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Operational Requirements for Primary Signal Transducers for New Generation of Relay Protection

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1 INTRODUCTION

New historic stage in power system automation and relay protection development is marked by wide involvement of digital technical facilities with practically inexhaustible processing power. At a time when construction of smart grids, digital substations and digital relay protection facilities of new generation are under way, the most topical problem is to provide digital facilities with adequate information concerning primary process under control. Therefore, study of relay protection signal characteristics should be the basic know-how for development of new primary signal transducers.

2 PRINCIPAL PART

Operating principles of most protection devices lay in response to currents and voltages (or their use to determine other parameters). Measurements and conversion of these primary input values into the form suitable for processing by digital devices should be carried out both in normal and emergency conditions. Moreover, new algorithm-based digital protection devices incorporated in protection systems should have non-distorted information on currents and voltages in the primary circuits of the objects under control. Since these signals are analog by nature, it is reasonable to consider requirements to primary signal transducers on the basis of analog approach.

The most intense changes in input signals lead to short-circuiting. As a rule, short circuit current contains DC component, fundamental AC component, a number of higher harmonic components and free oscillation components with frequency determined by the short circuit parameters.

In most cases, when used in respect to relay protection, it is acceptable to ignore some DC and free oscillation components and represent short-circuit current as the following sum:

$$i_K(t) = I_a e^{-\frac{t}{\tau}} + I_{(1)} \cos(\omega t - \psi_1) + \\ + I_{(2)} \cos(2\omega t - \psi_2) + I_{(3)} \cos(3\omega t - \psi_3) + \dots,$$

where I_a – principle short-circuit current DC component primary value начальное значение основной аperiodической составляющей тока КЗ; $\tau = \frac{L_K}{R_K}$ – short circuit time-constant; L_K and R_K – short

circuit inductance and resistance; $I_{(1)}$, $I_{(2)}$, $I_{(3)}$ – AC component short-circuit current amplitude of the first, second and third harmonic; ω – first harmonic AC current component angular frequency;

ψ_1, ψ_2, ψ_3 – angles characterizing respective current component phases at short-circuit inception.

Voltage in protection installation, as well as short circuit current, can contain DC components and a number of AC components and free oscillation components at different frequencies. Taking into account the above mentioned, it is possible to derive a generalized mathematic model of relay protection device input signal. The following mathematic expression can be used as a model:

$$x(t) = \sum_{l=1}^m X_{0l} e^{-\beta_{0l} t} + \sum_{k=1}^n X_{mk} \cos(\omega_k t - \psi_k),$$

where X_{0l}, β_{0l} – initial value and signal DC component attenuation factor under number l within 1 to m range; X_{mk}, ψ_k, ω_k – amplitude, initial phase and frequency of k -nth signal component. Moreover, in a general way frequency of separate signal DC components can not be multiple of the fundamental.

The following reasoning can help us derive concept of protection device input signal DC component initial level and AC component amplitude values.

In most cases protections control object currents from no-load maximum current (usually is taken to be equal to 0.1 of the rated current) up to maximum initial short-circuit current [1, 2]. Up-to-date generator external short-circuit current steady-state value usually exceeds rated current 6-7 times, and initial short-circuit current with DC component can be 10-15 times of the rated current. Possibility of iron core saturation [3] makes us take into account 150-200 times current increase in the protected circuits.

As a rule protection controls voltage within a more narrow range. Electric grids do not allow voltage increase 1.4 times of the rated voltage. In most cases minimum controlled voltage equals to 0.05 of the rated voltage. Thus voltage change dynamic range is 25 to 30. Note that some transients are accompanied by much heavier power surges equaling to 3-4 times of the rated voltage, but as a rule they are short and are controlled by special voltage transducers (transformer analogues).

In essence, there are two methods of describing signals. The first is based on mathematical signal representation in the form $y = x(t)$, where independent variable is t – time. This approach was used above. According to the second description signal mathematical representation has the form of $y = x(\omega)$, where independent variable is ω – frequency. These two forms of signal representation are linked with each other by Fourier transformation [4, 5].

When solving practical tasks, usually time function $x(t)$ is only determined at $t > 0$. At $t < 0$ time function is taken equal to $x(t) = 0$. In this case signal spectrum can be found using one-side Fourier transformation:

$$X(j\omega) = \int_0^{\infty} x(t) e^{-j\omega t} dt.$$

Using Fourier transformation it is possible to determine some commonly used signal spectrums. [1, 4].

Let there be given exponential waveform:

$$x(t) = \begin{cases} e^{-\beta t} & \text{npu } t \geq 0; \\ 0 & \text{npu } t < 0, \end{cases}$$

where β – attenuation factor.

Then:

$$X(j\omega) = \int_0^{\infty} e^{-\beta t} \cdot e^{-j\omega t} dt = \frac{1}{\beta + j\omega}.$$

The function modulus and argument give us amplitude spectrum and phase spectrum of the signal, respectively (Fig.1):

$$S(\omega) = |X(j\omega)| = \frac{1}{\sqrt{\beta^2 + \omega^2}};$$

$$\theta(\omega) = -\arctg \frac{\omega}{\beta}.$$

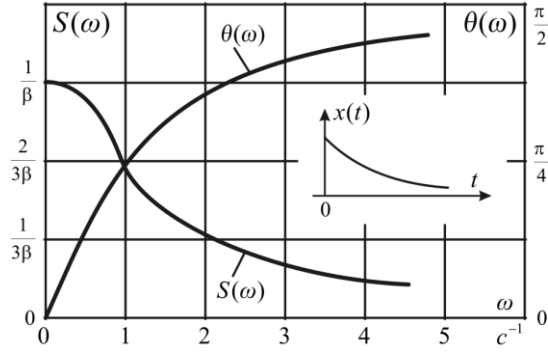


Fig. 1: Exponential-form signal spectrums

As we can see, amplitude spectrum has a form of decreasing function with zero frequency maximum value. It means that major part of the signal power carrying process information is contained in the frequency range near zero frequency.

Time range rectangular impulse:

$$x(t) = \begin{cases} 1 & \text{npu } 0 < t < t_1; \\ 0 & \text{npu } t > 0 \text{ u } t > t_1. \end{cases}$$

In the frequency range we shall have:

$$X(j\omega) = \int_0^{t_1} e^{-j\omega t} dt = \frac{1}{j\omega} (1 - e^{-j\omega t_1}) = \left[\frac{2}{\omega} \sin \frac{\omega t_1}{2} \right] e^{-j \frac{\omega t_1}{2}}.$$

Amplitude spectrum is equal to:

$$S(\omega) = \left| \frac{2}{\omega} \sin \frac{\omega t_1}{2} \right|.$$

Phase spectrum is determined in the following way:

$$\theta(\omega) = \frac{\omega t_1}{2} \text{ at } 0 < \omega < \frac{2\pi}{t_1};$$

$$\theta(\omega) = \frac{\omega t_1}{2} - \pi \text{ at } \frac{2\pi}{t_1} < \omega < \frac{4\pi}{t_1} \text{ и т.д.}$$

Fig. 2 shows finite-duration rectangular pulse spectrum.

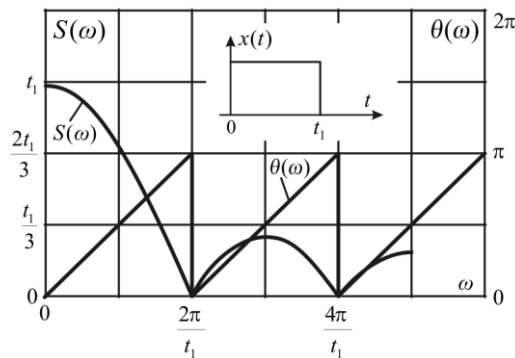


Fig. 2: Rectangular signal spectrums

With pulse duration increase its amplitude spectrum is being grouped within a more narrow range near zero frequency and its value increases tending to infinity.

Within limits of $t \rightarrow 0$ rectangular finite duration pulse turns into unit pulse function. In this case the spectrum is:

$$X(j\omega) = \lim_{t \rightarrow 0} \frac{\sin \frac{\omega t_1}{2}}{\frac{\omega t_1}{2}} e^{j\frac{\omega t_1}{2}} = 1.$$

This means that unit pulse function has continuous spectrum expressed by constant value, and that is why extends to infinity along the whole frequency range without attenuation.

However according to protection operating conditions the real process in the controlled circuit is observed over a definite period of time from the signal inception up to the current moment τ . In this case signal spectrum is calculated in the following way:

$$X(j\omega) = \int_0^{\tau} x(t) e^{-j\omega t} dt.$$

Practical interest is aroused by signal spectrum calculation represented as a sum of a number of components. Taking into account the Fourier transformation linearity, the spectrum of this signal can be determined as a sum of its separate components. Therefore according to the approach stated, it is possible to determine spectrum segments of exponential and cosine functions and then – complex spectrum.

Exponential form signal

$$x(t) = \begin{cases} e^{-\beta t} n p u & 0 \leq t \leq \tau; \\ 0 & n p u \quad t < 0 \text{ or } t > \tau. \end{cases}$$

has continuous spectrum:

$$X(j\omega) = \frac{1 - e^{(\beta + j\omega)\tau}}{\beta + j\omega} = G + jQ.$$

For amplitude and phase spectrum we have:

$$S(\omega) = \sqrt{G^2 + Q^2}; \quad \Theta(\omega) = \arctg \frac{Q}{G},$$

where

$$G = \frac{\beta(1 - e^{-\beta\tau} \cos \omega\tau) + \beta e^{-\beta\tau} \sin \omega\tau}{\beta^2 + \omega^2};$$

$$Q = \frac{\omega(1 - e^{-\beta\tau} \cos \omega\tau) - \omega e^{-\beta\tau} \sin \omega\tau}{\beta^2 + \omega^2}.$$

For the most probable β values ($5c^{-1} < \beta < 50c^{-1}$) amplitude spectrum is practically not changed as observation time changes (usually $\tau > 0.01$ s) and mostly is determined by attenuation factor β .

It is possible to determine signal spectrum in the form of cosine function segment with amplitude equal to 1:

$$x(t) = \begin{cases} \cos \Omega t \quad n p u & 0 \leq t \leq \tau; \\ 0 & n p u \quad t < 0 \text{ or } t > \tau, \end{cases}$$

where Ω – signal frequency.

Observing the signal for an integer number of oscillation periods, we shall have the following spectrum:

$$X(j\omega) = \frac{j\omega}{\Omega^2 - \omega^2} \left(1 - e^{-\frac{j\omega}{\Omega} 2\pi n} \right),$$

where n – cosine curve period integer observed for τ time.

This signal amplitude spectrum equals to:

$$S(\omega) = \left| \frac{\omega}{\Omega^2 - \omega^2} 2 \sin\left(\frac{\omega}{\Omega} \pi n\right) \right|.$$

Signal amplitude spectrum having cosine function segment form essentially depends on the observation time and along its increase n is grouping into more narrow frequency range near Ω .

Transmission and conversion of information signals is connected with transmission and conversion of power. Therefore for quantitative evaluation of signal parameters it is possible to establish frequency range containing major part of signal energy.

According to Rayleigh's theorem [4], definite energy density proportional to $|S(\omega)|$ is characteristic of each segment of signal amplitude spectrum. Therefore function type $|S(\omega)|$ allows us to judge approximately by its distribution within frequency range, not precisely calculating signal energy. Thus, the bulk of signal energy near-real by form is concentrated within 0 to 500Hz frequency range (Fig.3).

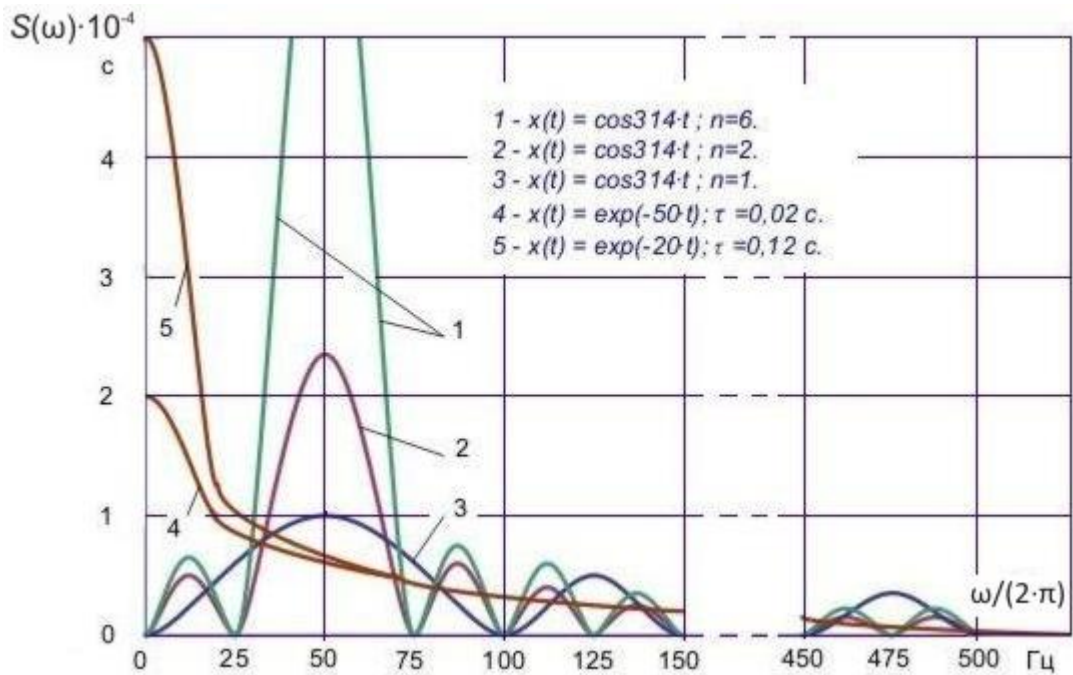


Fig. 3: Different form signal spectra

However it is worth mentioning that as signal observation time decreases (which corresponds to the protection operation time decrease), its amplitude spectrum expands and becomes more uniform. Therefore more high-speed protections, that undoubtedly will be developed in future, will require primary signal transducers having wider operating frequency range and providing non-distorting signal transmission.

All this should be taken into account at working out requirements to information converters for the relay protection systems. For example, transmission and conversion of signals in high-speed protections will be carried out with minimal loss of information provided that these incorporate elements with operating frequency range of 0 to 500Hz. As to time-delayed protections responsive only to AC component, it is possible to use information converters with more narrow operating frequency range.

It is possible to give demonstrative examples concerning relay protection signal transmission through conventional electromagnetic current transformers (CT) with linear properties and different frequency characteristics. [6].

Mathematic and physical modeling of a separate CT permitted to establish that their transformation properties under linear mode of operation in relay protection systems can be accurately pictured by transmission function [1,7]:

$$H_{TT}(p) = \frac{I_2(p)}{I_1'(p)} = \frac{bp}{a_2 p^2 + a_1 p + a_0},$$

where $I_2(p)$ и $I_1'(p)$ – Laplace representation of secondary current and primary current reduced to the secondary circuit; $a_0 - a_2$, b – constant ratios determined by winding and CT core parameters.

According to CT L-equivalent circuit (Fig.4): $a_0 = R_{II}R_2$; $a_1 = R_{II}(L + L_2) + LR_2$; $a_2 = LL_2$; $b = R_{II}L$; $R_2 = r_2 + R_H$; $L_2 = L_{d2} + L_H$; L и R_{II} – CT loss resistance and magnetizing inductance reduced to the second winding; L_{d2} и r_2 – CT secondary winding leakage inductance and resistance; L_H и R_H – CT load inductance and resistance.

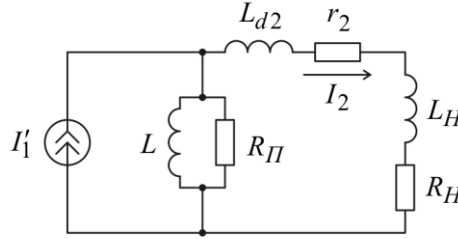


Fig. 4: CT equivalent circuit

Assume that sine signal $x(t)$ is applied onto CT input within 0 to τ time range:

$$x(t) = \begin{cases} \sin \omega_0 t & \text{at } 0 \leq t \leq \tau; \\ 0 & \text{at } t < 0, t > \tau. \end{cases}$$

Sine signal segment transmission through CT within time range leads to Abel's differential equation having awkward analytical solution and is difficult to be used for further analysis. [8]. That is why in order to simplify analytical process and obtain illustrative dependencies the input signal can be represented as a difference between two signals (Fig. 5):

$$x(t) = x_1(t) - x_2(t).$$

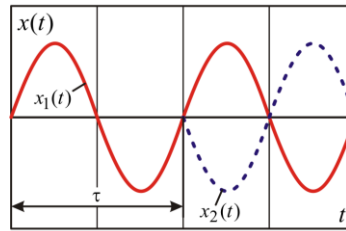


Fig. 5: CT signal representation

Here:

$$x_1(t) = \begin{cases} \sin \omega_0 t & \text{at } t \geq 0; \\ 0 & \text{at } t < 0. \end{cases}$$

$$x_2(t) = \begin{cases} (-1)^n \sin \omega_0 (t - \tau) & \text{at } t - \tau \geq 0; \\ 0 & \text{at } t - \tau < 0, \end{cases}$$

where $\tau = \pi \cdot n / \omega_0$; n – integer number of half-cycles; ω_0 – input signal angular frequency.

CT response to the input signal $x(t)$ is a difference between two signals:

$$y(t) = y_1(t) - y_2(t),$$

where $y_1(t)$ – CT response to $x_1(t)$ signal; $y_2(t)$ – CT response to $x_2(t)$ signal.

If $x_1(t)$ signal is applied on CT input, output signal Laplace image can be determined in the following way:

$$y_1(p) = x_1(p) \cdot H_{TT}(p).$$

Here $x_1(p) = \frac{\omega_0}{p^2 + \omega_0^2}$ – $x_1(t)$ output signal Laplace representation.

Response of $y_2(\delta)$ is determined similar to $y_1(t)$.

Since accuracy of CT output signal instantaneous values is very important, CT signal conversion quality should be characterized by absolute error of conversion of instantaneous signal values, i.e. by difference [10]:

$$\varepsilon(t) = K_{TT}x(t) - y(t),$$

where K_{TT} – CT ideal transmission factor; $x(t)$ и $y(t)$ – CT input and output signals respectively.

For convenience assume $K_{TT} = 1$.

Relationship between CT error and its parameters can be determined by using CT frequency characteristic limit parameters [1,7]:

$$f_H = \frac{A_H}{\sqrt{1-A_H^2}} \frac{R_2}{2\pi L} = \frac{A_H}{\sqrt{1-A_H^2}} \frac{1}{2\pi\tau_{TT}} \quad \text{or} \quad f_H = \frac{1}{2\pi\tau_{TT}\operatorname{tg}\varphi_H}.$$

Here: f_H – CT limit frequency; A_H and φ_H – gain curve admissible relative level and admissible phase shift at CT bandwidth lower limit; τ_{TT} – CT time constant.

Taking into account CT real ratio it is possible to take:

$$\tau_{TT} = \frac{L}{R_2} = T_1.$$

Taking into account the assumption: $T_1 = \frac{L}{R_2}$ and that $T_2 \ll T_0$, we obtain:

$$K_1 = \frac{T_1}{\sqrt{T_0^2 + T_1^2}};$$

$$\lim_{T_1 \rightarrow \infty} K_1 = \lim_{T_1 \rightarrow \infty} \frac{T_1}{\sqrt{T_0^2 + T_1^2}} = 1.$$

$$\theta = -\operatorname{arctg} \frac{T_1}{T_0} - \operatorname{arctg} \frac{T_2}{T_0} - 90^\circ.$$

It can be assumed that $\frac{T_2}{T_0} = 0$, then:

$$\lim_{T_1 \rightarrow \infty} \theta = \lim_{T_1 \rightarrow \infty} \left(-\operatorname{arctg} \frac{T_1}{T_0} \right) - \frac{\pi}{2} = -\pi.$$

Therefore, T_1 increase leads to CT periodic error component ε_1 decrease:

$$\lim_{T_1 \rightarrow \infty} \varepsilon_1 = 0.$$

Thus we can state that CT service band expansion into low frequency range also leads to CT error AC component decrease.

Taking into account earlier assumptions for DC component error, we obtain:

$$\varepsilon_2 = \frac{T_0 T_1}{T_0^2 + T_1^2} e^{-\alpha_1 t} - \frac{T_2}{T_0} e^{-\alpha_2 t}.$$

In case of real CT parameters, $\alpha_2 \gg \alpha_1$. Thus the second exponential attenuates much faster, and error ε_2 in a few microseconds after process inception is determined mainly by exponential:

$$K_2 e^{-\alpha_2 t}, \text{ где } K_2 = \frac{T_1 T_0}{T_1^2 + T_0^2}; \lim_{T_1 \rightarrow \infty} K_2 = \lim_{T_1 \rightarrow \infty} \frac{T_0}{2T_1} = \lim_{T_1 \rightarrow \infty} \frac{0}{2} = 0.$$

As we can see, T_1 increase (equivalent to CT lower frequency limit decrease) leads to decrease of the initial value of the first exponential component error. The second exponential component error nature is determined mainly by T_2 and practically does not depend on T_1 .

If the input signal disappears at $t \geq \tau$, CT output signal does not disappear instantaneously. It leads to origination of conversion error even at $t > \tau$:

$$\varepsilon_\tau = -T_0 b_1 C_1 e^{-\alpha_1 t} - T_0 b_1 C_1 e^{-\alpha_1 \delta} + T_0 b_1 C_2 e^{-\alpha_2 \delta}.$$

Dependence of ε_τ upon T_1 is similar to dependence of ε_2 upon T_1 , i.e. the higher T_1 , the lower initial exponential value.

Fig.6 shows dependence of CT signal conversion error in the form of sine function segment with $\omega_0 = 314 \text{ c}^{-1}$ frequency and 2 half-cycles duration on f_H frequency lower limit and running time in the form of 3D diagram.

Similar approach allows obtaining another relay protection characteristic signal in the form of exponential function segment through transducer with transmission function under consideration. Fig. 7 shows general view of $y(t)$ transducer output signal, when $x(t)$ rectangular waveform, that can be treated as a limiting particular case for exponential form signal, is applied to the input.

Transducer upper frequency limit determines the degree of the signal distortion for initial and finite intervals. The higher converter upper frequency, the nearer $y(t)$ output signal form to $x(t)$ input signal form at these intervals.

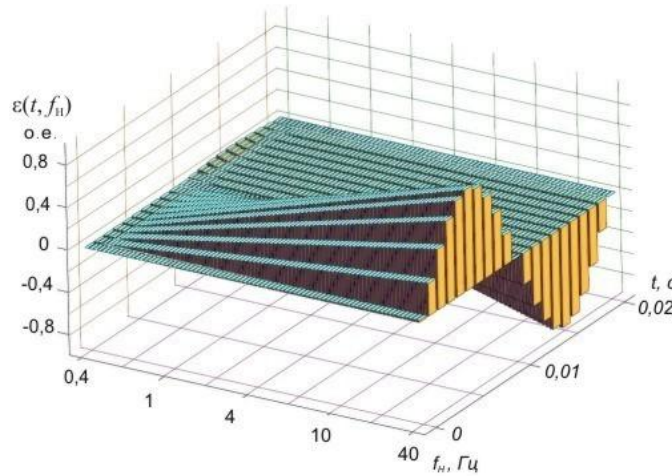


Fig. 6

Signal level distortion degree along the whole interval is determined by transducer lower frequency limit. The nearer this value to zero, the more accurate signal level is transmitted. Ideally at zero lower frequency limit level rectangular waveform level and exponential form signal is transmitted without distortion.

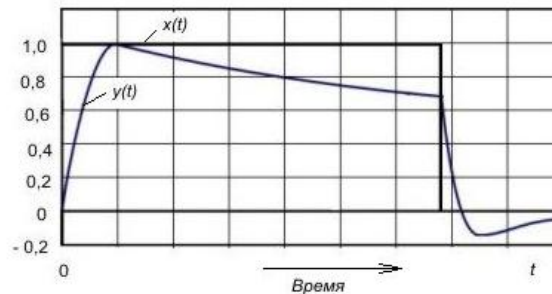


Fig. 7

Adequacy of mathematical model of the process under study is proved by CT physical model study results.

Patterns of transients obtained during physical modeling of signal transmission in the form of sine function segments through CTs with different lower frequency boundaries are shown in Fig.8. Here $x(t)$ and $y(t)$ – CT primary and secondary currents respectively.

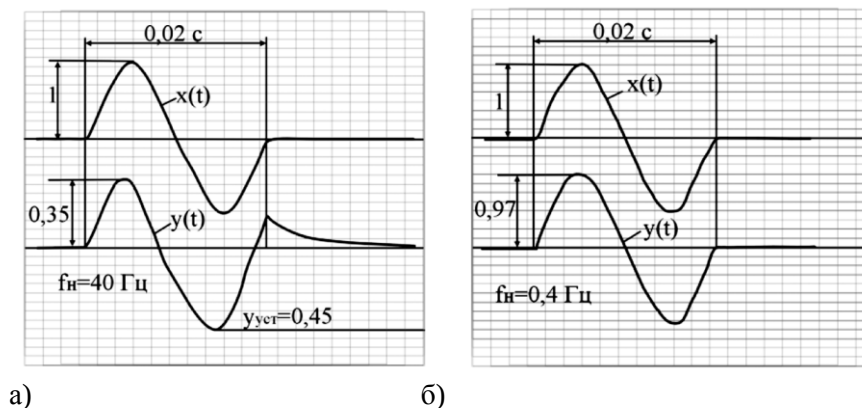


Fig. 8: Oscillograms of transients: a). $f_H=40$ Hz; б). $f_H=0,4$ Hz

As we can see (Fig.8a), CT output signal $y(t)$ with 40Hz lower frequency limit is essentially different in relevant amplitude and phase values from $x(t)$ output signal. Moreover, we can see that CT output signal at $t > \tau$ differs from zero, as it was mentioned earlier.

CT with $f_H=0.4$ Hz converts input signal more accurately (Fig.8, б). Its error does not exceed 5%.

Comparative analysis of physical and mathematic modeling results permitted to state that mathematic model of signal and primary signal transducers are adequate to the processes under study, and theoretical assumptions are valid.

3 CONCLUSIONS

1. Relay protection of new generation require primary current and voltage transducers providing non-distorted transmission of relay protection signal. In this case dynamic range of relay protection primary current distortionless conversion should be at least 200. For primary voltage transducers this range should be at least 30.
2. According to approximate estimates, relay protection system based on new concepts requires primary current and voltage transducers with 0 to 500 Hz operating frequency range. Moreover, maximum permissible conversion error (distortion) at frequency range limits and permissible degree for signal distortion should be established by detailed scientific study.
3. Impact of primary current transducer frequency characteristics on accuracy of conventional electromagnetic CTs has been studied. It is established that the errors are related with primary current transducer parameters by exponential functions decreasing with lower frequency limit. It has been demonstrated that primary transducer bandwidth reduction leads to output signal distortion in transients at characteristic relay protection signal transmission in the most vital situations.

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