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Model Reference Adaptive Controlled Application to the Vector Controlled Permanent Magnet Synchronous Motor Drive

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***Abstract*— This paper presents the parameters of permanent magnet synchronous motor i.e. speed (ω_r), stator resistance (R_S), q-axis inductance (L_q), and torque (T_s) is to be estimated by using Model Reference adaptive System(MRAS). To improve the performance of speed sensor less permanent magnet synchronous motor drives, especially at low speeds by identifying stator resistance together with speed. Several speed estimation methods for sensor less PMSM drives have been proposed but the Performance is not satisfactory at low speed. Model-based speed and stator resistance estimators are the most common schemes used in the literature. The stator resistance varies with the temperature of the machine, so it should be estimated adaptively. The proposed technique is completely Independent of stator resistance (R_s) and is less parameter sensitive, as the estimation-algorithm is only dependent on q-axis stator inductance (L_q). Also, the method requires less computational effort as the simplified expressions are used in the MRAS. In this proposed scheme sensor less technique is used, the aim at eliminating mechanical sensor, which are rather expensive and delicate, especially if accurate mounting and calibration are necessary, and at obtaining rotor position and angular velocity from the measurement of only electrical quantities. But the precision of position estimation often depends on motor's parameters. To control PMSM position and speed sensors are indispensable. So the vector control technique is used for the control the PMSM position and speed sensor. MATLAB/ simulink based simulation is discussed.**

***Index Terms*—Model reference adaptive system, Reactive power, Vector control, Permanent magnet synchronous motor.**

INTRODUCTION

Recently Permanent Magnet Synchronous Motor (PMSM) drives have received increased attention due to having several desirable features, such as, higher efficiency, higher power density, higher torque to inertia ratio etc. Vector controlled PMSM drive has very high dynamic performance and are widely used in applications like machine tools, electric vehicles etc. so the parameters having important role in the performance of the PMSM drive these are speed, stator resistance (R_S), q-axis inductance (L_q), and torque (T_s). Indirect vector controlled system requires the information of the speed: either from the speed encoder or from an estimator/observer.

Elimination of the speed encoder is highly encouraged to increase the mechanical robustness of the system and to make the drive cheaper. Moreover, there are some applications, where there is no room to put the speed sensor or the nature of the environment (such as explosive environment in some chemical industries) does not allow the use of any additional speed sensor. This has made speed Sensor less PMSM drive very attractive. Many online parameter estimation schemes are available in Literature. They are broadly classified as follows.

A. Back-emf Based Method

Use of back-emf to estimate the rotor speed has been reported. This method offers satisfactory performance at higher speed. However, at zero or very low speed the back-emf becomes negligible. This makes the speed estimation at lower speed very difficult. Also, the method is highly sensitive to machine parameters.

B. Signal Injection-Based Method

Some techniques exploited the saliency in the machine to extract the speed information. Note that the phase inductance varies for different rotor positions due to the saliency present in the rotor side. To extract the position from inductance profile, a high frequency voltage signal is fed to the motor phases. The merit of this method is that the technique is reliable at zero speed. The main drawbacks of signal injection based methods are the adverse effect of injecting signal on motor dynamics and the requirement of extra hardwire for the purpose of signal injection.

C. State Observer-Based Method

Reported estimation method also includes Extended Kalman Filter (EKF), Extended Luenburger observer (ELO), sliding mode observer, etc. The computational complexity, parameter sensitivity and the need of initial conditions degrade the superiority of the EKF based speed estimation technique. However, one good side is that the parameter can also be treated as the state and that can be estimated along with the speed. The sliding mode observer based technique is simple and robust against parameter variation. However, it has the demerit of the chattering phenomenon. In a low pass filter (LPF) has been used to overcome the problem. However, this is at the cost of system dynamics.

D. Model Reference Adaptive System (MRAS)-Based Techniques

Theoretically MRAS computes a desired state (called as the functional candidate) using two different models (i.e. reference and adjustable models). The error between the two models is used to estimate an unknown parameter (here speed is the unknown parameter). A condition to form the MRAS is that the adjustable model should only depend on the unknown parameter. Here, the reference model is independent of rotor speed, whereas the adjustable model is dependent on the same.

The error signal is fed to the adaptation mechanism. The output of the adaptation mechanism is the estimated quantity ($\omega_{r,est}$), which is used for the tuning in adjustable model and also for feedback. The stability of such closed loop estimator is achieved through Popov's Hyperstability criterion. The method is simple and requires less computation.

Depending on the quantity (i.e. the functional candidate) used to formulate the error signal; various kinds of MRAS are possible. In, an MRAS is developed with d- and q-components of flux. However, the method is heavily dependent on stator resistance variation and suffers from the integrator related problems like drift and saturation. To overcome the problem, an MRAS with on-line stator resistance estimation, Reactive power-based MRAS and Neural Network (NN) based MRAS is used. Among all of these methods, reactive power based MRAS is more popular for speed estimation as it is independent of stator resistance.

E. Other Methods

Several other approaches such as variable structure-based technique, passivity based technique, etc. are also reported to estimate the speed of a PMSM drive. The more recent approach based on Artificial Intelligence (AI) are the Artificial Neural Networks (ANN) and Fuzzy Logic for speed estimation. But, the AI-based methods require huge memory and involve computational complexity.

Out of all the techniques discussed so far, MRAS is widely accepted for speed estimation due to its simplicity and good stability. Also the method does not require any extra hardwire or signal injection or huge memory like EKF or ELO. Within the available MRAS-based methods, reactive power-based scheme is not dependant on stator resistance and has definite advantages over the other methods.

This paper deals with an MRAS, where the reference model utilizes instantaneous reactive power and the adjustable model uses steady-state reactive power. This means that the two different versions of the same quantity are used to formulate error signal. This type of approach rewards a speed estimator that depends only on 'L_q'. A mechanism for on-line estimation of 'L_q' will make the drive parameter independent. Such MRAS with instantaneous and steady-state reactive power was reported in for the speed and parameter estimation of induction motor drive. This work applies the concept to PMSM drive for the first time. The scheme is simulated in MATLAB/SIMULINK. It is observed that the proposed technique is working well with different possible situations under load and speed variation. Extensive simulation results are presented to highlight the performance of the estimation algorithm.

II PROPOSED SCHEME

A. MRAC-based Speed Estimation

Fig. 1 shows the MRAS based speed estimation scheme. It uses the outputs of two models: one independent of rotor speed (Reference Model) and the other dependant on rotor speed (Adjustable Model), to form an error signal. A PI controller is used in the adaptation mechanism for the convergence in the system.

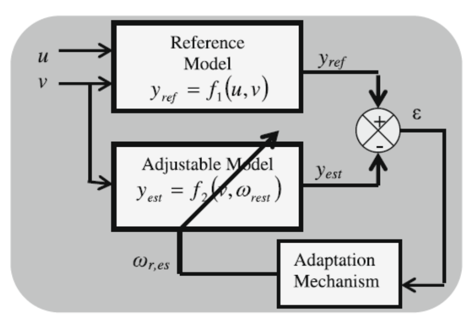

Fig. 1. Basic MRAS structure

B. Structure of proposed scheme

A block diagram of the proposed MRAS-based rotor speed estimator is shown in Fig.4.The reference model computes instantaneous reactive power (Q_{ref}) and the adjustable model computes steady-state reactive power (Q_{est}). Both the reactive powers are then compared to form the error signal. The error signal is then passed through an adaptation mechanism to estimate rotor speed. In the successive section it will be proved that a PI controller is sufficient for adaptation mechanism. The estimated rotor speed is used to tune the adjustable model until the two reactive powers (Q_{ref} and Q_{est}) become same. It is important to mention that in the proposed MRAS, continuous monitoring of speed error signal (e_{ω}) and reactive power error signal (ε) is required; otherwise instead of negative feed-back positive feed-back may take place and the system may become unstable.Fig.2 & Fig.3 shows the Active power and reactive power based MRAS. Active power based MRAS (P-MRAS) is used to estimate the stator resistance (R_s), and Reactive power based MRAS is used to estimate the q-axis inductance (L_q), speed (ω_r) and torque (T_e). The complete vector controlled Sensor less PMSM drive with MRAS based speed estimator is available in Fig.5.

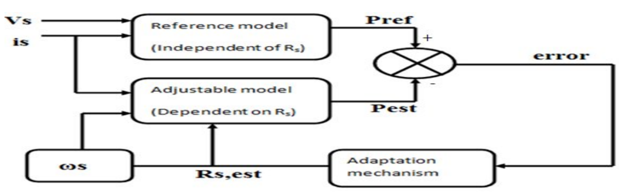

Fig.2 Active power based MRAS

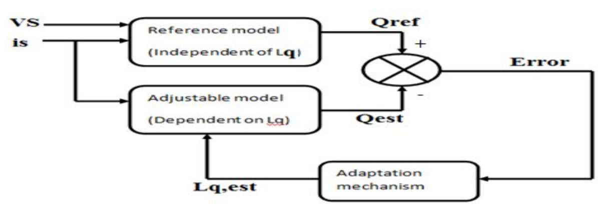

Fig 3. Reactive power based MRAS

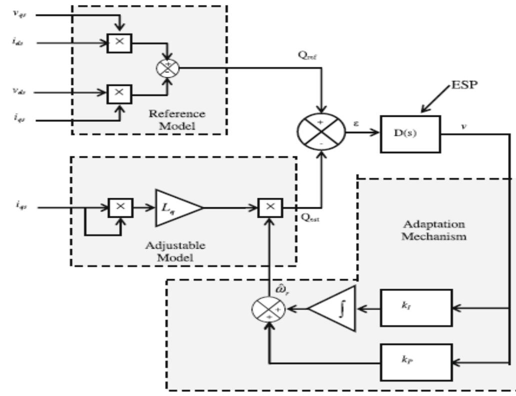

Fig. 4 structure of reactive power based MRAS.

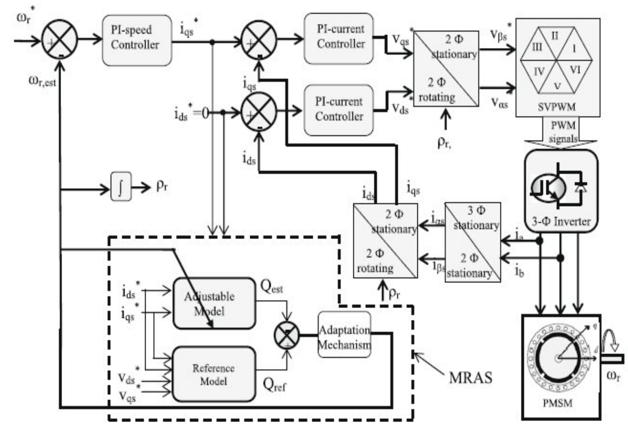

Fig. 5. Block diagram of the complete PMSM drive with MRAS-based rotor speed estimator.

C. Modeling of PMSM

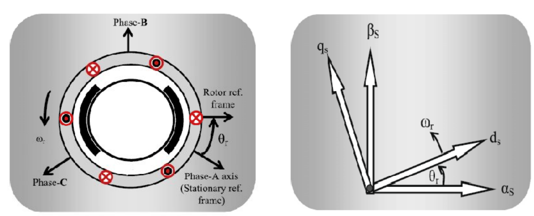

Fig.6. Surface mounted PMSM & Stationary and rotating reference frames

The d and q-axis stator voltages for PMSM referred to rotor reference frame may be expressed as

$$V_{ds} = R_s\, i_{ds} + L_d \text{ —— } - \omega_s L_q\, i_{qs} \qquad (1)$$

$$V_{qs} = R_s\, i_{qs} + L_q \text{ —— } - \omega_s L_d\, i_{ds} + \omega_s \lambda_{af} \qquad (2)$$

where P is the number of pole pair,'L_d' and' L_q'are the d- and q-axis stator inductances, Rs is the stator resistance, λ_{af} is theMutual flux linkage between rotor and stator due to permanent magnet and $\omega_s = p\,\omega_r$, Here, the PMSM is non-salient type with a sinusoidal back-EMF waveform. The α- and β-axis variables in stationary reference frame are related to the rotor reference frame with the following expression

$$\begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} = e^{-j\theta r} \begin{bmatrix} i_{\alpha s} \\ i_{\beta s} \end{bmatrix} \quad (3)$$

Where 'θr' is the angle between the stationary reference frame and the rotor reference frame, as shown in the developed electromagnetic torque can be expressed as

$$Te = - P \{\lambda_{af} i_{qs} + (L_d - L_q)\, i_{ds}.i_{qs}\} \quad (4)$$

The governing electromechanical equation is

$$T_e - T_L = J \text{ —— } + B\,\omega_r \quad (5)$$

Where 'T_L' is the load torque.

D. Expression of reactive power

The instantaneous reactive power (Q) can be expressed as

$$Q_1 = V_{qs}\, i_{ds} - V_{ds}\, i_{qs} \quad (6)$$

Substituting (1) and (2) in (6)

$$Q_2 = \omega_s (L_d\, i_{ds}^2 + L_q\, i_{qs}^2) + (Lq\, i_{ds}\, p\, i_{qs} - L_q\, i_{qs} p i_{ds}) + \omega_s\, i_{ds} \lambda_{af} \quad (7)$$

At steady-state derivative terms are zero and the new expression for Q becomes:

$$Q_3 = \omega_s (L_d\, i_{ds}^2 + L_q\, i_{qs}^2) + \omega_s\, i_{ds}\, \lambda_{af} \quad (8)$$

Now the condition for vector controlled PMSM drive ($i_{ds} = 0$) is imposed in (9). Therefore, the more simplified expression for Q is:

$$Q_4 = \omega_s\, L_q\, i_{qs}^2 \quad (9)$$

Among all the expressions of Q, Q1 is considered in the reference model as it is independent of the rotor speed. Out of the rest expressions, any one may be used in the adjustable model as all of them are dependent on the rotor speed. But, some advantages and short comings are associated with each choice of Q, which are discussed below.

Q2 in the adjustable model: It gives the better accuracy in the estimation of reactive power as all the transient terms (like derivatives of currents) are considered. However, computation of the derivative terms may be unreliable due to the presence of the noise in the system.

Q3 in the adjustable model: Derivative computation is not required. However, the expression is dependent on two machine parameters in accordance with the magnet strength.

Q4 in the adjustable model: Derivative computation is not needed and at the same time, the expression of reactive power is dependent only on L_q. The estimated reactive power is not accurate at transient as the steady-state terms are only considered here. However, the error due to neglecting the derivative terms is taken care of by the PI controller in the adaptation mechanism.

Therefore, out of all the versions of reactive power (i.e. Q2, Q3, and Q4), Q4 is chosen in the adjustable model for the following advantages:

The estimation algorithm is

1. Independent of stator resistance.
2. Less sensitive to machine parameter variation (as the MRAS is only dependent on one parameter, Lq).
3. Reduced computational complicacy as the simplified expressions are used both in reference and adjustable model.
4. Free from integrator related problems as back-emf estimation is not required.

E. Expression of Active power

The instantaneous active power (p) can be expressed

$$P_{inst} = v_{ds}\, i_{ds} + v_{qs}\, i_{qs} \quad (10)$$

By substituting 'v_{ds}'and 'v_{qs}' in above equation Then the steady state active power (p) becomes

$$P_{ss} = R_s\, i_{qs}^2 + \lambda_{af}\, \omega_s i_{qs} \quad (11)$$

Instantaneous active power is independent of stator resistance; the steady-state active power depends on stator resistance.

By equating equation (10) and (11)

$$P_{inst} = P_{ss}$$

We get speed equation as

$$\omega_s = V_{sq}\, i_{sq} - R_s i_{qs} / \lambda_{af} i_{sq} \quad (12)$$

From the above equations, it shows that rotor Speed 'ω_s' depends on the stator resistance R_s.

Stability of reposed MRAS

Design of a model reference adaptive controller relies on Hyperstability concept. This concerns the stability properties of a class of feedback systems as shown in Fig.7. The feedback system is said to be globally (asymptotically) stable if the following two conditions hold:

(i) Feed-forward gain of the system must be real-positive. In other words, the transfer function of the feed-forward linear
time invariant block must be strictly positive real.

(ii) The error should converge asymptotically i.e. the nonlinear time varying block satisfies the Popov's integral inequality.

$\eta(0, t_1) = \int^{!} W dt \geq$ for all $t_1 > 0$ (13)

Where v is the input vector, w is the output vector of the feedback block, and is a finite positive constant.

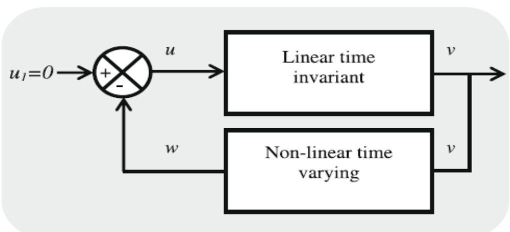

Fig. 7. Nonlinear time varying system

III SIMULATION RESULTS

To verify the effectiveness of the proposed parameters estimation has been simulated using MATLAB/Simulink.The parameters and the rating of the motor are available in appendix.

A. Active power (P) - MRAS Results

Active power based MRAS is used to estimate the Stator resistance (R_S) but this method has interior related problems. Observe the simulation results presented in the Fig.8 & 9 .The simulation results of the drive are being observed with and without 'R_s'compensation.

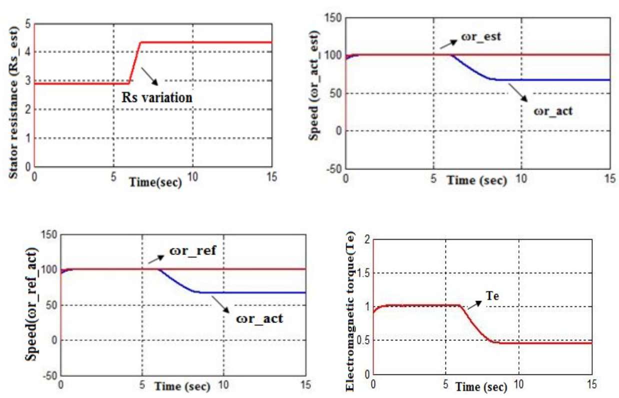

Fig. 8 simulation results for without ' R_s' compensation

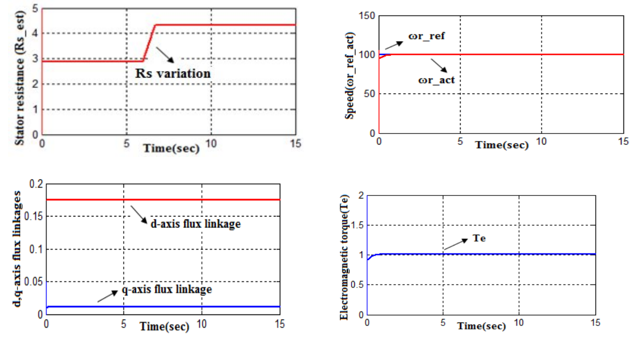

Fig.9. simulation results for with ' R_s' compensation

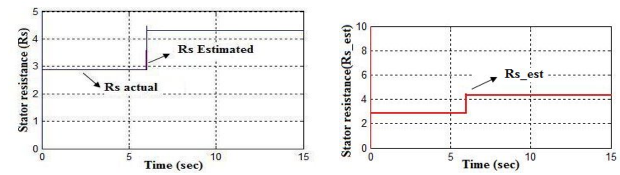

Fig.10. Stator resistance (R_S) estimated for step input

B. Reactive power (Q) - MRAS Results

The proposed relative power based MRAS is to independent of stator resistance (R_s) dependent on q-axis inductance (L_q). By using the Q-MRAS 'L_q' is estimated. The estimated q-axis inductance (L_q) is observed from the simulations Fig.11 &12, with and without 'L_q' compensation. From the simulation results observe that Reactive power based MRAS is more popular for to estimation of parameters.

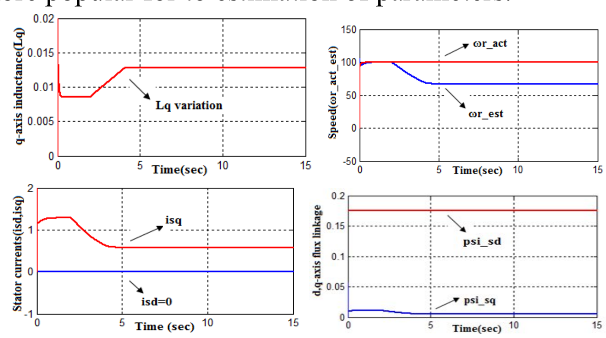

Fig.11. Simulation results for without 'L_q' compensation

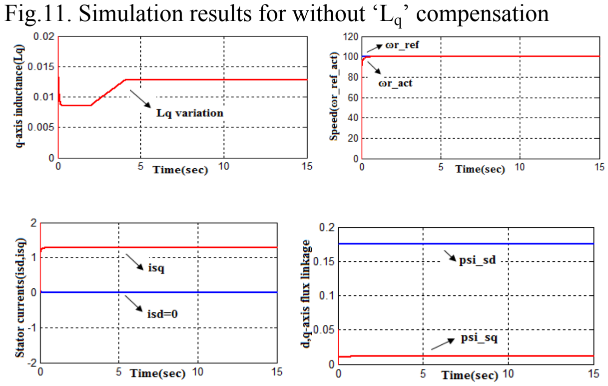

Fig.12. simulation results for with 'Lq' compensation

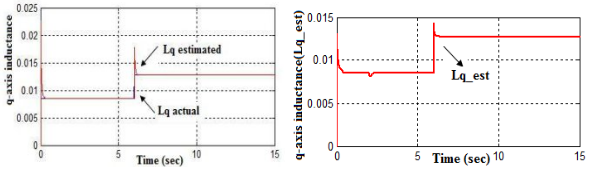

Fig.13. q-axis inductance (L_q) estimated for step input

C. Step response of drive with speed reversal

Fig.14.shows that simulation result for speed reversal in step. The motor reference speed is changed from 100rad/sec to -100rad/sec at 5 sec. and 10 sec. again speed is set to 100rad/sec at 10 sec. From the result it is observed that the actual motor speed takes 25msec to follow the reference speed with good accuracy. Reference speed and actual speeds are plotted in the same scale to observe the accuracy of MRAS-based speed estimator.

d-axis and q- axis stator currents are plotted vs. time. These stator currents components are shown for dc generator type load. For vector controlled PMSM drive d-axis stator current should be zero and the same is observed from the simulation results. Electromagnetic torque follows 'i_{sq}' because

$$T_e = (—).(—)\ \lambda_{af}\ i_{sq} \qquad (14)$$

where 'φ_f' is constant. So,'T_e' is proportional to'i_{sq}'.

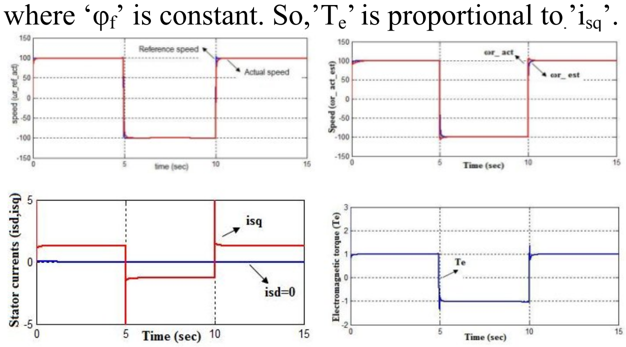

Fig.14. Step response of drive with speed reversal

D. Response of the drive for ramp type speed reference

The simulation is also performed for ramp type speed reference and the corresponding results are presented in Fig.15. It is observed that shaft speed is not tracking the reference speed near zero stator frequency. However, from it is noticed that estimated rotor speed follows reference one with good accuracy. This discrepancy can be overcome by proper adjustment of PI speed controller gains. Reflects the vector control operation of the drive i.e., i_{ds} = 0. Torque component of the stator current (i_{qs}) is also shown in for DC generator type load.

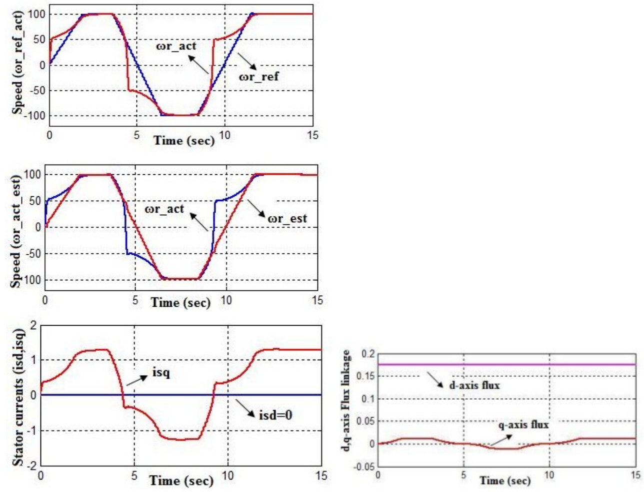

Fig.15. Ramp response of drive with speed reversal

E. Slow and zero speed performance of the drive

The proposed MRAS-based speed estimation algorithm is independent of stator resistance (R_s). Also, the method does not have any integrator related problems. Therefore, zero speed operation is possible to achieve. This is observed from the simulation results presented in Fig16, and The reference and actual speeds are appeared.. It is noticed that the motor is at stand still during 6 s to 10 s. The motor speed is maintained at 10 rad/s before and after that period. Reflects the accuracy of the speed estimation algorithm at zero speed. Finally, reflects that the condition for vector control operation is satisfied even at zero speed. Here constant load torque is considered.

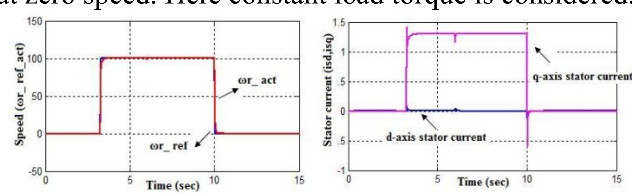

Fig.16 Simulation results for zero speed operation.

CONCLUSION

A model reference adaptive controller based parameters estimation technique has been presented. Both Active and Reactive power is used in the MRAS. The adaptation mechanism used the instantaneous reactive power in the reference model and the steady-state reactive power in the adjustable model. The use of steady-state reactive power eliminates the need of derivative computation. So, the method is less sensitive to noise. Also, the scheme does not need back-emf estimation and hence free from integrator related problems. This improves the performance of the estimator at very low and zero speed. Such unique formulation of MRAS makes the speed estimation algorithm independent of stator resistance (Rs), permanent-magnet-field-strength and d-axis inductance (L_d).

The speed estimator is only dependent on q-axis inductance (L_q) The technique is very simple and utilizes simplified expressions in the reference and adjustable models, which in turn reduces the computation time to execute the algorithm in real time platform. The proposed method may also be used in retrofit applications, because of No extra sensor or additional hardware is required for the realization of this technique.

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Appendix

Permanent Magnet Synchronous Motor Parameters

Symbol	Meaning	value
-	Power	1.1kw
V	Rated Voltage	220v
p	Pole pair d-axis	3
L_d	d-axis inductance	0.0085mH
L_q	q-axis inductance	0.0085mH
L_{af}	Mutual Flux Linkage	0.175Wb-tu
R_s	Stator Resistance	2.875Ω
ω_n	Nominal Speed	1500rpm
F	Frequency	50HZ
J	Machine Inertia	0.0008Kg-m^2
β	Viscous coefficient	0.00038818