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SPEED-CONTROLLED ELECTRICAL DRIVE WITH NOVEL DISTURBANCE OBSERVER

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Abstract. *This paper presents the design of a digitally-controlled speed electrical drive in the presence of arbitrary external immeasurable load disturbances. The extraction of a known class of external disturbances is achieved by using the novel DOB (Disturbance Observer), in which the discrete-time model of external disturbance is included implicitly. It is shown, analytically, by simulation, and experimentally, that the proposed modification of disturbance observer enables the entire rejection of a known class of immeasurable external disturbances, in the steady-state, regardless of the DOB filter cutoff frequency. Thus the speed of disturbance extraction and quality of closed-loop system set-point transient response can be achieved independently. The proposed design procedure is carried out by the speed-controlled drive with a vector-controlled induction motor. Both the simulation and experimental results illustrate the effectiveness and robustness of the proposed technique.*

Key words: *Disturbance observer, external load torque disturbance, disturbance model, speed-controlled electrical drive*

1. INTRODUCTION

One of the key tasks in the design of feedback control systems is to eliminate or to suppress, as much as possible, the influence of external immeasurable disturbances on the steady-state value of controlled variable (system output). To perform this task, a number of various controlling structures has been proposed, which can be classified into three main groups: (i) the control schemes that use the IMC (Internal Model Control), (ii) the schemes using IMP (Internal Model Principle), and (iii) DOB (Disturbance Observer), often referred to as the pseudo inverse control.

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The IMC based solutions are used in combination with conventional controllers [1] in different fields of engineering, including the motor drive applications. They enable the suppression of external disturbances, but when compared to IMP and DOB solutions they are less robust in relation to mismatching and/or variations of model parameters.

When compared to IMC, the IMP based solutions [2]-[4] are more robust, yet they are more sensitive to the propagation of measurement noise. Therefore, the DOB based solutions are proposed [5]-[10], which overcome the shortcomings of IMP and IMC controlling structures. Namely, DOB enables the disturbance estimation and rejection, while, at the same time, it is more robust in relation to model uncertainties and less sensitive to measurement noise. However, the disturbance rejection with the DOB is restricted by the cutoff frequency of DOB filter, i.e., the decrease of DOB filter cutoff frequency increases the steady-state error caused by the propagation of external disturbances [5]. In this paper, the novel DOB structure is proposed, designed by introducing a modified DOB filter, which enables the entire rejection, in steady-state, of a known type of immeasurable external disturbances. However, the conventional DOB cannot completely extract time varying disturbances due to the estimation error caused by amplitude attenuation and phase lag introduced by the filter [5]. By imbedding the model of disturbance into the modified DOB filter, zero steady-state error can be achieved regardless of the DOB filter cutoff frequency.

The efficiency of the proposed DOB controlling structure in extraction of disturbances is verified by the design of a disturbance invariant speed-controlled drive with induction motor. The results of simulation runs and measurements obtained by an experimental setup are presented for different types of external load torque disturbances. Also, the drive sensitivity as regards to mismatching of plant parameters is examined by simulation. Both the simulation and experimental measurements verify the entire rejection of disturbances from the steady-state value of motor speed and drive robustness with respect to changes of plant parameters.

The paper is organized in five sections. After the Introduction is presented in Section I, in Section II, the modified DOB control structure, together with the speed controller, is described in detail. It is analytically shown that the proposed controlling structure enables the desired continuous-time set-point transient response and rejection of external torque disturbances to be achieved independently in the presence of arbitrary external disturbances.

In Section III, the simulation results are presented, illustrating the drive operation for the case of a ramp profiled disturbance. Also, the simulation results of induction motor drive with detuned parameters are presented, in order to examine the drive robustness with respect to variations of plant parameters.

The comparison of measurements obtained by the experimental setup in cases when the control section with the proposed DOB is included and excluded is given in Section IV. Finally, Section V presents the conclusions.

2 SPEED-CONTROLLED DRIVE WITH MODIFIED DISTURBANCE OBSERVER

Fig. 1 shows the structure of a digitally speed-controlled induction motor drive. In the minor local loop of the structure, the proposed modified DOB is applied for extraction of disturbances. The induction motor drive is based on the IFOC (Indirect Field Oriented Control) torque control algorithm. The control portion of the structure includes the inverse nominal plant model, controller $C(z)$, prediction polynomial $D(z$, and filter polynomial $F(z)$.

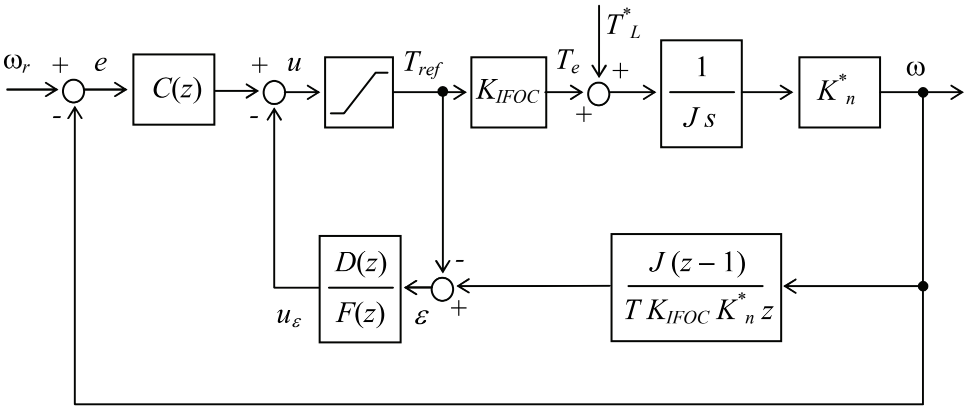


Fig. 1 DOB based speed-controlled drive.

The control plant comprises the IFOC based induction motor torque drive and incremental shaft encoder measuring the motor speed. The speed samples are obtained as

$$\omega(kT) = \frac{K_n}{2\pi}\omega(t) = K_n^*\omega(t) \tag{1}$$

where $\omega(t)$ denotes the shaft angular speed in radians per second, T the sampling period, and K_n^* is the number of quantum marks per radian of the incremental encoder.

The discrete zero-order-hold equivalent nominal model of the control plant comprises: (i) IFOC based induction motor drive, modeled by the equivalent gain K_{IFOC} and saturated torque output, due to the drive torque restraint determined by the IFOC drive and induction motor characteristics; and (ii) shaft encoder, modeled by the equivalent gain K_n^*. The zero-hold equivalent nominal model of the plant comprising the IFOC drive, induction motor, and incremental encoder may be approximated, in the linear regime, by

$$W^0(z) = \frac{\omega(z)}{u(z)} = Z\left[\frac{K_{IFOC}K_n^*}{J}\frac{(1-e^{-Ts})}{s^2}\right] \tag{2}$$

wherefrom one obtaines

$$W^0(z) = \frac{\omega(z)}{u(z)} = C_m\frac{1}{z-1} \tag{3}$$

where $C_m = K_{IFOC}K_n^*T/J$ represents the synthetic plant parameter, while K_{IFOC} and J denote the electromagnetic torque coefficient and motor inertia, respectively. Note that parameter C_m can be easily measured by an experimental setup.

Notice that the design of speed controller and disturbance observer is based on the nominal plant model. However, the plant model can differ from the nominal due to the mismatching and variations of the model parameter values in different drive operating conditions. For example, the temperature drift represents one of the major causes for deterioration of IFOC drive characteristics [11]. Therefore, the robustness of the proposed DOB is examined for these conditions, by the simulation runs that follow.

The controlling structure in Fig. 1 consists of the following two parts: main speed control loop and disturbance observer. The main control loop must provide the desired set-point transient response typical for the speed-servo drives (the closed-loop control system cutoff frequency of 100 Hz). This can be achieved by using the proportional controller $C(z) = K_p$. The local control loop with the proposed disturbance observer is designed to extract external disturbances. It will be shown later that the desired closed-loop system transient response and rejection of disturbance can be achieved independently.

From Fig.1, the closed-loop system transfer function $\omega(z)/\omega_r(z)$ is easily obtained as

$$\frac{\omega(z)}{\omega_r(z)} = \frac{K_p C_m \frac{1}{z-1}}{1 + K_p C_m \frac{1}{z-1}} . \tag{4}$$

After approximating load torque disturbance $T_L(t)$ by $T_L(t) = T_L^*(kT)$ for $kT \le t < (k+1)T, k = 0,1,2,...,$ the closed-loop transfer function $\omega(z)/T_L^*(z)$ becomes

$$\frac{\omega(z)}{T_L^*(z)} = \frac{1 - \frac{D(z)}{F(z)}}{1 + K_p C_m \frac{1}{z-1}} W_L(z) \tag{5}$$

where $W_L(z)$ denotes

$$W_L(z) = Z\left[\frac{1}{J}\frac{1-e^{-ts}}{s^2}\right] = \frac{T}{J}\frac{1}{z-1}. \tag{6}$$

2.1 Rejection of disturbance

From equations (5) and (6), the steady-state error in the presence of external disturbance $T_L(t)$ will be zero if

$$\lim_{z\to 1}(1-z^{-1}) \frac{1 - \frac{D(z)}{F(z)}}{1 + K_p C_m \frac{1}{z-1}} \frac{T}{J(z-1)} T_L^*(z) = 0 \cdot \tag{7}$$

where $T_L^*(z)$ represents the z-transform of the disturbance model, $T_L^*(z) = A(z)/B(z)$. Since

$$\lim_{z\to 1}\frac{1}{1+K_p C_m \dfrac{1}{z-1}}\frac{T}{J(z-1)}\neq 0 \tag{8}$$

equation (7) is satisfied if

$$\lim_{z\to 1}(1-z^{-1})\frac{F(z)-D(z)}{F(z)}\frac{A(z)}{B(z)}=0\ . \tag{9}$$

For a stable low-pass digital filter and since $A(1) \neq 0$, condition (9) is fulfilled for disturbance polynomial

$$B(z)=F(z)-D(z)\ . \tag{10}$$

Hence, after certain finite number of sampling periods, external disturbances $T_L(t)$ will be completely rejected from the state-state value of motor speed for

$$D(z)=F(z)-B(z)\ . \tag{11}$$

Consequently, to design the local control loop of the structure of Fig. 1 with the proposed modified DOB, it is necessary to adopt an appropriate filter polynomial $F(z)$ and to determine the disturbance polynomial $B(z)$ as the denominator of the disturbance model. For example, for the constant, ramp, parabolic, and sinusoidal ($T_L(t) = \sin\omega t$) torque disturbances, the denominator of the disturbance model $B(z)$ equals: $(z-1)$ $(z-1)^2$, $(z-1)^3$, and $z^2-2z\cos\omega T+1$, respectively. Furthermore, the disturbance polynomial $B(z)$ can also be determined for the cases of more complicated disturbances. For example, for a composed disturbance of the superposed ramp profile and sinusoidal signals, the disturbance polynomial $B(z)=(z-1)^2(z^2-2z\cos\omega T+1)$ should be used for the proposed DOB structure design. In such way, for any kind of simple or more complicated disturbances, the corresponding prediction polynomial $D(z)$ can be immediately determined by using equation (11).

Nevertheless, torque disturbance $T_L(t)$ is usually slow varying and therefore the employment of disturbance polynomial $B(z) = (z-1)^2$, which corresponds to extraction of ramp disturbances, will efficiently reject the influence of the torque disturbance on steady-state value of the motor speed. Moreover, the use of $B(z) = (z-1)^2$ for calculation of prediction polynomial $D(z)$ by equation (11) will strongly suppress low frequency stochastic disturbances that can be generated by double integration of white noise.

The stable filter polynomial $F(z)$ used in the proposed DOB is selected according to the speed of disturbance rejection and robustness requirements. In the selection of $F(z)$ the following criteria, given in [7] and [8], are to be taken into account: (i) the filter cutoff frequency should be selected to filter out the quantization noise from the measuring signal of motor speed generated by the optical incremental encoder; (ii) the filter section determines the cutoff frequency of the local control loop for disturbance rejection and therefore this cutoff frequency should be as high as possible, with unity gain, and low phase lag within the filter bandwidth. (For example, in the case of speed servo drive, the strong disturbance suppression requires filter cutoff frequency is to be equal or greater than 100 Hz. Hence, the selection of 100 Hz for the filter cutoff frequency satisfies both requirements (i) and (ii). It should be noted that, in the case of modified DOB proposed in this paper, the known external disturbance can be completely rejected, regardless of the filter cutoff frequency); (iii) according to [7], the system robustness is determined by the order of DOB. Namely, the system robustness increases as the relative degree of the orders of filter numerator and denominator decreases. In the case of the same relative degree, the increase of denominator order increases the system robustness. However, in the case of the proposed modified DOB the order of filter polynomial $F(z)$ is partially determined by the order of disturbance polynomial $B(z)$, according to equation (11). Namely, the order of filter polynomial $F(z)$ should be equal or greater than the order of disturbance polynomial $B(z)$. Consequently, the DOB filter polynomials $D(z)$ and $F(z)$ are designed as follows: (a) $F(z)$ is adopted as the denominator of the standard elliptic low-pass digital filter [12], with the cutoff frequency of 100 Hz and of the order equal to the order of the specified disturbance polynomial $B(z)$; (b) then nominator $D(z)$ of the DOB filter is derived from equation (11) by using the disturbance polynomial $B(z)$ and the adopted filter polynomial $F(z)$.

It should be noted that the proposed modified DOB filter with the unity pass-band gain enables complete extraction of any known class of external disturbances. It also rejects arbitrary disturbances in the same manner as the standard DOB implementation.

2.2. Setting of controller parameter

Controller $C(z)$ of the DOB structure in Fig. 1 may be determined by the desired closed-loop system transfer function. Since the closed-loop system is of the first order, its zero-hold equivalent pulse transfer function is given by

$$\frac{\omega(z)}{\omega_r(z)} = Z\left[\frac{1-e^{-Ts}}{s}\frac{1/T_p}{s+1/T_p}\right] \tag{12}$$

where time constant T_p determines the speed of the set-point transient response.

From equation (12) one obtains

$$\frac{\omega(z)}{\omega_r(z)} = \frac{1-\exp(-T/T_p)}{z-\exp(-T/T_p)}. \tag{13}$$

After equating identically equations (4) and (13), one obtains the proportional gain as

$$K_p = (1-\exp(-T/T_p))/C_m. \tag{14}$$

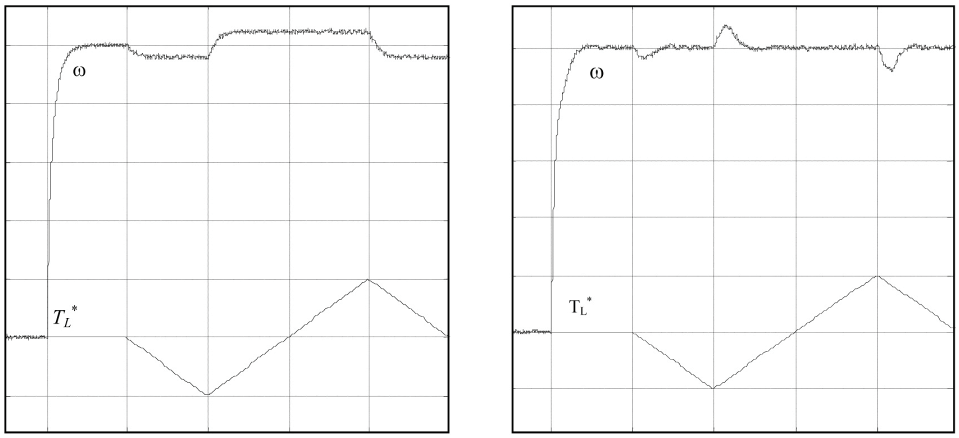
To the closed-loop system cutoff frequency of 100 Hz, corresponds T_p = 1.5 ms. For sampling period T = 1 ms and synthetic parameter C_m = 0.2215, the proportional gain K_p =2.1968 is calculated from equation (14).

It should be noted that the torque reference signal (T_{ref} in Fig. 1) needs to be bounded due to the torque limit determined by the torque driving characteristics of the IFOC drive. The limited torque command T_{ref} is fed into the IFOC drive section and disturbance observer section (Fig. 1).

3. SIMULATION

In order to examine the efficiency of the proposed modified DOB in extraction of load torque disturbances, several simulation runs have been carried out. First of all, we analyze the drive operation in the presence of ramp profiled external disturbances. Then, the system robustness with respect to mismatching of the control plant parameters is examined. To illustrate the advantages of the modified DOB, the corresponding simulation results of the standard and modified DOB are compared.

Simulation is performed by using the detailed model of servo-drive, which comprises a three phase induction motor of the nominal power P = 250 W, nominal voltage 220 V, and nominal frequency 50 Hz. Also, the simulation model includes the IGBT inverter based power amplifier stage and control section with the induction motor IFOC torque algorithm operating with sampling frequency 10 kHz and the speed and DOB control algorithms operating with sampling frequency 1 kHz.



time: 0.02 s/div T_L^*: 0.5 pu/div ω: 10 rpm/div
(a)

time: 0.02 s/div T_L^*: 0.5 pu/div ω: 10 rpm/div
(b)

Fig. 2. Rejection of a ramp profiled disturbance: (a) with the standard DOB, (b) with the proposed DOB modified for ramp disturbances.

3.1. Extraction of ramp disturbances

In the first simulation run given in Fig. 2 we analyzed the system behavior in the presence of ramp profiled load torque disturbance. Disturbance polynomial $B(z)=(z-1)^2$ (denominator of disturbance model) that corresponds to extraction of ramp disturbances is applied. Since this polynomial is of the second order, the denominator of the second order digital elliptic filter $F(z)=z^2-1.1997z+0.5158$, with the cutoff frequency 100 Hz and sampling period 1 ms, is adopted. The nominator $D(z)$ of DOB filter is determined from equation (11). Thus the following DOB filter having unity bandwidth gain and cutoff frequency 100 Hz is derived

$$\frac{D(z)}{F(z)} = \frac{0.8003z - 0.4842}{z^2 - 1.1997z + 0.5158} \tag{15}$$

Figs. 2 (a) and (b) show the set-point transient responses of the motor speed, in the presence of a ramp profiled load torque disturbance: (a) for the standard DOB low-pass filter, with cutoff frequency 100 Hz and (b) for the modified DOB filter (15). In both cases, the desired set-point transient response determined by the closed-loop system transfer function (13) is achieved. However, the simulation results in Figs. 2. (a) and (b) illustrate that the standard DOB low-pass filter fails to reject the ramp profiled external disturbance, in steady-state, while the proposed modified DOB filter keeps the steady state error equal to zero, with the time of disturbance rejection determined by the DOB filter cutoff frequency.

3.2. System robustness

In this subsection, the robustness of the controlling structure of Fig. 1 is examined in relation to the uncertainness and/or mismatching of plant parameters. To this end, the synthetic plant parameter C_m is changed to be three times less than the estimated $\hat{C}_m$, which is used in the section of disturbance observer. Then the simulation is repeated and shown in Fig. 3.

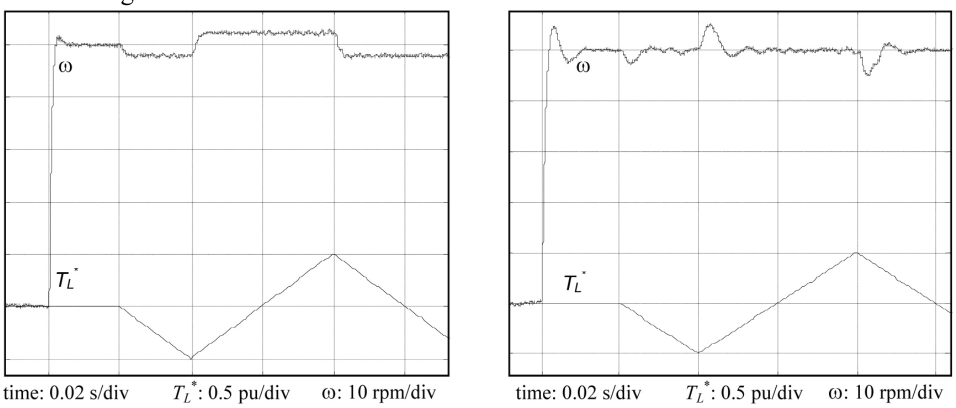


Fig. 3. Rejection of a ramp profiled disturbance in the case when $\hat{C}_m = 3C_m$:
(a) with the standard DOB, (b) with the proposed DOB modified for ramp disturbances.

By comparing Figs. 2(b) and 3(b), one can conclude that a considerable change of plant parameter does not reduce the ability of the proposed DOB in extraction of disturbance. Nevertheless, in both cases of the standard and proposed DOB, the change of plant parameter slightly prolongs the speed of transient response and time of disturbance extraction.

4 EXPERIMENTAL SETUP

For the experimental verification of the efficiency of the proposed DOB structure in rejection of immeasurable external disturbances, the experimental setup shown in Fig. 4 has been used. The setup includes: (i) four-pole induction motor of the nominal power of 250 W, nominal voltage of 220 V, nominal frequency of 50 Hz, and nominal speed of 1500 rev/min; (ii) three-phase IGBT voltage inverter; (iii) Hall effect based current transducers; (iv) incremental encoder giving 1000 pulses per revolution; (v) armature-controlled DC motor with power of 500 W, coupled to the shaft if induction motor as a mechanical brake in order to produce a regulated torque disturbance. The algorithms of stator currents regulation and vector control of induction motor are realized with the sampling period of 100 μs, while the speed control algorithm and other joined functions of the DOB structure are accomplished by the sampling period of 1 ms.

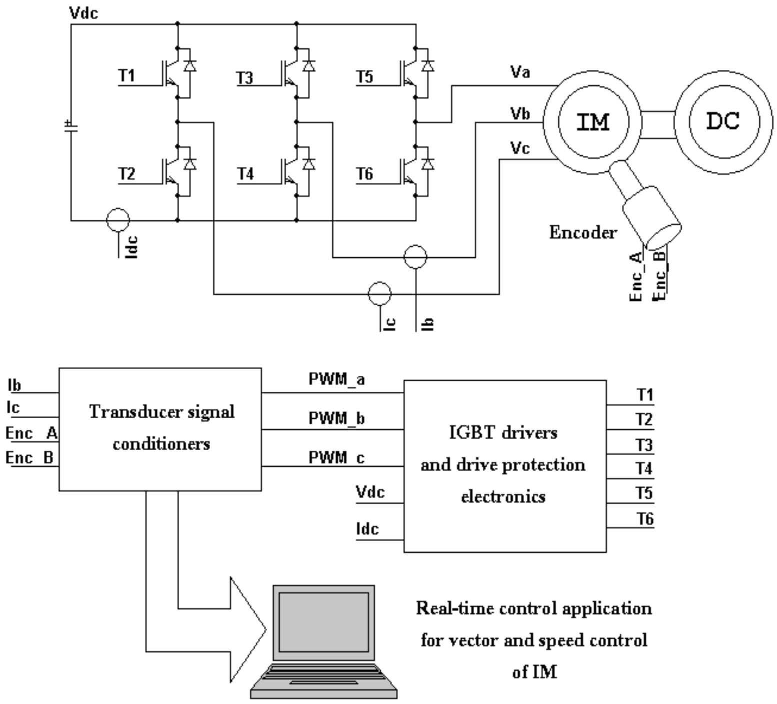


Fig. 4. Experimental setup.

In the first experimental measurement, the local feedback loop of the DOB structure of Fig. 1 was disconnected, and the ramp profile torque command is produced by armature current i_f of the DC brake coupled with the induction motor. In Fig. 5, the torque command signal i_q (quadrature current) is also shown. The figure shows significant variation of the motor $\omega(t)$ around its steady-state value.

Fig. 6 shows the motor speed and torque command after connection of the local feedback loop. Recall that this loop is designed by using disturbance polynomial $B(z)$ that corresponds to the extraction of ramp disturbances. Traces in Fig. 6 show that, after connection of the local feedback loop, the proposed DOB structure completely eliminates the influence of torque disturbance on steady-state value of the motor speed.

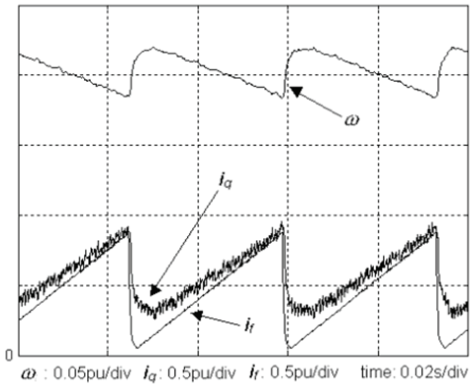


Fig. 5. Speed transient and torque command for load torque disturbance with excluded DOB control section.

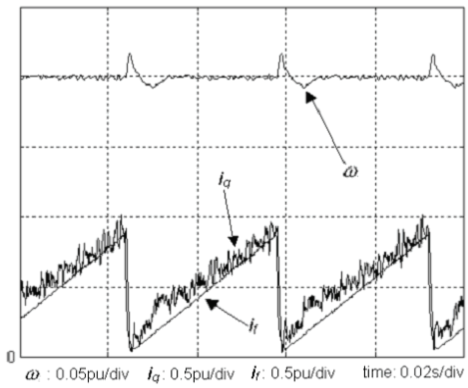


Fig. 6. Speed transient and torque command for combined ramp load torque disturbance with included DOB control section.

As it has been mentioned earlier, the proposed DOB designed by the use of disturbance polynomial $B(z) = (z-1)^2$ effectively reject not only ramp profiled disturbances but also any kind of slow varying disturbances, moreover it strongly suppressed low frequency stochastic disturbances. To prove this, the next experimental measurements were performed by generating the sinusoidal torque disturbance. Fig. 7 shows the disturbance and behavior of the motor speed when the local minor loop of the DOB structure is excluded. Like in the case of Fig. 5, the load torque disturbance is produced by armature current i_f of the DC brake.

From Fig. 7 it is seen that in the presence of disturbance the motor speed drastically fluctuates around its steady-state value.

Fig. 8 shows the torque command and behavior of the motor speed in the transient and steady-state after implementation of the DOB structure determined by disturbance polynomial $B(z) = (z-1)^2$. From Fig. 8 it is seen that the proposed DOB structure practically completely eliminates the influence of load torque disturbance from steady-state value of the motor speed. It is to be noticed that in all experimental measurements the prediction polynomial $B(z) = (z-1)^2$ that corresponds to the rejection of ramp disturbance was employed for calculation of DOB. The use of higher order disturbance polynomials as, e.g., $B(z) = z^2 - 2z\cos\omega T + 1$ and $B(z) = (z-1)^3$, that correspond respectively to the extraction of sinusoidal and parabolic disturbances, does not produce much better results in disturbance rejection.

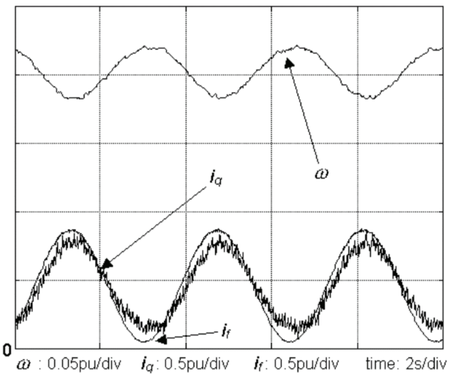


Fig. 7 Speed transient and torque command for sinusoidal load torque disturbance when the local loop of the DOB structure is disconnected.

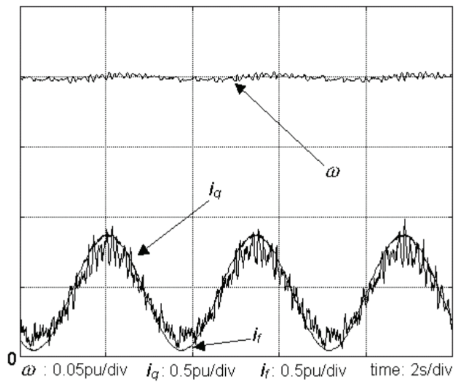


Fig. 8 Speed transient and torque command for sinusoidal load torque disturbance when the local loop of the DOB structure is connected.

5. CONCLUSION

We have proposed a modified DOB structure which rejects a known class of external disturbances, regardless of the DOB filter cutoff frequency. The proposed DOB is simulated and experimentally tested by using the speed-controlled drive with an IFOC based induction motor. The modification is based on the discrete time model of disturbance imbedded implicitly into the DOB filter. The results of simulation runs and by experimental measurements verify robust DOB operation in relation to mismatching or considerable variations of plant parameters. It is shown, analytically, through simulation, and experimental measurements, that the proposed modification of DOB structure enables complete extraction of a known class of external disturbances for any DOB filter cutoff frequency.

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BRZINSKI-REGULISANI ELEKTROMOTORNI POGON SA NOVIM OPSERVEROM POREMEĆAJA

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Ovaj rad predstavlja projektovanje digitalno-regulisanog brzinskog elektromotornog pogona u prisustvu proizvoljnih spoljnih nemerljivih poremećaja koji nastoje da odvuku sistem iz tekuće radne tačke. Ekstrakcija poznate klase spoljnih poremećaja se izvodi upotrebom novog opservatora poremećaja (DOB), u koji je implicitno uključen vremenski diskretan model spoljnih poremećaja. Pokazano je, analitički, simulacijom, i eksperimentalno, da predložena modifikacija opservera poremećaja omogućava celokupno odbijanje poznate klase nemerljivih spoljnih poremećaja, u ustaljenom stanju, bez obzira na graničnu frekvenciju DOB filtera. Na taj način je moguće dostići zasebno brzinu ekstrakcije poremećaja i kvalitet odziva sistema sa povratnom spregom. Predloženi postupak projektovanja obavlja se brzinski-regulisanim elektromotornim pogonom sa vektorski-upravljanim indukcionim motorom. Efikasnost i robusnost predložene tehnike potvrđuju kako simulacija tako i rezultati eksperimenta.

Ključne reči: *Opserver poremećaja, spoljni poremećaji momenta opterećenja, model poremećaja, brzinski-regulisan elektromotorni pogon*