Kalman Filter in Synchronous Frame for Parameter Estimation of Field Oriented Controlled Induction Machine

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In recent years electrical engineers have tried, via the so called *field oriented control*, to operate induction machine similarly to dc machine [1]. This control technique guarantees the decoupling between torque and flux by means of the current components.

In order to implement this technique, knowledge of the synchronous speed ω_e is needed to represent the actual variables into a reference frame whose two axes rotate at the synchronous speed. Indeed by forcing the rotor flux to be aligned with a synchronously rotating axis, we control the induction machine as a separately excited dc one.

This goal can be satisfied by two different approaches: the direct and the indirect vector control methods [2]. The first one provides the knowledge of ω_e by means of air-gap flux measurement. This operation needs Hall effect sensors, search coil or other kind of measurement techniques which reduce the motor robustness and introduce many implementation difficulties. On the other hand the indirect control method obtains the synchronous speed by adding the rotor speed and the slip frequency, which is set as a function of stator currents and several motor parameters. The fundamental problem dealing with this kind of vector control is the high sensitivity of the control system to the motor parameter mismatching which introduces errors in both dynamic and steady-state behaviour of flux and torque [3]. Particularly the control system effectiveness drastically decreases in case of rotor resistance variations, due to temperature and skin effects. Therefore it is necessary estimate the rotor resistance on the basis of the knowledge of some external variables as stator voltages, stator currents and rotor speed, which are directly measurable.

To this aim, an extended-state observer could be employed. However the noise introduced by the inverter and the sensors could greatly reduce the observer performance. Therefore we need an observer which minimises the noise influence on the estimated

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variables. The choice minimising the error covariance is, for linear systems, the Kalman filter [4]. Since the induction motor is a non-linear system, we must consider the extension of the Kalman filter to non-linear systems, i.e. the Extended Kalman Filter (EKF). The basic feature of the EKF is a step-by-step linearization of the non-linear system around the estimated state which is obtained in the previous step.

Recently the use of an EKF for the estimation of the rotor resistance has been proposed in literature [5]. In that work stator and rotor currents, and rotor resistance are employed as state variables of the EKF model; hence, a fifth order system (four plus one) is considered.

The main problem dealing with the on-line implementation of this EKF is the high computational burden needed to solve five non-linear differential equations and compute the Kalman gain matrix.

In this paper a new type of EKF for the rotor resistance estimation is proposed. Since the rotor speed and the stator currents can be straightforwardly measured, we can use them as input variables; then, a *reduced* EKF can be considered where only the rotor fluxes and the rotor resistance are used as state variables.

In particular, the EKF model we consider is as follows

$$\begin{cases} \dot{x}_1 = -\frac{1}{L_r} x_1 x_3 + u_1 x_2 + \frac{L_m}{L_r} u_2 x_3 \\ \dot{x}_2 = -u_1 x_1 - \frac{1}{L_r} x_2 x_3 + \frac{L_m}{L_r} u_3 x_3 \\ \dot{x}_3 = 0 \end{cases}$$

where the state and the input vectors are:

$$\mathbf{x} = [x_1 \quad x_2 \quad x_3]^T = [\Psi_q \quad \Psi_d \quad R_r]^T$$

$$\mathbf{u} = [u_1 \quad u_2 \quad u_3]^T = [\omega_r \quad i_Q \quad i_D]^T$$

and we used lower-case (upper-case) subscripts to indicate rotor (stator) quantities.

The implementation of this reduced filter requires a lower number of operations and then may represent a good solution to the computational problems of more traditional EKF.

In this framework quite crucial is the choice of the output variables, which are needed to construct the estimator.

One solution could be to consider the rotor fluxes as output variables: in this case, because of the above mentioned difficulties to obtain a direct measure, the fluxes should be obtained by integration of the stator voltages. However this approach cannot be used safely at low speed where leakage fluxes are not negligible. Here we avoid this problem by choosing as output variables the stator voltages and a component of the rotor flux in the synchronous rotating frame. The mathematical difficulties inherent in this approach can be overcome by a suitable use of some peculiarities of field oriented control.

Estimation of rotor resistance at low speed is presented in Fig. 1.

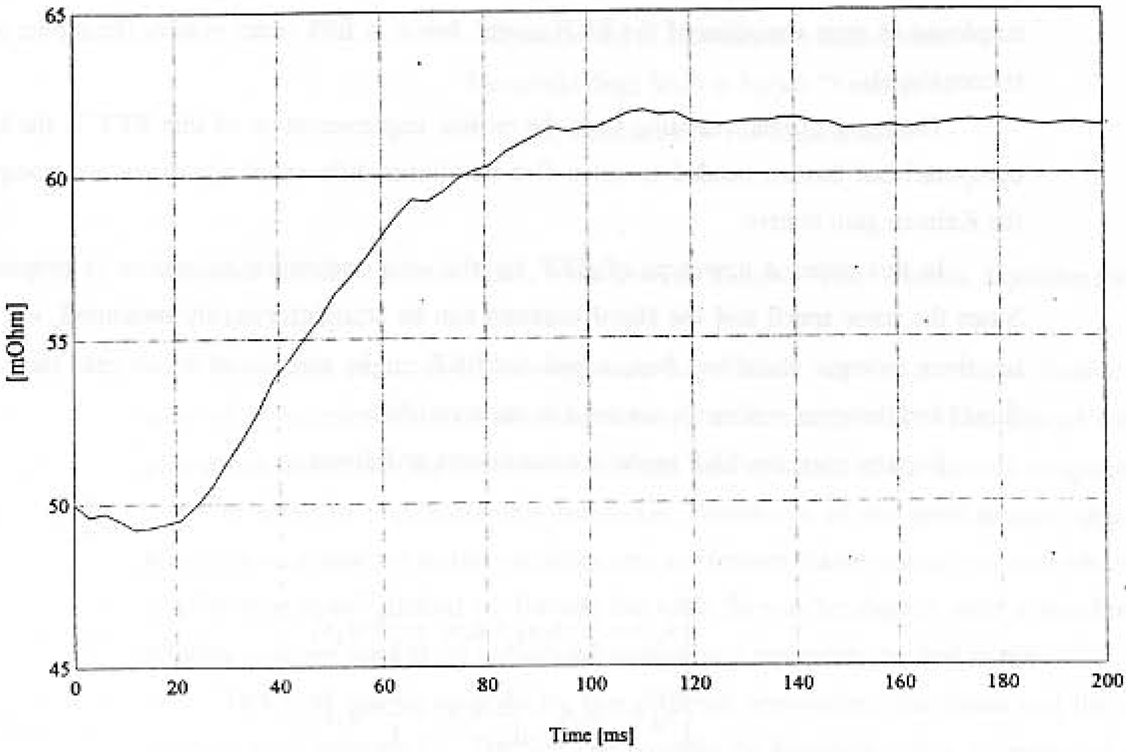

Fig. 1. Estimated rotor resistance

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