Adaptive Algorithms for Quantization Error Normalization of Digital Encoder-Based Tachometers

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Abstract. The authors' analysis of the instantaneous and average values digital tachometer quantization error assessment in the dynamic measurements of angular velocity with an encoder allowed to create an innovative a mathematical model for calculating the critical speed numerical value for an exponential mathematical model that adequately describes the transient process of the electric machine's operation. The authors discovered that the value of the critical speed depends on the resolution z of the encoder, the quantization frequency f_0, and the duration of the sample time interval t_0, which variation allows to measure the angular velocity with a predetermined normalized value of the quantization error during the transient process of the electric machine from the lower to the upper measurement limit. The practical significance of the proposed approach is as follows. At the beginning of measurements $n \leq n_c$, the transient characteristics of electric machines are characterized by dips, jumps, synchronous dips in angular velocity, the amplitude and duration of which must be determined with high accuracy. The most effective here is the structure and algorithm of the digital tachometer of instantaneous values. In the section of the transition characteristic, when $n > n_c$, such dips are not significant. In addition, the quantization error of instantaneous values also increases with the increase in angular velocity. Therefore, in this section of the transient characteristic, we advise to configure the hardware and software for the tachometer by using an average value.

Keywords: Electric Machine · Transient Characteristic · Encoder · Transfer Function · Quantization Error Equation · Critical Speed · Adaptive Algorithm · Microcontroller Tachometer · Normalized Value of Quantization Error

1 Introduction

Currently, to intensify the testing of electric machines (EM), most of the research is focused on the acceleration of the tests carried out in the "no load" experiment. The main one here is the transient characteristic (variable angular velocity over time *n(t)*),

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which is obtained in the dynamic mode of measuring object operation (electric machine) with practically zero moment of resistance on its shaft *(MC ≅ 0)* [1–5]. A feature of the experimental studies of this characteristic is the determination with high accuracy in real time of the available dips, sudden emissions, synchronous dips, which significantly affect the vibroacoustic characteristics of electric machines. This scientific and applied problem is solved by providing the maximum number of measurement results during the electric machine transient process, the quantization error of which during the measurement experiment should not exceed the normalized value.

To carry out such mutual dynamic measurements of the speed change as a function of time *n(t)* during the EM transient process, the vast majority of researchers use an encoder (EC) as a sensor, which shaft is connected to the EM through a coupling clutch (CC), as shown in Fig. 1 [6–11]. The pulse frequency from the EC output is converted into a binary code by frequency measuring channels (FMC).

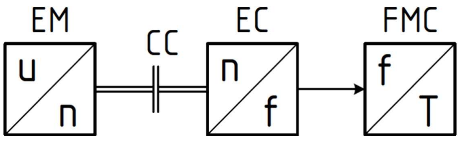

Fig. 1. Typical measurement channel block diagram: EM – electric machine, CC – coupling clutch, EC – encoder, FMC – frequency measuring channel.

Figure 2 shows the results of simulation of the transient process of an asynchronous electric machine in an idling test (the moment of resistance on the EM shaft $0 \approx 0$) for the exponential mathematical model $n = n_0 \cdot \left(1 - e^{-\frac{t}{\tau}}\right)$, where n_0 is the synchronous frequency of rotation of the shaft of the electric machine (EM) after the transient process, τ is the EM time constant [11].

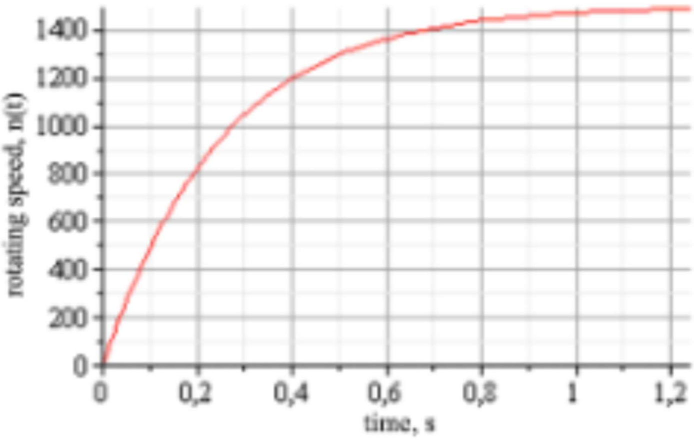

Fig. 2. Results of the transient process simulation.

Analysis of the given results allows us to state the following: during the transient process, when the angular velocity increases from zero to the maximum value, the quantization error is a variable value.

The purpose of the work is to develop a criteria and embedded tools for implementing an adaptive algorithm for real time measuring angular velocity, which quantization error will not exceed a predetermined normalized value.

2 Materials and Methods

After EM starting (see Fig. 1), during rotation process of the connected shafts of EM and EC, sensor converts the angular velocity into a sequence of electrical signals, which frequency is determined [4, 8, 12].

$$f_x = \frac{n \cdot \mathbb{Z}}{60}. \tag{1}$$

In the logic AND gate of the frequency measurement channel (FMC), the unknown $T_x = \frac{1}{f_x}$, and the sample T_0 periods are quantized. As a result of the comparison of the measured and exemplary physical quantities, the transfer function of the digital tachometer of instantaneous values is obtained, which unambiguously connects the input value angular velocity n with the output value N number of pulses in the binary counter of the frequency measurement channel

$$N_{\mathrm{IV}} = T_X \cdot f_0 = \frac{60 \cdot f_0}{n \cdot \mathbb{Z}}. \tag{2}$$

The dependence of the change in the number of pulses N in time, which is counted by the binary counter CT2 in each T_X period, is shown in Fig. 3a.

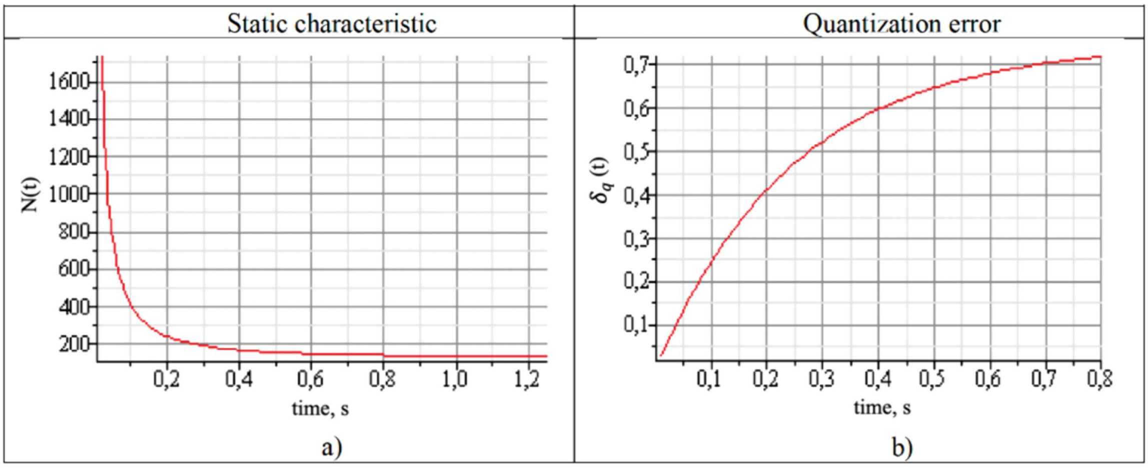

Fig. 3. Basic static metrological characteristics of instantaneous values digital tachometer.

As a result of quantization of unknown periods T_X by sample periods T_0, the analog value T_X, which has an infinite number of values, is replaced by the number of pulses N of the binary counter CT2. Which is the reason for the appearance of the quantization error (Fig. 3b), which relative value is

$$\delta_{IV} = \frac{1}{N_{IV}} 100\% = \frac{n \cdot \mathbb{Z}}{60 \cdot f_0} 100\%. \tag{3}$$

Analysis of the results shown in Fig. 3 shows that during the transient process, the speed n increases (Fig. 2), and the number of pulses N decreases (Fig. 3a). The quantization error also increases (Fig. 3b). Therefore, it is advisable to use such a digital frequency converter into a binary code for angular velocity dynamic measurements only at the beginning of the EM transient process to a certain value of angular velocity [12–27]. Let's call this value critical n_c.

If in the diagram shown in Fig. 1, instead of the instantaneous frequency meter, a frequency meter of average values is used, then for this measuring device we will have our own transfer function (static characteristic shown on Fig. 4a).

$$N_{AV} = t_0 \cdot f_X = \frac{n \cdot z \cdot t_0}{60}, \tag{4}$$

and its relative quantization error equation (dependency $\delta_{IV} = f(t)$)

$$\delta_{qa} = \frac{1}{N_{AV}} 100\% = \frac{60}{n \cdot z \cdot t_0} 100\%. \tag{5}$$

The static characteristics and the law of change of the quantization error over time of this tachometer are shown in Fig. 4. The quantization error decreases with the increase in angular velocity during the transient process of EM. Therefore, the field of its application is the measurement of large angular velocities [28–30, 31, 32].

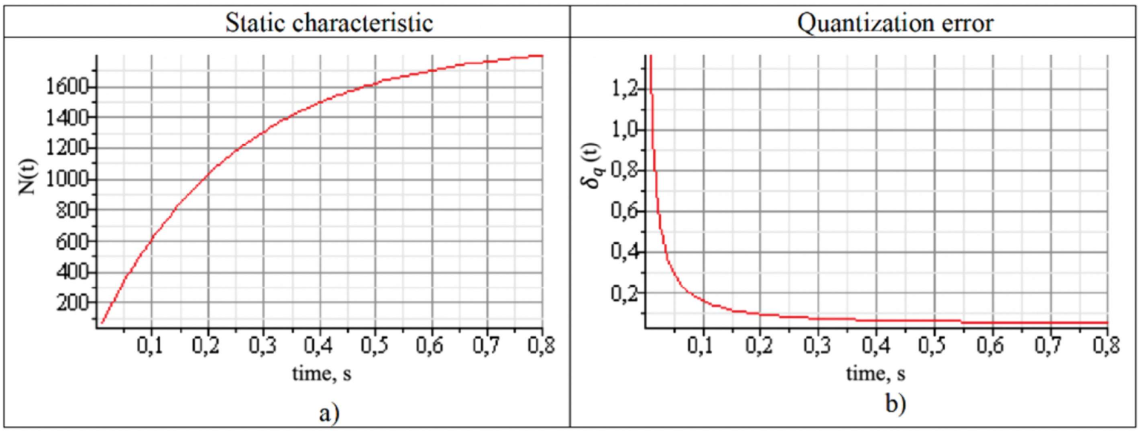

Fig. 4. Basic static metrological characteristics of an average values digital tachometer.

The analysis of the quantization error shows that during the transient process of the electric machine, quantization error changes significantly in the area of a possible change in angular velocity – from n_{xmin} to n_{xmax}. In this connection, the problem of normalizing the value of this methodical error component arises.

Let's analyze the possibility of implementing this task with a tachometer of instantaneous values. First, let's define the measurement range. The lower limit of measurement of a digital tachometer of instantaneous values (period meter), limited by the number of digits of a binary counter.

$$N_{max} = 2^n, \tag{6}$$

and its transformation equation has the following form:

$$N_{IV} = \frac{2\pi \cdot f_0}{n_x \cdot z}, \tag{7}$$

where z is the mark quantity in the photoelectric angular velocity sensor, f_0 is the quantization pulse frequency. Then the quantization error equation:

$$\delta_n = \frac{n_x \cdot z}{2\pi \cdot f_0} \cdot 100\%. \tag{8}$$

Taking into account (6), Eq. (7) can be written as follows

$$2^n = \frac{2\pi \cdot f_0}{n_{x\,min} \cdot z}. \tag{9}$$

Then we will determine the lower measurements boundary from Eq. (9):

$$n_{x\,min} = \frac{2\pi \cdot f_0}{2^n \cdot z}. \tag{10}$$

The upper measurements boundary for the instantaneous value tachometer is limited by the quantization error and is determined from Eq. (8):

$$\delta_{KN} = \frac{n_{x\,max} \cdot z}{2\pi \cdot f_0}, \tag{11}$$

from where

$$n_{x\,max} = \frac{2\pi\, \delta_{KN} \cdot f_0}{z \cdot 100\%}, \tag{12}$$

where δ_{KN} is the normalized value of the quantization error. Given the value of the quantization error $\delta_{KN} = 1\%$, we get

$$n_{x\,max} = 314\,\frac{rad}{s} \left| \begin{array}{l} f_0 = 5\,MHz \\ z = 1000 \end{array} \right.,$$

The given example shows that the tachometer of instantaneous values can be used to measure the angular velocity both in the transient modes of the electric machine operation as well as in the static mode.

In this case, the instantaneous values of the angular velocity are determined as:

$$n_x = \frac{2\pi \cdot f_0}{N_X \cdot z \cdot K(n)}, \tag{13}$$

where is the coefficient of the frequency divider of the timer, the value of which varies from 1 to the maximum, which is limited to n-bits of the binary counter.

The law of change of $K(n)$ is determined by two parameters:

- the law of change $n_x(t)$;
- normalized value of the quantization error $\delta_n \leq \delta_{KN}$.

The law of change of $K(n)$ ensures the fulfillment of the condition $\delta_n \leq \delta_{KN}$ in the measurement range of angular velocity from n_{xmin} to n_{xmax}.

A significant drawback of this method of normalization of the quantization error is the complexity and long duration of determining the values of the $K(n)$ coefficient at each moment of the transient process of the electric machine, which significantly limits the speed of measurement of the dependence of $n_x(t)$.

3 Experiments

Based on the comparative characteristics of quantization errors of instantaneous and average values, a tachometer adaptive to changes in angular velocity is proposed, which provides its dynamic measurements in a wide range with a quantization error that does not exceed the normalized value.

To implement such an approach, it is first necessary to synthesize an algorithm for software support of hardware for the microcontroller (MCU). If we equate the quantization errors of the instantaneous and average values of the tachometers

$$\frac{60}{n \cdot z \cdot t_0} 100\% = \frac{n \cdot z}{60 \cdot f_0} 100\,\%, \tag{14}$$

then we will get a dependence for estimating the value of the critical speed n_c

$$n_c = \frac{60}{z}\sqrt{\frac{f_0}{t_0}}. \tag{15}$$

For $t_0 = 5 \cdot 10^{-2} s, f_0 = 5 \cdot 10^6 Hz$ and $z = 1500$, the intersection point of the quantization errors δ_{qi} and δ_{qa} dependencies are shown in Fig. 5. Based on (7) and Fig. 5, the following algorithm adaptive to changes in angular velocity is proposed:

1. If the measured current value of the angular speed is less than the value of the critical speed ($n \leq n_c$), then two microcontroller timers implement the algorithm of instantaneous values tachometer in "adjacent" intervals.
2. Under the condition $n > n_c$, the third timer of the microcontroller is programmed to the tachometer algorithm of average values.

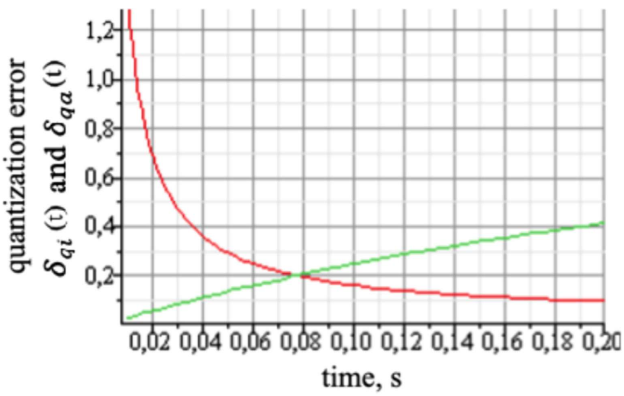

Fig. 5. To the question of determining the critical speed.

Analysis (7) shows that f_0 and z for a specific schematic implementation are constant values. It is possible to vary only $t_0 \rightarrow var$, which allows you to set the required value of the critical speed n_c. The dependence of n_c on the measurement time t_0 for the tachometer of average values is shown in Fig. 6.

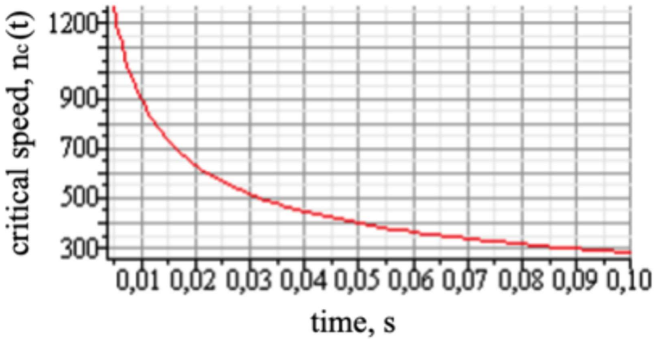

Fig. 6. The dependence of n_c on the measurement time of the average values tachometer.

4 Results

The structural diagram of the hardware and software implementation of the adaptive algorithm proposed on the basis of (7) (see Fig. 6) for the normalization of the quantization error for dynamic measurements of angular velocity during the transient EM process is shown in Fig. 7.

In order to develop the hardware and software implementation (see Fig. 7) of a microcontroller tachometer, adaptive to the EM angular velocity changing, during the transient process, which ensures normalization of the quantization error in a wide range of its change, the following requirements are set:

1. The presence of two timers in the MCU architecture for calculating the number of N sample periods T_0, which alternately quantize the periods T_n (input AIN 0) and $\overline{T_n}$(input AIN 1), formed, respectively, on the direct and inverse outputs of the frequency converter in the period f_n/T_n;
2. The presence of a third timer designed to form the measurement time t_0, during which it is quantized by periods T_n of the frequency f_n from the output of the encoder;
3. Transfer of binary codes generated by timers to the RAM in direct memory access (DMA) mode during the EM transient process;
4. After the measurements (of the transient process) have been completed, the EM is turning off and numerical values of the angular velocity with the defined measurement units are obtained according to the given conversion equations.

Figure 8 shows that for the f_0, z, t_0, n used in the scheme, the critical n_c value of the angular velocity is determined, the hardware and software implementation of the adaptive algorithm allows to ensure a predetermined normalized value of the quantization error in a wide range of its changes $\delta_{qn} \leq 0{,}2\%$.

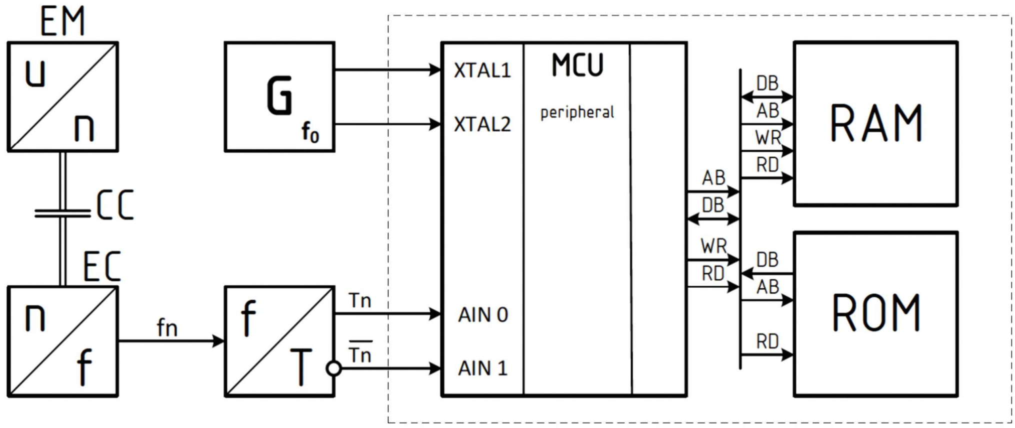

Fig. 7. Results of the transient process simulation. EM – three-phase asynchronous motor UAD-34; $n = 1500 rpm$; $\tau = 0.5 s$; LIR-250 A encoder; $z = 1500$; $f_0 = 5 \cdot 10^6 Hz$; $t_0 = 5 \cdot 10^{-2} s$.

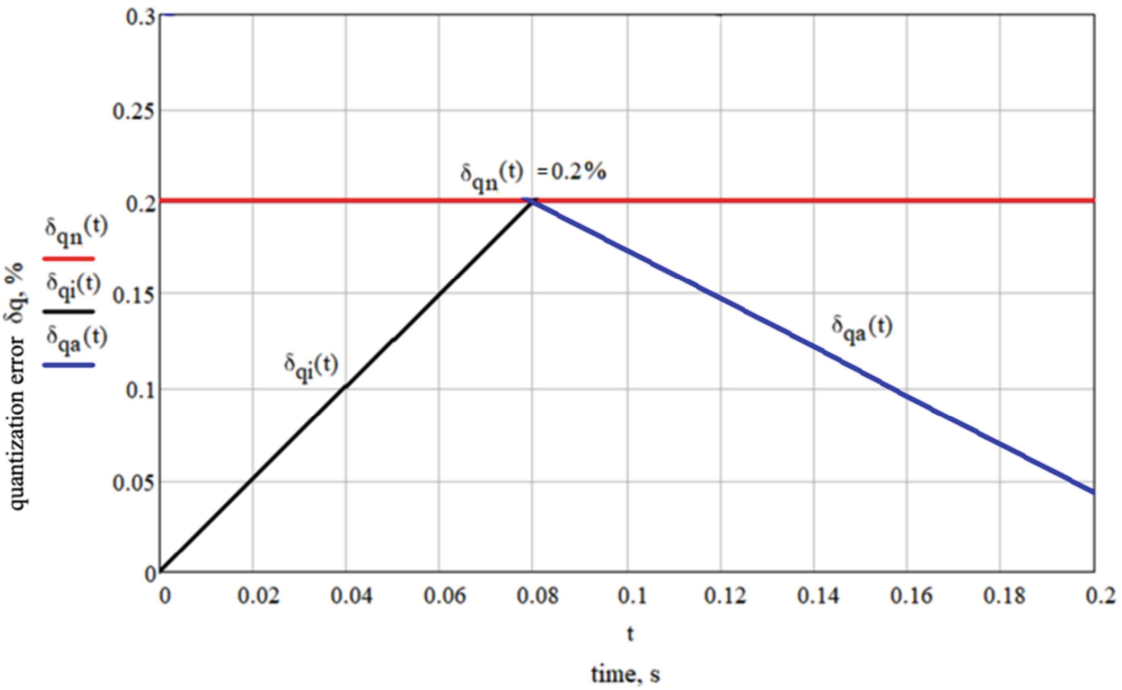

Fig. 8. Characteristics of the change in the normalized values of quantization errors.

5 Discussion

Significant scientific and applied problem is the normalization of the quantization error of dynamic measurements, the value of which changes significantly from the minimum (at the beginning of the transient process) to the maximum value (at the beginning of the steady state).

The problem was solved using the example of concurrent dynamic measurements of angular velocity during a short (few seconds) period of time. The extremely wide dynamic range of the angular velocity change during the transient process of the measurement object is the reason for the significant change in the quantization error. Therefore, the authors proposed two algorithms for adapting the microprocessor measuring device to the inertial properties of the object (electric machine).

For the practical implementation of the first adaptive algorithm, it is proposed to use a tachometer of instantaneous values, and criterion (13) is used as the basis for the normalization of the quantization error. The practical implementation of this approach requires the use of an additional counter (timer), the counting coefficient $K(n)$ of which changes in the process of measuring the angular velocity $n_x(t)$; in such a way that the quantization error in each period does not exceed the normalized value $\delta_n \leq \delta_{KN}$. At the beginning of the transition process, when the values of the angular velocity are small and correspondingly large, the values of the periods are proportional to them and there is enough time to calculate the numerical values of the coefficients $K(n)$, writing them into the previously included divider (one of the microcontroller timers). This approach makes it possible to ensure the normalization of the quantization error $\delta_n \leq \delta_{KN}$ in each period. As the angular velocity increases, the period at the output of the encoder also decreases, which leads to a decrease in the calculation time and a corresponding correction of the period duration. Therefore, it is problematic to provide a normalized value of the quantization error $\delta_{KN} \leq 1\%$ at the upper measurement boundary.

The combined use of a tachometer of instantaneous and average values has better metrological characteristics. The construction of such tool is based on (15).

If you set the constants under software initialization $t_0 = 0.05\ s,\ f_0 = 5\ MHz,\ Ƶ = 1200$, then the value of the critical speed will be equal to 500 rpm. Since the angular velocity values are small at the beginning of the transient process, the microcontroller tachometer is set to measure instantaneous values. With the arrival of each pulse from the output of the encoder, the current value n_x is determined and compared with n_c. If $n_x < n_c$, then the instantaneous value tachometer is working. When $n_x > n_c$, the microcontroller programmatically configures the average value tachometer circuit.

Analysis of the results shown in Fig. 5 confirms the advantage of this algorithm, compared to the previous one. For rather not rigid requirements for the quantization frequency, the duration of the sample time interval, and the resolution of the encoder, an adaptive algorithm is proposed, and its microprocessor implementation provides dynamic angular measurements speed in the range of its change from *1 rpm* to *3000 rpm* quantization error no exceeds 0.2%, which confirms its effectiveness.

6 Conclusions

The analysis of the main metrological characteristics of instantaneous and average values digital tachometers made it possible to propose criterion (7), the hardware and software implementation of which provided the synthesis of an adaptive (for the changes in angular velocity inherent the EM transients) algorithm of quantization error normalization.

Formulated requirements for hardware and software implementation of a microcontroller tachometer, adaptive to the change in angular velocity during the EM transient, which are shown in its structural diagram (see Fig. 7).

The essential differences of the synthesized adaptive algorithm are as follows: the first stage – the measurement of the angular velocity is carried out in real time during the transient EM process; the second stage is the processing of the obtained results after the end of the measurement process (transient process).

The usage of the advantages of instantaneous and average values tachometers in one tool ensures the implementation of dynamic measurements with a predetermined normalized value of the quantization error (see Fig. 8). Such adaptive microcontroller tachometers are advisable to use in cases where at the beginning of the transient characteristic of EM, the angular velocity changes significantly over time.

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