

# USING SIMPLIFIED OBSERVERS IN TORQUE CONTROL OF AN INDUCTION MACHINE WITHOUT SPEED SENSOR

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**Abstract** – A method is presented for on-line estimation of internal quantities to be used in the torque control of induction machines without speed sensor. In this paper simplified observers for rotor and stator flux linkages and for the electromechanically converted torque are discussed. These observers are obtained from induction machine dynamic equations and by using currents and voltages as input variables. Numerical results with such observers for rotor and stator flux linkages are shown, for evaluation of capacities and limitations. The quality of such observers, integrated in torque and flux control schemes, is verified by experimental results obtained by digital signal processing with a fast controller on the induction motor drive system.

**Keywords** – State observers, simplified observers, induction machine, stator and rotor flux linkages.

## 1. INTRODUCTION

Advanced methods for induction machine control requires on-line access to internal quantities, which are not directly accessible by physical measurement, namely: rotor and stator magnetic flux linkage and electromechanically converted torque. A number of solutions for the problem has been suggested based on the use of state observers, which are often quite complex. Recently, a considerable amount of research has been devoted to the control of induction machines without speed or position sensors as well, namely ([4] to [6]) a new method of control for induction machines known as the Stator Flux Vector Control (SFVC). The method uses the stator flux linkage components in the rotor flux reference frame as control variables, and is based on driving the estimated stator flux vector towards the reference vector defined by the input commands (torque and flux).

The control variables are not directly measurable and need to be reconstructed from the stator phase currents and phase voltages measured by conventional Hall sensors.

The originally proposed method has a drawback, characterized by an inherent non-zero steady state error in the controlled torque. In [7] to [9] improvements of the method were suggested that provides zero steady state error in the flux and torque.

For the reconstruction of stator or rotor flux of an induction machine using variables available for direct measurement (voltages and currents) several solutions have been proposed ([10] to [12]), based on considerably complex structures in closed loop.

In this paper simplified observers for the estimation of stator and rotor flux, based on machine dynamics equations, are used for the torque control of a three-phase induction motor drive without speed sensor. The electromechanical torque is also reconstructed on-line for performance evaluation purposes. Although the observer itself has not a dedicated closed loop, its integration inside external control loops reveal appropriate performance provided that parameters are known with enough accuracy.

Numerical and experimental results were obtained in order to validate the solutions under discussion.

## 2. RECONSTRUCTION OF FLUXES OF AN INDUCTION MACHINE USING COMPLEX OBSERVERS

Induction machine equations in the stator reference frame ( $\alpha\beta$ ), using fluxes and currents as state variables, and taking into account the usual assumptions of cylindrical core symmetry and sinusoidal winding structure, are as follows:

$$\dot{\bar{\psi}}_s = \bar{u}_s - R_s \bar{i}_s \quad (1a)$$

$$\dot{\bar{i}}_s = \frac{1}{\sigma L_s} \bar{u}_s - \left( \frac{1}{\tau} - j\omega_r \right) \bar{i}_s + \left( \frac{1}{\sigma \tau_r L_s} - j \frac{1}{\sigma L_s} \omega_r \right) \bar{\psi}_s \quad (1b)$$

$$T = \bar{\psi}_s \times \bar{i}_s \quad (1c)$$

Where  $\bar{u}_s$ ,  $\bar{i}_s$  and  $\bar{\psi}_s$  represent stator voltage, current and flux linkage vectors, respectively,  $\omega_r$  denotes the rotor angular speed and  $T$  the electromechanical torque.  $L_s$ ,  $L_r$  and  $M$  are symbols for stator, rotor and magnetizing inductances respectively, and other parameters are defined as follows:

$$\frac{1}{\tau} = \frac{1}{\sigma \tau_s} + \frac{1}{\sigma \tau_r}, \quad \tau_r = \frac{L_r}{R_r}, \quad \tau_s = \frac{L_s}{R_s}, \quad \sigma = \frac{L_s L_r - M^2}{L_s L_r}$$

As an example, the following equations show a second order model observer proposed by [11], for stator flux linkage of an induction machine:

$$\dot{\bar{\chi}} = \bar{\Gamma}(\omega_r)\bar{\chi} + \bar{v} \quad (2a)$$

$$\bar{\Gamma} = \left( -\frac{\omega_r}{\sigma L_s} - j b_1 \right) h \quad (2b)$$

$$\bar{v} = (b_2 - j b_3) \bar{i}_s + \left( 1 - j \frac{h}{\sigma L_s} \right) \bar{u}_s \quad (2c)$$

$$\hat{\bar{\psi}}_s = \bar{\chi} + j h \bar{i}_s \quad (2d)$$

where  $\bar{u}_s = u_{s\alpha} + j u_{s\beta}$ ,  $\bar{i}_s = i_{s\alpha} + j i_{s\beta}$  and  $\omega_r$  are continuously measured values, and  $\hat{\bar{\psi}}_s = \hat{\psi}_{s\alpha} + j \hat{\psi}_{s\beta}$  is the observed stator flux linkage vector. Remaining parameters are defined as follows:

$$b_1 = \frac{1}{\sigma L_s \tau_r}, b_2 = -R_s + \frac{h^2}{\sigma L_s \tau_r} + h \omega_r, b_3 = -\frac{h}{\tau} + \frac{h^2}{\sigma L_s} \omega_r$$

In the preceding observer structure a closed loop correction exists acting upon the error between measured and reconstructed voltage. Parameter  $h$  represents a compensation factor, as can be seen by rewriting the previous equations:

$$\dot{\hat{\bar{\psi}}}_s = \bar{u}_s - R_s \bar{i}_s + j \frac{h}{\sigma L_s} (\hat{\bar{\psi}}_s - \bar{u}_s) \quad (3a)$$

$$\hat{\bar{u}}_s = \sigma L_s \left( -\dot{\bar{i}}_s + \left( \frac{1}{\tau} - j \omega_r \right) \bar{i}_s - \left( \frac{1}{\sigma \tau_r L_s} - j \frac{h}{\sigma L_s} \omega_r \right) \hat{\bar{\psi}}_s \right) \quad (3b)$$

A similar structure was proposed for rotor flux observer [11]. Then, torque reconstruction can be made simply by a vectorial product of an observed flux and measured currents:

$$\hat{T} = \hat{\bar{\psi}}_s \times \bar{i}_s \quad (4)$$

Besides the requirement of measuring the rotor speed this observer is rather complex for on-line use in a control scheme. This paper presents a torque and flux control with numerical and experimental results using simplified observers embedded in the control scheme.

### 3. SIMPLIFIED OBSERVERS IN INDUCTION MACHINE TORQUE AND FLUX CONTROL

A block diagram shown in figure 1, represents the control of induction machine using simplified stator and rotor flux observers. Stator flux vector is a variable used in closed loop control, along with the argument of the rotor flux vector, to

produce the desired instantaneous torque and rotor flux values.

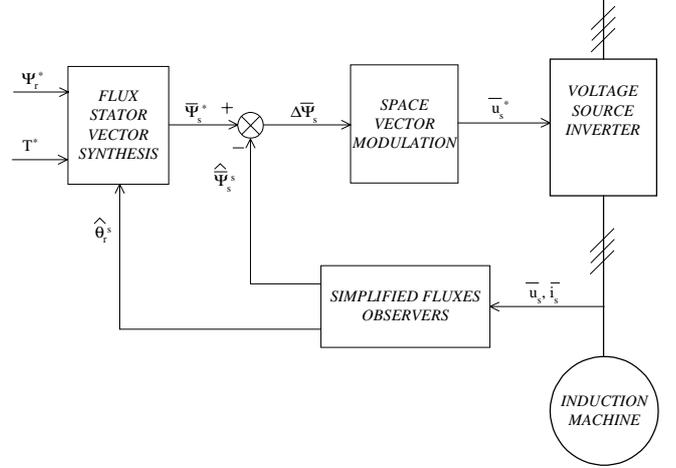


Fig.1 – Induction machine control scheme using current and voltage sensors, and simplified flux observers. Note the absence of speed sensor.

This electrical drive block diagram in closed loop is characterized by a Power Electronics section with a voltage-source inverter and an asynchronous machine.

#### 3.1 Observation section

The stator flux observer is obtained from equation (1a) by considering measured voltages and phase currents in the induction machine:

$$\hat{\psi}_{s\alpha} = \int (u_{s\alpha} - r_s i_{s\alpha}) dt \quad (5a)$$

$$\hat{\psi}_{s\beta} = \int (u_{s\beta} - r_s i_{s\beta}) dt \quad (5b)$$

Equations (5a) and (5b) can be implemented with a low pass filter using a low cut off frequency. This simple observer is dependant on the stator resistance.

The rotor flux observer is obtained from the reconstructed stator flux vector, as by (5), and the measured currents, as follows:

$$\hat{\psi}_{r\alpha} = \frac{L_r}{M} (\hat{\psi}_{s\alpha} - \sigma L_s i_{s\alpha}) \quad (6a)$$

$$\hat{\psi}_{r\beta} = \frac{L_r}{M} (\hat{\psi}_{s\beta} - \sigma L_s i_{s\beta}) \quad (6b)$$

The estimated phase angle of rotor flux is then used for Park's co-ordinate transformation of reference quantities to the stator reference frame. Equations (6) are also based on induction machine dynamic equations in the stator reference frame.

Electromechanical torque is reconstructed on-line for performance evaluation purposes, by using the induction machine model equation (4):

$$\hat{T} = \hat{\psi}_{s\alpha} i_{s\beta} - \hat{\psi}_{s\beta} i_{s\alpha} \quad (7)$$

### 3.2 Control loop

The flux stator vector control scheme, shown in fig. 1, begins with reference components  $\psi_{ds}^*$  and  $\psi_{qs}^*$ , in the stator flux reference frame.

These components are obtained from desired torque and desired rotor flux linkage (instantaneous reference values) as follows:

$$\psi_{ds}^* = \frac{L_s}{M} (1 + \sigma \tau_r s) \psi_r^* \quad (8a)$$

$$\psi_{qs}^* = \frac{L_s}{M} \frac{\sigma L_r}{\psi_r^*} T^* \quad (8b)$$

These components ( $\psi_{ds}^*$  and  $\psi_{qs}^*$ ) are still in rotor referenced co-ordinates. Then, they are transformed in  $\alpha\beta$  (stator) co-ordinates by Park's transformation with a rotation angle  $\theta_r^s$ . This angle is obtained from the rotor flux estimator, which is the phase angle of the rotor flux in the stator reference frame, as follows:

$$\begin{bmatrix} \psi_{\alpha s}^* \\ \psi_{\beta s}^* \end{bmatrix} = \begin{bmatrix} \cos \theta_r^s & -\sin \theta_r^s \\ \sin \theta_r^s & \cos \theta_r^s \end{bmatrix} \begin{bmatrix} \psi_{ds}^* \\ \psi_{qs}^* \end{bmatrix} \quad (9)$$

The method of flux and torque control thus uses the Space Vector Modulation (SVM) technique. It is based in the instantaneous application of the appropriate voltage vector by the voltage-source inverter. Although several techniques exist for the selection of instantaneous inverter configurations, in this study, the voltage vector is synthesized by pulse-width modulation (PWM) with constant switching frequency operation.

The instantaneous stator voltage is calculated from the error between the estimated flux and its reference vector, as shown next, and stands for each sampling period  $t_s$ :

$$\bar{u}_s^* = \frac{\bar{\psi}_s^* - \hat{\psi}_s}{t_s} + r_s \bar{i}_s^* \quad (10)$$

It can be shown that such a method still exhibits a static torque error that increases with rotor speed. Further compensations were proposed for control improvement ([7] – [9]). One of those compensation approaches [7] is shown in the control scheme of fig. 2, where the stator flux vector angle  $\hat{\omega}_s$  is reconstructed as follows:

$$\hat{\omega}_s = \frac{\hat{\psi}_{r\alpha} \hat{\psi}_{r\beta} - \hat{\psi}_{r\beta} \hat{\psi}_{r\alpha}}{\hat{\psi}_{r\alpha}^2 + \hat{\psi}_{r\beta}^2} \quad (11)$$

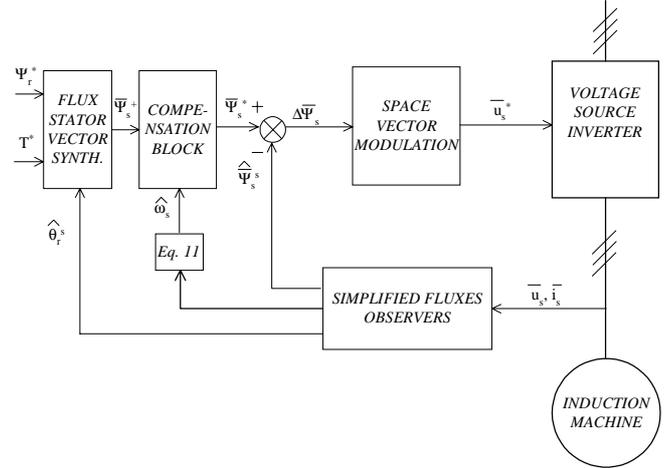


Fig.2 – Improvement of fig. 1 control scheme, introduced in order to compensate for the static torque error.

## 4. RESULTS

In order to test the proposed control solution using simplified observers, numerical and experimental results were obtained with a standard 0.57 kW, 4 poles induction motor.

### 4.1 Numerical results

The numerical results presented in the following figures were obtained by digital simulation by using Matlab/Simulink from Mathworks Inc. The Vectorial Space Vector Modulation technique was used with 20 kHz switching frequency and 100  $\mu$ s sampling period.

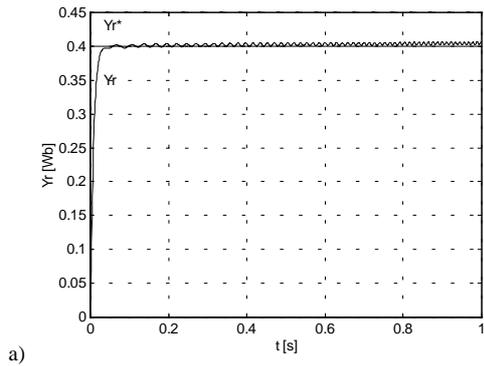
Fig. 3 shows the observed rotor flux and torque response to a step in torque reference using control scheme of fig.1; fluxes where previously established in the motor. A steady state error is visible in torque response that increases with speed.

Fig. 4 presents observed rotor flux and torque in a test similar to the one shown in fig. 3, now using control scheme of fig.2 (with delay compensation), and assuming exact parameter values. The torque response error was removed. The small frequency oscillations observed in both results are due to the simplified observers used; they are noticed mainly at low speed operation.

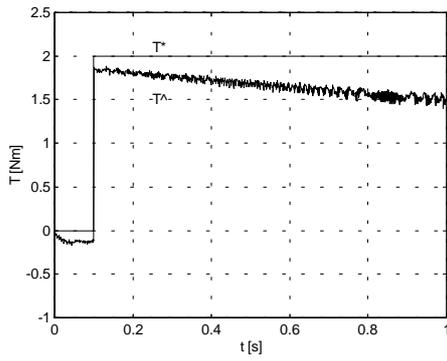
Fig. 5 shows a considerable sensitivity to stator resistance error. Fortunately this parameter is easily measurable and its variation with temperature should be additionally compensated. Fig. 6 shows the effect of errors in total stator and total rotor inductances.

### 4.2 Experimental results

The proposed system has been also implemented using a floating-point digital signal processor (DSP) for solving the stator and rotor flux observer equations, as well as the electromechanical torque. The instantaneous voltage vector to apply to the machine by the Voltage-Source Inverter is also calculated using the DSP.

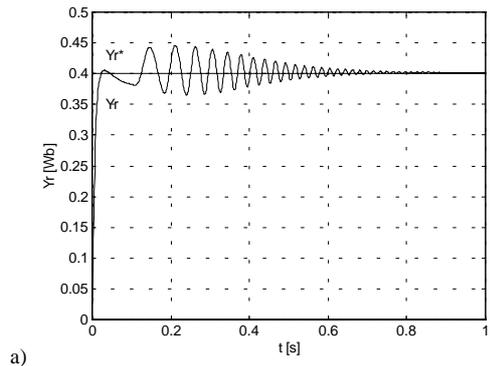


a)

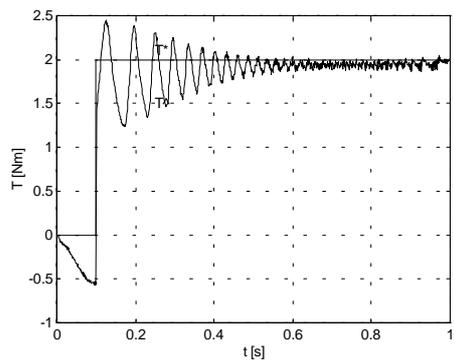


b)

Fig. 3 – Step response of SFVC without delay compensation, using exact parameters: a) observed rotor flux; b) observed torque.

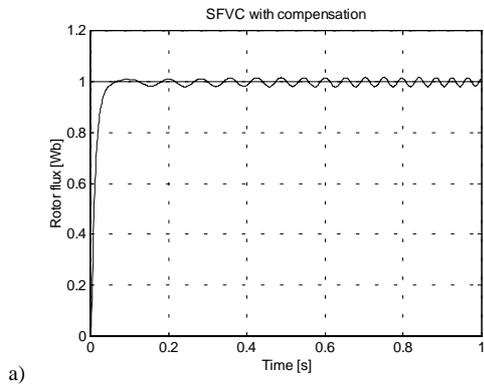


a)

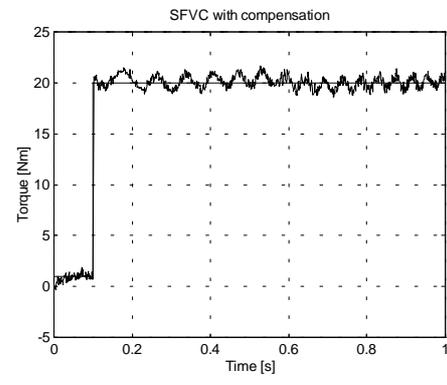


b)

Fig. 5 – Step response of SFVC with delay compensation, using  $R_s$  20% less than the exact value: a) observed rotor flux; b) observed torque.

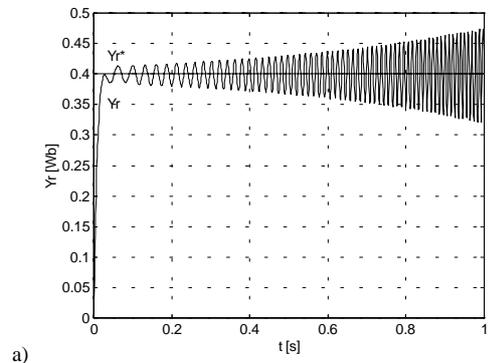


a)

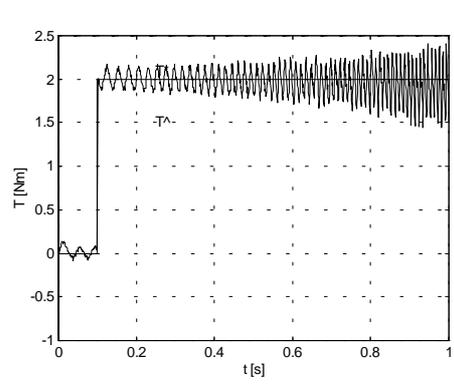


b)

Fig. 4 – Step response of SFVC with delay compensation, using exact parameters: a) observed rotor flux; b) observed torque.



a)



b)

Fig. 6 – Step response of SFVC with delay compensation, using  $R_s$  5% greater than the exact value: a) observed rotor flux; b) observed torque.

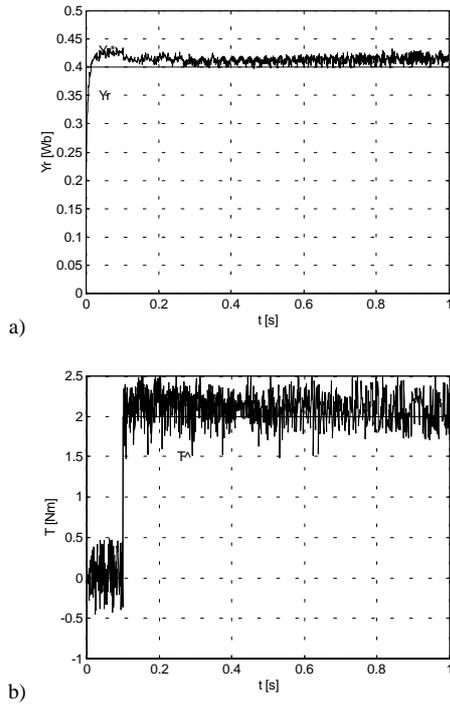


Fig. 7 – Step response of SFVC with delay compensation, using  $L_s$  and  $L_r$  5% less than the exact values: a) observed rotor flux; b) observed torque.

Fig. 8 exhibits experimental results showing the measured speed and a component of stator flux observed with our simple flux observer. After some time the voltage ceiling provided by the voltage-source inverter is achieved and saturation is visible in speed oscillogram. Fig. 9 shows the observed torque and the measured current and speed for the same system. In fig. 10 the response to square torque reference with compensated control scheme is shown, revealing a satisfactory performance for practical purposes.

## 5. CONCLUSION

Simplified flux linkage observers are shown to be effective for torque control of the induction machine, even without speed measurement. Experimental results presented in this paper, in conformance with simulation results, show satisfactory control performance of the proposed approach. Weak points are due to the sensitivity of some parameters.

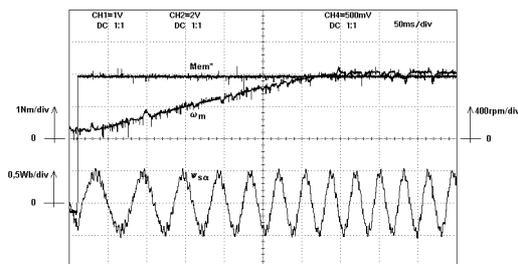


Fig. 8 – Estimated stator flux and speed response to a step change in torque reference.

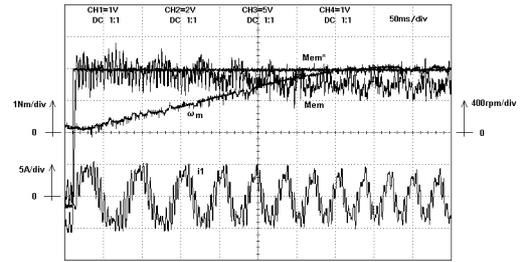


Fig. 9 – Measured current and estimated torque response to a step change in torque reference as in fig. 8.

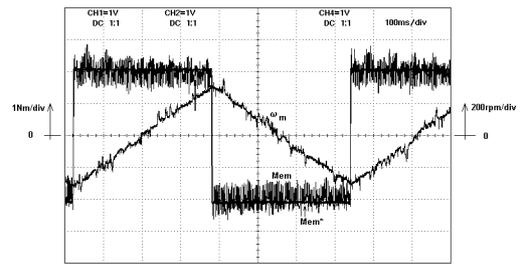


Fig.10 – Measured estimated torque response for a rectangular wave torque reference.

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