# Speed Sensorless Field Oriented Control of an Induction Motor at zero speed with identification of inverter parameters

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# Speed Sensorless Field Oriented Control of an Induction Motor at zero speed with identification of inverter model parameters

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*Abstract*— **Using adaptive Lyapunov design a new approach for the design of an observer for speed sensorless control is developed. The resulting scheme leads to a nonlinear full order observer for the motor states and for the motor and inverter parameters including the rotor speed. Assuming motor parameters known the design achieves stability with guaranteed region of attraction. Experiments demonstrate high dynamic performance even at zero rotor speed based only on the slip frequency caused by the load torque.**

## I. Introduction

Inverter-fed induction motors are the far most preferred solution for variable motor drives. The induction motor has all the well known benefits, it can operate brushless, the mechanical construction is simple, the price is low compared to other motor types and it is very robust. From a motor control point of view the induction motor is really not a trivial control object, indeed it has been a preferred object for new control disciplines and identification methods. The motor has all the features which violates all the assumptions in the classical control theory, because it is nonlinear and have time varying parameters due to temperature variations and change in magnetic saturation level. Nonlinear control problems can often be solved if full state information is available, in the induction motor case the rotor states are immeasurable and often the speed of the rotor is too costly to monitor.

The performance of a speed sensorless field oriented controlled induction motor is generally poor at very low speed. This is caused by offset and drift in the acquired feedback signals, nonlinear behavior of the switching converter and the increased sensitivity against model parameter mismatch.

In order to obtain robust control a good on-line dynamic models of the motor and the inverter are needed [2], this recalls for an observer capable to estimate both the states and the parameters in the model. Many schemes for the estimation of states variables and/or model parameters have been proposed in recent years. Some of these methods are based on observer theory, reduced or full order, open loop or closed loop, another category is methods based on optimal observer design by applying Kalman Filter theory see [1],[9]. These two approaches are used when only the state variables need to be estimated, when the parameters wanted to be estimated Extended Kalman Filter theory is used see [10]. Extended Kalman Filters in its original implementation [4] is known to give biased estimates when the dynamic system is corrupted by noise, see [6] and in the literature no convincing results have been present, in the authors opinion.

A novel nonlinear discipline called backstepping [3],[5] has in [8] and [7] been used for both estimating state variables and parameters including the rotor speed. These ideas are in this paper background for the Lyapunov design of an full order observer for the motor states and motor and inverter parameters including the rotor speed. A proof for stability of the observer is presented and the performance of a Rotor Field Oriented Controller using the estimates is shown both by simulation and by experiments on a real motor.

## II. Inverter and motor model

To avoid short-circuits of the bridge legs, a delay time $T_d$ must be introduced to the inverter control. This means that the phase voltage to the motor is delayed $T_d$ when the reference voltage goes high. When the reference voltage goes low the devices have their turnoff delayed $T_{st}$ owing to the storage effect of the minority carriers. The normalized voltage error in each phase is then given by

$$\Delta u = (T_d - T_{st})/T_{switch} sign(i)$$

Because $T_{st}$ change significantly with current level the following model is used

$$f(i) = \begin{cases} +U_{inv} & \text{for } i \geq b_{inv} \\ i/b_{inv}U_{inv} & \text{for -}b_{inv} < i < b_{inv} \\ -U_{inv} & \text{for } i \leq -b_{inv} \end{cases}$$

giving the phase voltages

$$\begin{aligned} u_{sA} =& \quad u_{sA,ref} - f(i_{sA}) \\ u_{sB} =& \quad u_{sB,ref} - f(i_{sB}) \\ u_{sC} =& \quad u_{sC,ref} - f(i_{sC}) \end{aligned}$$

The parameters $(U_{inv}, b_{inv})$ are found by an experiment using the setup in figure 1. Setting $i_{sq,ref} = 0$ and $i_{sd,ref}$ equal to a sine wave with a very low frequency, the result in figure 2 is obtained. Curve fitting gives $(U_{inv}, b_{inv}) = (7.5, 0.08)$. and $R_s = 6.5$. and the result is also shown in figure 2.

The dynamics for the motor is given by

$$\begin{aligned} u_s =& \quad R_s i_s + \dot{\psi}_s \\ 0 =& \quad R_r i_r + \dot{\psi}_r - j\omega_r \psi_r \end{aligned}$$

where $\omega_r = Z_p \omega_{mech}$ is the rotor speed $\omega_{mech}$ times the number of pole pair $Z_p$ and the flux linkages for the stator and rotor

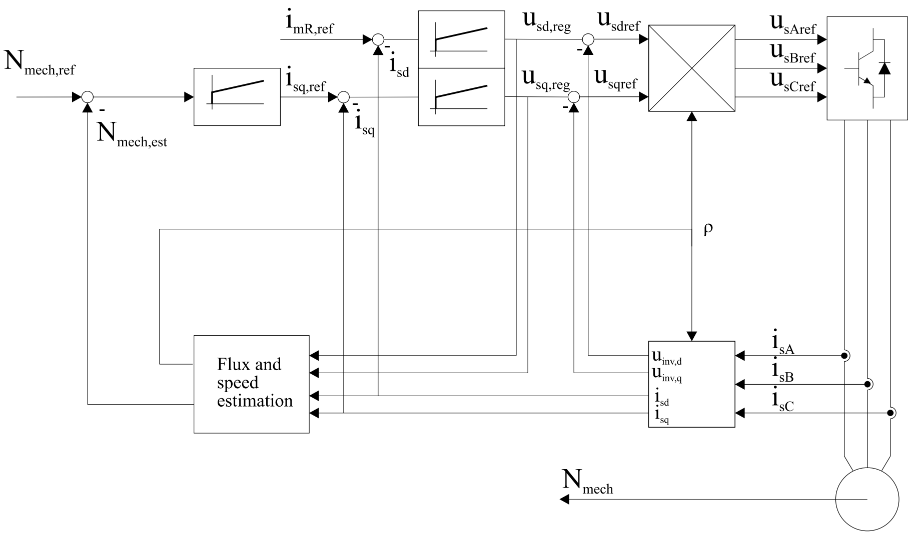



Fig. 1 – *Field Oriented Control*

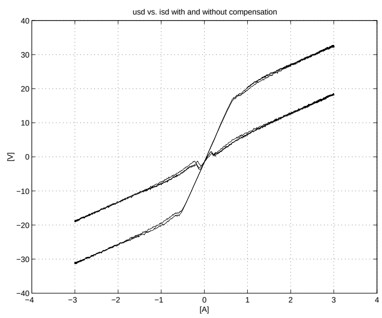



Fig. 2 – *Experiment for determination of inverter parameters* $(U_{inv}, b_{inv})$ *and stator resistance* $R_s$*.*

are

$$\begin{aligned}\psi_s &= L_s i_s + L_m i_r\\ \psi_r &= L_m i_s + L_r i_r\end{aligned}$$

Using $\psi_\sigma = \sigma L_s i_s$ and $\psi_s$ as state variables the following dynamical equations for the induction motor are obtained

$$\begin{aligned}\tfrac{d\psi_\sigma}{dt} &= \quad u_s - (\tfrac{R_s}{\sigma L_s} + \tfrac{R_r}{\sigma L_r} - j\omega_r)\psi_\sigma + (\tfrac{R_r}{L_r} - j\omega_r)\psi_s\\ \tfrac{d\psi_s}{dt} &= \quad u_s - R_s i_s\end{aligned}$$

The mechanical equation is

$$J\frac{d\omega_{mech}}{dt} = m_e - m_L$$

where $J$ is the moment of inertia, $m_L$ is the load torque and

$$m_e = -\frac{3}{2} Z_p \,\mathrm{Im}(\psi_s^* i_s)$$

is the developed electromagnetic torque.

## III. Lyapunov design of the observer

Assuming the following observer structure

$$\begin{aligned}\tfrac{d\hat{\psi}_\sigma}{dt} &= \quad u_s - (\tfrac{R_s}{\sigma L_s} + \tfrac{R_r}{\sigma L_r} - j\hat{\omega}_r)\sigma L_s i_s + (\tfrac{R_r}{L_r} - j\hat{\omega}_r)\hat{\psi}_s + v_1\\ \tfrac{d\hat{\psi}_s}{dt} &= \quad u_s - R_s i_s + v_2\end{aligned}$$

the "control inputs" $v_1$ and $v_2$ have to be designed by the Lyapunov method.

The dynamical equations for the prediction errors $\tilde{\psi}_\sigma = \hat{\psi}_\sigma - \psi_\sigma$, $\tilde{\psi}_s = \hat{\psi}_s - \psi_s$ and $\tilde{\omega}_r = \hat{\omega}_r - \omega_r$ are then given by

$$\begin{aligned}\tfrac{d\tilde{\psi}_\sigma}{dt} &= \quad (\tfrac{R_r}{L_r} - j\hat{\omega}_r)\tilde{\psi}_s - j\tilde{\omega}_r(\psi_s - \sigma L_s i_s) + v_1\\ \tfrac{d\tilde{\psi}_s}{dt} &= \quad v_2\end{aligned} \tag{1}$$

The derivative of the Lyapunov function candidate

$$V = \frac{1}{2}|\tilde{\psi}_\sigma|^2 + \frac{1}{2}|\tilde{\psi}|_s^2 + \frac{1}{2\gamma}\tilde{\omega}_r^2$$

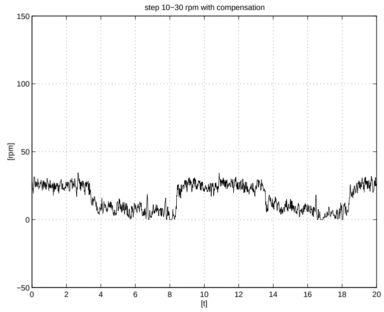
along the solution of (1) gives

$$\begin{aligned}\dot{V} = \quad & \mathrm{real}\{\tilde{\psi}_\sigma^*((\tfrac{R_r}{L_r} - j\hat{\omega}_r)\tilde{\psi}_s + v_1)\\ & + \mathrm{real}\{\tilde{\psi}_s^* v_2\}\\ & + \tilde{\omega}_r\{\tfrac{1}{\gamma}\tfrac{d\tilde{\omega}_r}{dt} - \mathrm{real}\, j\tilde{\psi}_\sigma^*(\psi_s - \sigma L_s i_s)\}\end{aligned}$$

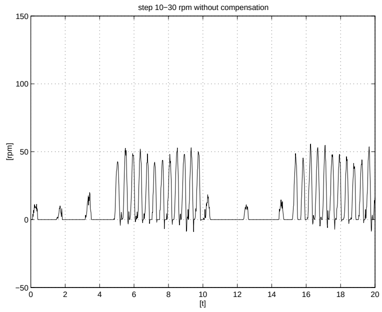
For

$$\begin{aligned}v_1 &= \quad -c_1\tilde{\psi}_\sigma - (\tfrac{R_r}{L_r} - j\hat{\omega}_r)\tilde{\psi}_s\\ v_2 &= \quad -c_2\tilde{\psi}_s\\ \tfrac{d\tilde{\omega}_r}{dt} &= \quad \gamma\,\mathrm{real}\{j\tilde{\psi}_\sigma^*(\psi_s - \sigma L_s i_s)\}\end{aligned}$$

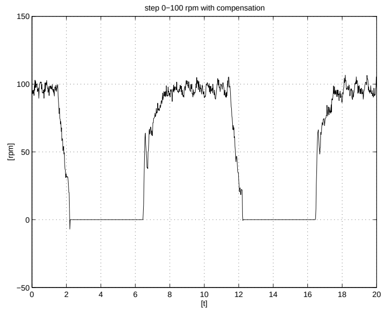
we obtain $\dot{V} = -c_1|\tilde{\psi}_\sigma|^2 - c_2|\tilde{\psi}_s|^2$. For $c_1 > 0$ and $c_2 > 0$ $V$ is negative definite leading to convergence to the subset $\tilde{i}_s = 0$ and $\tilde{\psi}_s = 0$. In this subset the solution to equation (1)



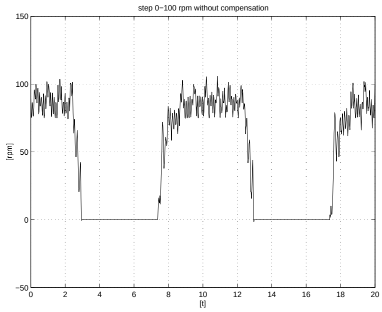

a) *Rotor speed for a* $10-30rpm$ *reference step (compensation)*



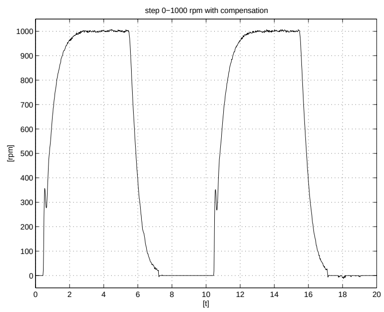

b) *Rotor speed for a* $10-30rpm$ *reference step (without compensation)*



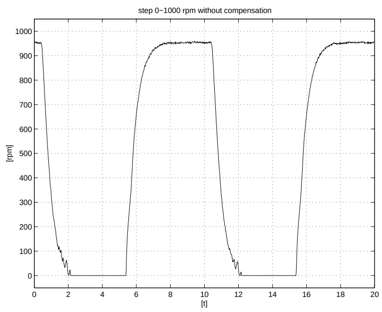

c) *Rotor speed for a* $0-100rpm$ *reference step (compensation)*




d) *Rotor speed for a* $0-100rpm$ *reference step (without compensation)*




e) *Rotor speed for a* $0-1000rpm$ *reference step (compensation)*




f) *Rotor speed for a* $0-1000rpm$ *reference step (without compensation)*

Fig. 3 – Rotor speed step response

gives $-j\tilde{\omega}_r(\psi_s-\sigma L_s i_s)=0$ leading to $\tilde{\omega}_r(\psi_s-\sigma L_s i_s)=\tilde{\omega}_r\psi_r\frac{L_m}{L_r}=0$. For $\psi_r\neq 0$ we then have $\tilde{\omega}_r=0$.

With the control shown in figure 1 a correct estimate of the rotor flux angle $\rho$ gives the rotor flux amplitude $L_m i_{mR,ref}$. An approximation of the stator flux $\psi_s$ is then obtained by

$$\psi_s=\frac{L_m^2}{L_r}i_{mR,ref}e^{j\rho}+\sigma L_s i_s$$

The Lyapunov designed observer then becomes

$$\begin{aligned}
\tilde{\psi}_\sigma &= \hat{\psi}_\sigma-\sigma L_s\imath_s\\
\tilde{\psi}_s &= \hat{\psi}_s-|\tfrac{L_m^2}{L_r}i_{mR,ref}+\sigma L_s i_s|e^{j\arg(\hat{\psi}_s)}\\
\hat{\psi}_r &= \tfrac{L_m}{L_r}(\hat{\psi}_s-\hat{\psi}_\sigma)\\
\rho &= \arg\hat{\psi}_r\\
\tfrac{d\hat{\psi}_\sigma}{dt} &= u_{s,reg}-(\tfrac{R_s}{\sigma L_s}+\tfrac{R_r}{\sigma L_r}-j\hat{\omega}_r)\sigma L_s\imath_s\\
&\quad+(\tfrac{R_r}{L_r}-j\hat{\omega}_r)(\hat{\psi}_s-\tilde{\psi}_s)-c_1\tilde{\psi}_\sigma\\
\tfrac{d\hat{\psi}_s}{dt} &= u_{s,reg}-R_s\imath_s-c_2\tilde{\psi}_s\\
\tfrac{d\hat{\omega}_r}{dt} &= \gamma\tfrac{L_r}{L_m}\,\mathrm{real}\{j\tilde{\psi}_\sigma^*\hat{\psi}_r\}
\end{aligned}$$

## IV. EXPERIMENTS

The nominal motor parameters are

| | $R_s$ | $R_r$ | $L_m$ | $L_s - L_m$ | $L_r - L_m$ |
|---|---|---|---|---|---|
| Nom. | 6.50 | 6.48 | 0.535 | 0.0134 | 0.0190 |

The parameters in the Adaptive Nonlinear estimator and the Field Oriented Controller are based on nominal parameters for the motor.

The experiments figure 3.a-f show measured rotor speed $N_{mech}$ but the control is as shown in figure 1 based on the estimated rotor speed $N_{mech,est}$.

Figure 3.a and b show step responses from $10-30rpm$ with and without compensation for the inverter nonlinearity. The lower speed value $10rpm$ is chosen to show the response at very low speed different from zero. Without compensation it is not possible to control this very low speed.

Figure 3.c and d show step responses from $0-100rpm$ with and without compensation for the inverter nonlinearity. The improvement obtained by the compensation is very good, but control without compensation is possible.

Figure 3.e and f show step responses from $0-1000rpm$ with and without compensation for the inverter nonlinearity. The improvement obtained by the compensation is as seen a better absolute estimated value.

In [1] many methods for speed sensorless control are described and for well known motor parameters all methods give good results. As the influence of these parameters dominates the estimation at lower speed, the steady state operation tends to be poor in the low speed range. A direct comparison of the different methods with respect to parameter variations is not possible due to the different simulation strategies in the papers referred, but it the method developed in this paper seems superior to them.

## V. CONCLUSION

A new adaptive rotor speed and flux observer based on Lyapunov design has been developed and used in a traditional Rotor Field Oriented Controller. The new method shows a systematic way of developing the field observer and the estimate of the rotor speed together with a Lyapunov function for proving stability.

Physical limits make speed sensorless control at zero stator frequency impossible using the fundamental field representation of for induction motor modelling. For a given load torque the stator frequency equals the slip frequency at zero rotor speed, which means that the rotor speed is observable for an inverter and motor with well known parameters. The inverter parameter estimation scheme developed in this paper gives a more accurate model and combined with the robust nonlinear observer design speed sensorless field oriented control at zero speed as well as at nominal speed is obtained.

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