DEVELOPMENT OF A SPEED SENSORLESS INDUCTION MOTOR DRIVES USING AN ADAPTIVE NEURO-FUZZY FLUX OBSERVER

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Abstract
In this paper, we propose an adaptive neuro-fuzzy inference system for high performance induction motor drive. The simultaneous observation of rotor speed and stator resistance in induction drive is obtained through a neuro-fuzzy observer trained with a backpropagation algorithm. The dynamic performance and robustness of the proposed neuro-fuzzy adaptive observer are evaluated under a variety of operation conditions. The suggested approach is designed and simulated in the laboratory and its effectiveness in tracking application is verified. The results have shown excellent tracking performance of the proposed speed sensorless control system and have convincingly demonstrated the usefulness of the hybrid neuro-fuzzy flux observer in high performance drives with uncertainties.

Keywords: Induction Motor, Sensorless Control, Adaptive flux observer, ANFIS, Estimation

1. Introduction
The sensorless control of induction motor drives based on the properties of the observability constitutes a vast subject, and the technology has further advanced in recent years. The control of the asynchronous machine is complex because the dynamics of the machine are non linear, multivariable, and highly coupled. Furthermore, there are various uncertainties and disturbances in the system. The induction motor is controlled through field orientation technique. The field oriented control method of sensorless vector control has been generally applied to drive the induction motor vector-controlled induction motor drives have been widely used in high-performance applications. Conventional vector control methods [1] require motor speed as a feedback signal. To obtain the speed information, transducers such as shaft-mounted tachogenerators, resolvers, or digital shaft position encoders are used, which degrade the system's reliability, especially in hostile environment. However, the speed accuracy is generally sensitive to model parameter mismatch if the machine is loaded, especially in the field-weakening region and in the low-speed range. The parameter contributing to this variation is [2]:

- Rotor resistance variation with temperature,
- Stator resistance variation with temperature,
- Stator inductance variation due to saturation of the stator teeth.

Conventional speed-sensorless flux estimators, such as the speed-adaptive full-order ux observer [3], are based on the standard dynamic motor model. Performance comparable to that of drives equipped with the speed sensor can be achieved in a wide speed and load range. However the application of the Neuro-Fuzzy observer have been successfully used for a few numbers of non linear and complex processes, ANFIS are robust and their performances are insensible to parameter variations contrary to conventional observer [4]. This work deals with sensorless control of induction motor drives and in particular with the stator resistance and rotor speed estimation by means of Adaptive flux observer and Adaptive Neuro-Fuzzy Inference System [5], based on the fundamental dynamic model of the induction machines. This paper is organized as follows: the adaptive flux
observer is presented in Section 2. In section 3 the adaptive Neuro-Fuzzy Inference System which describes the structure of the proposed ANFIS observer with resistance parameters and rotor speed estimation. In section 4, the implementation of the studied observer proposed is associated to the direct-field-oriented control where stator resistance and rotor speed was replaced by those delivered by the estimated. Finally, in section 5, we give some comments and conclusions.

2. Adaptive flux observer

2.1 Motor model

The state equations of an induction motor in the rotor- speed reference frame can be expressed as follows [6]:

\[
\frac{dX}{dt} = AX + BU \\
Y = CX 
\]

with:

\[
X = [i_{sd} \ i_{sq} \ \phi_{d} \ \phi_{q}]^T, \ Y = [i_{sd} \ i_{sq}]^T, \\
U = [u_{sd} \ u_{sq}]^T, \ A = \begin{bmatrix}
a_{11} & a_{12} \\
a_{21} & a_{22}
\end{bmatrix}
\]

\[
a_{11} = \frac{R_s}{(\sigma L_s)} + \frac{(1-\sigma)}{\sigma T_s} I = a_{11} I
\]

\[
a_{12} = \frac{L_m}{\sigma L_s T_s} (I - \omega_s J) = a_{12} J
\]

\[
a_{21} = \frac{L_m}{T_s} I + \omega_s J = a_{21} I + a_{22} J
\]

\[
a_{22} = -\frac{1}{T_s} I + \omega_s J = a_{12} I + a_{22} J
\]

\[
B = \frac{1}{\sigma L_s} I; \ I = \begin{bmatrix}
1 & 0 \\
0 & 1
\end{bmatrix}; \ J = \begin{bmatrix}
0 & -1 \\
1 & 0
\end{bmatrix}
\]

2.2 Adaptive, speed, flux and resistance observers

Let’s consider the speed like a constant and unknown parameter, it is about to determine a law of adaptation for estimating its value. The observer can be described by the following state equation:

\[
\frac{d\hat{X}}{dt} = \hat{A}\hat{X} + BU + C\begin{bmatrix}
\hat{i}_{sd} \\
\hat{i}_{sq}
\end{bmatrix}
\]

The matrix A is separated in two terms, one for the speed and the other for stator resistance, as follows:

\[
\hat{A} = A(\dot{\omega}_s) + A(\hat{R}_s)
\]

(4)

where

\[
A(\dot{\omega}_s) = \begin{bmatrix}
-a_1 L_m & 0 & a_1 & a_2 \dot{\omega}_r \\
0 & -a_1 L_m & -a_2 \dot{\omega}_r & a_1 \\
a_4 & 0 & a_4 & -\dot{\omega}_r \\
0 & a_3 & \dot{\omega}_r & a_4
\end{bmatrix}
\]

(5)

\[
A(\hat{R}_s) = \begin{bmatrix}
-a_5 R_s & 0 & 0 & 0 \\
0 & -a_5 R_s & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0
\end{bmatrix}
\]

(6)

Where

\[
a_1 = \frac{L_m}{\sigma L_s L_r T_s}; \ a_2 = -\frac{L_m}{\sigma L_s L_r}; \ a_3 = \frac{L_m}{\sigma L_r} ; \\
a_4 = -\frac{1}{T_s} ; \ a_5 = \frac{1}{\sigma L_r}
\]

The matrix G represents the gain of the observation matrix; it governs the dynamics and the observer’s robustness and is defined as follows [3]:

\[
G = \begin{bmatrix}
g_1 & g_2 & g_3 & g_4 \\
-g_2 & g_1 & -g_3 & g_3
\end{bmatrix}
\]

(7)

\[
g_1 = (k-1)(a_{11} + a_{22})
\]

(8)

\[
g_2 = (k-1)a_{12}
\]

(9)

\[
g_3 = (k^2-1)(a_{11} + a_{22}) - c(k-1)(a_{11} + a_{22})
\]

(10)

\[
g_4 = -c(k-1)a_{12}
\]

with

\[
c = (\sigma L_s L_r) / L_m
\]

The coefficient k is chosen for impose an observer dynamic faster than the system. The difference between the observer and the model of the motor, represents the estimation error of stator current and rotor, it is given by:

\[
\frac{d}{dt} e = (A + GC)e - \Delta A \hat{X}
\]

(12)

With:

\[
e = X - \hat{X}
\]
The Lyapunov theory gives the adaptation law for the speed [10]:

\[ \omega_t = \left( K_{po} + \frac{K_{ia}}{s} \right) \left( e_{isa} \hat{\phi}_{ri} - e_{isb} \hat{\phi}_{ra} \right) \]  

(14)

where

\[ e_{isa} = i_{isa} - i_{sat} \]
\[ e_{isb} = i_{isb} - i_{sat} \]

The stator resistance estimation is given by the second adaptation law defined by [11]:

\[ \hat{R}_s = \left( K_{pR} + \frac{K_{IR}}{s} \right) \left( e_{isa} \hat{i}_{sa} + e_{isb} \hat{i}_{sb} \right) \]  

(15)

\( K_{pR}, K_{IR} \) are positive constants.

The object of adaptive mechanisms is to minimize the following errors:

\[ \varepsilon_F = \left( e_{isa} \hat{\phi}_{ri} - e_{isb} \hat{\phi}_{ra} \right) \]
\[ \varepsilon_R = -\left( e_{isa} \hat{i}_{sa} - e_{isb} \hat{i}_{sb} \right) \]  

(16)

\[ \Delta A = A - A \]
\[ \begin{bmatrix} 0 & 0 & 0 & -a_\Delta \alpha \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \xi \x
Let $\eta_j(k)$ denote the learning rate parameter assigned to synaptic weight $w_{ji}(k)$ at iteration number $k$. Minimizing equation (18) leads to a sequence of update of the weight vector. The weights of the interconnections between two adjacent layers can be update based on the following formula:

$$w_{ji}(k+1) = w_{ji}(k) - \eta_j(k+1) \frac{\partial E_{k,w}}{\partial w_{ji}(k)} + \alpha \Delta w_{ji}(k)$$  

(18)

$\alpha$ is the momentum gain, is susceptible to local minima and needs additional computation for gradient evaluation and $\Delta w_{ji}(k)$ is weight change based on gradient of the cost function $E_{k,w}$ and $k$ is the iteration number.

**Fig. 2. An adaptive Neuro-Fuzzy based Adaptive observer**

The fig.1 show the structure of sensorless control induction motor equipped with ANFIS observer. The dynamic model of speed induction motor drive can be controlled by classic numerical PI (Proportional an Integral) regulator is well suited to regulating the torque. The regulation of the stator currents in direct filed oriented control of induction motor is assigned to two identical PI. Another PI controller regulates the rotor flux and minimizes the error between its reference value, obtained by field weakening block and its reference value delivered by the observer. In addition a decoupling block is introduced to separate the mutual action of the two orthogonal axes. The reference voltage impose the flux and electromagnetic torque, after reference change by an inverse transformation via the voltage inverter. Fig. 2 shows the adaptive Neuro-Fuzzy illustrate in Fig.1 [5]-[11], it contains seven inputs: $R_s(k-1)$, $\omega(k-1)$, $\phi_r$, $u_{ss}$, $i_{is}$, $i_{is}$ and two outputs $R_s$ and $\omega_{est}$, based on the error back-propagation training algorithm is adopted to perform the observer, which is applied to sensorless induction motor drive.

**4. Results and Discussion**

The described observer structure show in fig.3 was implemented in the environment software Matlab/Simulink, and tested in various operating conditions. This software allows digital simulation of the systems using a same expression of the ordinary differential equations in the dynamic machine model as well as the controller. The numerical method for solving the equations is Runge-Kutta method. Fixed-step mode is chosen for the computational time interval, this will emulate the fixed sampling frequency of the real-time control. The sampling period is $1e^{-4}$ sec. The parameters of the induction motor and gains of different controllers used are given in Appendix. Figure 3 shows the response of the proposed speed sensorless system based adaptive ANFIS observer with a speed reverse at $t=2$sec and under load change to the nominal motor parameters at $t=0.8$sec and $t=1.5$sec. Figure 4 illustrates the performances of the observer under conditions of load charge change between $10$ Nm and $-10$ Nm. These observers have good accuracy in the estimation of speed and stator resistance. The speed and fluxes responses confirm a very low sensitiveness to disturbances, a good precision around zero speed, and the control system rejects the load disturbances. These results show clearly very satisfactory performance for the proposed sensorless controller in tracking and a remarkable pursuit between measured and estimated speed of the reference model speed. Figure 5 illustrate a response of sensorless drive system during starting operation with load $10$ Nm, under conditions of low speed and with changes in load torque. The reference command imposes a speed step from $10$ to $-10$ rad/s, the results obtained show excellent performance even at low speeds, with precise estimates motor speed.
Fig. 3. Performance of adaptive ANFIS observer with speed reverse, current, and load charge change.

Fig. 4. Performance during starting operation with load variation.

Fig. 5. Performance at low speed region during speed reversal from 10 to -10 rad/s.
5. Conclusion
In this research, a robust controller using adaptive flux observer based neuro-fuzzy for sensorless speed control of induction motor drive the ANFIS observer is presented. The synthesis procedure of the adaptive observer with rotor speed and stator resistance estimations is based on the hyper-stability theory. The speed and stator resistance estimations method was implemented in a speed-sensorless space vector control system based adaptive ANFIS observer. The Neuro-Fuzzy observer has a number of advantages over conventional adaptive observer. The effectiveness of the proposed sensorless schemes was confirmed by simulated results.

Appendix

<table>
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<tr>
<th>TABLE 1. Induction Motor Parameters</th>
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<tr>
<td><strong>Rated values</strong></td>
</tr>
<tr>
<td>Power</td>
</tr>
<tr>
<td>Frequency</td>
</tr>
<tr>
<td>Voltage Δ/Y</td>
</tr>
<tr>
<td>Current Δ/Y</td>
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<tr>
<td>Motor Speed</td>
</tr>
<tr>
<td>Pole pair (p)</td>
</tr>
<tr>
<td><strong>Rated parameters</strong></td>
</tr>
<tr>
<td>R_1</td>
</tr>
<tr>
<td>R_s</td>
</tr>
<tr>
<td>L_m</td>
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<td>L_n</td>
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<tr>
<td><strong>Constants</strong></td>
</tr>
<tr>
<td>J</td>
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<tr>
<td>f</td>
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</tbody>
</table>

Nomenclature

- $s, r$: Stator and rotor subscripts
- $d, q$: Direct and quadrature Park subscripts
- $v, i$: Voltage/Current/Flux variables
- $\phi$: 
- $R_s, R_r$: Stator, rotor resistances
- $L_m, L_n$: Stator, rotor inductance
- $L_m$: Mutual magnetizing inductance
- $\sigma$: Total leakage factor
- $\sigma = 1 - \frac{L_m}{(L_s L_r)}$
- $\omega_s$: Stator frequency
- $\omega_r$: Rotor angular speed
- $\omega_m$: Nominal frequency
- $\Omega$: Rotor speed
- $\theta_r$: Rotor flux position
- $J$: Inertia
- $f$: Friction coefficient
- $T_r$: Rotor time constant

$^p$ Number of pole pair
$^\wedge$ Superscript of estimated quantity

References

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Abdelkader Mechernene was born in Manosque (France) in 1961. He received the BS and the MS degrees in electrical engineering from the Higher School of Technical Education (ENSET) of Oran-Algeria, in 1983 and 2008 respectively. Since 1983, he teaches in the field of electrical engineering in several technical schools. Currently, he is working as an assistant-teacher in Department GEE, Faculty of Technology of Tlemcen University Abou Bekr Belkaid and simultaneously, in the field of sensorless induction motor drives. His research interests include electric motor drive systems, application of artificial-intelligence (fuzzy logic and neural networks) with particular interest for sensorless-control algorithms to electrical drive systems.

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