

# 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

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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].

## 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,

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

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

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

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

Where,  $\psi$  - air gap flux linkage

The eqn. (1) is rewritten as

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

The electrical torque developed is

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

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

The torque balance equation is



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,  $\xi$  of dimension 'n' be defined as,

$$\xi = Lx \tag{12}$$

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

$$y' = C'x \tag{13}$$

If L is chosen such that  $[C' \ L]$  has an inverse, then from, the estimated states,  $\hat{x}$  comes out as,

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

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

$$\dot{\hat{\xi}} = D\hat{\xi} + Gu + Fy' \tag{15}$$

We choose F to be of the form

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

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

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

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

$$\begin{aligned} \dot{\tilde{\xi}} &= \dot{\hat{\xi}} - \dot{\xi} \\ &= D\tilde{\xi} + (G - LB)u + [F_1C' + (\omega_r - \omega_{d2})F_2C' - LA]x \end{aligned} \tag{18}$$

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

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

$$ii) LA_d - F_1C' - DL = 0 \tag{20}$$

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.

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

Where one possible solutions of full order observer is

$$\begin{aligned} l_{11} &= \frac{\Delta_1}{r_a l_{qr}} & l_{21} &= \frac{\Delta_1}{\omega_{d2} l_{ds} l_{qr}} \\ l_{12} &= \frac{\Delta_2}{\omega_{d2} l_{qs} (l_{dr} l_{fr} - l_{ad}^2)} & l_{22} &= \frac{\Delta_2}{r_a (l_{dr} l_{fr} - l_{ad}^2)} \\ l_{13} &= \frac{\Delta_1}{r_a l_{aq}} & l_{23} &= \frac{\Delta_1}{\omega_{d2} l_{aq} l_{ds}} \end{aligned}$$

$$\begin{aligned} l_{14} &= \frac{-\Delta_2}{\omega_{d2} l_{qs} l_{ad} (l_{ad} - l_{fr})} & l_{24} &= \frac{-\Delta_2}{r_a l_{ad} (l_{ad} - l_{fr})} \\ l_{31} &= \frac{\Delta_1}{r_{qr} l_{aq} l_{qs} l_{qr}} & l_{41} &= \frac{\Delta_1}{\omega_{d2} l_{ad} l_{qr}} \\ l_{32} &= \frac{\Delta_2}{\omega_{d2} l_{aq} (l_{dr} l_{fr} - l_{ad}^2)} & l_{42} &= \frac{-\Delta_2}{r_{dr} l_{ad} (l_{ad} - l_{fr}) (l_{dr} l_{fr} - l_{ad}^2) (l_{dr} l_{fr} - l_{ad}^2)} \\ l_{33} &= \frac{\Delta_1}{r_{qr} l_{aq} l_{qs}} & l_{43} &= \frac{\Delta_1}{\omega_{d2} l_{ad} l_{aq}} \\ l_{34} &= \frac{-\Delta_2}{\omega_{d2} l_{aq} l_{ad} (l_{ad} - l_{fr})} & l_{44} &= \frac{\Delta_2^2}{r_{dr} l_{ad}^2 (l_{ad} - l_{fr}) (l_{dr} l_{fr} - l_{ad}^2)} \end{aligned}$$

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

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

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

### V. RESULTS AND CONCLUSIONS

Simulation results for  $i_{qr}$ ,  $i_{dr}$ ,  $\omega_r$ ,  $\delta$ ,  $\Psi$  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.

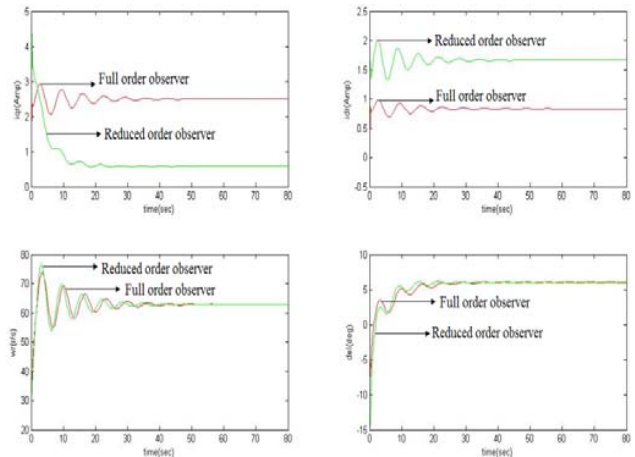


Fig. 2 Simulation results of PMSM drive with delta as variable for reduced and full order observers

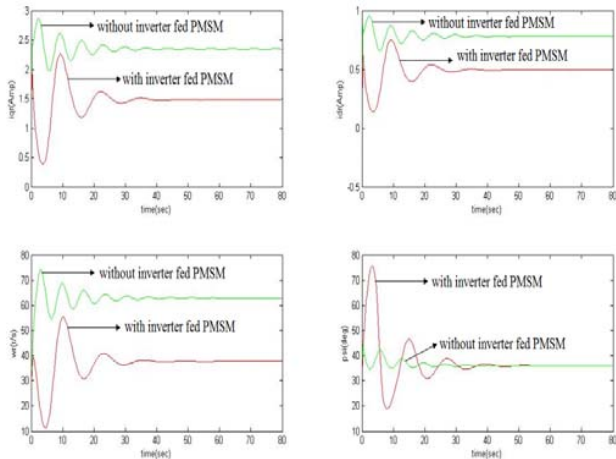


Fig. 3 Simulation results of full order observer with psi as variable for with and without inverter fed PMSM

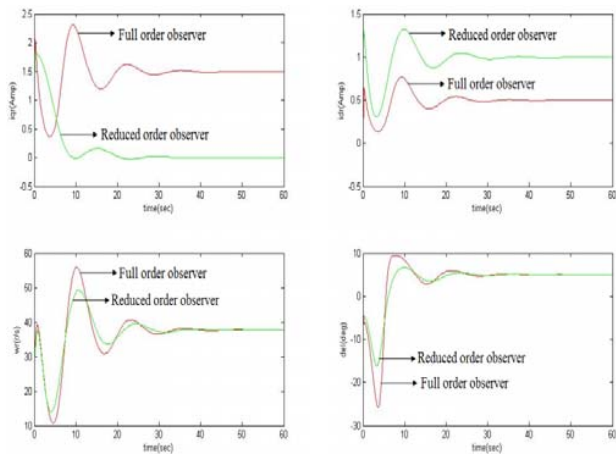


Fig. 4 Simulation results of VSI fed PMSM drive for field oriented case for reduced and full order observers

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.

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