SENSORLESS SPEED CONTROL SYSTEMS BASED ON ADAPTIVE OBSERVERS LUENBERGER AND GOPINATH

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Abstract – **This paper develops a high dynamic and robust sensorless control system for drives based on adaptive observer, Luenberger and Gopinath observer, and also comparision between them. The instantaneous speed is accurately estimated by an extended Luenberger and Gopinath observer. Extensive simulation results with the proposed control structure, applied to a asynchronous motor drive, prove high-dynamic performances in wide speed range.**

Keywords**:** *Induction motor drives, sensorless, adaptive observer, speed control.*

1. INTRODUCTION

The sensorless control is an important goal in industrial applications to obtain a good performance per price indices [1]. 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.
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.
Generally, using the induction motor state equations, the flux and speed can be calculated from the stator voltage and current values [2]. 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 andevaluate 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. THE MACHINE AND 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. It is particularly at lower speed that parameter errors have significant influence on the steady-state and dynamic performance of the drive system.
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. The machine equations

A rotating coordinate system is chosen ta estabilish voltage equations of induction motor. This coordinate system rotates at an angular stator velocity ω_k, where the value of ω_k is left unspecified to be as general as possible. When a specific solution of the system equations is sought, the coordinate system must be defined first.
The stator voltage equation in the general k-coordinate system is :

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

In the rotor, ω is the angular mechanical velocity of the rotor, and hence the rotor voltage equation is:

$$0 = r_r \boldsymbol{i}_r + \frac{d\boldsymbol{\psi}_r}{d\tau} + j(\omega_k - \omega)\boldsymbol{\psi}_r \tag{2}$$

Equation (1) and (2) represent the electromagnetic subsystem of the machine as a second order dynamic system by two state equation, however, in terms of four state variables: $\boldsymbol{i}_s, \boldsymbol{i}_r, \boldsymbol{\psi}_s, \boldsymbol{\psi}_r$.

The equation of the mechanical subsystem is :

$$\tau_m \frac{d\boldsymbol{\omega}}{d\tau} = T_e - T_L \qquad (3)$$

where τ_m is the mechanical time constant, T_e is the electromagnetic torque and T_L is the load torque. T_e is computed from the z-component of the vector product of two stare variables:

$$T_e = \boldsymbol{\psi}_s \times \boldsymbol{i}_s \big|_z = \psi_{s\alpha} i_\beta - \psi_{s\beta} i_\alpha \qquad (4)$$

where $\boldsymbol{\psi}_s = \psi_{s\alpha} + j\psi_{s\beta}$ and $\boldsymbol{i}_s = i_\alpha + j i_\beta$ are the selected state variables.

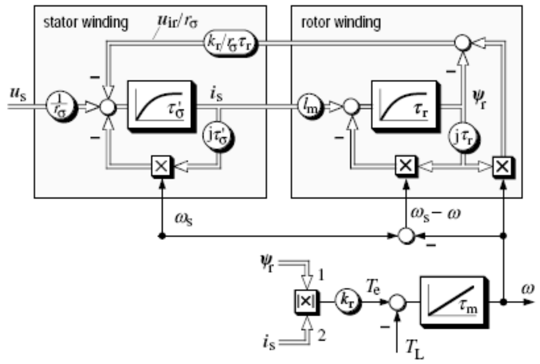


Figure 1: Induction motor signal; state variables: rotor flux vector, stator current vector; synchronous coordinates representation

2.2. The Luenberger observer

The Luenberger observer can be constructed from the stator voltage motor equations (1), the stationary coordinate system is chosen, for that: $\omega_k = 0$,

$$\tau'_\sigma \frac{d\boldsymbol{i}_s}{d\tau} + \boldsymbol{i}_s = \frac{k_r}{r_\sigma \tau_r}(1 - j\omega\tau_r)\boldsymbol{\psi}_r + \frac{1}{r_\sigma}\boldsymbol{u}_s \qquad (5a)$$

$$\tau_r \frac{d\boldsymbol{\psi}_r}{d\tau} + \boldsymbol{\psi}_r = j\omega\tau_r \boldsymbol{\psi}_r + l_m \boldsymbol{i}_s \qquad (5b)$$

These equations represent the machine model and they are visualized in the upper position of Figure 2.

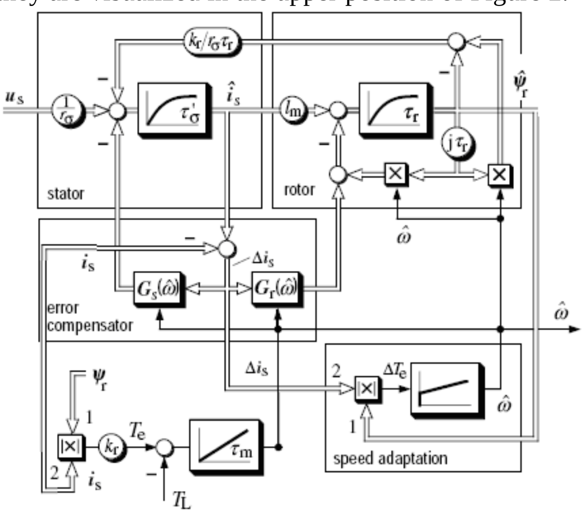


Figure 2: Full order nonlinear Luenberger observer

The model output is estimated angular mechanical speed $\hat{\omega}$. 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 (5):

$$\tau'_\sigma \frac{d\hat{\boldsymbol{i}}_s}{d\tau} + \hat{\boldsymbol{i}}_s = \frac{k_r}{r_\sigma \tau_r}(1 - j\omega\tau_r)\hat{\boldsymbol{\psi}}_r + \frac{1}{r_\sigma}\boldsymbol{u}_s - \boldsymbol{G}(\hat{\omega})\Delta\boldsymbol{i}_s \qquad (6)$$

$$\tau_r \frac{d\hat{\boldsymbol{\psi}}_r}{d\tau} + \hat{\boldsymbol{\psi}}_r = j\omega\tau_r \boldsymbol{\psi}_r + l_h \hat{\boldsymbol{i}}_s - \boldsymbol{G}(\hat{\omega})\Delta\boldsymbol{i}_s \qquad (7)$$

Kubota and al. [3] select the complex gain factors ***G***s ($\hat{\omega}$) and ***G***r ($\hat{\omega}$) such that the two complex eigenvalues of the observer $\lambda_{1,2obs} = \lambda_{1,2mach}$, where $\lambda_{1,2mach}$ are the machine eigenvalues, and k>1 is a real constant. Given the nonlinearity of the system, the resulting complex gains ***G***s ($\hat{\omega}$) and ***G***r ($\hat{\omega}$) in figure 2 depend on the estimated angular mechanical speed $\hat{\omega}$, [3].

2.3. The Gopinath 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. The observer was constructed as a combination between a flux simulator and a feedback of correction of a predictive estimated error, Figure 3.

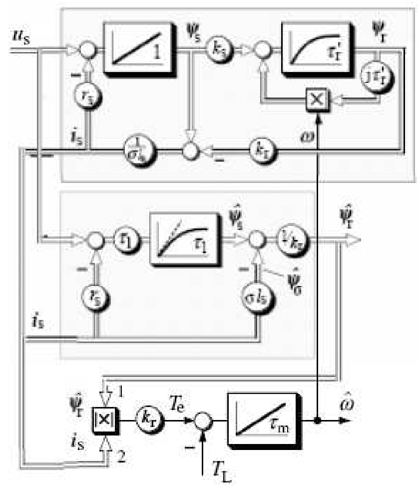


Figure 3: The Gopinath observer based on induction motor state model

$$\frac{d\hat{\boldsymbol{\psi}}_r}{d\tau} = (a_{22} - g a_{12})\hat{\boldsymbol{\psi}}_r + + (a_{21} - g a_{11})\boldsymbol{i}_s - g\boldsymbol{u}_s + g\frac{d\boldsymbol{i}_s}{d\tau}, \qquad (8)$$

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):

$$g_a = \left[\frac{r_r/l_r\,\alpha + \omega\beta}{(r_r/l_r)^2 + \omega^2} - 1\right]\frac{\sigma l_s l_r}{l_m} \qquad (9a)$$

$$g_b = \frac{\omega\alpha - r_r/l_r\,\beta}{(r_r/l_r)^2 + \omega^2}\cdot\frac{\sigma l_s l_r}{l_m} \qquad (9b)$$

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

The stator current estimated is given by follow equation :

$$\frac{d\hat{\boldsymbol{i}}_s}{d\tau} = \frac{1}{\sigma l_s}\cdot\left[\boldsymbol{u}_s - r_s^{'}\boldsymbol{i}_s + \left(\frac{r_r}{l_r} - j\omega\right)\hat{\boldsymbol{\psi}}_r - \left(\frac{r_r}{l_r} - j\omega\right)\sigma l_s \hat{\boldsymbol{i}}_s\right] \qquad (10)$$

3. SENSORLESS SPEED CONTROL SYSTEMS

3.1.Model reference adaptive system based on Luenberger observer

To complete a sensorless control system, a Luenberger estimator for the system is established. Figure 4 shows the signal flow graph. The rotor flux linkage vector is estimated using equation of machine. The angular mechanical velocity of the rotor is calculate by general equation (3). The rotor field angle is derived with reference from the components of the estimated rotor flux linkage vector.

The signal $\hat{\omega}$ is required to adapt the rotor structure of the observer to the mechanical speed of machine. The phase angle of $\hat{\boldsymbol{\psi}}_r$, that defines the estimated rotor field angle, then approximates the true field angle that prevails in the machine. The correct speed estimate is reached when the phase angle of the current error $\Delta\boldsymbol{i}_s$, and hence the torque error ΔT_e reduce to zero. The control scheme is reported to operate at minimum speed 50 rpm [3].

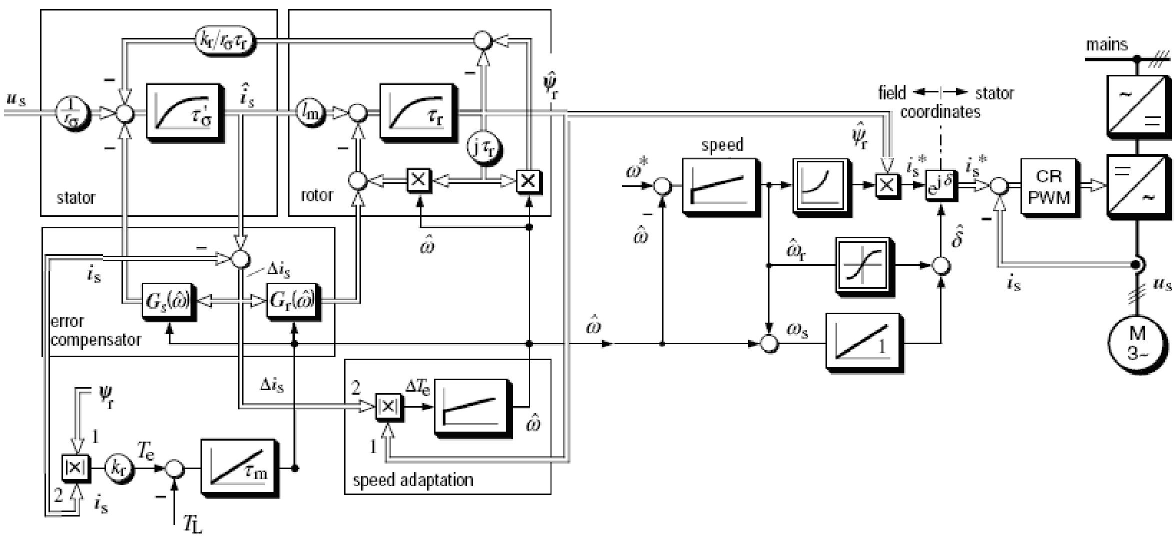


Figure 4: Speed and current control system for Luenberger observer

3.2.Model reference adaptive system based on Gopinarh observer

Figure 5 shows the signal flow graph of Gopinath observer and its sensorless control system who is like system based on Luenberger observer as construction. The otherness is who mechanical speed is computation; in the first case as vector product between the error vector, computed from the model current and the measured machine current, and the estimated rotor field (in fact, the term $\hat{\boldsymbol{\psi}}_r \times \Delta\boldsymbol{i}_s$ who represents the torque error ΔT_e).

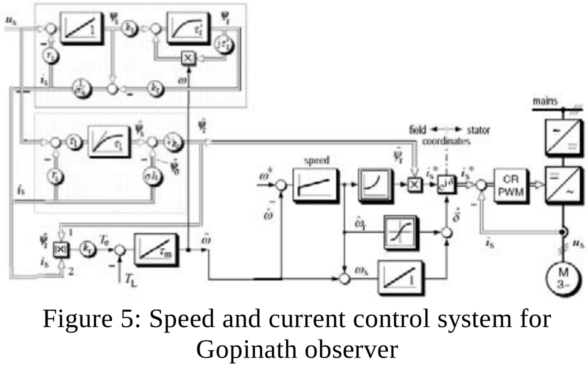


Figure 5: Speed and current control system for Gopinath observer

The second case is (Gopinath case) vector product between the stator current estimated and the rotor field estimated.

3.3. The models of sensorless speed control system with Luenberger and Gopinath observers

Figure 6 presentes the scheme of control speed starting from schemes 4 and 5. The testing is done with a Matlab/Simulink model which was used to evaluate the both speed evolution, real and estimate speed.

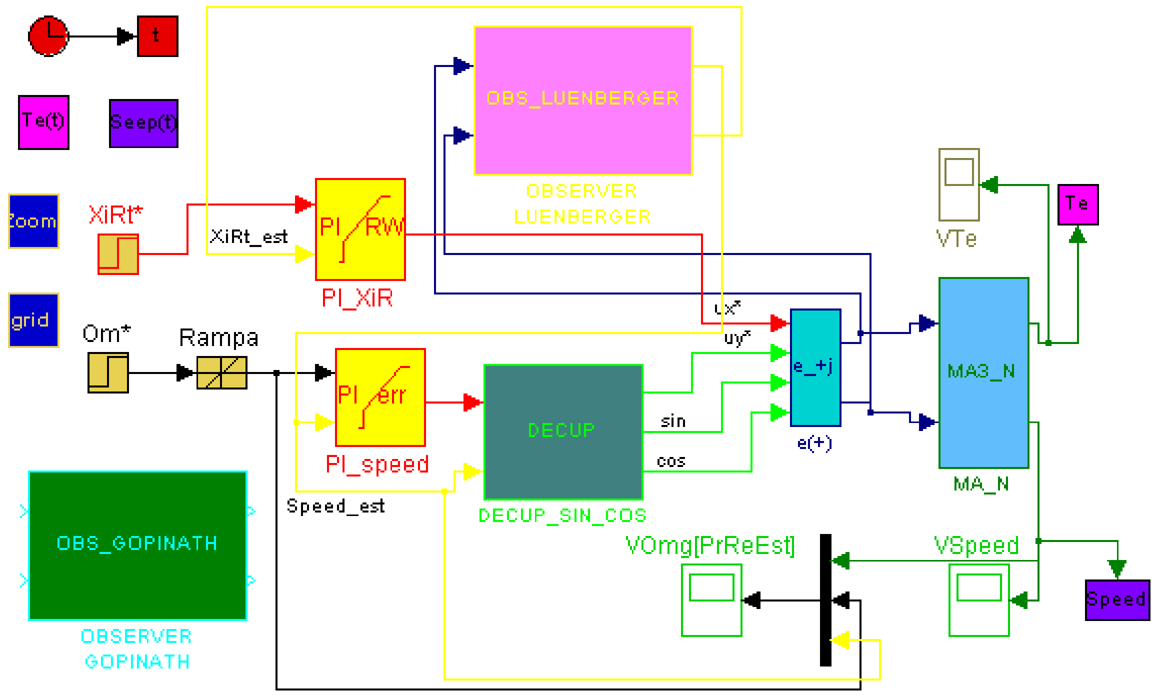


Figure 6: The Simulink model of speed and current control system without inverter

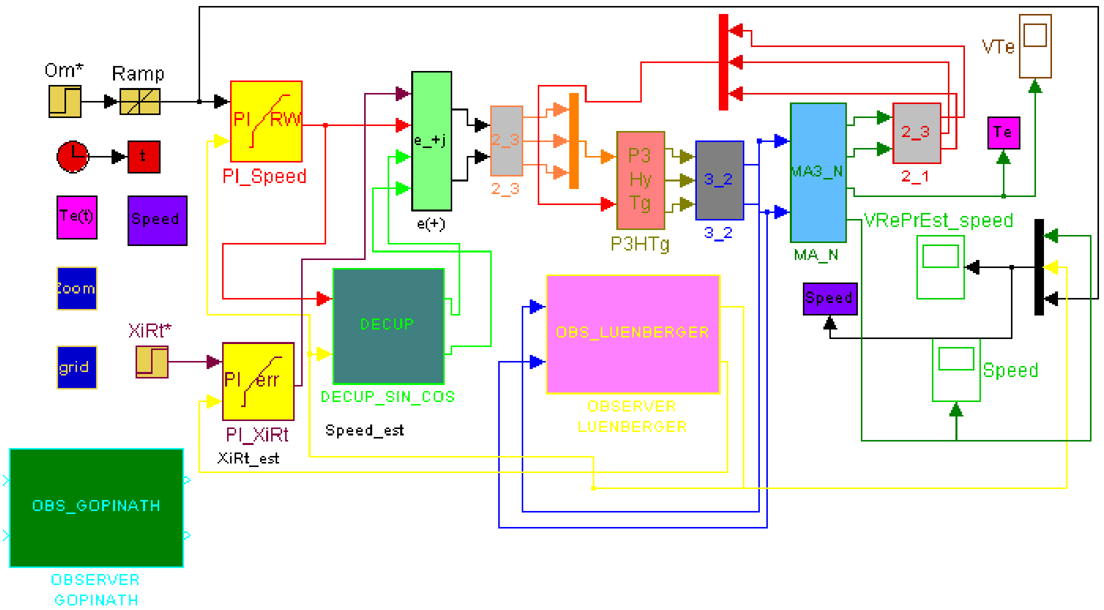


Figure 7: The Simulink model of speed and current control system with inverter

Figure 7 is similarly with 6, but it is contain the inverter of voltage. Both of schemes contain the following blocks:

- PI – speed controller with eschewal saturation by technical anti wind-up

(PI_Speed) and flux controller with error annulment (PI_XiRt)

- MA_N - asynchronous motor without saturation
- OBS_Luenberger and OBS_Gopinath full order nonlinear observers for estimate the instantaneous speed and flux
- P3HTg – voltage inverter with prescription currents

The load torque T_L is considered to be practical constant. The electromagnetic torque of the induction motor is calculated in every sampled period based on the stator voltages and currents.

4. SIMULATION RESULTS

The theoretical ideas are well supported by digital simulations. The drive system performances are tested at step speed references at low speed 10 rad/s and at high speed of 100 rad/s (Figure8)for the Luenberger observer and (Figure 9) for Gopinath observer, both of them for schemes without inverter.

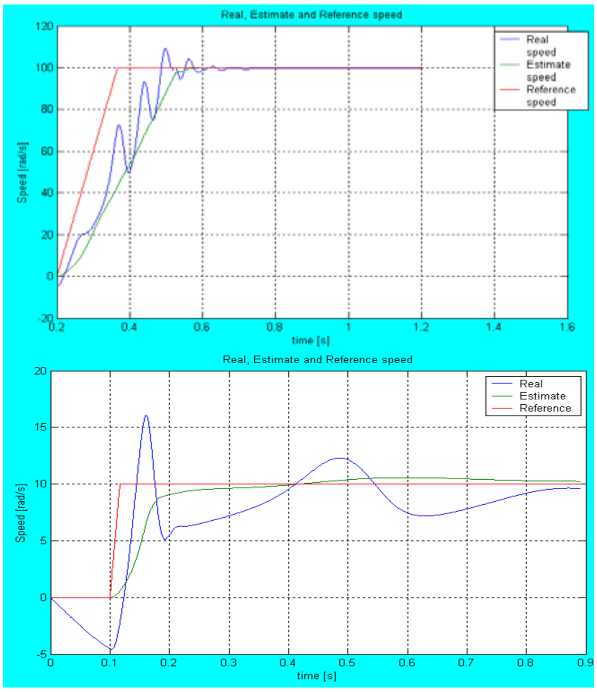
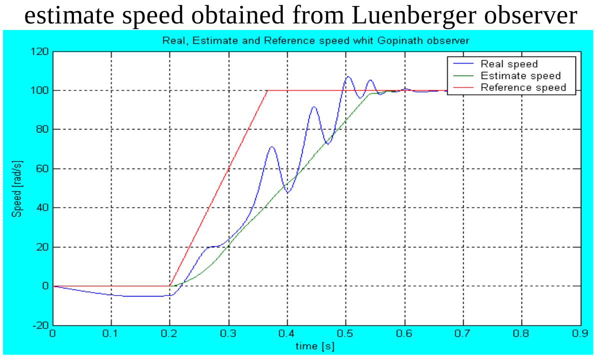


Figure 8: The waveforms of the reference, real and estimate speed obtained from Luenberger observer



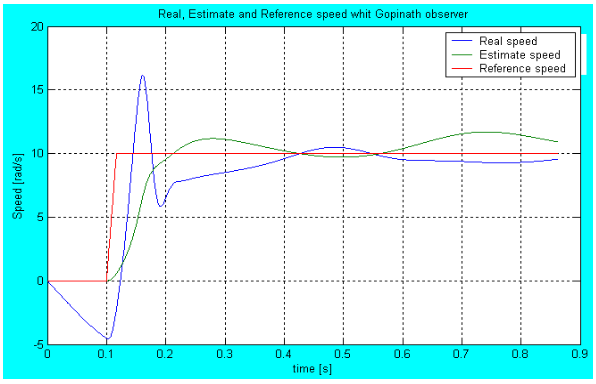


Figure 9: The waveforms of the reference, real and estimate speed obtained from Gopinath observer

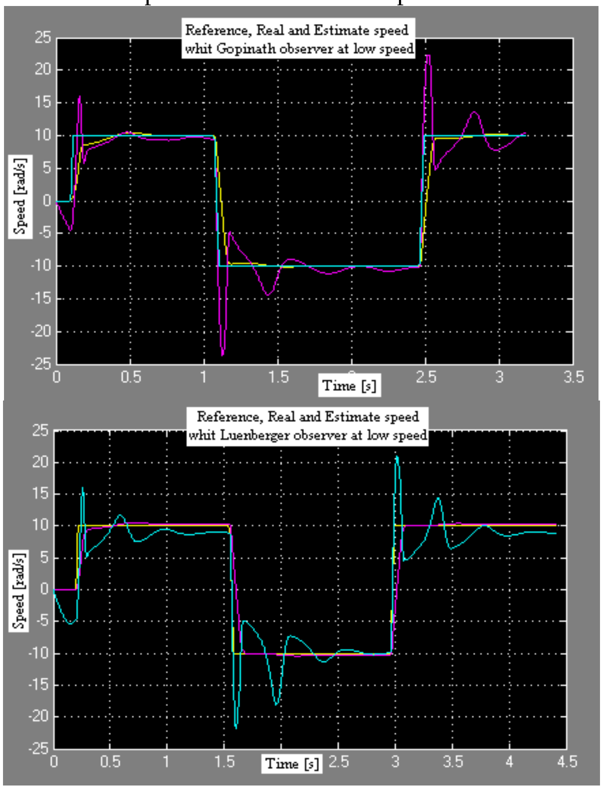
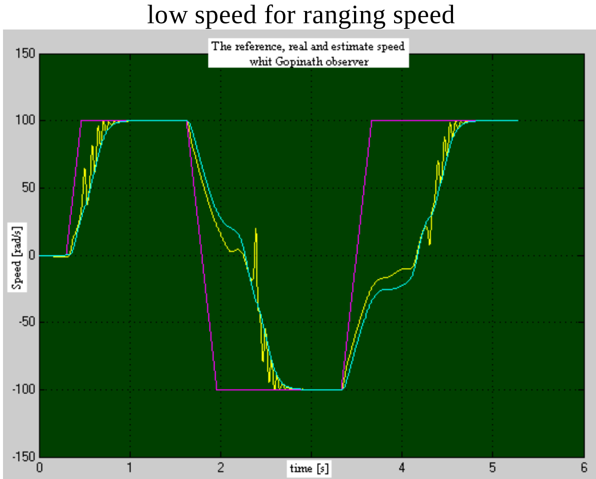


Figure 10: The reference, real and estimate speed obtained from Gopinath and Luenberger observer at low speed for ranging speed



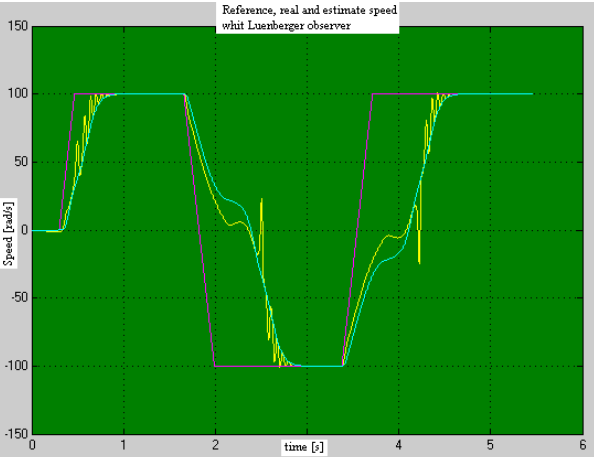


Figure 11: The reference, real and estimate speed obtained from Gopinath and Luenberger observer at high speed for ranging speed

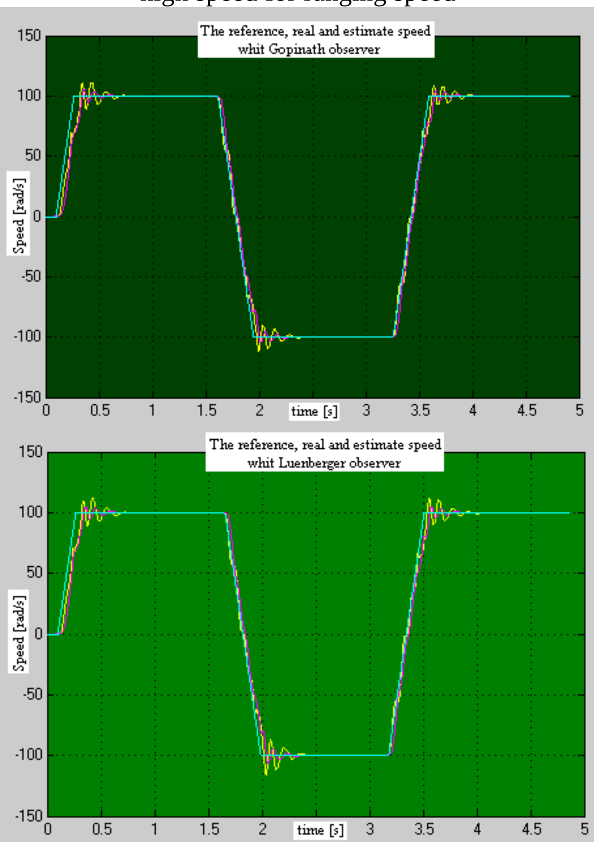


Figure 12: The reference, real and estimate speed obtained from Gopinath, Luenberger observer and Inverter with the ranging speed

5. CONCLUSIONS

Both observers presented in the paper can estimate the speed in an electrical drive system. The values of the speed estimated on-line can be used by the control of the electrical drive systems in low speed range. For both observers the drive system must be endowed an acquisition system for the electrical variables, which helps to calculate the electromagnetic torque of the electrical motor, who is based on the generally equation of motion the same in every drive system for any kind of electrical motor. The estimation performances of both observers are comparable. For the observers presented in this paper the drive's parameters were considered constant.

The main features are the following:

- The instantaneous speed is estimated by an extended Luenberger and Gopinath observers.
- To obtain a high-dynamic current sensorless control, a current to voltage feedforward decoupling and a dynamic correction to reduce the electric time constant are applied. Moreover, an accurate dynamic limitation of the real electromagnetic torque is obtained.
- Extensive simulation results using a asynchronous motor drive prove high-dynamic performances and robustness of the proposed control structure in dSPACE environment.

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