Nonlinear Adaptive Speed and Flux Estimator for Three Phase Induction Machine

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Abstract
This paper presents a nonlinear adaptive control method for estimation of speed and flux for three phase induction machine. Rotor speed and quadrature and direct rotor axis flux estimator for sensor less vector control is proposed using five state nonlinear induction motor model. The stability of estimator model is evaluated using Lyapunov Criteria. The model of estimator is build and performance is evaluated and analyzed with Matlab simulator.

Keywords: Speed estimation, Observer, Sensor less Control, Induction machine, Nonlinear Control.

Introduction
Induction motors are widely used in industry due to their relative low cost and high reliability. Larger Industrial applications require high performance motion control with four quadrant operation including field weakening, minimum torque ripple, rapid speed recovery under impact load torque and fast dynamic torque and speed responses. The induction motors are suitable for industrial drives, because of their simple and robust structure, higher reliability and ability to operate in hazardous environments. However there control is a challenging task because the rotor quantities are not accessible which are responsible for torque production. Although Torque and Flux are naturally decoupled in DC motor and can be controlled independently by the torque producing current and Flux producing current [1].

In the beginning of 1970’s There was a concept i.e. By splitting the stator current into two orthogonal components, one in the direction of flux linkage, representing magnetizing current or flux component of current, and other perpendicular to the flux linkage, representing the torque component of current, and then by varying both components independently, the induction motor can be treated as a separately excited DC motor [2].

The implementation of vector control requires information regarding the magnitude and position of the flux vector.

Depending upon the method of acquisition of flux information, the vector control or field oriented control method can be termed as: direct or indirect. In the direct method the position of the flux to which orientation is desired is strictly measured with the help of sensors, or estimated from the machine terminal variables such as speed and stator current/voltage signals [2].

The measured or estimated flux is used in the feedback loop, thus the machine parameters have minimal effect on the overall drive performance. But the measurement of flux using flux sensors necessitates special manufacturing process or modifications in the existing machines [1].

To get ideal decoupling, the controller should track the machine parameters and for this, various adaptation methods have been proposed [3] [4]. However it has been reported that the controller performance is adequate within normal operating temperatures for most of the high performance applications, and the parameter adaptations methods may be essential only in the case of critical applications.

In contrast to direct method the indirect method controls the flux in an open loop manner. Field orientation scheme can be implemented with reference to any of the three flux vectors: stator flux, air gap flux and rotor flux. It has been shown that out of the three the orientation with respect to rotor flux alone gives a natural decoupling between flux and torque, fast torque response and better stability. Hence in this work orientation along rotor flux is considered.

Vector control is the control of the torque and the flux separately. In order to decouple the vectors and realize the decoupled control most control schemes require accurate flux and motor rotor speed. This information is mainly provided by Hall sensors and sensing coils (flux measurement) and incremental encoder (rotor speed measurement). The use of these sensors implies more electronics, high cost, and lower reliability, difficulty in mounting, in some cases such as motor drives in harsh environment and high speed drives, increase in weight, increase in size and increase electrical susceptibility.
To overcome these problems, in recent years, the elimination of these sensors has been considered as an attractive prospect. The rotor speed and flux are estimated from machine terminal variables, voltages and currents. Here a flux and speed observer is proposed with adaptive choice of observer gain matrix.

The first section of paper describes the general introduction and prior in the sensor less control. The Section II introduces observes. The model of three phase induction machine is described in Section III. Section IV of paper includes speed and flux estimator design. The simulation results and analysis includes in Section V of the paper. The last section includes conclusion of the paper.

1. Observers

All states are not available for feedback in many cases and one needs to estimate unavailable state variables. Estimation of immeasurable state variables is commonly called observation. A device (or a computer program) that estimates or observes the states is called a state-observer or simply an observer. If the state observer observes all state variables of the system, regardless of whether some state variables are available for direct measurement, it is called a full-order state-observer [5]. An observer that estimates only the unmeasured state-vector is called reduced-order state-observer or simply a reduced-order observer. If the order of the reduced-order state-observer is the minimum possible, the observer is called minimum-order state-observer. Basically, there are two forms of the implementation of an estimator as open loop and closed-loop. The difference between these two is a correction term, involving the estimation error, used to adjust the response of the estimator [7].

A closed loop estimator is referred to as an observer. In open-loop estimators, especially at low speeds, parameter deviations have a significant influence on the performance of the drive both in steady state and transient state [2]. However, it is possible to improve the robustness against parameter mismatch and also signal noise by using closed loop observers. An observer can be classified according to the type of representation used for the plant to be observed. If the plant is deterministic, then the observer is a deterministic observer; otherwise it is a stochastic observer. There are a number of methods are available in art for design observer [8]-[15].

Proposed work is based on full order observer with assumed stator current, here stator voltages are measurable & rotor angular speed is also measurable. Proposed scheme of flux observer uses the observer in which poles can be allocated arbitrarily. Therefore, it can be applied to direct field oriented control.

2. Modeling Of Induction Motor

The idealized three–phase induction machine is assumed to have symmetrical air–gap. The reference frame is usually selected on the basis of convenience or computability with the representation of other network components. The two common frames useful for the analysis of this machine are stationary and synchronously rotating reference frames. Each has an advantage for some purpose.

However, if a machine is derived in an arbitrary reference frame, the effect of mutual coupling coefficients can be eliminated. Moreover, the equations of the machine derived in the arbitrary reference frame can be transformed to any other reference frame by simply substituting the speed of frame (for stationary frame, for synchronously rotating frame, for the rotor reference frame) [4].

Modeling of induction machine states that the variables and circuit parameters have to be expressed in form where \( \mathbf{x} = f(\mathbf{x}, \mathbf{u}) \) is state system vector variable, \( \mathbf{u} \) is the input vector \( (I, V) \). With reference to all the above assumptions, and considering equations of arbitrary reference frame of squirrel cage induction motor. Rotor windings of induction motor are short circuited. So \( v_q' = 0 \) and \( v_d' = 0 \) [4].

\[
\begin{align*}
\dot{r}_q' &= \frac{ω - ω_p}{ω_b} ψ_q' + \frac{p}{ω_b} ψ_p'' = 0 \\
\dot{r}_d' &= \frac{ω - ω_p}{ω_b} ψ_d' + \frac{p}{ω_b} ψ_p'' = 0
\end{align*}
\]

While,

\[
\begin{align*}
\dot{r}_q' &= \frac{1}{X_{qr}} \psi_q' - \frac{1}{X_{rr}} X_{Mq} i_q \\
\dot{r}_d' &= \frac{1}{X_{qr}} \psi_d' - \frac{1}{X_{rr}} X_{Mr} i_d
\end{align*}
\]

So, substituting values,

\[
\begin{align*}
\dot{r}_q' &= -\frac{1}{X_{qr}} ω_b r_p' ψ_p' - (ω - ω_p) ψ_p' + \frac{1}{X_{rr}} ω_b r_p' X_{Mq} i_q \\
\dot{r}_d' &= (ω - ω_p) ψ_p' - \frac{1}{X_{qr}} ω_b r_p' ψ_p' + \frac{1}{X_{rr}} ω_b r_p' X_{Mr} i_d
\end{align*}
\]
\[
\begin{align*}
v &= \omega_0 + \frac{d}{dt} L_{ds} + X_d \left( x'_{ds} \right) + \frac{1}{X_d} x'_{qs} \left( 1 - \frac{1}{X_d} x'_{ds} \right) + \frac{1}{X_d} x'_{qs} - \frac{1}{X_d} x'_{qs} \left( 1 - \frac{1}{X_d} x'_{ds} \right) \\
v &= \omega_0 + \frac{d}{dt} L_{ds} + X_d \left( x'_{ds} \right) + \frac{1}{X_d} x'_{qs} \left( 1 - \frac{1}{X_d} x'_{ds} \right) + \frac{1}{X_d} x'_{qs} - \frac{1}{X_d} x'_{qs} \left( 1 - \frac{1}{X_d} x'_{ds} \right) \\
\end{align*}
\]

Here, \( a_2 \), \( a_3 \) and \( a_4 \) are load parameters these parameters are defined as follows:

\[
\begin{align*}
a_2 &= \frac{a_0}{J} \quad a_3 = \frac{f}{J} \quad a_4 = \frac{k}{J}
\end{align*}
\]

Where, \( k_0, k_1 \) & \( k_2 \) denotes inertia load, friction and fan load coefficient respectively, where \( k_2 << k_1 << k_0 \).

### 3. Design Of Speed And Flux Estimator

Proposed scheme of speed adaptive flux observer uses the state observer which can allocate poles arbitrarily. Therefore, it can be applied to direct field oriented control, even in low speed region.

The speed-adaptive full-order flux observer consists of a full-order flux observer augmented with a speed-adaptation loop. The actual motor behaves as a reference model and the observer, including the rotor speed estimator as an adjustable model.

The outputs of a reference model and adaptive model are compared, and process the error between these two according to the appropriate adaptive laws that do not deteriorate the stability requirements of the applied system.

The adaptive law designs made use of the stability theory of Lyapunov, served as standard design method, yielding a guaranteed stable system. The adaptive scheme for speed estimation is derived from Lyapunov's theorem [16].

\[
T_x = \frac{3pX_M}{4\alpha_0 X_{vr}} (\psi'_{qr} - \psi'_{qr} I_d) \quad Nm
\]

Finally, Torque

**A. Mechanical dynamics**

The speed can be calculated by the following relationship [4],

\[
T_\omega = T_L + J p \omega
\]

\[
\dot{\omega} = \frac{3p}{4J} \left( \frac{X_M}{\alpha_0 X_{vr}} \right) (\psi'_{qr} l_q - \psi'_{qr} l_d) - T_L
\]

Let, \( x_o = \omega \), \( x_2 = \psi_{qr} \), \( x_3 = \psi_{dr} \), \( x_4 = I_q \), \( x_5 = I_d \), \( \omega_o \) being the speed of the arbitrary reference frame, and the excitation \( d-q \) axis voltage be \( u_1 = v_{qr} \) and \( u_2 = v_{dr} \) with the load disturbance \( v = T_L \). Then with this definition the dynamics of induction machine can be be written as,

\[
\begin{align*}
\dot{x}_o &= a_1 (x_o x_i - x_2 x_3) - v \\
\dot{x}_2 &= a_2 x_2 - (\omega_o x_i) x_3 + a_3 x_4 \\
\dot{x}_3 &= (\omega_o - x_i) x_2 + a_4 x_3 + a_5 x_5 \\
\dot{x}_4 &= a_6 x_2 - a_7 x_4 x_3 + a_8 x_4 - \omega_o x_5 + b u_1 \\
\dot{x}_5 &= a_9 x_3 x_2 + a_7 x_3 + a_8 x_4 + a_9 x_5 + b u_2
\end{align*}
\]

Where,

\[
\begin{align*}
a_1 &= \left( \frac{3p}{4J} \right) \left( \frac{X_M}{X_{vr} \alpha_0} \right) \\
a_2 &= -\frac{\alpha_0}{X_{vr}} \quad a_3 = \frac{\alpha_0}{X_{vr}} \quad a_4 = \frac{X_M}{D} \\
a_5 &= -\frac{\alpha_0}{DX_{vr}} \left( r_r X_{vr}^2 + r_r X_{vr}^2 \right) \\
D &= \frac{\alpha_0}{X_{vr}^2} - X_{vr}^2
\end{align*}
\]

And load disturbance,

\[
v = a_2 + a_3 x_i + a_4 x_i^2
\]
A. Observer design

The speed $\omega_x$ is taken as 'constant' as rated speed $\omega_r$. Then equations can be written in steady state form as

$$\dot{x} = Ax + Bu$$
$$y = Cx$$

Here we have,

$$A = \begin{bmatrix}
    a_1 & -a_2 & a_3 & 0 \\
    (a_2 - x_{o1}) & a_4 & 0 & a_5 \\
    a_6 & -a_7 & a_8 & a_9 \\
    a_{10} & a_1 & a_2 & a_3 \\
\end{bmatrix},
\quad B = \begin{bmatrix}
    0 & 0 & 0 & 0 \\
    0 & 0 & 0 & 0 \\
    0 & 0 & 0 & 0 \\
    0 & 0 & 0 & 0 \\
\end{bmatrix},
\quad C = \begin{bmatrix}
    0 & 0 & 1 & 0 \\
\end{bmatrix}$$

Let speed and flux are not measured and we are designing observer for better efficiency and control. It is assumed that only $d-q$ axis currents are measurable.

And also consider at first that the speed $x_1 = \omega_r$ is constant, and then these equations are rewritten as [6],

$$\dot{x}_1 = a_1 x_2 - (\omega_r - \dot{\omega}_r)x_3 + a_6 x_4$$
$$\dot{x}_3 = (\omega_r - \dot{\omega}_r)x_2 + a_7 x_3 + a_8 x_5$$

Let estimated dynamics of be,

$$\dot{\hat{x}}_2 = a_1 \hat{x}_2 - (\omega_r - \hat{\omega}_r) \hat{x}_3 + a_6 \hat{x}_4$$
$$\dot{\hat{x}}_3 = (\omega_r - \hat{\omega}_r) \hat{x}_2 + a_7 \hat{x}_3 + a_8 \hat{x}_5$$

The error dynamics is obtained by substituting from to give [4],

$$\dot{\hat{x}}_2 = a_1 x_2e + (\omega_r - \omega_x) x_{3e} + (\omega_r - \dot{\omega}_r) \hat{x}_3 + a_6 x_{4e}$$
$$\dot{\hat{x}}_3 = (\omega_r - \omega_x) \hat{x}_2 + a_7 x_3e + a_8 x_5e + (\omega_r - \dot{\omega}_r) \hat{x}_2 + a_8 x_{5e}$$

The estimated dynamics of motor becomes,

$$\dot{\hat{x}}_2 = a_1 \hat{x}_2 - (\omega_r - \hat{\omega}_r) \hat{x}_3 + a_6 \hat{x}_4$$
$$\dot{\hat{x}}_3 = (\omega_r - \hat{\omega}_r) \hat{x}_2 + a_7 \hat{x}_3 + a_8 \hat{x}_5$$
$$\dot{\hat{x}}_4 = a_3 \hat{x}_1 - a_4 \hat{x}_2 + a_4 \hat{x}_3 + \omega_x \hat{x}_4 + a_9 \hat{x}_5 + bu_1$$
$$\dot{\hat{x}}_5 = a_4 \hat{x}_1 - a_9 \hat{x}_3 + a_9 \hat{x}_4 + a_9 \hat{x}_5 + bu_2$$

With estimations equation becomes,

$$\dot{\hat{x}} = A\hat{x} + Bu$$

Subtracting from measured equations gives the error equations as,

$$\dot{\hat{x}} - \hat{x} = x_e = A x_e + \Delta \hat{x}$$

Where,

$$x_e = \begin{bmatrix}
    x_{2e} \\
    x_{3e} \\
    x_{4e} \\
    x_{5e}
\end{bmatrix},
\quad \Delta A = \begin{bmatrix}
    0 & x_{ie} & 0 & 0 \\
    -x_{ie} & 0 & 0 & 0 \\
    0 & -a_6 x_{ie} & 0 & 0 \\
    a_8 x_{ie} & 0 & 0 & 0 \\
\end{bmatrix}$$

Where $x_{ie} = \omega_r - \hat{\omega}_r$, $\omega_r$ is a rated speed of induction motor.

Let the observer equation be shown by,

$$\dot{\hat{x}} = A\hat{x} + Bu - Gu_o$$

In the observer input is given by $\hat{u_o}$ along with the observer input matrix $G$. And $u_o = Cx_e$. Then can be rewritten as,

$$\dot{\hat{x}} = A\hat{x} + Bu - GCx_e$$

Then subtracting measured, shall lead to the same equation with $Gu_o$ as additional term on the right hand side, and the estimation error dynamics becomes,

$$\dot{x}_e = (A + GC)x_e + \Delta \hat{x}$$

To minimize the estimation error let the Lyapunov function [16] be chosen as,

$$V = e^T e + \frac{(\omega_r - x_{ie})^2}{\gamma^2},$$
where $\gamma$ is a positive constant.

$$V = x_{ie}^T x_{ie} + \frac{1}{\gamma} x_{ie}^2$$

Then for asymptotic stability and convergence the time derivative of $V$ must be negative semi-definite or,
\[ \dot{V} = \dot{x}_e^T x_e + x_e^T \dot{x}_e + \frac{2}{\gamma} x_{ie} \dot{x}_{ie} \]

Substituting into with \( u_a = C x_e \) gives,

\[ \dot{V} = (x_e^T A^T + \dot{x}_e^T \Delta A^T + x_e^T C^T G^T) x_e + x_e^T (A x_e + \Delta A \hat{x} + GC x_e) + \frac{2}{\gamma} x_{ie} \dot{x}_{ie} \]

And \( x_{ie} = \omega_e - \dot{x}_{ie} \),

So \( \dot{x}_{ie} = -\dot{x}_{ie} \)

So equation becomes,

\[ \dot{V} = x_e^T ((A + GC)^T + (A + GC)) x_e + (\dot{x}_e^T \Delta A^T) x_e + \frac{2}{\gamma} x_{ie} \dot{x}_{ie} \]

The simplification of the middle term of is given in the following,

\[ \dot{x}_e^T \Delta A x_e = \left[ (-x_{ie} + a_e x_{ie}) \dot{x}_2 + (x_{ie} - a_e x_{ie}) \dot{x}_1 \right] x_{ie} \]

\[ x_e^T \Delta A \hat{x} = \left[ (-x_{ie} + a_e x_{ie}) \dot{x}_2 + (x_{ie} - a_e x_{ie}) \dot{x}_3 \right] x_{ie} \]

Note that \( a_e \) are same and therefore \( \dot{V} \) becomes,

\[ \dot{V} = x_e^T ((A + GC)^T + (A + GC)) x_e + 2 x_{ie}[-(-x_{ie} + a_e x_{ie}) \dot{x}_2 + (x_{ie} - a_e x_{ie}) \dot{x}_1] - \frac{2}{\gamma} x_{ie} \dot{x}_{ie} \]

For stability by Lyapunov Criteria, \( \dot{V} \leq 0 \) it is required to have,

1. \( \sigma(A + GC) < 0 \), that is Eigen values should have negative real parts. And,
2. \( \dot{x}_1 = \gamma \left\{ (-x_{ie} + a_e x_{ie}) \dot{x}_2 + (x_{ie} - a_e x_{ie}) \dot{x}_3 \right\} \] \[ \text{or} \]

\[ \dot{x}_1 = \gamma \left[ (\dot{x}_3 x_{ie} - \dot{x}_2 x_{ie}) + a_e (\dot{x}_1 x_{ie} - \dot{x}_3 x_{ie}) \right] \]

Thus, the speed \( x_1 \) is estimated as,

\[ \dot{x}_1 = \gamma \int \left[ (\dot{x}_3 x_{ie} - \dot{x}_2 x_{ie}) + a_e (\dot{x}_1 x_{ie} - \dot{x}_3 x_{ie}) \right] dt \]

Finally, observer equation (12) can be used for flux estimation with observer input \( u_a = C x_e \) and observer gain \( G \) is chosen in such a manner that \((A + GC)\) have the Eigen values in negative real part [17].

4. Simulation And Results

The rating and parameter of 3-phase induction motor taken for simulation are given in Appendix-A. In this work, MatLab7.3 Simulink is used for simulate the state dynamics of motor with observer.

The simulation is done in no load and under load conditions.

A. Under no load

Under no load conditions \( V = 0 \), the estimated rotor speed of induction motor is shown in Figure 2. Quadrature and direct rotor axis flux are described in Figure 3 and Figure 4 respectively.

![Fig. 2 Speed estimated by speed estimator.](image)

![Fig. 3 Observed quadrature axis rotor flux.](image)
Errors in estimation of rotor speed, quadrature axis rotor flux and direct axis rotor flux is shown in Figure 8, Figure 9 and Figure 10 respectively.
B. Under load

The load signal taken as step input of 1980 unit amplitude and applied at time \( t = 4 \) second. The Figure 11 shows the estimated rotor speed in which load disturbance is clearly trace with estimator at time 4 second. The Figure 12 and Figure 13 show quadrature and direct axis rotor flux under load conditions.

5. Conclusion

The adaptive nonlinear approach for estimation of speed and flux under no load and load conditions is proposed. The induction machine and estimator model is designed and performance is analyzed with Matlab simulator. The estimator models are estimating rotor speed and quadrature and direct axis fluxes with minimum errors. The more works is needed to works on transient response for both conditions.

References


