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An IEC Standard Digital Output Current Sensor

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Abstract—The article considers an International Electrotechnical Commission (IEC) standard digital output current sensor with improved current conversion characteristics and expanded functionality. The results of the study of primary electromagnetic current converters used in the current sensor are presented. It is proposed to combine the functions of converting signals into the digital format of the IEC 61850 standard and the functions of current relay protection in the current sensor. The features of the newly developed sensors are shown, allowing for a significant improvement in the main characteristics of relay protection.

Keywords: relay protection, digital current sensor, analog-to-digital converter, electromagnetic current converter, multiplexer

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Relay protection (RP) in electric distribution networks is traditionally based on current principles. When implementing relay protection in a digital environment, it is necessary to convert analog current into a digital code according to the International Electrotechnical Commission (IEC) standard. The task of converting current into code affects many factors and requires taking into account many conditions that are diverse in their physical nature. The primary analog current in the power circuits of electric networks reflects a complex, nonstationary electromagnetic or electromechanical process in the electric network, and so the primary current converter operates under difficult conditions. In addition, the input value of the current converter is at a high potential (6–20 kV), and so it is necessary to ensure galvanic isolation of the input and output circuits of the current sensor primary converter with appropriate electrical insulation.

The existing nonlinearities of the primary current converter and the digital part of the current sensor lead to signal distortions. Therefore, it is important to ensure the minimum possible distortion of the signal introduced by the primary current converter and the digital part of the current sensor, especially with rapidly changing signals. Effective protection against external interference and noise that can penetrate into the signal measurement path and ensuring the stability of the characteristics of the current sensor elements under operating conditions are important factors in the design of digital current sensors, so the task of creating digital output current sensors is relevant.

The purpose of the article is to develop the principles of constructing digital output current sensors according to the IEC standard, which are necessary for creating modern digital relay protection and automation (RPA) systems.

FUNCTIONAL DIAGRAM OF THE CURRENT SENSOR

A generalized current sensor functional diagram (Fig. 1) consists of functional units of primary conversion, input conversion, ADC and multiplexing with synchronization.

The primary converter performs the function of current-to-current conversion with a constant transfer coefficient and implements analog conversion of the primary measured current into a proportional secondary current. The input converter of the current sensor converts the output current of the primary converter into voltage with a constant transfer factor. Then, the analog output signal of the input converter is converted into a digital code using the ADC, which is fed to the input of the multiplexer via a communication channel. The multiplexer, which is a microprocessor computing device, converts the input digital code into a signal that meets the requirements of IEC 61850. The standard assumes that the signal is linked to a single time system in order to synchronize devices operating in a digital RPA network. Reference time marks in the output signal of the current sensor are formed in a special synchronization unit, which is connected permanently or at certain time lags with sources of uniform

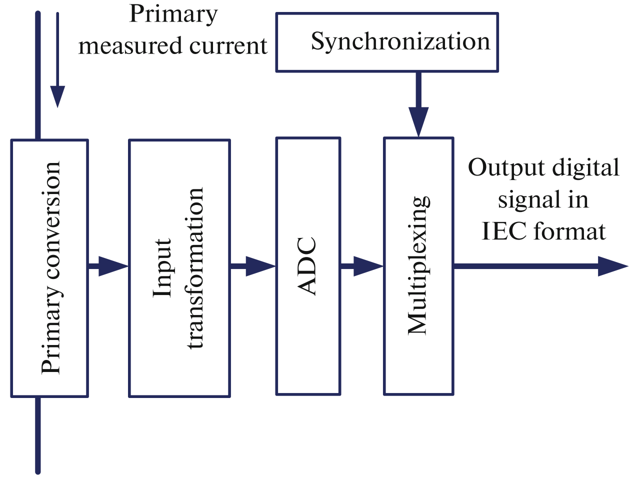

Fig. 1. Functional diagram of the current sensor.

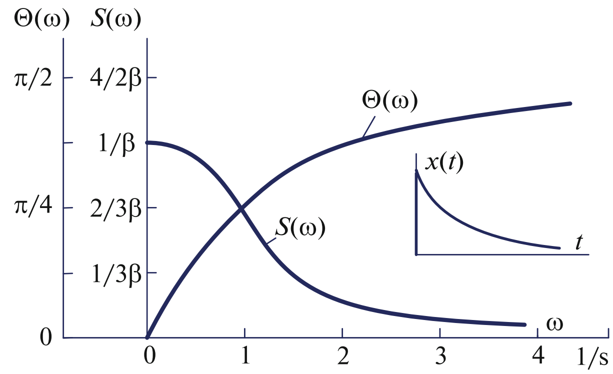

Fig. 2. Spectra of the signal amplitudes and phases in the form of an exponential curve.

time signals from GLONASS or GPS satellite systems in order to correct the passage of time in the local digital network of the substation. It should be noted that the signal encoding according to the IEC 61850 protocol requires significant computing resources. Hardware elements that perform these operations consume a significant amount of electricity, and so they are powered from the operational substation circuits.

INDIVIDUAL SPECTRA OF THE RELAY PROTECTION INPUT SIGNALS

The current in a short circuit observed by relay protection, as a rule, contains aperiodic components, a periodic component of industrial frequency, and a number of components of higher harmonics and free oscillatory components, the frequency of which is determined by the parameters of the short circuit.

In practice, the short-circuit current is represented as the following sum [1]:

$$i_K(t) = I_0 e^{-t/\tau} + I_{A1}\cos(\omega t - \psi_{A1})$$
$$+ I_{A2}\cos(2\omega t - \psi_{A2}) + I_{A3}\cos(3\omega t - \psi_{A3}) + \ldots,$$

where I_0 is the initial value of the main aperiodic component of the short-circuit current; $\tau = L_K/R_K$ is the time constant of the short-circuit circuit; L_K and R_K are the inductance and active resistance of the short-circuit circuit; I_{A1}, I_{A2}, and I_{A3} are the amplitudes of the periodic components of the short-circuit current of the first, second, and third harmonics; ω is the angular frequency of the periodic component of the first harmonic current; and ψ_{A1}, ψ_{A2}, and ψ_{A3} are the angles characterizing the phases of the corresponding current components at the moment of the short circuit.

To study the information content of the RPA input signals, they are represented in the frequency domain as a spectrum determined by the direct Fourier transform. Greatest interest is presented the spectra of aperiodic and harmonic signals.

Let there be a signal in the form of an exponential curve:

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

In the frequency domain, this signal can be represented as

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

The modulus and argument of this function, respectively, are the amplitude and phase spectra of the exponential signal (Fig. 2):

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

The amplitude spectrum has the form of a decreasing function, the maximum value of which corresponds to the zero frequency. This means that most of this signal energy carrying information about the process is concentrated in the frequency range near the zero frequency.

For quantitative assessments, the term “active spectrum band” of a signal is used—this is the frequency range in which the overwhelming share of the signal power is concentrated [2]. Consequently, the overwhelming part of the informative signal properties, which are necessary for adequate actions of the relay protection, is concentrated in this spectrum band.

According to the operating conditions of the relay protection, monitoring of the real process in the controlled circuit is carried out over a certain period of time from the moment the signal appears to current moment δ. In this case, the spectrum of the input signal of the relay protection is

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

Practical interest is presented by the evaluation of the signal spectrum containing the sum of several components. Taking into account the linearity of the Fourier transform, this signal spectrum can be defined as the sum of the spectra of its individual components: segments of the exponential and cosine functions, the sum of which represents the combined spectrum:

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

The amplitude and phase spectrum can be represented as

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

where

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

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

At the most typical values of β for electrical systems ($10\ \mathrm{s}^{-1} < \beta < 200\ \mathrm{s}^{-1}$), the amplitude spectrum remains almost unchanged with a change in the observation time (usually $\beta > 0.01$ s) and is determined mainly by attenuation coefficient β.

Another signal, which is most typical for relay protection, in the form of a cosine segment is

$$x(t) = \begin{cases} \cos\Omega t \text{ at } 0 \le t \le \delta, \\ 0 \text{ at } t < 0 \text{ and } t > \delta. \end{cases}$$

where Ω is the signal frequency.

The spectrum when observing this signal for an integer number of oscillation periods is

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

where n is an integer of cosine periods observed during time δ.

The amplitude spectrum of the signal in the form of a cosine segment is

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

Uncertainty of the 0/0 type, which occurs in the amplitude spectrum when $\omega = \Omega$, is revealed by L'Hôpital's rule:

$$S(\omega) = \frac{\pi n}{\Omega}.$$

It should be noted that the active signal band in the form of a cosine segment depends significantly on the observation time and thatm as number of observed periods n increases, it is grouped in an increasingly narrow frequency range near signal frequency Ω.

The signal, being a physical carrier of information for relay protection, transfers information from the input to the output of the signal converter in the form of energy. Thus, the transmission and conversion of information signals are associated with the transmission and energy transformation; therefore, for quantitative assessment of signal parameters, it is possible to establish the frequency range in which the main part of the signal energy is concentrated. The signal energy density in the frequency domain, in accordance with Parseval's equality, is proportional to the square of the modulus of the signal amplitude spectrum $|S(\omega)|^2$. Consequently, based on the type of the signal amplitude spectrum $|S(\omega)|$, without strictly calculating the signal energy, it is possible to approximately assess its distribution in the frequency domain. The overwhelming majority of the signal energy that are closest in form to real ones (exponential and harmonic with a duration of 10 to 60 ms at a fundamental frequency of 50 Hz) is concentrated in the frequency range from 0 to 2000 Hz (Fig. 3a). Figure 3b shows a 3D image of the spectrum with a change in the signal observation time, which clearly illustrates the expansion of the signal frequency band as the observation time decreases. It follows from Fig. 3 that, with a sufficiently long signal observation, its spectrum is concentrated near the fundamental frequency (for example, with an observation time of more than three periods of the fundamental frequency of the signal). With short-term observation (for example, within one period of the fundamental signal frequency), its spectrum expands. It is important to note that there is a significant expansion of the active signal band towards lower frequencies.

Thus, to represent the input signals of the relay protection in the frequency domain, it is necessary to use a frequency range of approximately from 0 to 2000 Hz.

However, it should be noted that, with a decrease in the signal observation time, which corresponds to an increase in the response speed of the protection, its amplitude spectrum expands and becomes more uniform. Therefore, the higher the response speed of the protection, the wider the operating frequency range of the signal converters should be.

MATHEMATICAL MODEL OF THE PRIMARY CURRENT CONVERTER

An important condition for nondistorting signal transmission in relation to the frequency domain is formulated simply and clearly. In order for the converter not to distort the signal shape, its amplitude-frequency characteristic must be uniform (in other words, the transfer coefficient must be constant), and

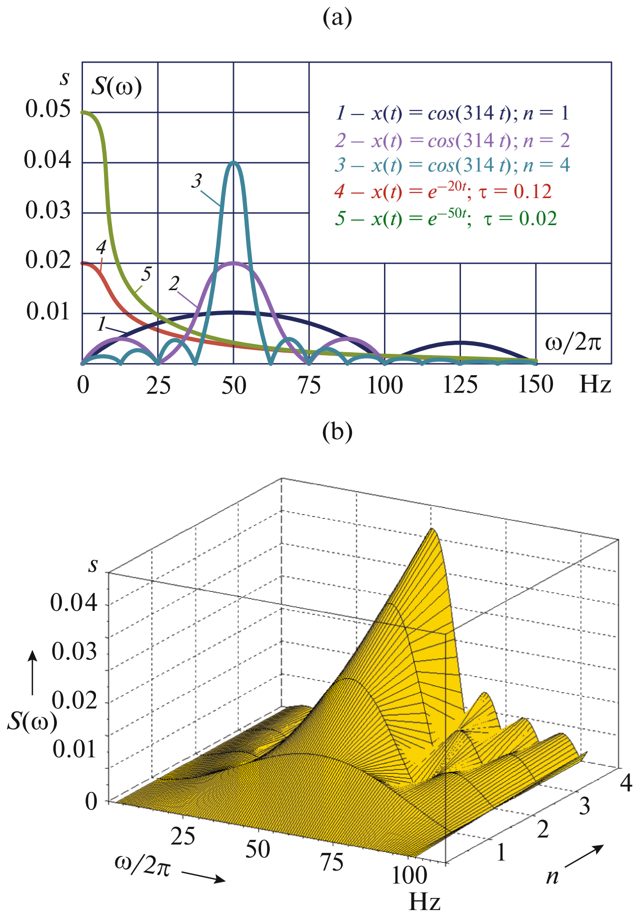

Fig. 3. (a) Function $|S(\omega)|$ for different observation time and decay time constants and (b) a 3D image of the spectrum variation with a change in observation time.

the phase-frequency characteristic must be linear (in other words, the phase shift must be related to the frequency by a linear dependence) in the active signal frequency band. Strict fulfillment of this requirement is possible only in ideal circuits with resistive parameters. In real converters and circuits with reactive elements, nondistorting signal transmission can be ensured only in a limited frequency range. The bandwidth (or frequency range within which the amplitude–frequency characteristic of the converter is sufficiently uniform to ensure the signal transmission without significant distortion of its shape) should cover the overwhelming majority of the active frequency band of the transmitted signal. The phase-frequency characteristic of the converter in this frequency band should be such that it can be considered linear. Thus, to transmit information about processes in primary electrical circuits to the input of the relay protection with minimal losses, it is necessary to have signal converters with a frequency band from 0 to 2000 Hz.

An electromagnetic primary converter (EC) in the linear mode of operation in the frequency range of relay protection signals can be represented by an equivalent circuit with lumped parameters reduced to the secondary winding (Fig. 4) [3].

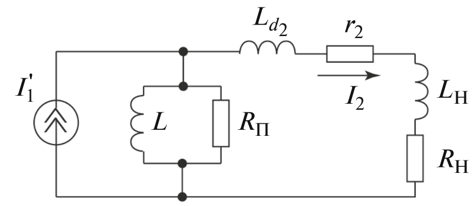

Fig. 4. Equivalent circuit of the EP: L and R_Π are the magnetization inductance and equivalent resistance of losses in the core; r_2 and L_{d_2} are the active resistance and leakage inductance of the secondary winding; R_H and L_H are the active resistance and inductance of the load.

In linear operating modes, when used in relay protection systems, EPs are quite accurately displayed by the transfer function [3]:

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

where $I_2(p)$ and $I_1'(p)$ are the Laplace representations of the secondary I_2 and the primary $I_1'(p)$ current reduced to the secondary circuit and a_0, a_1, a_2, and b are the constant coefficients determined by the parameters of the windings and the EP core.

In accordance with the L-shaped EP equivalent circuit (Fig. 4), $a = R_{Loss}R_2$, $a_1 = R_{Loss}(L + L_2) + LR_2$, $a_2 = LL_2$, and $b = R_{Loss}L$.

The modulus and argument of the complex transmission coefficient (Fig. 5) are

$$A_{EC}(\omega) = |H_{EC}(j\omega)| = \frac{1}{\sqrt{\left(1 + \frac{L_2}{L} + \frac{R_2}{R_{Loss}}\right)^2 - \sqrt{\left(\frac{R_2}{\omega L} - \frac{\omega L_2}{R_{Loss}}\right)^2}}};$$

$$\varphi_{EC}(\omega) = \frac{Im|H_{EC}(j\omega)|}{Re|H_{EC}(j\omega)|} = \arctan\frac{\frac{R_2}{\omega L} - \frac{\omega L_2}{R_{Loss}}}{1 + \frac{L_2}{L} + \frac{R_2}{R_{Loss}}}.$$

Having the amplitude and phase frequency characteristics, we can identify a frequency band in which the EP provides signal transmission with acceptable distortions. In the mid-frequency region, the EP phase-frequency characteristic crosses the zero line and the amplitude–frequency characteristic reaches a maximum at a frequency of ω_0:

$$\omega_0 = \sqrt{\frac{R_2 R_{Loss}}{L_2 L}}.$$

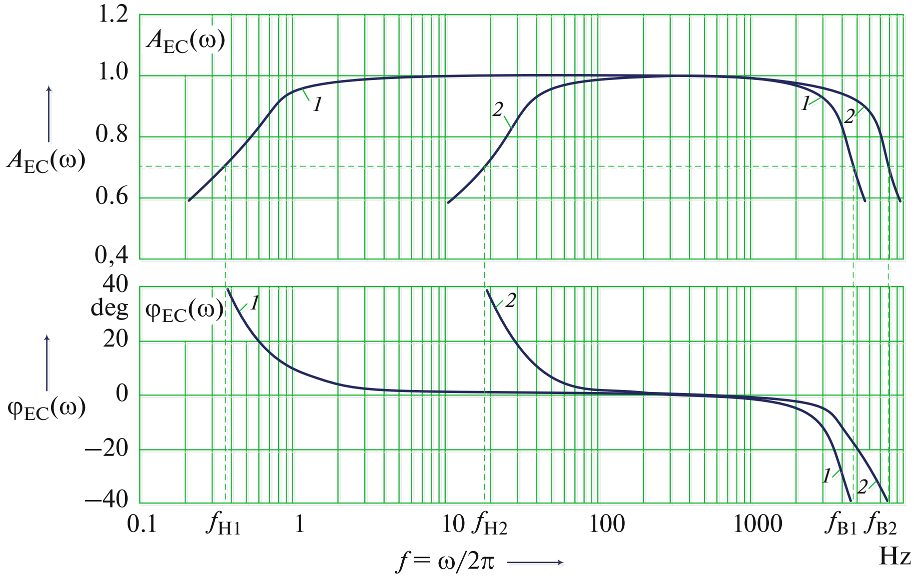

Fig. 5. EC frequency characteristics.

With a traditional EP design based on a annular (toroidal) core with a secondary winding uniformly placed on it, the following parameter ratios are observed: $L_2/L \ll 1$ and $R_2/R_{\text{Loss}} \ll 1$, and it can be assumed that $L_2/L = R_2/R_{\text{Loss}} = 0$. In the low-frequency region, $\omega L_2/R_{\text{Loss}} \ll R_2/\omega L$ and it can be assumed that $\omega L_2/R_{\text{Loss}} = 0$.

Taking into account the accepted assumptions and limitations for the lower cutoff frequency, a simple and clear expression can be written:

$$f_{\text{Low}} = \frac{R_2}{2\pi L \tan\varphi_{\text{Low}}}.$$

In the high-frequency region $R_2/\omega L \ll \omega L_2/R_{\text{Loss}}$; therefore, we can assume that $R_2/\omega L = 0$ and write for the upper cutoff frequency

$$f_{\text{High}} = \frac{\tan\varphi_{\text{Loss}} R_{\text{Low}}}{2\pi L_2},$$

where φ_{Low} and φ_{HIgh} are the permissible phase shifts at low and high frequencies.

For given permissible levels of amplitude–frequency characteristic roll-off at the boundaries of the EP bandwidth, the cutoff frequencies at low A_{L} and high A_{H} frequencies are

$$f_{\text{Low}} = \frac{A_{\text{Low}}}{\sqrt{1 - A_{\text{Low}}^2}} \frac{R_2}{2\pi L}; \quad f_{\text{High}} = \frac{\sqrt{1 - A_{\text{High}}^2}}{A_{\text{High}}} \frac{R_{\text{Loss}}}{2\pi L_2}.$$

Numerical examples of calculations at $A_{\text{L}} = A_{\text{H}} = 0.7$ show (Fig. 5) that EDs constructed on the basis of nanocrystalline cores have a wide operating frequency range from 0.2 Hz to 4.5 kHz (curves *1*, Fig. 5), and EDs based on a nonmagnetic gap core—from 18 Hz to 7 kHz (curves *2*, Fig. 5). Converters of the first type, having a lower cutoff frequency, ensure more accurate transmission of relay protection signals.

ANALYSIS OF EC DISTORTIONS

For an ideal EC, in accordance with the equivalent circuit (Fig. 4) and the transfer function, transfer coefficient $A_{\text{EC}}(\omega)$ must be equal to 1. Thus, the terms of the formula for $A_{\text{EC}}(\omega)$ following 1 in the denominator characterize the EC errors. As can be seen, the errors depend on the ratios of parameters L_2/L, R_2/R_{Loss}, R_2/L, and L_2/R_{Loss}.

The smaller the ratios L_2/L and R_2/R_{Loss}, the smaller the frequency-independent component of the errors. When negligibly small ($L_2/L = 0$ and $R_2/R_{\text{Loss}} = 0$), this component of the errors is practically absent. In particular, at $R_2 = 0$ (in the EC short-circuit mode) and L tending to infinity, it is minimal. In other words, the lower the resistance of the secondary circuit of the EC ($L_2 - R_2$) and the lower the current in the $L - R_{\text{Loss}}$ branch, the lower the errors in the conversion of the measured current.

The frequency-related component of errors is determined by the ratios of the parameters R_2/L and L_2/R_{Loss}. The smaller R_2 and the larger L, the lower the EC lower limit frequency. It is the expansion of the EC bandwidth into the low-frequency region that is important for ensuring nondistorting transmission of relay protection signals, since the energy (information content) of these signals is concentrated in the low-frequency region [4]. The smaller L_2 and the larger R_{Loss}, the higher the EC upper limit frequency. The parameters of real ECs are usually such that the upper

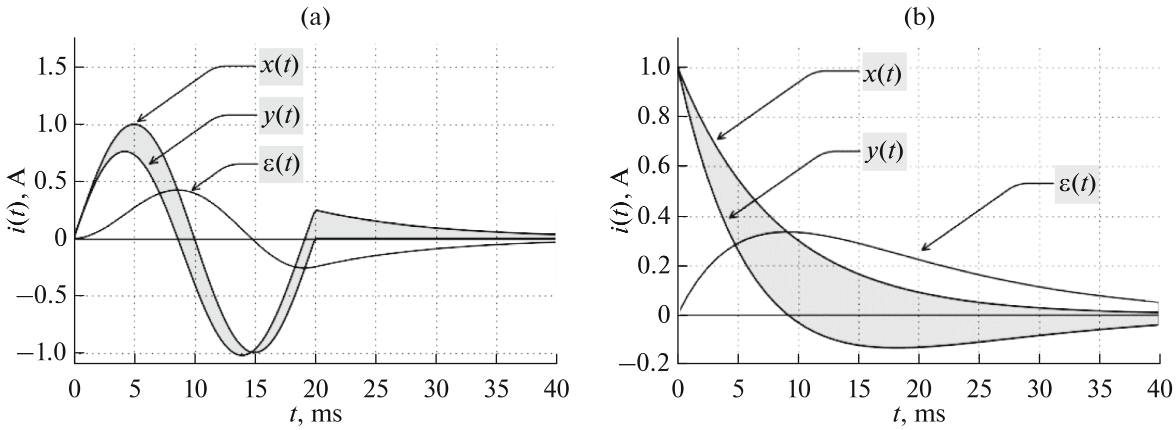

Fig. 6. Distortions typical for a narrow signal bandwidth EC: (a) signal in the form of a sine wave segment; (b) signal in the form of an exponential curve.

limit frequency is tens of kilohertz, which is quite sufficient for nondistorting transmission of any relay protection signals. The EC design must ensure not only nondistorting signal conversion, but also galvanic separation of the primary and secondary circuits in accordance with the requirements of the voltage class at which these ECs are used. Important conditions for the successful EC operation as part of current sensors are their mechanical strength, resistance to dynamic and static effects, and protection from negative environmental impacts.

The decision to implement the primary current converter in the current sensor (CS) based on a annular core is caused by the need to most fully comply with the entire set of requirements. In order to ensure the highest possible inductance L and the lowest leakage inductance, which mainly determines L_2, it is necessary to use an annular core made of a material with high relative magnetic permeability. The winding uniformly located on it has the lowest possible leakage inductance.

It should be noted that the use of a core with a nonmagnetic gap or a coil without a ferromagnetic core in the EC leads to a significant decrease in the equivalent inductance L, and in turn, to a significant increase in EC errors. Fig. 6 shows graphical images of the input $x(t)$ and output $y(t)$ signals, illustrating the distortions of $\varepsilon(t)$ when transmitting signals in the form of a 20-ms-long sinusoidal segment with a frequency of 50 Hz (Fig. 6a) and an exponent with a time constant of 15 ms (Fig. 6b).

In cases in which inductance L is small and the lower limit frequency of the EC at real R_2 is high, amplitude and phase distortions occur. As follows from Fig. 6a, the output signal differs from the reduced input signal in amplitude and is shifted in time, and the signal at the EC output does not disappear at the moment the input action ceases (the moment of 20 ms along the time axis). This effect can have a negative impact on the relay protection. When transmitting an exponential signal, an overshoot effect is also observed. As follows from Fig. 6b, the output signal changes sign, which can also disrupt the reliability of the relay protection. Good prospects are opened by the use of nanocrystalline materials with improved ferromagnetic properties for EC cores, for example, AMAG (amorphous magnetic) tape made of a nanocrystalline iron-based alloy and 18 μm thick with a relative magnetic permeability of at least 30 000, a wide linear range of the magnetization characteristic, and insignificant hysteresis.

FORMATION OF DIGITAL SIGNALS BY A CURRENT SENSOR

The output value in a current sensor must be represented as complex discrete signals, the structure of which is defined by the IEC–61850 standard. This entails the need to perform discretization and multiplexing operations in the sensor. In general, in terms of its functional essence, the CS is a measuring device for static and dynamic measurements (Fig. 7).

The CS input (primary winding) is connected in series to the power circuit with the measured current. In the primary converter (PC unit), implemented on the EC basis, the measured primary current is converted into a secondary current in analog form and galvanic separation of the input and output circuits of the CS is ensured.

The output current of the PC unit is converted into voltage by the input signal converter and after preliminary processing using an analog-to-digital converter (ADC) into a stream of discrete values. To ensure minimum information loss during signal digitization, an ADC with a differential input, a resolution of 16 bits, and a sampling frequency of 400 thousand samples per second was used.

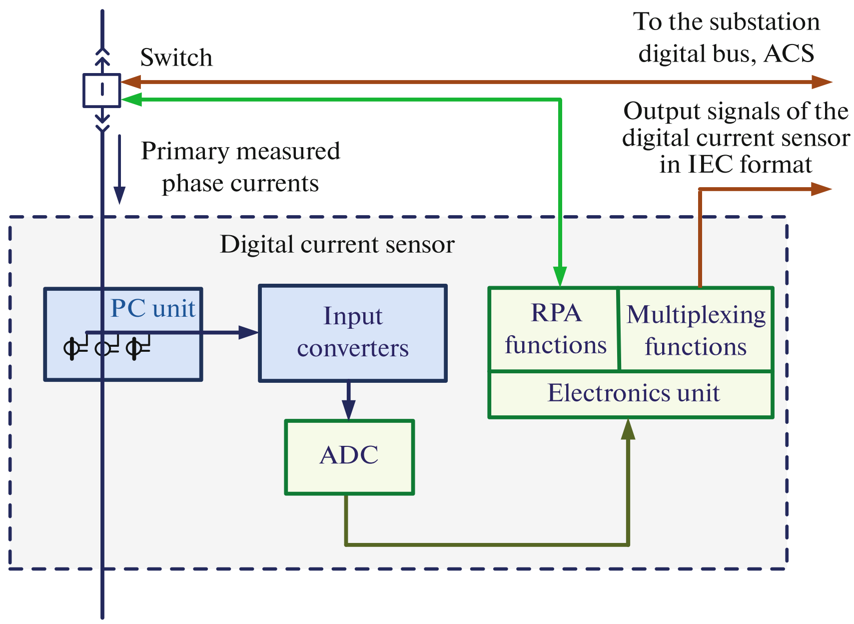

Fig. 7. Structural diagram of a current sensor with relay protection functions.

The discrete data stream from the ADC output is fed to the receiving input of the electronics unit, which provides coupling of the discrete signals generated by the ADC with digital devices, as well as implementing multiplexing functions, generating digital data packets in the format of the IEC–61850-9-2 or IEC 61850–9.2 LE standard, and implementing relay protection algorithms for the controlled bay [5].

RPA FUNCTIONS IN THE DIGITAL CURRENT SENSOR

The most important feature of the developed CS is that its electronic part combines the functions of multiplexing the measured currents and the relay protection functions for the bay where sensor is installed. Thus, the CS is not only a source of information about the supply current, but also a kind of trip unit that controls the bay state, generating a signal to trip the circuit breaker in cases of damage to the controlled connection. All the main protections are implemented in the EC: selective and nonselective current cutoffs, maximum current protections, current overload protection with a dependent time-current characteristic, and other current protections provided for by regulatory documents for 6- to 20-kV electrical networks.

The sensor structure with a combination of functions ensures high reliability of the relay protection. In the case of damage or malfunction of the substation data bus (as a rule, it is more vulnerable compared to relay protection devices), the relay protection can operate in a local (autonomous) mode, performing its functions and having the ability to act on the switch of the corresponding connection directly from the current sensor electronics unit.

TESTING OF PILOT CS SAMPLES

In accordance with the described approach, single- and three-phase pilot CS samples for a nominal voltage of 10 kV were developed and manufactured. The pilot samples were tested under operating conditions at an existing 110/10 kV substation. The test results confirmed the CS's compliance with the technical specifications and the validity of the design decisions.

As a result of the tests, it was established that the total relative error in converting primary current into a digital code according to the IEC standard does not exceed 5% in the entire regulated current range from 0.01 to 40 nominal sensor currents (Fig. 8).

It can also be noted that at currents from 0.01 to 1.2 nominal, the CS errors do not exceed the values established for the accuracy class of 0.2s. At small current multiplicities up to five times the nominal, the errors do not exceed 2.5%, while they are in the range from 2.5 to 5% at large ones (5–40 times nominal),. These results make it possible to consider the possibility of using the CS both for the purposes of information support of relay protection and automation and for current measurement systems.

CONCLUSIONS

(A) Prototypes of the digital output current sensor according to the IEC standard have improved current conversion characteristics and expanded functionality. Nanocrystalline ferromagnetic materials and

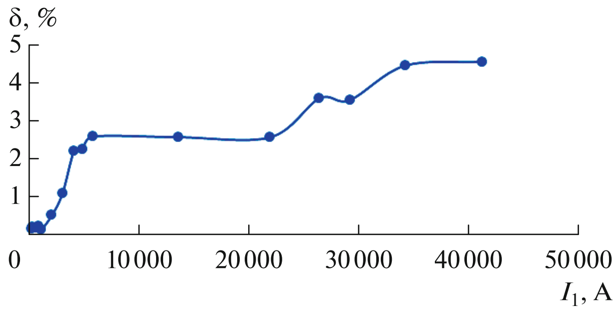

Fig. 8. Total error curve of the digital CS (δ%) depending on the input current obtained during testing of the digital CS prototype with a rated current of 1000 A.

domestically produced electronic components were used in the sensor design.

(B) The software and hardware part of the current sensor combines the functions of converting a signal into a digital code according to the requirements of the IEC 61850 protocol and the functions of bay relay protection, which allows expanding the functionality and increasing the reliability of relay protection.

(C) The current sensor has an acceptable accuracy of converting relay protection signals in both stationary and dynamic modes of controlled objects.

(D) The developed current sensor can be used as a current meter with a digital output in relay protection systems of highly automated substations at voltage taps of 6–20 kV.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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