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A REIVEW PAPER ON MRAS SPEED ESTIMATION METHODS FOR SENSOR LESS VECTOR CONTROL OF INDUCTION MOTOR

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Abstract* —Model Reference Adaptive System (MRAS) based speed estimation techniques are one of the best methods to estimate the rotor speed due to its performance and straightforward stability approach. In this technique two model one is a Reference model and other is an adjustable model are used for estimation of speed. The scheme uses the error vector from the comparison of both models as a feedback for speed estimation. Depending on the type of tuning signal driving the adaptation mechanism, there could be a number of schemes available such as rotor flux based MRAS, back e.m.f based MRAS, reactive power based MRAS and artificial neural network based MRAS. This paper aims at providing a review of the major model reference adaptive system (MRAS) based techniques applied for the estimation of speed.

Keywords- *Induction motor, speed sensor, sensor less, MRAS*

I. INTRODUCTION

Induction motor have several advantage compares to other electrical motor like low maintenance, rugged and inexpensive [1]. In many industries induction motors are used a drives for this the speed control of motor are required. In past many control methods are used for this which are [1],

- Rotor resistance methods (for slip ring IM)
- Stator voltage control method
- Frequency control methods and
- Scalar control (constant V/F) methods.

This all methods give satisfied operation in certain limit condition but give poor response in high performance applications. So after that new control methods are develop in last few year which are [1],

- Vector or field oriented control and
- Direct torque control

Which give good response in high performance application. For implement the speed control for induction motor by used of above methods the information of actual rotor speed is required. This actual rotor speed can be obtained by two methods [2].

- By used of speed sensor (physical sensor)
- Speed estimation methods (sensor less)

In first the physical speed sensor like techogenerator, optical encoder or other speed sensor are used to obtain the rotor speed. Due to this physical speed sensor following drawbacks are occurs the system reliability in hostile environment (high temperature, high pressure and high moisture) become degrades, It injects noise into the system. Moreover, it is difficult to mount sensors in certain applications, also sensor working life is less (depends on working condition) and also sensor are expensive. For these reasons, the development of alternative indirect methods becomes an important research topic [2].

Therefore, there is a great interest in the research community to develop a high performance induction motor drive that does not require a direct speed sensor for its operation; in other words, to develop a speed-sensor less induction motor drive. Many advantages are expected from speed-sensor less induction motor drives such as reduced hardware complexity, low cost, reduced size, elimination of direct sensor wiring, better noise immunity, increased reliability, and less maintenance requirements. Speed-sensor less motor drives are also preferred in hostile environments and high-speed applications [2]

In last few years several techniques are proposed to estimate the speed in a sensor less induction motor drive. They are broadly classified as: signal injection based methods and fundamental model based. In that the fundamental model based methods are more common because of their simplicity and less associated problems with the signal injection based methods like torque ripple and additional losses [7]. The measured stator voltages and currents are used to estimate the speed of induction motor in the fundamental model based methods, which can be classified as [7],

A. Open loop speed calculators

B. Adaptive Flux Observers
C. Kalman Filters
D. Sliding Mode Observers
E. Model Reference Adaptive Systems (MRAS)
F. Artificial Intelligence Techniques

Among these techniques, the MRAS estimators are the most conventional method because of their simple structure and less computation requirement compared with the other methods [7].

The primary objective of this paper is to review the various MRAS-based techniques for sensor less vector controlled IM drives widely adopted by the researchers last few years. In this regard, a brief discussion on the basic MRAS structure is discussed and also describes and reviews different MRAS models, based on the error minimization of the rotor flux, back EMF, reactive power and stator current.

II. MATHEMATICAL MODEL OF INDUCTION MOTOR

The dynamic behavior of an induction motor is complex due to the coupling effect between the stator and rotor phases. Fig. 2.1 and Fig. 2.2 shows the dynamic d-q equivalent circuits of an induction machine. The dynamic model of induction motor represented in terms of voltages and currents can be given in matrix form as [1]:

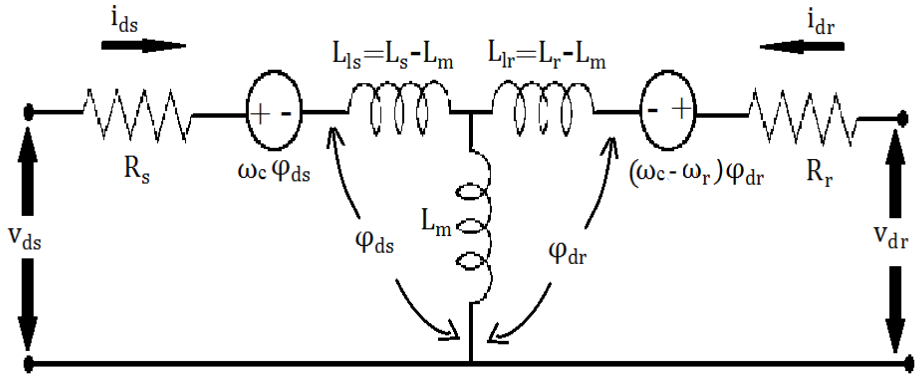

Fig-2.1 d-axis circuit of induction motor

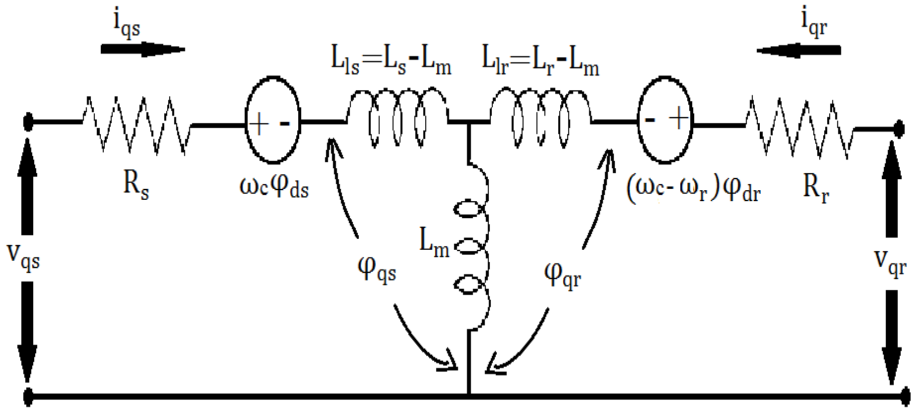

Fig-2.2 q-axis circuit of induction motor

These equations are expressed in general reference frame denoted by the superscript c and Þ represents the derivative operator, d/dt. The dynamic model of the induction motor can also be rearranged with the stator and rotor flux linkages as the state variables [1].

$$\begin{bmatrix} v_{qs}{}^{c} \\ v_{ds}{}^{c} \\ v_{qr}{}^{c} \\ v_{dr}{}^{c} \end{bmatrix} = \begin{bmatrix} R_s + L_s p & \omega_c L_s & L_m p & \omega_c L_m \\ -\omega_c L_s & R_s + L_s p & -\omega_c L_m & L_m p \\ L_m p & (\omega_c - \omega_r) L_m & R_s + L_r p & (\omega_c - \omega_r) L_s \\ -(\omega_c - \omega_r) L_m & L_m p & -(\omega_c - \omega_r) L_r & R_s + L_r p \end{bmatrix} \begin{bmatrix} i_{qs}{}^{c} \\ i_{ds}{}^{c} \\ i_{qr}{}^{c} \\ i_{dr}{}^{c} \end{bmatrix} \tag{1.1}$$

$$\begin{bmatrix} \dot{\psi}_{qs}{}^{c} \\ \dot{\psi}_{ds}{}^{c} \\ \dot{\psi}_{qr}{}^{c} \\ \dot{\psi}_{dr}{}^{c} \end{bmatrix} = \begin{bmatrix} \frac{-1}{\acute{\tau}_s} & -\omega_c & \frac{k_r}{\acute{\tau}_s} & 0 \\ \omega_c & \frac{-1}{\acute{\tau}_s} & 0 & \frac{k_r}{\acute{\tau}_s} \\ \frac{k_s}{\acute{\tau}_r} & 0 & \frac{-1}{\acute{\tau}_r} & -(\omega_c - \omega_r) \\ 0 & \frac{k_s}{\acute{\tau}_r} & (\omega_c - \omega_r) & \frac{-1}{\acute{\tau}_r} \end{bmatrix} \begin{bmatrix} \psi_{qs}{}^{c} \\ \psi_{ds}{}^{c} \\ \psi_{qr}{}^{c} \\ \psi_{dr}{}^{c} \end{bmatrix} + \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} v_{qs}{}^{c} \\ v_{ds}{}^{c} \end{bmatrix} \tag{1.2}$$

Where, $\acute{\tau}_s = \sigma \frac{L_s}{R_s}$, $\acute{\tau}_r = \sigma \frac{L_r}{R_r}$, $k_s = \frac{L_m}{L_s}$, $k_r = \frac{L_m}{L_r}$, $\sigma = 1 - k_s k_r = 1 - \frac{L_m{}^2}{L_s L_r}$

The speed ω_r in the above equations is related to the torque by the following mechanical dynamic equation,

$$T_e - T_l = J\frac{d\omega_r}{dt} + B\omega_r \tag{1.3}$$

$$T_e = \frac{3P}{4}\left(\psi_{ds} i_{qs} - \psi_{qs} i_{ds}\right) \tag{1.4}$$

III. REVIEW OF MODEL REFERENC ADAPTIVE SYSTEM

The basic structure of the MRAS consists of a reference model, an adjustable model and an adaption mechanism as shown in below Fig. 3.1 [1, 3].

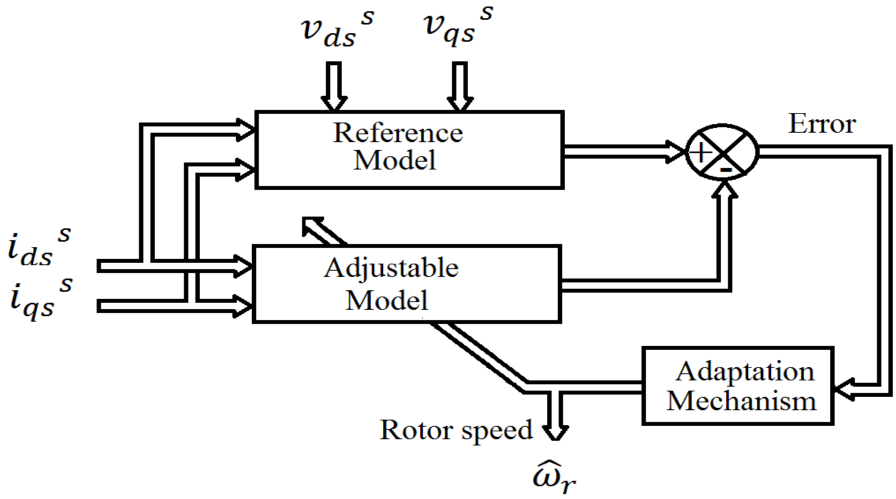

Fig-3.1 General structure of MRAS

The reference model is based on a set of equations which does not include the parameter to be estimated. On the contrary, the adjustable model is used to observe the same state variables with different sets of equations employing different inputs which include the parameter to be estimated [1].

The adaptation mechanism uses the error between the reference model and adjustable model to generate the estimated speed used in the adjustable model. There are several methods for speed estimation of the induction motor based on MRAS [1].

According to the signal generation from reference model and adjustable model the MRAS techniques is classifying below [7, 8],

A. Rotor flux error-based MRAS
B. Back-EMF error-based MRAS
C. Stator current error-based MRAS
D. Active power error based MRAS
E. Reactive power-error-based MRAS

A. ROTOR FLUX ERROR BASED MRAS

The rotor flux based MRAS speed estimator, developed by Schauder in [1], is the most popular scheme among MRAS speed observers due to its simplicity [3,9].

A structure of rotor-flux-error-based MRAS is shown in Fig.3.2 The reference model, which is independent of the rotor speed, calculates the rotor flux $\psi_{dr}{}^{s}$ and $\psi_{qr}{}^{s}$ from the machine terminal voltage and current signals while the adaptive model, which is dependent on the rotor speed, estimates the rotor flux $\bar{\psi}_{dr}{}^{s}$ and $\bar{\psi}_{ds}{}^{s}$. The error between

$X - Y = \widehat{\psi_{dr}}^s \psi_{qr}{}^s - \widehat{\psi_{qr}}^s \psi_{dr}{}^s$ these two state variables is then used to drive an adaptation mechanism which generates the estimated speed ($\widehat{\omega_r}$) [3].

- Reference model Stator equation

$$\begin{bmatrix} \dot{\Psi}_{dr}{}^s \\ \dot{\Psi}_{qr}{}^s \end{bmatrix} = \frac{L_r}{L_m}\left\{\begin{bmatrix} V_{ds}{}^s \\ V_{qs}{}^s \end{bmatrix} - \begin{bmatrix} (R_s + \sigma L_s S) & 0 \\ 0 & (R_s + \sigma L_s S) \end{bmatrix}\begin{bmatrix} i^s \\ i_{qs}{}^s \end{bmatrix}\right\} \tag{3.1}$$

- Adjustable model Rotor equation

$$\begin{bmatrix} \dot{\Psi}_{dr}{}^s \\ \dot{\Psi}_{qr}{}^s \end{bmatrix} = \begin{bmatrix} -\frac{1}{T_r} & -\omega_r \\ \omega_r & -\frac{1}{T_r} \end{bmatrix}\begin{bmatrix} \Psi_{dr}{}^s \\ \Psi_{qr}{}^s \end{bmatrix} + \frac{L_m}{T_r}\begin{bmatrix} i_{ds}{}^s \\ i_{qs}{}^s \end{bmatrix} \tag{3.2}$$

. The reference and adjustable model are obtained from the machine dynamics equations as (3.1) and (3.2) belong to the reference model, whereas (3.3) and (3.4) belong to the adjustable model. The error between the two models is given by

- Error signal

$$\xi = X - Y = \widehat{\psi_{dr}}^s \psi_{qr}{}^s - \widehat{\psi_{qr}}^s \psi_{dr}{}^s \tag{3.3}$$

- Estimated Rotor speed

$$\widehat{\omega}_r = \varepsilon\left(K_p + \frac{K_I}{s}\right) \tag{3.4}$$

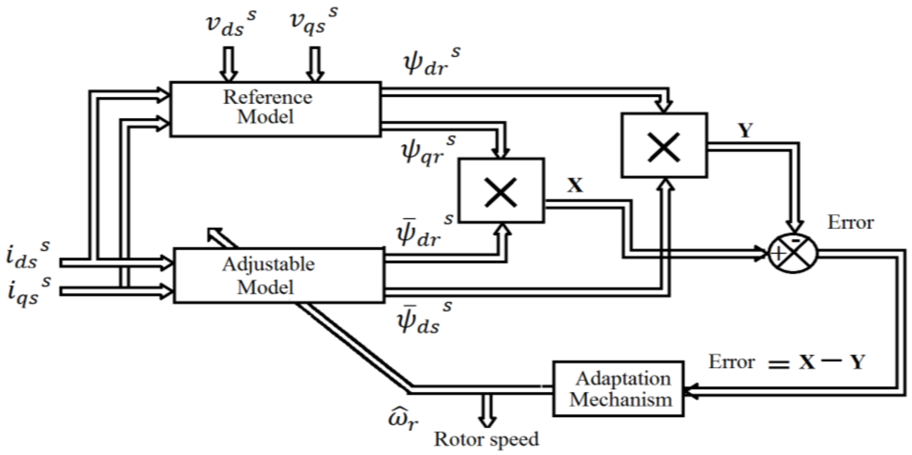

Fig.3.2 Rotor flux error-based MRAS

However, this method is sensitive to the stator resistance variations. In addition, the existence of pure integrator in the reference model leads to problems with initial condition, drift, and offset. To overcome the problem of pure integration, the pure integrator can be replaced with a low pass filter; however, the accuracy of speed estimation at low speeds is decreased and a time delay is produced [10, 11, and 9].

B. BACK EMF ERROR BASED MRAS

In 1994 Peng and Fukao proposed an alternative new MRAS scheme for estimating the rotor speed of induction motor using counter electromagnetic force or back EMF which overcome the drawback of rotor flux error-based MRAS.

The back-EMF-based MRAS technique does not require any pure integration in its reference and adjustable models. Instead of using the rotor fluxes in reference and adaptive models, the back EMF is estimated and compared with the measured quantity to produce a speed error correction signal [7-9]. The back EMF in terms of machine parameters is calculated with the help of following equations.

- Reference model equation

$$e_{md} = v_{sd} - \left[R_s i_{ds} + \sigma L_s \frac{di_{ds}}{dt}\right] \tag{3.5}$$

$$e_{mq} = v_{sq} - \left[R_s i_{qs} + \sigma L_s \frac{di_{qs}}{dt}\right] \tag{3.6}$$

- Adjustable model equation

$$\hat{e}_{md} = \frac{-L_m}{L_r}\left[\omega_r\left(L_m i_{qs} + L_r i_{qr}\right) + R_r i_{dr}\right] \tag{3.7}$$

$$\hat{e}_{mq} = \frac{-L_m}{L_r}\left[\omega_r\left(L_m i_{ds} + L_r i_{dr}\right) + R_r i_{qr}\right] \tag{3.8}$$

- Error signal equation

$$Error = \varepsilon = \hat{e}_{md} e_{mq} - \hat{e}_{mq} e_{md} \tag{3.9}$$

- Estimated rotor speed equation

$$\hat{\omega}_r = \varepsilon \left(K_p + \frac{K_I}{s}\right) \tag{3.10}$$

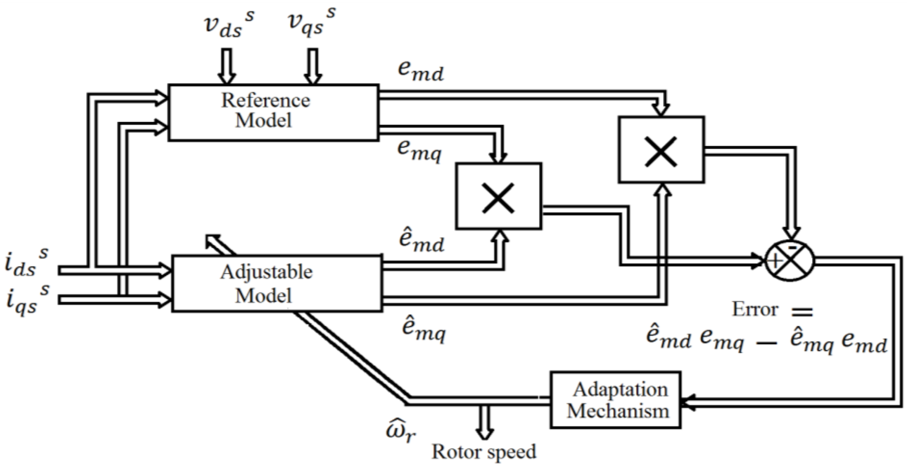

Fig.3.3 Back EMF error-based MRAS

The back-e.m.f based MRAS is dependent upon the variation of stator resistance due to the presence of stator resistance in the reference model. Therefore, accurate sensing of the back-e.m.f is impossible, especially at low speeds. In addition, the presence of derivative operator in the reference model reduces the signal-to-noise ratio considerably at low speeds [10, 11].

C. STATOR CURRENT ERROR BASED MRAS

The stator current based MRAS method, in which, the measured stator currents of the induction motor are used as the reference model, whereas the estimated stator currents of the induction motor are considered as the adjustable model [7, 8]. To estimate Performance of the stator current based MRAS is better than other rotor flux error based and back e.m.f error based MRAS speed estimator (especially at low speeds) due to absence of induction motor's parameters and derivative operator in the reference model. The main merits of MRAS method include [10, 11]: the stator currents, the information on the rotor fluxes are required. The rotor fluxes are calculated by using measured stator currents Eqn.3.11. The stator currents are estimated by Eqn.3.11. Finally, rotor speed is estimated by Eqn. 3.4 [8].

- Reference model equation

$$\frac{d}{dt}\begin{bmatrix}\psi_{dr}\\ \psi_{qr}\end{bmatrix} = \begin{bmatrix}\frac{L_m}{T_r} & 0 & \frac{-1}{T_r} & -\omega_r\\ 0 & \frac{L_m}{T_r} & \omega_r & \frac{-1}{T_r}\end{bmatrix}\begin{bmatrix}i_{ds}\\ i_{qs}\\ \psi_{dr}\\ \psi_{qr}\end{bmatrix} \tag{3.11}$$

- Adjustable model equation

$$\frac{d}{dt}\begin{bmatrix}\hat{i}_{ds}\\ \hat{i}_{qs}\end{bmatrix} = \begin{bmatrix}-a_1 & 0 & a_2 & a_3\omega_r\\ 0 & -a_1 & -a_3\omega_r & a_2\end{bmatrix}\begin{bmatrix}\hat{i}_{ds}\\ \hat{i}_{qs}\\ \psi_{dr}\\ \psi_{qr}\end{bmatrix} + \frac{1}{\sigma L_s}\begin{bmatrix}v_{ds}\\ v_{qs}\end{bmatrix} \tag{3.12}$$

- Estimated rotor speed equation

$$\hat{\omega}_r = \left(K_p + \frac{K_I}{s}\right)\left[(i_{ds} - \hat{i}_{ds})\psi_{qr} - (i_{qs} - \hat{i}_{qs})\psi_{dr}\right] \tag{3.13}$$

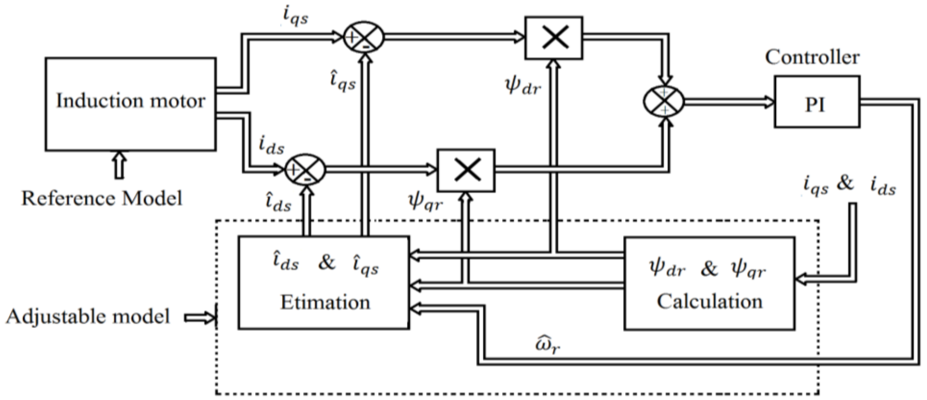

Fig-3.4 Stator Current based MRAS

The main advantages of this are MRAS Simple structure, Fast convergence, Robustness, Small computation time [8]. Disadvantages are arduousness of the adaptation mechanism design, Sensitivity to inaccuracy in the reference model [8]

D. ACTIVE POWER BASED MRAS

In active power based MRAS there are no requirement of any machine parameter except to rotor resistance. For implement this stator voltage and currents are only require. In that first stator voltages (v_{sa}, v_{sb} and v_{sc}) convert in $v_{s\alpha}, v_{s\beta}, v_{ds}$ and v_{qs} and stator current (i_{sa}, i_{sb} and i_{sc}) are convert to $i_{s\beta}, i_{s\alpha}, i_{ds}$ and i_{qs} by used of three phase to two phase transformation. After that by used of following equation reference model and adjustable model are implements [10-14].

- Reference model equation

$$P_r = v_{s\beta}{}^* i_{s\beta} + v_{s\alpha}{}^* i_{s\alpha} \tag{3.14}$$

- Adjustable model equation

$$P_s = v_{sq}{}^* i_{sq}{}^* + v_{sd}{}^* i_{sd}{}^* \tag{3.15}$$

Reference model generate Pr power and adjustable model generate Ps power this two power will compare with comparator and generate error signal which feed to adaptation mechanism which calculate to rotor speed of motor by following equation [13]

- Error signal.

$$\varepsilon = P_r - P_s \tag{3.16}$$

- Estimated rotor speed equation

$$\hat{\omega}_r = \varepsilon\left(K_p + \frac{K_I}{s}\right) \tag{3.17}$$

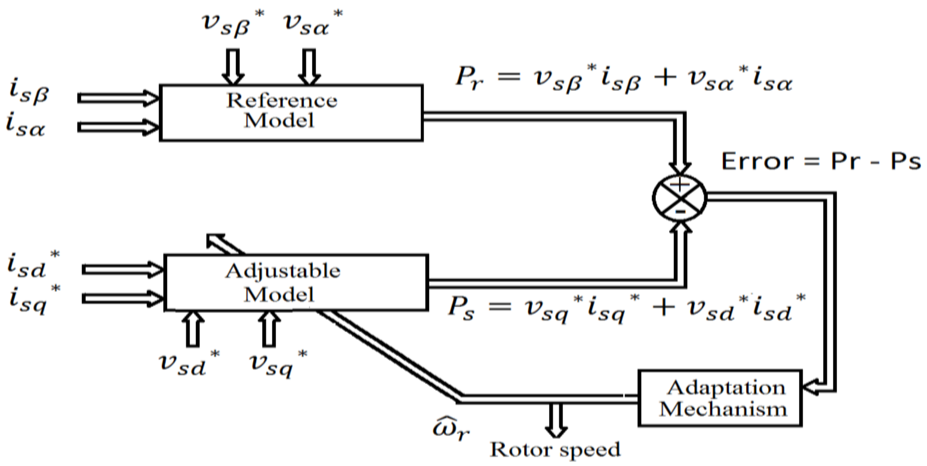

Fig.3.5 Active power based MRAS

In active power based MRAS have several advantages like it does not involve any machine parameters except the rotor resistance, computation of flux is not required and the controller is free from integrator and differentiator terms. Thus, the drive works very well at low speed compared to other MRAS but it unable to give stable operation in all four quadrants of operation [14]

E. REACTIVE POWER BASED MRAS

The reactive power is computed at the machine terminal. The structure of the machine terminal reactive power based MRAS is shown in Fig. 3.6, which Eqn.3.18 is utilized in the reference model and Eqn. 3.19, is utilized in the adjustable model. In the reference model, the measured stator currents are used to calculate the machine terminal reactive power where as in the adjustable model, estimated stator currents are used to estimate the machine terminal reactive power. The machine state space equations are utilized to estimate the stator currents. The adaptation mechanism consists of a PI controller where uses difference between calculated and estimated machine terminal reactive power as input. Therefore, estimated speed can be presented by Eqn. 3.21.

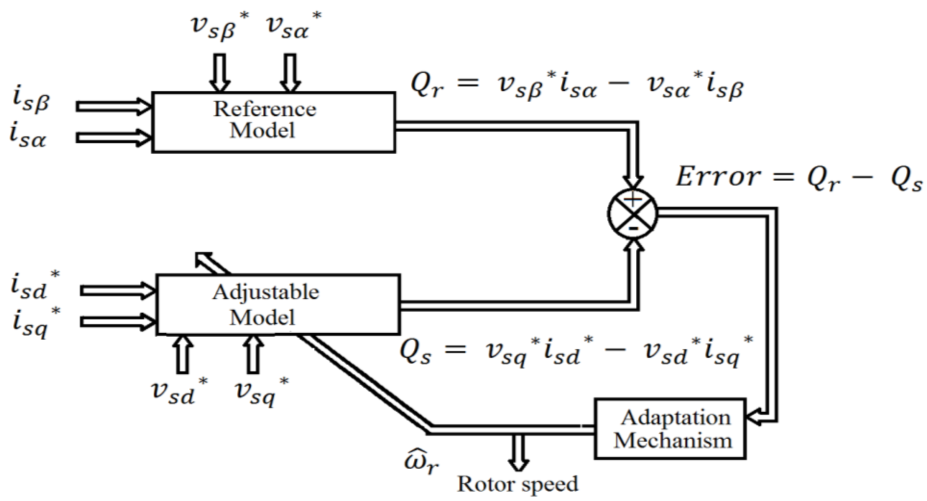

Fig.3.6 Reactive power based MRAS

- Reference model equation

$$Q_r = v_{s\beta}^* i_{s\alpha} - v_{s\alpha}^* i_{s\beta} \tag{3.18}$$

- Adjustable model equation

$$Q_s = v_{sq}^* i_{sd}^* - v_{sd}^* i_{sq}^* \tag{3.19}$$

- Error equation

$$\varepsilon = Q_r - Q_s \tag{3.20}$$

- Estimated rotor speed equation

$$\hat{\omega}_r = \varepsilon\left(K_p + \frac{K_I}{s}\right) \tag{3.21}$$

Advantages of reactive power based model reference adaptive system is stable in all the four quadrants of operation of the speed sensor less vector controlled induction motor drive. The form of Q-MRAS is also free from integration and differentiation terms and independent of stator resistance. Estimation of flux and extra hardware/sensors are not required for its implementation. The drive works well at low speeds.

IV. CONCLUSION

In this paper, different types of MRAS speed estimation methods for sensor less induction motor drive and corresponding merits and demerits have been presented and from the investigation of different MRAS methods it is found that In rotor flux error based MRAS, the stator resistance is appeared in the reference model and stator resistance varies with temperature, and this affects the stability performance of the speed observer, especially at low speeds Furthermore, the presence of pure integrators in the reference model leads drift and initial condition problems. To avoid these problems, low-pass filters are used instead of pure integrators; however, they cause serious problems at low speeds and introduce a time-delay. The back-e.m.f error based MRAS is dependent upon the variation of stator resistance due to the presence of stator resistance in the reference model. Therefore, accurate sensing of the back-e.m.f is impossible, especially at low speeds. In addition, the presence of Derivative operator in the reference model reduces the signal-to-noise ratio considerably at low speeds. In stator current error based MRAS is have Simple structure, Fast convergence, Robustness, Small computation time required but adaptation mechanism designing is difficult and Sensitivity in the reference model is to inaccurate. In active power based MRAS and reactive power based MRAS are does not involve any machine parameters except the rotor resistance, computation of flux is not required and the controller is free from integrator and differentiator terms. Thus, the drive works very well at low speed compared to other MRAS. Furthered more the reactive power MRAS is only give stable in all the four quadrants of operation of the speed sensor less vector controlled induction motor drive.

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