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Analysis of Methods for Determining Frequency of the Main Harmonic in the Centralized Systems of Relay Protection and Automation

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Abstract: The measuring of the alternating voltage and current frequency into modern microprocessor devices and systems of relay protection and automation is the major problem and reaction rate on preventing system or its part transition in the emergency mode depends on its solution. In this regard the important aspects are the speed and accuracy of the frequency determination depending on the method used as well as the assessment of the noise and harmonics effects on the frequency measurement as a function of the applied algorithm. The data on the accuracy of the frequency measurement by different algorithms were got and estimation of the highest harmonics and noise content in the input signal influence for calculating the signal frequency by different methods was conducted. The research results can be used in the development of new frequency measurement algorithms, including algorithms for multi-channel centralized relay protection and automation system which can affect the approach of modern relay protection and automation systems development as well as increase the functioning efficiency of the existing protection.

Key words: Frequency measurement, frequency measurement techniques, microprocessor terminals relay protection, systematic error, methodological error, fast fourier transform, frequency spectrum

INTRODUCTION

The measurement of electrical quantities in electric power industry is required for a wide range of applications: from relay protection and automation devices and systems to these which control and analyze the consumers electricity quality. In general, the electrical quantities are the voltage and current of the first harmonic of 50 Hz and higher harmonics. Their important controlled parameters are the phase currents and voltages actual values deviation from the nominal values, the fundamental harmonic frequency deviation from the nominal value, sinusoidal and coefficients of harmonic components (GOST, 1997).

Multi-channel centralized system of relay protection and automation as well as contemporary devices (terminals) of relay protection and automation is performed on microprocessor element basis, the information processing in such system and terminals is performed digitally. The advantages of this representation consist in accuracy and speed of information processing, reception quality and data transfer (Lizunov and Kozlov, 2011).

It is necessary to note that both traditional and modern microprocessor technologies of relay protection and automation must timely prevent not only electrical equipment damage but also abnormal modes of its work. The duration of emergency operation on the steadiness preservation conditions (Anonymous, 2003) should be limited for the regional networks of 100 kV and higher value no >0.3 sec after the short circuit and in urban and suburban networks of medium voltage under the terms of thermal and dynamic stability no >3 sec. The time of short-circuit tripping depends on many conditions and consists of the breaker and protection operation time. To ensure the modern standards of electric power systems and consumers systems power supply operation reliability and quality, it is necessary to improve the techniques and methods of controlled electrical quantities and their parameters measurement.

The operation of relay protection and automation devices and systems takes place upon reaching the valid or peak value of the AC voltage and/or current (controlled variable) of a certain threshold (set point). The calculation of the current value in microprocessor devices and systems of relay protection and automation is cyclically made by the following equation (Bessonov, 1973):

$$A = \sqrt{\frac{1}{N}\sum_{i=1}^{N} a_i^2} \quad (1)$$

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Where:

- A = Actual value of the controlled quantity
- a_i = Instantaneous values of controlled quantities)
- N = Number of samples of controlled quantities instantaneous values for the time period corresponding to the double period of time between transitions through the zero of controlled value

The period in the energy system changes dynamically under the influence of imbalances torques on the generators shafts and transients in electric systems, under the influence regulators of turbines rotation speed and frequency and is associated with the value of the energy systems turbines generators rotation frequency time constant t = 10 sec.

According to Eq. 1, the current value of the controlled value depends on the period of its change, respectively the more precisely it will be defined the more accurate the data on the current value of the controlled value will be. The period is inversely proportional to the frequency of the mains. To ensure the accuracy of calculating the effective value it is necessary to correlate each sample of instantaneous values with the data values about the frequency of controlled value at the present time.

Besides microprocessor devices and systems of relay protection, the definition of frequency of fundamental harmonic of controlled value is necessary for the functioning emergency control systems which provide reliable and synchronous operation of the power system as a whole.

MATERIALS AND METHODS

Overview of the frequency measurement methods: This article presents a comparative analysis of the traditional methods of frequency measurement in the devices of relay protection and automation, and the new ones which are realized in modern microprocessor devices and systems including those intended for the implementation in multi-channel centralized relay protection system (Lizunov and Kozlov, 2011). Also, we evaluated the methods effectiveness if there is a multiplicity of the fundamental frequency harmonic and noise in signal as well as if they are absent. We estimated the approaches without searching for determining the frequency by Osipov and Garin (2013) controlled parameter which define the frequency almost instantly. These frequency determining methods require the time for measurements accumulating and averaging to reduce the error. These methods with considerable time of results accumulation allow you to measure the carrier frequency with high accuracy and to provide a high resolution (Aleshechkin *et al*., 2008).

The most common way of measuring frequency in microprocessor technics of relay protection and emergency control is a method of discrete accounts but in the last decade fast Fourier transform algorithm (hereinafter-FFT) and Discrete Fourier transform (hereinafter-DFT) were widespread. FFT and DFT are used as a tool for the expansion of the signal into a series of harmonic functions which opens great possibilities for signal processing, the frequency determining, amplitude and phase of the signal and its harmonic components.

This trend is due to significant increase in microprocessor performance over the past decade. It should be noted that in addition to these methods, other methods are also known from technical literature and patent databases, they are not widely available due to technical difficulties in implementation.

These methods and corresponding algorithms have different precision, especially in the presence harmonics and noises in the input signal which distort the shape of a industrial frequency sine wave which arise at transients (inrush current in transformers, short circuit, load-on high power, when operating power semiconductor devices, etc). It is necessary to identify the most advantageous in terms of accuracy and stability to the effects of noise, method of frequency measurement for the implementation of the corresponding algorithm in a multi-channel system of relay protection and automation. The study describes the following methods. Method of discrete calculation (first method).

According to this method, the frequency measurement (by transition of instantaneous signal value through “0”) is as follows (Mustafin, 2014a,b) by changing the signal sign from negative to positive, a counting pulse is generated, further the number of such pulses within of some time for example, for 1 second or 100 sec is calculated and the value of frequency is determined.

Method based on fixation of the controlled voltage instantaneous values through the reference intervals (second method). This method allows to determine the frequency, amplitude and phase of the signal value by the three instantaneous values of the controlled value (Wolfowitz, 2011). Process according to length of the chord joining the vertices voltage vector U (t) with the voltage vector U (t+dt) (third method).

In this method the value of the alternating voltage amplitude U (t), the length of the chord joining the voltage vector vertex U (t) (at time t) and the vector U voltage (t+dt) (at time t+dt time) phase angle dφ turn of vector voltage U (t) in the time dt are estimated which help to calculate dynamic frequency F (t) for each step dt

(Seki, 2012). Method using the signals of all three phases Ua (ti), Ub (ti), Uc (ti) of industrial three-phase voltage (fourth method).

In the method for determining the frequency F they use the signals of all three phases Ua (ti), Ub (ti), Uc (ti) industrial three-phase voltage measured at the instants ti time where i-integer value, digitized with period of sampling dt = (t_i-t_{i-1}) and the value of dt is much smaller than the period T with the most frequency FB = 1/T of measuring range dt"T (Mustafin, 2014a, b). The method consists in the fact that the rotation frequency of the magnetic field vector generated by the three-phase system is determined.

Method of the phase change determination of controlled signal fundamental harmonic by the DFT for the time interval (fifth method).

At a constant frequency sampling, frequency of controlled value is defined as follow: they use two signal samples processed by the algorithm DFT with predetermined frequency Ff, then they define the value of phase signal vector φwith respect to the reference vector DFT of fundamental harmonic, then they determine difference of the phase dφ during the time dt, corresponding to the angular speed of sliding of signal vector $\Delta\omega = \omega_{signal}$-$\omega_f$ relative to the reference vector of the DFT. After that we determine frequency of fundamental harmonic of signal Fsig:

$$F_{sig} = \frac{\frac{d\varphi}{dt}}{2\pi 2} + F_f \qquad (2)$$

where, F_f is the fundamental frequency reference signal DFT.

Comparison of the frequency determining methods: We will make a comparison between the accuracy of the frequency determination by these operating methods (from first to fifth) determining the frequency of controlled electric value. Also, we will estimate the degree of influence on them of harmonics multiple to the fundamental (2nd, 3rd, 5th) and noise (±10%).

The calculations were performed in Mustafin (2014a, b) software package because it has all the required tools for calculation and convenience presentation of calculation results in numerical and graphical form.

The simulation of frequency calculation methods was created on the sinusoidal signal with a sampling frequency 1800 Hz (36 instantaneous values during the period, dt = 0,00055s) with the frequency 50 Hz, amplitude Am = 1, duration in three periods t = 0.06s (Fig. 1). The received results of calculated instantaneous frequency values are averaged over the period.

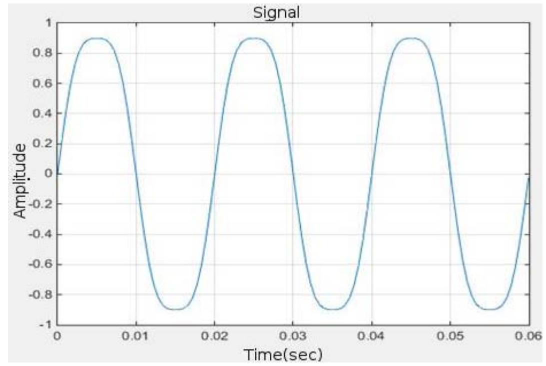

Fig. 1: Sinusoidal signal

Considering the discrete calculation method, the traditional method of determining the frequency: We form the condition under which the counting pulse will be generated:

$$Xi = \text{if } U_i > 0, \text{ then } 1; \quad U_i < 0, \text{ else } 0$$

We calculate the number of counting pulses for 36 measurements with step Δt_i (sampling period of ADC) through each k dimension in the period:

$$Yi = \sum_{i+k}^{36} Xi = 18$$

We determine the number of transitions through zero for the 36 measurements:

$$N = \frac{36}{Yi} = \frac{36}{18} = 2$$

We determine the vibration frequency during the observation:

$$F_1 = \frac{N}{2\times\sum_1^{36} t_i} = \frac{2}{2\times 0.02} = 50 \text{ Hz}$$

It is important to note that this approach to the determination of the frequency by the method of discrete calculation is applied to the signals, the counting pulse average value of which for the period is equal to zero that is without the constant component. The absolute error of frequency measurement:

$$\Delta F_1 = F - F_1 = 50 - 50 = 0 \text{ Hz}$$

This approach to determine the frequency by method of discrete calculation is applied to the signals that have an average value for the period equal to zero that is without the constant component.

Considering a method based on the fixing of the instantaneous values of controlled voltage via the reference intervals (second method): The frequency is determined according to Eq. 3:

$$F = \frac{1}{2\pi\Delta}\arccos\left(\frac{U_{i-1}+U_{i+1}}{2U_i}\right) \tag{3}$$

Where:

F = Measured frequency
Δ = Reference intervals (ADC sampling period)
U_{i-1}; U_{i+1}; U_i = The instantaneous values of the controlled quantity measured at intervals of time Δ

The average value of the frequency according to Eq. 2 F2 = 50,005 Hz. Absolute error:

$$\Delta F_2 = F - F_2 = 50 - 50{,}005 = 0{,}005 \text{ Hz}$$

Considering the method along the length of the chord joining the vertices voltage vector U (t) and the voltage vector U (t+dt) (third method): The sequence of calculations. We summarize the squares of the sinusoidal signal instantaneous values:

$$U = \sum_{i=0}^{35} \sin^2(10\times i) = 18$$

We summarize the square of difference between the sinusoidal signal instantaneous values:

$$dU = \sum_{i=0}^{35} \sin^2(10\times i)$$

We calculate the angle dϕ of vector rotation for dt:

$$d\varphi = 2\times \arcsin\left(\frac{dU}{2U}\right) = 0.174 \text{ rad}$$

We calculate the frequency:

$$F_3 = \frac{d\varphi}{(dt\times 2\pi)} = \frac{0.174}{0.000555\times 2\times 3.14} = 50 \text{ Hz}$$

The absolute error of measurements:

$$\Delta F_3 = F - F_3 = 50 - 50 = 0 \text{ Hz}$$

RESULTS AND DISCUSSION

Considering the simulation results for the method of determining the three phase frequency (fourth method): Defining the instantaneous values of the three sinusoidal signals which were shifted from each other by 120° with frequency 50 Hz, measured 36 times during period every 10° (Fig. 2).

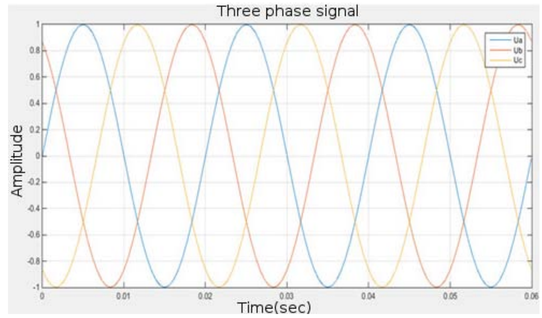

Fig. 2: Three-phase signal

Determining the projection of all the three voltage vectors on the x-axis for each ith values of controlled values:

$$Ux(ti) = \left(Uc(t_i)\setminus -Ub(t_i)\right)\cdot\frac{\sqrt{3}}{2}$$

Determining the projection of all the three voltage vectors in the Y-axis for each ith values of controlled values:

$$Uy(ti) = \left(2\cdot Ua(t_i)\setminus -Ub(t_i)\setminus -Uc(t_i)\right)\setminus /2$$

Determining the module of rotating field $U(t_i)$:

$$U(t_i) = \sqrt{}(Ux(t_i)^2)+(Uy(t_i)^2) = 1.5$$

for each ith time value. Determining the dependence from the time t_i of the increment phase dφi of rotating field U(ti) for the interval $dt = t_i+t_{i-1}$ by the equation:

$$|d\varphi i| = |\varphi(ti)\ \varphi(ti-1)| = 0.1745 \text{ rad}$$

Calculating the frequency:

$$F_4 = \frac{d\varphi}{dt\times 2\pi} = \frac{0.1745}{0.00055\times 2\times 3.14} = 50.005 \text{ Hz}$$

The absolute error:

$$\Delta F_4 = F - F_4 = 50 - 50.005 = 0.005 \text{ Hz}$$

Consider the results of the simulation method for determining the frequency by changing the phase of the fundamental harmonic of controlled signal by the FFT during the time interval (the fifth method): Forming an

Table 1: The results of calculation of frequency

Factors	Amplitude	The results of calculation of frequency and absolute errors (Hz)							
		F_1	ΔF_1	F_2	ΔF_2	F_3	ΔF_3	F_4	ΔF_4
The second harmonic	0.1	50	0	66.44	16.44	50.73	0.73	49.08	-0.92
F = 100 Hz	0.2	50	0	-	-	52.78	2.78	49.97	-0.03
	0.3	50	0	-	-	55.81	5.81	46.63	3.37
The third harmonic	0.1	50	0	76.88	26.44	51.9	1.9	50.05	0.05
F = 150 Hz	0.2	50	0	-	-	57.04	7.04	50.05	0.05
	0.3	50	0	-	-	64.2	14.2	50.05	0.05
The fifth harmonic	0.1	50	0	-	-	55.3	5.3	48.47	-1.53
F = 250 Hz	0.2	50	0	-	-	68.3	18.3	46.08	-3.92
	0.3	50	0	-	-	84.74	34.74	54.64	4.64
Noise	±10%	47.43 -51.38	-2.67-1.38	-	-	55-65	5-15	49-51	-1-1

array of signal x (t) with a frequency w = 50 Hz and reference Fourier arrays a(t) and b(t) with the frequency of the fundamental harmonic ω_f = 50 Hz:

$$x_i = \sin(\omega \times i(\Delta t))$$

$$a_i = \cos(\omega_f \times i \times (\Delta t))$$

$$b_i = \sin(\omega_f \times i \times (\Delta t))$$

where, Δt-ADC sampling period. We produce periodic signal decomposition of x (t) and x (t+Δt) in a Fourier series:

$$F(t) = \frac{\sum_{i=0}^{N-1}(m_i + w_i)\times 2}{N} = A_q \times e^{-j\varphi_q} = 1\times e^{|j\,1.57078|}$$

$$F(t+\Delta t) = \frac{\sum_{i=1}^{N}(m_{i+k} + w_{i+k})\times 2}{N} = A_{q+j} \times e^{-j\varphi_{q+j}} = 1\times e^{|j\,1.57075|}$$

where values:

$$N = \frac{T}{\Delta t} = \frac{0.02}{0.000555} = 36$$

$$m_i = x_i \times a_i,\ w_i = x_i \times b_i$$

$$m_{i+k} = x_{i+k} \times a_{i+k},\ w_{i+k} = x_{i+k} \times b_{i+k}$$

$$A_q = \sqrt{\left(\frac{2\times\sum_{i=0}^{N-1} m_i}{N}\right)^2 + \left(\frac{2\times\sum_{i=0}^{N-1} w_i}{N}\right)^2}$$

$$A_{q+j} = \sqrt{\left(\frac{2\times\sum_{i=1}^{N} m_{i+k}}{N}\right)^2 + \left(\frac{2\times\sum_{i=1}^{N} w_{i+k}}{N}\right)^2}$$

$$\varphi_q = \mathrm{arctg}\left(\frac{\frac{2\times\sum_{i=0}^{N-1} w_i}{N}}{\frac{2\times\sum_{i=0}^{N-1} m_i}{N}}\right),\ \varphi_{q+j} = \mathrm{arctg}\left(\frac{\frac{2\times\sum_{i=1}^{N} w_{i+k}}{N}}{\frac{2\times\sum_{i=1}^{N} m_{i+k}}{N}}\right)$$

Determining the frequency of the signal Fc:

$$F_c = \frac{\frac{d\varphi}{dt}}{2\pi} + F_\phi = \frac{1.57078 - 1.57075}{0.000555\times 2\times 3.14} + 50 = 49.999\ \text{Hz}$$

The absolute error:

$$\Delta F_5 = F - F_5 = 50 - 49.999 = 0.001\ \text{Hz}$$

All five methods showed high accuracy in determining the frequency of the signal without the effects of harmonics and noise in the next step to determine the accuracy of the algorithms with the presence of harmonics and noise in the signal for obtaining the resulting signal is added the main signal with the ith harmonic:

$$U = A1\sin(\omega t) + A2\sin(i\times\omega t)$$

and we determine the frequency and absolute error for each method as difference of the defined signal frequency (assumed value) and calculate signal frequency $\Delta F = F_c + F_{calculated}$, the results are summarized in Table 1.

In Table 1, F1-F5 frequency values which were calculated respectively for the first, second, third, fourth and fifth method, ΔF1-ΔF5 values of absolute errors, respectively of the first-fifth method.

The calculations revealed that with pure sinusoidal frequency F = 50 Hz, all the methods for determining the fundamental frequency gives an accurate result ±0.005 Hz.

It is also found that the first, fourth and fifth methods are the most accurate and insensitive to the influence of higher harmonics while the second and third ones have the most error and are unsuitable for calculating the frequency of fundamental harmonic when higher harmonics are contained in signal. The second and third methods are not suitable for the calculation of the frequency of fundamental harmonic in the presence of noise and harmonics. The fourth method of determining frequency of the magnetic field rotation can be used only

Table 2: Results of calculation of frequency and absolute errors

		The results of calculation of frequency and absolute errors (Hz)			
Factors	Amplitude	F_4	ΔF_4	F_5	ΔF_5
The second harmonic	0.1	49.08	-0.92	49.99	0.01
F = 100 Hz	0.2	49.97	-0.03	49.99	0.01
	0.3	46.63	3.37	49.99	0.01
The third harmonic	0.1	50.05	0.05	49.99	0.01
F = 150 Hz	0.2	50.05	0.05	49.99	0.01
	0.3	50.05	0.05	49.99	0.01
The fifth harmonic	0.1	48.47	-1.53	49.99	0.01
F = 250 Hz	0.2	46.08	-3.92	49.99	0.01
	0.3	54.64	4.64	49.99	0.01
Noise	±10%	49-51	-1-1	50.02	-0.02

for signals of one frequency. The first, fourth and fifth methods are less exposed to noise but for improving the accuracy of calculating the frequency are necessary to use signal filtering.

Basing on the research and the results of calculations, the most reliable and suitable for use in the technique of relay protection and automation, data of calculating the frequency of the fundamental harmonic controlled magnitude can be obtained while using the fifth method of determining the frequency through the phase change of the fundamental harmonic of controlled signal with the help of DFT during a time interval (Table 1 and 2).

CONCLUSION

Basing on studies and calculations we can see that in the modern microprocessor devices and systems including designed multi-channel centralized system of relay protection and automation, it is advisable to use more modern methods for determining the frequency. Methods based on numerical algorithms such as the method of determining frequency through change of the phase of fundamental harmonic of controlled signal by the FFT during the time interval, provide improved performance and accuracy of calculating the frequency in real time. In addition to these advantages, the method allows to determine directly the amplitude and phase of not only the fundamental harmonic but its multiples, higher harmonics. In addition to these advantages, the method allows to determine directly the amplitude and phase of not only the fundamental harmonic but also aliquot its, higher harmonic that is an important component for securing, using data on the higher harmonics. Through the use of window functions, it is possible to reduce the effect of noise and constant components. The above features will ensure the increasing of reliability and performance will reduce the probability of false alarm of relay protection systems and automation systems due to the reliability of the data.

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