SENSORLESS DIRECT TORQUE CONTROL OF INDUCTION MOTOR WITH MRAS AND EXTENDED KALMAN FILTER

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Abstract
The conventional Direct Torque Control (DTC) of Induction Motor using an open loop suffers from the well-known problems of especially in the low speed range of operation. To overcome this problem, the induction motor variables and parameters estimation is performed using a recursive non-linear observer known as Extended Kalman Filter. This proposed observer is used to estimate the stator currents, the rotor flux linkages, the rotor speed and the stator resistance. The main drawback of the conventional EKF is that the load dynamics has to be known which is not usually possible in the drives. Therefore, a Model Reference Adaptive System (MRAS) is used to estimate the rotor speed of an induction motor. The EKF is designed to estimate the rotor speed and stator flux and resistance. A new state space model of the IM is developed for estimation in EKF, with load torque as an input variable and not as an estimated quantity which is the case in most previous studies.The developed algorithm is validated using MATLAB-Simulink Estimated parameters are used for the closed loop speed sensorless control operation of the Induction Motor. In this paper, it has been demonstrated that the EKF estimation and sensorless DTC perform quite well in spite of the parameters and load variations that handled by the system. The simulation results are presented to validate the effectiveness of the overall control scheme.

Keywords: Induction motor; Direct Torque Control; Space Vector, Sensorless, Parameters estimation; Model Reference Adaptive System; Extended Kalman Filter and MATLAB-Simulink.

I. INTRODUCTION

In recent years significant advances have been made on the sensorless control of IM. One of the most well-known methods used for control of AC drives is the Direct Torque Control (DTC) developed by Takahashi in 1984 [1]. DTC of IMs is known to have a simple control structure with comparable performance to that of the field-oriented control (FOC) techniques developed by Blaschke in 1972 [2]. Unlike FOC methods, DTC techniques require utilization of hysteresis band comparators instead of flux and torque controllers [3-4]. To replace the coordinate transformations and pulse width modulation (PWM) signal generators of FOC, DTC uses look-up tables to select the switching procedure based on the inverter states [5]. The DTC strategy directly controls the inverter states based on the errors between the reference and estimated values of torque and flux. It selects one of eight voltage vectors generated by a voltage source inverter to keep torque and flux within the limits of two hysteresis comparators. Compared with Rotor Field Oriented Control, DTC has many advantages such as less machine parameter dependence (only the stator resistance), simpler implementation and quicker dynamic torque response [6]. There is no current controller needed in DTC, because it selects the voltage space vectors according to the errors of flux linkage and torque. The main drawback of the DTC is its relatively high torque and flux ripple. To improve the performance of the classical DTC, the stator flux locus is divided into twelve sectors instead of six so all six active states will be used in each sector. In the classical DTC, the stator flux vector which is estimated as the integral of the stator voltage vector as described [7]. This estimation suffers from the well known problems of the pure integration and on the other hand the stator resistance variation effect and this occur especially at low speed operation range [8]. Therefore we propose in this work to use the EKF to observe simultaneously the rotor speed and stator flux and resistance. The basic MRAS algorithm is very simple but its greatest drawback is the sensitivity to uncertainties in the motor parameters. On other method based on the Extended Kalman Filter (EKF) algorithm is used [9-10]. The

EKF is a stochastic state observer where nonlinear equations are linearized in every sampling period. An interesting feature of the EKF is its ability to estimate simultaneously the states and the parameters of a dynamic process [11]. This is generally useful for both the control and the diagnosis of the process. This observation does not depend on motor parameter except the stator resistance. A constant value of stator resistance is considered. However, in practice, this parameter changes due tovariation of stator windings temperature. This fact introduces errors in the flux and the electromagnetic torque estimations and the drive may become unstable. So the compensation of the stator resistance variation effect becomes necessary [12]. The main difference of closed loop estimator from open loop estimator is the inclusion of estimation error correction term to adjust the response of the estimator. Open loop estimators are not using this correction term but closed loop estimators are using this correction term and hence they are called as observers [13]. The estimators or observers used vary in terms of accuracy, robustness and sensitivity against model parameter variations. The speed sensorless control gives good performance in the higher ranges of speed but performance deteriorates at low speed including zero speed. The poor performance of estimators at low speeds is mainly due to the variation in measured motor voltage and current due to the domination of dc offset of electronic components involved, variation in machine parameters due to the change in winding temperature, drift problems associated with direct integration and noise in the low speed range [14]. The pure integration method used in the classical DTC of IMs suffers from the well known problems of integration especially at low speed operation range is replaced in this work by the EKF. This observer is used to estimate the stator currents, the rotor flux linkages, the rotor speed and the stator resistance. The speed estimation is affected by parameter variations especially the stator resistance due to temperature rises particularly at low speeds [15]. Therefore, it is adequate to compensate this parameter variation in sensorless induction motor drives using an online adaptation of the control scheme by the estimated stator resistance using the EKF. To overcome this problem, a novel speed estimator is used based on the MRAS strategy. In this paper MRAS and Extended kalman filter is used to simulate the induction motor drive using MATLAB-Simulink.

II. MATHEMATICAL MODELING OF INDUCTION MOTOR:

The steady state performance of the three-phase balanced supply fed 3-Φ induction motor can be assessed by a 1-phase equivalent circuit. But, in the variable speed drive applications the assessment of dynamic performance is important. Hence, to study the dynamic and steady state performance, an accurate mathematical model of induction motor is necessary. The flux linkages of 3-phase induction motor in the stator reference frame can be expressed as,

$$\lambda_{qs} = L_s i_{qs} + L_m i_{qr} \quad (1)$$

$$\lambda_{ds} = L_s i_{ds} + L_m i_{dr} \quad (2)$$

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

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

The IM model expressed in the stationary reference frame can be written in space vector notation as:

$$v_{ds} = R_s i_{ds} + \frac{d\lambda_{ds}}{dt} \quad (5)$$

$$v_{qs} = R_s i_{qs} + \frac{d\lambda_{qs}}{dt} \quad (6)$$

$$0 = R_r i_{dr} + \omega_r \lambda_{qr} + \frac{d\lambda_{dr}}{dt} \quad (7)$$

The expression of electromagnetic torque of a 3-phase induction motor can be given as,

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)\left(\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}\right) \quad (8)$$

III. DIRECT TORQUE CONTROL:

In recent years, the research has been focused to find out different solutions for the induction motor control having the features of precise and quick torque response and reduction of the complexity of field oriented control. The direct torque control (DTC) technique has been recognized as the viable solution to achieve these requirements. The DTC based induction motor drives were developed and presented more than two decades ago by I.Takahashi and M. Depenbrock. However, at present, ABB is the only industrial company who has introduced a commercially available direct torque controlled induction motor drive. This technique is based on the space vector approach, where the torque and flux of an induction motor can be directly and independently controlled without any coordination transformation. Though the DTC gives fast transient response, it gives large steady state ripples and variable switching frequency of the inverter.

The electromagnetic torque of a three-phase induction motor can be written as,

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{\sigma L_s L_r}|\psi_r||\psi_s|\sin\delta \qquad (9)$$

where δ is the angle between the stator flux linkage space vector ($\overline{\psi}_s$) and rotor flux linkage space vector ($\overline{\psi}_r$), as shown in Fig. 1 and σ is the leakage coefficient given by $\sigma = 1 - \left(\frac{L_m^2}{L_s L_r}\right)$.

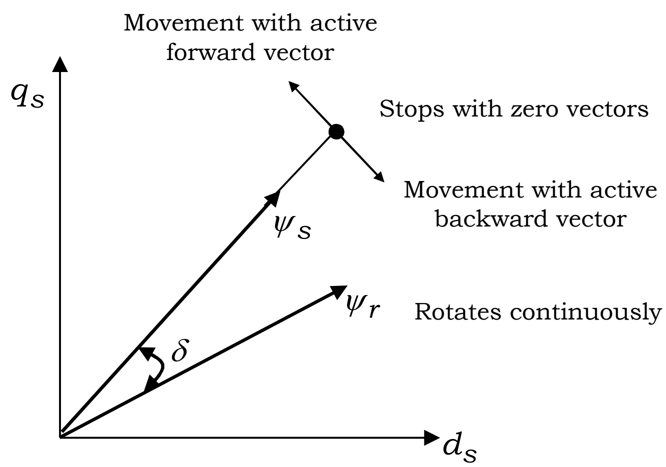

Fig. 1 $\overline{\psi}_s$ movement relative to $\overline{\psi}_r$ under influence of voltage vectors

By considering the three-phase, two-level, six pulse voltage source inverter (VSI), there are six non-zero active voltage space vectors and two zero voltage space vectors as shown in Fig. 3.3. The six active voltage space vectors can be represented as,

$$\overline{V}_k = \frac{2}{3}V_{dc}\exp\left[j(k-1)\pi/3\right] \qquad k = 1,2,\ldots,6 \qquad (10)$$

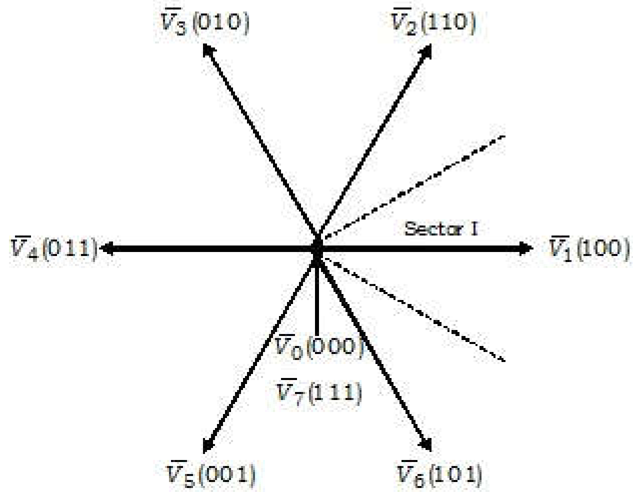

Fig. 2 Inverter voltage space vectors

Depending on the position of stator flux linkage space vector, it is possible to switch the appropriate voltage vectors to control both stator flux and torque.

IV. MODEL REFEREE ADAPTIVE SYSTEM (MRAS):

The MRAS is important since it leads to relatively easy to implement system with high speed of adaptation for a wide range of applications. The basic scheme of the parallel MRAS configuration is given in figure 3. The scheme consists of two models; reference and adjustable ones and an adaptation mechanism. The block “reference model” represents the actual system having unknown parameter values. The block “adjustable model” has the same structure of the reference one, but with adjustable parameters instead of the unknown ones. The block “adaptation mechanism” estimates the unknown parameter using the error between the reference and the adjustable models and updates the adjustable model with the estimated parameter until satisfactory performance is achieved.

Using a proportional plus integral (PI) observer, the IM speed observer equation is given by,

$$\hat{\omega}_r = K_p\left(\varepsilon_\beta \hat{\psi}_{r\alpha} - \varepsilon_\alpha \hat{\psi}_{r\beta}\right) + K_I \int_0^t \left(\varepsilon_\beta \hat{\psi}_{r\alpha} - \varepsilon_\alpha \hat{\psi}_{r\beta}\right) dt \qquad (11)$$

This expression depends on the unknown rotor flux components ($\psi_{r\alpha}$ and $\psi_{r\beta}$). Therefore, these two variables are added to the state vector and estimated using the EKF.

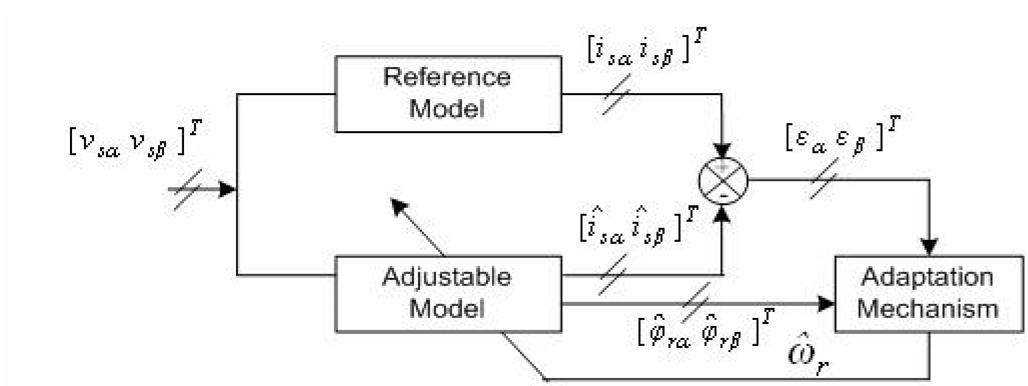

Fig 3. Schema of the rotor speed estimation based on MRAS structure

V. EXTENDED KALMAN FILTER:

The Kalman filter KF is a special kind of observer, which provides optimal filtering of noises in measurement and inside the system if the covariance matrices of these noises are known. The process and the measurement noises are both assumed to be Gaussian with a zero mean. For nonlinear problems, the KF is not strictly applicable since linearity plays an important role in its derivation and performance as an optimal filter. In addition, the KF has the ability to produce estimates of states that are not measurable.

This feature is particularly important for estimation problems associated with the squirrel cage IM as the rotor quantities are not directly accessible. Also the KF has the ability to produce estimates of states which are not measurable. If a simultaneous estimate of the machine parameter, let say stator resistance, is needed then it is defined as an auxiliary state variable. A new state vector containing the original states and the parameter is then established. Therefore, the Extended Kalman Filter (EKF) is more convenient suitable than the KF. The prediction and correction expressions were presented as,

$$\hat{x}((k+1)/k = F(k).\hat{x}(k/k) + G(k).u(k) \tag{12}$$

$$P((k+1)/k) = F(k).P(k/k).F^{T}(k) + Q \tag{13}$$

$$\hat{x}((k+1)/(k+1)) = \hat{x}((k+1)/k) + K(k+1)\left[y(k+1) - H(k+1).\hat{x}((k+1)/k)\right] \tag{14}$$

$$K(k+1) = P((k+1)/k).H^{T}(k+1).\left[H(k).P((k+1)/k).H^{T}(k) + R\right]^{-1} \tag{15}$$

$$P((k+1)/(k+1)) = P((k+1)/k) - K(k+1).H(k+1).P((k+1)/k) \tag{16}$$

where the estimation covariance error is:

$$P(k/k) = E\left\{(x(k) - \hat{x}(k))(x(k) - \hat{x}(k))^{T}\right\} \tag{17}$$

From the above equations, the EKF is designed in the simulink.

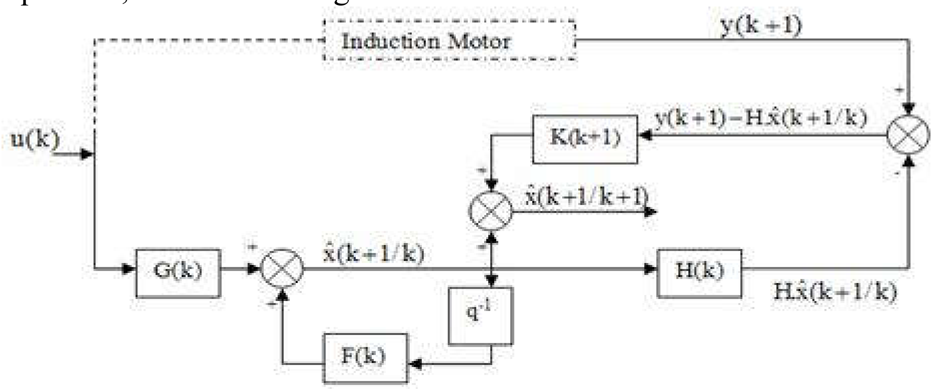

Fig. 4. The general diagram of the Extended Kalman Filter

VI. DIRECT TORQUE CONTROL OF INDUCTION MOTOR BASED ON MRAS AND EXTENDED KALMAN FILTER:

To reduce the complexity of the algorithm, in this paper, the required reference voltages to control the torque and flux cycle-by-cycle basis is constructed by using the errors between the reference d-axis and q-axis stator fluxes and estimated stator fluxes sampled from the previous cycle.

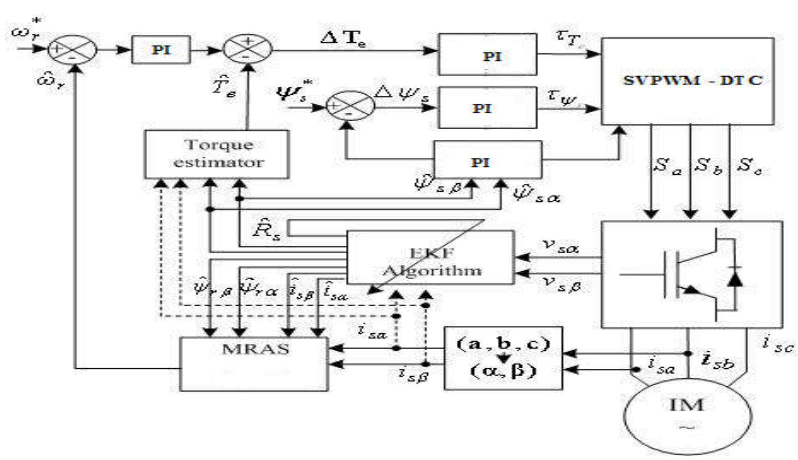

Fig. 5 Direct Torque Control IM drive with MRAS Extended Kalman Filter.

The block diagram of the proposed RZVDPWM algorithm based DTC is as shown in Fig.5 from which it can be seen that the proposed PWM based DTC scheme retains all the advantages of the CDTC, such as no co-ordinate transformation and robust to motor parameters but the complexity is increased in comparison with the CDTC method. In the proposed method, the position of the reference stator flux vector $\overline{\psi}_s^*$ is derived by the addition of slip speed and actual rotor speed. The actual synchronous speed of the stator flux vector $\overline{\psi}_s$ is calculated from the adaptive motor model. After each sampling interval, actual stator flux vector $\overline{\psi}_s$ is corrected by the error and it tries to attain the reference flux space vector $\overline{\psi}_s^*$. Thus the flux error is minimized in each sampling interval.

VII. SIMULATION RESULTS:

The proposed induction motor control scheme has been simulated in MATLAB/SIMULINK software package and the simulation results were presented. Motor parameters used in simulations are given as follows. Rated power = 3 kW, frequency = 50 Hz, $R_s = 2.3\ \Omega$, $R_r = 1.55\ \Omega$, $L_s = L_r = 0.261$ H, $M = 0.249$ H, $J = 0.0076$ kg.m^2. The ripple affecting both electromagnetic torque response Fig. 6 and flux response Fig. 7 is due to the use of hysteresis controllers. The real and estimated state variables using the EKF are given respectively in Fig. 8 to Fig. 11. It is clearly shown that the estimated variables are in close agreement with the real ones.

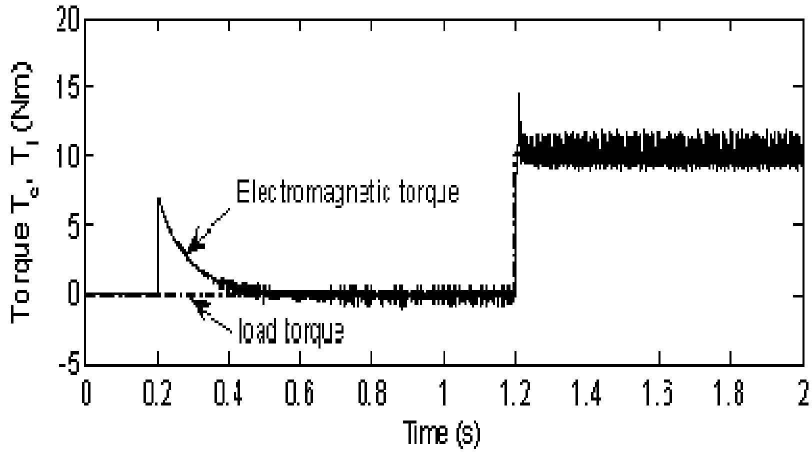

Fig 6. The electromagnetic and load torque.

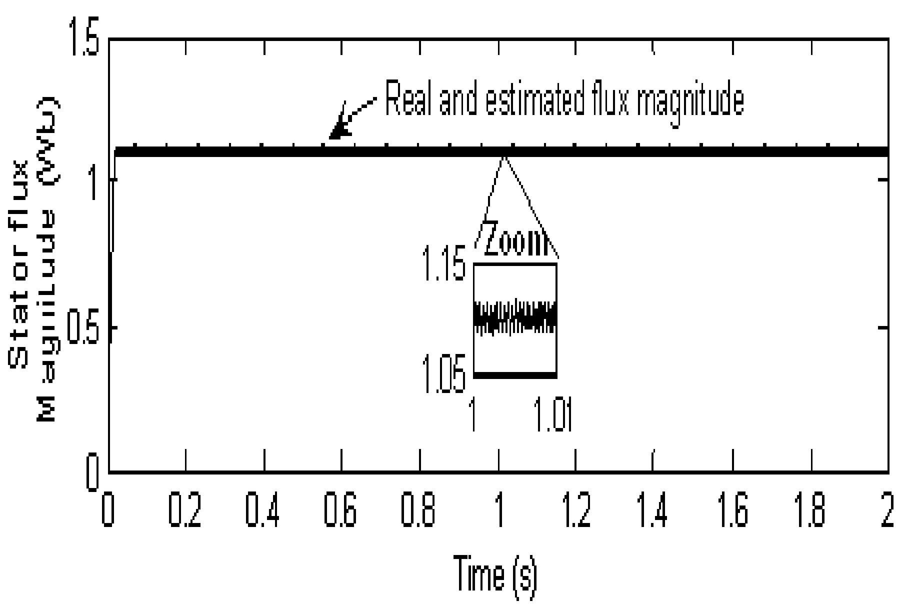

Fig 7. The stator flux magnitude

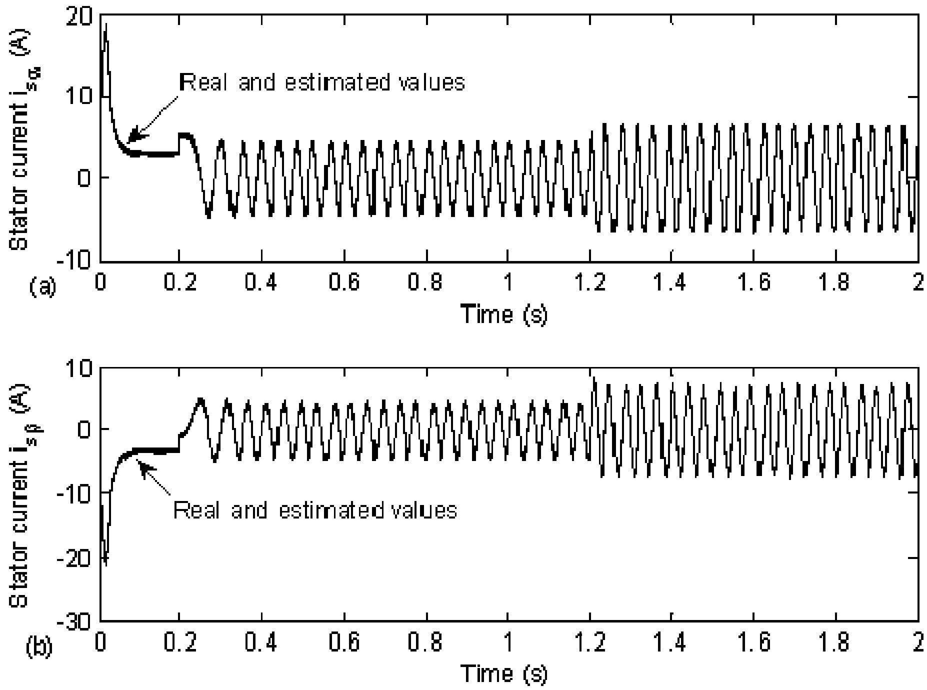

Fig 8. The actual and estimated stator currents

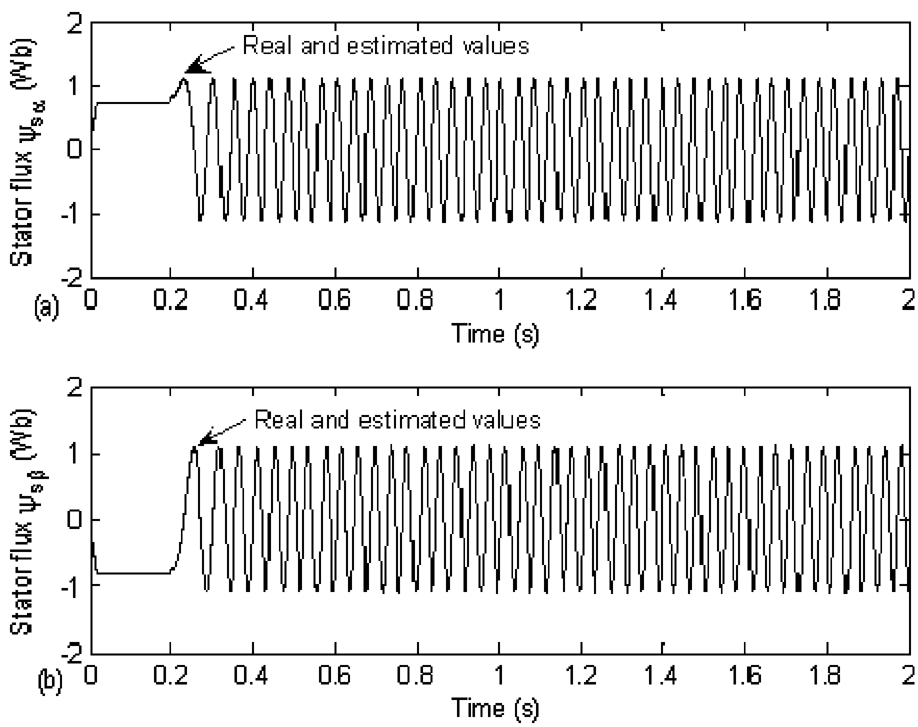

Fig 9. The actual and estimated stator flux linkages

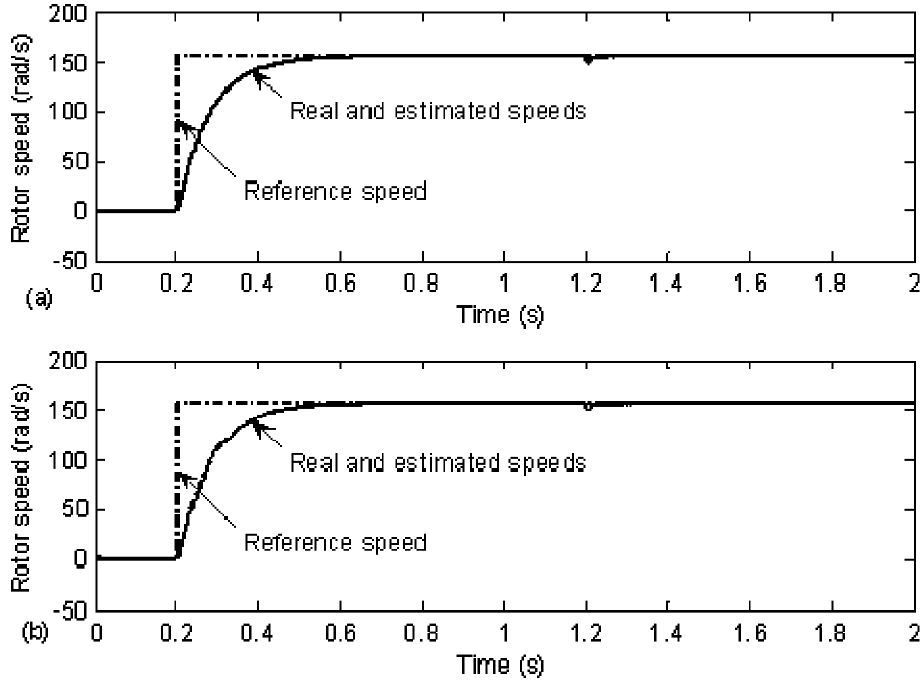

Fig 10. The actual and estimated speed (a) using the EKF, (b) using the MRAS

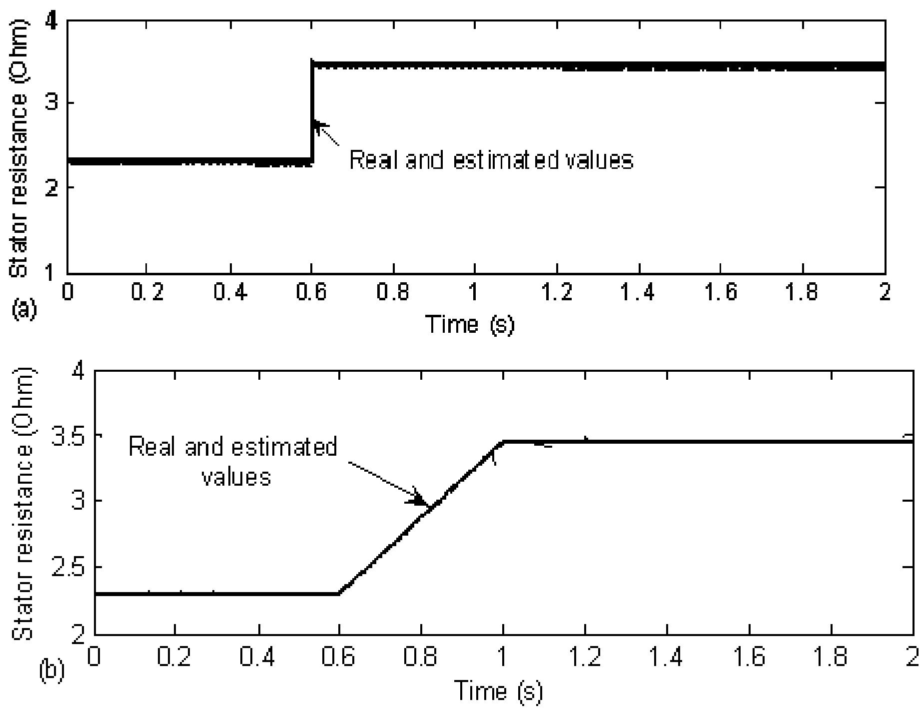

Fig 11. The actual and estimated stator resistance, (a) Abrupt variation, (b) Smooth variation

The real and estimated rotor speeds are given in Fig. 10 (a) using the EKF and Fig. 10 (b) using MRAS. It clearly appears that the EKF and the MRAS have the property of noises rejection. To compare the performance of the two speed observers EKF and MRAS, it is right to study their behavior at start-up and at steady state regions. Fig. 10 (a) and (b) show respectively, the actual and estimated speeds at starting using the EKF and the MRAS technique. The speed estimation error given by the two observers is negligible, but the error with the MRAS is slightly higher. The results are shown in Fig. 11 (a) and (b). Fig. 11 (a) shows the tracking of the stator resistance (for a smooth change). Fig. 11 (b) also shows the tracking of the stator resistance variations. It is clearly shown that the estimated stator resistance converges after less than 1 ms to the nominal value with a tiny error. This result demonstrates that even if the stator resistance changes abruptly, the EKF still gives a good estimate of this major parameter.

VIII. CONCLUSIONS :

In this paper, the well-known classical DTC of IM is detailed and modified to improve its performance, and a comparison between two nonlinear observers, the EKF and the MRAS is presented. The two observers are studied and compared in the same operating conditions and Simulation results show that both observers have the property of noise rejection and they are robust against parameters and load variations. The performance of the EKF is quite satisfactory and slightly better. But, this type of observer requires an accurate knowledge of the load torque and needs more computational time due to heavy matrices manipulations. By contrast, the MRAS strategy doesn’t need the load torque to be known and it is much easier to implement.

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