6TH INTERNATIONAL CONFERENCE ON ELECTROMECHANICAL AND POWER SYSTEMS
October 4-6, 2007 - Chişinău, Rep.Moldova

COMPARISON BETWEEN LUENBERGER OBSERVER AND GOPINATH OBSERVER USED IN ELECTRICAL DRIVES SYSTEMS WITHOUT SENSORLESS

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Abstract **– Controlled induction motor drives without mechanical speed sensors at the motor shafting have the attraction of low cost and high reliability. A method for accurately obtaining the PWM stator voltage is used to minimize the problem of estimating stator flux from the stator voltage equation. A Luenberger and Gopinath style stator flux observers are presented. Therefore, this paper presents a comparison between two dedicate observers and their capabilitys to compensate for stator voltage errors and usefully in electrical drivers systems without sensorless.**

Keywords: *sensorless control, induction motor drives, observers, modeling, voltage measurement in PWM circuits, indirect field oriented control.*

1. INTRODUCTION

Induction motor drives have been thoroughly studied in the past few decades and many vector control strategies have been proposed, ranging from low cost to high performance applications.
In order to increase the reliability and reduce the cost of the drive, a great effort has been made to eliminate the shaft speed or position sensor in most high performance induction motor drive applications [1].
Speed estimation is an issue of particular interest with induction motor drives where the mechanical speed of the rotor is generally different from the speed of the revolving magnetic field. The advantages of speed sensorless induction motor drives are reduced hardware complexity and lower cost, reduced size of the drive machine, better immunity, elimination of the sensor cable, increased reliability and less maintenance requirements.
The induction motor is however relatively difficult to control compared to other types of electrical motors. For high performance control, field oriented control is the most widely used control strategy. This strategy requires information of the flux in motor, however the voltage and current model observers are normally used to obtain this information.
These observers require knowledge of the motor's electrical parameters and variations in these parameters lead to incorrect flux estimation and thereby degraded motor performance [2]. The electrical parameters are often not accurately known and they may vary during motor operation due to rise in temperature or change of magnetizing level. Therefore it is desirable to design a flux observer that is less sensitive to parameter variations than the currently used observers.
Generally, using the induction motor state equations, the flux and speed can be calculated from the stator voltage and current values [3]. The flux is estimated or observed from the stator voltage equation and the speed is obtained using the estimate flux and the rotor equation.
The main objective of this paper is to analyze and evaluate two of optimum used flux observers (Luenberger and Gopinath) in electrical drivers systems without sensorless, and also their comparison.
The analysis is done by use of modern control theory and by extensive testing. The testing is done with a Matlab/Simulink model for two of them.

2. ADAPTIVE OBSERVERS

The accuracy of the open loop estimation models described in literature reduces mechanical speed. The limit of acceptable performance depends on how precisely the model parameters can be matched to the corresponding parameters in the real motor.
The robustness against parameter mismatch and signal noise can be improved by employing closed loop observers to estimate the variable, and the system parameters.

2.1. Nonlinear Luenberger observer

The Luenberger observer can be constructed from the stator voltage motor equations in the general k – coordinate system:

$$\boldsymbol{u}_s = r_s \boldsymbol{i}_s + \frac{d\boldsymbol{\psi}_s}{d\tau} + j\omega_k \boldsymbol{\psi}_s \qquad (1)$$

where $r_s \boldsymbol{i}_s$ is the resistive voltage drop and r_s is the stator resistance. The stationary coordinate system is chosen, $\omega_k = 0$,

$$\tau_\sigma' \frac{d\boldsymbol{i}_s}{d\tau} + \boldsymbol{i}_s = \frac{k_r}{r_\sigma \tau_r}(1 - j\omega\tau_r)\boldsymbol{\psi}_r + \frac{1}{r_\sigma}\boldsymbol{u}_s \quad (2a)$$

$$\tau_r \frac{d\boldsymbol{\psi}_r}{d\tau} + \boldsymbol{\psi}_r = j\omega\tau_r\boldsymbol{\psi}_r + l_m \boldsymbol{i}_s \quad (2b)$$

These equations represent the motor model which are visualized in the upper portion of figure 1.

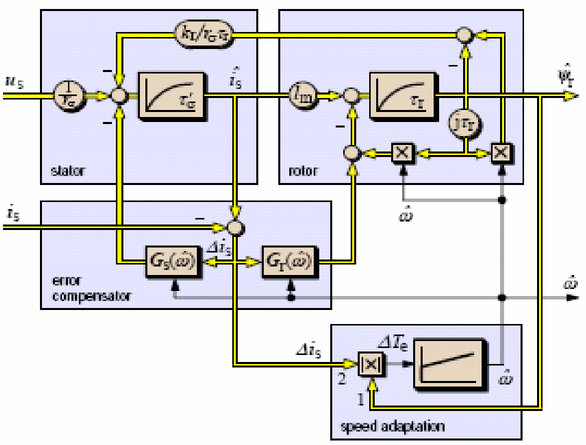

Figure 1: Nonlinear Luenberger observer; the model of the induction motor is shown in the upper portion

The model outputs the estimated values $\hat{\boldsymbol{i}}_s$ and $\hat{\boldsymbol{\psi}}_r$ of the stator current vector and rotor flux vector.

Adding an error compensator to the model establishes the observer. The error vector computed from the model current and the measured motor current is $\Delta\boldsymbol{i}_s = \hat{\boldsymbol{i}}_s - \boldsymbol{i}_s$, and is used to generate correcting inputs to the electromagnetic subsystems that represent the stator and the rotor in the motor model.

The equations of the nonlinear observer are then established in accordance with (2):

$$\tau_\sigma' \frac{d\hat{\boldsymbol{i}}_s}{d\tau} + \hat{\boldsymbol{i}}_s = \frac{k_r}{r_\sigma \tau_r}(1 - j\omega\tau_r)\hat{\boldsymbol{\psi}}_r + \frac{1}{r_\sigma}\boldsymbol{u}_s - \boldsymbol{G}(\hat{\omega})\Delta\boldsymbol{i}_s \quad (3a)$$

$$\tau_r \frac{d\hat{\boldsymbol{\psi}}_r}{d\tau} + \hat{\boldsymbol{\psi}}_r = j\omega\tau_r\hat{\boldsymbol{\psi}}_r + l_h \hat{\boldsymbol{i}}_s - \boldsymbol{G}(\hat{\omega})\Delta\boldsymbol{i}_s \quad (3b)$$

Kubota and al. [4] select the complex gain factors $\boldsymbol{G}_s(\hat{\omega})$ and $\boldsymbol{G}_r(\hat{\omega})$ such that the two complex eigenvalues of observer $\lambda_{1,2\text{observer}} = k \cdot \lambda_{1,2\text{motor}}$, where $\lambda_{1,2\text{motor}}$ are the motor eigenvalues, and k>1 is a real constant. Given the nonlinearity of the system, the resulting complex gains $\boldsymbol{G}_s(\hat{\omega})$ and $\boldsymbol{G}_r(\hat{\omega})$ in figure 1 depend on the estimated angular mechanical speed $\hat{\omega}$, [4].

2.2. The Gopinth observer

In order to evaluate the effect of the voltage measuring scheme and whether a flux observer is able or not to compensate for the voltage errors, a reduced order Gopinath stator flux observer was implemented. A feedback term based on the derivative of the stator current error was added to the stator voltage equation in a stator reference frame to improve the observer dynamic response.

$$\frac{d\boldsymbol{\psi}_s}{d\tau} = \boldsymbol{u}_s - r_s \boldsymbol{i}_s$$
$$\frac{d\hat{\boldsymbol{\psi}}_s}{d\tau} = \boldsymbol{u}_s - r_s \boldsymbol{i}_s - \boldsymbol{L}\left(\frac{d\boldsymbol{i}_s}{d\tau} - \frac{d\hat{\boldsymbol{i}}_s}{d\tau}\right) \quad (4)$$

The observer was constructed as a combination between a flux simulator and a feedback of correction of a predictive estimated error.

$$\frac{d\hat{\boldsymbol{\psi}}_r}{d\tau} - (a_{22} - g_a a_{12})\hat{\boldsymbol{\psi}}_r = (a_{21} - g_a a_{11})\boldsymbol{i}_s - g_b \boldsymbol{u}_s + g_b \frac{d\boldsymbol{i}_s}{d\tau} \quad (5)$$

where g is Gopinath observer gate. The coefficients are obtained from exposure of poles on real axis in complex plane (x = - α, y = β = 0):

$$g_a = \left[\frac{(r_r/l_r)\alpha + \omega\beta}{(r_r/l_r)^2 + \omega^2} - 1\right]\frac{\sigma l_s l_r}{l_m},$$
$$g_b = \frac{\omega\alpha - (r_r/l_r)\beta}{(r_r/l_r)^2 + \omega^2} \cdot \frac{\sigma l_s l_r}{l_m} \quad (6)$$

where β = 0, $\alpha = k\sqrt{(r_r/l_r)^2 + \omega^2}$ and k > 0.

The stator current derivative in equation (4) is calculated from stator voltage, stator current and stator flux, using the induction motor state model:

$$\frac{d\boldsymbol{i}_s}{d\tau} = \frac{1}{\sigma l_s} \cdot \left[\begin{array}{l} \boldsymbol{u}_s - r_s' \boldsymbol{i}_s + ((r_r/l_r) - j\omega)\boldsymbol{\psi}_r - \\ -((r_r/l_r) - j\omega)\sigma l_s \boldsymbol{i}_s \end{array}\right]$$
$$\frac{d\hat{\boldsymbol{i}}_s}{d\tau} = \frac{1}{\sigma l_s} \cdot \left[\begin{array}{l} \boldsymbol{u}_s - r_s' \hat{\boldsymbol{i}}_s + ((r_r/l_r) - j\omega)\hat{\boldsymbol{\psi}}_r - \\ -((r_r/l_r) - j\omega)\sigma l_s \hat{\boldsymbol{i}}_s \end{array}\right] \quad (7)$$

where $r_s' = r_s + r_r \cdot (l_m^2 / l_r^2)$.

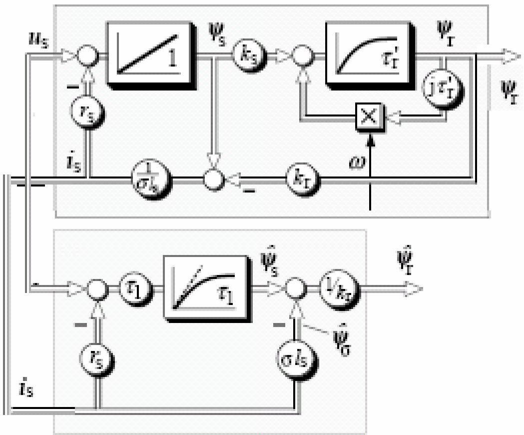

Figure 2: The Gopinath observer based on induction motor state model

The stator flux error is governed by

$$\frac{\mathrm{d}\varepsilon}{\mathrm{d}\tau}=\frac{\mathrm{d}\boldsymbol{\psi}_{\mathrm{r}}}{\mathrm{d}\tau}-\frac{\mathrm{d}\hat{\boldsymbol{\psi}}_{\mathrm{r}}}{\mathrm{d}\tau}=\boldsymbol{L}\frac{1}{\sigma l_{\mathrm{s}}}\left(\frac{1}{\tau_{\mathrm{r}}}-\mathrm{j}\omega\right)\boldsymbol{\varepsilon} \qquad (8)$$

or by matrix form

$$\dot{\boldsymbol{\varepsilon}}=\frac{1}{\sigma l_{\mathrm{s}}}\begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}\boldsymbol{\varepsilon} \qquad (9)$$

considering

$$a_{11}=\left(l_1/\tau_{\mathrm{r}}\right)-l_2\omega;\quad a_{12}=l_1\omega-l_2/\tau_{\mathrm{r}};$$

$$a_{21}=-\left(l_1\omega-\left(l_2/\tau_{\mathrm{r}}\right)\right);\quad a_{22}=\left(l_1/\tau_{\mathrm{r}}\right)-l_2\omega,$$

and

$$\boldsymbol{L}=\begin{bmatrix} l_1 & l_2 \\ l_2 & l_1 \end{bmatrix}.$$

Any observer dynamics can be easily imposed by an adequate choice of l_1 and l_2. In observation that the real part of the eigenvalues to be independent from the speed, l_2 will be chosen equal to zero. Also, the observer poles are

$$s_{1,2}=\frac{1}{\sigma l_{\mathrm{s}}}\left(\frac{l_1}{\tau_{\mathrm{r}}}\pm \mathrm{j}\omega l_1\right) \qquad (10)$$

As it can be seen, ω influences only the imaginary part of the eigenvalues. However, l_1 cannot be arbitrarily chosen for the discrete time flux computation requires a limited sampling rate.

3. MODELING THE FLUX OBSERVERS

3.1. The model of Luenberger observer

To achievement of Luenberger observer was used (3a,b) equations writing as differential equations

- for the stator model

$$\begin{aligned}\frac{\mathrm{d}i_{\mathrm{sd}}}{\mathrm{d}\tau}&=\mathrm{T}i_{\mathrm{sd}}+\mathrm{O}\quad_{\mathrm{rd}}+\omega\cdot \mathrm{k_r}\cdot\mathrm{E}\cdot\quad_{\mathrm{rq}}+\mathrm{E}u_{\mathrm{sd}}\\ \frac{\mathrm{d}i_{\mathrm{sq}}}{\mathrm{d}\tau}&=\mathrm{T}i_{\mathrm{sq}}+\mathrm{O}\psi_{\mathrm{rq}}-\omega\cdot \mathrm{k_r}\cdot\mathrm{E}\quad_{\mathrm{rd}}+\mathrm{E}u_{\mathrm{sq}}\end{aligned} \qquad (11)$$

- for the rotor model

$$\begin{aligned}\frac{\mathrm{d}\psi_{\mathrm{rd}}}{\mathrm{d}\tau}&=-\frac{1}{\tau_{\mathrm{r}}}\psi_{\mathrm{rd}}-\omega\quad_{\mathrm{rq}}+\frac{l_{\mathrm{m}}}{\tau_{\mathrm{r}}}i_{\mathrm{sd}}\\ \frac{\mathrm{d}\psi_{\mathrm{rq}}}{\mathrm{d}\tau}&=-\frac{1}{\tau_{\mathrm{r}}}\psi_{\mathrm{rq}}+\omega\psi_{\mathrm{rd}}+\frac{l_{\mathrm{m}}}{\tau_{\mathrm{r}}}i_{\mathrm{sq}}\end{aligned} \qquad (12)$$

- for the observer model

$$\begin{aligned}\frac{\mathrm{d}\hat{i}_{\mathrm{sd}}}{\mathrm{d}\tau}&=\mathrm{T}\hat{i}_{\mathrm{sd}}+\mathrm{O}\;\hat{}_{\mathrm{rd}}+\omega\cdot\mathrm{k_r}\cdot\mathrm{E}\cdot\;\hat{}_{\mathrm{rq}}+\\ &+\mathrm{E}\cdot u_{\mathrm{sd}}+\mathrm{T}\cdot 1.75\cdot\left[\hat{i}_{\mathrm{sd}}-i_{\mathrm{sd}}\right]\\ \frac{\mathrm{d}\hat{i}_{\mathrm{sq}}}{\mathrm{d}\tau}&=\mathrm{T}\hat{i}_{\mathrm{sq}}+\mathrm{O}\hat{\psi}_{\mathrm{rq}}-\omega\cdot\mathrm{k_r}\cdot\mathrm{E}\cdot\;\hat{}_{\mathrm{rd}}+\\ &+\mathrm{E}\cdot u_{\mathrm{sq}}+\mathrm{T}\cdot 1.75\cdot\left[\hat{i}_{\mathrm{sq}}-i_{\mathrm{sq}}\right]\end{aligned} \qquad (13)$$

$$\begin{aligned}\frac{\mathrm{d}\hat{\psi}_{\mathrm{rd}}}{\mathrm{d}\tau}&=-\frac{1}{\tau_{\mathrm{r}}}\hat{\psi}_{\mathrm{rd}}-\omega\;\hat{}_{\mathrm{rq}}+\frac{l_{\mathrm{m}}}{\tau_{\mathrm{r}}}\hat{i}_{\mathrm{sd}}-\\ &-\frac{1}{\tau_{\mathrm{r}}}\cdot 1.75\cdot\left[\hat{i}_{\mathrm{sd}}-i_{\mathrm{sd}}\right]\\ \frac{\mathrm{d}\hat{\psi}_{\mathrm{rq}}}{\mathrm{d}\tau}&=-\frac{1}{\tau_{\mathrm{r}}}\hat{\psi}_{\mathrm{rq}}+\omega\hat{\psi}_{\mathrm{rd}}+\frac{l_{\mathrm{m}}}{\tau_{\mathrm{r}}}\hat{i}_{\mathrm{sq}}-\\ &-\frac{1}{\tau_{\mathrm{r}}}\cdot 1.75\cdot\left[\hat{i}_{\mathrm{sq}}-i_{\mathrm{sq}}\right]\end{aligned} \qquad (14)$$

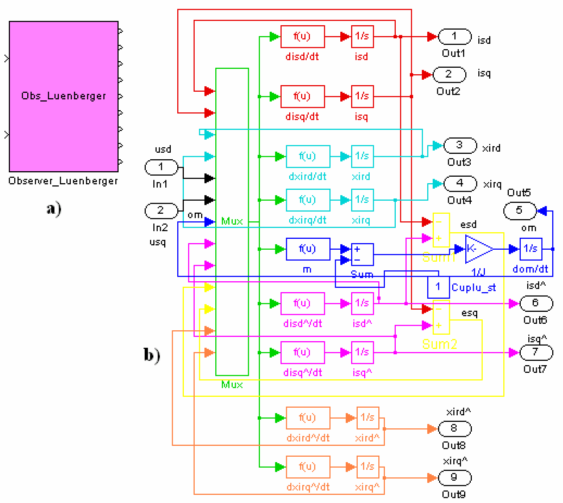

Figure 3: The SIMULINK model of Luenberger observer; a) mask block; b) uncoiled model

3.2. The model of Gopinth observer

For execution of model Simulink observer was used the equations similarly as Luenberger observer

- for the observer model

$$\frac{d\hat{\psi}_{rd}}{d\tau} = (a_{22} - g_d a_{12})\hat{\psi}_{rd} + (a_{21} - g_d a_{11}) i_{sd} - \\ - g_d u_{sd} + g_d \frac{di_{sd}}{d\tau}$$

$$\frac{d\hat{\psi}_{rq}}{d\tau} = (a_{22} - g_q a_{12})\hat{\psi}_{rq} + (a_{21} - g_q a_{11}) i_{sq} - \\ - g_q u_{sq} + g_q \frac{di_{sq}}{d\tau} \qquad (15)$$

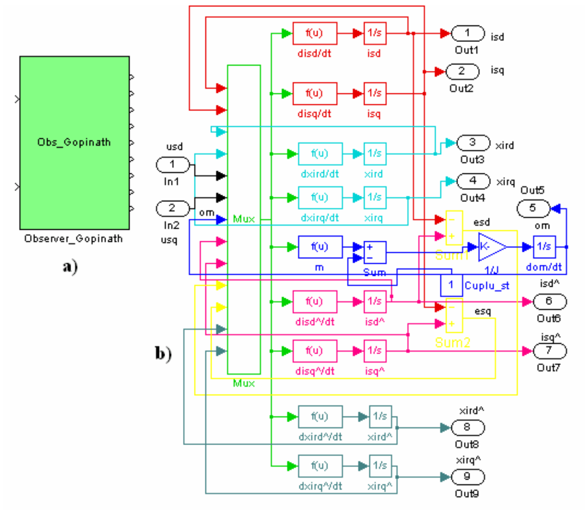

Figure 4: The SIMULINK model of Gopinath observer; a) mask block; b) uncoiled model

$$\frac{d\hat{i}_{sd}}{d\tau} = \frac{1}{\sigma l_s} \cdot \left[u_{sd} - r_s' \hat{i}_{sd} + \frac{r_r}{l_r} \hat{\psi}_{rd} - \frac{r_r}{l_r} \sigma l_s \hat{i}_{sd} \right] \qquad (16)$$

$$\frac{d\hat{i}_{sq}}{d\tau} = \frac{1}{\sigma l_s} \cdot \left[u_{sq} - r_s' \hat{i}_{sq} - \omega \hat{\psi}_{rq} + \omega \sigma l_s \hat{i}_{sq} \right]$$

Both of observers generally equation added

$$\frac{d\omega}{d\tau} = \frac{1}{j} \left[\frac{k_r}{\tau_m} \cdot \left(\psi_{rd} i_{sq} - \psi_{rq} i_{sd} \right) - T_L \right] \qquad (17)$$

4. SIMULATION RESULTS

In this paper two different kinds of advanced flux observers are evaluated. At Luenberger observer flux error in stationary regime between real rotor flux and estimate is mentioned, while to Gopinath observer error is practically zero.

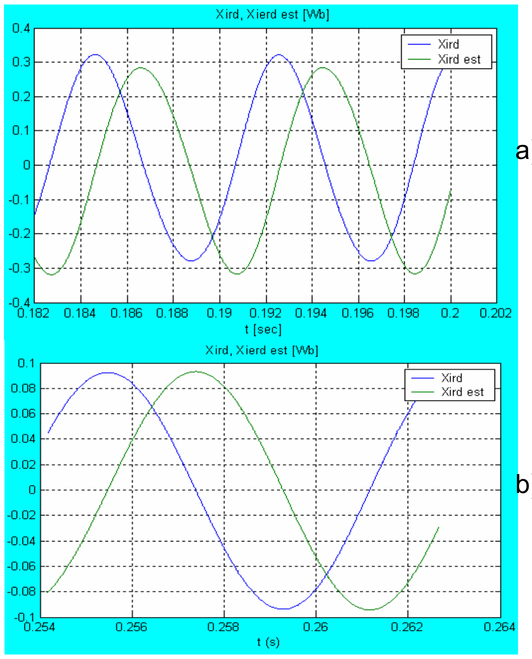

Figure 5: The results of simulation a) for Luenberger observer; b) for Gopinath observer

4. CONCLUSIONS

Both observers are stable, because the position of poles is making as stability function. Though, the Gopinath observer presented high performances when the coefficient of gate are calculated on bases of poles positions in negative complex plane. When the computation of flux is strong whit parameters variations, the importance of computation parameters decrease.

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