MRAS Based Estimation of Speed in Sensorless PMSM Drive

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***Abstract*— To increase the mechanical robustness of drive system and to make the drive cheaper elimination of the position sensor is highly encouraged. Sensors are not reliable in explosive environment like in chemical industries and may cause the EMI problem. This has made the speed and position sensorless drive very attractive. A speed and position estimator for PMSM drive has been investigated. In the algorithm the PMSM used as reference model. The adaptation mechanism uses a PI controller to process the error between reference model and adjustable model. The estimation algorithm used is independent of stator resistance, computationally less complex, free from integrator problem because back-emf estimation is not required and provides stable operation of drive system. So the performance at low and zero speed is also good. The estimation algorithm is implemented in MATLAB. Simulations results show the validity of MRAS estimator presented here.**

Keywords—*adaptive mechanism; estimation; MRAS; PMSM; sensorless; SVM;*

I. INTRODUCTION

The main features of drive system refer to its capability to follow the reference command value, operate in specified limits of voltage current and power rating. With the recent developments in digital electronics, DSPs and ASICs PMSMs are gradually replacing the DC motors in wide range of drive applications. The development in high energy permanent magnets like NdBFe PMSM is becoming more popular in adjustable speed drive applications. The advantages of PMSM over dc motor like less audible noise, longer life, spark less, higher speed, higher power density and smaller size, better heat transfer makes them more suitable for adjustable speed rive application. The ac motors are suitable for constant speed operation, but due to recent development of power electronic devices, very large scale integrated (VLSI) technologies and efficient use of microprocessors, ac motors can also be used for variable speed drives. The ac motors can be used for high performance drive systems using closed loop vector control techniques. Among the ac motors, induction motors (IM) have been widely used and considered as a workhorse in the industry because of their good efficiency, low cost, reliability and ruggedness [1-3]. However, there are some limitations of the induction motor. One of the limitations is that it always runs at a lagging power factor because the rotor field voltage is induced from the stator side[4]. Another limitation is that the IM drive system is not highly efficient due to slip power loss.

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As the IM runs at a speed always less than the synchronous speed, the control of these motors is very complex[5]. Moreover, the real time implementation of these motor drives needs accurate estimation of motor parameters and sophisticated modeling with complex control circuitry. Higher efficiency and higher power factor are the advantages of PMSM over IM.

Advantages of PMSM over induction motors are; higher efficiency, higher power factor, higher power density and smaller size, and better heat transfer. Moreover popularity of PMSM comes from their desirable features; compact size, high efficiency, low noise and robustness, high torque to inertia ratio, high torque to current ratio, high air gap flux density, and high acceleration and deceleration rate.

Conventional PMSM drives employ a shaft `mounted position sensor to provide the position of rotor flux which maintains the synchronism. To implement the vector control algorithm rotor position is required to implement the current control in rotor reference frame. To increase the mechanical robustness of system and to make the drive cheaper elimination of the position sensor is highly encouraged. Sensors are not reliable in explosive environment like in chemical industries and may cause the EMI problem. This has made the speed and position sensorless drive very attractive. So online parameter estimation techniques are to be used to make the drive robust and reliable with high dynamic performance[6].

Back-emf based method offers satisfactory performance at higher speed, but at low or zero speed the magnitude of back-emf becomes negligible and difficult to measure. This makes speed estimation at low speed difficult and this method is also highly sensitive to machine parameters. Signal injection methods exploit the saliency of machine to extract the position information. Due to saliency present in machine the phase inductance varies with rotor position. A high frequency signal is injected to motor phases to extract the rotor position. This method is reliable at zero speed but there is adverse effect of signal injection on motor dynamics and requirement of extra hardware. As reported in literature the in state observer based methods (extended kalman filter, extended luenburger observer, sliding mode observer) parameters are used as state and can be estimated along with position and speed [7-9]. Extended Kalman Filter (EKF) is computationally complex, needs initial conditions, which degrade the superiority of this method [10-15]. The sliding mode observer based techniques are simple and robust against variation of machine parameter but it suffers from chattering problem.

The Model Reference Adaptive System (MRAS) based estimators provide the desired state from two different models, one is reference model and another one is adjustable model[16-20]. The error between two models is used to estimate the unknown parameter (speed in this case). In MRAS only adjustable model should depend on unknown parameter[21], the reference model is independent of speed. The error signal is fed into adaptation mechanism, which provides the estimated quantity which is used to tune the adjustable model. This method is simple and requires less computation.

Many other estimation techniques like passivity based techniques, variable structure based techniques etc are reported in literature to estimate the speed and position of PMSM drives. The schemes based on artificial intelligence (fuzzy logic and neural network) are also in recent trends, but these methods requires large memory space and is computationally complex.

II. MATHAMATICAL MODEL OF PMSM

Mathematical modeling of motor is required for simulation and analysis of drive system. PMSM equations are presented in dq reference frame[5].

An equivalent two-phase circuit model of three-phase PMSM and their equivalent two-phase quantities is given.

Following assumptions are made:

- Stator winding produce sinusoidal mmf distribution. Space harmonics in air-gaps are neglected.
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- Air –gap reluctance has a constant component as well as a sinusoidally varying component.
- Balanced three-phase supply voltage is considered
- Saturation is neglected although it can be taken into account by parameter changes.
- The back emf is sinusoidal.
- Eddy currents and hysteresis losses are negligible.

$$V_{qs} = R_q I_{qs} + p\lambda_{qs} + \omega_r \lambda_{ds} \quad (1)$$

$$V_{ds} = R_d I_{ds} + p\lambda_{ds} - \omega_r \lambda_{qs} \quad (2)$$

The d and q axes Flux Linkages in rotor reference frame are given by

$$\lambda_{qs} = L_s i_{qs} + L_m i_{qr} \quad (3)$$

$$\lambda_{ds} = L_s i_{ds} + L_m i_{dr} \quad (4)$$

The PM excitation can be modeled as a constant current source i_{fr}. The rotor flux is along the d-axis, so the d-axis rotor current is i_{fr}. The q-axis current in the motor is zero, because there is no flux along this axis in the rotor, by assumption

$$\lambda_{qs} = L_q i_{qs} \quad (5)$$

$$\lambda_{ds} = L_d i_{ds} + L_m i_{fr} \quad (6)$$

Where Lm= mutual inductance between the stator winding and rotor magnets.

$$V_{qs} = R_q I_{qs} + p\lambda_{qs} + \omega_r \lambda_{ds} \quad (7)$$

Let $\lambda_f = L_m i_{fr}$

Above voltage equations can be represented in matrix form as given below

$$\begin{bmatrix} V_q \\ V_d \end{bmatrix} = \begin{bmatrix} R_s + \rho L_q & \omega_r L_d \\ -\omega_r L_q & R_s + \rho L_d \end{bmatrix} \begin{bmatrix} i_q \\ i_d \end{bmatrix} + \begin{bmatrix} \omega_r \lambda_f \\ \rho \lambda_f \end{bmatrix} \quad (8)$$

This is the dynamic model of PMSM used in vector control.

The developed torque motor is being given by

$$T_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\left[\lambda_d i_q - \lambda_q i_d\right] \quad (9)$$

The mechanical Torque equation is

$$T_e = T_L + B\omega_m + J\frac{d\omega_m}{dt} \quad (10)$$

Solving for the rotor mechanical speed form equation (10)

$$\omega_m = \int \left[\frac{T_e - T_L - B\omega_m}{J}\right] dt \quad (11)$$

And $\omega_m = \omega_r \left(\frac{2}{P}\right)$ (12)

In the above equations ω_r is the rotor electrical speed where as ω_m is the rotor mechanical speed.

Transformations used in vector control are given as

$$\begin{bmatrix} V_q \\ V_d \\ V_o \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta_r & \cos(\theta_r - 120) & \cos(\theta_r + 120) \\ \sin\theta_r & \sin(\theta_r - 120) & \sin(\theta_r + 120) \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (13)$$

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta_r & \sin\theta_r & 1 \\ \cos(\theta_r - 120) & \sin(\theta_r - 120) & 1 \\ \cos(\theta_r + 120) & \sin(\theta_r + 120) & 1 \end{bmatrix} \begin{bmatrix} V_q \\ V_d \\ V0 \end{bmatrix} \quad (14)$$

III. ESTIMATOR SYNTHESIS

MRAS is an effective method in sensorless AC drives for speed and position estimation. A sensorless control algorithm is employed here as shown in fig. 1. PMSM is considered as reference model and the stator current equations are considered as adjustable model[22].

In the adaptation mechanism the PI controller is used to tune the adjustable model. The estimated rotor speed is used for tuning of adjustable model based on current equations of motor. Speed error is continuously monitored to ensure negative feedback and hence stability of overall system.

The current equations of PMSM are given as

$$\frac{di_d}{dt} = -\frac{R_s}{L_s} i_d + \omega_r i_q + \frac{v_d}{L_s} \tag{15}$$

$$\frac{di_q}{dt} = -\frac{R_s}{L_s} i_q - \omega_r i_d - \frac{\psi_r}{L_s}\omega_r + \frac{v_q}{L_s} \tag{16}$$

Where v_d and v_q are d-axis and q-axis component of stator voltage, L_s and R_s are stator inductance and resistance respectively, ω_r is rotor speed and ψ_r is rotor flux.

The above current equations can be written

$$p\begin{bmatrix} i_d^{'} \\ i_q^{'} \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L_s} & \omega_r \\ -\omega_r & -\frac{R_s}{L_s} \end{bmatrix} \cdot \begin{bmatrix} i_d^{'} \\ i_q^{'} \end{bmatrix} + \frac{1}{L_s}\begin{bmatrix} v_d^{'} \\ v_q^{'} \end{bmatrix} \tag{17}$$

Where

$$i_d^{'} = i_d + \frac{\psi_r}{L_s},\quad i_q^{'} = i_q,\quad v_d^{'} = v_d + \frac{R_s \psi_r}{L_s},\quad v_q^{'} = v_q$$

The equation (17) is having speed as variable and will be used for adjustable model. PMSM is used as reference model and provides i_d and i_q. In this algorithm estimated value of rotor speed is calculated as per the fig. 2.

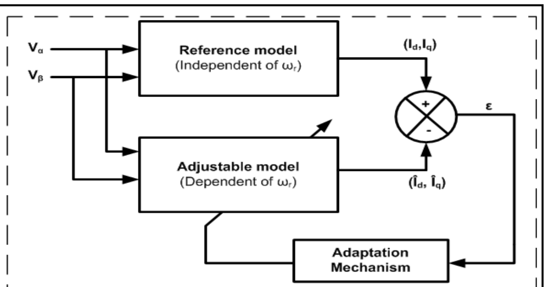

Figure 1. Structure of Model Reference Adaptive System.

The equation (17) can be written in terms of estimated values as given in (18)

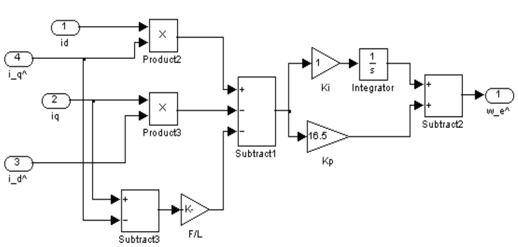

Figure 2. Adaptive mechanism for MRAS

$$p\begin{bmatrix} \hat{i}_d^{'} \\ \hat{i}_q^{'} \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L_s} & \omega_r \\ -\omega_r & -\frac{R_s}{L_s} \end{bmatrix} \cdot \begin{bmatrix} \hat{i}_d^{'} \\ \hat{i}_q^{'} \end{bmatrix} + \frac{1}{L_s}\begin{bmatrix} v_d^{'} \\ v_q^{'} \end{bmatrix} \tag{18}$$

Adaptive mechanism use four variables, $\hat{i}_d^{'}$ and $\hat{i}_q^{'}$ provided by adjustable model and i_d and i_q provided by PMSM acting as reference model. It uses PI controller to process the error and to tune the adjustable model to achieve the estimated value of rotor speed. The rotor position is obtained by integrating the rotor speed and used in transformations.

IV. Result And Discussion

The MRAS based speed estimator is implemented for PMSM drive in MATLAB. MRAS used in this system designed based on the current model of PMSM and uses PI controller. The estimation algorithm used is is independent of stator resistance, computationally less complex, free from integrator problem because back-emf estimation is not required and provides stable operation of drive system. The block diagram of PMSM employing MRAS as speed estimator is shown in fig. 3.

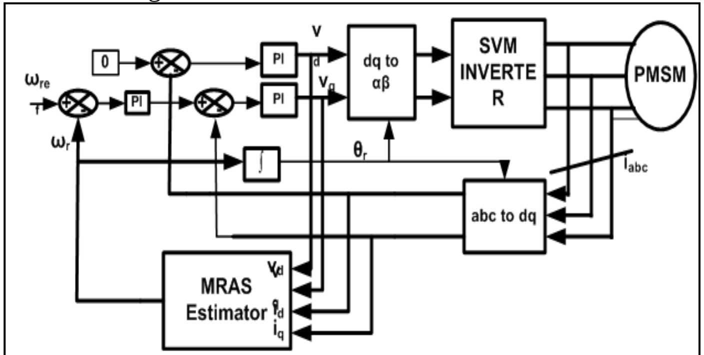

Figure 3. Block diagram of sensorless PMSM drive with MRAS based speed estimator

In the drive system three PI controllers are used; one as speed controller and two as current controllers (d-axis current and q-axis current). The space vector pulse-width modulated inverter is used to feed the three-phase power to the PMSM. V_α and V_β are the control inputs to SVM inverter, modulation index is kept 0.9.

Fig. 4 shows three-phase stator currents of PMSM when the load torque applied to motor are changed from 0-10-15-10 Nm. As the load on motor is changing, the stator current is changing accordingly. The top portion of fig. 4 shows the zoomed view of stator currents which are sinusoidal. Fig. 5 shows the electromagnetic torque generated by PMSM as step-change (0Nm at 0 sec, 10Nm at 0.5 sec, 15 Nm at 1 sec and 10Nm at

1.5 sec) in load torque applied to motor. The vector control of PMSM makes instantaneous control of currents at load changes. Two current controllers are used in this drive system. The q-axis current is directly related to torque applied to motor, and d-axis current reference is kept zero in this case to optimize the torque generated per ampere.

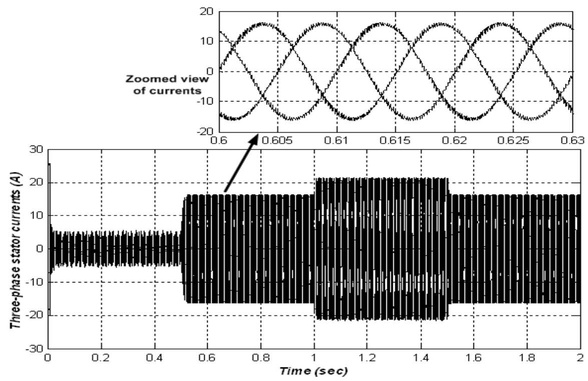

Figure 4. Three-phase stator currents of PMSM

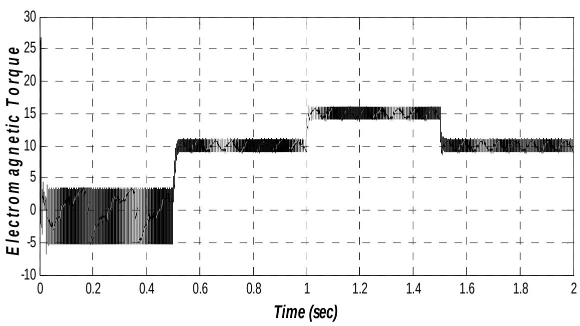

Figure 5. Electromagnetic Torque generated by PMSM with step change in load torque 0-10-15-10 Nm.

Fig. 6 shows the speed of motor as the speed reference to drive is changed 700-400-700 rpm at 0-0.5-1.0 sec. It is clear from fig. 6 that speed of motor is following the reference speed.

Fig. 7 shows the actual and estimated rotor position of PMSM with MRAS based estimation of speed and position.

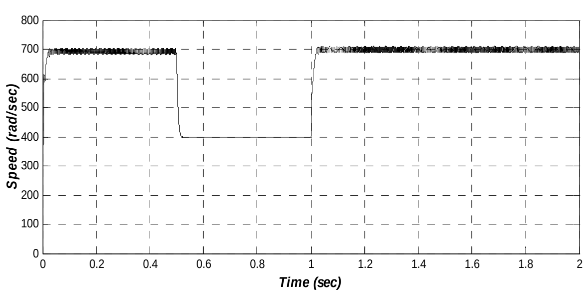

Figure. 6. Speed error with reference speed 1000 rpm

The performance of MRAS estimator is based on controller used in adaptation mechanism. Here in his case a PI controller is used to tune the adaptive model based on reference model. The controller forces the error to be zero.

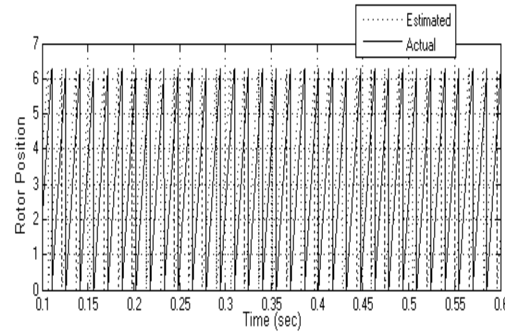

Figure. 7. Estimated and actual rotor position

V. CONCLUSION

A model reference adaptive system has been investigated to estimate the rotor speed and position, by using PMSM as reference model, PMSM current equations as adjustable model and an adaptation mechanism. The estimation algorithm used is independent of stator resistance, computationally less complex, free from integrator problem because back-emf estimation is not required and provides stable operation of drive system. So the performance at low and zero speed is also good. Adaptation mechanism uses a PI controller to process the error and to tune the adjustable model to achieve the estimated value of rotor speed. The rotor position is obtained by integrating the rotor speed and used in transformations.

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