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Research Article

# MRAS state estimator for speed sensorless ISFOC induction motor drives with Luenberger load torque estimation

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ABSTRACT

This paper presents a novel method for estimating the load torque of a sensorless indirect stator flux oriented controlled (ISFOC) induction motor drive based on the model reference adaptive system (MRAS) scheme. As a matter of fact, this method is meant to inter-connect a speed estimator with the load torque observer. For this purpose, a MRAS has been applied to estimate the rotor speed with tuned load torque in order to obtain a high performance ISFOC induction motor drive. The reference and adjustable models, developed in the stationary stator reference frame, are used in the MRAS scheme in an attempt to estimate the speed of the measured terminal voltages and currents. The load torque is estimated by means of a Luenberger observer defined throughout the mechanical equation. Every observer state matrix depends on the mechanical characteristics of the machine taking into account the vicious friction coefficient and inertia moment. Accordingly, some simulation results are presented to validate the proposed method and to highlight the influence of the variation of the inertia moment and the friction coefficient on the speed and the estimated load torque. The experimental results, concerning to the sensorless speed with a load torque estimation, are elaborated in order to validate the effectiveness of the proposed method. The complete sensorless ISFOC with load torque estimation is successfully implemented in real time using a digital signal processor board DSpace DS1104 for a laboratory 3 kW induction motor.



## 1. Introduction

Induction motors are the most widely used at variable speed and torque control because of their simplicity, ruggedness, efficiency and reliability. Nowadays, a significant advance in the fields of power electronics and microelectronics has made possible the implementation of efficient controls for induction motor drive.

However, many problems remain due to its complex and nonlinear mathematical model, which depends on electrical and mechanical parameters variations and other operating conditions. The parameters variations have significant effects on the accuracy of control speed and torque. The main external factor which affects the motor control system performance is the disturbance torque applied on the motor shaft. By considering the load torque estimation applied on the motor shaft, better controllers could be designed to make the sensorless speed controlled ISFOC induction motor drive robust to load variations.

In the literature, several works have been fulfilled to estimate the load torque. In fact, these works present a wide variety of approaches which depend on the estimation techniques, observation and interconnection of whether an observer and an estimator or two observers. In Ref. [1] the authors present a novel speed sensorless field-oriented control scheme of induction motor (IM) using extended Kalman filter (EKF) based on the synchronous reference coordinate. In this paper two methods which are used the rotor speed as state variable; also the load torque is incorporated as a state variable and compensated to the system as a feedforward. Moreover, the authors in Ref. [2] introduce an estimation algorithms using the EKF, this method could be used in combination with the speed-sensorless field-oriented control and direct-torque control of IM. Furthermore, the reference [3] shows a novel estimation strategy based on the unscented Kalman filter for sensorless control of permanent magnet synchronous motor (PMSM) drive. In this method the speed estimation, rotor position and load torque are resolved by the measurement of the motor current. In all of these estimation methods, the load torque resulting from the torque observer is injected into the mechanical equation defining the EKF. The advantage of this solution lies in

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**Nomenclature**

| | |
|---|---|
| $v_{ds}$, $v_{qs}$ | $d$, $q$ – axis stator voltage components. |
| $i_{ds}$, $i_{qs}$ | $d$, $q$ – axis stator current components. |
| $\phi_{ds}$, $\phi_{qs}$ | $d$, $q$ – axis stator flux components. |
| $\phi_{\alpha s}$, $\phi_{\beta s}$ | $\alpha$, $\beta$ – axis stator flux components. |
| $R_s$, $R_r$ | Stator and rotor winding resistance. |
| $L_s$, $L_r$ | Stator and rotor self-inductance. |
| $M$ | Mutual inductance. |
| $n_p$ | Number of pole pairs. |
| $p=\frac{d}{dt}$ | Differential operator |
| $\omega_s$, $\omega$ | Synchronous and rotor angular speed. |
| $\omega_{sl}$ | Slip angular speed ($\omega_s-\omega$). |
| $T_e$, $T_l$ | Electromagnetic and load torque. |
| $J$ | Inertia moment. |
| $f$ | Friction coefficient. |
| $\tau_s$, $\tau_r$ | Stator and rotor time constant. |
| $k_{vi}$ | Integral gain of the integral plus proportional IP speed controller. |
| $k_{vp}$ | Proportional gain of the integral plus proportional IP speed controller. |
| $k_{ii}$ | Integral gain of the proportional plus integral PI current controller. |
| $k_{ip}$ | Proportional gain of the proportional plus integral PI current controller. |
| $\sigma$ | Total leakage constant. |
| $\hat{}$, $^*$ | Estimated and reference value. |

the decoupling of the observation dynamics for considering the torque disturbance as an input for the EKF. In [4], the controller by back-stepping is used to estimate the load torque. This technique, in fact, allows for the synthesis of the control laws by, possibly, taking the disturbances or ignorance of the system parameters into consideration. The basic objective of the controller by back-stepping is to make the loop-systems equivalent to the sub-systems of order one in a stable cascade within the Lyapunov sense. This endows it with the qualities of robustness, a total asymptotic stability as well as a good trajectory tracking of the estimated and the measured load torque. Additionally, the rejection of disturbance is very satisfactory in both low and high speed. Nevertheless, there is a minor gap between the moments of application of the load torque and those of its cancellation. One may note that these outstanding performances are obtained thanks to the perfect estimation value of the stator resistance by an adaptive observer. In [5], the estimation of the load torque is shown according to the three synthesis techniques of observers: bearing in mind the cascade observer inter-connected with an estimator, the observer with a great gain inter-connected with an estimator and two inter-connected great gain observers. Actually, these observation techniques allow for the reconstruction of the mechanical variables (speed and load torque) by using the currents and the stator voltages of the asynchronous machine as the sole information.

By using MRAS method for sensorless ISFOC induction motor, it is impossible to estimate simultaneously the speed and the load torque. One may propose, in what follows, an adaptive Luenberger observer inter-connected with the MRAS estimator to estimate the speed and load torque simultaneously. The torque is estimated by means of a Luenberger observer defined by the mechanical equation. This new technique for simultaneous estimation of the speed and load torque has a reduced computing time as other method such as the unscented Kalman-filter and the back-stepping controller. Once more, the performances of the controller by the other method control are obtained due to good knowledge of the machine parameters.

The observer state matrix depends on the mechanical characteristics which are the friction and the inertia moment. In industrial automation, the typical areas of inertia variation are the robot axis control due to the movements of the links. To solve this problem, identification in real time of inertia is used. The estimated speed which is injected into the mechanical equation and defines the Luenberger observer results from the estimator of MRAS scheme.

This paper is organized as follows. Section 2 formulates the estimation of speed in a sensorless ISFOC induction motor drive based on the MRAS technique. Section 3 presents the estimation of the load torque using a Luenberger observer. The simulation results are proposed in Section 4. In Section 5, the theoretical analysis is confirmed by the experimental tests of the sensorless drive system with load torque estimation. Finally, Section 6 draws the final conclusions.

## 2. MRAS based rotor speed estimation

In the rotating reference frame, the dynamic induction motor model can be represented according to the usual d and $q$-axis components as follows [8]:

$$\left[\frac{dX}{dt}\right]=[A][X]+[B][U] \tag{1}$$

$$X=\begin{bmatrix} i_{ds} & i_{qs} & \phi_{ds} & \phi_{qs} & \omega \end{bmatrix}^T,\ U=\begin{bmatrix} v_{ds} & v_{qs} & n_p & T_l \end{bmatrix}^T$$

$$[A]=\begin{bmatrix} 0 & \omega_s & -R_s & 0 & 0 \\ -\omega_s & 0 & 0 & -R_s & 0 \\ \frac{1}{\sigma\tau_r L_s} & \frac{\omega}{\sigma L_s} & -\frac{1}{\sigma}\left(\frac{\tau_s+\tau_r}{\tau_s\tau_r}\right) & \omega_{sl} & 0 \\ -\frac{\omega}{\sigma L_s} & \frac{1}{\sigma\tau_r L_s} & -\omega_{sl} & -\frac{1}{\sigma}\left(\frac{\tau_s+\tau_r}{\tau_s\tau_r}\right) & 0 \\ -\frac{n_p^2}{J}i_{qs} & \frac{n_p^2}{J}i_{ds} & 0 & 0 & -\frac{f}{J} \end{bmatrix},$$

$$[B]=\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ \frac{1}{\sigma L_s} & 0 & 0 \\ 0 & \frac{1}{\sigma L_s} & 0 \\ 0 & 0 & -\frac{1}{J} \end{bmatrix}$$

with: $\tau_r=\frac{L_r}{R_r}$, $\tau_s=\frac{L_s}{R_s}$ and $\sigma=1-\frac{M^2}{L_sL_r}$

For the speed controller, we have designed an integral proportional (IP) regulator in order to stabilize the speed-control loop [7]. The gains of the IP controller, $K_{vi}$ and $K_{vp}$, are determined using a design method to obtain a damping ratio of 1.

For the current controller, we have designed a proportional integral (PI) regulator. Using the same method as a speed controller, the gains of the PI controller are $K_{ip}$ and $K_{ii}$.

To estimate the speed, it makes sense to use a reference frame related to the stator. This transformation does not need rotor position which is estimated by the MRAS tchnique [6–16].

In order to identify $\omega$, we attempt to represent the components of the stator flux vector ($\phi_{\alpha s}$, $\phi_{\beta s}$) in terms of accessible stator variables, that is, the stator currents ($i_{\alpha s}$, $i_{\beta s}$) and the stator voltages ($v_{\alpha s}$, $v_{\beta s}$). Therefore, two independent observers are constructed. The first is derived by integrating the stator voltage equation and the second is based on the rotor voltage equation