State Estimation of Permanent Magnet Synchronous Motor Drive Using Non-linear Full Order Observer

Jallu hareesh kumar[1], Adavipalli Chandana[2], Janardhan[3]

[1]*Assistant Professor, Dept. Of EEE, SVCET, Srikakulam, Andhra Pradesh, (India)*

[2]*Assistant Professor, Dept. Of EEE, SVCET, Srikakulam, Andhra Pradesh,(India)*

[3]*PG Scholar, Dept. Of EEE, SVCET, Srikakulam, Andhra Pradesh, (India)*

ABSTRACT

This paper presents the stability analysis, robust control and estimation of damper winding currents for the non-salient pole permanent magnet synchronous motor (PMSM). The proposed work combines State feedback Controller (SFC) with a non-linear full order observer 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, a state feedback controller is designed in order to control the system performance. 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.

Keywords: Non-linear full-order observer, Permanent Magnet synchronous Motor, PI controller, Rotor reference frame, State feedback controller.

I. 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. The PMSM is a synchronous machine only, but the electrical excitation was replaced by permanent magnet-excitation, therefore there is no excitation voltage source, field winding, collecting rings and brushes, resulting in improving efficiency. By considering all the features of PMSM such as good dynamic performance, easy controllability, high torque to inertia ratio, high efficiency and improved power factor [2] these drives are used in robotics, machine tools, pumps, ventilators, compressors etc.

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 importance of damper windings, the damper winding currents are to be estimated with fair amount of accuracy. For this purpose a non-linear observer is designed. To get stability and control a State Feedback Controller [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] [6] [7] is designed to estimate both accessible and inaccessible states.

II. MODELING OF PMSM

The design of control system for high performance drive requires a mathematical model [8] [9] of motor. The advantage of modeling of any machine is, to limit the complexity of the calculations for machine with non constant mutual inductances and also it decouples the stator and rotor windings in order to control independently. 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.

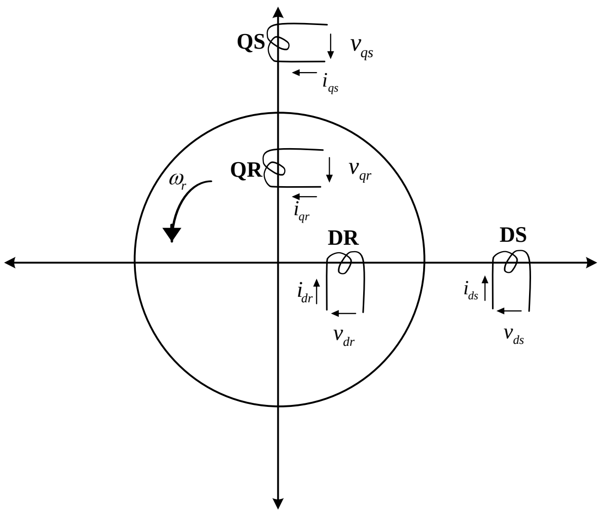

Fig 1: Schematic of PMSM with damper windings

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

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

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

$$v_{dr} = r_{dr} i_{dr} + l_{dr} p i_{dr} + l_{ad} p i_{ds} \tag{3}$$

$$v_{qr} = r_{qr} i_{qr} + l_{qr} p i_{qr} + l_{aq} p i_{qs} \tag{4}$$

The electrical torque developed is,

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

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

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

The above equations can be written in matrix form as,

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

Now to bring these equations in terms of state space representation and the modified equations as,

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

From the above equation we can define the following matrices for simplification,

$$A_x = \begin{bmatrix} r_a & \omega_r l_{ds} & 0 & \omega_r l_{ad} \\ -\omega_r l_{qs} & r_a & -\omega_r l_{aq} & 0 \\ 0 & 0 & r_{qr} & 0 \\ 0 & 0 & 0 & r_{dr} \end{bmatrix} \tag{9}$$

$$A_y = \begin{bmatrix} l_{qs} & 0 & l_{aq} & 0 \\ 0 & l_{ds} & 0 & l_{ad} \\ l_{aq} & 0 & l_{qr} & 0 \\ 0 & l_{ad} & 0 & l_{dr} \end{bmatrix} \tag{10}$$

$$x = \begin{bmatrix} i_{qs} & i_{ds} & i_{qr} & i_{dr} \end{bmatrix}^T \tag{11}$$

$$B_x = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \tag{12}$$

Thus, equation (8) can be written in the form,

$$A_y \dot{x} = A_x x + B_x u \tag{13}$$

or it will be modified as,

$$\dot{x} = Ax + Bu \tag{14}$$

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

III. 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][11][12][13] to estimate the states of synchronous machine. Out of all, observers are desirable, which augment or replace sensors in a control system. The Observer [10] can be defined as an algorithm that produces observed signals from the sensed signals with the knowledge of the control system. These observed signals are accurate, less expensive and more reliable than sensed signals. In PMSM, four states such as stator currents and damper currents have to be estimated to implement SFC. For this, a nonlinear full order observer [14][15][16] is designed to estimate all the states and fed back to the SFC.

The design of a nonlinear full order observer is as follows:

The system and the output equations of a PMSM can be written in state space form as,

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

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

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 is a dynamical system driven by the inputs and outputs of the actual system and can be represented by,

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

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

Here, F to be chosen as

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

The nonlinearity of observer can be cancelled out by using the matrix F_2, which can be chosen 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 nonlinear term magnitude remains small. Now, the matrix F_3 is chosen as,

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

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

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

For an asymptotically accurate estimate of ζ

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

The effect of u in equation (24) can be eliminated by choosing

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

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

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

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

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

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

(iii)D should be a stable matrix with the restriction 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

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

We can solve the simultaneous equations from conditions (i) and (ii) to find F_1 and D matrixes, where

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

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

IV. DESIGN OF A CONTROL SYSTEM

Fig. 2 shows the proposed control system for the motor drive represented in the conventional two-loop structure. In these two loops, outer loop is speed loop using a PI controller and the inner loop is current loop for an SPWM voltage source inverter [17-18] fed PMSM drive.

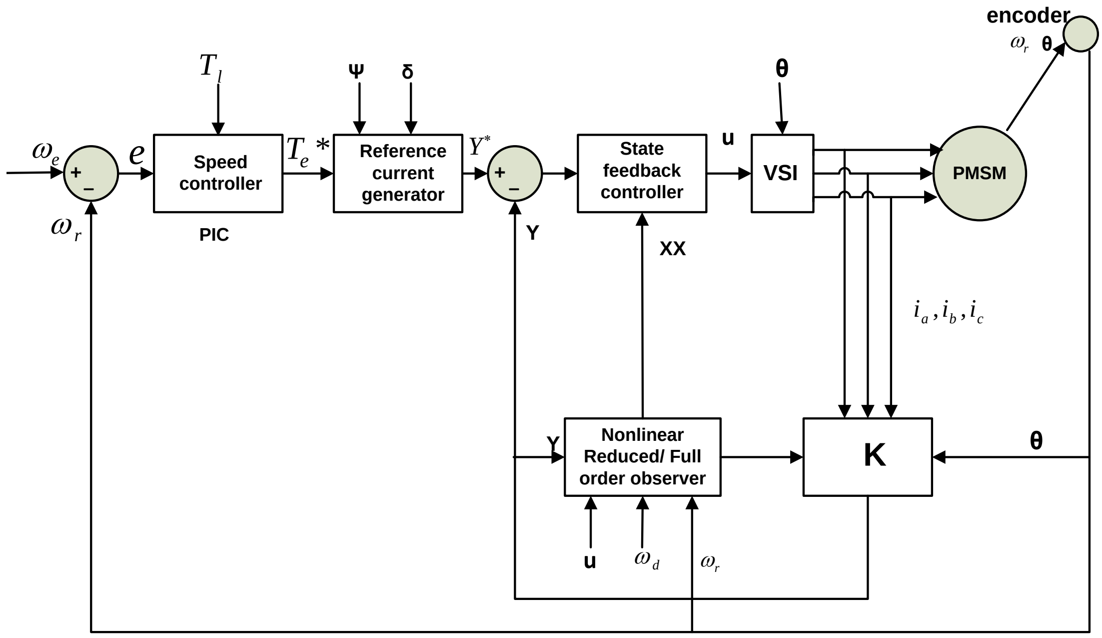


Fig 2: Block diagram of the proposed control system

4.1 State Feedback Controller

For the regulator model of given multivariable system, the linear feedback control [4] law is applied with a gain matrix of K. In addition, to have complete control over the system dynamics a pole placement technique [17] is used. In this, 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_{bs} and K_{is}, 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

$$\dot{u} = Kz = \begin{bmatrix} K_{bs} & K_{is} \end{bmatrix} \begin{bmatrix} \dot{x} \\ y - y_r \end{bmatrix} \quad (33)$$

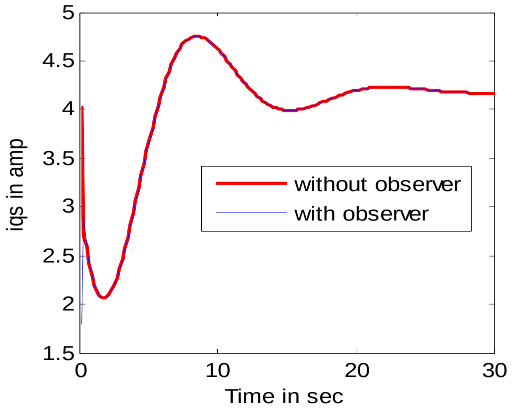
Integrating and simplifying, the control law come out as

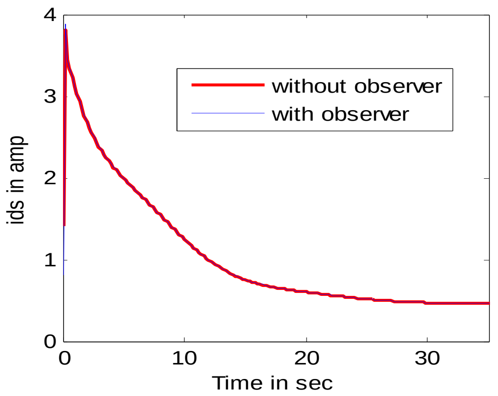
$$u = K_{bs}x + K_{is}\int_0^t (y - y_r)dt \qquad (34)$$

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

V. RESULTS AND DISCUSSION

From the results shown in figure 3, the estimated states such as d-q axes damper winding currents (i_{qr} & i_{dr}) in its 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 since the states with the observer converges very fast. The other estimated states such as stator d-q currents (i_{qs} & i_{ds}) are nearly similar to the actual states. Figure 4 and 5 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.





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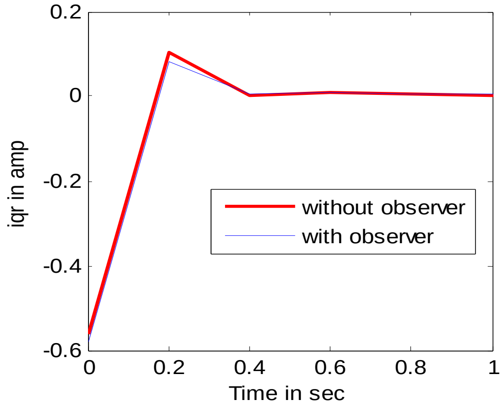


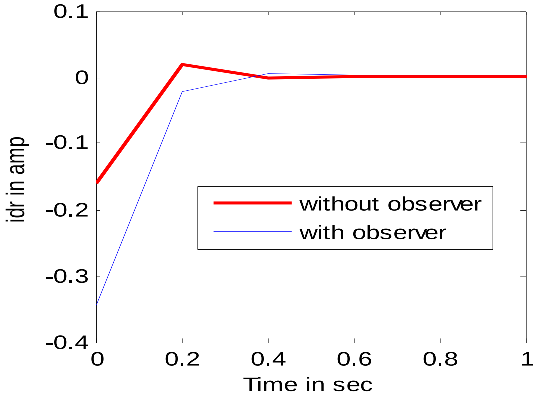
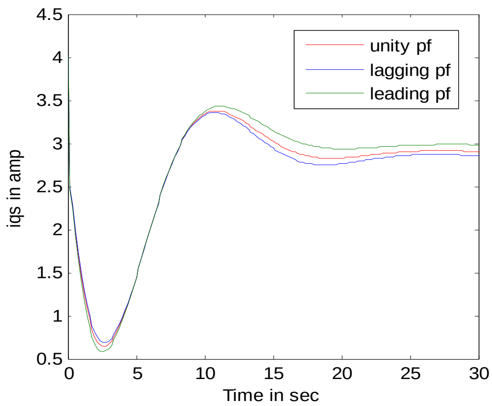
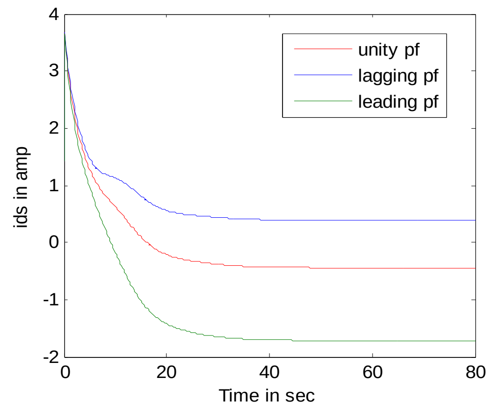


Fig 3: Simulation results of PMSM drive with and without non-linear full order observer





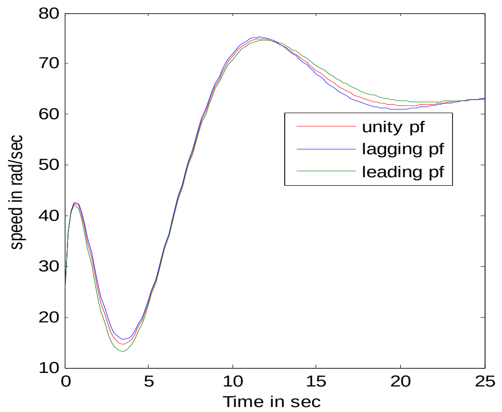
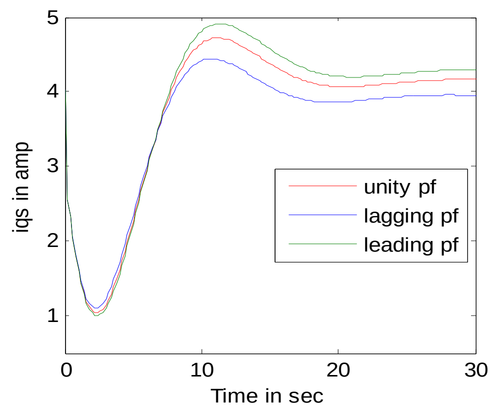


Fig 4: Simulation results of PMSM drive for delta variation (a) δ=8.735^0 (u.p.f) (b)) δ=5^0 (lagging p.f) (c) δ=15^0 (leading p.f)



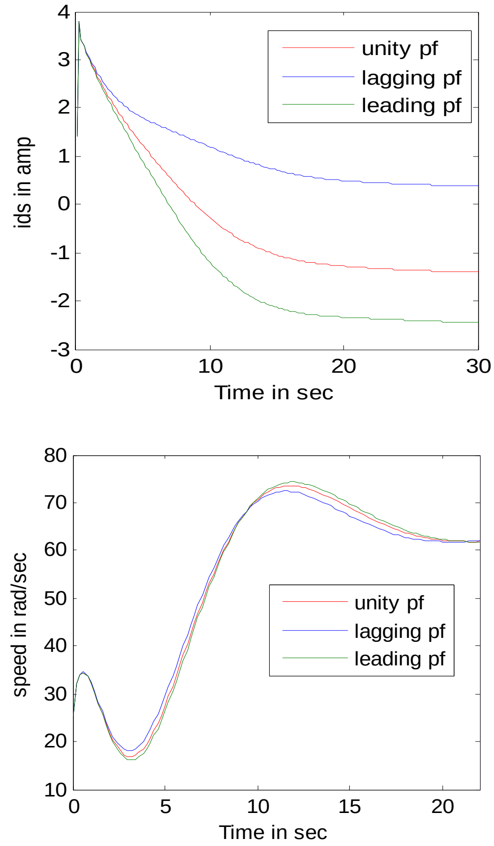


Fig 5: Simulation results of PMSM drive for psi variation (a) ψ=-19.1^0(u.p.f) (b) ψ=5^0(lagging p.f) (c) ψ=-30^0(leading p.f)

VI. 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 nonlinear full order observer is designed for the estimation of both accessible and inaccessible states in orders to feedback all states to state feedback controller. By designing of 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

Ratings of Permanent Magnet Synchronous Motor:

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

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