AN ADAPTIVE SLIDING-MODE OBSERVER INCORPORATING CORE LOSS

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ABSTRACT

A novel adaptive sliding-mode observer has been developed for a three-phase squirrel-cage induction motor. With the new scheme taking core loss into account, the observer can accurately estimate rotor flux and speed, resistances of stator, rotor and core loss by using measured stator voltages and currents. Essences of switching conditions and adaptive manners are based on Lyapunov stability.

1. INTRODUCTION

At present, the vector-controlled induction motors are attractive current technology even though not many of them are available as commercial drives. One of the attractive features is high performance achieved with sensorless. The sensorless scheme often requires a fast and sophisticated processor to execute some tedious codes. This speed estimation process is complex and generally grouped as open- and closed-loop estimators [1]. One type of the closed-loop estimators known as adaptive flux observer is commonly classified into four subgroups namely : standard Luenberger (or full-order) observer, sliding-mode (or variable structure) observer, extended Kalman filter observer and AI-based observer. Among them, an adaptive sliding-mode observer is an attractive technology due to its robustness against disturbances, parameter deviations and measurement noise, whereras the rest of these flux observers have some inherent disadvantages, for example the influence of noise characteristic, large computation burden, long development time and the need of expert knowledge for system setup. Previously, the adaptive sliding-mode observer was derived from an induction motor model neglecting core loss [2][3], while an adaptive Luenberger observer taking the core loss into account was investigated to compare its precision of estimated rotor speed with that of the conventional adaptive Luenberger observer [4]. The former is superior to the latter within a wide variation of load torque. Thus, it will be worthwhile to further develop an adaptive sliding-mode observer that incorporates core loss. Better performance of speed estimation is surely expected. Our paper elucidates the development of this observer.

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2. INDUCTION MOTOR MODEL

The type of an induction motor considered herein is a 3ϕ-y-connected squirrel-cage motor having identically distributed stator windings with 120° displacement. Under the $\alpha\!-\!\beta$ stator reference frame, the motor models taking core loss into account are as follows [4]

$$\dot{x} = Ax + Bv_s + D\psi_r \quad (1)$$

$$i_s = Cx \quad (2)$$

where $x = [\, i_{s\alpha} \;\; i_{s\beta} \;\; \psi_{r\alpha} \;\; \psi_{r\beta} \,]^T$ is the state vector, $v_s = [\, v_{s\alpha} \;\; v_{s\beta} \,]^T$ is the stator voltage vector (input vector), $i_s = [\, i_{s\alpha} \;\; i_{s\beta} \,]^T$ is the output vector (stator currents), $\psi_r = [\, \psi_{r\alpha} \;\; \psi_{r\beta} \,]^T$ denotes the rotor flux linkage vector (Wb), α, β stand for the components of a vector with respect to the fixed stator coordinate , $C = [\, I \;\; 0 \,]$, and

$$A = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix}, \quad B = \begin{bmatrix} B_1 \\ 0 \end{bmatrix}, \quad D = \begin{bmatrix} D_1 \\ D_2 \end{bmatrix}$$

where $A_{11} = a_{r11} I = -\frac{1}{\sigma L_s}\left(R_s + \frac{M^2 R_r}{L_r^2} \right) I$, $I = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$,

$A_{12} = \frac{1}{\varepsilon}\left(\frac{R_r}{L_r} I - \omega_r J \right)$, $A_{21} = \frac{M R_r}{L_r} I$, $A_{22} = -\varepsilon A_{12}$,

$B_1 = \frac{1}{\sigma L_s} I$, $J = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$, $D_1 = -\frac{R_m (L_r - sM)}{\varepsilon M L_r} I$,

$D_2 = -\frac{s R_m}{L_r} I$, $\omega_m = \frac{2\omega_r}{p}$, $s = \frac{\omega_s}{\omega} = \frac{\omega - \omega_r}{\omega}$,

$\sigma = 1 - \frac{M^2}{L_s L_r} > 0$, $\varepsilon = \frac{\sigma L_s L_r}{M} > 0$, $\omega = 2\pi f$, $R_m = k_c \omega^{1.6}$

, R_s is stator resistance (Ω), R_r is rotor resistance (Ω), L_s represents stator self-inductance (H), L_r denotes rotor self-inductance (H), M stands for mutual inductance (H), R_m is core loss resistance (Ω), σ means total leakage factor, s represents slip, ω denotes stator angular velocity (rad/sec), f stands for stator or supply frequency (Hz), ω_s is angular velocity of slip (rad/sec), ω_r is electrical angular velocity of rotor or rotor speed (rad/sec), ω_m is mechanical angular velocity of rotor or shaft speed (rad/sec), p denotes the number of poles, and k_c stands for a constant value (rated $R_m \div$ rated $\omega^{1.6}$). The D term is an approximate expression. These stator and rotor resistances may vary with the motor temperature and skin effect while the core loss resistance is affected by operating frequency and flux level. When the above model of the induction motor is rewritten by splitting it into stator and rotor windings, the following relations are obtained as

$$\left(di_s/dt\right) = A_{11}i_s + A_{12}\psi_r + B_1 v_s + D_1\psi_r \quad (3)$$

$$\left(d\psi_r/dt\right) = A_{21}i_s + A_{22}\psi_r + D_2\psi_r . \quad (4)$$

3. NEW ADAPTIVE SLIDING-MODE OBSERVER

In view of the shaft speed dynamics slower than the electromagnetic dynamics, the proposed adaptive sliding-mode observer taking core loss into account for simultaneous rotor flux and stator current estimations can be constructed in the following form :

$$\left(d\hat{i}_s/dt\right) = \hat{A}_{11}\hat{i}_s + \hat{A}_{12}\hat{\psi}_r + B_1 v_s + \hat{D}_1\hat{\psi}_r + U_o \quad (5)$$

$$\left(d\hat{\psi}_r/dt\right) = \hat{A}_{21}\hat{i}_s + \hat{A}_{22}\hat{\psi}_r + \hat{D}_2\hat{\psi}_r \quad (6)$$

where ^ denotes the estimated value or vector,
$\hat{i}_s = \left[\hat{i}_{s\alpha} \quad \hat{i}_{s\beta}\right]^T$, $\hat{\psi}_r = \left[\hat{\psi}_{r\alpha} \quad \hat{\psi}_{r\beta}\right]^T$, $\hat{A}_{22} = -\varepsilon\hat{A}_{12}$,
$\hat{A}_{11} = \hat{a}_{r11}I = -\frac{1}{\sigma L_s}\left(\hat{R}_s + \frac{M^2\hat{R}_r}{L_r^2}\right)I$, $\hat{A}_{21} = \frac{M\hat{R}_r}{L_r}I$,
$\hat{A}_{12} = \frac{1}{\varepsilon}\left(\frac{\hat{R}_r}{L_r}I - \hat{\omega}_r J\right)$, $\hat{D}_1 = -\frac{\hat{R}_m\left(L_r - \hat{s}M\right)}{\varepsilon M L_r}I$,
$\hat{D}_2 = -\frac{\hat{s}\hat{R}_m}{L_r}I$, $\hat{\omega}_m = \frac{2\hat{\omega}_r}{p}$, $\hat{s} = \frac{\hat{\omega}_s}{\omega} = \frac{\omega - \hat{\omega}_r}{\omega}$ and U_o is the correction vector applied to drive the estimation error to zero. Let the mismatches between estimated and real vectors as well as between estimated and real parameters be

$$e_i = \begin{bmatrix} e_{i\alpha} \\ e_{i\beta} \end{bmatrix} = \begin{bmatrix} i_{s\alpha} - \hat{i}_{s\alpha} \\ i_{s\beta} - \hat{i}_{s\beta} \end{bmatrix} , \quad e_\psi = \begin{bmatrix} e_{\psi\alpha} \\ e_{\psi\beta} \end{bmatrix} = \begin{bmatrix} \psi_{r\alpha} - \hat{\psi}_{r\alpha} \\ \psi_{r\beta} - \hat{\psi}_{r\beta} \end{bmatrix}$$

$$\Delta R_s = R_s - \hat{R}_s \quad , \quad \Delta R_r = R_r - \hat{R}_r$$

$$\Delta R_m = R_m - \hat{R}_m \quad \text{and} \quad \Delta\omega_r = \omega_r - \hat{\omega}_r .$$

Then, two error equations can be developed as follows

$$\dot{e}_i = A_{11}e_i + \left(A_{12} + D_1\right)e_\psi + \Delta A_{11}\hat{i}_s + \left(\Delta A_{12} + \Delta D_1\right)\hat{\psi}_r - U_o \quad (7)$$

$$\dot{e}_\psi = A_{21}e_i + \left(A_{22} + D_2\right)e_\psi + \Delta A_{21}\hat{i}_s + \left(\Delta A_{22} + \Delta D_2\right)\hat{\psi}_r \quad (8)$$

where $\Delta A_{21} = \frac{M}{L_r}\Delta R_r I$,

$\Delta A_{12} + \Delta D_1 = \frac{1}{\varepsilon}\left\{\left[\frac{\Delta R_r}{L_r} - \frac{L_r - \hat{s}M}{M L_r}\Delta R_m - \frac{R_m}{\omega L_r}\Delta\omega_r\right]I - \Delta\omega_r J\right\}$,

$\Delta A_{11} = \left(a_{r11} - \hat{a}_{r11}\right)I = -\frac{1}{\sigma L_s}\left(\Delta R_s + \frac{M^2}{L_r^2}\Delta R_r\right)I$ and

$\Delta A_{22} + \Delta D_2 = -\frac{1}{L_r}\left(\Delta R_r + \hat{s}\Delta R_m - \frac{R_m}{\omega}\Delta\omega_r\right)I + \Delta\omega_r J$.

Now one defines the integral of the stator current error vector and the switching vector in the following forms, respectively [3] :

$$\dot{z}_i = -e_i \quad (9)$$

$$S_i = e_i - K z_i \quad (10)$$

where $z_i = \begin{bmatrix} z_{i\alpha} \\ z_{i\beta} \end{bmatrix}$, $S_i = \begin{bmatrix} s_{i\alpha} \\ s_{i\beta} \end{bmatrix}$ and $K = \begin{bmatrix} k_1 & 0 \\ 0 & k_2 \end{bmatrix}$ is the integral gain matrix that is positive definite. From (7), (9) and (10), one has the time derivative of switching vector

$$\dot{S}_i = \left(A_{11} + K\right)e_i + \left(A_{12} + D_1\right)e_\psi + \Delta A_{11}\hat{i}_s + \left(\Delta A_{12} + \Delta D_1\right)\hat{\psi}_r - U_o \quad (11)$$

where $(A_{12} + D_1)e_\psi$ becomes an unknown term since $\psi_{r\alpha}$, $\psi_{r\beta}$ are inaccessible and ω_r , s are not measured intentionally. This term can be expressed by

$$\left(A_{12} + D_1\right)e_\psi = \begin{bmatrix} f_1 \\ f_2 \end{bmatrix} = \begin{bmatrix} \frac{1}{\varepsilon}\left\{\frac{R_r}{L_r} - \frac{R_m\left(L_r - sM\right)}{M L_r}\right\}e_{\psi\alpha} + \frac{\omega_r}{\varepsilon}e_{\psi\beta} \\ \frac{1}{\varepsilon}\left\{\frac{R_r}{L_r} - \frac{R_m\left(L_r - sM\right)}{M L_r}\right\}e_{\psi\beta} - \frac{\omega_r}{\varepsilon}e_{\psi\alpha} \end{bmatrix}. \quad (12)$$

Let the correction vector U_o be decomposed into

$$U_o = \Phi_1 e_i + \Phi_2 K z_i + \Lambda \quad (13)$$

, in which $\Phi_1 = \begin{bmatrix} \phi_{1\alpha} & 0 \\ 0 & \phi_{1\beta} \end{bmatrix}$, $\Phi_2 = \begin{bmatrix} \phi_{2\alpha} & 0 \\ 0 & \phi_{2\beta} \end{bmatrix}$ and $\Lambda = [\ \Lambda_\alpha \quad \Lambda_\beta\ ]^T$ are the correction gain matrices. In order to determine these correction gains and the parameter updating laws, the candidate Lyapunov function is selected as follows

$$V = \frac{1}{2}S_i^T S_i + \frac{\Delta R_s^2}{2\sigma L_s\lambda_1} + \frac{\Delta R_r^2}{2\varepsilon L_r\lambda_2} + \frac{\Delta R_m^2}{2\varepsilon M L_r\lambda_3} + \frac{\Delta\omega_r^2}{2\varepsilon\lambda_4} \quad (14)$$

where λ_1 , λ_2 , λ_3 and λ_4 are the positive adaptation gains. Differentiating this function along time results in

$$\dot{V} = S_i^T\dot{S}_i - \frac{\Delta R_s}{\sigma L_s}\left(\frac{\dot{\hat{R}}_s}{\lambda_1}\right) - \frac{\Delta R_r}{\varepsilon L_r}\left(\frac{\dot{\hat{R}}_r}{\lambda_2}\right) - \frac{\Delta R_m}{\varepsilon M L_r}\left(\frac{\dot{\hat{R}}_m}{\lambda_3}\right) - \frac{\Delta\omega_r}{\varepsilon}\left(\frac{\dot{\hat{\omega}}_r}{\lambda_4}\right) \quad .(15)$$

By substituting (11) and (13) into (15) and assuming that R_s, R_r, R_m and ω_r are constant in comparison with the dynamics of state variables, then the time derivative $\dot{V}$ becomes

$$
\begin{aligned}
\dot{V} &= \left(a_{r11} + k_1 - \phi_{1\alpha}\right)s_{i\alpha}e_{i\alpha} + \left(a_{r11} + k_2 - \phi_{1\beta}\right)s_{i\beta}e_{i\beta} \\
&\quad + \left(f_1 - \Lambda_\alpha\right)s_{i\alpha} + \left(f_2 - \Lambda_\beta\right)s_{i\beta} - \phi_{2\alpha}k_1 s_{i\alpha}z_{i\alpha} - \phi_{2\beta}k_2 s_{i\beta}z_{i\beta} \\
&\quad - \frac{\Delta R_s}{\sigma L_s}\left[\frac{\dot{\hat{R}}_s}{\lambda_1} + \left(s_{i\alpha}\hat{i}_{s\alpha} + s_{i\beta}\hat{i}_{s\beta}\right)\right] \\
&\quad - \frac{\Delta\omega_r}{\varepsilon}\left[\frac{\dot{\hat{\omega}}_r}{\lambda_4} + \left(s_{i\beta}\hat{\psi}_{r\alpha} - s_{i\alpha}\hat{\psi}_{r\beta}\right) + \frac{R_m}{\omega L_r}\left(s_{i\alpha}\hat{\psi}_{r\alpha} + s_{i\beta}\hat{\psi}_{r\beta}\right)\right]. \\
&\quad - \frac{\Delta R_m}{\varepsilon M L_r}\left[\frac{\dot{\hat{R}}_m}{\lambda_3} + \left(L_r - \hat{s}M\right)\left(s_{i\alpha}\hat{\psi}_{r\alpha} + s_{i\beta}\hat{\psi}_{r\beta}\right)\right] \\
&\quad - \frac{\Delta R_r}{\varepsilon L_r}\left\{\frac{\dot{\hat{R}}_r}{\lambda_2} - \left[\left(s_{i\alpha}\hat{\psi}_{r\alpha} + s_{i\beta}\hat{\psi}_{r\beta}\right) - M\left(s_{i\alpha}\hat{i}_{s\alpha} + s_{i\beta}\hat{i}_{s\beta}\right)\right]\right\}
\end{aligned} \tag{16}
$$

Subsequently, since a necessary condition for uniformly asymptotic stability is that $\dot{V}$ must be negative definite, this can be satisfied by ensuring that the last four terms with square brackets on the right-hand side of (16) diminish while the other terms are always semi-negative. The zero settings of such the terms result in the adaptive mechanism of our proposed observer. At this stage, the adaptation laws are integral in nature. Ref. [1] recommends the use of proportional plus integral approach for a better estimation performance. Here, we modify the existing adaptation laws to contain the PI-terms as expressed by

$$\hat{R}_s = \hat{R}_{s0} - k_{sp}\left(s_{i\alpha}\hat{i}_{s\alpha} + s_{i\beta}\hat{i}_{s\beta}\right) - k_{si}\int_0^t\left(s_{i\alpha}\hat{i}_{s\alpha} + s_{i\beta}\hat{i}_{s\beta}\right)d\tau \tag{17a}$$

$$
\begin{aligned}
\hat{R}_r &= \hat{R}_{r0} + k_{rp}\left\{s_{i\alpha}\hat{\psi}_{r\alpha} + s_{i\beta}\hat{\psi}_{r\beta} - M\left(s_{i\alpha}\hat{i}_{s\alpha} + s_{i\beta}\hat{i}_{s\beta}\right)\right\} \\
&\quad + k_{ri}\int_0^t\left\{s_{i\alpha}\hat{\psi}_{r\alpha} + s_{i\beta}\hat{\psi}_{r\beta} - M\left(s_{i\alpha}\hat{i}_{s\alpha} + s_{i\beta}\hat{i}_{s\beta}\right)\right\}d\tau
\end{aligned} \tag{17b}
$$

$$
\begin{aligned}
\hat{R}_m &= \hat{R}_{m0} - k_{mp}\left(L_r - \hat{s}M\right)\left(s_{i\alpha}\hat{\psi}_{r\alpha} + s_{i\beta}\hat{\psi}_{r\beta}\right) \\
&\quad - k_{mi}\int_0^t\left\{\left(L_r - \hat{s}M\right)\left(s_{i\alpha}\hat{\psi}_{r\alpha} + s_{i\beta}\hat{\psi}_{r\beta}\right)\right\}d\tau
\end{aligned} \tag{17c}
$$

$$
\begin{aligned}
\hat{\omega}_r &= k_{\omega p}\left\{s_{i\alpha}\hat{\psi}_{r\beta} - s_{i\beta}\hat{\psi}_{r\alpha} - \frac{R_m}{\omega L_r}\left(s_{i\alpha}\hat{\psi}_{r\alpha} + s_{i\beta}\hat{\psi}_{r\beta}\right)\right\} \\
&\quad + \hat{\omega}_{r0} + k_{\omega i}\int_0^t\left\{s_{i\alpha}\hat{\psi}_{r\beta} - s_{i\beta}\hat{\psi}_{r\alpha} - \frac{R_m}{\omega L_r}\left(s_{i\alpha}\hat{\psi}_{r\alpha} + s_{i\beta}\hat{\psi}_{r\beta}\right)\right\}d\tau
\end{aligned} \tag{17d}
$$

where k_{sp}, k_{rp}, k_{mp}, $k_{\omega p}$ are the positive proportional gains, k_{si}, k_{ri}, k_{mi}, $k_{\omega i}$ are the positive integral gains, $\hat{R}_{s0}$, $\hat{R}_{r0}$, $\hat{R}_{m0}$ and $\hat{\omega}_{r0}$ are the initial estimates of relevant $\hat{R}_s$, $\hat{R}_r$, $\hat{R}_m$ and $\hat{\omega}_r$. Therefore, equation (16) is truncated into a shorter form as

$$
\begin{aligned}
\dot{V} &= \left(a_{r11} + k_1 - \phi_{1\alpha}\right)s_{i\alpha}e_{i\alpha} + \left(a_{r11} + k_2 - \phi_{1\beta}\right)s_{i\beta}e_{i\beta} \\
&\quad + \left(f_1 - \Lambda_\alpha\right)s_{i\alpha} + \left(f_2 - \Lambda_\beta\right)s_{i\beta} - \phi_{2\alpha}k_1 s_{i\alpha}z_{i\alpha} - \phi_{2\beta}k_2 s_{i\beta}z_{i\beta}
\end{aligned}. \tag{18}
$$

Via Lyapunov stability theorem the $V \geq 0$ and $\dot{V} \leq 0$ conditions must be obeyed to guarantee the stability of the proposed observer. By forcing the time derivative of V to be strictly semi-negative, the sufficient conditions for satisfying (18) are

$$
\begin{aligned}
&(a_{r11} + k_1 - \phi_{1\alpha})s_{i\alpha}e_{i\alpha} \leq 0\,,\ (a_{r11} + k_2 - \phi_{1\beta})s_{i\beta}e_{i\beta} \leq 0 \\
&\quad -\phi_{2\alpha}k_1 s_{i\alpha}z_{i\alpha} \leq 0\quad,\quad -\phi_{2\beta}k_2 s_{i\beta}z_{i\beta} \leq 0 \\
&\quad (f_1 - \Lambda_\alpha)s_{i\alpha} \leq 0 \ \text{ and } \ (f_2 - \Lambda_\beta)s_{i\beta} \leq 0\,.
\end{aligned} \tag{19}
$$

By expanding (19), one obtains the following necessary conditions to assure the convergence of S to zero. This yields

$$
\begin{array}{llll}
\text{if} & s_{i\alpha}e_{i\alpha} > 0 & \text{then} & \phi_{1\alpha} > |\,a_{r11} + k_1| \\
\text{if} & s_{i\alpha}e_{i\alpha} < 0 & \text{then} & \phi_{1\alpha} < -|\,a_{r11} + k_1| \\
\text{if} & s_{i\beta}e_{i\beta} > 0 & \text{then} & \phi_{1\beta} > |\,a_{r11} + k_2| \\
\text{if} & s_{i\beta}e_{i\beta} < 0 & \text{then} & \phi_{1\beta} < -|\,a_{r11} + k_2| \\
\text{if} & s_{i\alpha}z_{i\alpha} > 0 & \text{then} & \phi_{2\alpha} > 0 \\
\text{if} & s_{i\alpha}z_{i\alpha} < 0 & \text{then} & \phi_{2\alpha} < 0 \\
\text{if} & s_{i\beta}z_{i\beta} > 0 & \text{then} & \phi_{2\beta} > 0 \\
\text{if} & s_{i\beta}z_{i\beta} < 0 & \text{then} & \phi_{2\beta} < 0 \\
\text{if} & s_{i\alpha} > 0 & \text{then} & \Lambda_\alpha > |\,f_1| \\
\text{if} & s_{i\alpha} < 0 & \text{then} & \Lambda_\alpha < -|\,f_1| \\
\text{if} & s_{i\beta} > 0 & \text{then} & \Lambda_\beta > |\,f_2| \\
\text{if} & s_{i\beta} < 0 & \text{then} & \Lambda_\beta < -|\,f_2|\,.
\end{array} \tag{20}
$$

4. SIMULATION RESULTS AND DISCUSSION

The feasibility of our proposed approach has been assessed by simulations. The key nominal parameters per phase of the 3 kW squirrel-cage motor under test are : $R_s = 2.15\ \Omega$, $R_r = 2.33\ \Omega$, $L_s = L_r = 0.21$ H, M = 0.2025 H, $R_m = 4.48\ \Omega$, $p = 4$, $J_m = 0.008$ kgm^2, $f^{\,rated}$ = 50 Hz, and ω_m^{rated} = 1420 rpm. The motor is coupled to load having its inertia J_L of 0.084 kgm^2. According to direct-on-line starting, at the initial instant of time (t = 0) the motor previously de-energized at standstill is connected directly to a 220 V, 50 Hz three-phase sinusoidal ac supply. Thus, all initial conditions are zero. The estimated resistance values are initialized to be half of the nominal values at the start of execution. The load torque that takes place and is applied to the motor shaft, is independent of speed. The integral gains k_1 and k_2 are set to 5. The possible correction gains for the observer are : $|\phi_{1\alpha}| = |\phi_{1\beta}| = 290$, $|\phi_{2\alpha}| = |\phi_{2\beta}| = 1$, and $|\Lambda_\alpha| = |\Lambda_\beta| = 10$. The PI gains of adaptation laws are arbitrarily set to $k_{sp} = k_{si} = 0.00329$, $k_{rp} = k_{ri} = 0.0178$, $k_{mp} = k_{mi} = 30.01$, and $k_{\omega p} = k_{\omega i} = 20$. In order to compare some numerical results between the proposed observer that includes core loss and the previous one [3] that excludes core loss, the speed and rotor flux estimation errors derived from these two observers are revealed in Fig. 1, 2 and 3. These figures confirm that the proposed scheme gives relatively smaller steady-state error magnitudes than the previous one does. The load torque is supposed to be constant at 5 Nm. For convenience, the integral of the speed estimation error magnitude ($\int_0^t |\omega_r - \hat{\omega}_r| d\tau$) is traced instead of plotting this error without integration. Fig. 4 and 5 show the case of employing the proposed observer while applying a train of stepwise changeable load disturbances, comprising of 5 Nm at 0 sec, 20 Nm at 10 sec, 10 Nm at 16 sec, 20 Nm at 22 sec and 10 Nm at 30 sec, consecutively. The results illuminate that the estimation errors converge nicely to zero. Hence, the proposed observer can obviously provide an accurate estimation.

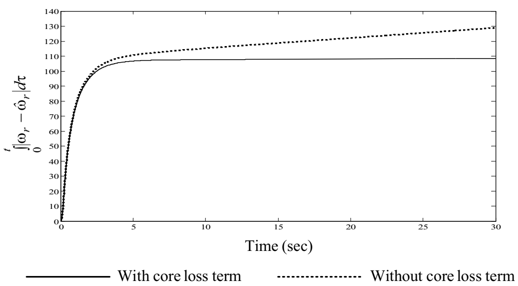

Figure 1. Comparison between $\int_0^t |\omega_r - \hat{\omega}_r| d\tau$'s achieved from the proposed and the previous observers

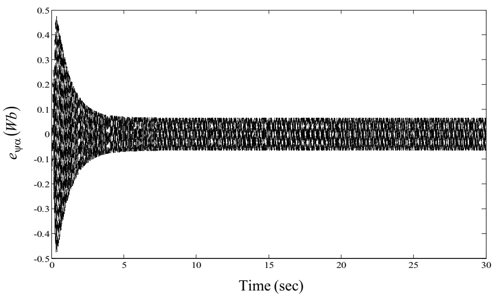

Figure 2. $e_{\psi\alpha}$ of the previous observer

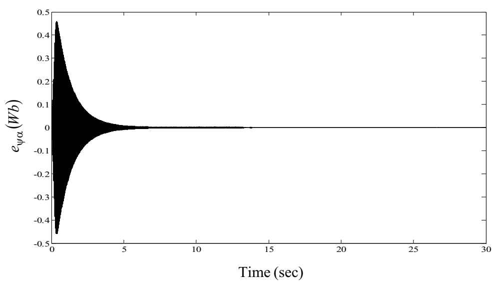

Figure 3. $e_{\psi\alpha}$ of the proposed observer

5. CONCLUSION

This paper has described a new adaptive sliding-mode observer providing the estimations of stator currents, rotor fluxes and speed, as well as resistances of stator, rotor, and core loss. The proposed observer taking core loss into account is far more accurate than that without core loss consideration as our simulation results indicate. Based on the α-β model of induction motors, the switching and adaptive essences of the observer have been derived with reference to Lyapunov stability criterion.

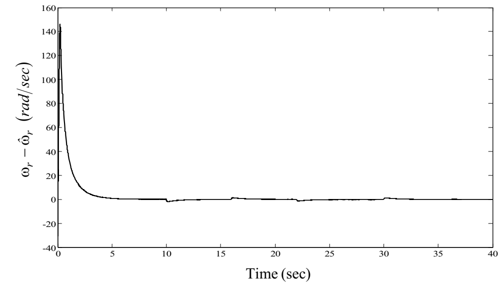

Figure 4. $\Delta\omega_r$ derived from the proposed observer under stepwise changeable load torques

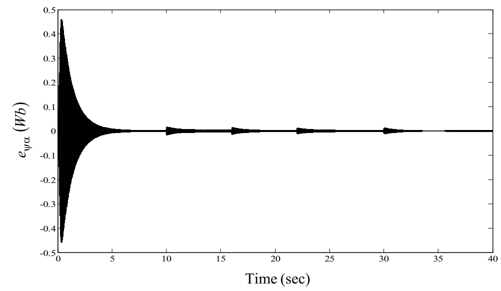

Figure 5. $e_{\psi\alpha}$ derived from the proposed observer under stepwise changeable load torques

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