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Comparison of incremental encoder digital signal processing techniques for the induction motor flux-torque vector control systems

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ABSTRACT

The article presents the results of a study on the effectiveness of various techniques for synchronous reference frame angular position numerical calculation in flux-torque vector control system of induction motor. Investigation was caried out taking into account the discrete nature of the angular speed signal obtained using an incremental encoder. In this work for investigation by simulation used a direct torque vector control system, which, in the presence of an ideal rotor angular speed signal, ensures direct asymptotic field orientation, asymptotic tracking of torque-flux reference trajectories, as well as asymptotic decoupling torque and flux subsystems. The parameters of the induction motor and encoder used in the study correspond to those existing in traction electromechanical systems of city trolleybuses. It is shown that the discrete nature of the angular speed signal, which used in synchronous reference frame position equation of flux-torque vector control systems, introduces field orientation errors and leads to current and torque ripples, which in a real system increase acoustic noise and can cause mechanical vibrations and resonance phenomena. An analysis of possible ways to reduce the influence of the speed signal discreteness on flux-torque control is performed, and a method for practical implementation of the synchronous reference frame angular position numerical calculation is proposed. This method allows ensuring conditions for more precise field orientation and, by using an additional filter for the angular speed signal, reducing the level of current and torque ripples to negligibly small values without affecting the field orientation processes. The proposed solution can be used in the development of high dynamic flux-torque vector control systems for induction motors using incremental encoders, including for electric vehicles.

Keywords: simulation; traction drive; speed measurement; digital signal processing; induction motor; vector control

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INTRODUCTION

Vector control systems for induction motors (IM) with angular speed measurement [1] find wide application in industry, municipal and agricultural sectors, electric transportation, and power generation systems [2], [3].

The most common method of obtaining a signal about the rotor's angular speed is through the use of incremental encoders, which can be of the photoelectric, magnetic, or inductive type [4], [5], [6]. The advantages of encoders include their high dimensional characteristics, low inertia, and relatively low cost. However, they have a significant drawback – the signal about the angular speed has a discrete nature [8], [9]. This property limits the performances of speed control loops [10] as it leads to the emergence of additional disturbances in the vector control system and requires their consideration during real electric drives development.

Reducing the impact of discreteness can be achieved by increasing the resolution of the encoder, but this somewhat increases its cost, reduces reliability, and may not always be feasible, especially in traction electric drives where sensors of the inductive type are used, typically with a resolution of less than 256 p/rev. Overcoming the problem of increasing speed measurement accuracy can be achieved by increasing the time interval for counting encoder pulses and installing a software filter at the measurement channel output. However, such measures add delay to the feedback signal and additional dynamics in the angular speed measurement channel introduced by the filter. In particular, direct input of filtered speed into the equation of angular position dynamics of the synchronous reference frame leads to significant violations of field orientation conditions and, consequently, to errors in tracking the torque of the induction motor.

LITERATURE REVIEW

A significant number of methods have been proposed in the literature to increase the accuracy of angular speed and position measurements based on processing quadrature signals from the encoder.

In publications [11, 12], [13], ways to improve the accuracy of speed measurement using various types of observers and Kalman filtering are considered, including the application of an adaptive extended Kalman observer for estimating low speeds with low resolution encoders.

In the study [14], a model was developed to investigate the influence of the discrete nature of the encoder feedback signal on the coordinate control loops of the electric drive.

Work [15] is dedicated to speed and acceleration measurement for traction applications in the presence of speed sensor defects. It is shown that the algorithm proposed by the authors for identifying periodic disturbances effectively eliminates their negative influence without introducing phase shift, unlike the results obtained using notch filters.

Various modifications of methods for identifying the shaft encoder speed based on classical methods of processing quadrature signals are presented in [16, 17], [18, 19], [20, 21], [22], which allow compensating or reducing measurement errors, including those caused by lack of synchronization between output pulses and sampling periods. In [18], a method for error compensation based on the use of a sliding mode observer is proposed. The effectiveness of this method is experimentally confirmed in vector control system with permanent magnet synchronous motor.

In publication [23], a two-stage method of averaging measured values is proposed to reduce measurement errors of angular speed.

A modification of the speed measurement method based on determining the time interval between two adjacent edges of encoder pulses is discussed in [24]. The use of a timer-counter variable frequency is proposed to increase the accuracy of angular speed measurement.

The use of FPGA for combining two classical methods of encoder signal processing with automatic switching between them is proposed in the study [25]. The effectiveness of the proposed measurement method is confirmed by the results of experimental studies.

Reducing the negative influence of the encoder on control processes using fuzzy logic methods is discussed in [26].

The described solutions have different effectiveness and practical implementation complexity, but they all are considered from the perspective of pure speed and angular position measurement without considering the structure of vector control systems for induction motors.

The purpose of this study is to analyze the influence of the discrete nature of the speed signal measured using quadrature signals from the incremental encoder on the torque-flux vector control and to provide recommendations for configuring the angular speed measurement channel and the procedure for the computing of synchronous reference frame angular position.

CONTROL ALGORITHM

Based on the concept of direct field orientation, the control algorithm for torque and flux vector magnitude is defined by the following equations (see [27] for the case of constant flux linkage):

– flux controller

$$\begin{aligned} i_d^* &= \frac{1}{\alpha L_m}\left(\alpha\psi^* + \dot{\psi}^* - k_\psi e_\psi - x_\psi\right), \\ \dot{x}_\psi &= k_{\psi i} e_\psi; \end{aligned} \tag{1}$$

– flux observer

$$\dot{\hat{\psi}} = -\alpha\hat{\psi} + \alpha L_m i_d, \tag{2}$$

with the synchronous reference frame angular position dynamics equation

$$\dot{\varepsilon}_0 = \omega_0 = \omega p_n + \alpha L_m \frac{i_q}{\hat{\psi}}; \tag{3}$$

– current controllers

$$\begin{aligned} u_d &= \sigma\Big(\gamma i_d^* - \omega_0 i_d^* - \alpha\beta\hat{\psi} + \dot{i}_d^* - \\ &\quad - k_i \tilde{i}_d + x_d\Big), \\ \dot{x}_d &= -k_{ii}\tilde{i}_d; \end{aligned} \tag{4}$$

$$u_q = \sigma\left(\gamma i_q^* + \omega_0 i_q^* + \beta\omega p_n \hat{\psi} + \dot{i}_q^* - \right.$$
$$\left. - k_i \tilde{i}_q + x_q\right), \qquad (5)$$
$$\dot{x}_q = -k_{ii} \tilde{i}_q;$$

– torque controller

$$i_q^* = \frac{1}{\mu_1}\frac{M^*}{\psi^*},\ \hat{\psi} > 0, \qquad (6)$$
$$\dot{i}_q^* = \frac{1}{\mu_1}\left(\frac{\dot{M}^*}{\psi^*} - \frac{M^*\dot{\psi}^*}{\psi^{*2}}\right),$$

where $\alpha = \frac{R_2}{L_2}$; $\sigma = L_1 - \frac{L_m^2}{L_2}$; $\beta = \frac{L_m}{\sigma L_2}$; $\gamma = \frac{R_1}{\sigma} + \alpha\beta L_m$; $\mu_1 = \frac{3}{2}\frac{L_m}{L_2}$; R_1, R_2 and L_1, L_2 are the active resistances and inductances of the stator and rotor respectively; L_m is magnetizing inductance; p_n – number of pole pairs; i_d^*, i_q^* are excitation current reference and stator torque-producing current reference; ω is rotor angular speed; u_d, u_q are components of the stator control voltage vector; ε_0, ω_0 are angular position and speed of the synchronous (d-q) reference frame relative to the stationary (a-b); $\hat{\psi}$ is estimated rotor flux; ψ^* is rotor flux reference; M^* is torque reference; $\tilde{i}_d = i_d - i_d^*$, $\tilde{i}_q = i_q - i_q^*$ are stator current errors; $e_\psi = \hat{\psi} - \psi^*$ is estimated flux tracking error; $(k_\psi, k_{\psi i}) > 0$ are coefficients of proportional and integral components of the flux regulator; $(k_i, k_{ii}) > 0$ are coefficients of proportional and integral components of the current regulators.

The vector control algorithm, defined by equations (1)-(6), provides: asymptotic field orientation, asymptotic tracking of the torque and flux referenced trajectories, asymptotic decoupling of torque and flux subsystems.

SPEED MEASUREMENT SUBSYSTEM

At the output of the incremental encoder, two pulse sequences A and B are generated, shifted relative to each other by a quarter period, as shown in Fig. 1a. The typical hardware structure of the microcontroller module, which allows processing such a quadrature signal, is shown in Fig. 1b. Initially, the input encoder sequences pass through a logic circuit that detects the fronts of sequences A and B and generates the resulting sequence S, which is directly fed to the counter CT. The counting direction (shaft rotation) is determined depending on the relative position of the fronts of signals A and B with the static state of the opposite signal. The value at the output of counter Q is passed to the user program for further processing.

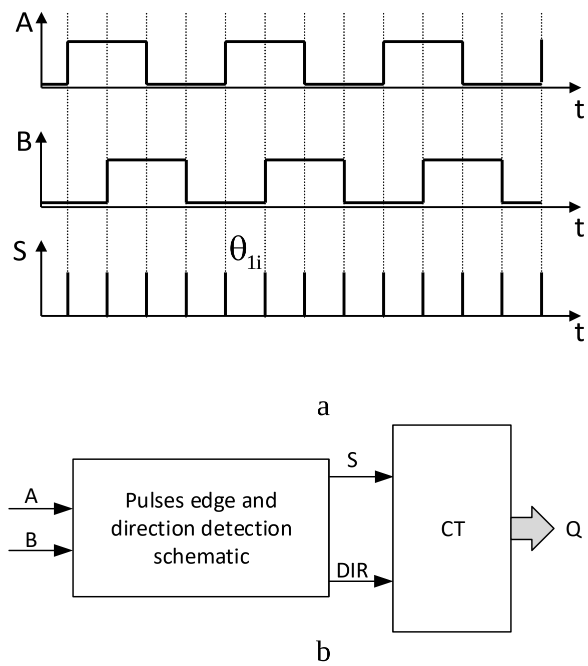

Fig. 1. **Quadrature signal processing: a – pulses; b – measurement channel structure**
Source: **compiled by the authors**

The simplest methods of measuring angular speed are either differentiating angular position based on information about the received number of pulses over a fixed time, or measuring the time interval between two consecutive pulses of sequence S with subsequent conversion into angular speed [3].

Within this study, the first method is considered, which is formalized as follows:

$$\omega_e = \frac{n\theta_{1i}}{T_s} = \frac{2\pi n}{4NT_s}, \qquad (7)$$

where ω_e is calculated value of the actual angular speed; θ_{1i} is angle through which the encoder shaft rotates to generate one pulse of the resulting sequence S; $n = Q_{k+1} - Q_k$ is number of pulses received from the encoder over a fixed time interval T_s, where k is the measurement cycle number; N is encoder resolution.

The main problem with applying (7) in practice is the high level of discretization of angular speed measurement. The maximum error introduced during direct application of expression (7) is determined as

$$\delta = \frac{2\pi}{4NT_s}. \tag{8}$$

For example, when using an encoder with a resolution of 1000 pulses per revolution and a measurement time $T_s = 200\,\text{мкс}$ the speed measurement channel error will be 7.85 rad/s. In practice, this means that at a shaft rotation speed of 7.85 rad/s, one pulse of sequence S will be received from the encoder. In the case of shaft rotation speeds lower, no pulses will be received for several cycles, which will be perceived by the control system as zero speed. Thus, high-frequency step-like transitions appear in the speed feedback signal, in the example considered with a magnitude of 7.85 rad/s, which introduce additional disturbances into the control system and limit the possibilities of increasing the performances of the speed control loops [6].

To smooth the speed feedback signal, a simple first-order low-pass filter can be applied:

$$W_f = \frac{\omega_f}{\omega_e} = \frac{1}{\tau p + 1}, \tag{9}$$

where ω_f is filtered speed value ω_e; τ is filter time constant.

The input to this filter is the sequence of calculated values ω_e, obtained from expression (7), and the output is the filtered value of the measured speed, which can be used in the control algorithm equations

Another option for reducing the level of angular speed measurement ripples is to apply averaging of measured values over a number of recent measurement cycles according to the following expression:

$$\omega_{av} = \frac{\sum_{i=0}^{H-1} \omega_{e(k-i)}}{H}, \tag{10}$$

where $\omega_{e(k)}$ is value ω_e at the current measurement cycle; H is number of cycles for averaging.

PROPOSED IMPLEMENTATION SCHEME

Let's consider the dynamics equation of the synchronous reference frame angular position (3) and perform integration by splitting the expression into two components

$$\begin{aligned}\varepsilon_0 &= \int_0^T \omega_0 dt = \int_0^T \left(\omega p_n + \alpha L_m \frac{i_q}{\hat{\psi}}\right) dt = \\ &= \theta p_n + \int_0^T \alpha L_m \frac{i_q}{\hat{\psi}} dt.\end{aligned} \tag{11}$$

As seen from (11), the angular position ε_0 of the synchronous reference frame is determined by two components – the electrical angle θp_n and the angle obtained by integrating the slip angular speed. This allows using for ε_0 calculation information about the motor shaft angular position θ directly and avoiding additional errors associated with measuring angular speed and its subsequent integration.

To account for the time delay in obtaining information about the rotor position, we modify expression (11) by adding a component $p_n \omega_f T_s / 2$

$$\varepsilon_0 = \theta p_n + p_n \omega_f T_s / 2 + \int_0^T \alpha L_m \frac{i_q}{\hat{\psi}} dt. \tag{12}$$

Adding component $p_n \omega_f T_s / 2$ adjusts the value of the (d-q) coordinate system position angle by the amount corresponding to the shaft rotation angle for half of the quantization cycle T_s. The feasibility of such a slight correction is justified by the fact that in a real control system, the calculation of a new control action, and particularly the position of the coordinate system, is carried out over a time interval that is close to the midpoint of the quantization cycle. Compensation can also use signal ω_{av} instead of ω_f.

SIMULATION RESULTS

In the study, the following parameters of the induction motor 6DTA.002.1U2 were used: rated power P = 180 kW, rated line voltage 420 V, rated frequency 50 Hz, rated slip 1.5%, power factor 0.88, stator resistance R1 = 0.01 Ohm, rotor resistance R2 = 0.0085 Ohm, stator winding inductance L1 = 0.0061 H, rotor winding inductance L2 = 0.0061 H, magnetizing inductance L_m = 0.0058 H, number of pole pairs p_n = 2, total rotor inertia J = 6 kg·m^2, viscous friction coefficient $\nu = 0.15\,c^{-1}$. The tuning coefficients of the torque and flux vector control algorithm (1)-(6) are set as follows: $k_i = 700$, $k_{ii} = 120000$, $k_\psi = 100$, $k_{\psi i} = 5000$. Encoder resolution 256 imp/rev, pulse counting time $T_s = 200\,\text{mcs}$, speed filter time constant $\tau = 1.6$ мс.

Tests were conducted according to the following sequence of motor control operations (Fig. 2): during the time interval t = 0-0.5 s the IM is excited to the value $\psi^* = 0.9$ Vb; starting from time t = 0.75 s, the motor is required to track a predefined torque trajectory, as shown in Fig. 2, which includes acceleration, coasting, and braking stages, typical for electric vehicle motion. Upon completion of the torque trajectory, the motor accelerates to an angular speed of 60 rad/s and decelerates to zero speed (Fig.2). The non-discretized angular speed signal (ω) is shown by the solid red line in Fig. 2. The signal obtained from the encoder (ω_{enc}) using equation (7) has a discrete nature, with a discretization level of approximately 30 rad/s. The use of a first-order filter with a time constant of 1.6 ms smoothes the signal (see Fig. 2) but does not eliminate pulsations completely.

Transients during the torque and flux trajectories tracking in the system with non-discretized angular speed signal are shown in Fig. 3.

From the analysis of the graphs in Fig. 3, it is established that the control algorithm (1)-(6) under idealized conditions of mathematical simulation provides asymptotic tracking of the torque reference trajectories (the torque error $\tilde{M} = M - M^*$ tends to zero, where M – is the motor torque), as well as asymptotic rotor flux orientation ($\psi_q = 0$). Since after completing the field orientation process, changes in torque do not lead to changes in the rotor flux vector magnitude, it can be concluded that asymptotic decoupling of torque and rotor flux subsystems is also achieved.

Transients in the system, where the angular speed signal are formed using the incremental encoder and equation (7) are shown in Fig. 4. As can be seen from Fig. 4, introducing the encoder into the system, and consequently, a time delay of 200 μs in the speed measurement channel, led to the appearance of flux linkage along the q-axis, indicating a violation of field orientation conditions, as well as errors in d-axis flux. Changes in motor torque started to cause changes in the rotor flux vector magnitude, indicating a certain level of coupling between torque and flux subsystems. Additionally, the discrete nature of the speed signal led to the appearance of torque-producing current ripples at a level of 20 A, and correspondingly, motor torque ripples at level of 50 N·m, constituting 11 % of the reference signal.

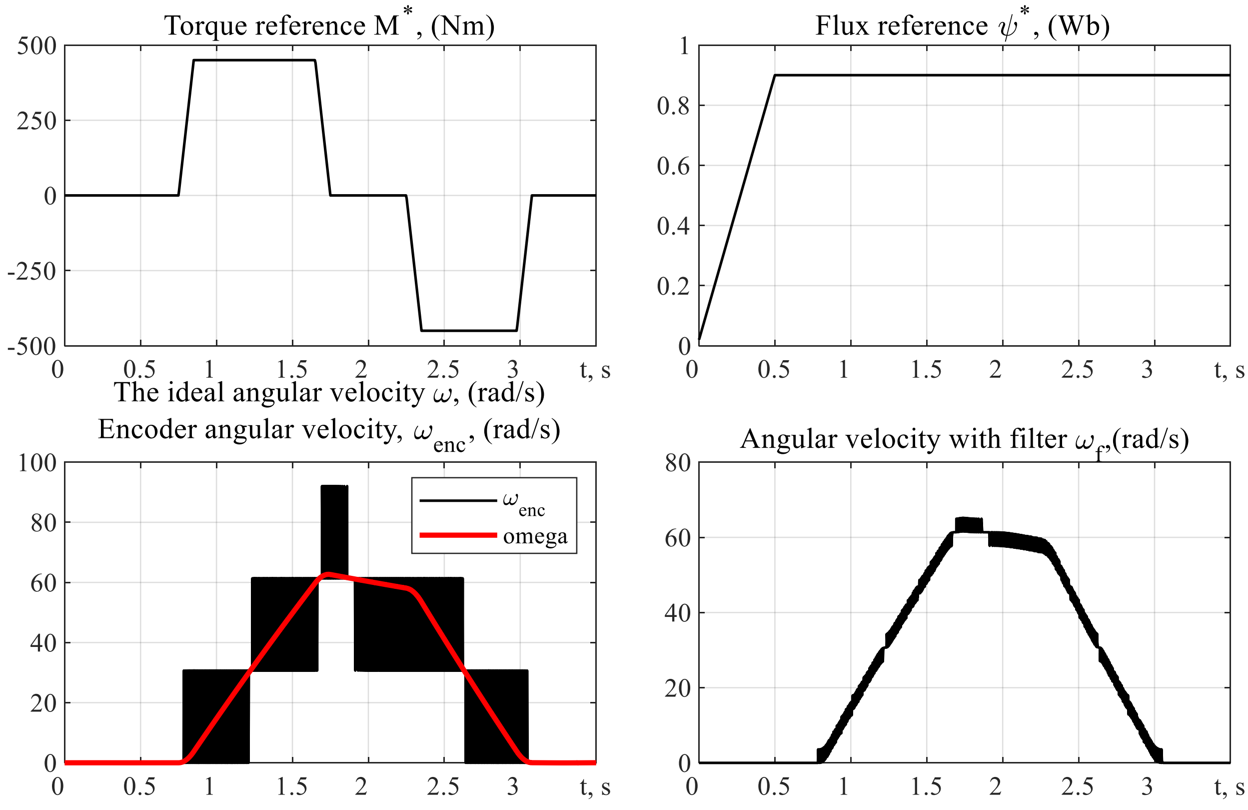

Fig. 2. **Control operations sequence and rotor angular speed signals**
Source: **compiled by the authors**

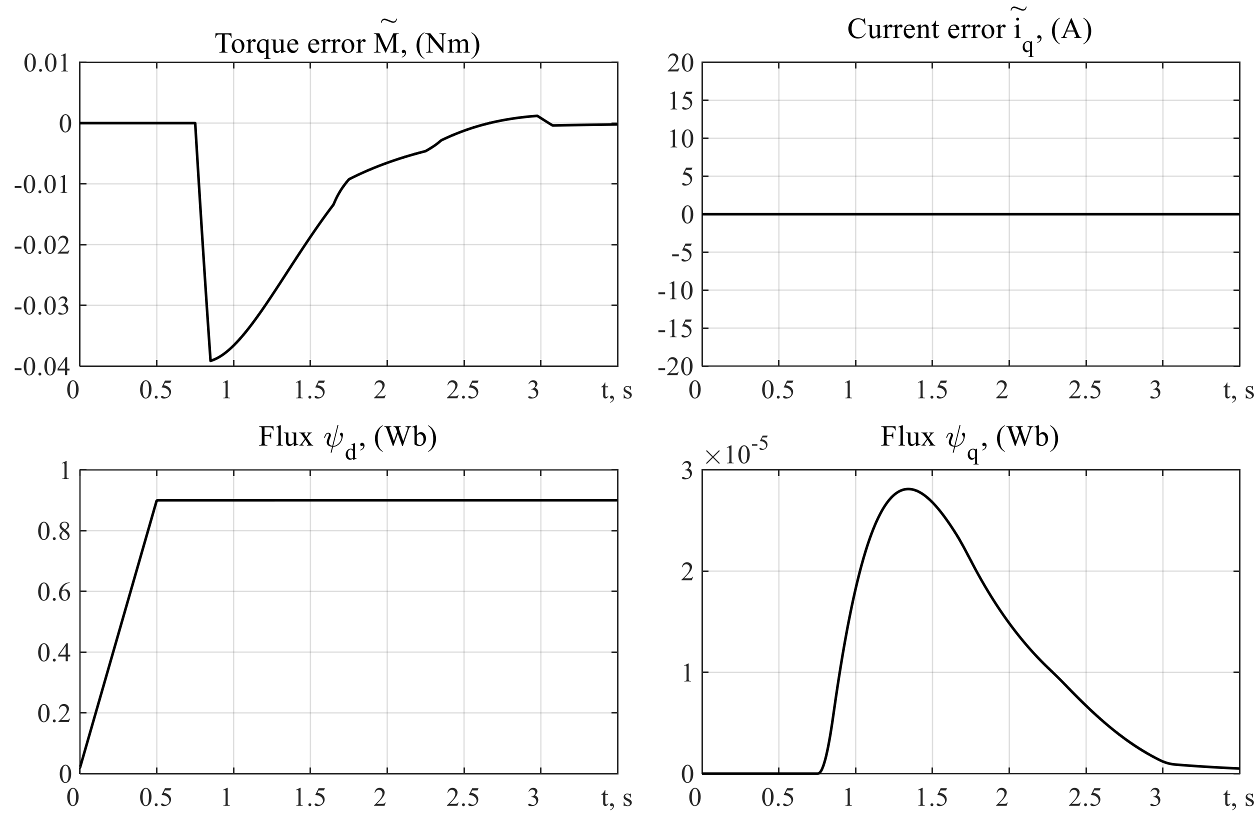

Fig. 3. **Transients when using an ideal speed signal**
Source: **compiled by the authors**

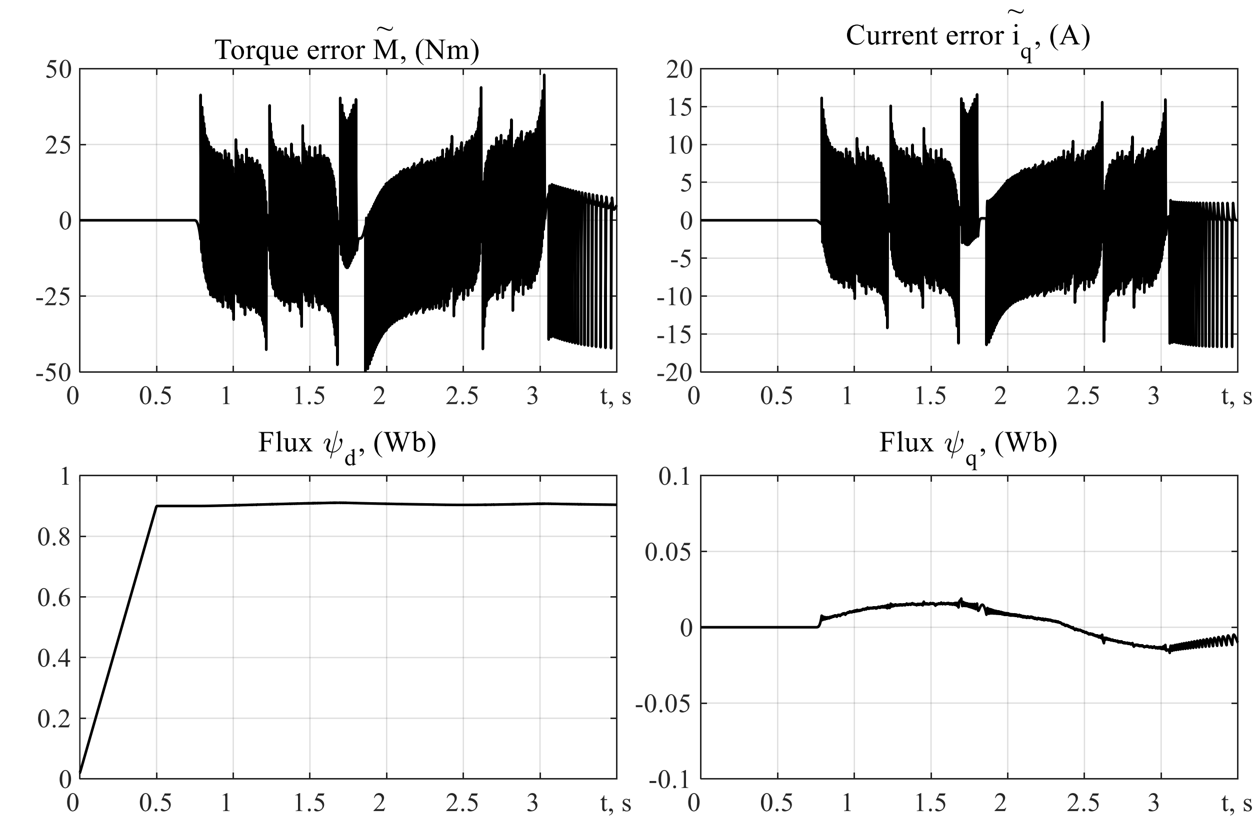

Fig. 4. **Transients when using a speed signal from the encoder**
Source: **compiled by the authors**

Consider a method to reduce current and torque ripples by introducing a filter (9) in the speed measurement channel. Transients for such a system configuration are shown in Fig. 5. By comparing Fig. 5 with Fig. 4, it can be seen that introducing a filter allowed to reduce the level of current pulsations to 5 A, and torque to 10 N·m. However, due to the increased resulting delay of the speed signal, the field orientation conditions deteriorated further (the maximum deviation of flux linkage along the q-axis increased from 0.02 Wb to 0.1 Wb), and a more pronounced coupling between torque and flux control subsystems was observed. The increase in flux linkage tracking error, in turn, led to an increase in torque tracking error to 40 N·m.

To reduce the impact of the speed filter on the flux control processes, it is proposed to use the unfiltered angular speed signal in the equation of synchronous reference frame angular speed dynamics (2) and the filtered value in the PI-regulator equation of the stator current torque-producing component (5). Transients for such a combined speed measurement channel are shown in Fig. 6. By comparing Fig. 4, Fig. 5 and Fig. 6, it can be concluded that this approach allows maintaining a level of field orientation similar to Fig. 4 when using an unfiltered encoder, while reducing the level of current pulsations to 6 A and torque to 18-20 N·m compared to Fig. 4. Since the filter no longer affects the field orientation error, its time constant can be increased.

The results of the test using the averaged speed signal with H=8 are shown in Fig. 7. From Fig. 7, it can be seen that compared to the unfiltered speed signal, using (10) with H=8 reduces the level of pulsations by half, albeit with worse field orientation.

Transient processes in the system obtained using the calculation algorithm (12) are shown in Fig. 8. Since the speed filter time constant when using (12) does not affect the field orientation processes, in order to reduce ripples, it was increased to 0.05 s. As can be seen from the graphs in Fig. 8, simultaneous application of (12) with a reinforced speed filter allowed reducing torque and current pulsation levels to negligible values, whiling ensuring asymptotic field orientation, as $\lim_{t\to\infty} \psi_q = 0$.

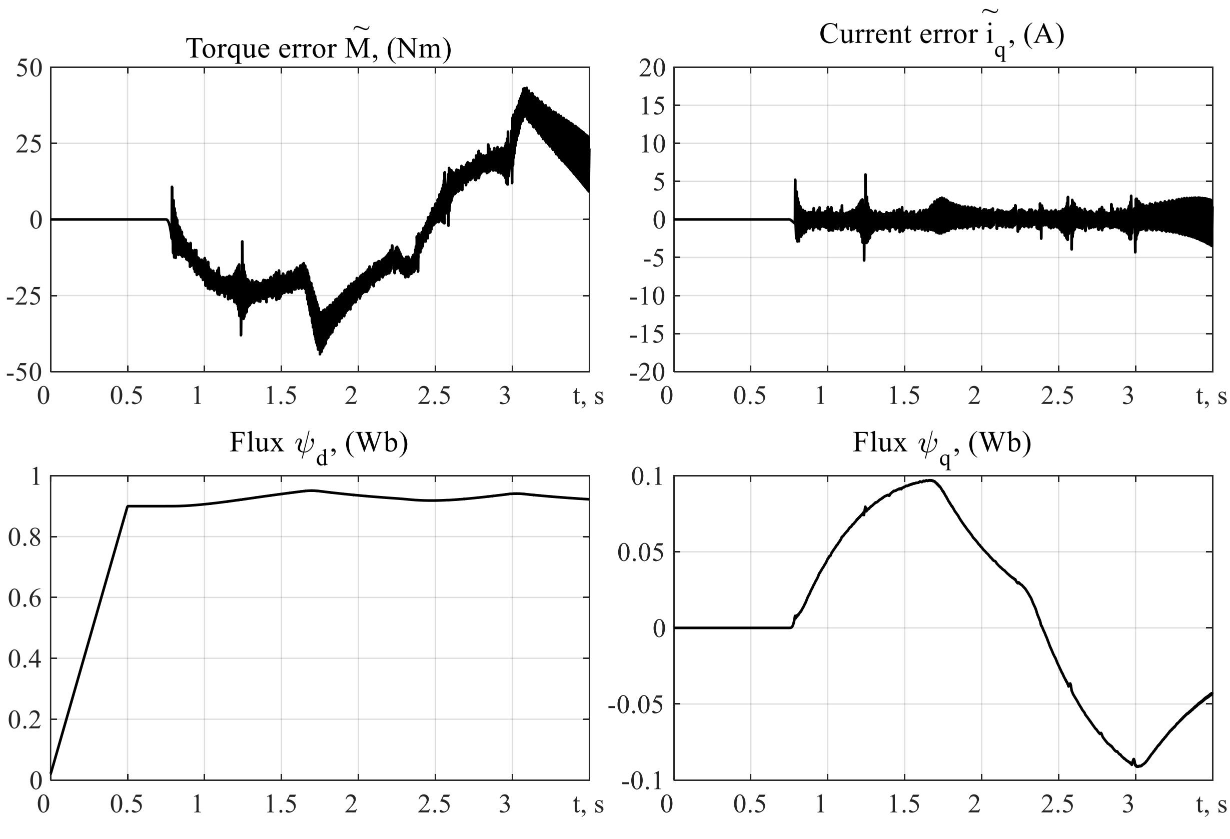

Fig. 5. **Transients when using a filtered speed signal from the encoder**
***Source:* compiled by the authors**

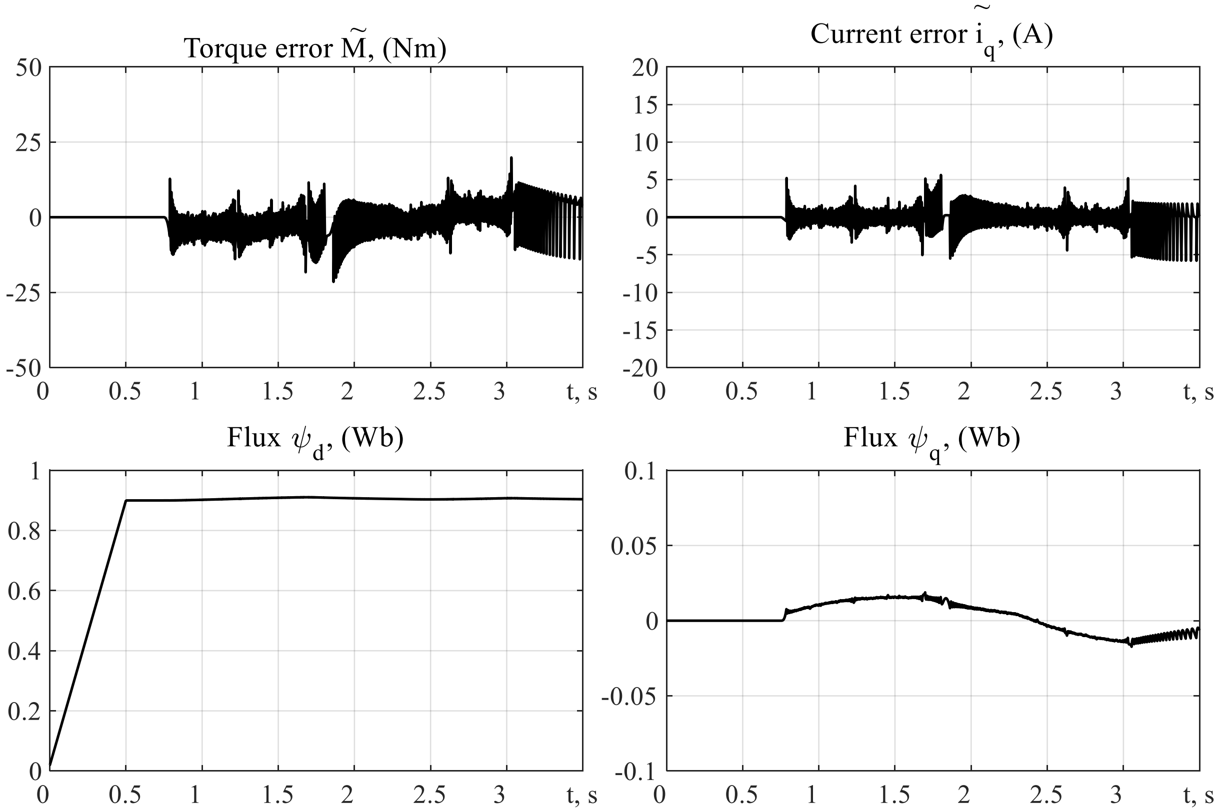

Fig. 6. **Transients when using signals of filtered encoder speed in the current controller and without filtration in the flux observer**
***Source:* compiled by the authors**

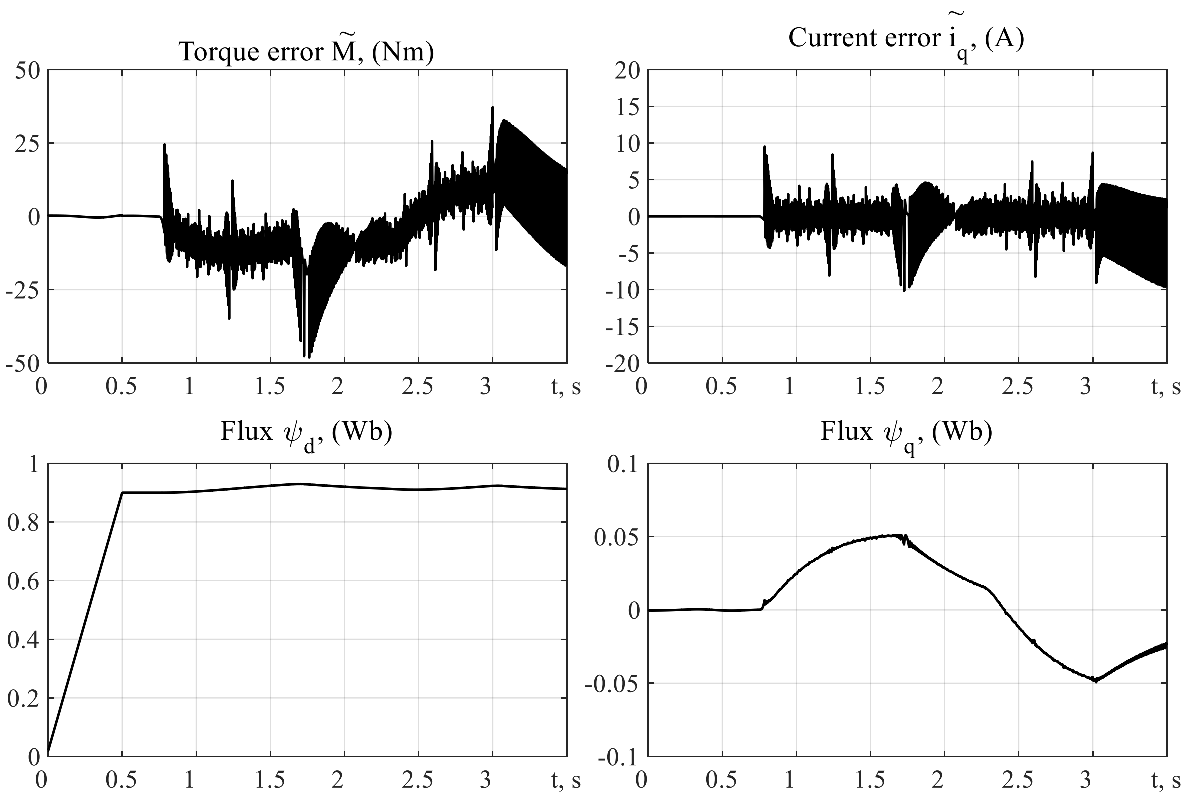

Fig. 7. **Transients when using signals of averaged encoder speed in the current controller and flux observer**
***Source:* compiled by the authors**

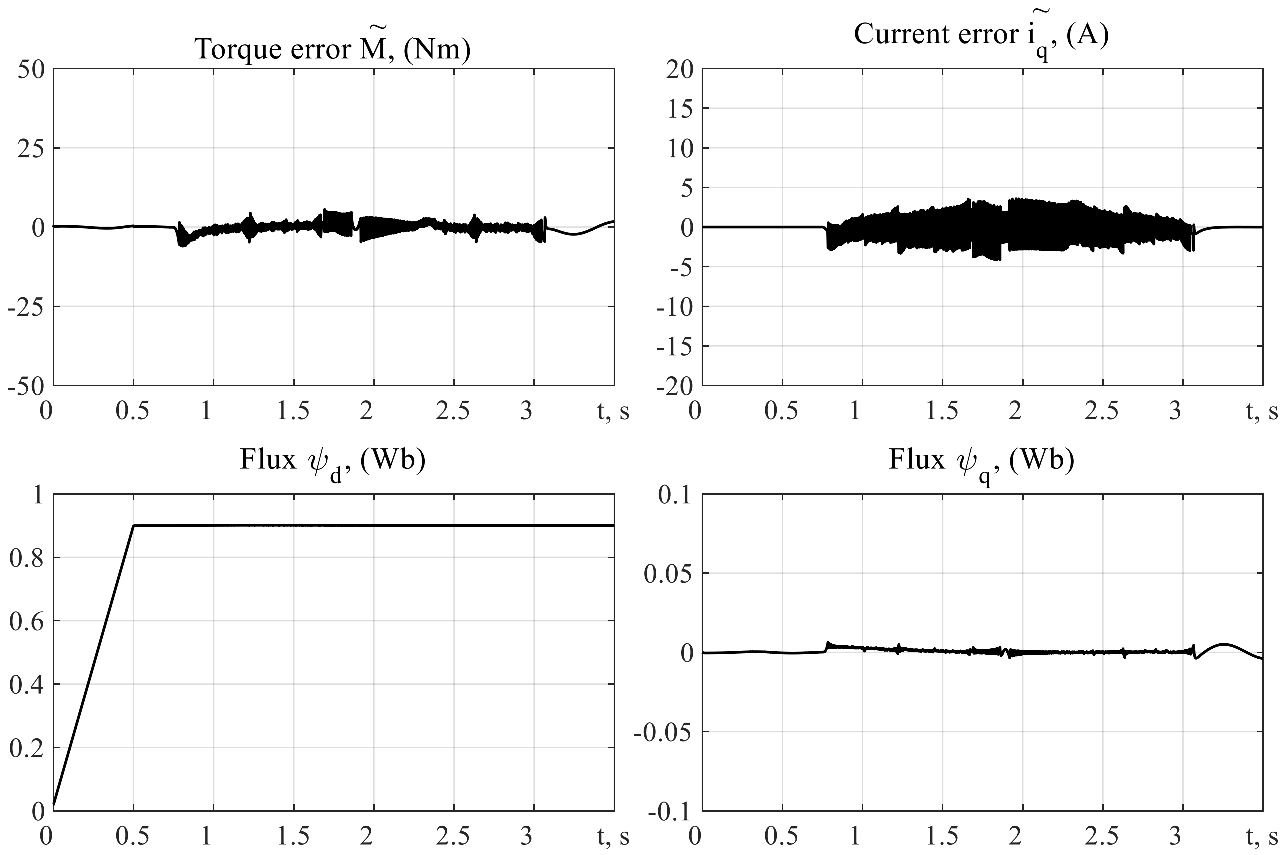

Fig. 8. **Transients when using calculation algorithm (12) and filtered speed with a time constant of 0.05 s**
Source: **compiled by the authors**

CONCLUSIONS

The conducted study has determined that the discrete nature of the speed signal measured using an encoder significantly influences the vector flux-torque control of induction motor, leading to slight deviations from asymptotic convergence of coordinates and field orientation conditions, as well as significant ripples in the torque-producing component of stator current and motor torque. Direct application of a simple filter in the form of a first-order aperiodic link in the speed measurement channel or averaging speed values over several cycles reduces the level of current and torque ripples but leads to further degradation of control performances. The combined use of unfiltered and filtered speed signals from the encoder reduces the level of current and torque ripples while maintaining control performances at a level comparable to the system with an unfiltered encoder signal. However, it does not completely eliminate the violation of field orientation conditions. The proposed algorithm for calculating the angular position of the synchronous reference frame, based on direct use of rotor angular position information, ensures close to asymptotic field orientation and negligible small ripples level in current and torque.

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Порівняння способів цифрової обробки сигналів інкрементального енкодера для систем векторного керування моментом-потокозчепленням асинхронних двигунів

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ABSTRACT

В роботі представлено результати дослідження ефективності різних способів практичної реалізації рівняння динаміки кутового положення синхронної системи координат векторно-керованого асинхронного електроприводу із врахуванням дискретного характеру сигналу кутової швидкості, отриманого з використанням інкрементального енкодера. Дослідження виконано методом математичного моделювання для системи прямого векторного керування моментом, яка, за наявності ідеального сигналу про кутову швидкість ротора, забезпечує пряме асимптотичне полеорієнтування, асимптотичне відпрацювання заданих траєкторій моменту та модуля вектора потокозчеплення ротора, а також асимптотичну розв'язку процесів керування моментом та потоком. Параметри асинхронного двигуна та енкодера, які використовуються в дослідженні, відповідають параметрам, що існують в тягових електромеханічних системах тролейбусів. Показано, що дискретний характер сигналу кутової швидкості, який має місце в системах векторного керування координатами асинхронних двигунів, вносить похибки полеорієнтування, а також призводить до виникнення пульсацій струму і моменту, які в реальній системі підвищують акустичний шум та можуть викликати механічні вібрації і резонансні явища. Виконано аналіз можливих шляхів зменшення впливу дискретності сигналу кутової швидкості на процеси керування, та запропоновано метод практичної реалізації рівняння динаміки кутового положення синхронної системи координат, який дозволяє забезпечити умови якісного полеорієнтування та, за рахунок застосування додаткового фільтра сигналу кутової швидкості, зменшити рівень пульсацій струму і моменту до нехтувано малих значень без впливу на процеси полеорієнтування. Запропоноване рішення може використовуватися при створенні високодинамічних систем векторного керування моментом асинхронних двигунів з використанням інкрементальних енкодерів, в тому числі для електричного транспорту.

Keywords: математичне моделювання; тяговий електропривод; вимірювання швидкості; цифрова обробка сигналів енкодера; асинхронний двигун; векторне керування

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