World Academy of Science, Engineering and Technology
International Journal of Electrical and Computer Engineering
Vol:5, No:8, 2011

Design of a Non-linear Observer for VSI Fed Synchronous Motor

P. Ramana , K. Alice Mary, M. Surya Kalavathi, M. Phani Kumar

Abstract**—**This paper discusses two observers, which are used for the estimation of parameters of PMSM. Former one, reduced order observer, which is used to estimate the inaccessible parameters of PMSM. Later one, full order observer, which is used to estimate all the parameters of PMSM even though some of the parameters are directly available for measurement, so as to meet with the insensitivity to the parameter variation. However, the state space model contains some nonlinear terms i.e. the product of different state variables. The asymptotic state observer, which approximately reconstructs the state vector for linear systems without uncertainties, was presented by Luenberger. In this work, a modified form of such an observer is used by including a non-linear term involving the speed. So, both the observers are designed in the framework of nonlinear control; their stability and rate of convergence is discussed.

Keywords**—**Permanent magnet synchronous motor, Mathematical modelling, Rotor reference frame, parameter estimation, Luenberger observer, reduced order observer, full order observer

I. INTRODUCTION

THE permanent magnet synchronous motor is an excellent machine for servo and high performance applications because of its high torque to inertia ratio, high power density and high efficiency [9]. In high performance variable speed drive systems the motor speed should closely follow a specified reference trajectory regardless of load disturbances, parameter variations and model uncertainties [6]. Among AC drives, the permanent magnet synchronous motor has become popular due to its advantageous features. So, nowadays industries showing greater interest especially for applications in low-medium power range, since they have superior features such as compact size, high torque/ weight ratio, high torque/ inertia ratio and absence of rotor losses. Due to these advantages this type of drive is preferred for aerospace or automotive applications, where their high reliability is also a very important aspect, more than efficiency and sometimes even more than a reduced cost [11]. Also, some applications and processes rely on variable speed AC drives based on permanent magnet synchronous motors. Due to their advantages, these machines are replacing classical DC and induction motor drives and it is expected that they can become more important in the future. But the useful life of industrial synchronous motors is dependent on many factors including ambient temperature, severity of over and under voltages and voltage imbalances [12].The electric drive is the source of mechanical energy at various systems. They have a lot of advantages in comparison with the others sources of mechanical energy. Especially it is high efficiency, great power density, excellent behaviour at dynamic states and wide speed and torque ranges. The synchronous machine with permanent magnets (SMPM) can be considered as the most modern of them. The development of these machines is given by the evolvement of permanent magnets. Accurate estimation of machine parameters is quite important for the development of a high performance controller. Several methods have been presented so far for estimating the machine parameters for synchronous machine [13]. Of which, observers can be used to augment or replace sensors in a control system. Observers are algorithms that combine sensed signals with other knowledge of the control system to produce observed signals [23]. These observed signals can be more accurate, less expensive to produce, and more reliable than sensed signals. Observers offer designers an inviting alternative to add new sensors or upgrading existing ones [19].

P. Ramana is with GMR Institute of Technology, Rajam, AP. He is presently working as an Associate Professor, EEE Department. (email: pramana.gmrit@gmail.com)

Dr. K. Alice Mary is with Vignan Institute of Information Technology, Visakhapatnam, AP. She is presently working as a Professor & Head, EEE Department. (email: k.alicemary@gmail.com)

Dr.M. Surya Kalavathi is with JNTU, Hyderabad, AP. She is presently working as a Professor, EEE Department (email: munugala123@yahoo.com)

M. Phani Kumar is with the GMR Institute of technology, Rajam, AP, Pursuing M.Tech. (email: phani.yourfriend@gmail.com)

II. MODELLING OF PMSM

The permanent magnet motors are similar to the salient pole motors, except that there is no field winding and the field is provided instead by mounting permanent magnets in the rotor. The excitation voltage can’t be varied. The elimination of field coil, dc supply and slip rings reduces the motor loss and complexity. These motors, also known as “Brushless Motors” are finding increasing applications in robots and machine tools.

The voltage equations for the permanent magnet motor are,

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

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

$$v_{qr} = r_{qr} i_{qr} + l_{qr} p i_{qr} + l_{aq} p i_{qs} \quad (3)$$

$$v_{dr} = r_{dr} i_{dr} + l_{dr} p i_{dr} + l_{ad} p i_{ds} \quad (4)$$

Where, ψ- air gap flux linkage

The eqn. (1) is rewritten as

$$v_{qs}' = \left(v_{qs} - \omega_r \psi\right) = r_a i_{qs} + l_{qs} p i_{qs} + l_{aq} p i_{qr} + \omega_r l_{ds} i_{ds} + \omega_r l_{ad} i_{dr} \quad (5)$$

The electrical torque developed is

$$T_e = \frac{3}{2}\frac{P}{2}\left[\left(l_{ad} - l_{aq}\right) i_{qs} i_{ds} + l_{ad} i_{qs} i_{dr} - l_{aq} i_{qr} i_{ds} + \psi i_{qs}\right] \quad (6)$$

The above equations are also applicable to constant field motors, with flux linkage, $\Psi = l_{ad} i_{fr}$

The torque balance equation is

$$\frac{2}{P} jp\omega_r = T_e - T_l - \frac{2}{P}\beta\omega_r \qquad (7)$$

where all voltages (v) and currents (i) refer to the rotor reference frame. The subscripts qs, ds, qr and dr correspond to q and d axis quantities for the stator(s) and rotor(r) in all combinations, r_a denotes the armature resistance and inductances are denoted by l_{qs}, l_{ds}etc. and T_e is the developed torque. The rotor speed is given by ω_r and the load torque by T_l. J is moment of inertia, P is the number of poles and β is the coefficient of viscous friction. The derivative operator is represented by the symbol p.

The voltage equations can be represented in matrix form as

$$\begin{bmatrix} v'_{qs} \\ v_{ds} \\ v_{qr} \\ v_{dr} \end{bmatrix} = \begin{bmatrix} r_a & \omega_r l_{ds} & 0 & \omega_r l_{ad} \\ -\omega_r l_{qs} & r_a & -\omega_r l_{aq} & 0 \\ 0 & 0 & r_{qr} & 0 \\ 0 & 0 & 0 & r_{dr} \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} + \begin{bmatrix} l_{qs} & 0 & l_{aq} & 0 \\ 0 & l_{ds} & 0 & l_{ad} \\ l_{aq} & 0 & l_{qr} & 0 \\ 0 & l_{ad} & 0 & l_{dr} \end{bmatrix} \begin{bmatrix} pi_{qs} \\ pi_{ds} \\ pi_{qr} \\ pi_{dr} \end{bmatrix} \qquad (8)$$

It may be noted that v_{qr}=v_{dr}=0, as these relate to damper windings, in *d-q* axes. Representing these equations in state space form, the system matrix and the input matrix are given by

$$A = \begin{bmatrix} \frac{-r_a l_{qr}}{\Delta_1} & \frac{-\omega_r l_{ds} l_{qr}}{\Delta_1} & \frac{r_{qr} l_{aq}}{\Delta_1} & \frac{-\omega_r l_{ad} l_{qr}}{\Delta_1} \\ \frac{\omega_r \left(l_{dr} l_{fr} - l_{ad}^2\right) l_{qs}}{\Delta_2} & \frac{-r_a \left(l_{dr} l_{fr} - l_{ad}^2\right)}{\Delta_2} & \frac{\omega_r l_{aq} \left(l_{dr} l_{fr} - l_{ad}^2\right)}{\Delta_2} & \frac{-r_{dr} l_{ad} \left(l_{ad} - l_{fr}\right)}{\Delta_2} \\ \frac{r_a l_{aq}}{\Delta_1} & \frac{\omega_r l_{aq} l_{ds}}{\Delta_1} & \frac{-r_{qr} l_{qs}}{\Delta_1} & \frac{\omega_r l_{ad} l_{aq}}{\Delta_1} \\ \frac{\omega_r l_{ad} \left(l_{ad} - l_{fr}\right) l_{qs}}{\Delta_2} & \frac{-r_a l_{ad} \left(l_{ad} - l_{fr}\right)}{\Delta_2} & \frac{\omega_r l_{aq} l_{ad} \left(l_{ad} - l_{fr}\right)}{\Delta_2} & \frac{-r_{dr} \left(l_{dr} l_{fr} - l_{ad}^2\right)}{\Delta_2} \end{bmatrix}$$

and

$$B = \begin{bmatrix} \frac{l_{qr}}{\Delta_1} & 0 \\ 0 & \frac{\left(l_{dr} l_{fr} - l_{ad}^2\right)}{\Delta_2} \\ \frac{-l_{aq}}{\Delta_1} & 0 \\ 0 & \frac{l_{ad}\left(l_{ad} - l_{fr}\right)}{\Delta_2} \end{bmatrix}$$

It may be observed that some of the elements of the matrix, A are proportional to speed, ω_r and thus, the system is nonlinear, as speed is one of the states of the overall system. As it happens, the matrix, A can be partitioned into linear and nonlinear components. This will be convenient in our subsequent design of controllers and observers.

Now the equation can be written as,

$$\dot{x} = (A' + \omega_r A'')x + Bu \qquad (9)$$

where A' and A'' are given by,

$$A' = \begin{bmatrix} \frac{-r_a l_{qr}}{\Delta_1} & 0 & \frac{r_{qr} l_{aq}}{\Delta_1} & 0 \\ 0 & \frac{-r_a \left(l_{dr} l_{fr} - l_{ad}^2\right)}{\Delta_2} & 0 & \frac{-r_{dr} l_{ad} \left(l_{ad} - l_{fr}\right)}{\Delta_2} \\ \frac{r_a l_{aq}}{\Delta_1} & 0 & \frac{-r_{qr} l_{qs}}{\Delta_1} & 0 \\ 0 & \frac{-r_a l_{ad} \left(l_{ad} - l_{fr}\right)}{\Delta_2} & 0 & \frac{-r_{dr} \left(l_{dr} l_{fr} - l_{ad}^2\right)}{\Delta_2} \end{bmatrix}$$

$$A'' = \begin{bmatrix} 0 & \frac{-l_{ds} l_{qr}}{\Delta_1} & 0 & \frac{-l_{ad} l_{qr}}{\Delta_1} \\ \frac{\left(l_{dr} l_{fr} - l_{ad}^2\right) l_{qs}}{\Delta_2} & 0 & \frac{l_{aq} \left(l_{dr} l_{fr} - l_{ad}^2\right)}{\Delta_2} & 0 \\ 0 & \frac{l_{aq} l_{ds}}{\Delta_1} & 0 & \frac{l_{ad} l_{aq}}{\Delta_1} \\ \frac{l_{ad} \left(l_{ad} - l_{fr}\right) l_{qs}}{\Delta_2} & 0 & \frac{l_{aq} l_{ad} \left(l_{ad} - l_{fr}\right)}{\Delta_2} & 0 \end{bmatrix}$$

and

$$u' = [v'_{qs} \quad v_{ds}]^T$$

Where

$$\Delta_1 = l_{qs} l_{qr} - l_{aq}^2, \;\; \Delta_2 = l_{ds} l_{dr} - l_{ad}^2, \;\; v'_{qs} = v_{qs} - \omega_r \psi$$

III. CONTROLLER AND POWER PROCESSING UNIT

The proposed control system represented in the conventional two-loop structure for the motor drive is shown in fig.1. The outer loop is the speed controller, the output of which is the reference value of the torque, T_e^*. From this value, the reference values of the currents i_{qs}^* and i_{ds}^*, are computed for a desired internal angle *(ψ)* and a desired torque angle *(δ)*. This gives the flexibility in choosing the power factor of the motor from lagging to leading values including unity p.f. The field oriented control is the special case, which is obtained by setting the power factor angle equal to the torque angle, by decoupling the armature flux and field flux in order to bring dc motor like behavior. In this sense, the proposed control scheme is more general than conventional field oriented control.The inner (current) loop is then considered. A linear state feedback control law based on pole placement technique including the integral of output error (IOE) is used in order to achieve zero steady state error with respect to reference current specification, while at the same time for improving the dynamic response. The state feedback control requires the knowledge of all states for feedback. Therefore, the inaccessible damper winding currents need to be estimated. However, such observers are usually developed based on linearized system model around nominal operating conditions making it difficult to assess large signal stability of the systems. A reduced order observer is designed elsewhere to achieve the linear dynamics of the observation error by introducing a nonlinear term. And when we want to estimate all the parameters irrespective of whether those are accessible or not we need a full order observer. So, a full order observer is designed to estimate all the parameters and it will be fed back to the controlling circuit where required operation can be done on those parameters so as to bring the performance of the system to the desired.

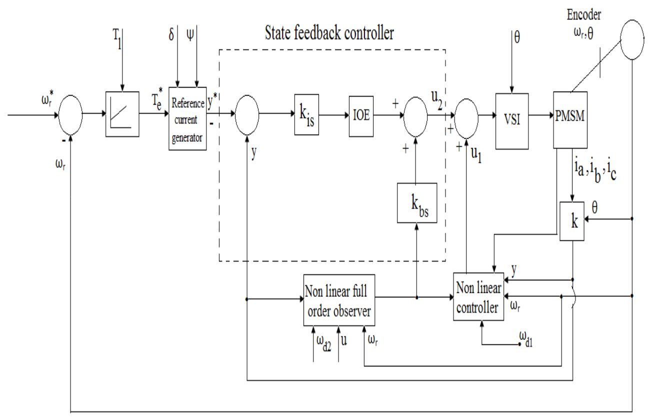

Fig. 1 Block diagram of proposed control scheme

IV. FULL ORDER OBSERVER

From the state space representation, the system equation and the output equation can be written as,

$$\dot{x} = Ax + Bu \qquad (10)$$

$$y = Cx \qquad (11)$$

In case of reduced order observer we will take the rank of matrix C be q, where q≤r, ‘r’ is the number of outputs, ‘n’ is the number of states. This implies that only ‘q’ number of states are accessible, the other (n-q) number of states are to be reconstructed. Where as in case of full order observer we will have the same condition with the matrix ‘C’, but as we know that a full order observer is one which will be used to estimate all the states irrespective of whether those are accessible or not, so here we have to reconstruct ‘n’ number of states not ‘n-q’. This is the main difference associated with reduced and full order observers.

Let a new vector, ξ of dimension ‘n’ be defined as,

$$\xi = Lx \quad (12)$$

Let $C^{'}$ be a matrix comprising the maximum number of linearly independent rows of C, and the output of this subsystem be $y^{'}$.

$$y^{'} = C^{'}x \quad (13)$$

If L is chosen such that $\begin{bmatrix} C^{'} & L \end{bmatrix}^{T}$ has an inverse, then from, the estimated states, $\hat{x}$ comes out as,

$$\hat{x} = \begin{bmatrix} C^{'} \\ L \end{bmatrix}^{-1} \begin{bmatrix} y^{'} \\ \hat{\xi} \end{bmatrix} \quad (14)$$

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

$$\dot{\hat{\xi}} = D\hat{\xi} + Gu + Fy^{'} \quad (15)$$

We choose F to be of the form

$$F = F_1 + (\omega_r - \omega_{d2})F_2 \quad (16)$$

introducing nonlinearity at the input of the observer. The matrix F_2 linearizes the observer error dynamics and can be chosen as

$$F_2 = L(A_2^{-1})F_3 \quad (17)$$

Differentiating eqn.(12) and using eqns.(10) & (14), the error in the estimate of ξ can be given by

$$\dot{\tilde{\xi}} = \dot{\hat{\xi}} - \dot{\xi}$$

$$= D\hat{\varsigma} + (G - LB)u + [F_1C^1 + (\omega_r - \omega_{d2})F_2C^1 - LA]x \quad (18)$$

For the error in the estimate of ξ, $\dot{\tilde{\xi}} = \dot{\hat{\xi}} - \dot{\xi}$ to decay,

$$i)\ L(A^{"} - A_2^{-1}F_3C^{'}) = 0 \quad (19)$$

$$ii)\ LA_d - F_1C^{'} - DL = 0 \quad (20)$$

These conditions guide us in the selection of matrices D, L and F_1.

A matrix L is chosen, such that the condition (i) is satisfied.

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

Where one possible solutions of full order observer is

$$l_{11} = \frac{\Delta_1}{r_a l_{qr}} \qquad l_{21} = \frac{\Delta_1}{\omega_{d2} l_{ds} l_{qr}}$$

$$l_{12} = \frac{\Delta_2}{\omega_{d2} l_{qs}\left(l_{dr} l_{fr} - l_{ad}^2\right)} \qquad l_{22} = \frac{\Delta_2}{r_a\left(l_{dr} l_{fr} - l_{ad}^2\right)}$$

$$l_{13} = \frac{\Delta_1}{r_a l_{aq}} \qquad l_{23} = \frac{\Delta_1}{\omega_{d2} l_{aq} l_{ds}}$$

$$l_{14} = \frac{-\Delta_2}{\omega_{d2} l_{qs} l_{ad}\left(l_{ad} - l_{fr}\right)} \qquad l_{24} = \frac{-\Delta_2}{r_a l_{ad}\left(l_{ad} - l_{fr}\right)}$$

$$l_{31} = \frac{\Delta_1}{r_{qr} l_{aq} l_{qs} l_{qr}} \qquad l_{41} = \frac{\Delta_1}{\omega_{d2} l_{ad} l_{qr}}$$

$$l_{32} = \frac{\Delta_2}{\omega_{d2} l_{aq}\left(l_{dr} l_{fr} - l_{ad}^2\right)} \qquad l_{42} = \frac{-\Delta_2^2}{r_{dr} l_{ad}\left(l_{ad} - l_{fr}\right)\left(l_{ds} l_{fr} - l_{ad}^2\right)\left(l_{dr} l_{fr} - l_{ad}^2\right)}$$

$$l_{33} = \frac{\Delta_1}{r_{qr} l_{aq}^2 l_{qs}} \qquad l_{43} = \frac{\Delta_1}{\omega_{d2} l_{ad} l_{aq}}$$

$$l_{34} = \frac{-\Delta_2}{\omega_{d2} l_{aq} l_{ad}\left(l_{ad} - l_{fr}\right)} \qquad l_{44} = \frac{\Delta_2^2}{r_{dr} l_{ad}^2\left(l_{ad} - l_{fr}\right)^2\left(l_{ds} l_{fr} - l_{ad}^2\right)}$$

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

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

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

V. RESULTS AND CONCLUSIONS

Simulation results for i_{qr}, i_{dr}, ω_r, δ, Ψ and field oriented case are studied and compared for full order observer and reduced order observer and also with and without inverter fed PMSM are analyzed. It should be known that here three cases exist. The first case being analyzed through the performance of PMSM for delta as variable, second case for psi as variable and finally for field oriented case where psi made equal to zero.

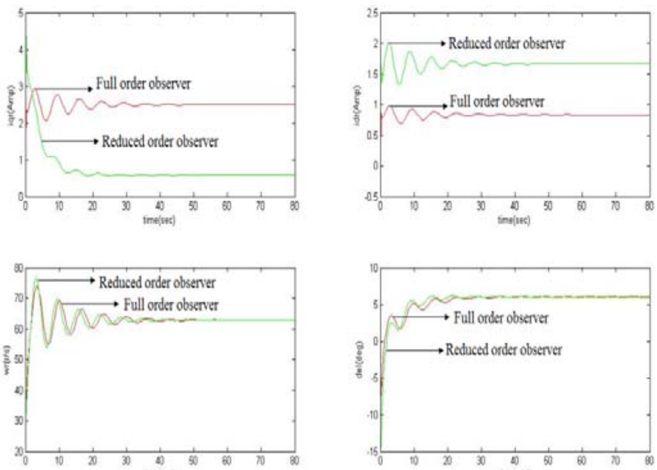

Fig. 2 Simulation results of PMSM drive with delta as variable for reduced and full order observers

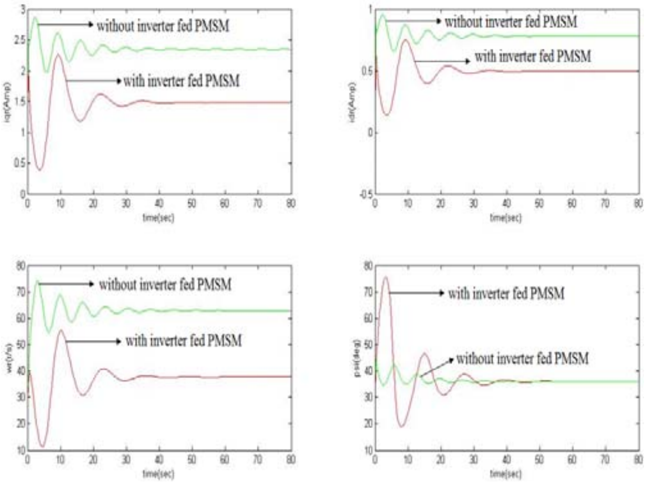

Fig. 3 Simulation results of full order observer with psi as variable for with and without inverter fed PMSM

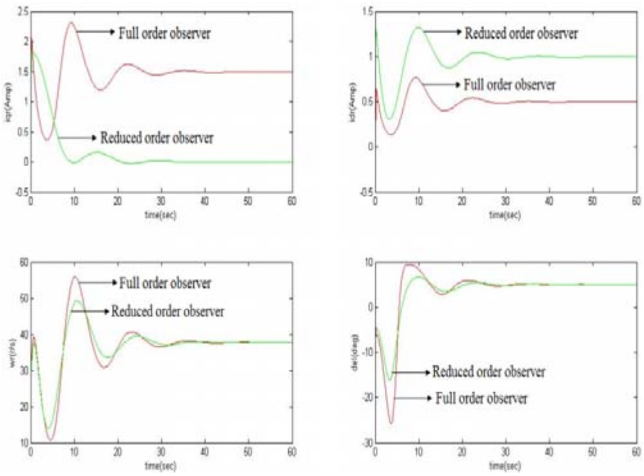

Fig. 4 Simulation results of VSI fed PMSM drive for field oriented case for reduced and full order observers

The above figures shows the performance of PMSM for reduced and full order observer's, for with and without inverter equations. From the figures it can be noted that there are less spikes for full order observer when compared to reduced order observer even though settling times isn't a major difference. Same like that the inverter fed PMSM has less spikes compared to that of without inverter fed PMSM. Here, the interesting point is we are accessing the parameters which are accessible directly and by using a reduced order observer, we are estimating the inaccessible ones. So, the question arises here is what is the need to use a full order observer when we are getting all variables by using reduced order observer. The answer to this one is that when we use a reduced order observer, we will access the accessible parameters by using sensors, but when we use sensors we will have certain disadvantages like it increases cost, it reduces reliability etc. So, to avoid these and for accurate measurement of parameters we are going for VSI fed PMSM working with a full order observer.

REFERENCES

[1] K. Alice Mary, 'Speed Control of An SPWM inverter Driven Non Linear PMSM Drive with Pole Placement Technique-11', IEEE International conference on Electrical energy systems and power electronics in emerging economics ICEESPEEE 2009. SRM University, Chennai 16-17 April 2009 413-417

[2] K. Alice Mary, 'Design performance of the speed control systems for inverter driven Nonlinear Permanent magnet synchronous motor using exact feedback linearization', 1st international conference on computer communications, control and information technology",06-07-feb2009

[3] P. S. Bimbra, 'Generalized theory of Electrical machines', Khanna Publishers.

[4] Paul C. Krause, 'Analysis of Electrical Machinery and drive systems', 2nd edition, Wiley Inter science A John wiley and sons; INC Publications.

[5] R. Krishnan, 'Electric motor drives: Modeling analysis and control', Prentice Hall, 2001 edition.

[6] Noureddine Guersi, Messaoud Fjeghaba and Messaoud Ramdani, 'Comparative analysis of intelligent controllers for permanent magnet synchronous motor drive systems, Asian journal of Information Technology, Medwell journals, 2007.

[7] Pragasen Pillay and Ramu Krishnan, 'Modelling, simulation and analysis of Permanent magnet motor drives, part-1: The permanent magnet synchronous motor drive, IEEE transactions, March/April 1989.

[8] S. Vaez-Zadeh, 'High performance Control of Permanent Magnet Synchronous Motors', Tutorial Proposal for MED 2007 Conference.

[9] Mihai Comanescu, 'Reduced order observers for Rotor Position Estimation of Nonsalient PMSM', IEEE transactions, 2009.

[10] Jorge A. Solsona and Maria I, 'A Nonlinear Reduced Order Observer for Permanent Magnet Synchronous Motors', IEEE transactions, 2006.

[11] A. B .Dehkordi and M. Gole, 'Permanent Magnet Synchronous Machine Model for real time simulation', International conference on power systems transients, June 19-23, 2005.

[12] Joseph O. Ojo and Thomas A. Lipo, 'An Improved Model for Saturated Salient Pole synchronous motors' Wisconsin Electric Machines and Power Electronics Consortium', January 1988.

[13] Khwaja M. Rahman and Silva Hiti, 'Identification of Machine parameters of a Synchronous Motor', IEEE transactions, 2003

[14] P. Brandstetter, P. Rech, and P. Simonik, 'Sensorless Control of Permanent Magnet Synchronous Motor Using Luenberger Observer', PIERS Proceedings, Cambridge, USA, July 5-8, 2010.

[15] Pradeep K. Nandam, and Paresh C. Sen, 'A Comparative Study of a Luenberger Observer and Adaptive Observer-Based Variable Structure Speed Control System Using a Self-Controlled Synchronous Motor', IEEE transactions on industrial electronics, APRIL 1990.

[16] Joohn-,Sheok Kim and Seung-,Ki SUI, 'High Performance PMSM Drives without Rotational Position Sensors Using Reduced Order Observer', IEEE transactions, 1995.

[17] Jorge A. Solsona and Maria I, 'Disturbance and Nonlinear Luenberger Observers for Estimating Mechanical Variables in Permanent Magnet Synchronous Motors Under Mechanical Parameters Uncertainties', IEEE transactions, August 2003.

[18] Hyungbo Shim and Laurent Praly, 'Remarks on equivalence between full order and reduced order nonlinear observers', Conference on Decision and Control, December 2003.

[19] Fanglai Zhu, 'The Design of Full-order and Reduced-order Adaptive Observers for Nonlinear Systems', IEEE International Conference on Control and Automation, June 2007.

[20] K. Alice Mary, A. Patra, N. K. De, 'A Generalized Approach to the Design of the Speed Control system for Inverter-Driven Permanent Magnet Synchronous Motor', IET-UK International Conference on Information and Communication Technology in Electrical Sciences (ICTES 2007), Dr. M.G.R. University, Chennai, Tamil Nadu, India. Dec. 20-22, 2007.

[21] Mihai Comanescu and Todd D. Batzel, 'Full Order EMF Observer for PMSM Design, Analysis and Performance under Improper Speed Signal', IEEE transactions, 2010.

[22] C. Elmas and H.Zelaya-De La Parra, 'Application of a full-order extended Luenberger observer for a position sensor less operation of a switched reluctance motor drive', IEEE transactions, September 1996.

[23] George Ellis, 'Observers in Control Systems', Academic press, 2002.