A Stator Resistance Estimation Scheme for Speed Sensorless Rotor Flux Oriented Induction Motor Drives

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***Abstract* – Accurate knowledge of stator resistance is of utmost importance for correct operation of a number of speed sensorless induction motor control schemes in the low speed region. Since stator resistance inevitably varies with operating conditions, stable and accurate operation at near-zero speed requires an appropriate on-line identification algorithm for the stator resistance. The paper proposes such an identification algorithm, which is developed for the rotor flux based MRAS type of the speed estimator in conjunction with a rotor flux oriented control scheme. In this speed estimation method only one (out of the two available) degree of freedom is utilized for speed estimation. It is proposed to utilize the second available degree of freedom as a mean for adapting the stator resistance on-line. The parallel stator resistance and rotor speed identification algorithm is developed in a systematic manner, using Popov's hyperstability theory. It increases the complexity of the overall control system insignificantly and enables correct speed estimation and stable drive operation at near-zero speeds. The proposed speed estimator with parallel stator resistance identification is at first verified by simulation. Extensive experimentation is conducted next at low speeds of rotation and successful stator resistance identification is achieved down to 0.5 Hz frequency of rotation.**

***Index Terms* – Sensorless vector control, Stator resistance estimation, MRAS estimator.**

I. INTRODUCTION

Accurate knowledge of stator resistance is not required in indirect rotor flux oriented control (RFOC) scheme, which has become an industrial standard for sensored induction motor drives in the nineties [1]. Since correct operation of the indirect vector controller requires an accurate value of the rotor time constant, most of the research effort in the early days of vector control was directed towards development of on-line methods for rotor time constant (rotor resistance) identification. The situation has however changed dramatically with the advent of speed sensorless vector control [2] and direct torque control (DTC) [3].

Vast majority of speed estimation schemes rely on utilization of an induction motor model in the process of speed estimation [2] and require an accurate knowledge of all (or the most of) the motor parameters, including the stator resistance. In the basic configuration of DTC stator resistance is additionally required for stator flux and torque estimation. An accurate value of the stator resistance is of crucial importance for correct operation of a sensorless drive in the low speed region, since any mismatch between the actual value and the value used within the speed estimator may lead not only to a substantial speed estimation error but to instability as well [4]. As a consequence, numerous on-line schemes for stator resistance estimation have been proposed in recent past [5-25].

The available stator resistance on-line identification schemes can be classified into a couple of distinct categories. In general, all the methods rely on stator current measurement and predominantly require an information regarding stator voltages as well (measured or reconstructed). The first group includes all methods which utilize some measured quantities and an appropriate induction motor steady state model to calculate the stator resistance explicitly [5-8]. In [5], the reactive power is evaluated first, stator and rotor flux are calculated next, and electromagnetic torque is then evaluated. An explicit expression for stator resistance calculation is finally derived, as a function of the previously calculated quantities. The method of [6] is based on the so-called back-emf detector and it calculates stator resistance in the reference frame aligned with the stator current space vector. The method of [7] calculates stator resistance from the stator (voltage) model, with the rotor flux space vector value obtained from the rotor (current) model, while [8] evaluates stator resistance from the active power balance of the machine.

The second group of stator resistance on-line identification methods is by far the most frequently met and it includes all the estimators where an updated stator resistance value is obtained through an adaptive mechanism [9-19]. Proportional-integral (PI) or integral (I) controllers are used for this purpose. In principle, two distinct sub-categories exist. In observer based systems [11,12,15,18,19] the error quantity, which serves as an input into the stator resistance adaptation mechanism, is determined with the difference between the measured and the observed stator current. In MRAS based systems [9,10,13,14,16,17] the choice of the error quantity is more versatile. The scheme of [9] operates in the rotating reference frame and the error quantity is determined with the difference between the rotor flux d-axis components obtained from the voltage and current models. The method of [10] is similar, except that it utilizes the rotor flux reference and only one estimate of the rotor flux d-axis component in formation of the error quantity. The error quantity in [13] is based on active power, while the one in [14] is obtained as a sum of the products of rotor current and rotor flux d-q axis components. The error signal of [17] utilizes an error in the stator d-axis current component as the input of the integral controller, while the error quantity of [18] is formed in such a way that the stator resistance identification is independent of the total

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leakage inductance. From the point of view of the method of stator resistance on-line identification proposed in this paper, especially relevant are the MRAS schemes of [9,10,16], as discussed shortly.

The third major category of stator resistance on-line identification schemes relies on utilization of artificial intelligence techniques in the process of stator resistance adaptation [20-25]. Artificial neural networks (ANNs) [20,21], fuzzy logic (FL) control [22-24] or neuro-fuzzy control [25] can be used for this purpose. In principal, schemes with ANNs can be regarded as a special sub-category of the first group of methods, where an explicit calculation of the stator resistance is replaced with a neural network based approximation. Similarly, FL based methods can be looked at as a sub-category of the second group of methods, where the classical adaptive mechanism (PI or I controller) is replaced with an FL adaptive mechanism.

This paper proposes a method for stator resistance on-line identification, which belongs to the second group of methods. The scheme is MRAS based and it combines ideas of [9,10,16] to propose a simple method for stator on-line resistance identification. Stator resistance estimation is developed in conjunction with the rotor flux based MRAS speed estimator and it operates in the stationary reference frame (in contrast to the schemes of [9,10]). It does however utilize the idea of [9,10] related to the creation of the error quantity for adaptive stator resistance identification. The error quantity is formed on the basis of differences in rotor flux component values, obtained at the output of the reference and the adjustable model. The observation of [16], that the role of the reference and the adjustable model is interchangeable for the purposes of speed and stator resistance estimation, is utilized as well. However, in contrast to [16], the operation of the speed and stator resistance estimators is in parallel rather than sequential. This difference is made possible by the observation that the MRAS speed estimator utilizes an error quantity related to instantaneous phase difference between the two estimates of the rotor flux. The same error quantity was used in [16] for stator resistance estimation, while the second degree of freedom, the difference in amplitudes of two rotor flux estimates, was not utilized. This difference is used in this paper as the basis for stator resistance identification. A detailed derivation of the parallel rotor speed and stator resistance estimation algorithms is provided in the paper and the proposed scheme is verified by some simulation results and extensive experimentation. Accurate stator resistance estimation is achieved down to 0.5 Hz frequency of rotation.

II. Basic Speed Estimator and Vector Control Scheme

The speed estimator, analyzed in the paper, is the one originally proposed in [26] and illustrated in Fig. 1, where the two left-hand side blocks perform integration of equations (1) and (2). It relies on measured stator currents and measured (or reconstructed) stator voltages and is composed of the reference (voltage) and the adjustable (current) model. The estimator operates in the stationary reference frame (α, β) and it is described with the following equations [26]:

$$p\underline{\hat{\psi}}_{rV}^{s} = \frac{L_r}{L_m}\left[\underline{u}_s^s - \left(\hat{R}_s + \sigma L_s p\right)\underline{i}_s^s\right] \tag{1}$$

$$p\underline{\hat{\psi}}_{rI}^{s} = \frac{L_m}{T_r}\underline{i}_s^s - \left(\frac{1}{T_r} - j\hat{\omega}\right)\underline{\hat{\psi}}_{rI}^{s} \tag{2}$$

$$\hat{\omega} = \left(K_{p\omega} + \frac{K_{I\omega}}{p}\right)e_\omega \tag{3}$$

$$e_\omega = \underline{\hat{\psi}}_{rI}^{s} \times \underline{\hat{\psi}}_{rV}^{s} = \hat{\psi}_{\alpha rI}\hat{\psi}_{\beta rV} - \hat{\psi}_{\beta rI}\hat{\psi}_{\alpha rV} \tag{4}$$

A hat above a symbol in (1)-(4) denotes estimated quantities, symbol p stands for d/dt, T_r is the rotor time constant and $\sigma = 1 - L_m^2/\left(L_s L_r\right)$. All the parameters in the motor and the estimator are assumed to be of the same value, except for the stator resistance (hence a hat above the symbol in (1)). Underlined variables are space vectors, and sub-scripts V and I stand for the outputs of the voltage (reference) and current (adjustable) models, respectively. Voltage, current and flux are denoted with u, i and ψ, respectively, and subscripts s and r stand for stator and rotor, respectively. Superscript s in space vector symbols denotes the stationary reference frame.

As is evident from (1)-(4) and Fig. 1, the adaptive mechanism (PI controller) relies on an error quantity that represents the difference between the instantaneous positions of the two rotor flux estimates. The second degree of freedom, the difference in amplitudes of the two rotor flux estimates, is not utilized. The parallel rotor speed and stator resistance MRAS estimation scheme, which will be developed in the next section, will make use of this second degree of freedom to achieve simultaneous estimation of the two quantities. The role of the reference and the adjustable model will be interchanged for this purpose, since the rotor flux estimate of (2) is independent of stator resistance.

The rotor flux oriented control scheme for an induction motor, utilized in the paper in simulation and experimental investigation, is illustrated in Fig. 2. It includes, apart from a speed controller, rotor flux and torque controllers as well. The required feedback quantities for the torque and rotor flux closed loop control are obtained from the reference model (1). Induction motor data are given in the Appendix. A DSP system, based on DS1102 controller board from dSPACE, is used for experimental investigation. Motor stator currents are measured, while stator voltages are reconstructed from the known PWM pattern and the measured dc voltage.

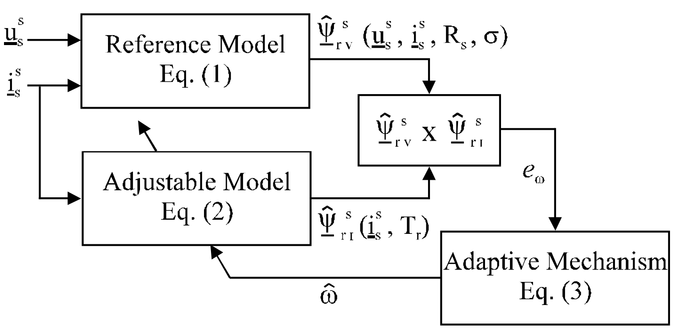


Fig. 1. Basic configuration of the rotor flux based MRAS speed estimator.

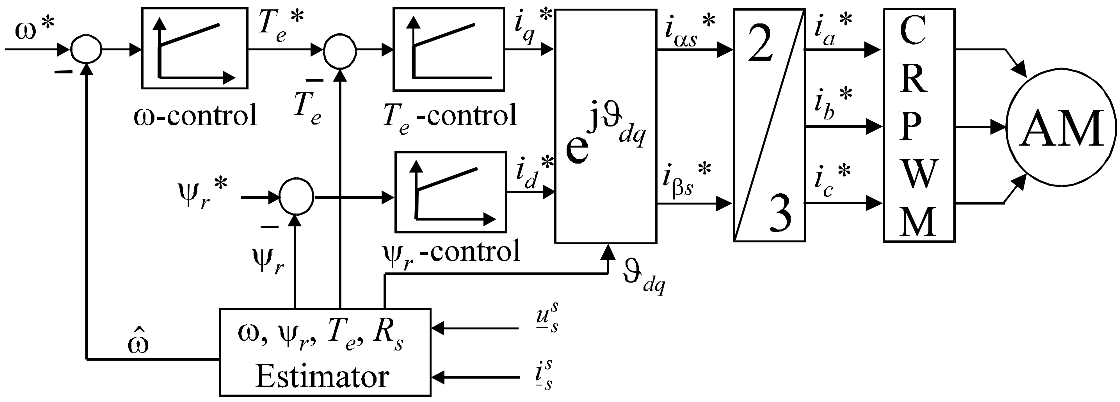


Fig. 2. Structure of the speed sensorless current-fed rotor flux oriented induction motor drive, used in simulation and experimental work (CRPWM = current regulated PWM inverter, AM = asynchronous machine, * = reference quantity).

III. Parallel Stator Resistance and Rotor Speed Estimation

Proposed parallel rotor speed and stator resistance estimation scheme is designed based on the concept of hyperstability [26] in order to make the system asymptotically stable. For the purpose of deriving an adaptation mechanism it is valid to initially treat rotor speed as a constant parameter, since it changes slowly compared to the change in rotor flux. The stator resistance of the motor varies with temperature, but variations are slow so that it can be treated as a constant parameter, too. The configuration of the proposed parallel rotor speed and stator resistance is shown in Fig. 3 and is discussed in detail next.

Let R_s and ω denote the true values of the stator resistance in the motor and rotor speed, respectively. These are in general different from the estimated values. Consequently, a mismatch between the estimated and true rotor flux space vectors appears as well. The error equations for the voltage and the current model outputs can then be written as

$$p\underline{\varepsilon}_V = -\frac{L_r}{L_m}\left(R_s - \hat{R}_s\right)\underline{i}_s^s \tag{5a}$$

$$\underline{\varepsilon}_V = \underline{\psi}_{rV}^s - \underline{\hat{\psi}}_{rV}^s = \varepsilon_{\alpha V} + j\varepsilon_{\beta V} \tag{5b}$$

$$p\underline{\varepsilon}_I = \left(j\omega - \frac{1}{T_r}\right)\underline{\varepsilon}_I + j\left(\omega - \hat{\omega}\right)\underline{\hat{\psi}}_{rI}^s \tag{6a}$$

$$\underline{\varepsilon}_I = \underline{\psi}_{rI}^s - \underline{\hat{\psi}}_{rI}^s = \varepsilon_{\alpha I} + j\varepsilon_{\beta I} \tag{6b}$$

Symbols $\underline{\psi}_{rV}^s, \underline{\psi}_{rI}^s$ in (5b), (6b) stand for true values of the two rotor flux space vectors. Equations (5)-(6) can be re-written in matrix notation as

$$p\begin{bmatrix}\varepsilon_{\alpha I}\\ \varepsilon_{\beta I}\\ \varepsilon_{\alpha V}\\ \varepsilon_{\beta V}\end{bmatrix} = \begin{bmatrix}-\frac{1}{T_r} & -\omega & 0 & 0\\ \omega & -\frac{1}{T_r} & 0 & 0\\ 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0\end{bmatrix}\cdot\begin{bmatrix}\varepsilon_{\alpha I}\\ \varepsilon_{\beta I}\\ \varepsilon_{\alpha V}\\ \varepsilon_{\beta V}\end{bmatrix} - \mathbf{W} = \mathbf{A}\underline{\varepsilon} - \mathbf{W} \tag{7}$$

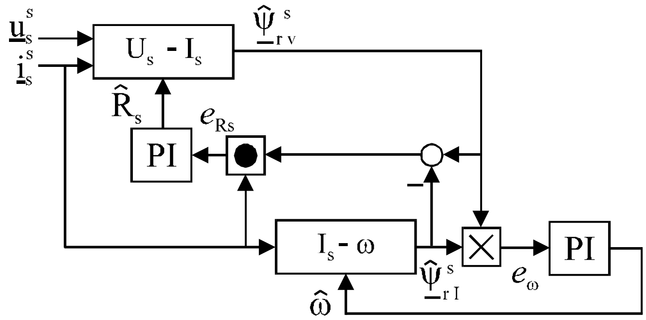


Fig. 3. Structure of the MRAS system for parallel rotor speed and stator resistance estimation.

where $\underline{\varepsilon}^T = \left[\varepsilon_{\alpha I} \quad \varepsilon_{\beta I} \quad \varepsilon_{\alpha V} \quad \varepsilon_{\beta V}\right] = \left[\underline{\varepsilon}_I^T \quad \underline{\varepsilon}_V^T\right]$, and $\mathbf{W}$ is the nonlinear block, defined as follows:

$$\mathbf{W} = \begin{bmatrix} -\Delta\omega\begin{bmatrix}0 & -1\\ 1 & 0\end{bmatrix} & \begin{matrix}0 & 0\\ 0 & 0\end{matrix}\\ \begin{matrix}0 & 0\\ 0 & 0\end{matrix} & \frac{L_r}{L_m}\Delta R_s\begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}\end{bmatrix}\cdot\begin{bmatrix}\hat{\psi}_{\alpha rI}\\ \hat{\psi}_{\beta rI}\\ i_{\alpha s}\\ i_{\beta s}\end{bmatrix} \tag{8}$$

$$\mathbf{W} = \begin{bmatrix}-\Delta\omega\mathbf{J} & 0\\ 0 & \frac{L_r}{L_m}\Delta R_s\mathbf{I}\end{bmatrix}\cdot\begin{bmatrix}\hat{\mathbf{\Psi}}_{rI}^s\\ \mathbf{i}_s^s\end{bmatrix}$$

Here $\Delta\omega = \omega - \hat{\omega}$, $\Delta R_s = R_s - \hat{R}_s$, $\hat{\mathbf{\Psi}}_{rI}^s = \left[\hat{\psi}_{\alpha rI} \quad \hat{\psi}_{\beta rI}\right]^T$, $\mathbf{i}_s^s = \left[i_{\alpha s} \quad i_{\beta s}\right]^T$, $\mathbf{J} = \begin{bmatrix}0 & -1\\ 1 & 0\end{bmatrix}$ and $\mathbf{I} = \begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}$.

The system is hyperstable if the input and output of the nonlinear block $\mathbf{W}$ satisfy Popov's criterion [26]:

$$S = \int_0^{t_1} \underline{\varepsilon}^T \cdot \mathbf{W}dt \geq -\gamma^2, \quad \forall t_1 \tag{9}$$

where, using (8)

$$\underline{\varepsilon}^T \cdot \mathbf{W} = -\Delta\omega\left(\underline{\varepsilon}_I^T \cdot \mathbf{J} \cdot \hat{\mathbf{\Psi}}_{rI}^s\right) + \frac{L_r}{L_m}\Delta R_s\left(\underline{\varepsilon}_V^T \cdot \mathbf{i}_s^s\right) \tag{10}$$

Substitution of (10) into (9) yields

$$S = \int_0^{t_1} \boldsymbol{\varepsilon}^T \cdot \mathbf{W} dt = \underbrace{-\int_0^{t_1} \Delta\omega \left(\underline{\boldsymbol{\varepsilon}}_I^T \cdot \mathbf{J} \cdot \hat{\boldsymbol{\Psi}}_{rI}^s\right) dt}_{S_1} + \frac{L_r}{L_m} \underbrace{\int_0^{t_1} \Delta R_s \left(\underline{\boldsymbol{\varepsilon}}_V^T \cdot \mathbf{i}_s^s\right) dt}_{S_2}$$

$$S = S_1 + \frac{L_r}{L_m} \cdot S_2 \geq -\gamma^2, \ \forall t_1 \quad (11)$$

The validity of (11) can be verified by means of inequalities (12) and (13) with adaptive mechanisms given in (14), (15) for rotor speed estimation and stator resistance identification, respectively:

$$S_1 = -\int_0^{t_1} \Delta\omega \left(\underline{\boldsymbol{\varepsilon}}_I^T \cdot \mathbf{J} \cdot \hat{\boldsymbol{\Psi}}_{rI}^s\right) dt \geq -\gamma_1^2 \quad (12)$$

$$S_2 = \int_0^{t_1} \Delta R_s \left(\underline{\boldsymbol{\varepsilon}}_V^T \cdot \mathbf{i}_s^s\right) dt \geq -\gamma_2^2 \quad (13)$$

$$\hat{\omega} = \left(K_{p\omega} + \frac{K_{I\omega}}{\mathrm{p}}\right) \left(\underline{\boldsymbol{\varepsilon}}_I^T \cdot \mathbf{J} \cdot \hat{\boldsymbol{\Psi}}_{rI}^s\right) = \left(K_{p\omega} + \frac{K_{I\omega}}{\mathrm{p}}\right) e_\omega \quad (14)$$

$$\hat{R}_s = \left(K_{pR_s} + \frac{K_{IR_s}}{\mathrm{p}}\right) \left(-\underline{\boldsymbol{\varepsilon}}_V^T \cdot \mathbf{i}_s\right) = \left(K_{pR_s} + \frac{K_{IR_s}}{\mathrm{p}}\right) e_{Rs} \quad (15)$$

where $K_{p\omega}$, $K_{I\omega}$, K_{pRs}, K_{IRs}, are PI controller parameters of rotor speed and stator resistance adaptation mechanisms, respectively. The value of $\underline{\boldsymbol{\varepsilon}}_I^T \cdot \mathbf{J} \cdot \hat{\boldsymbol{\Psi}}_{rI}^s$ in (12), (14) is evaluated by taking into account that, for speed estimation, the output of the reference model (1) is taken as equal to the true rotor flux space vector. Hence $\underline{\boldsymbol{\varepsilon}}_I = \underline{\psi}_{rI}^s - \underline{\hat{\psi}}_{rI}^s = \underline{\hat{\psi}}_{rV}^s - \underline{\hat{\psi}}_{rI}^s$, since $\underline{\psi}_{rI}^s \equiv \underline{\hat{\psi}}_{rV}^s$. Thus

$$\underline{\boldsymbol{\varepsilon}}_I^T \cdot \mathbf{J} \cdot \hat{\boldsymbol{\Psi}}_{rI}^s = \left[\hat{\psi}_{\alpha rV} - \hat{\psi}_{\alpha rI} \quad \hat{\psi}_{\beta rV} - \hat{\psi}_{\beta rI}\right] \cdot \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} \cdot \begin{bmatrix} \hat{\psi}_{\alpha rI} \\ \hat{\psi}_{\beta rI} \end{bmatrix} =$$

$$= \left[\hat{\psi}_{\alpha rV} - \hat{\psi}_{\alpha rI} \quad \hat{\psi}_{\beta rV} - \hat{\psi}_{\beta rI}\right] \cdot \begin{bmatrix} -\hat{\psi}_{\beta rI} \\ \hat{\psi}_{\alpha rI} \end{bmatrix} = \underline{\hat{\psi}}_{rI} \times \underline{\hat{\psi}}_{rV} = e_\omega(t) \quad (16)$$

The error quantity for speed estimation is therefore the one of (4). The value of $-\underline{\boldsymbol{\varepsilon}}_V^T \cdot \mathbf{i}_s$ in (13), (15) needs to be evaluated next. In order to do this, it is necessary to take into account that, for stator resistance estimation, reference and adjustable model (1), (2) change the roles. The true value of the rotor flux space vector is now taken to be the output of (2). Hence $\underline{\boldsymbol{\varepsilon}}_V = \underline{\psi}_{rV}^s - \underline{\hat{\psi}}_{rV}^s = \underline{\hat{\psi}}_{rI}^s - \underline{\hat{\psi}}_{rV}^s$, since $\underline{\psi}_{rV}^s \equiv \underline{\hat{\psi}}_{rI}^s$. One further has

$$-\underline{\boldsymbol{\varepsilon}}_V^T \cdot \mathbf{i}_s = \left[\hat{\psi}_{\alpha rV} - \hat{\psi}_{\alpha rI} \quad \hat{\psi}_{\beta rV} - \hat{\psi}_{\beta rI}\right] \cdot \begin{bmatrix} i_{\alpha s} \\ i_{\beta s} \end{bmatrix} =$$

$$= i_{\alpha s}\left(\hat{\psi}_{\alpha rV} - \hat{\psi}_{\alpha rI}\right) + i_{\beta s}\left(\hat{\psi}_{\beta rV} - \hat{\psi}_{\beta rI}\right) = \mathbf{i}_s^s \cdot \left(\underline{\hat{\psi}}_{rV} - \underline{\hat{\psi}}_{rI}\right) = e_{R_s}(t) \quad (17)$$

The error quantity for stator resistance estimation is therefore

$$e_{Rs} = i_{\alpha s}\left(\hat{\psi}_{\alpha rV} - \hat{\psi}_{\alpha rI}\right) + i_{\beta s}\left(\hat{\psi}_{\beta rV} - \hat{\psi}_{\beta rI}\right) \quad (18)$$

It follows from these considerations that the role of the reference and the adjustable models is interchangeable in the parallel system of rotor speed and stator resistance estimation. The speed and stator resistance can be estimated in parallel using (14), (15) at any speed. The rotor speed adaptation mechanism (14) is the same as in the customary MRAS speed estimator reviewed in Section II. Stator resistance adaptation mechanism (15) is, at the first sight, similar to the one of [9,10]. However, stator resistance is here estimated in the stationary reference frame (rather than in the rotor flux oriented reference frame), and error quantity is obtained using two rotor flux space vector estimates (rather than the reference and a single estimated value, as in [10]). Further, stator resistance and rotor speed estimation operate in parallel, rather than sequentially as in [16]. This is enabled by utilizing the second available degree of freedom (the difference in rotor flux amplitudes) in the process of stator resistance estimation.

IV. Verification of the Parallel Estimation Scheme

A. Simulation Results

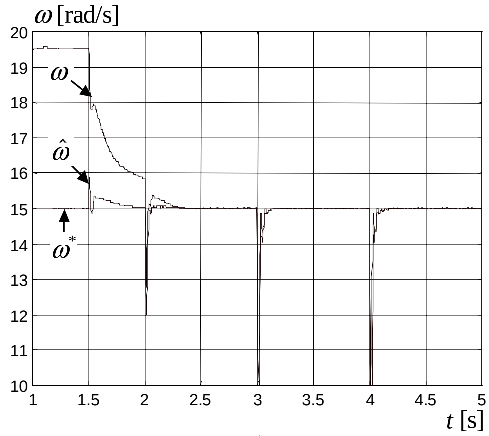
A sample of simulation results is presented here. The sensorless vector controlled induction motor drive, shown in Fig. 2, is started under no-load conditions, with the stator resistance estimator turned off. The actual stator resistance in the motor is taken as 25% higher than the nominal motor resistance (10 Ω), while the value in the estimator in Fig. 2 is set to the nominal value. Reference speed equals 15 rad/s (electrical). Upon completion of the starting transient (which is not shown in Fig. 4) there exists a substantial speed estimation error (Fig. 4a), as well as a substantial error in the rotor flux (Fig. 4b). The error in rotor flux is a consequence of the use of the output of the reference model (1) for closed loop flux and torque control. The stator resistance adaptation mechanism is turned on at $t = 1.5$ s and load torques equal to 1 Nm, 3 Nm and 5 Nm are applied in a step-wise manner at time instants equal to 2 s, 3s and 4 s.

Activation of the stator resistance adaptation mechanism corrects initial stator resistance error in the estimator in less than one second (Fig. 4c), although the first load torque is applied prior to the complete compensation of the initial speed estimation error. The speed estimate converges towards the actual speed and correct rotor flux orientation is established since rotor flux q-axis component reduces to zero, with simultaneous equalization of the rotor flux d-axis component and the reference rotor flux value (Fig. 4b). Subsequent load torque changes have no consequence on the accuracy of either the speed estimate or the stator resistance estimate.

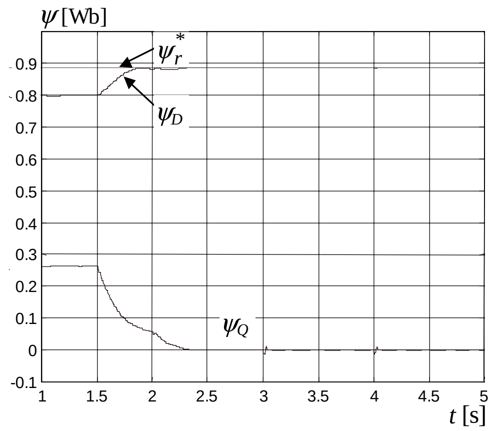
B. Experimental Verification

Broadly the same procedure as in simulation is followed in the experiments. The drive is allowed to operate initially with a detuned stator resistance in certain steady state and the stator resistance estimator is then turned on (at $t = 3$ s). All the be seen in Fig. 5, activation of the stator resistance adaptation mechanism quickly compensates the initial error in the estimator stator resistance value and therefore compensates the initial speed estimation error.

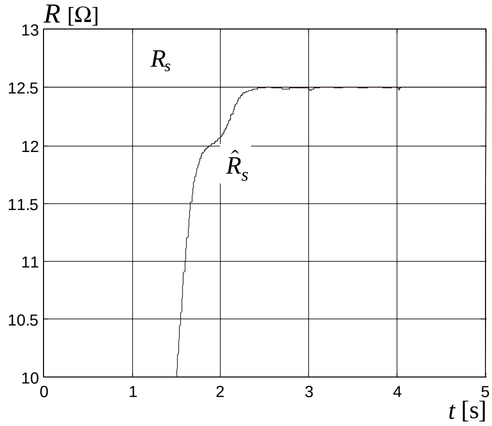
The same experiment is repeated at 1 Hz reference frequency of rotation under no-load conditions and the results are given in Fig. 6. The initial detuning in the stator resistance takes values of ± 10% and ± 20%, and the situation without detuning is included once more. In all the cases stator resistance estimator (activated at t = 5 s) quickly removes the initial stator resistance error, enabling complete elimination of the speed estimation error.



a.



b.



c.

Fig. 4. Verification of the parallel speed and stator resistance estimation by simulation: reference speed is 15 rad/s and stator resistance estimator is turned on at t = 1.5 s.

a. Speed reference, actual speed and estimated speed.
b. Rotor flux reference and rotor flux d-q axis components (ψ_D, ψ_Q).
c. Stator resistance in the motor and stator resistance estimate.

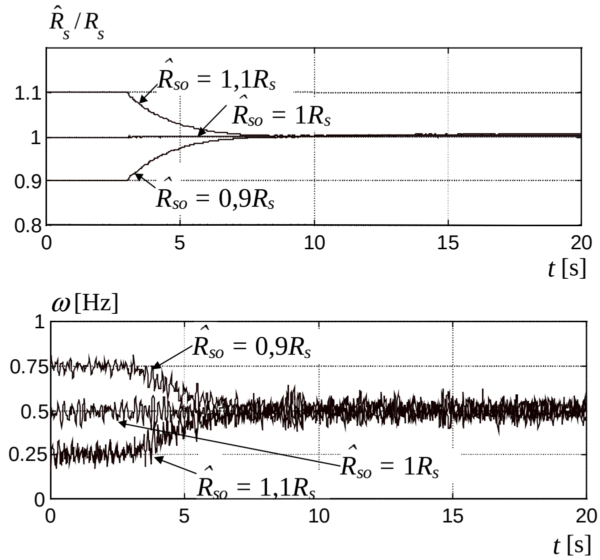


Fig. 5. Experimental verification of the parallel stator resistance and speed estimation scheme at 0.5 Hz reference frequency of rotation with rated load torque: ratio of the estimator to actual stator resistance and estimated speed of rotation. Stator resistance adaptation is activated at t = 3 s.

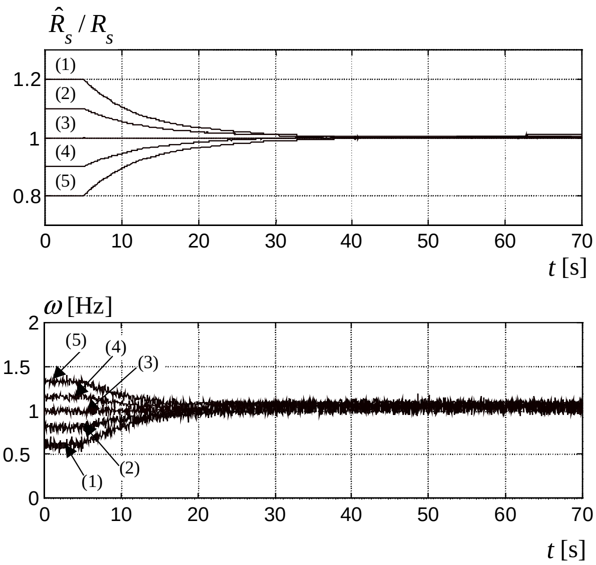


Fig. 6. Experimental verification of the parallel stator resistance and speed estimation scheme at 1 Hz reference frequency of rotation under no-load conditions: ratio of the estimator to actual stator resistance and estimated speed of rotation. Stator resistance adaptation is activated at t = 5 s. Traces (3) correspond to zero initial detuning.

1- $\hat{R}_{so} = 1{,}2R_s$, 2- $\hat{R}_{so} = 1{,}1R_s$, 4- $\hat{R}_{so} = 0{,}9R_s$, 5- $\hat{R}_{so} = 0{,}8R_s$

experiments are conducted in the sensorless mode. Fig. 5 illustrates the process of speed estimation and stator resistance estimation for rated load torque operation at a reference speed that corresponds to 0.5 Hz (15 rpm). Ratio of the estimator stator resistance to actual motor stator resistance is shown. The initial detuning in the stator resistance is ± 10% and the situation without detuning is included as well in Fig.5. As can

It is well known that the MRAS type of the speed estimator, analyzed in this paper, cannot operate stably at zero speed for prolonged time intervals. However, the estimator is capable of temporary short-term operation at zero speed, provided that the stator resistance in the estimator exactly matches the one in the motor. In order to prove this statement, the motor is started under no-load conditions with the stator resistance in the estimator equal to 85 % of the actual one and the tuning mechanism off. Reference speed is initially set to 5 Hz frequency of rotation and stator resistance adaptation is turned on at t = 10 s. After approximately 49 seconds speed reference is reduced to zero Hz and is then at 50 s increased to 15 Hz. Fig. 7 shows the experimental results and confirms that, due to the accurate stator resistance estimation, the drive does not loose stability during temporary operation at zero speed.

Very much the same situation arises during reversing transient, since these correspond to a very short-term operation at zero speed. Fig. 8 illustrates actual and estimated speed for a reversing transient from 5 Hz to − 5 Hz, which takes place at t = 50 s. Prior to this transient (from zero to 4 s) the drive operated under no-load conditions, a load torque equal to 20% of the rated value was applied at t = 4s, and the stator resistance estimator was off until t = 10 s. Activation of the stator resistance estimator leads to elimination of the initial speed estimation error and the estimated and the actual speed are in excellent agreement further on, including the reversing transient with rapid transition through zero speed.

In all the tests illustrated so far and, indeed, in all the theoretical considerations, it was assumed that all the parameters (except for the stator resistance) of the parallel rotor speed and stator resistance estimator exactly match those in the motor. The other important motor parameter that appears in (1)-(2) is the rotor time constant. The sensitivity of the stator resistance estimation to detuning in the rotor time constant is therefore investigated next. The rotor time constant in the estimator is deliberately varied, as shown in Fig. 9b,

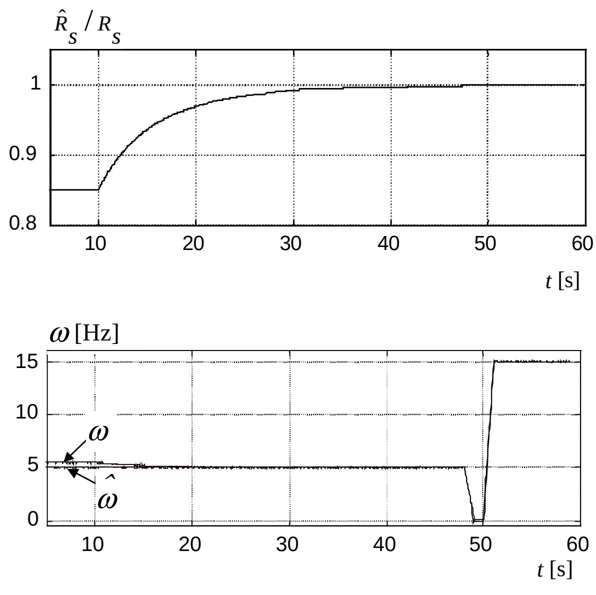


Fig. 7. Experimental verification of the capability of the drive with stator resistance adaptation to operate for short time intervals at zero speed.

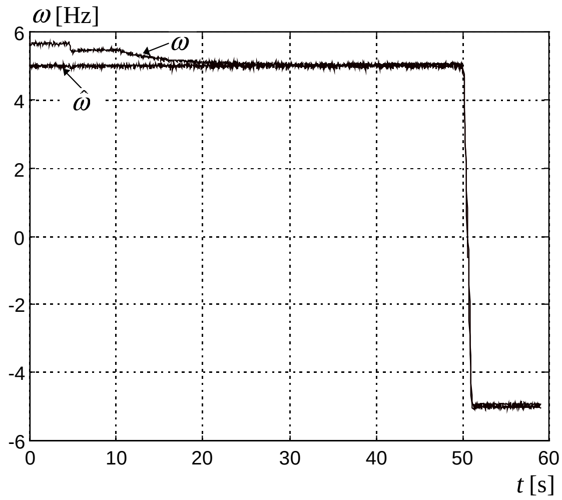


Fig. 8. Actual and estimated speed (through sensorless mode operation) during a reversing transient in the low speed region. Stator resistance estimation is activated at t = 10 seconds.

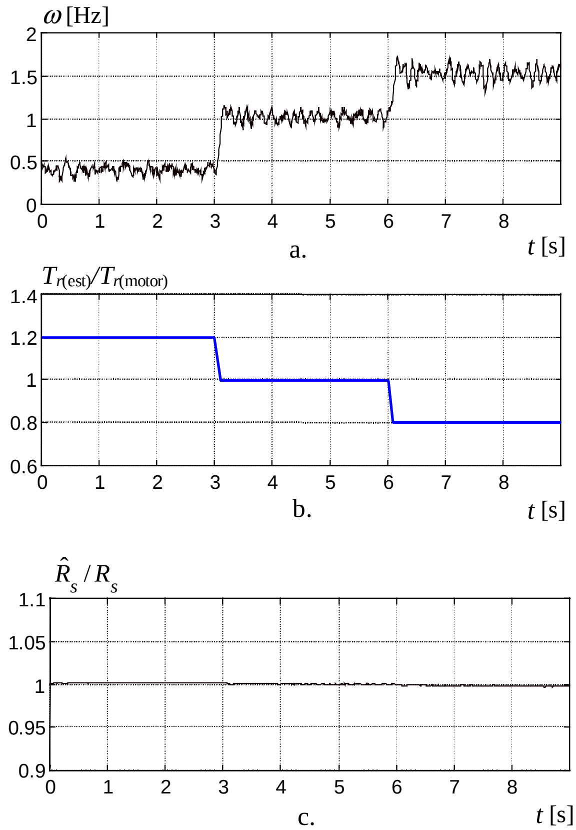


Fig. 9. Experimental investigation of the impact of the incorrect rotor time constant setting in the estimator on stator resistance estimation accuracy:
a. Estimated speed.
b. Ratio of the estimator to motor rotor time constant.
c. Ratio of the estimated to actual stator resistance.

during operation with rated load torque and speed reference setting of 1 Hz. As expected, detuning in the rotor time constant causes a substantial speed estimation error (Fig.9a). However, the process of stator resistance estimation remains unaffected by the incorrect setting of the rotor time constant within the parallel MRAS estimation system (Fig. 9c). This is so since the closed loop rotor flux and torque control, as well as the orientation of the reference frame, are achieved in the scheme of Fig. 2 by using the output of the reference model (1). Hence an inaccurate setting of the rotor time constant in the speed and stator resistance estimator does not affect the accuracy of orientation and the actual rotor flux value. The amplitude of the rotor flux, obtained from the adjustable model (2), is not affected either. As stator resistance estimation utilizes an error signal related to the amplitudes of the two rotor flux estimates, variation of the rotor resistance does not have any negative impact on stator resistance estimation. Of course, speed estimation error is an undesirable consequence of the rotor time constant mismatch, which can be easily compensated for, by varying the rotor resistance in the same ratio as the estimated stator resistance varies. Alternatively, a separate rotor time constant (rotor resistance) identification algorithm can be applied.

As noted in Section II, stator voltages, required for the estimator operation, were obtained by reconstruction, using measured dc link voltage and inverter switching functions. Since accurate stator resistance identification is of utmost importance at low speeds (i.e. low voltages), inverter dead-time needs to be considered. Dead time of the inverter used in the experiments equals 2 µs and, in all the experiments illustrated so far, it was correctly compensated. If the actual inverter dead-time is different from the value used in the compensation, a substantial stator resistance estimation error may result. This is illustrated in Fig. 10, where the drive operates at 5 Hz reference frequency of rotation, stator resistance tuning mechanism is on throughout, and the inverter dead-time is artificially increased from 2 µs to 4 µs at t = 15 s, by increasing the voltage brought to the input of the reference model in the software. While the accuracy of the speed estimate remains unaffected by this change (except for a transient), stator resistance estimation becomes erroneous, with an error of approximately 8% in the final steady-state. The result of Fig. 10 shows that stator resistance estimation will automatically compensate for the impact of the inverter dead-time on accuracy of speed estimation, by yielding an inaccurate stator resistance value. Since the sole reason for using the stator resistance on-line estimation is to provide as accurate as possible a speed estimate, this means that inverter dead-time compensation is not necessary at all. This represents a very good feature of the proposed stator resistance identification algorithm.

V. CONCLUSION

The paper presents a parallel MRAS estimator that enables simultaneous estimation of rotor speed and stator resistance. The structure of the estimator is derived using hyperstability theory and it utilizes both degrees of freedom, available within the standard rotor flux based MRAS speed estimator. The error in the instantaneous phase position of the two rotor flux estimates is utilized for rotor speed identification, this being the same as in the standard approach. The second degree of freedom, the error in the amplitudes of the two rotor flux estimates, is used for parallel stator resistance estimation.

The proposed parallel MRAS system is insignificantly more complex than its counterpart with speed estimation only and it enables very good speed estimation accuracy down to very low speeds, including short-term operation at zero speed. The effectiveness of the developed parallel MRAS structure is verified by simulation and by extensive experimental testing in the low-speed region. The capability of the drive to operate at zero speed for short time intervals is demonstrated. It is shown that the stator resistance estimation is independent of the setting of the rotor time constant (in contrast to the speed estimation), while speed estimation is independent of the inverter dead-time (in contrast to stator resistance estimation).

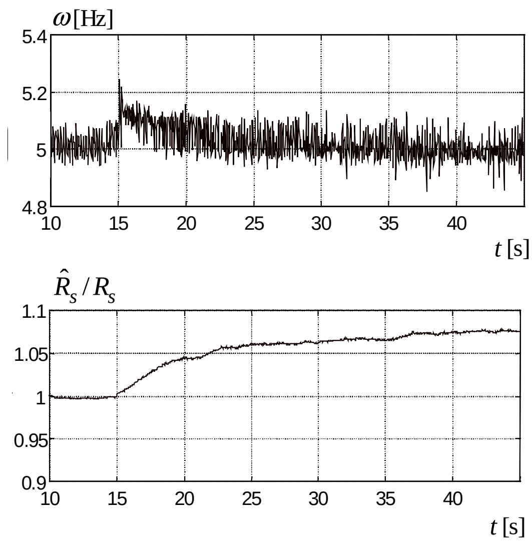


Fig. 10. Impact of inaccurate dead-time compensation on rotor speed and stator resistance estimation: estimated speed and ratio of the estimator to actual stator resistance (inverter dead-time changed from 2 to 4 µs at t = 15 s).

APPENDIX

Induction Motor Data

380 V, 2.1 A, 750 W, 5 Nm, 50 Hz, four-pole, star

L_s [H]	L_r [H]	L_m [H]	R_s [Ω]	R_r [Ω]
0,464	0,461	0,421	10	6,3

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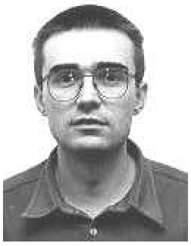

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