OBSERVER-BASED FIELD-ORIENTED ADAPTIVE CONTROL OF INDUCTION MOTOR

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Abstract

This paper deals with the control and observation of an induction motor using adaptive field-oriented control. Our aim is to regulate the speed and the rotor flux components to specified references. The reduced current model is used to estimate the rotor flux components. In addition, the load torque is estimated to ensure the speed tracking convergence. The simulation results show that the proposed control system is effective in the estimation and control of the induction motor rotor flux and speed.

1. INTRODUCTION

The field-oriented control for induction motors was introduced for the first time by Blaschke in the early 1970s [1]. The main objective of this control method is, as in separately excited DC machines, to independently control the torque and the flux; this is done by choosing a d-q rotating reference frame synchronously with the rotor flux space vector [5][10][11]. Once the orientation is correctly achieved, the torque is controlled by the torque producing current, which is the q-component of the stator current space vector. At the same time, the flux is controlled by the flux producing current, which is the d-component of the stator current space vector.

The two basic forms of rotor flux orientation for induction motor drives are, by now, direct field-orientation and indirect field-orientation. Direct field-orientation relies on direct measurement or estimation of the rotor flux vector, and indirect field-orientation utilizes an inherent slip relationship to align the rotor flux vector with the d-axis [1]. Because an indirect field-orientation is essentially a feedforward scheme, it is naturally sensitive to deviation in the motor parameters, particularly the rotor time-constant.

The development of parameter adaptation and identification has been presented in many publications [2-5]. Direct field-orientation via air-gap flux measurement is difficult and complicated to implement by locating the intrusive flux sensors within the machine air gap [6].

On the other hand, estimation rather than measurement of the rotor flux as an alternative approach for direct field-orientation has received considerable attention [6-13]. As for the adaptive flux observer [11,12], it is a full-order estimator, and the observer gain is a function of the rotor speed so that the designed poles of the observer are assigned to the left-half plane for a wide range of rotor speeds. However, the transient performance depending on the location of the observer poles is varied during the control transient. The robustness of the motor parameters is not discussed. The extended Kalman filter method is also utilized to estimate the rotor flux linkages [13]. Consequently, the Kalman filter method takes much computation time for estimating the rotor flux. Therefore, high-speed calculation hardware is needed for the extended Kalman lter observer.

An adaptive field-oriented control tuning is developed in this study. Based on the rotor flux observation from a simple current-model. That is, the proposed adaptive field-oriented control is robust to variation in load torque. Moreover, due to the simple algorithm structrure the real-time implementation is possible. The simulation results show good and effective performance.

In this paper, the following notations are used:

ω mechanical speed;
ω_{ref} speed reference;
I_d , I_q stator currents;
ψ_d , ψ_q rotor fluxes;
ψ_{ref} rotor flux reference;
R_r , L_r rotor inductance and resistance;
M mutual inductance;
J moment of inertia;
P pair of poles;
T_l load torque; $\alpha = R_r / L_r$ and $\mu = PM / JL_r$.

2. FIELD-ORIENTED CONTROL

The current-fed induction motor mathematical model established in d-q coordinate system rotating at synchronous speed ω_s is given by the following equations.

$$\dot{\psi}_d = -\alpha\psi_d + \omega_{sl}\psi_q + \alpha M I_d \tag{1}$$

$$\dot{\psi}_q = -\alpha\psi_q - \omega_{sl}\psi_d + \alpha M I_q \tag{2}$$

$$\dot{\omega} = \mu\left(\psi_d I_q - \psi_q I_d\right) - \frac{T_l}{J} \tag{3}$$

where $\omega_{sl} = \omega_s - P\omega$ is the slip frequency.

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In the direct field control the speed is required to follow a reference speed ω_{ref}. The q-axis ψ_q is forced to zero and the d-axis flux ψ_d is forced to track the reference flux ψ_{ref}.

Using the above field-oriented control definition and the induction machine model (1)-(3), the speed and flux tracking errors are given by

$$\dot{e}_d = \dot{\psi}_{ref} + \alpha\psi_d - \omega_{sl}\psi_q - \alpha M I_d \quad (4)$$

$$\dot{e}_q = -\alpha e_q + \omega_{sl}\psi_d - \alpha M I_q \quad (5)$$

$$\dot{e} = \dot{\omega}_{ref} - \mu\left(\psi_d I_q - \psi_q I_d\right) + \frac{T_l}{J} \quad (6)$$

where $e_d = \psi_{ref} - \psi_d$, $e_q = -\psi_q$ and $e = \omega_{ref} - \omega$.

If the flux is measured and the load torque is known, the following control inputs

$$I_q = \frac{1}{\mu\psi_{ref}}\left(k_1 e + \dot{\omega}_r + \frac{T_l}{J}\right) \quad (7)$$

$$I_d = \frac{1}{\alpha M}\left(k_2 e_d + \dot{\psi}_r + \alpha\psi_r + \varepsilon_d\right) \quad (8)$$

$$\omega_{sl} = \frac{1}{\psi_{ref}}\left(-k_2 e_q + \alpha M I_q + \varepsilon_q\right) \quad (9)$$

yields the closed loop tracking errors

$$\dot{e}_d = -\left(\alpha + k_2\right)\ e_d + \omega_{sl} e_q - \varepsilon_d \quad (10)$$

$$\dot{e}_q = -\left(\alpha + k_2\right)\ e_q - \omega_{sl} e_d - \varepsilon_q \quad (11)$$

$$\dot{e} = -k_1 e + \mu e_d I_q - \mu e_q I_d \quad (12)$$

To check the stability of closed loop dynamic, let's define the Lyapunov function

$$V = \frac{1}{2}e^2 + \frac{1}{2}\left(e_d^2 + e_q^2\right) \quad (13)$$

The differentiation of (13) along (10)-(12) yields

$$\begin{aligned}\dot{V} = &-k_1 e^2 - \left(\alpha + k_2\right)e_d^2 - \left(\alpha + k_2\right)e_q^2 \\ &e\left(\mu e_d I_q - \mu e_q I_d\right) - \varepsilon_d e_d - \varepsilon_q e_q\end{aligned} \quad (14)$$

Then, making the following choices

$$\varepsilon_d = \mu I_q e \quad (15)$$

$$\varepsilon_q = -\mu I_d e \quad (16)$$

and replacing in (14) yields

$$\dot{V} = -k_1 e^2 - \left(\alpha + k_2\right)\ e_d^2 - \left(\alpha + k_2\right)\ e_q^2 \quad (17)$$

The result (17) indicates that, in the ideal case, the speed and flux tracking errors converge exponentially to zero.

3. OBSERVER-BASED ADAPTIVE CONTROL

To estimate the unavailable flux components, the following flux observer is designed

$$\dot{\hat{\psi}}_d = -\alpha\hat{\psi}_d + \omega_{sl}\hat{\psi}_q + \alpha M I_d + \varepsilon_d \quad (18)$$

$$\dot{\hat{\psi}}_q = -\alpha\hat{\psi}_q - \omega_{sl}\hat{\psi}_d + \alpha M I_q + \varepsilon_q \quad (19)$$

where $\hat{\psi}_d$ and $\hat{\psi}_q$ are flux components estimations. The terms ε_d and ε_q are designed to compensate for coupling terms from the speed tracking loop.

Then, the flux estimation errors are given by

$$\dot{\hat{\psi}}_d = -\alpha\hat{\psi}_d + \omega_{sl}\hat{\psi}_q - \varepsilon_d \quad (20)$$

$$\dot{\hat{\psi}}_q = -\alpha\hat{\psi}_q - \omega_{sl}\hat{\psi}_d - \varepsilon_q \quad (21)$$

where $\hat{\psi}_d = \psi_d - \hat{\psi}_d$, $\hat{\psi}_q = \psi_q - \hat{\psi}_q$.

To realize the speed tracking, the q-axis current is defined as

$$I_q = \frac{1}{\mu\psi_{ref}}\left(k_1 e + \dot{\omega}_r + \frac{\hat{T}_l}{J}\right) \quad (22)$$

where $\hat{T}_l$ is the estimated load torque.

Using (22) and (6), the closed loop speed tracking error is given by

$$\dot{e} = -k_1 e + \mu e_d I_q - \mu e_q I_d + \frac{\hat{T}_l}{J} \quad (23)$$

where $\hat{T}_l = T_l - \hat{T}_l$ is the load torque estimation error.

Observing that $e_d = \hat{e}_d - \hat{\psi}_d$ ($e_q = \hat{e}_q - \hat{\psi}_q$), (23) can be rewritten as

$$\begin{aligned}\dot{e} = &-k_1 e + \frac{\hat{T}_l}{J} + \mu I_q \hat{e}_d - \mu I_d \hat{e}_q \\ &-\mu I_q \hat{\psi}_d + \mu I_d \hat{\psi}_q\end{aligned} \quad (24)$$

The estimated flux tracking errors dynamic are given by

$$\dot{\hat{e}}_d = \dot{\psi}_{ref} + \alpha\hat{\psi}_d - \omega_{sl}\hat{\psi}_q - \alpha M I_d - \varepsilon_d \quad (25)$$

$$\dot{\hat{e}}_q = -\alpha\hat{e}_q + \omega_{sl}\hat{\psi}_d - \alpha M I_q - \varepsilon_q \quad (26)$$

The control inputs are chosen such as

$$I_d = \frac{1}{\alpha M}\left(k_2\hat{e}_d + \dot{\psi}_{ref} + \alpha\psi_{ref} + \upsilon_d\right) \quad (27)$$

$$\omega_{sl} = \frac{1}{\psi_{ref}}\left(-k_2\hat{e}_q + \alpha M I_q + \upsilon_q\right) \quad (28)$$

Then, substituting (27)-(28) in (25)-(26) yields

$$\dot{\hat{e}}_d = -\left(\alpha + k_2\right)\ e_d + \omega_{sl}\hat{e}_q - \varepsilon_d - \upsilon_d \quad (29)$$

$$\dot{\hat{e}}_q = -\left(\alpha + k_2\right)\ \hat{e}_q - \omega_{sl}\hat{e}_d - \varepsilon_q + \upsilon_q \quad (30)$$

To check the stability of the observer-based adaptive control, consider the Lyapunov function

$$V = \frac{1}{2}e^2 + \frac{1}{2}\left(\hat{e}_d^2 + \hat{e}_q^2\right) + \frac{1}{2\gamma_1}\left(\hat{\psi}_d^2 + \hat{\psi}_q^2\right) + \frac{1}{2\gamma_2}\hat{T}_l^2 \quad (31)$$

The differentiation of (31) along (24), (29)-(30), gives

$$\begin{aligned}\dot{V} = &-k_1 e^2 - \left(\alpha + k_2\right)\ e_d^2 - \left(\alpha + k_2\right)\ \hat{e}_q^2 \\ &-\frac{\alpha}{\gamma_1}\hat{\psi}_d^2 - \frac{\alpha}{\gamma_1}\hat{\psi}_q^2 \\ &+e\left(\mu I_q\hat{e}_d - \mu I_d\hat{e}_q - \mu I_q\hat{\psi}_d + \mu I_d\hat{\psi}_q\right) \\ &+\hat{e}_d\left(-\varepsilon_d - \upsilon_d\right) + \hat{e}_q\left(-\varepsilon_q + \upsilon_q\right) \\ &-\frac{1}{\gamma_1}\hat{\psi}_d\varepsilon_d - \frac{1}{\gamma_1}\hat{\psi}_q\varepsilon_q - \frac{1}{\gamma_2}\hat{T}_l^2\dot{\hat{T}}_l + \frac{1}{J}\hat{T}_l e\end{aligned} \quad (32)$$

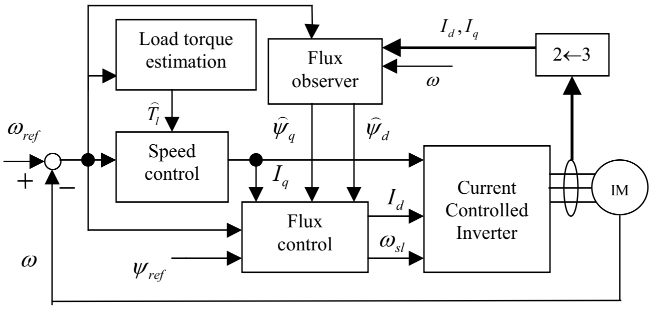

Fig. 1: Observer-based adaptive control structure.

Then, using the following choices

$$\varepsilon_d = -\gamma_1 e \mu I_q \quad (33)$$

$$\varepsilon_q = \gamma_1 e \mu I_d \quad (34)$$

$$\upsilon_d = \varepsilon_d - e \mu I_q \quad (35)$$

$$\upsilon_q = \varepsilon_q + e \mu I_d \quad (36)$$

$$\dot{\hat{T}} = \gamma_2 \frac{1}{J} e \quad (37)$$

and replacing in (32) yields

$$\dot{V} = -k_1 e^2 - \frac{\alpha}{\gamma_1}\left(\tilde{\psi}_d^2 + \tilde{\psi}_q^2\right) - (\alpha + k_2)\ \left(\tilde{e}_d^2 + \tilde{e}_q^2\right) \quad (38)$$

The last result (38) demonstrates that the tracking and observation errors converge asymptotically to zero. Since $\tilde{\psi}_d$ $\left(\tilde{\psi}_q\right)$ and $\hat{e}_d$ $\left(\hat{e}_q\right)$ converge to zero, $e_d = \hat{e}_d - \tilde{\psi}_d$ $\left(e_q = \hat{e}_q - \tilde{\psi}_q\right)$ converge also to zero.

Remark: *The proposed observer-based adaptive scheme is globally asymptotically stable without singularity even at the motor start-up when* $\phi_d = \phi_q = 0$. *This makes the application more simple, without any modification.*

4. SIMULATION

Figure 1 shows the implemented block diagram of the induction motor adaptive field-oriented control, based on the rotor flux estimation. The used induction motor and the adaptive control parameters are listed in the appendix

Figure 2 gives the performance of the implemented algorithm for a constant load torque. Figure 3 depicts the performance for a change of the load torque from 2 Nm to 0 Nm at 1 sec. Figure 4 shows the control performance under flux weakening regime, where the speed is changed from 50 rd/sec to 100 rd/sec at 1 sec (overspeed). Finally, figure 5 illustrates the performance control under speed inversion, where the speed is changed from 50 rd/sec to -50 rd/sec at 1 sec. It is clear from the depicted plots that load torque and flux components are correctly estimated, the controlled speed and flux converge to their respective references. and the control inputs reacts fast and promptly to any change in the references or parameters.

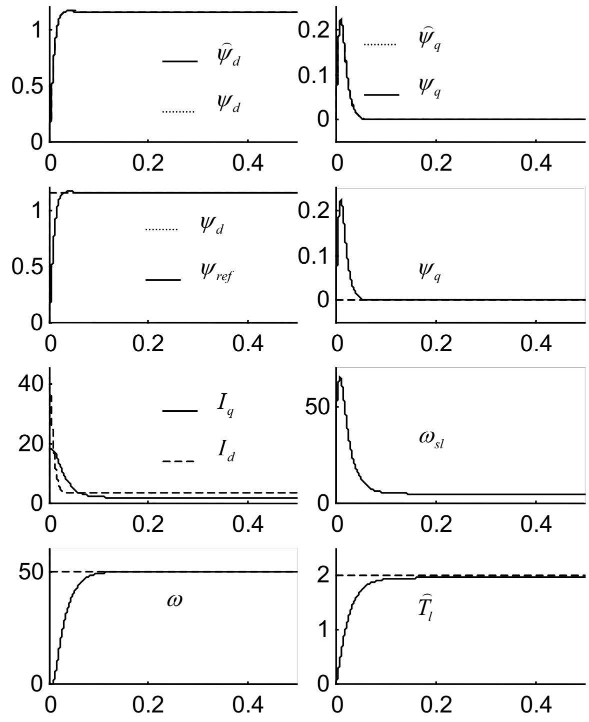

Fig. 2: Constant load torque.

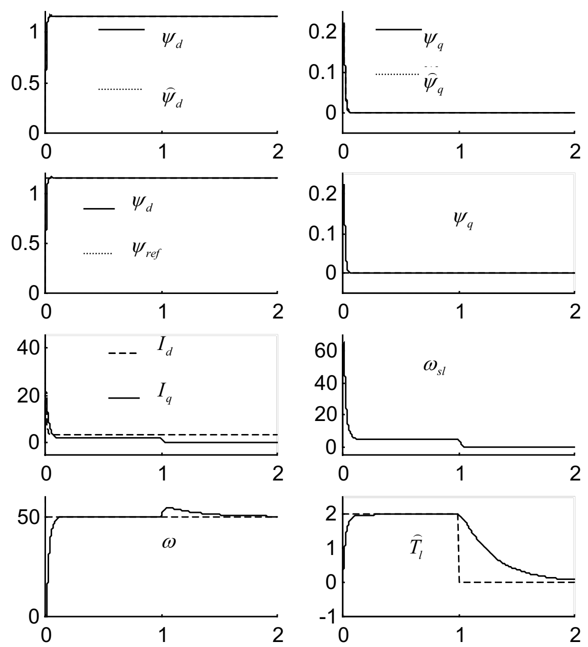

Fig. 3: Load torque change.

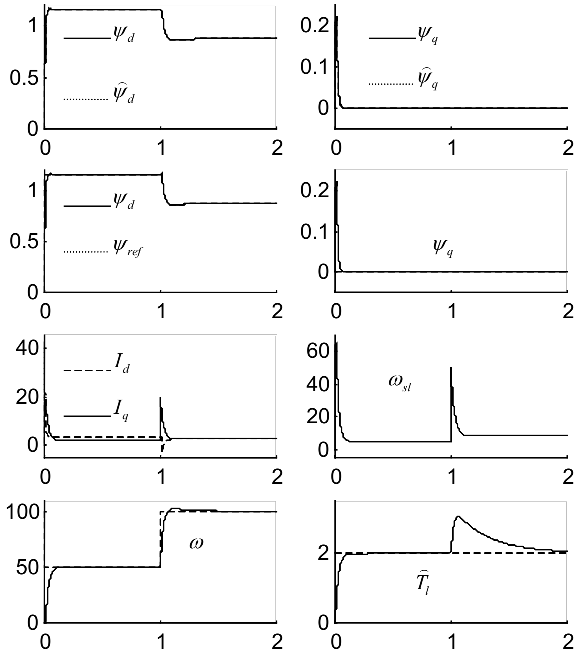

Fig. 4: Flux weakening.

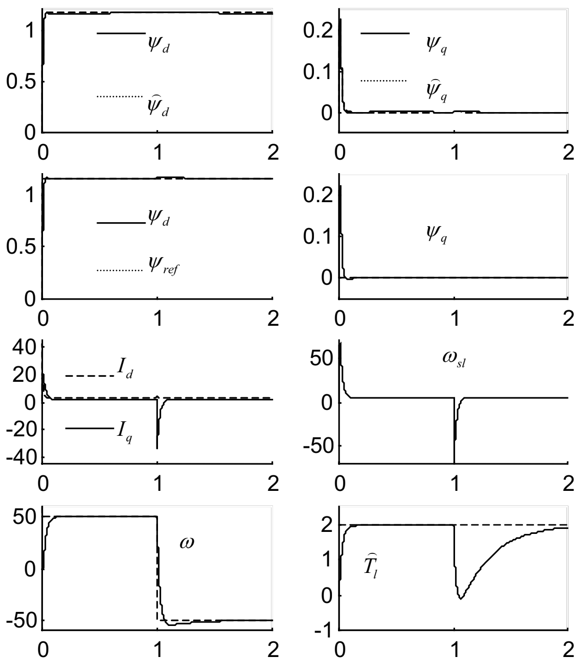

Fig. 5: Speed inversion.

5. CONCLUSION

An observer-based adaptive field control is proposed. Based on current-fed induction machine model the flux observer is designed to guarantee the estimation convergence. The q-axis current, the d-axis current and the slip frequency are used as three control inputs to ensure the tracking of the speed and flux components references. Future work is directed to include the saturation effect on the control and estimation performance.

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Induction motor parameters:

ϕ_{ref} = 1.16Wb, R_r = 3.3 Ω, $L_r = 0.375H$, $M = 0.34H$, $J = 0.0075$ Kg.m², $P = 1$.

Control design parameters:

$k_1 = 50$, $k_2 = 100$, $\gamma_1 = 10^{-6}$, $\gamma_2 = 0.009$.