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TORQUE-SPEED ADAPTIVE OBSERVER AND INERTIA IDENTIFICATION WITHOUT CURRENT TRANSDUCERS FOR CONTROL OF ELECTRIC DRIVES

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This paper develops a high dynamic and robust speed-torque control system for servo drives based on adaptive observer and self-tuning techniques with on-line inertia identification. Only the rotor position is measured even for a low precision shaft encoder. The instantaneous speed and the disturbance torque are accurately estimated by an extended Luenberger observer inertia adaptive. A current to voltage decoupling and disturbance torque feedforward compensation realize a fast current sensorless torque control with dynamic torque limitation. The mechanical inertia, used for the self-tuning of both speed controller and Luenberger observer, is on-line identified by a discrete time recursive gradient algorithm. Extensive simulation results with the proposed control structure, applied to a permanent magnet synchronous motor (PMSM) drive, prove high-dynamic performances in wide speed range. A good robustness to 1:10 inertia variation at rated load torque is obtained.

Key words: Current sensorless, Adaptive state-disturbance observer, Recursive gradient algorithm, Inertia identification, Self-tuning controller, Feedforward decoupling, Torque control, PMSM drives.

1. INTRODUCTION

The sensorless control is an important goal in industrial applications to obtain a good performance per price indices [1]. However, the robust and high-dynamic control of robots and machine tools require precise position control loop, thus the position transducer is always present. Usually, the robust control of electric drives comprises an internal current-loop using current sensors. In this case, the power source operates as a current source and a torque control is expected. However, real currents are affected by a lot of noises, e.g., inverter switching, and thus they are difficult to measure especially at no load. Linked sensor cables and ADC interface constitute sources of failures. A promising solution is observer-based current sensorless control [2].

The disturbance torque estimation and compensation is used to obtain a robust motion control when the load torque and parameters change. Moreover, auto-tuning techniques based on parameter identifications are also employed [1]. Different approaches to on-line identify the inertia were developed in the last ten years for self-tuning speed controller. They could be: least square (LS) method [1], recursive extended least squares (RELS) method [3-4], Landau discrete time recursive algorithm [5]. To estimate the instantaneous speed and disturbance torque the following solutions could be used: extended Kalman filter [3], adaptive extended Kalman filter [4], minimal-order Gopinath observer [5]. In all these cases, a current loop with measured currents and a position transducer are always present. In most cases, the computation effort is quite heavy.

This paper proposes a new robust current sensorless control for high-dynamic electric drives using only position transducer. This solution is based on: current sensorless torque control, speed-load torque observer, auto-tuning speed controller and on-line inertia identification. A representative application is the robot axis control with efficient compensation of inertia variation and equivalent complex coupled-disturbance terms.

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2. STRUCTURE OF CURRENT SENSORLESS SPEED-TORQUE CONTROL

The proposed current sensorless speed-torque control structure for electric drives is presented in Fig. 1.

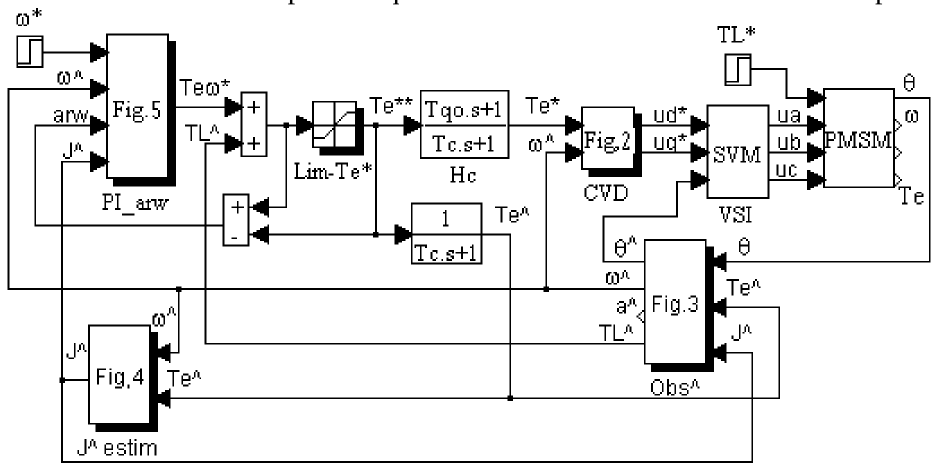

Fig. 1. Structure of current sensorless speed-torque control based on adaptive observer and inertia identification.

where:
- PMSM with position transducer, voltage source inverter (VSI) with space vector modulation (SVM),
- current to voltage decoupling (CVD – Fig. 2) for torque control,
- dynamic correction (Hc),
- disturbance torque feedforward compensation ($T_L^\wedge$),
- adaptive extended Luenberger state-disturbance observer (Obs$^\wedge$ – Fig. 3) for speed-load torque estimation,
- inertia identification with discrete time recursive gradient algorithm (J$^\wedge$ estim – Fig. 4),
- PI self-tuning speed controller with anti-windup (PI_arw – Fig. 5).

3. TORQUE CONTROL – CURRENT TO VOLTAGE DECOUPLING

Electric machines models can be separated into two subsystems: an electromagnetic model (EM) and a mechanical model (M), coupled by the electromagnetic torque (T_e) and by the mechanical rotor speed ω. The M model is (1), where: θ - mechanical rotor position, J - mechanical inertia, B - damping factor, T_L - load torque.

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{bmatrix}\theta\\ \omega\end{bmatrix} = \begin{bmatrix}0 & 1\\ 0 & -B/J\end{bmatrix}\begin{bmatrix}\theta\\ \omega\end{bmatrix} + \begin{bmatrix}0\\ 1/J\end{bmatrix}T_e + \begin{bmatrix}0\\ -1/J\end{bmatrix}T_L, \quad \begin{bmatrix}\theta\\ \omega\end{bmatrix}_{t=0} = \begin{bmatrix}\theta_0\\ \omega_0\end{bmatrix}. \tag{1}$$

In a particular case, e.g., for a salient-pole PMSM, the EM model in d,q rotor reference is a nonlinear coupled MIMO given by (2) and (3). It is assumed that the airgap magnetic flux is sinusoidal distributed, there are no damper windings and the iron losses are neglected [6].

$$\begin{aligned} u_d &= R\,i_d + L_d\,\mathrm{d}i_d/\mathrm{d}t - p\omega L_q i_q, & i_d(0) &= i_{d0} \\ u_q &= R\,i_q + L_q\,\mathrm{d}i_q/\mathrm{d}t + p\omega(\lambda_0 + L_d i_d), & i_q(0) &= i_{q0} \end{aligned}, \tag{2}$$

$$T_e = 3/2\,p i_q[\lambda_0 - (L_q - L_d)i_d], \quad L_q > L_d, \tag{3}$$

where: $\mathbf{i}^{\mathbf{r}}(i_d, i_q)$ - stator current vector, $\mathbf{u}^{\mathbf{r}}(u_d, u_q)$ - stator voltage vector, p – number of pole pair, R - stator resistance, λ_0 - PM flux, L_d, L_q - d, q axis inductances.

Based on (2), a feedforward current to voltage decoupling control (4) is used to obtain a torque control.

$$\begin{aligned} u_d^* &= R_o\, i_d^* - pL_{qo}\,\hat{\omega}\hat{i}_q \\ u_q^* &= R_o\, i_q^* + p\hat{\omega}(\lambda_{0o} + L_{do}\hat{i}_d) \end{aligned}, \tag{4}$$

where: $\mathbf{u}^{r*}(u_d^*, u_q^*)$ - stator voltage reference, $\mathbf{i}^{r*}(i_d^*, i_q^*)$ - current vector reference, superscript " ^ " - estimated variables, subscript "$_o$" - estimated parameters. The $\mathbf{i}^{r*}$ is given by an optimal criteria from the torque reference T_e^* delivered by the motion controller [6]. For current vector control with $i_d^* = 0$, therefore $T_e^* = K_{To}\, i_q^*$, where $K_{To} = 3/2p\, \lambda_{0o}$. In this case, the current to voltage decoupling is presented in Fig. 2.

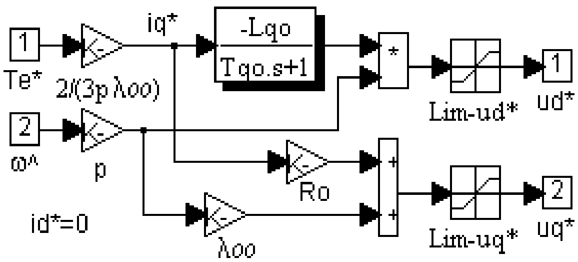

Fig. 2. Current to voltage decoupling. PMSM torque control with $id^* = 0$.

We anticipate the result from (5) $i_q^\wedge / i_q^* = 1/(1 + sT_{qo})$ that expresses the delay due to the stator time constant T_{qo}. The decoupling procedure is sensitive to PMSM electromagnetic parameters, excepting L_d.

For an ideal VSI, $\mathbf{u}^r = \mathbf{u}^{r*}$. In the ideal tuned case, i.e., the estimated parameters are equal to the PMSM parameters, a decoupling between d, q axis is obtained from (2) and (4). The current transfer functions are equivalent to two first-order lag elements (5) with time constants $T_{do} = L_{do}/R_o$ and $T_{qo} = L_{qo}/R_o$, respectively. In the case $i_d^* = 0$, the torque transfer function is: $T_e/T_e^* = 1/(1 + sT_{qo})$, i.e., the requested torque control.

$$H_d(s) = \frac{i_d}{i_d^*} = \frac{1}{1 + sT_{do}}\,, \quad H_q(s) = \frac{i_q}{i_q^*} = \frac{1}{1 + sT_{qo}}\,. \tag{5}$$

Dynamic correction Hc (Fig. 1) is used to obtain a faster torque response $T_e/T_e^{**} = 1/(1 + sT_c)$, $T_c < T_{qo}$.

Feedforward equivalent disturbance-torque compensation $T_L^\wedge$ is realized for a fast torque control with accurate dynamic-torque limitation (Fig. 1).

4. INSTANTANEOUS SPEED AND DISTURBANCE TORQUE OBSERVER

The instantaneous speed $\omega^\wedge$ and disturbance torque $T_L^\wedge$ estimations (Fig. 3) are based on extended Luenberger observer inertia adaptive [2], [7] (6). The load torque T_L is considered to be practical constant in a sampling interval h. The main observer input $T_e^\wedge$ leads to a reduced phase lag. The compensator design uses the pole allocation method (7). Real negative poles p_1, p_2, p_3 are chosen for fast convergence without oscillations. According to the Shannon sampling theorem: $min\,(1/p_i) > 2h$.

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{bmatrix}\hat{\theta}\\ \hat{\omega}\\ \hat{T}_L\end{bmatrix} = \begin{bmatrix}0 & 1 & 0\\ 0 & 0 & -1/\hat{J}\\ 0 & 0 & 0\end{bmatrix}\begin{bmatrix}\hat{\theta}\\ \hat{\omega}\\ \hat{T}_L\end{bmatrix} + \begin{bmatrix}0\\ 1/\hat{J}\\ 0\end{bmatrix}\hat{T}_e + \begin{bmatrix}k_1\\ k_2\\ k_3\end{bmatrix}(\theta - \hat{\theta}), \quad \begin{bmatrix}\hat{\theta}\\ \hat{\omega}\\ \hat{T}_L\end{bmatrix}_{t=0} = \begin{bmatrix}\hat{\theta}_0\\ \hat{\omega}_0\\ \hat{T}_{L0}\end{bmatrix}. \tag{6}$$

$$k_1 = -(p_1 + p_2 + p_3);\; k_2 = p_1 p_2 + p_2 p_3 + p_3 p_1;\; k_3 = -p_1 p_2 p_3. \tag{7}$$

With decoupling and the dynamic correction Hc, the estimated electromagnetic torque $T_e^\wedge$ is given by $T_e^\wedge / T_e^{**} = 1/(1 + sT_c)$. There are two ways $\omega^\wedge$ and $\omega_1^\wedge$ to estimate the speed (Fig. 3). For high-dynamic response, the better choice is $\omega_1^\wedge$ estimation because it has additionally a position correction term k_1.

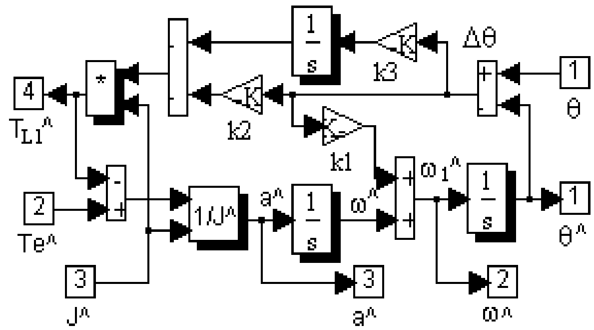

Fig. 3. Extended Luenberger observer inertia adaptive to estimate: $\theta^{\wedge}$, $\omega^{\wedge}$, $a^{\wedge}$, $T_L^{\wedge}$.

5. INERTIA IDENTIFICATION

There are servo drives applications where the inertia has a large variation, e.g., 1:10 range in robotics. Both the Luenberger observer (6) and the speed controller are sensitive to the inertia J deviation; thus dynamic performances are affected. In this case, the estimated equivalent disturbance torque $T_L^{\wedge}$ contains to terms: the load torque and the components generated from parameter variations [1]. However, because the load torque is not possible to be separately estimated, the electromagnetic torque T_e^{**} (Fig. 1) in transient and steady state regimes is not correctly limited. To avoid these disadvantages, an inertia on-line identification is proposed to self-tune both the Luenberger observer and the speed controller.

The basic equation for inertia identification is a simplified discrete-time mechanical model given by (8), obtained from (1) using the delayed Euler method, i.e., $s = (1 - z^{-1}) / z^{-1}$. Assuming that rapid changes in load torque are not expected in few sampling periods h, thus T_L is practically constant. The difference between two time-consecutive of (8) gives the discrete process (9), where the load torque T_L is missing [1], [5].

$$\omega_k = \omega_{k-1} + b(T_{e\,k-1} - T_{L\,k-1}), \quad b = h / J \,, \tag{8}$$

$$\omega_k = 2\omega_{k-1} - \omega_{k-2} + b\Delta T_{e\,k-1}, \quad \Delta T_{e\,k-1} = T_{e\,k-1} - T_{e\,k-2} \,. \tag{9}$$

The on-line inertia identification is based on a discrete time recursive gradient algorithm in a model-reference adaptive approach [8]. According to reference model (9), where ω is replaced by $\omega^{\wedge}$, the prediction adaptive model ϖ is given by (10) where a parameter adaptation mechanism $b^{\wedge}(J)$ with adaptive correction C_1 (11) is used. The stability is guarantied for any gain $f > 0$. Notation: any discrete-time variable x_{k-i} is writing x_k.

$$\tilde{\omega} = 2\hat{\omega}_1 - \hat{\omega}_2 + \hat{b}_1\,\Delta\hat{T}_{e1}, \quad \hat{\omega}_1(0) = \hat{\omega}_{10}, \quad \hat{\omega}_2(0) = \hat{\omega}_{20}\,, \tag{10}$$

$$\begin{aligned} &\hat{b} = \hat{b}_1 + C_1\,e, \quad C_1 = f\,\Delta\hat{T}_{e1}/(1 + f\,\Delta\hat{T}_{e1}^2), \quad \hat{b}_1(0) = \hat{b}_{10} \\ &e = \hat{\omega} - \tilde{\omega}, \Delta\hat{T}_{e1} = (\hat{T}_{e1} - \hat{T}_{e2}), \hat{T}_{e1}(0) = \hat{T}_{e10}, \quad \hat{T}_{e2}(0) = \hat{T}_{e20} \end{aligned}\,. \tag{11}$$

The implementation of the discrete-time algorithm for inertia identification $J^{\wedge}$ is presented in Fig. 4. A limitation and a digital fist-order lag filter is added for $J^{\wedge}$ to reduce the noises.

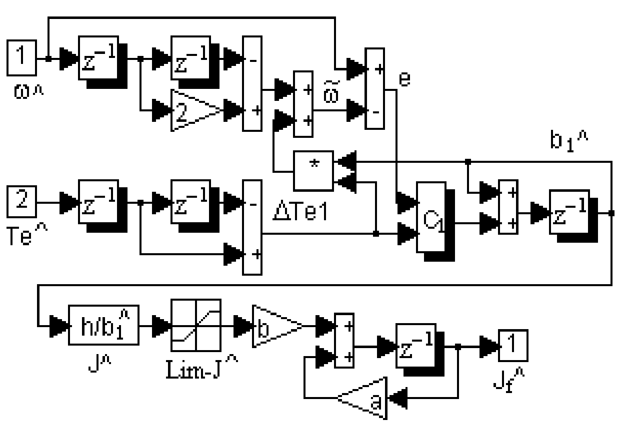

Fig. 4. Discrete-time recursive gradient algorithm for inertia identification.

With a correct inertia identification there is a dynamic decoupled control action between the requested electromagnetic torque components (Fig. 1): i) the estimated torque $T_L^{\wedge}$ that compensate the load torque T_L, and ii) the transient torque from the speed controller $T_{e\omega}^{*}$ that appears during changes in the requested speed ω^{*} or in the real speed ω. An accurate dynamic limitation of the real electromagnetic torque T_e can be realized.

6. SELF-TUNING SPEED CONTROLLER

The simplified transfer function of the torque control system from Fig. 1, for $T_L^{\wedge} = 0$ is given by

$$H(s) = \frac{\omega}{T_{e\omega}^{*}} = \frac{k}{s(1+sT)}, \quad k = \frac{1}{J}, \quad T = T_c. \tag{12}$$

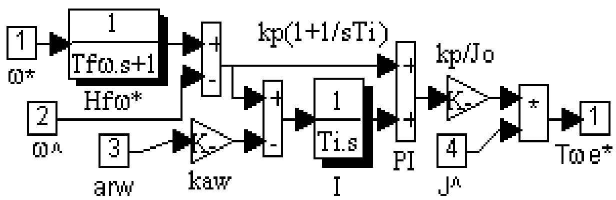

Fig. 5. Speed controller PI anti-windup with reference filter and inertia adaptive.

The speed controller design is based on a generalization of the Kessler symmetrical optimum method [9]. There is a single parameter m to be chosen, and for each selected solution, the maximum value for the phase margin is obtained. According to this method applied in our case, the speed controller is proportional integral (PI) type with a first order-lag filter on the speed reference ω^{*}. A dynamic limitation T_{emax} of the requested torque T_e^{**} is obtained by using an anti-windup procedure applied to the integral component. The speed controller structure is given in Fig. 5. The design relations are:

$$k_p = 1/(mTk), \quad T_i = m^2 T, \quad T_{fw} = T_i. \tag{13}$$

To obtain robust transient speed responses to inertia variation and because only k_p gain strongly depends on inertia J, the k_p gain is self-tuned using the estimated inertia $J^{\wedge}$.

7. SIMULATION RESULTS

The parameters of the control system are the following:

- PMSM rated data: T_{eo} = 2.3 Nm, ω_o = 1000 rpm, I_{ao} = 3 A, V_{dco} = 120 V, and parameters: p = 4, λ_{0o} = 0.1 Wb, L_{do} = 0.012 H, L_{qo} = 0.02 H, R_o = 1.8 Ohm, J_o = 0.005 kgm^2, B_o = 0.001 Nms/rad.
- Luenberger observer: $p_1 = -300$, $p_2 = -400$, $p_3 = -500$, and thus k_1 = 1200, k_2 = 470e3, k_3 = 60e6.
- recursive gradient algorithm for inertia identification: h = 1 ms, f = 50, T_f = 40 ms, a = 0.975, b = 0.025.
- PI-arw speed controller: T_{qo}= 11ms, T_c= 3.7ms, m = 2.5, $T_i = T_{fw}$ = 23ms, k_{aw}= 15, T_{emax}= 5Nm, kp/J_o= 110.

The theoretical ideas are well supported by digital simulations. The simulations are performed in conditions of extreme inertia changes from 10J_o to 0.5J_o. The drive system performances are tested at step speed references at low speed of 20 rpm (Figs. 6 and 7) and at high speed of 400 rpm (Figs. 8 and 9). The speed is reversed at 0.35 s, and a step load torque of 2 Nm is applied at 0.85 s.

The Matlab-Simulink package with Runge-Kutta 3 and h = 1 ms is used. The transient responses are studies as following: ω - real speed, T_e - real electromagnetic torque, $T_{e\omega}^{*}$ - reference torque from the speed controller, $T_L^{\wedge}$ - estimated disturbance torque, $J^{\wedge}$ - estimated inertia.

In Fig. 6, in the first 100 ms - when the inertia $J^{\wedge}$ is in transient identification, the speed responses oscillates and the disturbance torque $T_L^{\wedge}$ does not estimate the real load torque but the component due to inertia variation. That fact is so because both the speed controller and the Luenberger observer are detuned. On the other hand, the estimated inertia $J^{\wedge}$ converge in all cases and accurate estimated variables are obtained.

In Figs. 6 and 8, at step reverse speed, the load torque $T_L^{\wedge}$ is correctly estimated. Furthermore, there is a correct decoupling between the load torque estimation $T_L^{\wedge}$ and the transient torque $T_{e\omega}^{*}$. Therefore, a correct limitation of the electromagnetic torque to 5 Nm in transient regimes is obtained. A quite fast speed response at load torque changes is expected.

In Figs. 7 and 9, for $J = 0.5J_o$, the electromagnetic torque is not in limitation. Thus, robust fast speed-responses invariants to reference speed are obtained. The inertia identification algorithm is base on torque variations. Therefore, when torque variations are small values then the convergence time is longer (Fig. 7).

In Fig. 8, at a large step speed reference, the electromagnetic torque is limited for a long time. The speed response is naturally longer but without overshoot, i.e., the speed controller anti-windup facility.

Fig. 10 shows the robustness to electric parameters uncertainty, used in Fig. 2, i.e., stator resistance R_o and PM flux λ_{0o} at high speed of 400 rpm. For a temperature rise of 50°C, the resistance increases by 20% and the PM flux decreases by 10% in the case of ferrite magnet. The inductances are not affected by temperature. The estimated $J^{\wedge} = 0.03$ kgm^2 is slightly different from the real $J = 0.025$ kgm^2.

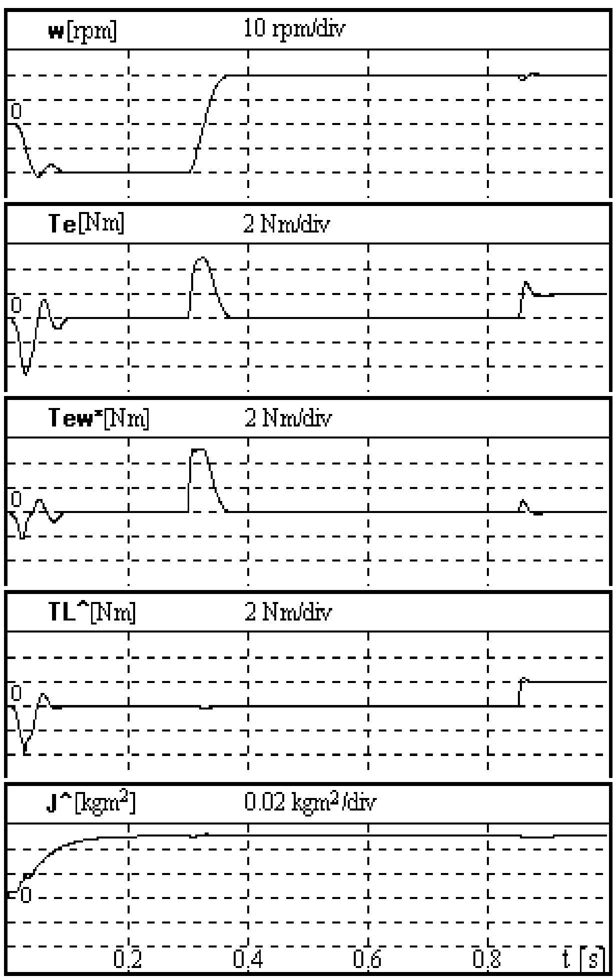

Fig. 6. Transient responses for $\omega^* = \pm 20$ rpm, $J = 10\ J_o$.

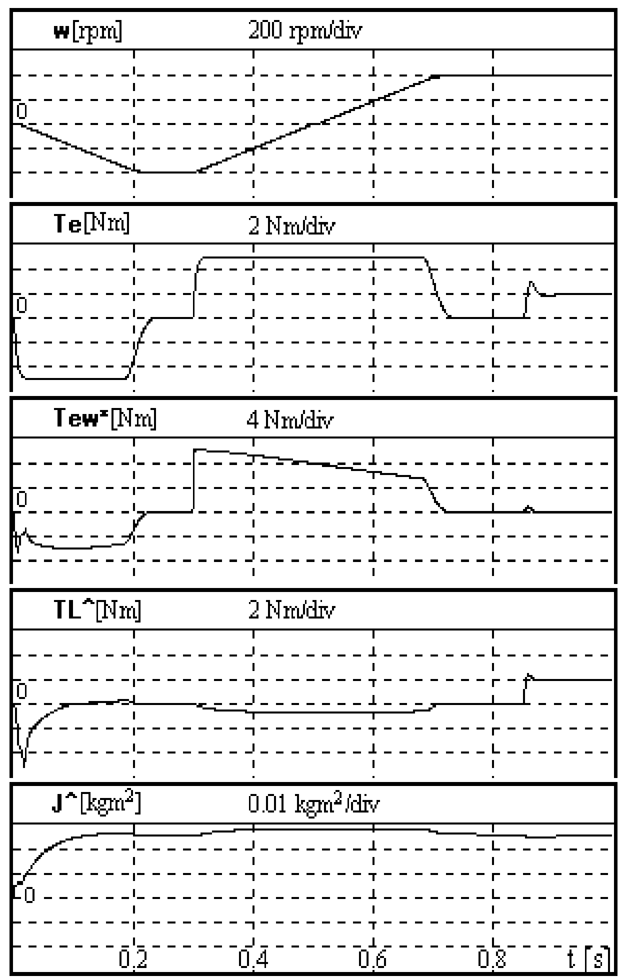

Fig. 8. Transient responses for $\omega^* = \pm 400$ rpm, $J = 5\ J_o$.

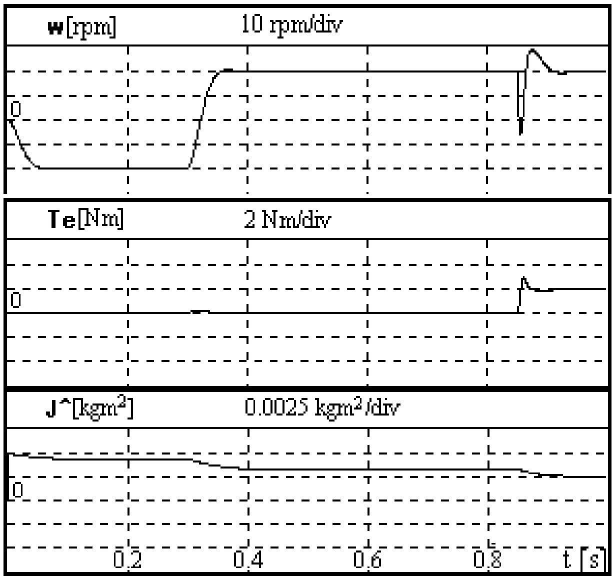

Fig. 7. Transient responses for $\omega^* = \pm$ 20 rpm, $J = 0.5\ J_o$.

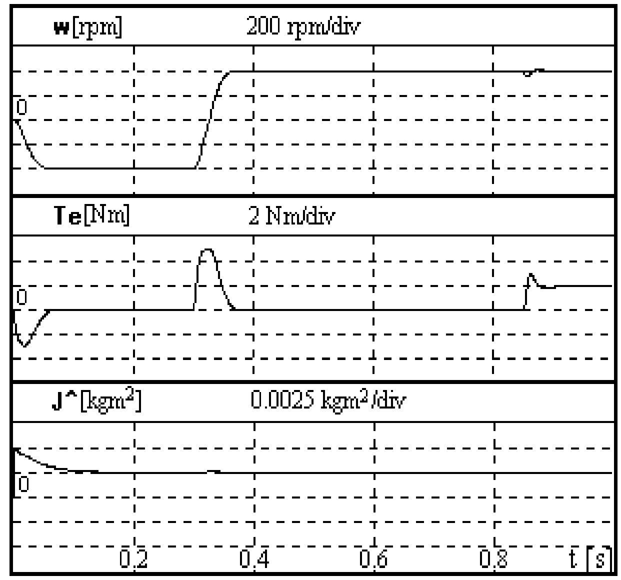

Fig. 9. Transient responses for $\omega^* = \pm$ 400 rpm, $J = 0.5\ J_o$.

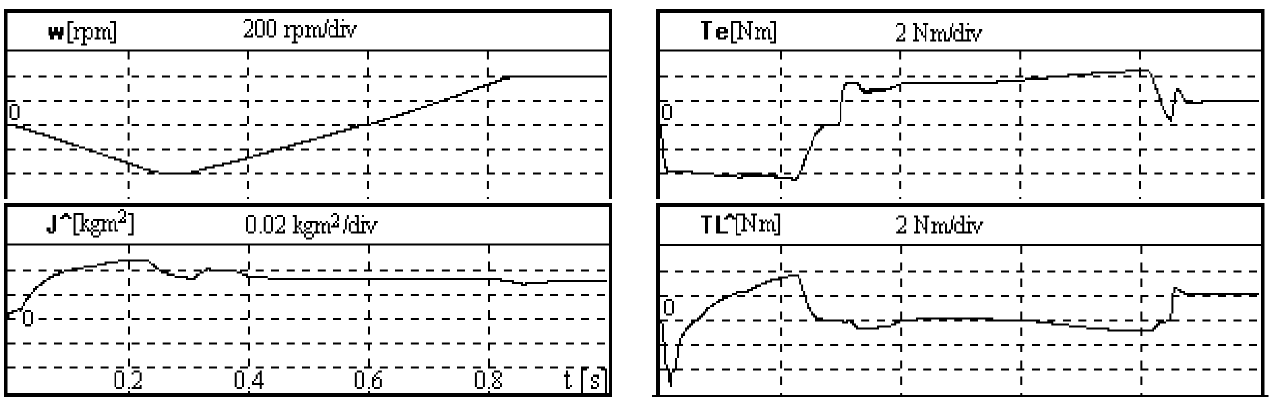

Fig. 10. Transient responses for $\omega^* = \pm$ 400 rpm, detuned case: $J = 5J_o$, $R = 1.2R_o$, $\lambda_0 = 0.9\lambda_{0o}$.

8. CONCLUSIONS

A new high-dynamic and robust speed-torque control structure based on adaptive observer with on-line inertia identification using only the position transducer is developed for the control of electric drives, particularly for PMSM. The main features are the following.

- The instantaneous speed and disturbance torque are estimated by an extended Luenberger observer inertia adaptive, with fast convergence, using the estimated motor torque and the measured position.
- To obtain a high-dynamic current sensorless torque-control, a current to voltage feedforward decoupling (for PMSM or specific for different motor types) and a dynamic correction to reduce the electric time constant are applied. Also, a feedforward compensation of the disturbance torque is used for robustness.
- On-line inertia identification given by a Landau discrete-time recursive gradient algorithm is used for robust adaptive tuning of both PI anti-windup speed controller and extended Luenberger observer.
- With correct inertia identification, there is a dynamic de-coupled action between the requested electromagnetic torque components, i.e., the torque from the speed controller and the torque to compensate the load torque. Moreover, an accurate dynamic limitation of the real electromagnetic torque is obtained.
- Extensive simulation results using a PMSM drive prove high-dynamic performances and robustness of the proposed control structure in wide speed range, with rated load torque, and large 1:10 inertia variation.

• The application area of the proposed control structure covers high-dynamic ac or dc servo drives, robust to parameter variations and load torque, in wide speed range. A typical example is a robot axis control with efficient compensation of inertia variation and equivalent complex coupled-disturbance terms.

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