where

$$F_1 = \begin{bmatrix} f_{11} & f_{12} \\ f_{21} & f_{22} \\ f_{31} & f_{32} \\ f_{41} & f_{42} \end{bmatrix} \tag{31}$$

$$D = \begin{bmatrix} d_{11} & d_{12} & d_{13} & d_{14} \\ d_{21} & d_{22} & d_{23} & d_{24} \\ d_{31} & d_{32} & d_{33} & d_{34} \\ d_{41} & d_{42} & d_{43} & d_{44} \end{bmatrix} \tag{32}$$

DESIGN OF A CONTROL SYSTEM

[Fig. 2] shows block diagram of the proposed control system [18] in the conventional two-loop structure; the outer speed loop and the inner current loop for an SPWM voltage source inverter fed PMSM drive.

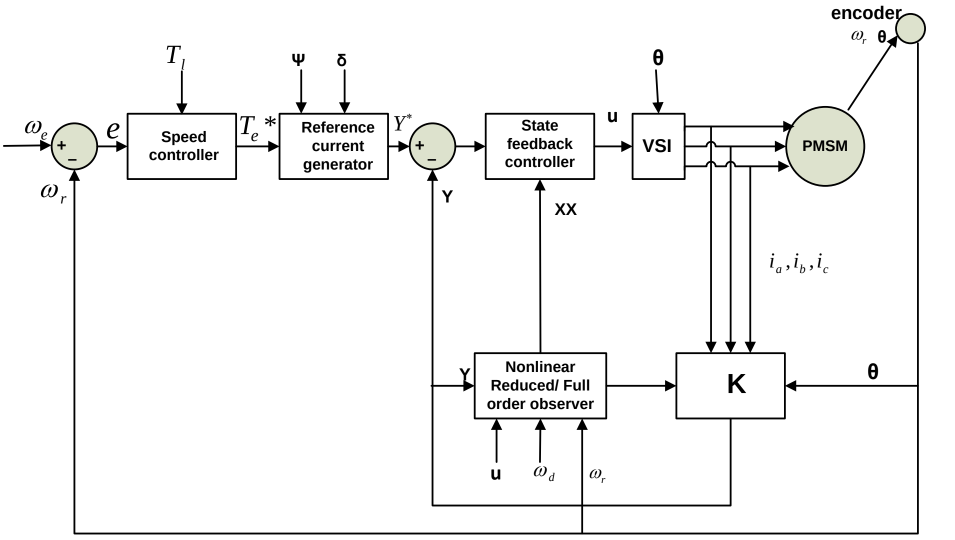

Fig. 2: Block diagram of the proposed control system

Design of Speed Controller

In the outer loop, PI controller is used as speed controller and the output of this controller is reference torque T_e*, from which the reference currents i_q* and i_d*are generated. The PI controller gain constants are designed as given below:

Considering the torque balance equation for number of poles P=4

$$p\omega_r = \frac{2}{J}\left[T_e - T_1 - \frac{\beta\omega_r}{2}\right] \tag{33}$$

The equation of speed controller is

$$T_e^* = K_p e + K_i \int_0^t e dt \tag{34}$$

Where, $e = \omega_e - \omega_r$ =speed error (35)

Substituting equations (34) & (35) in equation (33) and taking Laplace transform, we get

$$(s\omega_r - \omega_{r0}) = \frac{2}{J}\left[\left(K_p + \frac{K_i}{s}\right)(\omega_e - \omega_r) - T_1 - \frac{\beta\omega_r}{2}\right]$$

For T_l=0 and ω_{r0}= ω_e, rearranging the terms in the above equation

$$\left[s + \frac{\beta}{J} + \frac{2}{J}\left(K_p + \frac{K_i}{s}\right)\right]\omega_r = \left[\frac{2}{J}\left(K_p + \frac{K_i}{s}\right) + 1\right]\omega_e \tag{36}$$

From which the ratio, (ω_r/ω_e) is obtained as

$$\left(\frac{\omega_r}{\omega_e}\right) = \frac{\frac{2}{J}\left(K_p + \frac{K_i}{s}\right) + 1}{s + \frac{\beta}{J} + \frac{2}{J}\left(K_p + \frac{K_i}{s}\right)} = \frac{\left[\frac{2}{J}K_p + 1\right]s + \frac{2}{J}K_i}{s^2 + \left[\frac{\beta}{J} + \frac{2}{J}K_p\right]s + \frac{2}{J}K_i} \tag{37}$$

The characteristic equation of the above system is

$$s^2 + \left[\frac{\beta}{J} + \frac{2}{J}K_p\right]s + \frac{2}{J}K_i = 0 \tag{38}$$

The standard second order control system characteristic equation is

$$s^2 + 2\xi\omega_n s + \omega_n^2 = 0 \tag{39}$$

On comparing equations (38) & (39)

$$K_i = \frac{J}{2}\omega_n^2 \tag{40}$$

$$K_p = J\xi\omega_n - \frac{\beta}{2} \tag{41}$$

Where,

ξ =damping ratio, and ω_n= natural frequency of oscillations.

Assigning proper values of ξ and ω_n, using the machine parameters of J and β, the gain constants K_p and K_i are computed.

Determination of reference currents

The developed electrical torque given by equation (5) is a non-linear function of stator and rotor currents of PMSM. So for the generation of same torque, different values of reference currents are possible. To obtain unique solution for reference currents, the following three conditions are imposed

(a)Arbitrary setting of ψ.
(b)Arbitrary setting of δ
(c) Reference currents should be real valued.

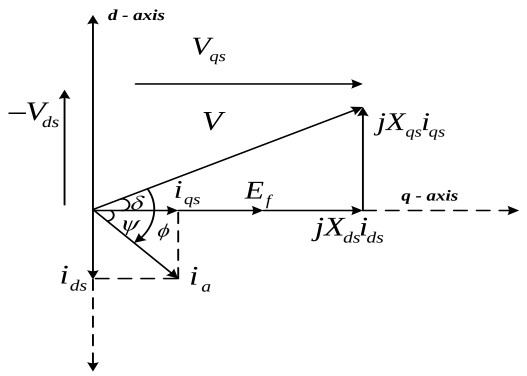

Fig: 3. Phasor diagram

From the phasor diagram of a PMSM as shown in figure 3

$$\tan\delta = \frac{-v_{ds}}{v_{qs}} \tag{42}$$

Substituting v_{qs} and v_{ds} values in eqn. (42)

$$\tan\delta = \frac{-r_a i_{ds} - l_{ds} p i_{ds} - l_{ad} p i_{ds} + \omega_r l_{qs} i_{qs} + \omega_r i_{aq} i_{qr}}{r_a i_{qs} + l_{qs} p i_{qs} + l_{aq} p i_{qr} + \omega_r l_{ds} i_{ds} + \omega_r l_{ad} i_{dr} + \omega_r \Psi} \quad (43)$$

Under steady state condition all p or $\frac{d}{dt}$ terms as well as i_{dr} and i_{qr} assumed to be zero. So

$$\tan\delta = \frac{\omega_r l_{qs} i_{qs} - r_a i_{ds}}{r_a i_{qs} + \omega_r l_{ds} i_{ds} + \omega_r \Psi} \quad (44)$$

Also,

$$i_{ds} = i_{qs} \tan\psi \quad (45)$$

With a permanent magnet on the rotor, the motor has a constant flux linkage (Ψ). Three sets of formulae for reference currents are derived-one with specified δ, second one with specified ψ and the third one for field oriented case.

The reference currents with δ specification are given as

$$i_{qs}^* = \frac{T_e^*}{3(l_{ad} - l_{aq}) i_{ds} + \Psi} \quad (46)$$

$$i_{ds}^* = \frac{-q_2 \pm \sqrt{q_2^2 - 4q_1 q_3}}{2q_1}. \quad (47)$$

where

$$q_1 = 3(l_{ad} - l_{aq})(-r_a - \omega_r l_{ds} \tan\delta)$$

$$q_2 = -3(l_{ad} - l_{aq})\omega_r \Psi \tan\delta + 3\Psi(-r_a - \omega_r l_{ds} \tan\delta)$$

$$q_3 = -3\Psi^2 \omega_r \tan\delta - (r_a \tan\delta - \omega_r l_{qs}) T_e^*$$

The reference currents with ψ specification are given as

$$i_{qs}^* = \frac{-3\Psi \pm \sqrt{9\Psi^2 + 12 T_e^* (l_{ad} - l_{aq}) \tan\psi}}{6(l_{ad} - l_{aq}) \tan\psi} \quad (48)$$

$$i_{ds}^* = i_{qs}^* \tan\psi \quad (49)$$

The reference currents for field oriented case are given as

$$i_{qs}^* = \frac{T_e^*}{3\Psi} \quad (50)$$

$$i_{ds}^* = 0 \quad (51)$$

State Feedback Controller

For the regulator model of given multivariable system, the linear feedback control [4, 20] law is applied with a gain matrix of K. In addition, to have complete control over the system dynamics a pole placement technique [19] is used.

Now partitioning K into K_{bs} and K_{is}, multiplied with the regulator model, the control signal 'u' can be given as

$$\dot{u}_2 = Kz = \begin{bmatrix} K_{bs} & K_{is} \end{bmatrix} \begin{bmatrix} \dot{x} \\ y - y_r \end{bmatrix} \quad (52)$$

Integrating and simplifying the above equation, the control law becomes

$$u_2 = K_{bs} x + K_{is} \int_0^t (y - y_r) dt \quad (53)$$

From the above equation, it is concluded that IOE feedback makes the controller as robust from the modelling imperfections and step like disturbances.

Pole Placement by State Feedback

In order to have complete control over the system dynamics the controller has been designed by placing the poles of the closed loop system at the desired locations in the s-plane.

For a linear time invariant system represented by

$$\dot{x} = Ax + Bu_2 \quad (54)$$

with the state feedback control law as

$$u_2 = K_2 x \quad (55)$$

the closed loop system becomes

$$\dot{x} = (A + BK_2)x \quad (56)$$

which can have arbitrary or prescribed eigen values, if and only if, the pair (A, B) is controllable.

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RESULTS AND DISCUSSION

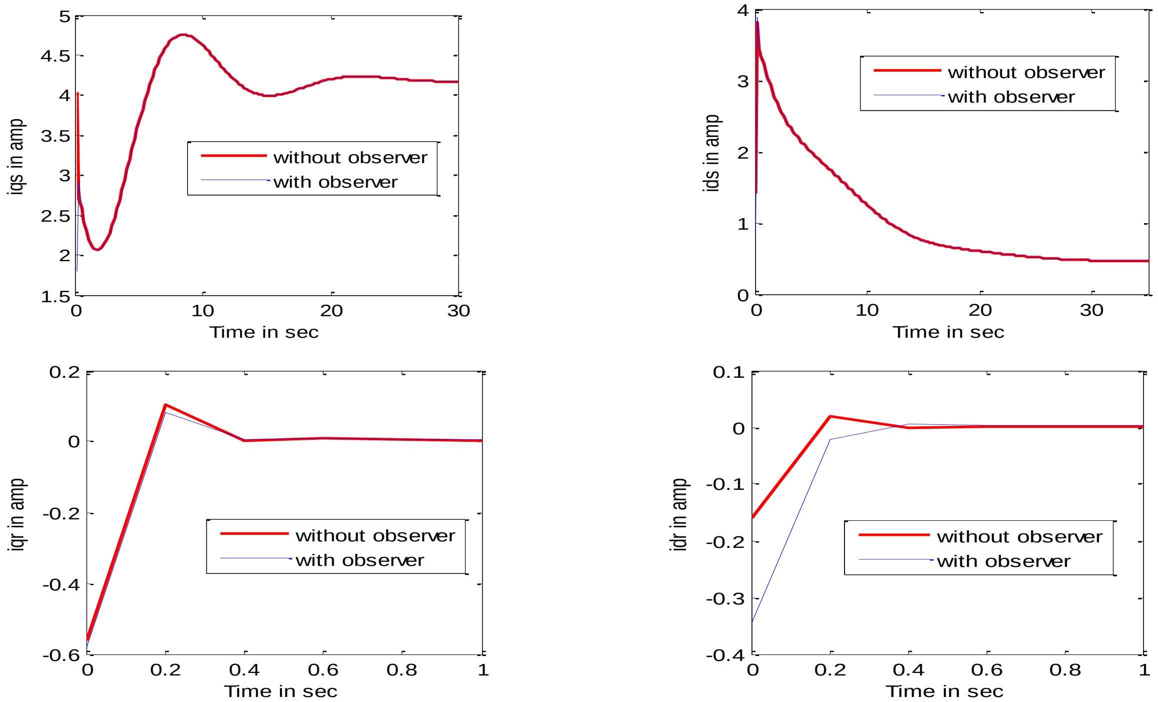

Fig. 4: Simulations results of PMSM drive with and without non-linear full order observer

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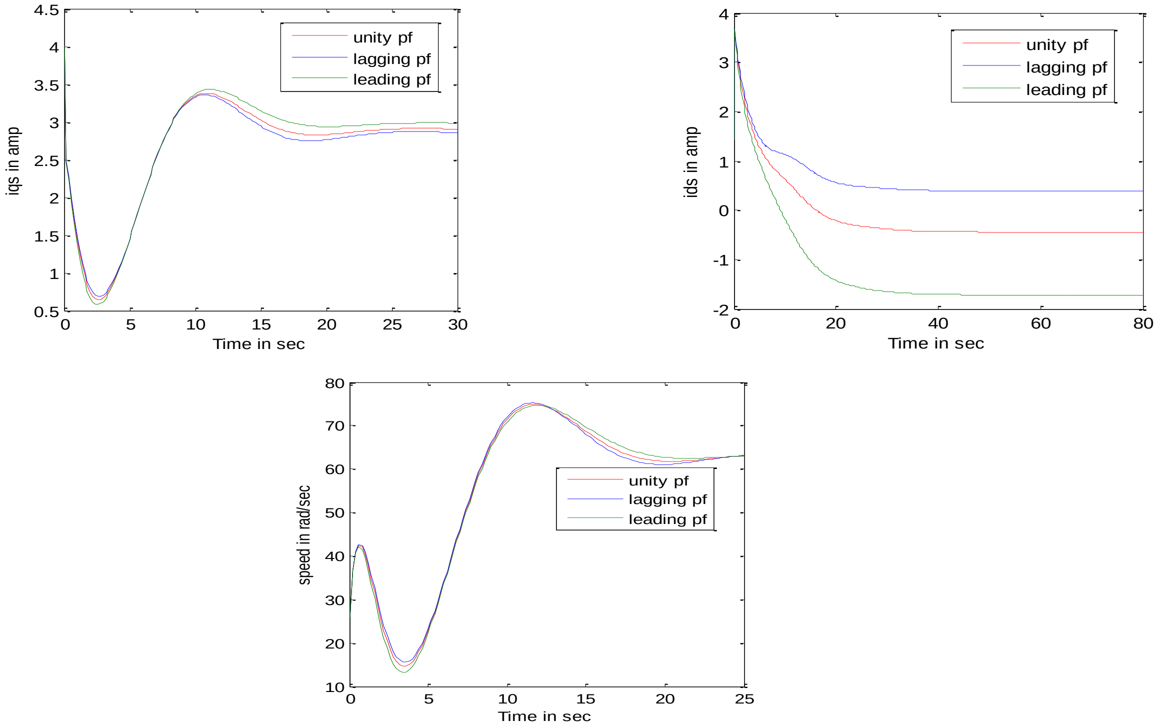

Fig.5: Simulation results of PMSM drive for delta variation (a) δ=8.735^0 (u.p.f) (b)) δ=5^0 (lagging p.f) (c) δ=15^0 (leading p.f)

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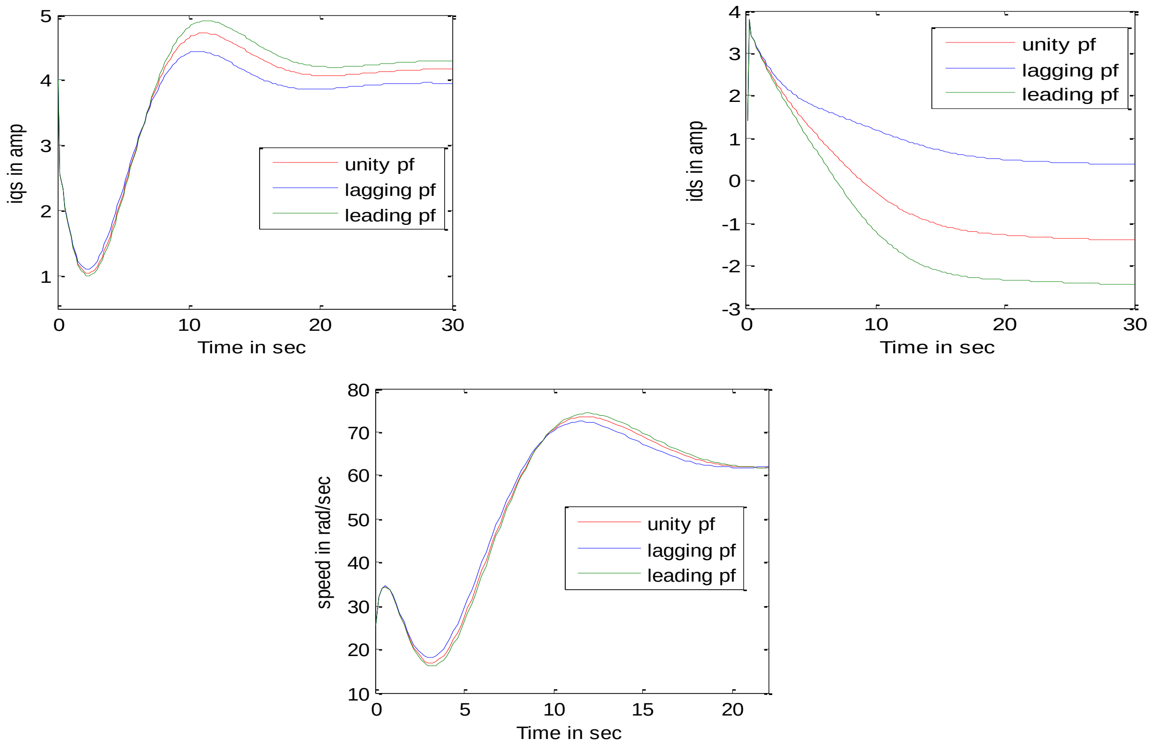

Fig: 6. Simulation results of PMSM drive for psi variation (a) ψ=-19.1⁰(u.p.f) (b) ψ=5⁰(lagging p.f) (c) ψ=-30⁰(leading p.f)

From the results shown in [Fig. 4], the estimated damper winding currents (i.e. i_{qr} & i_{dr}) in it's steady state are observed as zero; the initial currents are only affected, as damper currents exist only under transient conditions and goes to zero at steady state. The transient response of these currents is oscillatory in nature and very close to that with the actual states. The other estimated states such as stator currents (i.e. i_{qs} & i_{ds}) are nearly similar to the actual states. [Fig. 5 and 6] shows the simulation results of the drive for different values of ψ and δ resulting in variation of power factor from lagging to leading including unity. From the results it is clear that the settling values of i_{ds} has large variations for different values of power factor, which clearly indicates the effect of magnetizing current for corresponding values of power factor.

Table 1. Performance PMSM drive with and without non-linear full order observer

Variable	Actual values			Estimated values		
	Initial peak value	Steady state value	Settling time (sec)	Initial peak value	Steady state value	Settling time (sec)
i_{qs}	4.03	4.188	40	2.91	4.188	40
i_{ds}	3.81	0.44	41	3.88	0.44	41
i_{qr}	0.105	0.00	01	0.08	0.00	0.4
i_{dr}	0.021	0.00	01	0.006	0.00	0.3

Table 2. Performance figures of PMSM with variable δ

Design Specifi-cations						Achieved performance figures				
	δ (deg.)	ψ (deg.)	ϕ (deg.)	cosϕ	Vari-able	Change in ω_r		Change in T_l		Settling time (sec.)
						S.S. Value	Peak Value	S.S. Value	Peak Value	
δ =3.8⁰ (min.)	3.8	19.6	23.4	-0.14	i_{qs} i_{ds} ω_r	3.87 1.38 62.83	4.5 3.8 74.7	3.87 1.38 62.83	4.62 3.6 76.1	26.0 38.5 39.0
δ =8.73⁰	8.73	-8.73	0.0	1.0	i_{qs} i_{ds} ω_r	2.91 -0.42 62.8	3.37 3.66 74.9	2.99 -0.37 62.8	3.40 3.52 75.5	25.5 33.5 37.0
δ =35⁰ (max.)	35.0	-40.6	-5.6	0.78	i_{qs} i_{ds} ω_r	4.54 -3.89 62.83	5.22 3.72 77.2	4.54 -3.89 62.83	5.3 3.4 78.3	27.0 35.0 38.0

Table 3. Performance figures of PMSM with variable ψ

Design Specifications	Achieved performance figures									
	δ (deg.)	ψ (deg.)	ф (deg.)	cosф	Variable	Change in ω_r		Change in T_l		Settling time (sec.)
						S.S. value	Peak value	S.S. value	Peak value	
ψ=-49⁰ (min.)	43.67	-49	-5.33	0.76	i_{qs}	4.54	5.55	4.8	5.92	26.4
					i_{ds}	-5.23	3.75	-5.5	3.56	29.5
					ω_r	62.84	78.3	62.83	80.0	24.16
ψ=-19.1⁰	19.1	-19.1	0.0	1.0	i_{qs}	4.16	4.72	4.22	4.83	27.6
					i_{ds}	-0.38	3.67	-1.42	3.6	29.6
					ω_r	62.8	74.9	62.9	74.5	24.14
ψ=62⁰ (max.)	-14.73	62.0	47.27	-0.99	i_{qs}	3.39	3.9	3.39	4.07	27.8
					i_{ds}	6.37	6.5	6.38	6.5	29.7
					ω_r	62.77	69.7	62.83	71.4	24.16

From [Table 1] it is clear that, the initial peak values of estimated variables are low when compared to the actual values. The steady state values are equal in both actual and estimated, also settled at equal time. But in case of estimated damper winding currents the settling time is very low i.e, the observer converges very fast.

From [Table 2] it is clear that, for the design specifications of torque angle δ, the motor reaches its speed at a steady value of 20π rad/sec either as a result of change in reference frequency or load torque. Here the settling time lies between 25sec-39sec.

From [Table 3] it is clear that, for the design specifications of internal p.f angle ψ, the motor reaches its speed at a steady value of 20π rad/sec either as a result of change in reference frequency or load torque. Here the settling time lies between 24sec-30sec.

CONCLUSION

In order to implement sophisticated control schemes for PMSM drive, the state feedback approach is usually employed. The implementation of state feedback control requires that all the system states are available for feedback. So, a non-linear full order observer is designed for the estimation of both accessible and inaccessible states in orders to feedback all the states to state feedback controller. By designing full order observer, the information which is provided by sensors is completely eliminated from the control system. Although in the particular design, because of the special structure of the system matrices, the non-linear term automatically gets cancelled through the full order observer design. Due to this, the system becomes less expensive, more accurate and reliable.

Appendix-A: Machine Ratings

Rated voltage=400V, Rated current=2.17A, Rated speed=1500rpm, No. of poles=4, Power rating: 1.2/1.5 kW, 0.8/1.0 p.f

CONFLICT OF INTEREST

There is no conflict of interest.

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None

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