

Disturbance Torque Observers for the Induction Motor Drives

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Abstract – The paper presents a comparative study on the performances of two disturbance torque observers in a induction motor drives. The first observer is a very simple one and is based on the mechanical system equation while the second one is a well-known observer, based on the reduced-order Gopinath's method. To estimate the disturbance torque the electrical drive systems must be endowed with a low-resolution encoder and an acquisition system for the electrical variables, which helps to calculate the electromagnetic torque of the motor. The values of the estimated disturbance torque can be used, either for an instantaneous low-speed observer or for the control algorithm (feedforward control).

Index terms – Induction motor drives, disturbance torque observers.

I. INTRODUCTION

The disturbance torque observer is very useful in the control algorithms of the drive systems in order to reject efficiently the effect of the load torque on the speed or on the position (*feedforward control*). For example, this kind of control is used by the direct-drive systems that function in low speed range [4-6]. Also, the values of the estimated disturbance torque are necessary if an instantaneous speed observer is used [7-10]. Because in the direct-drive systems the position/speed sensor is coupled on the common motor-load shaft, it is difficult to measure with precision the value of speed in low speed range. Usually, the incremental position sensors are used in the direct-drive applications (robotics, tools-machines etc.). Based on these encoders the speed is obtained from the position information at every sampling time. In fact, with the help of a position difference between two sampling points the average value of speed can be calculated and these values come with a delay equal with half of the detection period.

The paper presents, comparatively, two methods that can estimate the values of the disturbance torque in an electrical drive system. The first method is based on the mechanical equation, the same in every drive system for any kind of electrical motor and the second based on the reduced-order Gopinath's method [4-11]. For both observers the electrical drive system must be endowed with a low-resolution encoder and an acquisition system for the electrical variables (currents and voltages) used to calculate the electromagnetic

torque of the electrical motor. The experimental data are obtained with the help of a laboratory stand conceived and performed by the authors.

II. THE ALGORITHM OF THE DISTURBANCE TORQUE OBSERVER BASED ON THE MECHANICAL EQUATION

To estimate the disturbance torque, at first it is necessary to calculate (measure) the average low speed $\bar{\omega}(k)$ on $[k]$ time intervals – see Fig.1 and Fig. 2. The length of $T_\omega(k)$ time intervals must be chosen to obtain a good resolution of the average speed. At the same time, to approximate a linear evolution of the speed during these time intervals, the values $T_\omega(k)$ must be smaller than the mechanical time T_m of the direct-drive system: $T_\omega(k) < T_m$. The position transducer is a low resolution incremental encoder.

In Fig.1, $m_e(t)$ and $m_d(t)$ are respectively, electromagnetic and disturbance torque, K_m is the torque constant, J is the moment of inertia of the direct-drive system, T_s is the sample period of the digital controller, $\hat{m}_d(k)$ is the estimated disturbance torque on $[k]$ intervals, $\hat{\omega}(k, j)$ is the estimated instantaneous low speed at (k, j) sample points (see Fig.2) and $i_{(k, j)}$ is the discrete value of the current at the same moments. Assuming that the disturbance torque has a slow variation, we can approximate to be constant within $T_\omega(k)$ time period. Also, assuming that the speed has a linear variation within some intervals, the average value $\bar{\omega}(k)$ is equal with the instantaneous speed of the middle of the $[k]$ interval, as Fig.2 shows.

Therefore, we can estimate the constant values of the disturbance torque within T intervals using the average values of speed and the mechanical equation written with small variations:

$$\begin{aligned} \bar{m}_e(T) &= \hat{m}_d(T) + J \cdot \frac{\Delta \bar{\omega}(k)}{\Delta t} \Rightarrow \\ \hat{m}_d(T) &= \bar{m}_e(T) - J \cdot \frac{\bar{\omega}(k) - \bar{\omega}(k-1)}{T_\omega} \end{aligned} \quad (1)$$

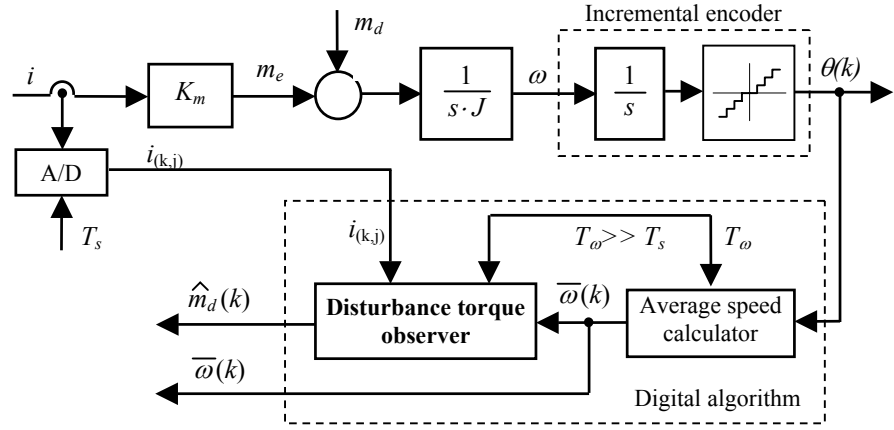


Fig. 1. The disturbance torque observer algorithm.

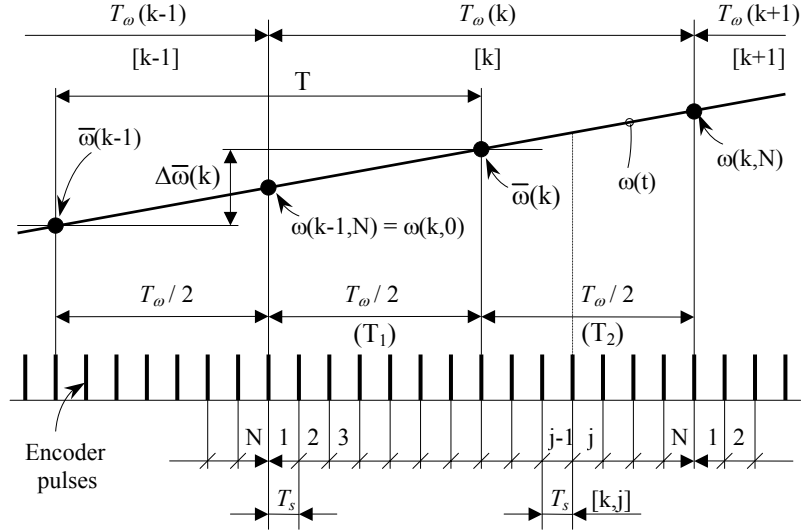


Fig. 2. The timing diagram of the disturbance torque observer.

where: $\bar{m}_e(T)$ is the average value of the electromagnetic torque within T interval. N is an even integer number meaning the number of sample periods included in T_ω intervals:

$$T_\omega = N \cdot T_s \quad (2)$$

If the value of the torque calculated with the equation (1) is extended to the entire $[k]$ interval, we obtain the recursive equation to estimate the disturbance torque:

$$\hat{m}_d(k) = \bar{m}_e(T) - J \cdot \frac{\bar{\omega}(k) - \bar{\omega}(k-1)}{T_\omega} \quad (3)$$

Nevertheless, the value of the disturbance torque given by equation (3) can be calculated at the end of $[k]$ time interval. Therefore, this value can be used in the next time interval, $[k+1]$. Having assumed the slow variation of the disturbance torque, we therefore

have:

$$\hat{m}_d(k+1) = \hat{m}_d(k) \quad (4)$$

III. THE ALGORITHM OF THE DISTURBANCE TORQUE OBSERVER BASED ON THE REDUCED-ORDER GOPINATH'S METHOD

To compare the experimental results obtained with the disturbance torque observer proposed above, a well-known observer based on the minimal-order Gopinath's method was used [4-11]. This observer can be applied if the mathematical model of the system contains state variables that are in the same time observable variables, which can be measured. Taking into the consideration the mechanical equation of the drive system and assuming that the disturbance torque has a slow variation the mathematical model of the system in the discretizing time domains is:

$$\begin{aligned} X(k+1) &= A \cdot X(k) + B \cdot U(k) \Leftrightarrow \\ \Leftrightarrow \begin{cases} \bar{\omega}(k+1) = \bar{\omega}(k) - \frac{T_\omega}{J} \cdot m_d(k) + \frac{T_\omega}{J} \cdot \bar{m}_e(k) \\ m_d(k+1) = m_d(k) \end{cases} \end{aligned} \quad (5)$$

$$Y(k) = C \cdot X(k) = \bar{\omega}(k) \quad (6)$$

where: $\bar{\omega}(k)$, $\bar{m}_e(k)$ are the average values of the speed (measured) and the electromagnetic torque within $[k]$ intervals, respectively. The average values of the electromagnetic torque can be calculated with the recursive relation:

$$\bar{m}_e(j) = \frac{(j-1) \cdot \bar{m}_e(j-1) + m_e(j)}{j}, \quad j = \overline{1, N} \quad (7)$$

and $\bar{m}_e(k) = \bar{m}_e(j)$ when $j = N$.

Assuming that the average value of the speed $\bar{\omega}(k)$ is the state variable that can be measured, the following matrix and vectors result:

$$\begin{aligned} X(k) &= \begin{bmatrix} \bar{\omega}(k) \\ m_p(k) \end{bmatrix} = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \begin{matrix} p \\ n-p \end{matrix}, \quad U(k) = \begin{bmatrix} \bar{m}_e(k) \end{bmatrix} \\ Y(k) &= [x_1] = [\bar{\omega}(k)] \\ A &= \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{matrix} p \\ n-p \end{matrix} = \begin{bmatrix} 1 & -\frac{T_\omega}{J} \\ 0 & 1 \end{bmatrix}, \\ B &= \begin{bmatrix} b_1 \\ b_2 \end{bmatrix} \begin{matrix} p \\ n-p \end{matrix} = \begin{bmatrix} \frac{T_\omega}{J} \\ 0 \end{bmatrix}, \quad C = [c_1 \quad c_2] = [1 \quad 0] \end{aligned}$$

The observability matrix is:

$$\begin{aligned} Q_o &= \begin{bmatrix} C \\ C \cdot A \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 1 & -\frac{T_\omega}{J} \end{bmatrix}, \\ \det Q_o &= -(T_\omega / J) \neq 0 \Rightarrow \\ \Rightarrow \text{rang } Q_o &= n = 2 \end{aligned} \quad (8)$$

The relation (8) emphasized that the system is observable and the reduced-order Gopinath's method can be applied to estimate the disturbance torque.

The internal variable z of the reduced-order observer verifies the following equation [11]:

$$\begin{aligned} \dot{z} &= (a_{22} - L \cdot a_{12}) \cdot z + (a_{21} - L \cdot a_{11}) \cdot x_1 + \\ &+ (b_2 - L \cdot b_1) \cdot u_1 + (a_{22} - L \cdot a_{12}) \cdot L \cdot x_1 \end{aligned} \quad (9)$$

By replacing the values of the constants in the discretizing time domains the equation (8) is:

$$\begin{aligned} z(k+1) &= \left(1 + L \cdot \frac{T_\omega}{J}\right) \cdot z(k) + (0 - L) \cdot Y(k) + \\ &+ \left(0 - L \cdot \frac{T_\omega}{J}\right) \cdot U(k) + \left(1 + L \cdot \frac{T_\omega}{J}\right) \cdot L \cdot Y(k) \Leftrightarrow \end{aligned}$$

$$\begin{aligned} z(k+1) &= \left(1 + L \cdot \frac{T_\omega}{J}\right) \cdot z(k) + L^2 \cdot \frac{T_\omega}{J} \cdot \bar{\omega}(k) - \\ &- L \cdot \frac{T_\omega}{J} \cdot \bar{m}_e(k) \end{aligned} \quad (10)$$

The values of the observer gain results from the convergence condition in equation (10):

$$\left|1 + L \cdot \frac{T_\omega}{J}\right| < 0 \Rightarrow L \cdot \frac{T_\omega}{J} < -1 \Rightarrow L < -\frac{J}{T_\omega} \quad (11)$$

IV. THE ELECTRICAL DRIVE STAND

Fig.3 shows the drive stand configuration used to study the observers' algorithms described above. The main part of the test stand consists of a standard cage induction motor (1,5kW, Y/Δ 380/220V, 3.8A, 50Hz, 1410 rpm) supplied by a voltage source PWM inverter both controlled by a TMS320C31 Motion Control Development Board (MCDB) and dedicated interfaces. The PWM inverter, performed for laboratory studies, has a flexible structure [12]. In the power stage IGBT transistors are used (Semikron modules - SKM200GB122D, 200A, 1200V). For an individual control of each transistor, the HCPL 316J integrated gate drivers were used. To generate the PWM control signals for the inverter transistors, the sinusoidal pulse width modulation technique was used. The same MCDB can acquire the phase voltages and currents of the induction motor through an acquisition system that contains Hall transducers (LEM module). The speeds are measured by the MCDB with the help of a low-resolution encoder (1,000 pulses/rotation).

The second part of the test stand is the mechanical loading system that is conceived with a DC motor (1.5kW, 110V, 1450rpm) and a four-quadrant IGBT chopper [13]. The DC machine is digitally controlled (torque controlled system) to emulate any torque-speed characteristic, any mode of operating and the dynamic characteristic of the real load. The power switches used for the DC-DC converter are the same IGBT transistors - SKM200GB122D. To control the power devices, the hybrid dual IGBT drivers SKHI22H4 were used.

The complementary non-overlapping PWM signals with controlled dead time, applied on the inputs of the

SKHI22H4 modules, are generated by the PWM interface, performed by the authors with the dedicated integrated circuit IXDP610. In this way the digital

system that implements the torque regulator, can control the armature current of the DC motor

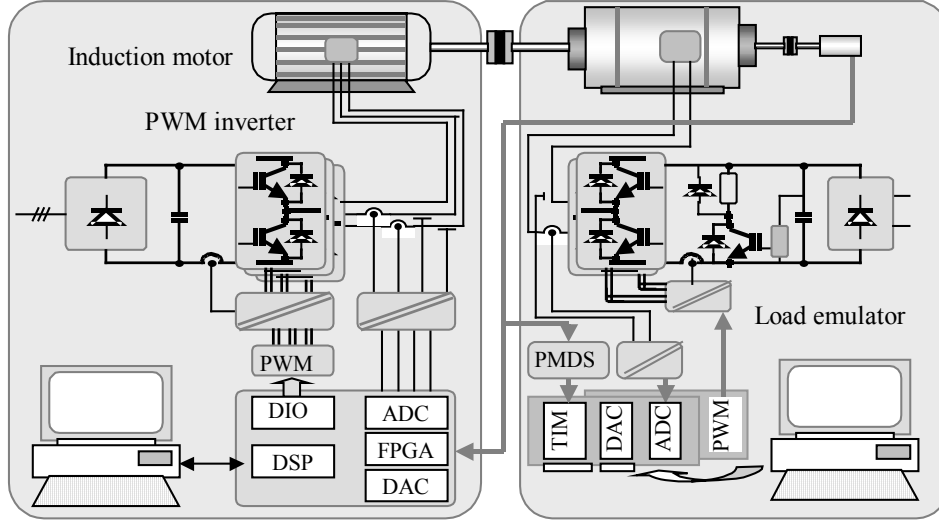


Fig. 3. The drive stand configuration.

through the duty ratio of the two complementary PWM signals. To close the current loop the armature current is measured with the help of a Hall transducer (LEM module), filtered and acquired by the acquisition system (Data Board Acquisition).

V. EXPERIMENTAL RESULTS

The electromagnetic torque of the induction motor is calculated in every sampled period T_s (j moments) based on the stator voltages and currents. Thus, in a stationary d^s-q^s frame the relation of the electromagnetic torque is:

$$m_e(j) = p \cdot [\Psi_{sd}(j) \cdot i_{sq}(j) - \Psi_{sq}(j) \cdot i_{sd}(j)] \quad (12)$$

where: p is the number of the poles pairs, $\Psi_{sd}(j)$ is the d -axis stator flux linkage, $\Psi_{sq}(j)$ is the q -axis stator flux linkage, $i_{sd}(j)$ is the d -axis stator current and $i_{sq}(j)$ is the q -axis stator current at the j moments.

The flux linkage values are estimated with the following recursive expressions in terms of the stator voltages and currents [14]:

$$\begin{aligned} \Psi_{sd}(j) &\approx k_F \cdot \Psi_{sd}(j-1) + k_f \cdot [u_{sd}(j) - R_s \cdot i_{sd}(j)] \\ \Psi_{sq}(j) &\approx k_F \cdot \Psi_{sq}(j-1) + k_f \cdot [u_{sq}(j) - R_s \cdot i_{sq}(j)] \end{aligned} \quad (13)$$

where: R_s is the stator windings resistance, $u_{sd}(j)$ is the d -axis phase voltage and $u_{sq}(j)$ is the q -axis phase voltage at the j moments. The coefficients k_F and k_f are obtained with the relations:

$$k_F = \frac{T_f}{T_f + T_s}, \quad k_f = \frac{T_f \cdot T_e}{T_f + T_s}$$

$T_f \in [0.2 \dots 0.5]$ rad/sec is a filter constant.

An example of the experimental values of the electromagnetic torque obtained with the help of a laboratory drive stand and the relations' (12) and (13) is presented in Fig.4. The following values were chosen for the experiment: sampled period $T_s = 400\mu\text{sec}$, $T_e = 40\text{msec}$, $k = 100$, the frequency of the supply voltage $f = 30\text{Hz}$.

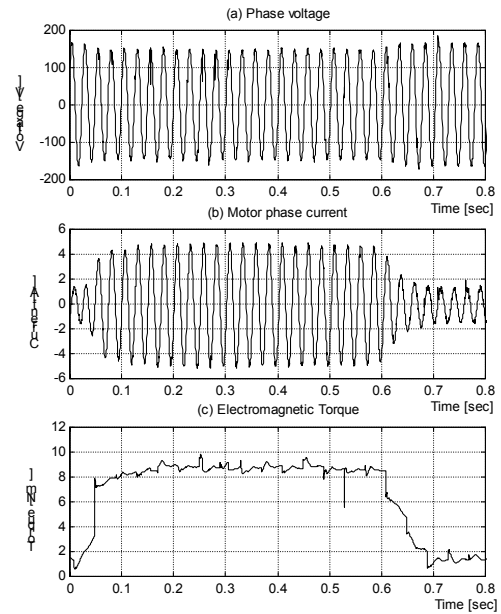


Fig. 4. The calculated values of the electromagnetic torque

Fig.5 shows the disturbance torque estimated by the first observer based on the mechanical equation. During the experiments the drive system operate in open loop configuration and the load system generate pulses of constant torque with a 7[Nm] amplitude. These pulses are added to the friction torque (1.4[Nm]).

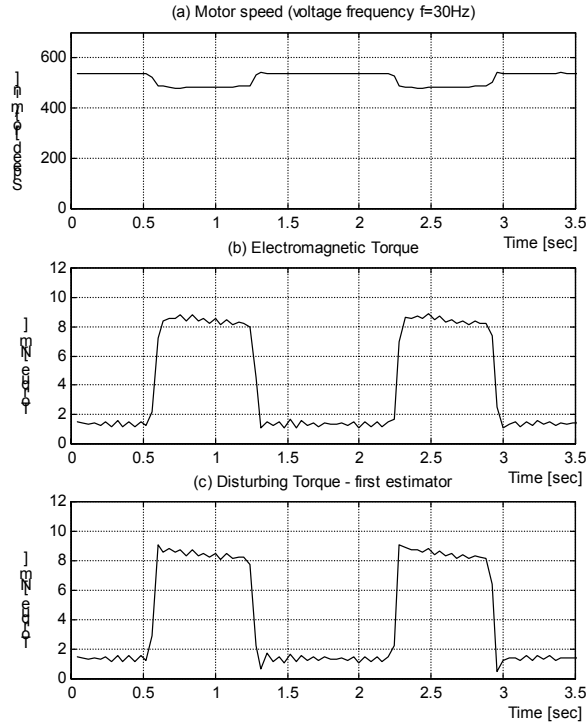


Fig. 5. The results of the torque observer based on the mechanical equation of the drive system.

The pulses of load torque are not square because the armature current of the DC load motor can not suddenly increase. Also, the slopes of the electromagnetic torque are smaller than the slopes of the disturbance torque because of the system inertia's moment.

Fig.6 shows the values of the disturbance torque estimated with the help of the torque observer based on the reduced-order Gopinath's method for the various values of the observer gain L . The convergence condition (10) applied to the laboratory stand is:

$$L < -\frac{J}{T_{\omega}} = -6$$

The optimum value for the gain observer is $L = -6$ (Fig.6(a)). If the value of the L is greater ($L=-4$) than the optimum value the observer will become slow (Fig.6(b)) and if the value of the L is smaller ($L=-8$)

than the optimum value, the observer will immediately become unstable (Fig.6(c)).

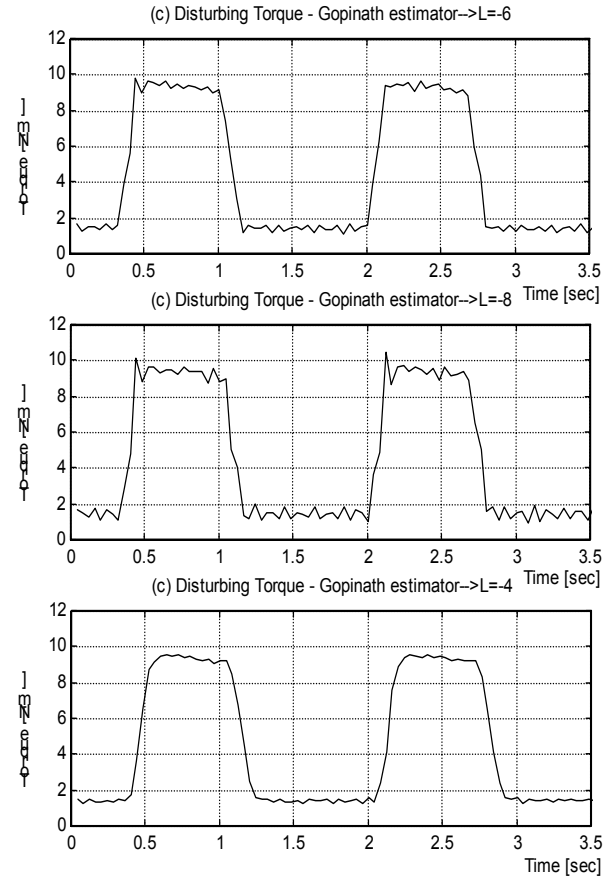


Fig. 6. The torque observer results based on the reduced -order Gopinath's method for various values of the observer gain L .

Fig.7 presents, comparatively, the waveforms of the electromagnetic torque (Fig.7(a)), the disturbance torque estimated with the help of the torque observer based on the reduced-order Gopinath's method (Fig.7(b)) and the disturbance torque estimated by the first observer based on the mechanical equation (Fig.7(c)). The waveform of the disturbance torque obtained with the observer based on the mechanical equation is the closest to the theoretical waveform. This confirms that this observer based on the mechanical equation is better than the acknowledged observer based on the minimal-order Gopinath's method from the point of view of the estimation precision. Taking into consideration the simplicity of the observer based on the mechanical equation and the complexity as well as the convergence problems of the Gopinath observer, the use of the first observer has more advantages in many situations.

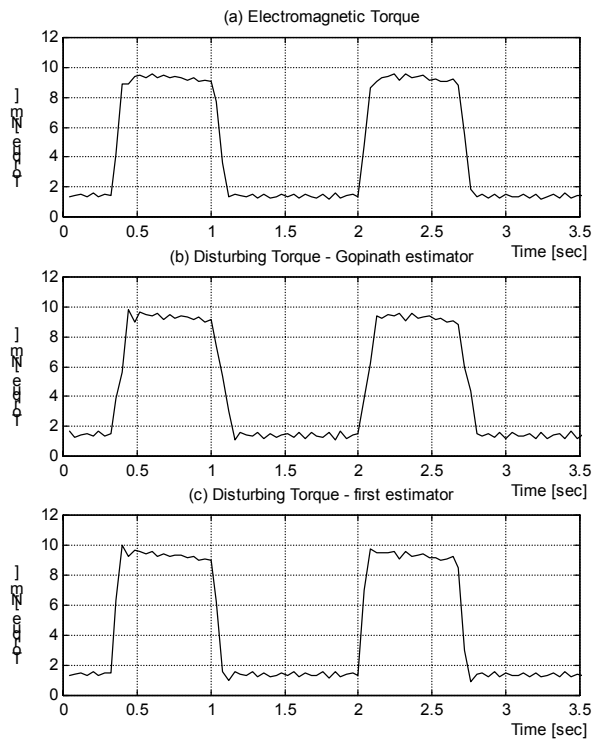


Fig. 7. The disturbance torque obtained with the help of both observers.

VI. CONCLUSIONS

Both observers presented in the paper can estimate the disturbance torque in an electrical drive system. The values of the disturbance torque estimated on-line can be used by the control algorithm of the electrical drive systems in low speed range and/or by the instantaneous speed observers. For both observers the drive system must be endowed with a low-resolution encoder and an acquisition system for the electrical variables, which helps to calculate the electromagnetic torque of the electrical motor. The first observer of the disturbance torque is based on the mechanical equation, the same in every drive system for any kind of electrical motor. The second observer is based on the reduced-order Gopinath's method. The estimation performances of both observers are comparable. Taking into consideration the simplicity of the observer based on the mechanical equation and the

complexity as well as the convergence problems of the Gopinath observer, the use of the first observer has more advantages in many situations. For the observers presented in this paper the drive's parameters were considered constant.

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