Global Stabilization of Induction Motor controller Based - Interconnected Observer

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***Abstract*—In this paper, a sensorless speed control for induction machines (IM) is proposed. In order to improve the robust properties of the controller, the control approach is synthesised based on the Lyapunov theory.**
Moreover, an interconnected observer is presented to estimate the rotor speed.
Stability analysis of the closed loop system is developed and proved. Finally, simulation results have been presented in order to exhibit the performances of the suggested control under parametric uncertainties.

Keywords: control, Lyapunov theory, global stability, closed loop system, interconnected observer.

I. Introduction

The interest in ac-motor drives has seen an important growth in several applications such as aerospace, military and automotive industries.
Improving the performances of IM has known a progressively increasing attention as a topic research. In fact, several control schemes have been proposed such as the linearization technique [1]-[2] where the control design in this category is based on a linear model around an equilibrium point [3]-[4].
Other methods using adaptive control approaches has been proposed in [5]-[7]. Indeed, authors in [5] have suggested that the flux the rotor resistance and the load torque are estimated while the speed is assumed to be known.
Moreover, sliding mode control has been proposed in [8]-[10]. An Integral sliding surface for vector control has been described in [9].
Another kind of control is called, the Backstepping control [11]-[12]. The control design is divided into two steps. The first one is to synthesize a virtual control variable. Then, the second step is to determine the actual command using appropriate Lyapunov functions.
The knowledge of the rotor speed is very important for the induction machine control. Speed sensors, traditionally used, increases the complexity of the arrangements and imposes additional costs.
Sensorless control has been considered as an important solution. Several approaches for speed/position estimation have been investigated such as : Model reference Adaptive System (MRAS)[13]-[14], Extended Kalman filter (EKF) [15]-[16], Lunberger observer (ELO) [17]-[19], newly fuzzy logic and neuronal network observers [20]-[21]
The proof of the global stability of the closed loop system (Control + Observer) is the major difficulty for the sensorless speed control . Indeed, few works have proposed a comprehensive demonstration of this approach, except [22]-[23].
In this paper, we propose a robust control for induction machine based on the Lyapunov theory. In fact, this approach is made up of a PI Flux and speed regulators, whose provides the IM park current reference.
The control laws can be determined systematically using an appropriate Lyapunov function. Then, an interconnected observer is presented. This observer was synthesised under parametric uncertainties.
The global stability study of the closed loop system (Control + Observer) has been analyzed and proved based on Lyapunov theory.

The rest of the paper is arranged as following: Section II presents the Control technic for the IM based on the Lyapunov approach. The third section is reserved to present the interconnected observer. In section IV, the stability study of Observer-Controller has been analyzed. Simulations results are reported in Section V to illustrate the effectiveness of the proposed control topology.

II. Control technic for induction machine based on the Lyapunov approach

In this section, we present a robust control approach for IM based on the Lyapunov stability theory.
The main objective of this control technic is to ensure the global stability of the closed loop system based on an appropriate choice of the voltage control values.
Two PI controllers for the Flux and the speed are applied allowing a better tracking characteristics of The IM. The associate PI gains are calculated by pole placement method. Robustness study against parametric variations is developed.
The state model of the induction machine with rotor flux orientation in the d-q reference is represented by :

$$\begin{bmatrix} \dot{i}_{sd} \\ \dot{i}_{sq} \\ \dot{\phi}_{rd} \\ \dot{\Omega} \end{bmatrix} = \begin{bmatrix} -\gamma_1 i_{sd} + \frac{\gamma_2}{\tau_r}\phi_{rd} + p\Omega i_{sq} + \frac{L_m}{\tau_r}\frac{i_{sq}^2}{\phi_{rd}} \\ -\gamma_1 i_{sq} - p\Omega i_{sd} - p\Omega\gamma_2\phi_{rd} - \frac{L_m}{\tau_r}\frac{i_{sd}i_{sq}}{\phi_{rd}} \\ \frac{L_m}{\tau_r}i_{sd} - \frac{1}{\tau_r}\phi_{rd} \\ m\phi_{rd}i_{sq} - c\Omega - \frac{T_l}{J} \end{bmatrix} + \begin{bmatrix} \frac{1}{\sigma L_s} & 0 \\ 0 & \frac{1}{\sigma L_s} \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} u_{sd} \\ u_{sq} \end{bmatrix}$$

where:
Ω: Rotational speed.
ϕ_{rd}, ϕ_{rq}: d-q components of the magnetic rotor flux.
i_{sd}, i_{sq}: d-q components of the stator current.
u_{sd}, u_{sq}: d-q components of the stator voltage.
T_l: Load torque.
Parameters σ, τ_r, c, γ_1 and γ_2 are defined by:

$$\sigma = 1 - \frac{L_m^2}{L_r L_s}, \tau_r = \frac{L_r}{R_r}, c = \frac{f}{J}$$
$$\gamma_1 = \frac{\frac{L_m^2}{L_r^2}R_r + R_s}{\sigma L_s}, \gamma_2 = \frac{L_m}{L_r L_s \sigma}$$

with (R_r, R_s): rotor and stator resistances, σ: leakage coefficient, τ_r: rotor time constant, L_s: stator inductance, L_r: rotor inductance, L_m: mutual inductance, p: number of pole pairs, J: rotor moment of inertia.
U=$[u_{sd}, u_{sq}]^T$ presents the control voltage. Outputs of the flux and the speed controllers are i_{sd} and i_{sq}.
I^*=$[i_{sd}^*, i_{sq}^*]^T$ is the current reference.
The control law is defined based on the global stability study using Lyapunov functions.

A. Flux regulator Synthesis:

We define the reference current i_{sd}^*:

$$\begin{aligned} i_{sd}^* &= KI_{\phi rd}\int_0^t \phi_{rd}^* - \phi_{rd} d\tau + KP_{\phi rd}\left(\phi_{rd}^* - \phi_{rd}\right) \\ &+ \frac{\tau_r}{L_m}\dot{\phi}_{rd}^* + \frac{1}{L_m}\phi_{rd}^* \end{aligned}$$

Where $KI_{\phi rd}$ and $KP_{\phi rd}$ present respectively the integral and the proportional constant of the first (PI) regulator.
The dynamics of the flux errorΔ_ϕ is defined by:

$$\begin{aligned} \dot{\Delta}_\phi &= \dot{\phi}_{rd}^* - \dot{\phi}_{rd} \qquad (1) \\ &= \frac{-1}{\tau_r}\left(1 + L_m KP_{\phi rd}\right)\Delta_\phi - \frac{L_m KI_{\phi rd}}{\tau_r}\int_0^t \Delta_\phi(\tau)d\tau \end{aligned}$$

Let define the following coordinates:

$$\Gamma_\phi = [\int_0^t \Delta_\phi(\tau)d\tau, \Delta_\phi]^T \qquad (2)$$

Equation (1) becames:

$$\dot{\Gamma}_\phi = A_\phi \Gamma_\phi \qquad (3)$$

where $A_\phi = \begin{bmatrix} 0 & 1 \\ \beta_{1\phi} & \beta_{2\phi} \end{bmatrix}$ with $\beta_{1\phi} = -\frac{L_m KI_{\phi rd}}{\tau_r}$, $\beta_{2\phi} = \frac{-1}{\tau_r}\left(1 + L_m KP_{\phi rd}\right)$.
The gains $KI_{\phi rd}$ and $KP_{\phi rd}$ are obtained in such away that the matrix A_ϕ is stable.
Based on the pole placement technique,λ_1 and λ_2 where $(p+\lambda_1)(p+\lambda_2) = 0$ it yields:

$$KI_{\phi rd} = \frac{\lambda_1\lambda_2\tau_r}{L_m}, KP_{\phi rd} = \frac{-(\lambda_1+\lambda_2)\tau_r - 1}{L_m} \qquad (4)$$

B. Speed regulator Synthesis:

By ensured that the speed is equal to zero, we can establish the rotor flux in the machine.
Thus, ($\phi_{rd} = \phi_{rd}^* = constant$), the equation of the electromechanical torque become $C_{em} = K_T i_{sq}^*$ with K_T is a positive constant defined by $p\frac{L_m}{L_r}\varphi_{rd}$.
The quadrature reference current i_{sq}^* is defined as :

$$\begin{aligned} i_{sq}^* &= \frac{1}{K_T}[KI_\Omega \int_0^t \left(\Omega^* - \Omega\right)d\tau + KP_\Omega\left(\Omega^* - \Omega\right)] \\ &+ \frac{1}{L_m\phi_{rd}}[\dot{\Omega}^* + \Omega + \frac{T_l}{J}] \qquad (5) \end{aligned}$$

The dynamics of the speed error Δ_Ω is given by:

$$\dot{\Delta}_\Omega = \dot{\Omega}^* - \dot{\Omega} = -\frac{KP_\Omega}{J}\Delta_\Omega - \frac{KI_\Omega}{J}\int_0^t \Delta_\Omega(\tau)d\tau \qquad (6)$$

Consider the coordinates change as :

$$\Gamma_\Omega = \left[\int_0^t \Delta_\Omega(\tau)d\tau, \Delta_\Omega\right]^T \qquad (7)$$

Equation (6) in the new coordinates becomes:

$$\dot{\Gamma}_\Omega = A_\Omega \Gamma_\Omega \qquad (8)$$

where $A_\Omega = \begin{bmatrix} 0 & 1 \\ \beta_{1\Omega} & \beta_{2\Omega} \end{bmatrix}$ with $\beta_{1\Omega} = -\frac{KI_\Omega}{J}$, $\beta_{2\Omega} = -\frac{KP_\Omega}{J}$.
The gains KI_Ω and KP_Ω are determined using the same way as the d-axis current controller gains
Thus,

$$KI_\Omega = \lambda_1\lambda_2 J; KP_\Omega = -(\lambda_1+\lambda_2)J \qquad (9)$$

Remark 1. Since A_ϕ andA_Ω are two stable matrixes, so $\forall\ Q_\phi \geqslant 0$ and $Q_\Omega \geqslant 0$,
$\exists\ P_\phi = P_\phi^T \geqslant 0$ and $P_\Omega = P_\Omega^T \geqslant 0$ defined as:

$$\begin{aligned} P_\phi A_\phi + A_\phi^T P_\phi &= -Q_\phi \qquad (10) \\ P_\Omega A_\Omega + A_\Omega^T P_\Omega &= -Q_\Omega \end{aligned}$$

Theorem 1. [27] Consider the IM model represented by equation (1) with the reference signals Ω^* and ϕ_{rd}^*. $U = [u_{sd}, u_{sq}]^T$ is a control law for system (1) that forces the IM states variables to follow their references, with:

$$u_{sd} = \sigma L_s \left(K_{isd}\Delta_{isd} + i_{sd}^* - \delta_1\right) \quad (11)$$

$$u_{sq} = \sigma L_s \left(K_{isq}\Delta_{isq} + i_{sq}^* - \delta_2\right) \quad (12)$$

Where:
$\Delta_{isd} = i_{sd}^* - i_{sd}, \Delta_{isq} = i_{sq}^* - i_{sq}$
$\delta_1 = -\gamma_1 i_{sd} + \frac{\gamma_2}{\tau_r}\phi_{rd} + p\Omega i_{sq} + \frac{L_m}{\tau_r}\frac{i_{sq}^2}{\phi_{rd}}$,
$\delta_2 = -\gamma_1 i_{sq} - p\Omega i_{sd} - p\Omega\gamma_2\phi_{rd} - \frac{L_m}{\tau_r}\frac{i_{sd}i_{sq}}{\phi_{rd}}$
K_{isd}, K_{isq} tow positive constants.

III. Interconnected observer

A. Observer design

The induction machine model 1can be seen as the interconnection between two subsystems as follows:

$$\begin{cases} \dot{x}_1 = A_1(x_2)\,x_1 + g_1(u, x_2, x_1) \\ y_1 = C_1 x_1 \end{cases} \quad (13)$$

$$\begin{cases} \dot{x}_2 = A_2(x_1)\,x_2 + \phi(u, y) \\ y_2 = C_2 x_2 \end{cases} \quad (14)$$

with
$A_1(x_2) = \begin{bmatrix} 0 & \gamma_2 p\phi_{r\beta} \\ 0 & 0 \end{bmatrix}$,
$A_2(x_1) = \begin{bmatrix} -\gamma_1 & -\gamma_2 p\Omega & \frac{\gamma_2}{\tau_r} \\ 0 & \frac{-1}{\tau_r} & -p\Omega \\ 0 & p\Omega & \frac{-1}{\tau_r} \end{bmatrix}$
$g_1(u, x_2, x_1) = \begin{bmatrix} -\gamma_1 i_{s\alpha} + \frac{\gamma_2}{\tau_r}\phi_{r\alpha} + m_1 u_{s\alpha} \\ -m\left(\phi_{r\alpha} i_{s\beta} - \phi_{r\beta} i_{s\alpha}\right) - c\Omega + \frac{1}{J}T_l \end{bmatrix}$,
$\phi(u, y) = \begin{bmatrix} m_1 u_{s\beta} \\ \frac{L_m}{\tau_r} i_{s\alpha} \\ \frac{L_m}{\tau_r} i_{s\beta} \end{bmatrix}$
$C_1 = C_2 = \begin{bmatrix} 1 & 0 \end{bmatrix}$
where $x_1 = [i_{s\alpha}\Omega]^T$, $x_2 = [i_{s\beta}\phi_{r\alpha}\phi_{r\beta}]^T$ are respectively the state vectors of systems (13) and (14).
The interconnected observer is based on the interconnection between several observers and requires some properties as the property of the input persistence.
Remark 2. It is clear that :

- $A_1(x_2)$ is globally lipschitz with respect to x_2.
- $g_1(u, x_2, x_1)$ is globally lipschitz with respect to the pair (u, x_1).
- $A_2(x_1)$ is globally lipschitz with respect to x_1.

Then, a high gain observers for the system (13)-(14) are given respectively by:

$$\begin{cases} \dot{\hat{x}}_1 = A_1(\hat{x}_2)\,\hat{x}_1 + g_1(u, \hat{x}_2, \hat{x}_1) + M_1(\hat{x}_2, \theta_1)(y_1 - \hat{y}_1) \\ \dot{\hat{y}}_1 = C_1\hat{x}_1 \end{cases} \quad (15)$$

$$\begin{cases} \dot{\hat{x}}_2 = A_2(\hat{x}_1)\,\hat{x}_2 + \phi(u, y) + M_2(\theta_2, \hat{x}_1)(y_2 - \hat{y}_2) \\ \dot{\hat{y}}_2 = C_2\hat{x}_2 \end{cases} \quad (16)$$

where
$\hat{x}_1 = [\hat{i}_{s\alpha}\hat{\Omega}]^T$is the estimated vector of $x_1\hat{x}_2 = [\hat{i}_{s\beta}\hat{\phi}_{r\alpha}\hat{\phi}_{r\beta}]^T$ is the estimated vector of x_2
$A_1(\hat{x}_2) = \begin{bmatrix} 0 & \gamma_2 p\hat{\phi}_{r\beta} \\ 0 & 0 \end{bmatrix}$,
$A_2(\hat{x}_1) = \begin{bmatrix} -\gamma_1 & -\gamma_2 p\hat{\Omega} & \frac{\gamma_2}{\tau_r} \\ 0 & \frac{-1}{\tau_r} & -p\hat{\Omega} \\ 0 & p\hat{\Omega} & \frac{-1}{\tau_r} \end{bmatrix}$
And $g_1(u, \hat{x}_2, \hat{x}_1)$ is the estimation term of $g_1(u, x_2, x_1)$.
The observer gain $M_1(\hat{x}_2, \theta_1)$ is given by:

$$M_1(\theta_1, \hat{x}_2) = \Gamma^{-1}(\hat{x}_2) S_1^{-1} C_1^T \quad (17)$$

Where :
$\Gamma(\hat{x}_2) = \begin{bmatrix} 1 & 0 \\ 0 & \gamma_2 p\hat{\phi}_{r\beta} \end{bmatrix}$ is the solution of the following equation:

$$\dot{S}_1(\theta_1) = -\theta_1 S_1(\theta_1) - A_0^T S_1(\theta_1) - S_1(\theta_1)A_0 + C_1^T C_1$$

with θ_1 is a positive constant and $A_0 = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}$.
The second observer gain is:

$$M_2(\theta_2, \hat{x}_1) = S_2^{-1} C_2^T \quad (18)$$

is obtained by solving the differential equation:

$$\begin{aligned} \dot{S}_2(\theta_2, \hat{x}_1) &= -\theta_2 S_2(\theta_2, \hat{x}_1) - A_2^T S_2(\theta_2, \hat{x}_1) \\ &\quad - S_2(\theta_2, \hat{x}_1)A_2 + C_2^T C_2 \end{aligned} \quad (19)$$

with θ_2 is a positive constant
An estimator of the load torque T_l is given by the following equation:

$$\begin{aligned} \hat{T}_l &= J\frac{d}{dt}\hat{\Omega} + f\hat{\Omega} + Jm\left(\hat{\phi}_{r\alpha}\hat{i}_{s\beta} - \hat{\phi}_{r\beta}\hat{i}_{s\alpha}\right) \\ &\quad + \Gamma^{-1}(\hat{x}_2) S_1^{-1} C_1^T C_1 (i_{s\alpha} - \hat{i}_{s\alpha}) \end{aligned} \quad (20)$$

B. Stability analysis of the interconnected observer under parametric variations

The estimation errors are defined by:

$$e_1 = x_1 - \hat{x}_1; e_2 = x_2 - \hat{x}_2 \quad (21)$$

The dynamics error e_1 is given by:

$$\begin{aligned} \dot{e}_1 &= [A_1(\hat{x}_2) - \Gamma^{-1}(\hat{x}_2) S_1^{-1} C_1^T C_1]e_1 + g_1(u, x_2, x_1) \\ &\quad - g_1(u, \hat{x}_2, \hat{x}_1) + [A_1(x_2) - A_1(\hat{x}_2)]\,x_1 \end{aligned} \quad (22)$$

The dynamics error e_2 is defined as:

$$\dot{e}_2 = A_2(x_1)x_2 - A_2(\hat{x}_1)\hat{x}_2 - S_2^{-1}(\theta_2,\hat{x}_1)C_2^T C_2 e_2 \tag{23}$$

Considering the uncertainties on the IM parameters, equations (22) and (23) become:

$$\begin{aligned}\dot{e}_1 &= [A_1(\hat{x}_2) - \Gamma^{-1}(\hat{x}_2)S_1^{-1}C_1^T C_1]e_1 + g_1(u,x_2,x_1)\\ &\quad -g_1(u,\hat{x}_2,\hat{x}_1) + \delta g_1(u,x_2,x_1)\\ &\quad +[A_1(x_2) - A_1(\hat{x}_2) + \delta A_1(x_2)]x_1\end{aligned} \tag{24}$$

$$\begin{aligned}\dot{e}_2 &= [A_2(x_1) + \delta A_2(x_1)]x_2\\ &\quad -A_2(\hat{x}_1)\hat{x}_2 - S_2^{-1}(\theta_2,\hat{x}_1)C_2^T C_2 e_2\end{aligned} \tag{25}$$

where $\delta g_1(u,x_2,x_1)$, $\delta A_1(x_2)$ and $\delta A_2(x_1)$ are respectively the uncertain terms of $g_1(u,x_2,x_1)$, $A_1(x_2)$ and $A_2(x_1)$.
The machine states and parameters are known accurately and they are bounded.

$$\begin{cases} \|\delta g_1(u,x_2,x_1)\| & \leqslant \alpha_1\\ \|\delta A_1(x_2)\| & \leqslant \alpha_2\\ \|\delta A_2(x_1)\| & \leqslant \alpha_3\end{cases} \tag{26}$$

Lemma 1. Assume that the input w is regularly persistent for a given state affine system and consider the Lyapunov differential equation defined as:

$$\dot{S}(t) = -\theta S(t) - A^T(w(t))S(t) - S(t)A(w(t)) + C^T C$$

with $S(0) \geqslant 0$, then $\exists\theta_0, \forall\theta \geqslant \theta_0, \exists\alpha > 0, \beta > 0, t_0 > 0$: $\forall t_0$, $\alpha I \leqslant S(t) \leqslant \beta I$ where I is the identity matrix.
Remark 3.
It is clear that $w = \hat{x}_2$ and $S(t) = S_1$ for subsystem (15), and $w = \hat{x}_1$ and $S(t) = S_2$ for the second subsystem (16).
Theorem 3. [28] Consider the Induction Motor model presented by (13) and (14), system (15)-(16), is a high gain interconnected observer for system (13)-(14) respectively.

IV. Observer-controller scheme stability analysis:

The main goal is to achieve a control without a mechanical sensor for the IM. Speed and flux are not measured, so the outputs of the speed and flux regulator will be presented as follows :

$$\begin{aligned} i_{sq}^* &= \frac{1}{K_T}[KI_\Omega \int_0^t \left(\Omega^* - \hat{\Omega}\right)d\tau + KP_\Omega\left(\Omega^* - \hat{\Omega}\right)]\\ &\quad + \frac{1}{m\hat{\phi}_{rd}}[\dot{\Omega}^* + c\hat{\Omega} + \frac{\widehat{T_l}}{J}]\end{aligned} \tag{27}$$

$$\begin{aligned} i_{sd}^* &= KI_{\phi rd}\int_0^t \left(\phi_{rd}^* - \hat{\phi}_{rd}\right)(\tau)\,d\tau\\ &\quad + KP_{\phi rd}\left(\phi_{rd}^* - \hat{\phi}_{rd}\right) + \frac{\tau_r}{L_m}\dot{\phi}_{rd}^* + \frac{1}{L_m}\phi_{rd}^*\end{aligned} \tag{28}$$

where $\hat{\Omega}$ and $\hat{\phi}_{rd}$ are the estimated values of the speed and flux given by the adaptive observer.
The reduced closed loop model of the controlled machine become:

$$\begin{bmatrix}\dot{\Omega}\\ \dot{\phi}_{rd}\end{bmatrix} = \begin{bmatrix} m\phi_{rd} i_{sq}^*\left(\hat{\Omega},\hat{\phi}_{rd}\right) - c\Omega - \frac{T_l}{J}\\ \frac{L_m}{\tau_r} i_{sd}^*\left(\hat{\phi}_{rd}\right) - \frac{1}{\tau_r}\phi_{rd}\end{bmatrix}$$

or

$$\begin{bmatrix}\dot{\Omega}\\ \dot{\phi}_{rd}\end{bmatrix} = \begin{bmatrix} m\phi_{rd} i_{sq}^*(\Omega,\phi_{rd}) - c\Omega - \frac{T_l}{J}\\ +m\phi_{rd}\left[i_{sq}^*\left(\hat{\Omega},\hat{\phi}_{rd}\right) - i_{sq}^*(\Omega,\phi_{rd})\right]\\ \frac{L_m}{\tau_r} i_{sd}^*(\phi_{rd}) - \frac{1}{\tau_r}\phi_{rd}\\ +\frac{L_m}{\tau_r}\left[i_{sd}^*\left(\hat{\phi}_{rd}\right) - i_{sd}^*(\phi_{rd})\right]\end{bmatrix}$$

The dynamic errors equations (3) and (8) become, respectively:

$$\begin{cases}\dot{\Gamma}_\phi = A_\phi\Gamma_\phi + B_\phi\chi_\phi(\varepsilon_\phi)\\ \dot{\Gamma}_\Omega = A_\Omega\Gamma_\Omega + B_\Omega\chi_\Omega(\varepsilon_\Omega)\end{cases} \tag{29}$$

where $\varepsilon_\phi = \phi_{rd} - \hat{\phi}_{rd}$

$$\begin{aligned}\chi_\phi(\varepsilon_\phi) &= -\frac{L_m}{\tau_r}\left[KP_{\phi rd}\varepsilon_\phi + KI_{\phi rd}\int_0^t \varepsilon_\phi(\tau)\,d\tau\right]\\ \chi_\Omega(\varepsilon_\Omega) &= \chi_1(\varepsilon_\Omega) + \chi_2(\varepsilon_\phi) + \chi_3(\varepsilon_\Omega,\varepsilon_\phi)\\ \chi_1(\varepsilon_\Omega) &= \frac{KI_\Omega}{J}\int_0^t \varepsilon_\Omega(\tau)\,d\tau + \left[\frac{KP_\Omega}{J} - c\right]\varepsilon_\Omega\\ \chi_2(\varepsilon_\phi) &= \frac{\varepsilon_\phi}{\hat{\phi}_{rd}}\left[\Omega^* + c\hat{\Omega} + \frac{\hat{T}_l}{J}\right] - \frac{KP_\Omega}{J}\left(\frac{\varepsilon_\phi}{\hat{\phi}_{rd}}\right)\Delta_\Omega\\ &\quad - \frac{KI_\Omega}{J}\left(\frac{\varepsilon_\phi}{\hat{\phi}_{rd}}\right)\int_0^t \Delta_\Omega(\tau)\,d\tau\\ \chi_3(\varepsilon_\Omega,\varepsilon_\phi) &= \frac{\varepsilon_\phi}{\hat{\phi}_{rd}}\left[\frac{KP_\Omega}{J}\varepsilon_\Omega + \frac{KI_\Omega}{J}\int_0^t \varepsilon_\Omega(\tau)\,d\tau\right]\end{aligned}$$

$$B_\phi = B_\Omega = \begin{bmatrix}0\\1\end{bmatrix}$$

For the closed loop system, The dynamic error is given by:

$$\begin{aligned}\dot{\Gamma}_\phi &= A_\phi\Gamma_\phi + B_\phi\chi_\phi(\varepsilon_\phi)\\ \dot{\Gamma}_\Omega &= A_\Omega\Gamma_\Omega + B_\Omega\chi_\Omega(\varepsilon_\Omega)\\ \dot{e}_1 &= [A_1(\hat{x}_2) - \Gamma^{-1}(\hat{x}_2)S_1^{-1}C_1^T C_1]e_1 + g_1(u,x_2,x_1)\\ &\quad +\delta g_1(u,x_2,x_1)[A_1(x_2) - A_1(\hat{x}_2) + \delta A_1(x_2)]x_1\\ &\quad -g_1(u,\hat{x}_2,\hat{x}_1)\\ \dot{e}_2 &= [A_2(x_1) + \delta A_2(x_1)]x_2 - A_2(\hat{x}_1)\hat{x}_2\\ &\quad -S_2^{-1}(\theta_2,\hat{x}_1)C_2^T C_2 e_2\end{aligned}$$

Theorem 4. Consider the reduced model of the induction machine. If the speed and the flux regulators use the estimated variables given by the interconnected observer (15)-(16), then the errors of the flux and the speed asymptotically converge to zero.

Proof of Theorem 4

The control voltage u_{sd} and u_{sq} are chosen as:

$$u_{sd} = \sigma L_s \left(K_{isd}\varepsilon_{isd} + i^*_{sd}\left(\hat{\phi}_{rd}\right) - \delta_1 \right) \quad (30)$$

$$u_{sq} = \sigma L_s \left(K_{isq}\varepsilon_{isq} + i^*_{sq}\left(\hat{\Omega}, \hat{\phi}_{rd}\right) - \delta_2 \right) \quad (31)$$

with $\varepsilon_{isd} = i^*_{sd}\left(\hat{\phi}_{rd}\right) - i_{sd}; \varepsilon_{isq} = i^*_{sq}\left(\hat{\Omega}, \hat{\phi}_{rd}\right) - i_{sq}$

Consider the Lyapunov function defined as:

$$V_{oc} = V_o + V_c = V_1 + V_2 + \Gamma_\phi^T P_\phi \Gamma_\phi + \Gamma_\Omega^T P_\Omega \Gamma_\Omega + \frac{1}{2}(\varepsilon_{isd}^2 + \varepsilon_{isq}^2) \quad (32)$$

Admitting the equation (39) in [28], we have

$$\dot{V}_o \leqslant -\left(1-\varepsilon\right)\lambda_1 \mathrm{V} \leqslant \delta_0 \mathrm{V}; \forall \left\|\mathrm{e}\right\| \geqslant \frac{\lambda_2 \psi}{\varepsilon \lambda_1} \quad (33)$$

with $\delta_0 = (1-\varepsilon)\lambda_1$.

The derivative of equation (32) is given by:

$$\begin{aligned} \dot{V}_{oc} \leqslant\ & -\delta_0 \left\|e\right\|^2 + \Gamma_\varphi^T (P_\phi A_\phi + A_\phi^T P_\phi)\Gamma_\phi \quad (34) \\ & + \Gamma_\Omega^T \left(P_\Omega A_\Omega + A_\Omega^T P_\Omega\right)\Gamma_\Omega - K_{isq}\varepsilon_{isq}^2 \\ & + 2\Gamma_\phi^T P_\phi B_\phi \chi_\phi + 2\Gamma_\Omega^T P_\Omega B_\Omega \chi_\Omega - K_{isd}\varepsilon_{isd}^2 \\ & + \varepsilon_{isd}\left(K_{isd}\varepsilon_{isd} + i^*_{sd} - \delta_1 - \frac{1}{\sigma L_s} u_{sd}\right) \\ & + \varepsilon_{isq}\left(K_{isq}\varepsilon_{isq} + i^*_{sq} - \delta_2 - \frac{1}{\sigma L_s} u_{sq}\right) \end{aligned}$$

Replacing the control voltages by their value, equation (34) become:

$$\begin{aligned} \dot{V}_{oc} \leqslant\ & -\delta_0 \left\|e\right\|^2 - \eta_\phi \left\|\Gamma_\phi\right\|^2 - \eta_\Omega \left\|\Gamma_\Omega\right\|^2 \\ & + 2l_1 \left\|\Gamma_\phi\right\| \left\|e\right\| + 2l_2 \left\|\Gamma_\Omega\right\| \left\|e\right\| - K_{isd}\varepsilon_{isd}^2 \\ & - K_{isq}\varepsilon_{isq}^2 \quad (35) \end{aligned}$$

where

$$\left\|\chi_\phi(\varepsilon_\phi)\right\| \leqslant l_1 \left\|e\right\| and \left\|\chi_\Omega(\varepsilon_\Omega)\right\| \leqslant l_2 \left\|e\right\|, l_1 > 0, l_2 > 0$$

Considering the following inequalities:

$$\begin{aligned} \left\|e\right\| \left\|\Gamma_\phi\right\| &\leqslant \frac{\zeta_1}{2}\left\|\Gamma_\phi\right\|^2 + \frac{1}{2\zeta_1}\left\|e\right\|^2 \\ \left\|e\right\| \left\|\Gamma_\Omega\right\| &\leqslant \frac{\zeta_2}{2}\left\|\Gamma_\Omega\right\|^2 + \frac{1}{2\zeta_2}\left\|e\right\|^2 \end{aligned}$$

$\forall \zeta_1, \zeta_2 \in]0, 1[$

We obtain :

$$\begin{aligned} \dot{V}_{oc} \leq\ & -\delta_0 \left\|e\right\|^2 - \eta_\phi \left\|\Gamma_\phi\right\|^2 - \eta_\Omega \left\|\Gamma_\Omega\right\|^2 + l_1\zeta_1 \left\|\Gamma_\phi\right\|^2 \\ & + l_2\zeta_2 \left\|\Gamma_\Omega\right\|^2 - K_{isd}\varepsilon_{isd}^2 - K_{isq}\varepsilon_{isq}^2 + \frac{l_1}{\zeta_1}\left\|e\right\|^2 \\ & + \frac{l_2}{\zeta_2}\left\|e\right\|^2 \quad (36) \end{aligned}$$

This gives:

$$\begin{aligned} \dot{V}_{oc} \leq\ & -(\delta_0 - \frac{l_1}{\zeta_1} - \frac{l_2}{\zeta_2})\left\|e\right\|^2 - (\eta_\phi - l_1\zeta_1)\left\|\Gamma_\phi\right\|^2 \quad (37) \\ & -(\eta_\Omega - l_2\zeta_2)\left\|\Gamma_\Omega\right\|^2 - 2K_{isd}(\frac{1}{2}\varepsilon_{isd}^2) - 2K_{isq}(\frac{1}{2}\varepsilon_{isq}^2) \end{aligned}$$

We define

$$v = \min(\sigma_1, \sigma_2, \sigma_3, 2K_{isq}, 2K_{isd})$$

where

$$\sigma_1 = \delta_0 - \frac{l_1}{\zeta_1} - \frac{l_2}{\zeta_2}, \sigma_2 = \eta_\phi - l_1\zeta_1, \sigma_3 = \eta_\Omega - l_2\zeta_2$$

The derivative of V_{oc} becomes:

$$\dot{V}_{oc} \leqslant -v V_{oc} \quad (38)$$

By choosing η_ϕ, η_Ω and δ_0 such that σ_1, σ_2 and σ_3 are greater than zero. Then, flux and speed errors converge asymptotically to zero.

V. SIMULATION RESULTS

Simulation results have been carried out using Matlab/Simulink. The nominal parameters of the IM used in simulations are given in Table 1.

TABLE I
IM NOMINAL PARAMETERS

Magnitude	Value
P_nNominal power	3kW
V_n Nominal voltage	220V
Ω	1460 tr/min
p	2
f_n	50Hz
R_s	1.411Ω
R_r	1.045Ω
L_s	0.1164H
L_r	0.1164H
L_m	0.1113H
J	$0.0116 kg.m^2$

Figure 1 illustrates the simulation results of the sensorless control for IM with nominal parameters.

The evolution of the speed and the flux are presented in Figures 1.(a) and 1.(c) respectively. The speed error is displayed in Figure 1.(b), the Flux error is displayed in Figure 1.(d). It is obvious that the estimated speed and Flux track their actual values very well.

In order to illustrate the robustness of the sensorless control scheme, the influence of parameter deviations is investigated. First, Figure 2 shows the responses for a 50% increase of the stator and rotor resistances.

Secondly, Figure 3 presents the robustness with respect to the inductances variations. According to Figures 2.(b), 2.(d), 3.(b) and 2.(d), the observer converges perfectly and gives desirable results which proves the robustness of the suggested sensorless control.

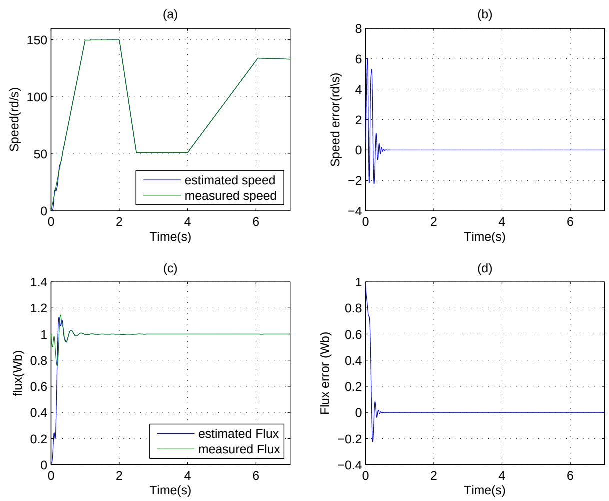

Fig. 1. Speed and Flux Tracking nominal case. Legend: (a): Speed tracking, (b): Speed error, (c): Flux tracking , (d): Flux error

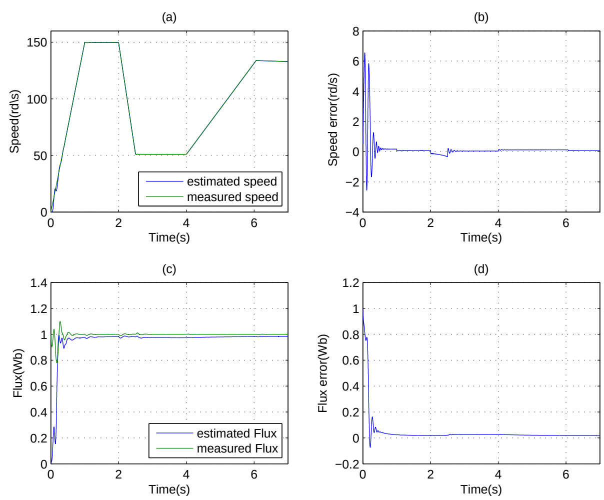

Fig. 2. Speed and Flux Tracking with respect to +50% on R_s and R_r. Legend: (a): Speed tracking, (b): Speed error, (c): Flux tracking , (d): Flux error

VI. CONCLUSION

In this paper we have developed a sensorless control for IM combining a new control approach with an interconected observer. The global stability of both controller and observer is guaranteed by Lyapunov stability analysis. Simulation results confirm the effectiveness of the proposed method under uncertainties parameter.

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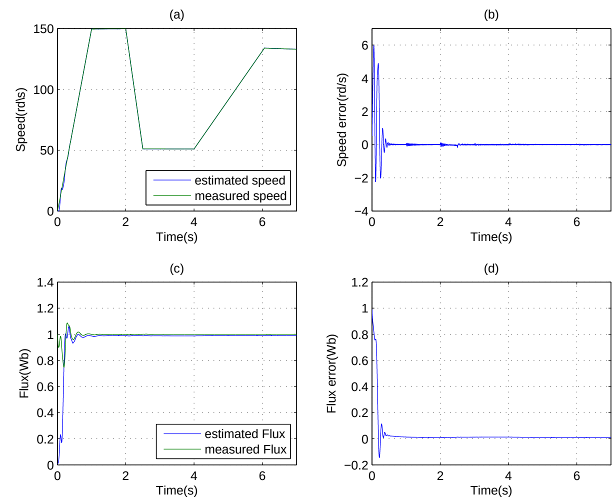

Fig. 3. Speed and Flux Tracking with respect to -20% on L_m, $L_r$and L_s. Legend: (a): Speed tracking, (b): Speed error, (c): Flux tracking , (d): Flux error

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