Conference Paper

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Speed Estimation Applying Sinc-filter to a Period-based Method for Incremental Position Encoder

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***Abstract*—Precise speed estimation and short measurement time delay is compulsory for high-performance electric drives. Rotary incremental position encoders are widely used together with speed estimation techniques such as period-based, frequency-based, constant elapse time, and synchronous-measurement methods. This paper proposes the speed estimation technique, which helps to obtain higher accuracy by means of filtering the results of period-based method using third order Sinc-filter. As the sequence of period-based method estimations has the properties of delta-sigma modulated signal, extra information can be extracted. For the specified measurement time that gives higher accuracy than moving average filter. The developed speed estimation method was tested using experimental setup showing better accuracy compared to conventional methods.**

Keywords—speed estimation, time quantization, incremental encoder, sinc-filter

I. INTRODUCTION

Motor control systems require information about current angular velocity and position of the motor shaft. Incremental encoders are commonly used for this purpose as a feedback to the controllers in the control system. Accuracy of the position estimation, which is defined by the resolution of the encoder, is enough for the torque control. High-performance electric drivers with speed and position control require precise speed feedback. Accurate speed estimation guarantees speed stability, which is also essential for position loop [1]. The typical configuration of an electric drive with a speed loop is shown in Fig. 1[2].

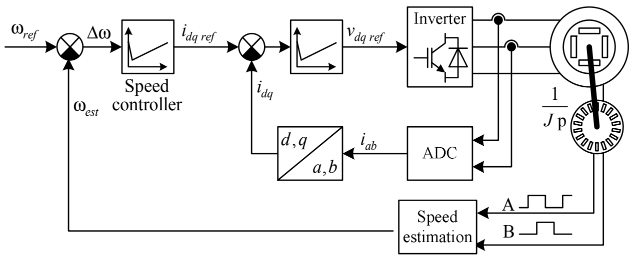

Fig. 1. Typical configuration of an electric drive with speed loop.

Additionally, to the precision the speed feedback should have small delay caused by the duration of a single measurement. This is necessary to make speed loop settling time smaller. The delay in the speed estimation together with the passband of the nested current loop, limits the performance of the speed regulation. Thus, the delay in the speed feedback or speed estimation time should be as small as possible, while the reduced speed estimation time results in increase of the estimation error due to digital timer quantization effect.

The incremental encoder produces two square signals — "A" and "B" shifted by 90°. The resolution K of the encoder is defined by the number of pulses per revolution (ppr). The sign of the phase-shift between "A" and "B" signals determines the direction of the rotation. The modern microcontrollers have a peripheral module of quadrature decoding of signals eQAP–Quadrature Encoder Pulse Module (see Fig. 2), which can be used for signal processing.

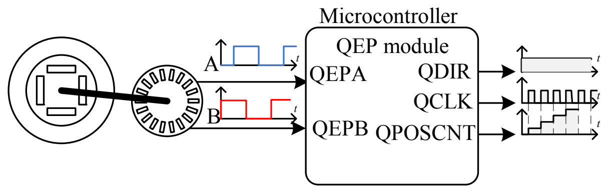

Fig. 2. Interface of the microcontroller with an incremental sensor.

The inputs of this peripheral device receive signals from the sensor QEPA and QEPB, and it generates signals QDIR, which determine the direction of the rotation, and the pulses of the encoder QCLK are generated by each edge of the "A" and "B" signals. The QPOSCNT register counts QCLK pulses with respect to the direction of the rotation QDIR providing the actual rotor angular position to the control system. The total number of QCLK pulses per revolution is four time bigger than resolution of the encoder, due to the fact that encoder has two channels with rising and falling edges giving:

$$N = 4K. \qquad (1)$$

There are several methods of speed estimation in electric drives using incremental encoders [3]. The frequency-based method which counts the number of pulses Δc from the encoder during fixed sampling time T_s, which is normally equal to the speed controller execution period. The period-based method measures the elapsed time for specified amount of rotation. This method has high accuracy at low speeds, but with the increase of the speed the quantization

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effect of time measurement increases. Modified period-based methods are proposed in paper [4, 5, 6], which consider averaging of several period-based estimations. In [2, 7] constant elapse time methods were considered limiting the CPU burden.

This paper proposes an improved method for calculating speed using the period-based method. The measurement time for speed estimation system can be equal to the period between execution of the speed controller. If there are more than one speed estimation during measurement time, these estimations have the properties of the delta-sigma modulated signal and can be processed using high-order Sinc-filter.

II. The Influence of The Quantization Effect on Speed Estimation

The period-based method measures the time needed to rotate to a certain angle. The speed n can be estimated by the following expression:

$$n_p = \frac{60}{T_s} \cdot \frac{\Delta c}{N}, \tag{2}$$

where Δc is the fixed value of the amount of rotation represented by the number of QCLK pulses, which corresponds to $360/N$ mechanical degrees. Usually, the amount of rotation is selected multiple of four, due to the inaccuracies of the position encoder inside a single pulse count [6]. In order to measure the speed with minimum delay at low speeds Δc is set to four. T_s is the time elapsed to rotate to the specified angle. An example of quadrature encoder pulse module operation during speed estimation is shown in Fig. 3.

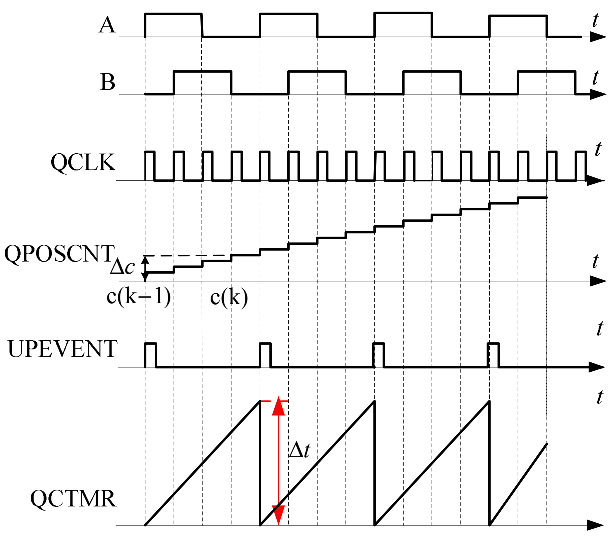

Fig. 3. Period-based method diagram for the amount of rotation of 4 QCLK encoder pulses. c[k]–pulse counter QPOSCNT value in moment k, c[k–1]–pulse counter QPOSCNT value in moment k–1, Δt–measured time.

Fig. 3 shows an example for the amount of rotation Δc, which equals to 4 QCLK encoder pulses. The register QCTMR counts pulses of CPU clock SYSCLKOUT. The counter is reset and the Δt value is written into the QUPRD register by an event UPEVENT, which occurs after certain amount of QCLK encoder pulses.

Accuracy of measurement of the elapsed time is determined by the minimal discrete of time h, which is inverse to the CPU frequency:

$$T_s = h \cdot \Delta t = \frac{\Delta t}{f_{CPU}}. \tag{3}$$

Consequently, the relative error for the estimated speed is:

$$\delta n_p = \frac{h}{T_s} = \frac{h \cdot n \cdot N}{60 \cdot 4}. \tag{4}$$

The number of CPU pulses Δt can be only an integer, and incoming pulses from the encoder and *SYSCLKOUT* are not synchronous [8]. Fig. 4 shows an example explaining the appearance of a high quantization error. During a single period of "A" signal 6 or 7 increments of the CPU timer occur. If the speed is evaluated each incoming QCLK signal, then the estimation error is about 16% for this particular case. However, there is no need to evaluate speed every 6 or 7 CPU cycles because the current loop bandwidth is limited by PWM frequency, and the speed loop is at least twice slower. Therefore, the measurement time can be set to a distance between two sequential executions of the speed controller.

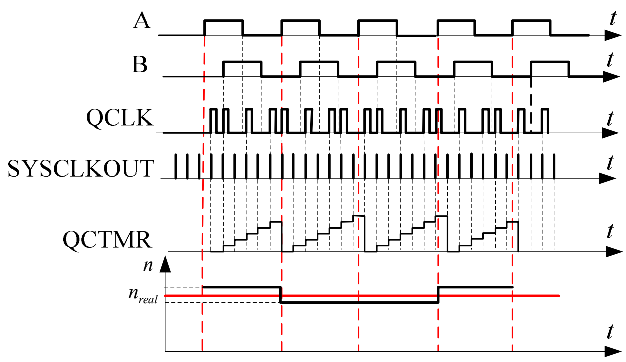

Fig. 4. Speed estimation based on measuring the pulses period.

The easiest way to improve accuracy of the speed measurement is to evaluate moving average of the speed estimations with the window size equal to the period of speed controller execution T_{SC} [9]. Then speed n in rpm can be estimated by the following equation:

$$n_{av} = \frac{1}{S}\sum_{i=1}^{S}\left(\frac{60}{T_s[i]} \cdot \frac{4}{N}\right) = \frac{4 \cdot 60}{S \cdot N \cdot \sum_{i=1}^{S} T_s[i]}, \tag{5}$$

where S is the number of pulses from the encoder during speed measurement, which can be evaluated as follows:

$$S = int\left(\frac{n \cdot N \cdot T_{SC}}{60}\right). \tag{6}$$

III. Improved Period-Based Speeed Estimation

The delta-sigma modulation is widely used to digitize analog signals [10]. The structure of analog-to-digital converter using delta-sigma modulation is displayed (see Fig.7).

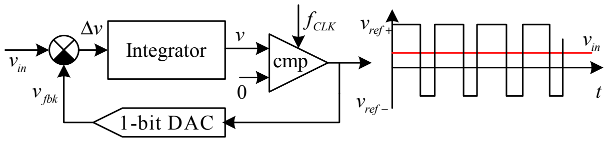

Fig. 5. Delta-sigma modulator structure.

The modulator input receives analog signal and it is immediately compared with the 1-bit DAC output, where logical one corresponds to the positive reference voltage, and the logical zero–to the negative one. The difference between the input and the feedback is fed to the analog integrator, which accumulates the error. The signal from the integrator passes to the comparator, which generates feedback to the input signal. The signal is sampled at frequency f_{CLK}. The output signal is a sequence of ones and zeros, which forms the bitstream. Demodulation of the bitstream can be performed using low-pass filters, such as high order Sinc-filters [11]. The application of the third-order filter has shown good results for current measurement using a shunt [12].

It was noticed that the estimations of the period-based method have the properties of delta-sigma modulated signals. In both cases, the signal has two levels, and the true value lies between them. Similarity of properties of the period-based method and delta-sigma modulated signal was considered in the paper [13], where speed measurement was improved by oversampling.

In this paper it is suggested to increase accuracy of speed estimation using third order Sinc-filter. The first-order Sinc-filter is a moving average filter, which structure for oversampling ratio equal to N is shown in the Fig. 6.

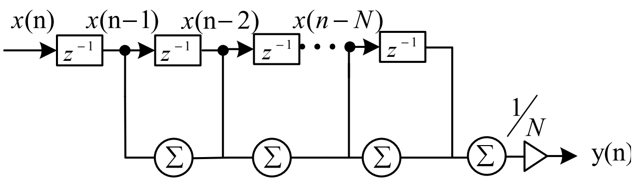

Fig. 6. Structure of the first-order Sinc-filter.

The higher-order filters and be implemented by serial of connection of first-order filters (see Fig. 7).

Fig. 7. Structure of the therd - order sink filter.

So, the amount of encoder pulses should be multiple of four, and for using Sinc3 it should multiple of three. Therefore, values of S should multiple of twelve. The equations of the three-order Sinc-filter is shown below:

$$\begin{cases} Sinc1[n] = \frac{3}{S}\sum_{k=0}^{S/3} x[n+k]; \\ Sinc2[m] = \frac{3}{S}\sum_{k=0}^{S/3} Sinc1[m+k]; \\ Sinc3 = \frac{3}{S}\sum_{k=0}^{S/3} Sinc2[k], \end{cases} \quad (7)$$

where n varies from zero to $2S/3$, and m varies from zero to $S/3$.

For the speed estimation the oversampling ratio of the filter should vary with the speed of the motor. The higher is the speed, the bigger number of elapsed time estimations are produced with each upcoming pulse of the incremental encoder during single speed control cycle. Taking into account encoder non-idealities, the minimal amount of QCLK pulses should be set to 12 with, where Sinc-filter oversampling ratio is set to 4 and it is multiplied by the order of the filter.

IV. Experimental Result

The suggested algorithm is implemented using LaunchPad XL TMS 320F28379D from Texas Instruments [14]. It operates at 200 MHz core frequency. This microcontroller has an event capture unit (eCAP) and peripheral module eQEP. Also, the testbench includes BLDC motor FL57BLS04, which has maximum speed of 5000 rpm. The motor is fed by the inverter board DRV8302-HC-C2-KIT from Texas Instruments connected to 28 V DC power supply. The controller PCB is based on Piccolo microcontroller unit TMS320F28035. The motor is coupled with incremental encoder HEDM-5500#B06 having 1000 pulses per revolution. The experimental setup is shown in Fig. 7.

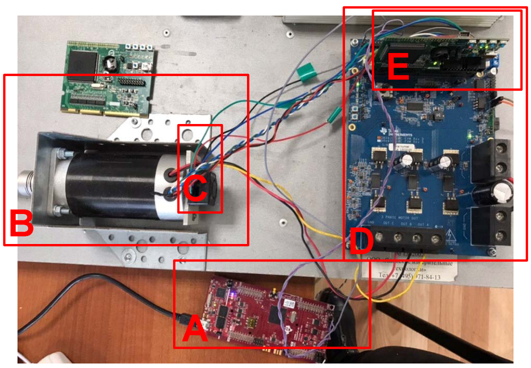

Fig. 8. The testbench, where A–LaunchPad XL TMS 320F28379D; B–BLDC motor FL57BLS04; C–incremental encoder HEDM-5500#B06; D–inverter board DRV8302-HC-C2-KIT; E–Piccolo microcontroller unit TMS320F28035.

The measurement system is written in C in Code Composer Studio with the speed loop interrupt working at f_{CL} 1 kHz executing every 1 ms. The module eCAP is used for capturing each edge of the encoder signals "A" and "B" and current time value Δt. In order to improve visualization of the experiments, the accuracy of time measurement was artificially decreased. So, the eQEP capture timer clock prescaler was set to 128 with h equal to 0.64 us instead of original 5 ns. The effect of quantization is increasing and it allows to notice the difference between the average method and the proposed method using Sinc3-filter. Then, for the averaging method the relative error equals to:

$$\delta n_p = h \cdot f_{CL} = 0.064\%. \quad (8)$$

But the results of the conducted experiment did not show what was expected (see Fig. 10). The speed deviation for both methods was too high to make some accuracy analysis.

It happens for two reasons. One of them is that the sensor has low mechanical accuracy, which affects the speed estimation higher than time quantization. Another problem occurs due to relatively small inertia, which affects speed stability. Therefore, it is impossible to conduct a pure experiment considering the impact only of time quantization.

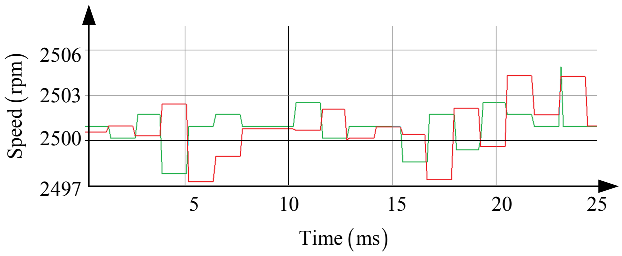

Fig. 9. Motor operates at the constant speed: green–speed estimation by average method, red–speed estimation using Sin3-filter.

The experimental conditions were modified, and the reference encoder signals were produced using the PWM module of the same microcontroller. For the ideal encoder signal the several experiments were conducted to show difference between methods. The speed estimation using Sinc3-filter shows more accurate result than the estimation with average filter for the same number of incoming pulses.

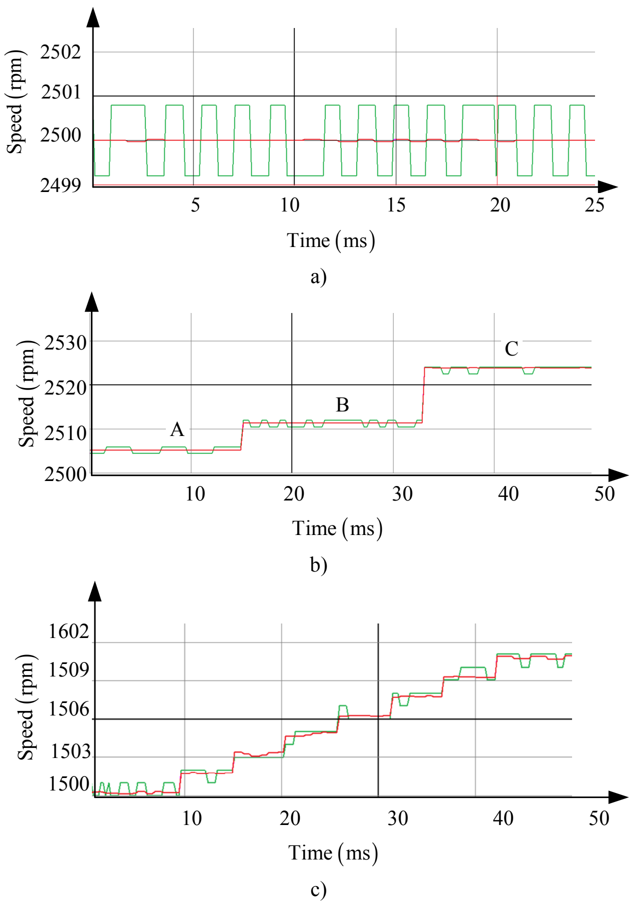

Fig. 10. Speed estimation: green–speed estimation using average filter, red–speed estimation using Sinc3-filter.

V. CONCLUSIONS

In this paper the effect of quantization on speed estimation was considered. The period-based method with Sinc3-fiter was proposed. It reduces quantization noise effect and shows more accurate results compared to average method. The future research will be devoted to implementation of the encoder calibration procedure in order to increase speed estimation accuracy with the real equipment.

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