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Olimpiu Stoicuta, Teodor Pana

New Adaptive Observer for Sensorless Induction Motor Drives

The paper deals with a new type of observer for the rotor flux and speed of the induction motor. The new observer is designed to be used within a speed sensorless direct rotor field oriented control of induction motors. In order to present the performances of the new observer, it was compared to extended Luenberger observer. The comparative analysis was simulated using Matlab – Simulink – dSPACE platform.

Keywords: induction motor drives, adaptive observers, simulation

1. Introduction

The researches of the last two decades in the field of induction motor speed vector control systems, such as direct field oriented control have concentrated on four main directions: elimination of the speed transducer; estimation of the module and the position of the rotor flux; online estimation and verification of a series of parameters of the induction motor and tuning the controllers of the control system.

The results of the researches lead to the development of a series of sensoless vector control systems, de tip sensorless, for which the rotor speed together with the module and the position of the rotor flux are simultaneously estimated.

The methods imposed during the simultaneous estimation of the module and the position of the rotor flux as well as the rotor speed of the induction motor are those based on the use of an adapting mechanism.

These observers are realised based on two models the output of which are compared resulting therefore their output errors. One of the models is also called "Reference Model", because it does not depend on the rotor speed, while the other model is also called "Adaptive Model" because it permanently adapts in relation to the estimated value of the rotor speed. The estimated rotor speed is obtained at the output of the adaptive mechanism following the error processing, errors obtained following a comparison of the output of the two models using an adaptive law. The following are some of the most known observers of this type: the observer proposed by C. Schauder [1] and the observer proposed by H. Kubota [2].

Considering the actual tendencies of increasing the performances of signal processors, the design of observers more complex than the ones previously mentioned does not raise any impediment during the implementation.

Considering the aforementioned, the paper proposes a new type of rotor speed and flux observer, more complex, based on an adaptive mechanism. This type of observer as well as the sensorless vector control system comprising such an observer will more dynamically and more robustly perform at the variations of the parameters of the induction motor than the observer previously mentioned.

2. Adaptive Rotor Flux Observer

In order for the equations defining the new type of observer to be expressed, the equation system defining the mathematic model “stator currents – rotor flux” [3] of the induction motor will be presented:

$$\frac{dx}{dt} = A \cdot x + B \cdot u \tag{1}$$

where: $u = \begin{bmatrix} u_{ds} & u_{qs} \end{bmatrix}^T$; $x = \begin{bmatrix} i_{ds} & i_{qs} & \cdot_{dr} & \cdot_{qr} \end{bmatrix}^T$;

$$A = \begin{bmatrix} a_{11} & 0 & a_{13} & a_{14} \cdot z_p \cdot \mu_r \\ 0 & a_{11} & -a_{14} \cdot z_p \cdot \mu_r & a_{13} \\ a_{31} & 0 & a_{33} & -z_p \cdot \mu_r \\ 0 & a_{31} & z_p \cdot \mu_r & a_{33} \end{bmatrix}; \; B = \begin{bmatrix} b_{11} & 0 \\ 0 & b_{11} \\ 0 & 0 \\ 0 & 0 \end{bmatrix};$$

$$a_{11} = -\left(\frac{1}{T_s \cdot \pm} + \frac{1-\pm}{T_r \cdot \pm} \right); \; a_{13} = \frac{L_m}{L_s \cdot L_r \cdot T_r \cdot \pm}; \; a_{14} = \frac{L_m}{L_s \cdot L_r \cdot \pm}; a_{31} = \frac{L_m}{T_r};$$

$$a_{33} = -\frac{1}{T_r}; \; b_{11} = \frac{1}{L_s \cdot \pm}; \; T_s = \frac{L_s}{R_s}; \; T_r = \frac{L_r}{R_r}; \; \pm = 1 - \frac{L_m^2}{L_s \cdot L_r}.$$

Considering the expressions presented before, the adaptive observer of the state variables of the induction motor is defined by the following relation:

$$\frac{d\hat{x}}{dt} = A \cdot \hat{x} + B \cdot u + S \cdot C \cdot \left(\frac{dx}{dt} - \frac{d\hat{x}}{dt} \right) \tag{2}$$

where the form of the amplification matrix of the observer is:

$$S = \begin{bmatrix} s_{11} & s_{12} & s_{21} & s_{22} \\ -s_{12} & s_{11} & -s_{22} & s_{21} \end{bmatrix}^T; \quad C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \tag{3}$$

If the parameters of the induction motor are supposed to be constant then the estimation error is defined by the following relation:

$$\pounds = x - \hat{x} \tag{4}$$

Therefore, using relations (1), (2) and (4) the dynamics of the estimation error is given by the following expression:

$$\frac{d\pounds}{dt} = A \cdot \pounds - S \cdot C \cdot \frac{d\pounds}{dt} \tag{5}$$

In order for the values of the coefficients defining the amplification matrix S to be determined, it shall be supposed that:

$$\det\left(I_4 + S \cdot C\right) \neq 0 \tag{6}$$

Therefore, relation (5) becomes:

$$\frac{d\pounds}{dt} = M \cdot \pounds \ ; \ M = \left(I_4 + S \cdot C\right)^{-1} \cdot A \tag{7}$$

The eigenvalues of matrix M from the right side of the differential equations system (7) shall be marked with a_e, and the eigenvalues of matrix A from the mathematic model of the induction motor shall be marked with a_m.

The eigenvalues of matrix M are given by the following equation system:

$$\det\left(a_e \cdot I_4 - M\right) = 0 \tag{8}$$

while, the eigenvalues of matrix A are obtained by solving the following system:

$$\det\left(a_m \cdot I_4 - A\right) = 0 \tag{9}$$

In order to determine the coefficients defining the amplification matrix the proportionality relation shall be ensured between its eigenvalues:

$$a_e = k \cdot a_m \ ; \quad k > 1 \tag{10}$$

where k is the constancy of proportionality.

A system of algebraic equations results from (8), (9) and (10) where the unknown is the coefficients of the amplification matrix. After solving the equation system the following solution is obtained:

$$\begin{cases} s_{11} = \dfrac{1-k^2}{k^2} \\ s_{12} = 0 \end{cases} ; \quad \begin{cases} s_{22} = \dfrac{k-1}{k} \cdot \dfrac{z_p \cdot \mu_r \cdot a_{11}}{a_{14} \cdot \left(z_p^2 \cdot \mu_r^2 + a_{33}^2\right)} \\ s_{21} = \dfrac{k-1}{a_{14} \cdot k^2} - s_{22} \cdot \dfrac{a_{33}}{z_p \cdot \mu_r} \end{cases} \tag{11}$$

Considering the solutions given by (11), condition (6) becomes:

$$\det\left(I_4 + S \cdot C\right) = \frac{1}{k^4} \tag{12}$$

The above presented relation shows that for a constancy of proportionality $k > 1$, the value of the determinant is always different from 0 therefore ensuring the existence and uniqueness of the inverted matrix $\left(I_4 + S \cdot C\right)^{-1}$ which appears within the system of differential equations (7). Therefore, the observer given by relation (2) is completely defined. In order for the performances of the new type observer to be highlighted, a new comparison will be made with Luenberger's observer [2]. The equations defining Luenberger's rotor flux observer proposed by Hisao Kubota are given by the following relation:

$$\frac{d\hat{x}}{dt} = A \cdot \hat{x} + B \cdot u + L \cdot C \cdot \left(x - \hat{x}\right) \tag{13}$$

where the state vector as well as matrixes A, B, and C are identical to those comprised by the new type observer. Luenberger's amplification matrix is:

$$L = \begin{bmatrix} l_{11} & l_{12} & l_{21} & l_{22} \\ -l_{12} & l_{11} & -l_{22} & l_{21} \end{bmatrix}^T \tag{14}$$

The coefficients of matrix (14) are:

$$\begin{cases} l_{11} = (1-k)\cdot(a_{11} + a_{33}) \\ l_{12} = z_p \cdot \mu_r \cdot (1-k) \end{cases} ; \quad \begin{cases} l_{22} = -¥ \cdot l_{12} \\ l_{21} = \left(a_{31} + ¥ \cdot a_{11}\right)\cdot\left(1-k^2\right) - ¥ \cdot l_{11} \end{cases} \tag{15}$$

where: $¥ = \dfrac{\pm \cdot L_s \cdot L_r}{L_m}$.

The two types of observers have been analysed using the real time simulation.

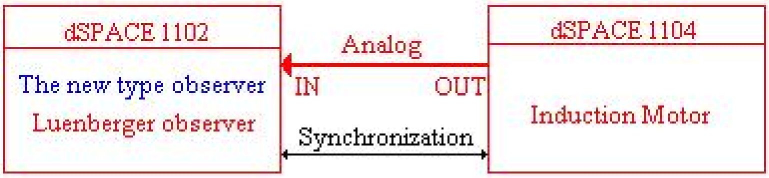

Figure 1. The structure of the biprocessor real time simulation system

The observer algorithm has been implemented on the dSPACE 1102 and the model of the drive (induction motor and load) on the dSPACE 1104.

The observers were simulated in an open loop. The induction motor was simulated based on the mathematic model "stator currents – rotor flux". The movement equation of the induction motor corresponding to the stator currents – rotor flux model is [5]:

$$\frac{d\mu_r}{dt} = H_{m_1} \cdot \left(\cdot_{dr} \cdot i_{qs} - \cdot_{qr} \cdot i_{ds} \right) - H_{m_2} \cdot \mu_r - H_{m_3} \cdot M_r \tag{16}$$

where: $H_{m_1} = \dfrac{3}{2} \cdot \dfrac{z_p}{J} \cdot \dfrac{L_m}{L_r}$; $H_{m_2} = \dfrac{F}{J}$; $H_{m_3} = \dfrac{1}{J}$.

The electrical and mechanical parameters of the induction motor used for the simulation are presented by the following relations:

$$P_N = 790[\mathrm{W}];\ U_N = 200[\mathrm{V}];\ n_N = 11400[\mathrm{rot/min}];\ f_N = 400[\mathrm{Hz}];$$

$$z_p = 2;\ R_s = 2.35[\Omega];\ R_r = 1.82[\Omega];\ L_s = 0.0383[\mathrm{H}];\ L_r = 0.0371[\mathrm{H}];$$

$$L_m = 0.0362[\mathrm{H}];\ J = 5.1\cdot 10^{-6}\left[\mathrm{Kg}\cdot\mathrm{m}^2\right];\ F = 2\cdot 10^{-7}[\mathrm{N}\cdot\mathrm{m}\cdot\mathrm{sec/rad}].$$

The coefficient of proportionality k, both for the new type observer as well as for Luenberger's observer is: $k = 1.2$. In order to highlight the performances of the new type observer, the simulation considered the variation of the rotor resistance depending on temperature. Thus, Figure 2 present the errors the "dq" components of both the real and estimated rotor flux, based on the two observers, if the rotor resistance is modified together with the variation of temperature.

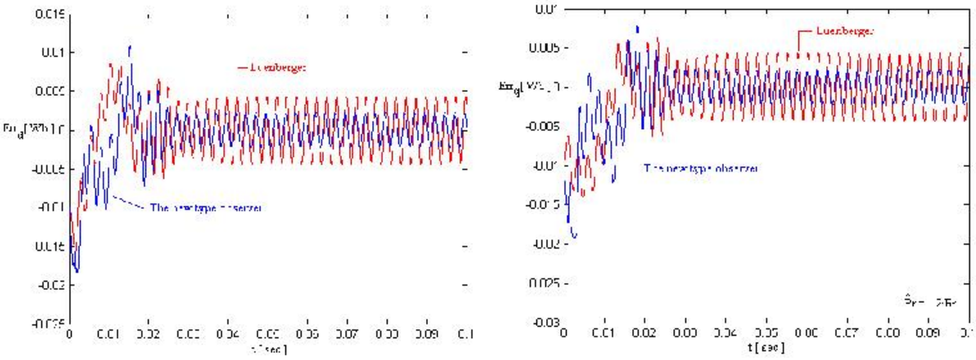

Figure 2. The influence of rotor resistance variation on the estimation of component "dq" of the rotor flux.

The simulations consider that the induction motor starts with a resisting torque varying based on the step type distribution, the value of which is equal to the nominal electromagnetic torque of the induction motor.

The graphic representations in Figure 2 show that after the end of the transitional starting regime of the induction motor the error obtained are smaller than if Luenberger's observer had been used. The figures were obtained for a direct start of the induction motor for a rotation equal to the nominal rotation. The above mentioned conclusion stays valid in the case of the operation of the induction motor at very low speeds.

3. Speed Estimator

Obtaining a sensorless vector control system, supposes a simultaneous estimation of the rotor flux and speed. Therefore, the speed will be determined based on an adaptive mechanism.

In order to determine the adaptive law, the mathematic model of the induction machine shall be considered as the reference model (1), and the adjustable model shall be given by the new observer (2).

$$\frac{d\hat{x}}{dt} = \tilde{A} \cdot \hat{x} + B \cdot u + \tilde{S} \cdot C \cdot \left(\frac{dx}{dt} - \frac{d\hat{x}}{dt} \right) \tag{17}$$

Considering the adjustable model, the matrices A and S of the observer are marked with " $\sim$ ", because the matrices depend on the estimated speed.

Thus, the estimation error is given by the following relation:

$$e_x = x - \hat{x} \tag{18}$$

Deriving into (18) relation to time and considering relations (1) and (17), the following is obtained:

$$\frac{de_x}{dt} = A \cdot e_x + \left(A - \tilde{A} \right) \cdot \hat{x} - \tilde{S} \cdot C \cdot \frac{de_x}{dt} \tag{19}$$

Considering (6), the above expression becomes:

$$\frac{de_x}{dt} = N \cdot A \cdot e_x + N \cdot \left(A - \tilde{A} \right) \cdot \hat{x} \ ; \ N = \left(I_4 + \tilde{S} \cdot C \right)^{-1} \tag{20}$$

In order to infer the adaptive mechanism for system (20) the following Lyapunov's candidate function shall be chosen:

$$V = e_x^T \cdot e_x + \frac{\left(\hat{\mu}_r - \mu_r \right)^2}{a} \tag{21}$$

where a is a positive constancy.

Deriving the above mentioned expression in relation to time, the following is obtained:

$$\frac{dV}{dt} = e_x^T \cdot G \cdot e_x + e_x^T \cdot H \cdot \hat{x} + \hat{x}^T \cdot H^T \cdot e_x + 2 \cdot \frac{\Delta\mu_r}{a} \cdot \frac{d\Delta\mu_r}{dt} \tag{22}$$

where: $G = N \cdot A + \left(N \cdot A \right)^T ; \ H = N \cdot \left(A - \tilde{A} \right)$

$$\Delta\mu_r = \hat{\mu}_r - \mu_r ; \ A - \tilde{A} = -\Delta\mu_r \cdot A_{er} ; A_{er} = \begin{bmatrix} 0 & 0 & 0 & a_{14} \cdot z_p \\ 0 & 0 & -a_{14} \cdot z_p & 0 \\ 0 & 0 & 0 & -z_p \\ 0 & 0 & z_p & 0 \end{bmatrix}.$$

If the rotor flux estimation errors are neglected, then (22) becomes:

$$\frac{dV}{dt} = e_x^T \cdot G \cdot e_x + 2 \cdot \frac{\Delta\mu_r}{a} \cdot \frac{d\Delta\mu_r}{dt} - 2 \cdot z_p \cdot \Delta\mu_r \cdot k^2 \cdot a_{14} \cdot \left(e_a \cdot \hat{\cdot}_{qr} - e_b \cdot \hat{\cdot}_{dr} \right) \tag{23}$$

where: $e_a = i_{ds} - \hat{i}_{ds}$; $e_b = i_{qs} - \hat{i}_{qs}$.

Therefore, in order for the derivative of Lyapunov's function to be negatively defined, the following equality shall be imposed:

$$\frac{d\Delta\mu_r}{dt} = a_{14} \cdot z_p \cdot a \cdot k^2 \cdot \left(e_a \cdot \hat{\cdot}_{qr} - e_b \cdot \hat{\cdot}_{dr}\right) \tag{24}$$

If the estimated speed variation is larger than the real speed, then (24) becomes:

$$\frac{d\hat{\mu}_r}{dt} = k_s \cdot \left(e_a \cdot \hat{\cdot}_{qr} - e_b \cdot \hat{\cdot}_{dr}\right) \tag{25}$$

The relation presented above considered a as a positive constancy.

If expression (25) is integrated, the following is obtained:

$$\hat{\mu}_r = k_s \cdot \int_0^t \left(e_a \cdot \hat{\cdot}_{qr} - e_b \cdot \hat{\cdot}_{dr}\right) \cdot d2 \tag{26}$$

Expression (26) represents the general formula for constructing the adaptive law. Constancy k_s is chosen for a better dynamic estimation regime. The need of having two coefficients to control the dynamics of speed estimation leads to the use of the following expression instead of formula (26):

$$\hat{\mu}_r = k_R \cdot \left(e_a \cdot \hat{\cdot}_{qr} - e_b \cdot \hat{\cdot}_{dr}\right) + k_I \cdot \int_0^t \left(e_a \cdot \hat{\cdot}_{qr} - e_b \cdot \hat{\cdot}_{dr}\right) \cdot d2 \tag{27}$$

where: $k_I = k_R / T_R$.

Therefore, the "extended observer" is composed of the adaptive mechanism of speed (27) and the rotor flux observer (2). Figure 3 presents the block diagram of the rotor speed and flux observer.

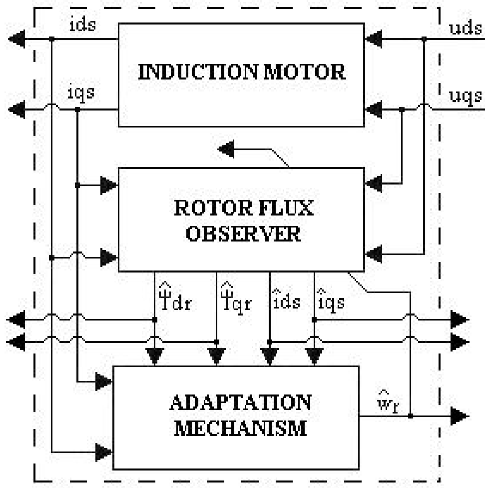

Figure 3. Block diagram of the rotor speed and flux observer

In order to present the performances of the above presented observer, it was compared to extended Luenberger observer. The comparative analysis was simulated using Matlab – Simulink - dSPACE platform (Figure 1). The coefficients defining the adaptive law are described by the following relation:

$$k_R = \frac{10}{T_{d_1} \cdot k_T} \; ; \; T_R = \frac{T_{d_2}}{50} \; ; \; k_T = a_{14} \cdot z_p \cdot \cdot {}_{r_N}^{2} \qquad (28)$$

where: $T_{d_1} = 0.001[\text{sec}]$; $T_{d_2} = 0.0075[\text{sec}]$; $\cdot_{r_N} = \left(U_N \cdot \sqrt{2/3}\right) / \left(2 \cdot ® \cdot f_N\right)$.

The above presented relations are valid both for the new type observer as well as for the extended Luenberger observer. The simulation of both types of observers is made in the same conditions as in the previous paragraph. Therefore, Figure 4 presents the diagram of the real speed of the induction motor compared to the speed estimated by the two observers.

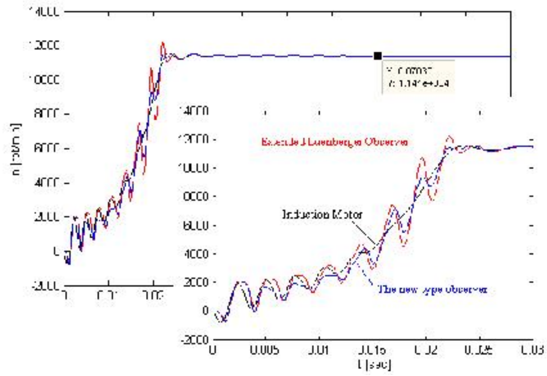

Figure 4. The real speed in tandem with the speed estimated by the extended Luenberger observer as well as by the new type observer

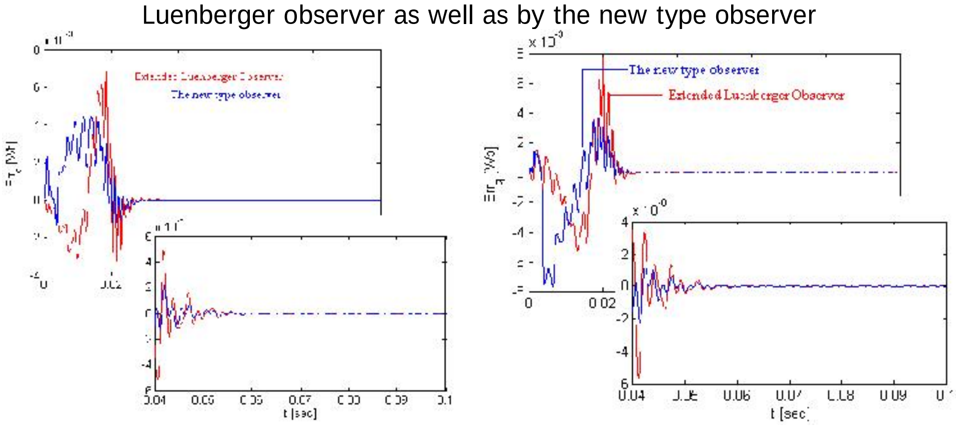

Figure 5. The error between the real rotor flux and component “dq” of the estimated rotor flux.

On the other hand, Figure 5 present the errors between the two “dq” components of the rotor flux and the estimated one based on the two observers. For a better analysis of the new type observer, Figure 6 and Figure 7 present the influence of the variation of rotor resistance on the estimation of the rotor flux and speed of the induction motor.

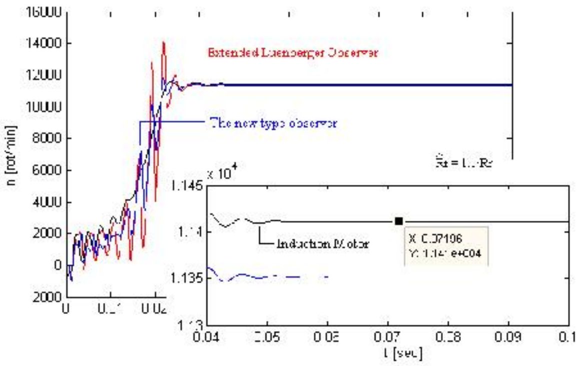

Figure 6. The influence of the variation of rotor resistance on the estimation of the speed of the induction motor

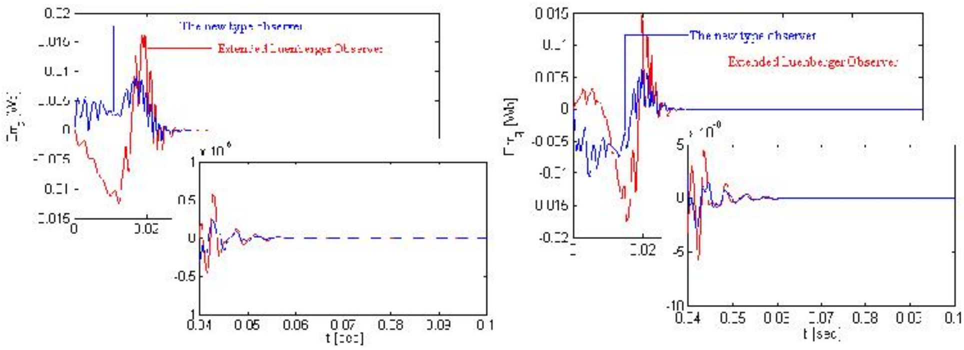

Figure 7. The influence of the variation of the rotor resistance on the component “dq” of the rotor flux.

It results from the previous presented diagrams that the new type observer has a better dynamics than the extended Luenberger observer. The errors between the components “dq” of the real and estimated rotor flux are smaller for the new type observer than for the extended Luenberger observer.

Figure 6 show that the variation of the rotor speed produces a non-null stationary error between the measured speed and the estimated speed of the induction motor. The previously presented conclusions remain also valid for the operation of the induction motor at low speed.

New types of observers for the stator resistance and rotor resistance of the induction motor may be designed using the same design principle as for the adaptive mechanism.

4. Closed Loop Analysis of the Rotor Flux and Speed Observer

The sensorless control system performances analysis comprising in its loop the new type observer is made through the Matlab – Simulink - dSPACE simulation platform. The control system to be described is presented in Figure 8.

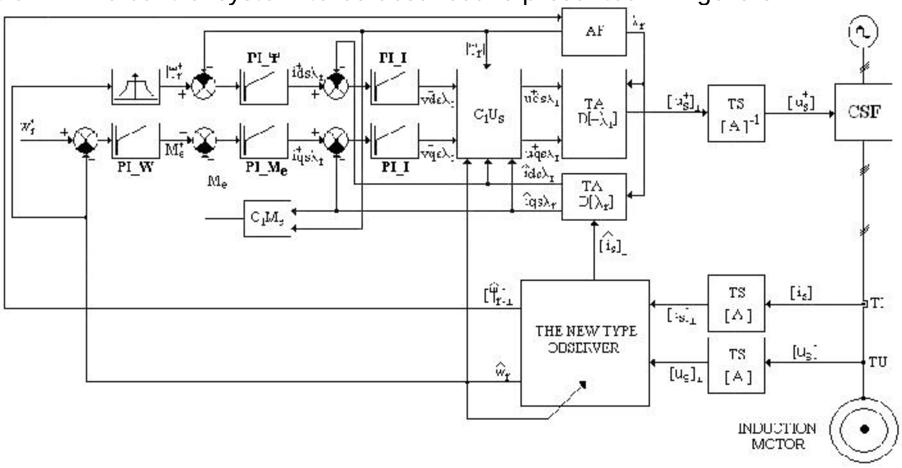

Figure 8. Block diagram of the sensorless direct field oriented vector speed control system.

Besides the induction motor and the rotor speed and flux observer, the main blocks composing the control system are presented in articles [4] and [7]. The automatic controllers comprised by the control system are tuning using the formulas presented in articles [6] and [7].

The commutation frequency of the transistors during the simulation is $10[\mathrm{kHz}]$ and the induction machine starts with a static moment varying based on a step like distribution, the value of which is equal to the nominal electromagnetic moment of the induction machine.

The vector control algorithm has been implemented on the dSPACE 1102 and the model of the drive (induction motor and load) on the dSPACE 1104 (Figure 9).

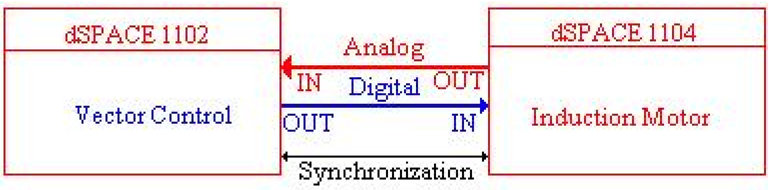

Figure 9. The structure of the biprocessor real time simulation vector control system.

In order to highlight the performances of the control system, the simulation considers the variation of the rotor resistance. Therefore, Figure 10 and Figure 11 represent the influence of the rotor resistance variation on the estimation of the rotor flux and speed of the induction motor.

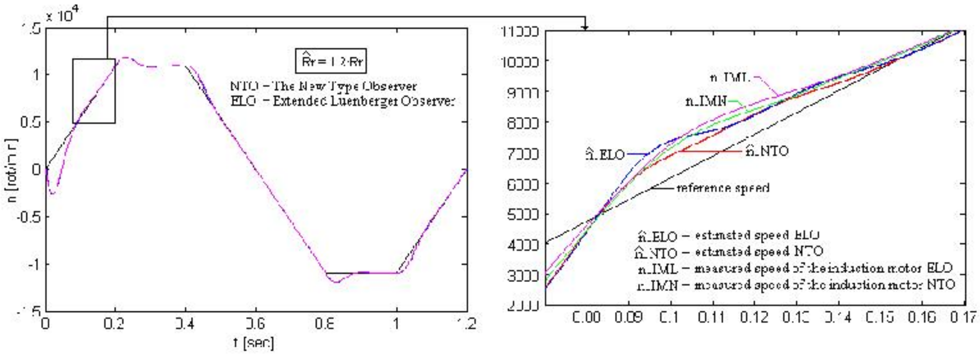

Figure 10. The influence of the rotor resistance variation on the estimation of the speed of the induction motor

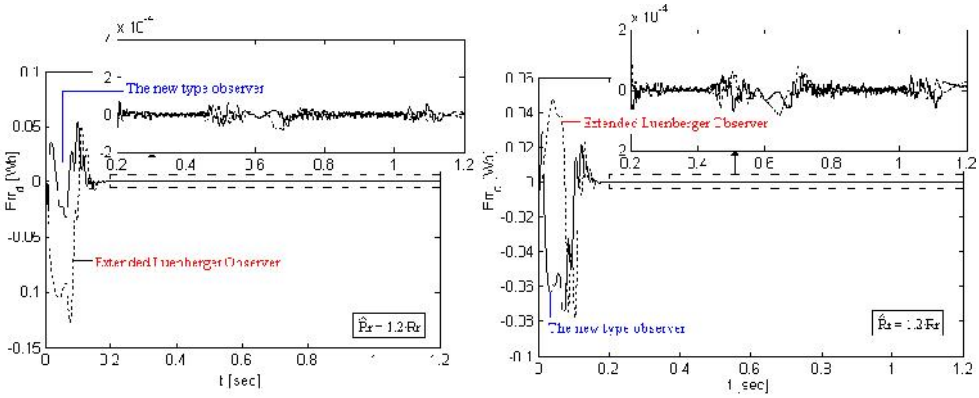

Figure 11. The influence of the rotor resistance variation on the estimation of the component “dq” of the rotor flux.

Figures 10 and 11 show that the control system comprising in its loop the “New Type Observer” (NTO) has a very good dynamics and robustness towards rotor resistance variation. These conclusions are also valid in the field of low speeds.

5. Conclusion

The paper presents a new type of observer for the rotor flux and speed of the induction motor. The observer proposed is destined for the use inside sensorless direct field oriented vector control systems.

The form of the observer for the state vector of the induction motor is a general one and may be used by other fields of science as well.

The dynamic performances as well as the robustness of the new type observer, for the rotor resistance variation, recommends its use in industrial applications where there is the need to control the speed of the induction motor using a sensorless direct field oriented vector control system.

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Addresses:

- Lect. Ph.D. Eng. Olimpiu Stoicuta, University of Petrosani, Universitatii Street, nr. 20, 332006, Petrosani, OlimpiuStoicuta@upet.ro
- Prof. Ph.D. Eng. Teodor Pana, Technical University of Cluj – Napoca, Memorandumului Street, nr. 28, 400114, Cluj – Napoca, pana@bavaria.utcluj.ro