Sensorless control methods for variable speed drives with induction motor used in traction application

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Abstract

In this paper there are proposed several methods for sensorless control of the rotor field oriented induction motor, such as: speed estimators, rotor slots ripple speed estimators, Model Reference Adaptive Systems, Luenberger speed observer. It is described the mathematical model for the rotor field oriented system with induction motor, which uses the estimated speed and rotor flux, based on a Model Reference Adaptive System or Luenberger speed observer, as well as the real-time approach. The estimated speed is used for the speed feedback control. The stability and the convergence of these estimators are improved on the basis of hyperstability theory for the non-linear systems. The proposed MRAS speed estimator or Luenberger estimator can be applied for traction application because the integration of sensed variables was avoided, increasing in this way the system stability. Rotor flux integration in the reference model is avoided, using the counter-EMF vector. Because of this, the system can operate at very low speed and high speed also, even if the rotor resistance is quite wrong or in overload operation. The real-time controller and estimator are implemented with a dual TMS320C44 floating-point digital signal processor. The validity of the proposed method was verified by simulation, the sensorless control being also tested on the propulsion system simulator used for the development of Korean High-Speed Railway Train. The simulation and experimental tests are performed also, to compare different sensorless methods.
1 Introduction

The adjustable speed ac drives and especially the vector control drives are widely used due to the development of power electronics and modern control technology. The vector control represents a high performance control of the induction motor. In general it needs a speed sensor for obtaining the speed information (tacho-generator, pulse-encoder) and sensing coils (or Hall sensors) for obtaining the flux information. The utilization of speed and flux sensors is expensive, sensitive at noise and reduces the inherent robustness of the induction motor. That is why, the research in the domain of sensorless-control represent an active goal of many researchers for eliminate these two kind of transducers. For the speed sensorless vector system there are proposed several methods, such as:

- by estimating the slip frequency using the harmonic voltage due to the rotor slot in the motor phase voltage [1],
- by estimating the slip frequency from voltage, current and motor parameters [2],
- by calculating the rotor speed so that the main flux axis should be coincided with the calculated one in a vector control system [3],
- using the third harmonic component of the air gap flux [4-5],
- using Extended Kalman Filter [6] or neural networks [7],
- using different kinds of MRAS [8].

The proposed methods for estimate the induction motor speed, are using the error between voltage model and current model of the induction machine. These methods introduce the least errors in comparison with other methods because of the adaptive control.

2 The model for sensorless control without rotor flux derivation

The control of the induction machine is a vectorial one and that is why it is necessary to use the space phasor model. So, the well-known [p.u.] state equations (voltages, fluxes and torque equations) of the induction motor, in the general reference frame $d-q$ which is rotating with synchronous speed $\omega_n$, are:

\[
\begin{align*}
\frac{\text{d}u_s}{\text{d}t} &= r_s i_s + \frac{1}{\omega_n} \frac{\text{d}\psi_s}{\text{d}t} + j v_s \psi_s; \\
0 &= r_r i_r + \frac{1}{\omega_n} \frac{\text{d}\psi_r}{\text{d}t} + j(v_s - v)\psi_r \\
\psi_s &= x_{s} i_s + x_m i_r; \\
\psi_r &= x_m i_s + x_r i_r \\
t_e &= \Im[\psi_r \cdot i_s] = \Im[\psi_r \cdot i_r] \\
\frac{\text{d}v}{\text{d}t} &= t_e - t_r; \\
T_m &= \frac{J \omega_n}{p T_n}.
\end{align*}
\]

Where: $\omega_o$ is the rated synchronous speed, $T_n$ is the rated torque, $J$ is the total inertia and $p$ is number of pole pairs.

Because the measured quantities are the voltages and the currents in the stationary reference frame $\alpha-\beta$, the state equations of the induction machine have to be written in this frame and then, one can obtain the voltage model and the current model. These two models will be used for speed estimation. The flux derivation can lead sometimes to the instability of vector control system, especially at low-speed...
operation and at overload conditions. So, the general system (1) can be rearranged in such a manner, to evidence the counter-EMF vector, avoiding the rotor flux derivation:

\[
\begin{align*}
\dot{u}_x &= r_i i_x + e_m + \frac{1}{\omega_s} \sigma x_x \frac{di_x}{dt} + j \nu_1 \left(x_m i_m^* + \alpha x_x i_x \right) \\
-u_x &= 0 = r_x \left(i_m - i_x \right) + \frac{1}{\omega_s} \frac{di_m}{dt} + j \nu_3 \left(\nu - \nu \right) i_m \\
\psi_x &= x_m i_m^* , \quad \dot{i}_m = i_x + \frac{x_m}{x_x} \dot{i}_x \\
e_m &= \frac{1}{\omega_s} \frac{x_x}{x_x} \frac{d\psi_x}{dt} = \frac{1}{\omega_s} \frac{x_x}{x_x} \frac{d\psi_x}{dt} \\
n_m &= \frac{1}{\omega_s} \frac{x_x}{x_x} \frac{d\psi_x}{dt} = \frac{1}{\omega_s} \frac{x_x}{x_x} \frac{d\psi_x}{dt}
\end{align*}
\]

Where: \( \sigma = 1 - \frac{x_m^2}{x_x x_x} \) is the total leakage coefficient of the induction machine and \( i_m \) is the magnetizing current that corresponds to the rotor flux.

From the model (2) of the induction machine, the voltage model written in the stator reference frame \( \alpha-\beta \), can be expressed as it follows:

\[
\begin{align*}
\begin{bmatrix} e_{m\alpha} \\ e_{m\beta} \end{bmatrix} &= \begin{bmatrix} u_{\alpha} \\ u_{\beta} \end{bmatrix} - \begin{bmatrix} r_x & 0 \\ 0 & r_x \end{bmatrix} \begin{bmatrix} i_{\alpha} \\ i_{\beta} \end{bmatrix} - \frac{1}{\omega_s} \frac{d}{dt} \begin{bmatrix} \alpha x_x & 0 \\ 0 & \alpha x_x \end{bmatrix} \begin{bmatrix} i_{\alpha} \\ i_{\beta} \end{bmatrix}
\end{align*}
\]

and the current model is:

\[
\begin{align*}
\begin{bmatrix} e_{m\alpha} \\ e_{m\beta} \end{bmatrix} &= \frac{1}{\omega_s} \frac{x_x}{x_x} \frac{d}{dt} \begin{bmatrix} i_{m\alpha} \\ i_{m\beta} \end{bmatrix}
\end{align*}
\]

Where:

\[
\begin{align*}
\frac{1}{\omega_s} \frac{d}{dt} \begin{bmatrix} i_{m\alpha} \\ i_{m\beta} \end{bmatrix} &= \begin{bmatrix} r_x & -\nu_x \\ \nu_x & -r_x \end{bmatrix} \begin{bmatrix} i_{m\alpha} \\ i_{m\beta} \end{bmatrix} + \begin{bmatrix} r_x & -\nu_x \\ \nu_x & -r_x \end{bmatrix} \begin{bmatrix} i_{\alpha} \\ i_{\beta} \end{bmatrix}
\end{align*}
\]

Taking into account that the voltage model (3) does not contain the rotor speed \( \nu \), this observer may be regarded as a reference model of the induction machine, and the current model (4) which contains the rotor speed may be regarded as an adjustable one. If it will be constituted an adaptive law so that, the output of the voltage model coincides with the output of the current model, one can estimate the rotor speed and the orthogonal components of the rotor flux space phasor.

In this case, according with the Popov hyperstability criterion, the error that has to be minimised (to be maintained near zero) is the following:

\[
\mathcal{E}' = \mathcal{E}_{m\alpha} \cdot \mathcal{E}_{m\beta} - \mathcal{E}_{m\beta} \cdot \mathcal{E}_{m\alpha}
\]

Because the reference model does not require integration, this system can achieve good performance at high speed as well as at low speed, even the stator resistance varies with the temperature or the value of rotor circuit time constant is quite wrong.

The schematic representation of the MRAS (Model Reference Adaptive
System), based on the above equations of the voltage and current models, is presented in figure 1.

\[ \text{Reference model of the induction machine Eqn (3)} \]
\[ \text{Adjustable system (parallel rotor speed estimation model of vector controlled induction machine) Eqn (4) & Eqn (5)} \]
\[ \text{Rotor speed identification algorithm} \]

Figure 1: The schematic representation of the MRAS.

2.1 Experimental system configuration

The control system used for performing traction tests, presented in figure 2 is an indirect-rotor field control of the induction machine.

Figure 2: The indirect-rotor field control of the induction machine with sensorless estimator.

From the baseline model of KHSRT, a downscaled model of a propulsion system is developed [9]. This simulator can be divided into two parts. One is the electrical part consisting of traction and electrical braking units and the other is a mechanical part simulating train characteristics and the mechanical brakes.

Figure 3 shows the electrical systems of the simulator. Electrical parts of the system consist of a main transformer, two traction units and four traction motors, two rheostat braking systems and an Eddy current brake system. The PWM inverter generates the three-phase VVVF source for two induction motors at a switching
frequency of 540Hz. The traction motors of the simulator are 3-phase squirrel cage asynchronous motors. The ratings for the induction motors are given in Table 1 in Appendix.

The propulsion system simulator of the high-speed railway train is controlled by a traction control unit. It consists of main controller board, I/O interface board and network interface board. The main controller board is based on a dual TMS320C44 floating-point digital signal processor and performs the sensorless control algorithm, inverter control, AC-DC converter control, anti-slip/slide control and electrical braking control.

2.2 Experimental results

The rotor speed and orthogonal counter-EMF components and also the rotor flux components are estimated using an adaptive control, and it is introduced as a controller into a rotor field oriented system with induction machine. This estimator can also be used in other direct or indirect vector control schemes as well as in scalar schemes.

In figure 4.a. is presented the system behaviour simulation of the indirect rotor field control using MRAS; there are shown the plots of ramp-reference speed $v_r^*$, the estimated motor speed $\hat{v}$, the real motor speed $v$, and the difference $v^* - v$.

The stability and the least errors are maintained all over the operation range concerning the rotor speed and electromagnetic torque.
Figure 4: The system behaviour. 1 - ramp-reference speed $v_r^*$; 2 - estimated speed $v^e$; 3 - real speed $v$; 4 - speed error $v^e - v$ (652rpm/div., 200V/div., time-20s/div.)

Figure 4.b. shows the experimental system behavior in the same condition as in simulation to show the real performances of the MRAS estimator and to prove a very good time response in estimation of the induction motor speed. It can be seen also a good agreement between simulation and the experimental results. Because this MRAS estimator doesn’t require integration in the reference model, it can operate without errors and instabilities all over the speed range (the maximum motor speed of KHSRT - 4200rpm) as is presented in figure 5. In this figure are shown from bottom to top the plots of real motor speed $v$, the estimated motor speed $v^e$, ramp-reference speed $v_r^*$ and step-reference speed $v_s^*$.  

Figure 5: The system traction operation from zero to the maximum train speed. 1 - measured speed $v$; 2 - estimated speed $v^e$; 3 - ramp-reference speed $v_r^*$; 4 - step-reference speed $v_s^*$ (1355rpm/div., 50s/div.; $n_{\text{max}}=4200$rpm.-350km/h, time-50s/div.)

One can be seen a very good dynamic of the sensorless system and also a very good agreement between the measured speed and the estimated one all over the speed range. As it was mentioned above, this MRAS can also operate in good conditions at very low speed. So, both experiments and simulations (figure 6.a and figure 6.b) were done for 25rpm and 50rpm, to show the very good stability (for the real KHSRT, 25rpm corresponds to 2km/h).
Simulation (a)

Experimental (b)

Figure 6: Low-speed operation. 1 - reference speed $v^*$; 2 - estimated speed $v'$; 3 - real speed $v$; 4 - speed error $v' - v$; (50rpm/div., time-20s/div.)

Taking into account the above conclusions, the proposed MRAS speed estimator is suitable for traction application. Using this MRAS there are avoided speed pulse-encoders and also phase voltage transducers. There are used only the line current transducers and one DC voltage transducer that represents the minimum number of transducers which are needed for the indirect vector control system.

3 Luenberger Speed Observer

The rotor flux is estimated by one observer and the estimated speed is derived by the stator current error and the estimated rotor flux. In terms of classification, the schemes which adopt an observer could be also treated as MRAS, where the motor is considered as Reference Model and the observer is considered as an Adjustable Model; so the *Popov hyperstability criterion* must be also applied. The stator current and rotor flux components are estimated by the full order Luenberger Observer.

The basic scheme of LSO is presented in figure 7.

Figure 7: The basic scheme of the Luenberger Speed Observer.
This kind of observer applied to induction motor speed estimation is based on the stator and rotor equations in stator coordinates \( \alpha-\beta \). The LSO is low sensitive at parameters variation and can be applied at very low speed (\( \leq 20 \text{rpm} \)) also. The computation time is almost the same as in case of MRAS, but LSO is less noise affected.

The induction model in terms of state variables in stationary reference frame \( \alpha-\beta \):

\[
\text{State equation: } \frac{1}{\omega_s} \frac{d}{dt} \begin{bmatrix} i_x \cr \psi_x \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \begin{bmatrix} i_x \cr \psi_x \end{bmatrix} + \begin{bmatrix} B_1 \cr 0 \end{bmatrix} u_1 = A \begin{bmatrix} i_x \\ \psi_x \end{bmatrix} + B \cdot u_1 \tag{7}
\]

\[
\text{Measure equation: } \begin{bmatrix} i_x \\ \psi_x \end{bmatrix} = C \cdot \begin{bmatrix} i_x \\ \psi_x \end{bmatrix} \tag{8}
\]

Where: \( A \) is the motor parameter matrix (it contains speed also),

\[
A_{11} = \begin{bmatrix} -r_s - x_s^2 r_e & 0 \\ x_s & x_s^2 \\ 0 & -x_s & x_s \\ x_s & x_s \\ 0 & x_s & x_s \end{bmatrix} ; \quad A_{12} = \begin{bmatrix} x_s r_e & \psi_r \\ x_s^2 & x_s r_e \\ 0 & -x_s & x_s \\ x_s & x_s & x_s \\ 0 & x_s & x_s \end{bmatrix} \\
A_{21} = \begin{bmatrix} x_s r_e \\ x_s \\ 0 \end{bmatrix} ; \quad A_{22} = \begin{bmatrix} -r_e \\ x_s \\ 0 \end{bmatrix} \\
\]

\[
B = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix} ; \quad C = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} ; \quad \begin{bmatrix} i_x \\ \psi_x \end{bmatrix} = \begin{bmatrix} \alpha_x \\ \alpha \end{bmatrix} ; \quad \begin{bmatrix} i_x \\ \psi_x \end{bmatrix} \tag{9}
\]

is the input matrix is the output matrix is the state variables vector, and \( u_1 \) is the command

The stator current and the rotor flux are estimated by the full order Luenberger State Observer:

\[
\frac{1}{\omega_s} \frac{d}{dt} \begin{bmatrix} i_x^e \cr \psi_x^e \end{bmatrix} = A \begin{bmatrix} i_x^e \\ \psi_x^e \end{bmatrix} + B \cdot u_1 + L \cdot (i_x^e - i_x) \tag{11}
\]

Where: \( L \) is the observer gain matrix, which is calculated to have the observer poles proportional to those of the induction machine.

The motor speed can be estimated by applying the Popov hyperstability criterion as it follows:

\[
\eta = K_\rho ( \epsilon_{i_{\alpha}} \psi_{\rho_\beta} - \epsilon_{i_{\beta}} \psi_{\rho_\alpha} ) + K_{L} \int \epsilon_{i_{\alpha}} \psi_{\rho_\beta} - \epsilon_{i_{\beta}} \psi_{\rho_\alpha} \text{dt} \tag{12}
\]

Where: \( \epsilon_{i_{\alpha}} = i_{\alpha}^e - i_{\alpha} \) and \( \epsilon_{i_{\beta}} = i_{\beta}^e - i_{\beta} \) are the stator current errors calculated as the difference between the estimated and measured currents.

The experiments from figure 8 and figure 9 were done using a direct vector
control of the rotor flux orientated induction machine.

![Figure 8: Real and estimated speed at full load condition.](image1)

![Figure 9: Estimated torque at the same conditions of figure 7.](image2)

4 Speed estimators

Speed estimators are generally based on the classical definition of rotor speed $v^r$.

$$v^r = v^s_e - v^r_e$$  \hspace{1cm} (13)

Synchronous speed $v^s_e$ may be calculated in stator reference frame $\alpha-\beta$, based on the formula:

$$v^s_e = \frac{1}{\omega_b} [\text{Arg}(\psi^s_r)] = \frac{1}{\omega_b} \frac{\text{d}\theta_s}{\text{dt}} , \text{ where: } \psi^s_r = \psi^s_{\alpha} + j\psi^s_{\beta}$$  \hspace{1cm} (14)

Taking into account eqn (14), Slip frequency $v^s_e$ becomes:

$$v^s_e = \frac{t_e r_s}{\psi^s_r} = \frac{(\psi^s_{\alpha}i_\beta - \psi^s_{\beta}i_\alpha)x_n}{\psi^s_j} x_r$$  \hspace{1cm} (15)

This speed estimator is based on the Voltage model open-loop flux observer

5 Rotor slots ripple speed estimators

The rotor slot ripple speed estimators are based on the fact that rotor slot opening causes stator voltage and current harmonics $v_{sl,2}$ related to rotor speed $v^r$, the number of rotor slot $N_r$ and synchronous speed $v^s_r$.

$$v_{sl,2} = N_r v^s_r \pm v^r$$  \hspace{1cm} (16)

Band pass filters centered on the rotor slot harmonics $v_{sl,2}$ are used to separate $v_{sl,2}$ and thus to calculate $v^r$. The response tends to be rather slow and thus the method, through immune to machine parameters, is mostly
favorable for a wide speed range, but for low dynamics operation.

6 Conclusion

The interest for schemes without shaft sensors, especially for Field Oriented Control is growing.

First of all, two categories of sensorless methods have been reviewed: the first one based on "estimation techniques" (MRAS, LSO) and the second one, based on "indirect measurement" (SE, RSR).

As a general conclusion, one can say that, if a suitable analog electronic detection circuitry is available, RSR has a behavior that is very close to methods using the measured speed. However, it has the drawback that it can not properly operate at zero speed. All the other methods are based on extensive digital computation, but are more precisely and the very low speed can be estimated too.

Appendix

Table 1: Induction motor ratings and parameters.

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<th>Quantity</th>
<th>Symbol</th>
<th>Value</th>
<th>Quantity</th>
<th>Symbol</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Output power</td>
<td>P_n</td>
<td>7500 W</td>
<td>Stator resistance</td>
<td>r_s</td>
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<td>Phase voltage, rms.</td>
<td>U_2m</td>
<td>220 V</td>
<td>Rotor resistance</td>
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References

