SENSORLESS SPEED ESTIMATION TECHNIQUE FOR PMSM

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ABSTRACT

A Permanent Magnet Synchronous Motor (PMSM) attracting the researchers and industries due to its features like higher efficiency, higher power density, noiseless operation, higher speed range and higher torque weight ratio compared to other AC drives. Vector controlled PMSM drive requires speed and rotor position as feedback. In conventional drives mechanical sensors are used to sense the speed and rotor position, but these mechanical sensors are not reliable in explosive environment like in chemical industries and may cause EMI problem. The feedback information is generated through a technique known as estimation. This paper deals with the design and development of the sensorless speed estimation for a sensorless PMSM drive using Model Reference Adaptive System(MRAS). The performance analysis of sensorless PMSM has to be simulated in MATLAB/SIMULINK environment.

Keywords: *Adaptive system, MRAS, PMSM, sensorless speed estimation.*

1. INTRODUCTION

Recently, controlled AC drives have been extensively employed in various high performance industrial applications. This has been conventionally achieved by using DC drives with their simple structure. AC machines are generally inexpensive compact and robust with low maintenance requirements compared to DC machines but require complex control. However, recent advances in control techniques and signal processing have led to significant developments in AC drives. Permanent Magnet Synchronous Motors (PMSM) are increasingly replacing traditional DC motors in a wide range of applications where the fast dynamic response is required [1]. The ac motors are used for constant speed operation, but due to recent development in power electronic devices ac motors can also be used for variable speed drives. Among ac motors induction motor widely used in industrial applications because of their good efficiency, low cost, reliability [2-4]. However, there are some limitations like it runs at lagging power factor,[5] due to slip power loss it is not highly efficient and the induction motor runs at below synchronous speed so it is complex to control[6]. The advantages of PMSM over induction motors are higher efficiency, higher power factor, higher power density, smaller size and better heat transfer.

As the shape of the induced E.M.F in permanent magnet synchronous motor is sinusoidal it has less torque ripples. The speed control of the PMSM can be achieved by using the scalar and vector control techniques or field oriented control technique (FOC). The problem with scalar control is that motor flux and torque in general are coupled. This inherent coupling affects the response and makes the system prone to instability if it is not considered. By using the vector control technique, separately excited DC motor like characteristics can be

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obtained from the PMSM which are most desirable for some specific applications. It means we can control the flux and torque of the PMSM independently. Vector control offers attractive benefits including wide range of speed control, precise speed regulation fast dynamic response, lesser torque ripples, and operation above speed etc. To implement the vector control technique for PMSM drives, the speed and position of the rotor is required.

Hall Effect sensors, optical encoders and resolvers are used to detect the rotor speed. However, these sensors impair the ruggedness, reliability and simplicity of the PMSM. Moreover, they require careful mounting and alignment and special attention is required with electrical noises. Speed sensor needs additional space for mounting and maintenance and hence increases the cost sensor needs additional space for mounting and maintenance and hence increases the cost and the size of the drive system. Moreover, using a speed sensor in a hostile environment like chemical industries is not practical. To overcome the above difficulties, it is always encouraged to eliminate the mechanical sensors in electrical drive applications. In sensorless PMSM drive the speed and rotor position of the rotor are estimated rather than measured. Such control reduces the drive's cost, size and maintenance requirements while increasing the system's reliability, robustness and noise immunity. Model Reference Adaptive System based state estimation technique is to be use to estimate the speed and rotor position.

2. MATHEMATICAL MODELLING OF PMSM

Recent research has indicated that the permanent magnet motor drives became serious competitors to the induction motor for servo applications. The PMSM has a sinusoidal back emf and requires sinusoidal stator currents to produce constant torque. The PMSM is very similar to the wound rotor synchronous machine expect that the PMSM that is used for servo applications tends not to have any that damper windings and excitation is provided by a permanent magnet instead of a field winding. Hence d, q model of the PMSM can be derived from the well-known model of the synchronous machine with the equations of the damper windings and field dynamics removed. This chapter deals with the detailed modeling of a permanent magnet synchronous motor [7].

The model of PMSM without damper winding has been developed on rotor reference frame using the following assumptions:

1) Saturation is neglected.
2) The induced EMF is sinusoidal.
3) Core losses are negligible.
4) There are no field current dynamics.

It is also be assumed that rotor flux is constant at a given operating point and concentrated along the d axis while there is zero flux along the q axis, an assumption similarly made in the derivation of indirect vector controlled induction motor drives.

The rotor reference frame is chosen because the position of the rotor magnets determine independently of the stator voltages and currents, the instantaneous induced emf and subsequently the stator currents and torque of the machine. When rotor references frame are considered, it means the equivalent q and d axis stator windings are transformed to the reference frames that are revolving at rotor speed. The consequences is that

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there is zero speed differential between the rotor and stator magnetic fields and the stator q and d axis windings have a fixed phase relationship with the rotor magnet axis which is the d axis in the modeling. The stator equations of the induction machine in the rotor reference frames using flux linkages are taken to derive the model of the PMSM as shown in Fig 1

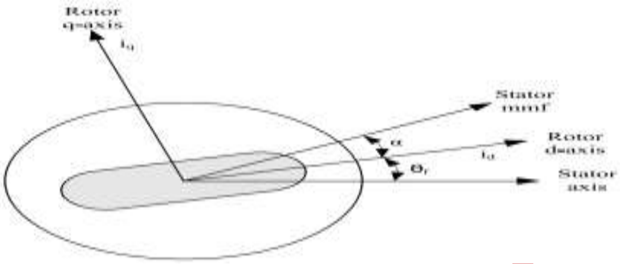

Fig 1: Permanent Magnet synchronously rotating d-q reference frame

$$v_{ds}^{\ r} = R_s i_{ds}^{\ r} + \rho\lambda_{ds}^{\ r} - \omega_r \lambda_{qs}^{\ r} \qquad (1)$$

$$v_{qs}^{\ r} = R_s i_{qs}^{\ r} + \rho\lambda_{qs}^{\ r} + \omega_r \lambda_{ds}^{\ r} \qquad (2)$$

Where,

$$\lambda_{qs}^{\ r} = L_q i_{qs}^{\ r} \qquad (3)$$

$$\lambda_{ds}^{\ r} = L_d i_{ds}^{\ r} + \lambda_{af} \qquad (4)$$

Where λ_{af} Is the magnet mutual flux linkage

$$T_e = \frac{3}{2}\frac{P}{2}\left(\lambda_{ds}^{\ r} i_{qs}^{\ r} - \lambda_{qs}^{\ r} i_{ds}^{\ r}\right) \qquad (5)$$

Then T_e becomes

$$T_e = \frac{3}{2}\frac{P}{2}\left[\left(L_d - L_q\right) i_{ds}^{\ r} i_{qs}^{\ r} + \lambda_{af} i_{qs}^{\ r}\right] \qquad (6)$$

Mechanical equation of the motor given by

$$T_e = T_l + B\omega_r + J\frac{d\omega_r}{dt} \qquad (7)$$

Hence in state space form Equations can be written as

$$\rho i_d = \frac{\left(v_{ds}^{\ r} - R_s i_{ds}^{\ r} + \omega_r L_q i_{qs}^{\ r}\right)}{L_d} \qquad (8)$$

$$\rho i_q = \frac{\left(v_{qs}^{\ r} - R_s i_{qs}^{\ r} + \omega_r L_{ds} i_{ds}^{\ r} - \omega_r \lambda_{af}\right)}{L_q} \qquad (9)$$

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3. CONTROL THEORY OF PMSM

The principle of vector control (FOC) of electrical drives is based on the control of both the magnitude and the phase of each phase stator current and voltage. This control is based on projections which transform a three phase time and speed dependent system into a two coordinate (d and q) time invariant system. These projections lead to a structure similar to that of a DC machine control. In order for the PMSM to behave like DC motor, the control needs knowledge of the position of the instantaneous rotor flux or rotor position. The idea of Field Oriented Control method is to control the current of the machine in space quadrature with the magnetic flux created by the permanent magnets as in the case of DC motors[8].

Vector control reconstructs orthogonal components of the stator current in AC machine as torque producing current and magnetic flux producing current. In order to create the perpendicular components of the stator current of PMSM which is in the form of a vector, concept of coordinate transformation is required assume that the three phase supply voltage is balanced. The Clark and Parke transformation is a transformation of coordinates from the three phase stationary coordinate system to the d-q rotating coordinate system. Figure 2 shows the three phase and two phase stator windings.

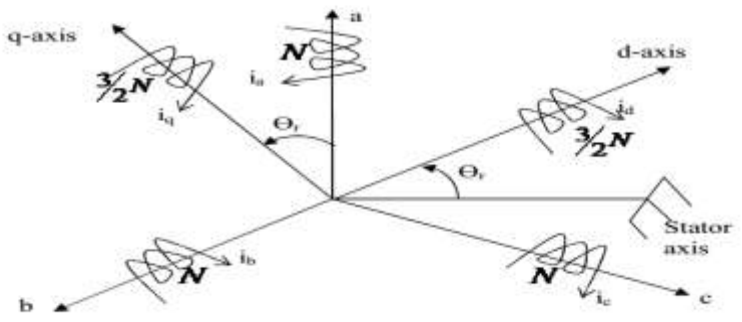

Fig 2: Three-phase and two phase stator windings.

Let the magneto motive force mmf=f=NI

$$f_q = \frac{3}{2} N i_q = \cos\theta_r\, i_a N + \cos\left(\theta_r - \frac{2\pi}{3}\right) i_b N + \cos\left(\theta_r + \frac{2\pi}{3}\right) i_c N \qquad (10)$$

$$f_d = \frac{3}{2} N i_d = \sin\theta_r\, i_a N + \sin\left(\theta_r - \frac{2\pi}{3}\right) i_b N + \sin\left(\theta_r + \frac{2\pi}{3}\right) i_c N \qquad (11)$$

Removing N from both sides results a matrix equation to determine the d & q stator current components in the rotor reference frame directly from ia, ib, & ic in the stationary reference frame.

$$\begin{bmatrix} i_q \\ i_d \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta_r & \cos\left(\theta_r - \frac{2\pi}{3}\right) & \cos\left(\theta_r + \frac{2\pi}{3}\right) \\ \sin\theta_r & \sin\left(\theta_r - \frac{2\pi}{3}\right) & \sin\left(\theta_r + \frac{2\pi}{3}\right) \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \qquad (12)$$

$$i_{qd} = [T_{abc}]\, i_{abc} \qquad (13)$$

$$i_{qd} = [i_q \quad i_d] \tag{14}$$

$$i_{abc} = [i_a \quad i_b \quad i_c]^t \tag{15}$$

$$T_{abc} = \frac{2}{3}\begin{bmatrix} \cos\theta_r & \cos\left(\theta_r - \frac{2\pi}{3}\right) & \cos\left(\theta_r + \frac{2\pi}{3}\right) \\ \sin\theta_r & \sin\left(\theta_r - \frac{2\pi}{3}\right) & \sin\left(\theta_r + \frac{2\pi}{3}\right) \end{bmatrix} \tag{16}$$

The transformation from the two-phase stator currents in rotor reference frame to three-phase stator currents in stationary reference frame can be obtained as in equation.

$$i_{abc} = [T_{abc}]^{-1} i_{qd} \tag{17}$$

$$[T_{abc}]^{-1} = \begin{bmatrix} \cos\theta_r & \sin\theta_r \\ \cos\left(\theta_r - \frac{2\pi}{3}\right) & \sin\left(\theta_r - \frac{2\pi}{3}\right) \\ \cos\left(\theta_r + \frac{2\pi}{3}\right) & \sin\left(\theta_r + \frac{2\pi}{3}\right) \end{bmatrix} \tag{18}$$

As from the equations (16) and (18), the coordinate transformations from the stationary reference frame to rotating reference frame and vice versa needs an accurate rotor flux position θ_r.

3.1 SPACE VECTOR PULSE WIDTH MODULATION:

The space vector PWM method is an advanced PWM method and is possibly the best among all the PWM techniques for variable drive applications. Space Vector Modulation (SVM) was originally developed as vector approach to Pulse Width Modulation (PWM) for three phase inverters. It is a more sophisticated technique for generating sine wave that provides a higher voltage to the motor with lower total harmonic distortion. Space vector modulation for three leg VSI is based on the representation of the three phase quantities as vectors in two (α, β) dimensional plane.

Now, in analogy with the fluxes, if a three-phase sinusoidal and balanced voltages given by the equations (19), (20) & (21)

$$V_a = V_m \cos \omega t \tag{19}$$

$$V_b = V_m \cos\left(\omega t - \frac{2\pi}{3}\right) \tag{20}$$

$$V_c = V_m \cos\left(\omega t + \frac{2\pi}{3}\right) \tag{21}$$

is applied to the windings of a three-phase machine, a rotating voltage space vector may be takes place. The resultant voltage space-vector will be rotating uniformly at the synchronous speed and will have a magnitude equal to 1.5 times the peak magnitude of the phase voltage.

3.2 SWITCHING STATES:

For 180° mode of operation, there exist six switching states and additionally two more states (V0 and V7), which make all three switches of either upper arms or lower arms ON. To code these eight states in binary (one-zero representation), it is required to have three bits ($2^3 = 8$). And also, as always upper and lower switches are commutated in complementary fashion, it is enough to represent the status of either upper or lower arm switches. There are eight possible output voltage states. Two of the output states are null vectors (V0 and V7) whereas the other six output vectors are spatially spaced 60° apart as shown in the Figure 3 Both V_0 (000) and V_7 (111) are called the zero voltage space vector, and the other six vectors are called the effective vectors.

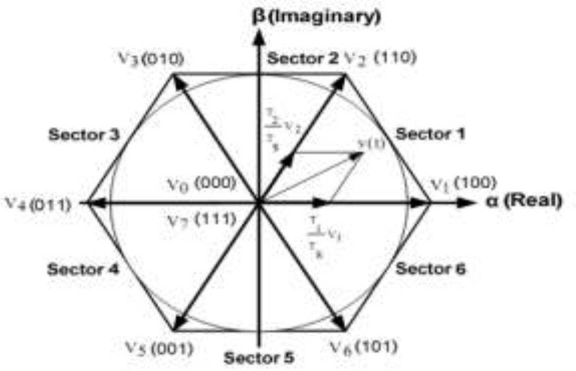

Fig 3 Voltage space-vectors output by a 3-phase Inverter

4. SPEED ESTIMATION OF PMSM USING MODEL REFENCE ADAPTIVE SYSTEM

Estimation can be defined as the determination of constants or variables for any system, according to a performance level and based on measurements taken from the process. Speed Sensorless estimation as the name implies, is the determination of speed signal from the PMSM drive system without using any rotational sensors. It makes use the dynamic equations of the PMSM to estimate the rotor speed component for control purposes. Estimation is carried out using the terminal voltages and currents which are readily available from motor. There are various rotor speed estimation schemes are there based on different algorithms with the purpose to improve the performance of the speed estimation process. Back emf method this method only suitable for high speed, at low speed this method is negligible. Signal injection method the merit of this method is reliable at zero speed but this method needs extra hardware for purpose of signal injection [9-11]. State observer method includes Kalman filter, extended Luenburger observer the main drawback of this method is it is expensive other methods are artificial intelligence(AI), artificial neural networks(ANN) and fuzzy logic for speed estimation but these required huge memory and involves computational complexity.

W.Yaonan has proposed a speed estimation technique based on the Model Reference Adaptive System in 1987. Two years later, Schauder presented an alternative MRAS scheme which is less complex and more effective. The MRAS approach uses two models. The model that does not involve the quantity to be estimated (the rotor speed ω_r) is considered as the reference model. The model that has the quantity to be estimated involved is considered as the Adaptive model or Adjustable model. The output of the adaptive model is compared with that of the reference model, and the difference is used to drive a suitable adaptive mechanism whose output is the quantity to be estimated (the rotor speed). The adaptive mechanism should be designed to assure the stability of the control system. A successful MRAS design can yield the desired values with less computation and often simpler to implement [12].The structure of MRAS is shown in fig 4.

The model reference adaptive system (MRAS) is one of the major approaches for adaptive control. Among various types of adaptive system configuration, MRAS is important since it leads to relatively easy to implement systems with high speed of adaption for a wide range of applications.

One of the most noted advantages of this type of adaptive system is its high speed of adaption. This is due to the fact that a measurement of the difference between the outputs of the reference model and adjustable model is obtained directly by the comparison of the outputs of the reference model with those of the adjustable system. The block "reference model" represents demanded dynamics of actual control loop. The block "adjustable model" has the same structure as the reference one, but with adjustable parameters instead of the unknown one.

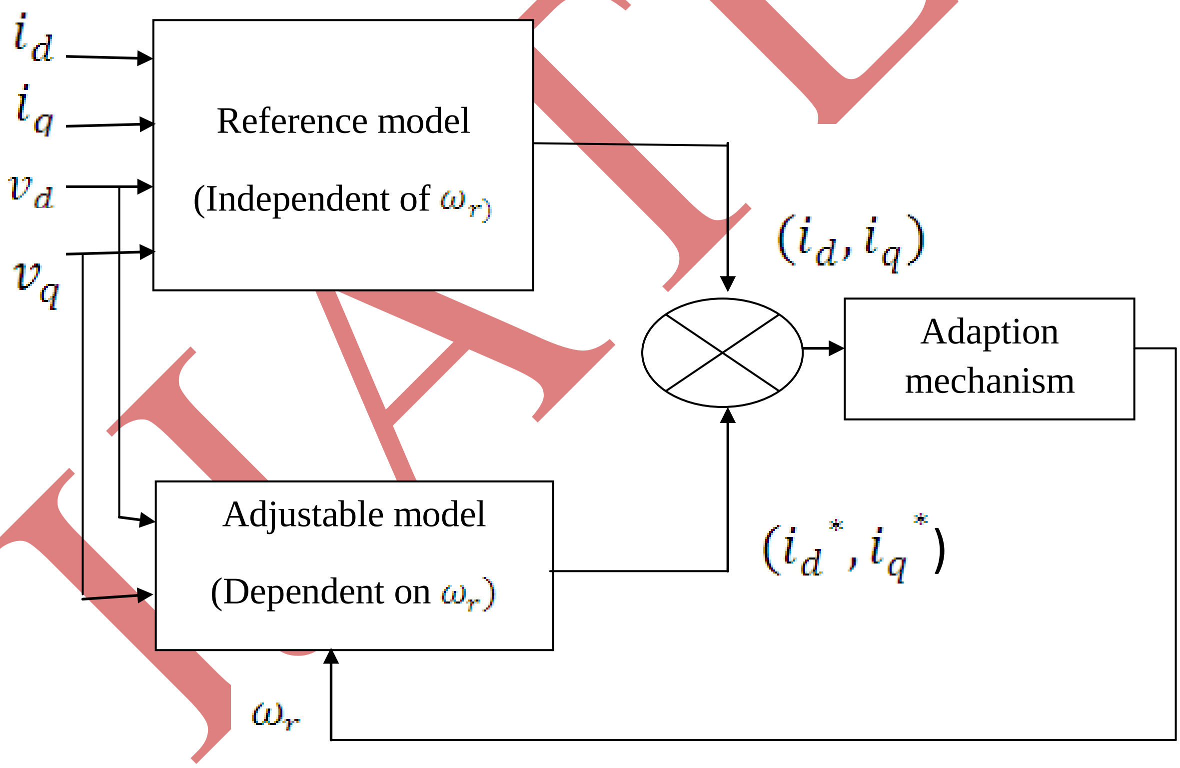

Fig 4: Structure of MRAS

Three issues are important regarding this approach:

1. Stability of the adaption control loop
2. Convergence of the adaption algorithm
3. Integrator drift/inaccuracy

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4. The overall stability of the system can be achieved using popov's hyperstability criteria. The complete block diagram of the vector controlled PMSM drive with Model Reference Adaptive System is shown in fig 5.

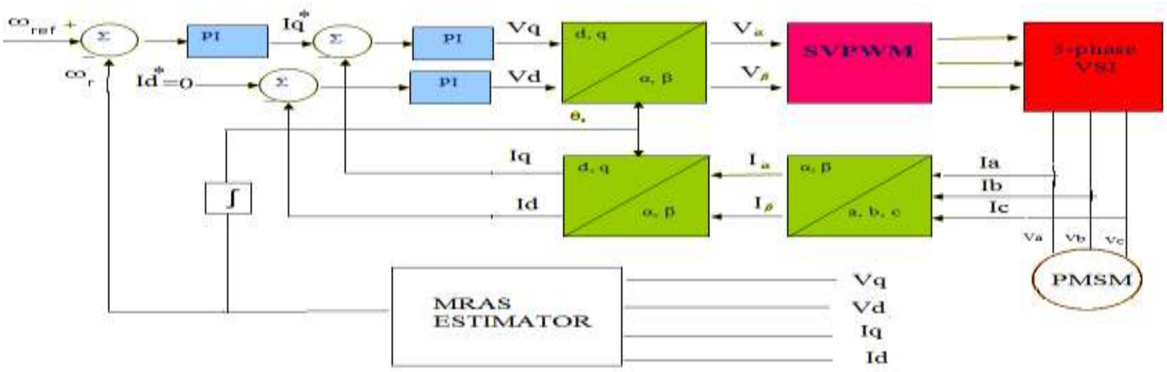

Fig 5: Complete block diagram of vector controlled PMSM drive with MRAS

5. SIMULATION RESULTS

The Sensorless vector control of PMSM using MRAS is simulated on MATLAB/SIMULINK platform. The complete simulation block diagram of the PMSM with MRAS is given in fig 6. The main subsystems of the model are SVPWM, Clark and Parks transformations, motor model and Model Reference Adaptive System.

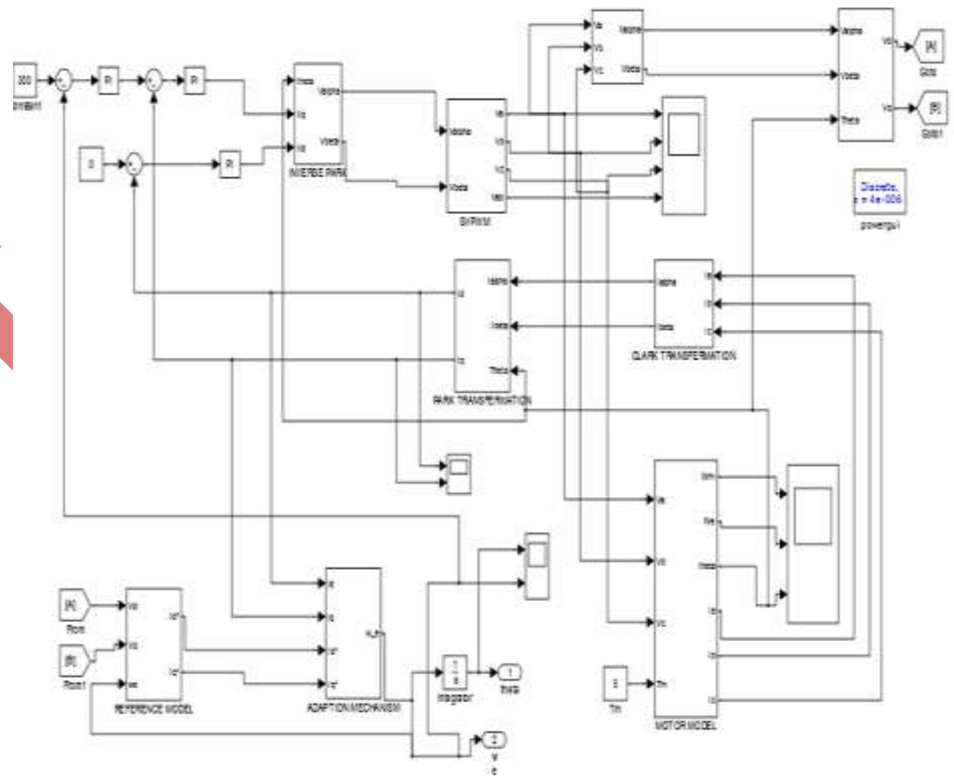

Fig 6 : Simulink block diagram of PMSM with MRAS

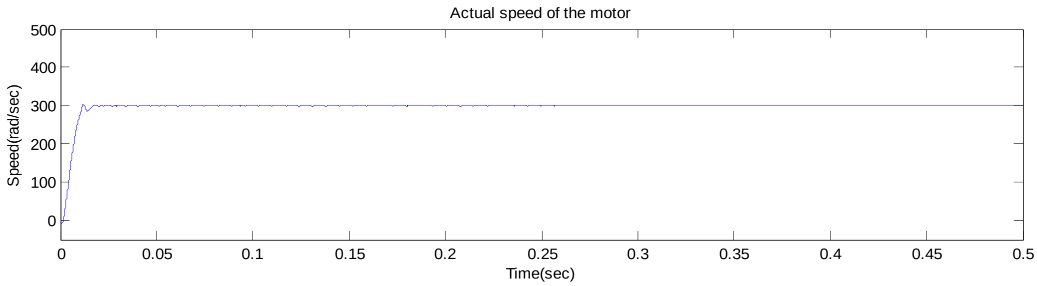

Fig 7(a): Actual speed of PMSM for a constant load torque of 5N-m

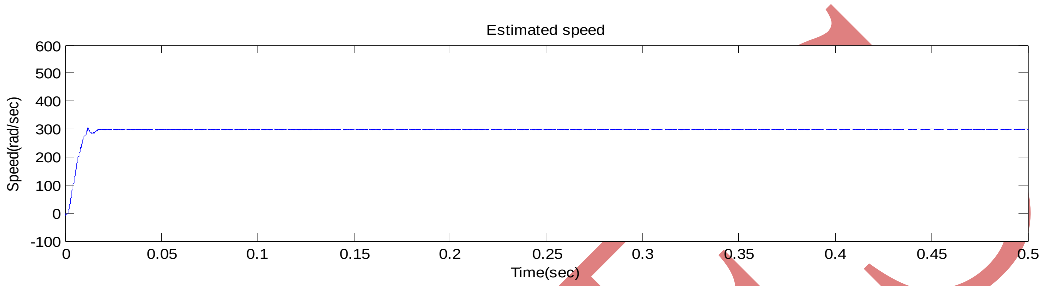

Fig 7(b): Estimated speed of PMSM for a constant load torque of 5N-m

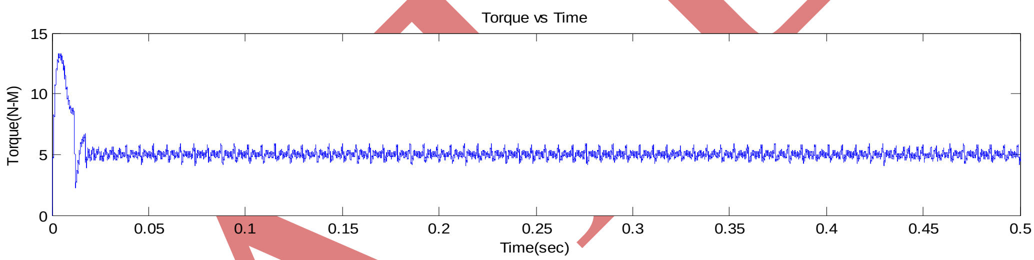

Fig7(c): Electromagnetic Torque generated by PMSM for a constant load torque of 5N-m

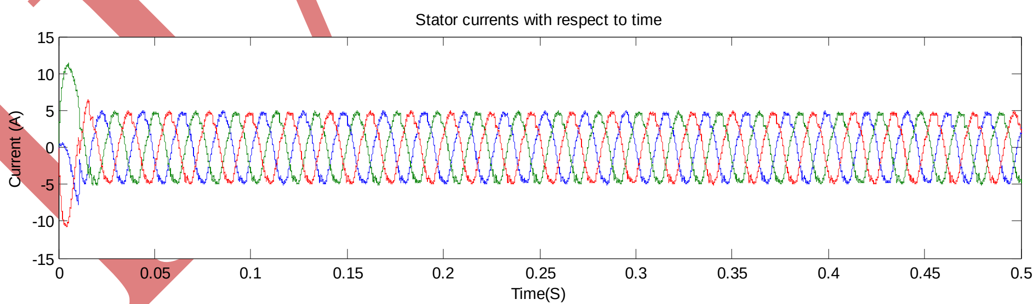

Fig 7(d): 3-phase stator currents of PMSM for a constant load torque of 5N-m

Fig 7(a), 7(b), 7(c) and 7(d) shows the Actual speed, estimated speed , Electromagnetic Torque and 3-phase stator currents of PMSM respectively for a constant load torque of 5N-M. When a reference speed of 300rad/sec is applied to the motor it reaches the set speed at 0.01 sec as shown in fig 7(a). The estimated speed by using the Model Reference Adaptive System is exactly followed the actual speed of the motor as shown in fig 7(b).The estimated speed is also reaches its steady state value at 0.01 sec.

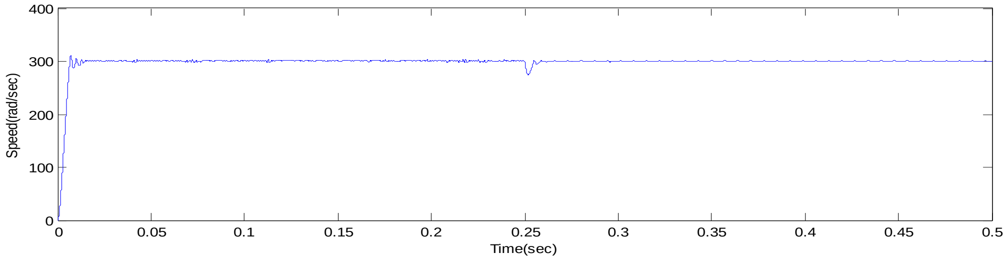

Fig 8 (a): Actual speed of PMSM for a step change in load at 0.25 sec

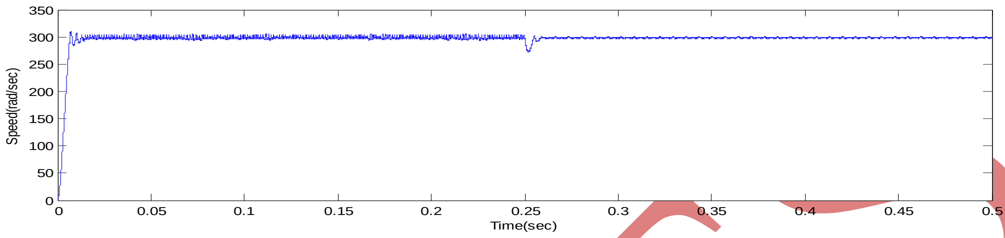

Fig 8 (b): Estimated speed of PMSM for a step change in load at 0.25 sec

Fig 8(a), 8(b) shows the Actual speed and estimated speed of PMSM respectively for a constant load torque of 5N-M applied at 0.25 sec. Initially under no load condition motor slowly develops its speed. At=0.01 sec the motor reached reference speed of 300rad/sec and it is constant up to 0.25 sec where the load is applied suddenly. When a load of 5N-M is applied suddenly at t=0.25 sec the speed of the motor slightly falls and later reaches reference speed as shown in fig 8(a).

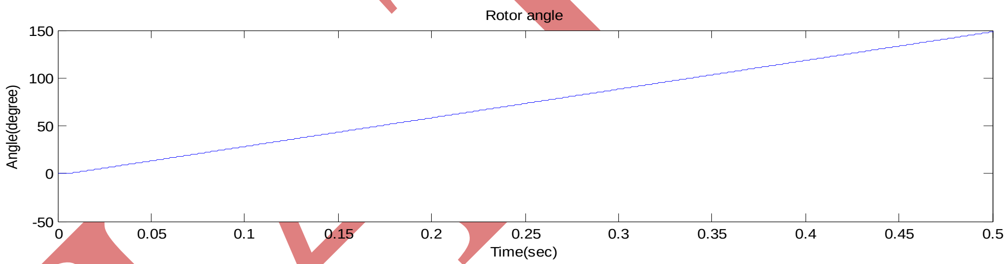

Fig 9(a): Actual rotor position of the motor

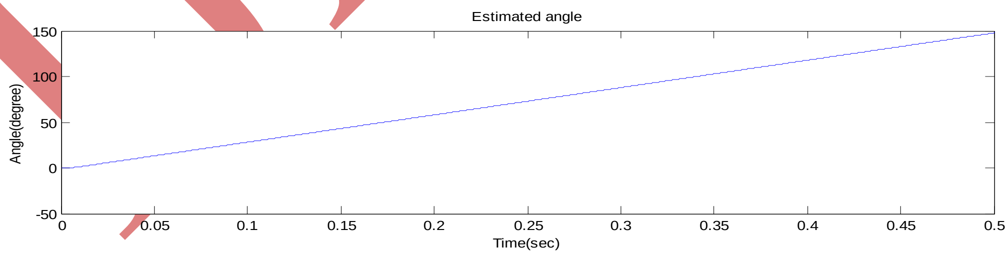

Fig 9(b): Estimated rotor position of the motor

The rotor position is obtained by integrating the speed of the motor. Fig 9(a) and 9(b) shows the actual and estimated rotor positions of PMSM respectively when a constant load torque of 5N-M is applied. It can be concluded from the fig 9(a) and 9(b) that estimated rotor position of PMSM by using Model Reference Adaptive System(MRAS) is exactly followed the actual rotor position.

6. CONCLUSION

In this paper sensorless control of PMSM with Model Reference Adaptive System (MRAS) technique has been considered to estimate the speed and rotor position of the motor. Sensorless control gives the benefits of vector control without using any shaft encoder. Space vector pulse width modulation (SVPWM) technique has been implemented to give switching pulses to the three phase bridge inverter. In the Model Reference Adaptive System, PMSM model is directly used as a reference model and PMSM current equations are used as an adjustable model. Adaption mechanism uses a PI controller to process the error and to tune the adjustable model to achieve the estimated value of rotor speed. Popov's hyperstability criterion is used in the Adaption mechanism to study the stability of the system.

REFERENCES

[1] R. Krishnan, "Permanent Magnet Synchronous and Brushless DC Motor Drives", Electrical and Computer Engineering Department, Virginia Tech Blacksburg, Virginia, U.S.A., CRC Press Taylor & Francis Group, 2010

[2] W. Leonhard, Control of electrical drives: Springer Verlag, 2001.

[3] G. R. Slemon, "Modelling of induction machines for electric drives," IEEE Transactions on Industry Applications, vol. 25, pp. 1126-1131, 1989.

[4] N.Tesla, "A new system of alternate current motors and transformers," Transactions of the American Institute of Electrical Engineers, pp. 308- 327, 1888.

[5] P. C. Krause, O. Wasynczuk, S. D. Sudhoff, and I. P. E. Society, Analysis of electric machinery and drive systems vol. 2: IEEE press Piscataway, NJ, 2002.

[6] Sakorn Po-ngam "Speed-controller Design of Induction Motor and Permanent Magnet Synchronous Motor for High Performance drives" Power Electronics & Motor Drives Laboratory (PEMD)

[7] P. Vas, Sensorless vector and direct torque control vol. 729: Oxford university press Oxford, UK, 1998.

[8] Xudong Wang ,Risha Na and Ning Liu, "Simulation of PMSM Field-Oriented Control Based on SVPWM" 2009 IEEE International Conference on vehicle Power and Propulsion,pp.1465-1469.

[9] K. Hongryel, S. Jubum, and L. Jangmyung, "A High-Speed Sliding- Mode Observer for the Sensorless Speed Control of a PMSM," IIEEE Transactions on industrial Electronics, vol. 58, pp. 4069-4077.

[10] C. Song, Z. Zheng, and X. Longya, "Sliding-Mode Sensorless Control of Direct-Drive PM Synchronous Motors for Washing Machine Applications," IEEE Transactions on Industrial Electronics, vol. 45, pp. 582-590, 2009.

[11] H. Yoon-Seok, C. Jung-Soo, and K. Young-Seok, "Sensorless PMSM drive with a sliding mode control based adaptive speed and stator resistance estimator," IEEE Transactions on Magnetics, vol. 36, pp. 3588-3591, 2000.

[12]Ambarisha Mishra, Vasundhara Mahajan, Pramod Agarwal and S.P.Srivastava "MRAS Based Estimation of Speed in Sensorless PMSM Drive". IEEE conference on Power India, pp:1-5,2012

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