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Increasing the accuracy of electricity accounting by digital information-measuring systems

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ABSTRACT

Significant non-technological losses of electricity are observed in 0.38 kV distribution networks, which lead to financial damages of energy supply companies. The reason for their occurrence is the deficiencies in the accounting units functioning in the reduced load mode, which occurs during the downtime of the main technological equipment. The purpose of the study is to increase the accuracy of electricity measurement by a commercial accounting unit in the reduced load mode based on mathematical modeling of measurement uncertainty. Evaluation of regression parameters for the static characteristics of measuring current transformers in the reduced load mode is carried out using the covariance analysis methods and analysis of regression residuals. Estimation of the non-random uncertainty of electricity measurement by one measuring channel of the accounting unit was carried out using the fuzzy set theory. The polynomial approximation of the experimental values of the membership function for the measured quantity was carried out according to the maximum norm method. The least square method was used to approximate the boundaries of fuzzy functions. As a result of research, a universal static characteristic of a measuring current transformer of a certain accuracy class was obtained at a reduced primary current. It was established that the sample estimates uncertainty of the current transformer error of the 0.5 S accuracy class changes from ±11.7 % to ±1.7 %. The uncertainty of electricity measurement by the commercial accounting unit in the reduced load mode is proposed to be estimated by a fuzzy function. The developed mathematical model takes into account the dependence of the fuzzy interval boundaries, which characterizes the measurement result, on the phase currents asymmetric values. Comparison of the analytically obtained membership function for the relative deviations of the readings of the accounting units with the empirically obtained value of such a deviation made it possible to establish the limit value of the confidence level, which was not less than 0.54 at the minimum permissible value of 0.4 of the adequacy criterion. This confirms the adequacy of the results of mathematical modeling with experimental data. Estimating the electricity metering uncertainty with a fuzzy interval increases the accuracy of the measurement, as it allows clarifying the monthly electricity consumption by taking into account the energy that was consumed during the reduced load mode.

Keywords: Electricity meter; measurement uncertainty; reduced load; current transformers

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INTRODUCTION

Reduction of technological and non-technological losses of electricity is one of the main priorities for the development of the energy sector of any country. In particular, for 9 months of 2021, the amount of total technological energy losses in the power grids of Ukraine amounted to 10.6 % of the total supply of electricity [1]. During the post-war reconstruction of the Ukrainian energy system, the issue of reducing electricity losses becomes especially relevant, as it will allow decreasing the financial costs of energy supply companies, directing the saved funds to the reconstruction of power grids.

The data of automated system for commercial accounting of power consumption, as well as the possibilities of advanced measuring infrastructure, are used to estimate electricity losses. However, electricity accounting units based on digital meters are characterized by insufficient measurement accuracy in the reduced load mode. This mode accompanies the downtime of the main production equipment, when electricity is consumed for auxiliary purposes (lighting, security etc.). Measurements for industrial enterprises showed that the level of underaccounting can exceed 50 % [2].

The need to improve the accuracy of electricity accounting in order to reduce the economic losses of energy supply companies determines the relevance of the study.

LITERATURE REVIEW

Commercial accounting of electricity in distribution 0.38 kV grids is carried out with the help of accounting units, which include measuring equipment: measuring current transformers and a meter [3]. Current transformers of electromagnetic type are most often used, but proposals to use a Rogowski coil [4] or Hall effect sensors are known. The volume of the global measuring current transformers market for accounting units in 2022 is about USD 300 million and will grow by 2028 [5]. Permissible measurement errors, determined by the accuracy class of the current transformer, are provided only in the normalized range of primary currents [6].

Electricity measurement is based on time integration of the power consumed by the load. Induction meters, due to low accuracy and sensitivity, are replaced by more advanced measuring devices. Static electricity meters are widely utilized, in which analog-to-digital conversion is used to measure current and voltage. The calculated value of the active power is converted into the pulses frequencies, which are sent to the counting mechanism. The latter performs energy calculation by integrating the power and saving the result. Such devices are being actively replaced by digital electricity meters.

The operation of the digital meter is based on the analog-to-digital conversion of currents and voltages instantaneous values and the implementation of the measurement principle by a microcontroller at the software level [7].

Based on discrete readings of voltage $u(n)$ and current $i(n)$, the active energy can be calculated as [8]:

$$W = \frac{\sum_{n=0}^{N} u[n] \cdot i[n]}{F_s}, \tag{1}$$

where N is the number of counts; $F_s = F_t/(P_r+1)$ – sampling frequency; F_t is the frequency of the timer with the setting of the counter register P_r.

The accuracy of the measurement is significantly determined by the metrological characteristics of analog-to-digital converters [9], among which the sigma-delta and sequential approximation converters are most widely used.

Many algorithms for measuring power components and, accordingly, energy in the time and frequency domains were developed. In particular, in [10], the spectral composition of voltage and current is determined for two samples of measured values using the discrete Fourier transform. Based on the processing of the real and imaginary parts of both spectra, the power components are obtained in real time. The active power measurement algorithm proposed in [11] involves the use of filters with an infinite impulse response to separate the component signals by voltage and current while minimizing noise. The overall estimate of the active power is determined using an adaptive low-pass filter of the specified type for averaging instantaneous power values.

Successes in the development of digital protocols for remote data exchange made it possible to build automated systems for commercial electricity accounting [12]. With the increase in the amount of electricity accounting data, the issue of their verification and validation to ensure financial calculations, accuracy, completeness, integrity and reliability is receiving more and more attention [13].

The construction of micro grids and smart grids [14] led to the need to allocate a separate class of electricity meters – "smart" devices [15]. The global smart electricity meter market for 2021 was estimated at USD 25 billion, for 2022 – more than USD 28 billion. By 2030, the market is expected to expand to USD 55 billion with an annual growth of about 11% [16]. A characteristic feature of smart electricity meters is the possibility of two-way data exchange, which permits to implement the concept of advanced metering infrastructure [17].

The latter allows reading measurement information in real time, as well as sending a dynamic price to the meter (time-based pricing), providing demand response for the purpose of reducing demand and, accordingly, electricity prices during peak hours, remotely disconnecting a consumer [18].

Today, phasor measurement units, which are considered one of the key components of future grids, are being intensively implemented [19].

For example, ABB RES670, SATEC PM180 etc. Such devices provide estimation of the position of complex vectors. The current (or voltage) of the grid is represented by a dynamic vector $\bar{\mathbf{X}}$ with variable amplitude and frequency:

$$\bar{\mathbf{X}}(t) = a(t) \cdot e^{j\varphi(t)}, \tag{2}$$

where $a(t) = X_m \cdot g(t)/\sqrt{2}$ is amplitude of the dynamic vector; $X_m \cdot g(t)$ is modulated amplitude of the measured signal; $\varphi(t)$ is phase of the vector.

At the same time, the devices measure the values of the vector (2) discretized with the period T_s, which are described by the dependence:

$$\bar{\mathbf{X}}(nT_s) = a(nT_s) \cdot \exp[j(\omega_0 nT_s + \varphi(nT_s)]. \tag{3}$$

The rotating vector (3) can be multiplied by $e^{-j\omega_0 nT_s}$ to stop.

The discredited values of the stationary complex vector for current or voltage are obtained:

$$\bar{\mathbf{X}}(nT_s) = a(nT_s) \cdot e^{j\varphi(nT_s)}, \tag{4}$$

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according to which the state of the grid is analyzed.

The evaluation of the phase of complex vectors is carried out in synchronization with the global positioning system, which ensures the unity of measurements at different points of the power grid. The measurement results, obtained from the specified devices, are used, in addition to the grids protection, also for accounting of active, reactive and total energy [20].

The functioning of smart electricity meters as a part of advanced measuring infrastructure has actualized the issue of remote, without physical access to the meter, assessment of accounting accuracy and automatic detection of devices whose error exceeds permissible limits. In particular, there is a known method of online estimation of the smart meter error based on an array of daily indicators, which involves the selection of accounting errors, constant losses, and losses in lines [21]. Estimating the error of the consumer meter is possible based on the analysis of the nodal meter readings in a tree-like topology by means of k-means clustering and regularization [22]. There is also a well-known proposal to estimate the error of a digital electricity meter, which takes into account the errors of analog-to-digital conversion and data transmission, using the Monte Carlo method [23]. The improved local outlier factor method [24] is used to detect outliers (measurement results stood out from the total sample) due to external noise and disturbances. Moreover it is proposed to find a combined estimate of the measurement error and external disturbances using kernel support vector regression. A method for detecting deviations from the acceptable limits of errors of smart meters by applying multiple linear regressions to data coming from an advanced measuring infrastructure, with the involvement of Tikhonov regularization and optimization based on generalized cross-validation in the distribution grid of a tree-like structure is also proposed [25].

There are known developments in the direction of remote calibration and verification of smart electricity meters, which should replace standard methods (watt-second, a digital source method etc.). In particular, it is proposed to include a calibration circuit with a stabilized voltage source in the meter for remote calibration in automatic mode [26]. Another approach involves estimating the accuracy of the measurement based on the analysis of the data from the meter, using a recursive algorithm [27].

In recent years, a lot of attention has been paid to evaluating the reliability indicators of the operation of smart meters and studying the effect of aging on the accuracy of accounting. It is known about the use of the Monte Carlo method and the failure tree to predict the reliability and fail-safe operation of smart electricity meters [28]. A method for estimating the measurement error that takes into account the degradation of smart meter elements under the influence of external factors (temperature, humidity, current load in the operating mode) is proposed. To approximate the degradation characteristic, a feed-forward neural network is involved [29]. There is also a known method for estimating the measurement error for smart meters, which is based on a modified back propagation method for a neural network [30]. The method makes it possible to detect meters with abnormally large error values.

The current error of measuring current transformers has a significant impact on the accuracy of electricity metering by a digital meter [31]. Errors arise due to the distortion of the static characteristic $I_s(I)$ of the current transformer in normalized operating modes [32]. In the area of small loads, the resulting error of the measuring channel of the accounting unit can reach from −30 % to −90 % [33]. Therefore, the authors suggest taking into account the dependence of the calculation errors on the current for the correction of the measurement results in automatic mode. The measurement accuracy, especially in the low primary currents range (up to 10% of the nominal value) of the measuring transformer, is significantly affected by the material from which the core is made. For cold-rolled steel, the current error is from –3 % to −5.5 %. The error can be reduced to –1 % on average when using a core made of nanocrystalline materials or their combination with steel [34]. To minimize the error when operating in non-standard conditions, a multi-winding current transformer can be used [35].

Thus, in digital and smart electricity meters the principle of measurement is implemented at the software level. The functioning efficiency of the energy market is determined by the accuracy of commercial accounting, which depends on the metrological characteristics of electricity meters and measuring transformers. The construction of information-measuring systems for commercial electricity accounting allows for remote control and correction of errors of accounting means, which transfers the implementation of the task of maintaining the specified accuracy of accounting to the software level of advanced measuring infrastructure. Known studies analyze the errors accompanying overloading of meters by current, at the same time, insufficient attention is paid to the issue of accounting accuracy in the reduced load mode.

THE PURPOSE AND TASKS OF THE STUDY

The purpose of the study is to increase the accuracy of electricity measurement by an accounting unit in the reduced load mode based on mathematical modeling of measurement uncertainty. This will make it possible to clarify financial calculations between suppliers and consumers of electricity.

To achieve the purpose, it is necessary to solve the following tasks:

– to improve the procedure for identifying the metrological characteristics of the accounting unit in the reduced load mode;

– to substantiate a mathematical model for estimating the uncertainty of electricity measurement in the reduced load mode;

– to assess the adequacy of the proposed mathematical model with experimental data.

MATERIALS AND RESEARCH METHODS OF ELECTRICITY ACCOUNTING ACCURACY ESTIMATION

The following methods were used to evaluate the parameters of the static characteristics of measuring current transformers in the reduced load mode. The methods of analysis of covariance were used to evaluate the influence significance of the parameters of individual measuring current transformers on the nature of the regression dependence describing the static characteristic, and to evaluate its parameters. Verification of the appropriateness of the selected regression model for describing the static characteristics of current transformers was carried out by analyzing the regression residuals. At the same time, statistical hypotheses were checked using the Student's, Fisher’s, Kolmogorov-Smirnov and Durbin-Watson tests.

The assessment of the non-random uncertainty of electricity measurement by one measurement channel of the accounting unit was carried out using the theory of fuzzy sets based on the method proposed in manuscript [36]. The polynomial approximation of the experimental values of the membership function of the measured quantity was carried out according to the criterion of the maximum norm method. When approximating the boundaries of fuzzy functions, the least square method was used, for the numerical implementation of which the simplex Nelder-Mead method of minimizing the function of several variables was applied.

For an experimental study of the accuracy of electricity accounting in the reduced load mode of the accounting unit, the following equipment was used: transformer connected meter NIK2307 ART T.1600.M2.21, measuring current transformers T-0.66-600/5 and T-0.66-300/5. The actual energy value was determined by the direct connection meter NIK2307 ARP3 T.1600.M2.21. The accuracy class of measuring devices is 0.5 S. Incandescent lamps were used to create an active load.

RESEARCH RESULTS OF ELECTRICITY ACCOUNTING ACCURACY ESTIMATION

Metrological characteristics identification of the accounting unit in the reduced load mode

The accuracy of electricity measurement by the ζ={A, B, C} measuring channel of the accounting unit in the reduced load mode can be estimated by the relative deviation δW_ζ of the active energy measured for the time interval Δt between the readings of the transformer connected meter (PI1) and the direct connected meter (PI2), which is determined under the assumption of zero current in the other two channels [37]:

$$\delta W_\zeta(\Delta t, I_\zeta) = \frac{W_{PI1.\zeta}(\Delta t, I_\zeta)}{W_{PI2.\zeta}(\Delta t, I_\zeta)} - 1. \qquad (5)$$

The deviation of the readings of the transformer connected meter from the direct connected meter for three measuring channels can be determined taking into account the currents I_ζ of the channels [38]:

$$\delta W(I_A, I_B, I_C) = \frac{\sum_\zeta I_\zeta \cdot \delta W_\zeta(I_\zeta)}{\sum_\zeta I_\zeta}. \qquad (6)$$

Suppose that for the ζ-th measuring channel at a fixed value of the load current $I_{\zeta\gamma}$ (γ is the number of the current level) sample values of the relative deviations of the meters readings $\delta W_{\zeta\gamma i}(I_{\zeta\gamma})$ were obtained, where the index i denotes the number of the sample value. Let's establish a set $\{\lambda_j^*\}$ of confidence levels, and $\lambda_j^* > \lambda_{j+1}^*$. For each current level $I_{\zeta\gamma}$, the L–R boundaries of the fuzzy interval for the relative deviations of meter readings can be found at a given confidence level λ_j^*:

$$\delta W_{\zeta\gamma} = \left[\delta W_{L\zeta\gamma}\Big|_{\lambda_j^*}; \quad \delta W_{R\zeta\gamma}\Big|_{\lambda_j^*} \right]. \qquad (7)$$

At the confidence level λ_j^*, the obtained L–R boundaries of fuzzy intervals for each of the γ

current levels can be approximated by the dependences $\delta W_{L\zeta}(I_\zeta)\big|_{\lambda_j^*}$, $\delta W_{R\zeta}(I_\zeta)\big|_{\lambda_j^*}$. Let us assume that the approximation of the left and right boundaries of sets of fuzzy functions is carried out by nonlinear dependencies F.

Let us denote the sets of parameters for the left $\{L_{\zeta j}\}$ and right $\{R_{\zeta j}\}$ boundaries, then:

$$\delta W_{L\zeta}(I_\zeta)\big|_{\lambda_j^*} = F\left[I_\zeta, \{L_{\zeta j}\}\right], \tag{8}$$

$$\delta W_{R\zeta}(I_\zeta)\big|_{\lambda_j^*} = F\left[I_\zeta, \{R_{\zeta j}\}\right]. \tag{9}$$

The dependencies represent the boundaries of the fuzzy function, which for λ_j^* describes the accuracy of accounting for the ζ measuring channel:

$$\delta W_\zeta(I_\zeta) = \left[\delta W_{L\zeta}(I_\zeta)\big|_{\lambda_j^*};\quad \delta W_{R\zeta}(I_\zeta)\big|_{\lambda_j^*}\right]. \tag{10}$$

Thus, the dependence of the relative deviation of meter readings on one measuring channel on the current is proposed to be represented by a fuzzy function (10). Such a function, at a given significance level, characterizes the accuracy under the condition that the current flows only in the specified phase of the accounting unit.

Mathematical model for estimating the uncertainty of electricity measurement

Representation of the measuring channels characteristics by fuzzy functions (10) makes it possible, in accordance with the dependence (6), to obtain a fuzzy function that characterizes the uncertainty of electricity measurement by a three-phase accounting unit for the given values of the phase currents I_A, I_B, I_C:

$$\delta W(I_A, I_B, I_C) = \frac{\sum_\zeta I_\zeta \cdot \delta W_\zeta(I_\zeta)}{\sum_\zeta I_\zeta}. \tag{11}$$

The calculated empirical points, corresponding to the boundaries of the fuzzy function $\delta W(I_A, I_B, I_C)$ for a set of confidence levels, can be approximated.

As a result, the membership function μ_{abc} for δW can be obtained, namely:

$$\mu_{abc}(\delta W) = \begin{cases} \mu_{abc_L}(\delta W), & \text{if } \delta W \le \delta W_\upsilon; \\ \mu_{abc_R}(\delta W), & \text{if } \delta W > \delta W_\upsilon. \end{cases} \tag{12}$$

Such a membership function corresponds to the given values of the channels currents. The accuracy of electricity measurement by a specific accounting unit is evaluated according to μ_{abc}, taking into account the limit level of confidence λ_b^*. For specific measuring means, the value λ_b^* can be determined in advance on the basis of experiments number. They can be planned as a full factorial experiment, when the levels of phase currents are considered as independent factors. The objective function in each of the implementations of experiments is the value δW_e, by which, according to the membership function μ_{abc}, it is possible to calculate the sample value of the confidence level λ_e^*. The sample of λ_e^* obtained in this way is checked for the random outliers, and after rejecting them, it is possible to check the hypothesis of a normal distribution of the sample values according to one of the known tests. If the hypothesis of a normal distribution of empirical sample values of confidence levels is not rejected (at the accepted level of significance), it is possible to calculate the sample values of mean $m[\lambda_e^*]$ and standard deviation $s[\lambda_e^*]$.

Then, to find the limit confidence level, it is suggested to use the dependence, which includes empirical values with a probability of 0.95, namely:

$$\lambda_b^* = m[\lambda_e^*] - 2\sigma[\lambda_e^*]. \tag{13}$$

Since measuring current transformers have a significant impact on the accuracy of accounting, the mathematical model should be supplemented with the static characteristic of such a measuring transformer at a low primary current.

Suppose that the following statistical model corresponds to the specified characteristic:

$$\hat{I}_s^*(I^*) = \hat{\mu} + \tau + \hat{\beta} \cdot (I^* - \bar{I}^*), \tag{14}$$

where $\hat{I}_s^*$ is statistical estimate of the relative value of the secondary current of the current transformer; I^* is relative value of the primary current of the current transformer; $\bar{I}^*$ is average relative value of the primary current in the reduced load mode of the accounting unit; $\hat{\mu}$ is estimation of the average value of the secondary currents of the measuring transformer; τ is the parameter corresponding to the influence of the transformation coefficient of the measuring transformer; $\hat{\beta}$ is estimate of the linear regression coefficient.

The proposed mathematical model for estimating the uncertainty of electricity measurement by an accounting unit during reduced load mode is summarized in the block diagram, Fig. 1. Blocks of subsystem I provide identification of metrological characteristics of the accounting unit in the reduced load mode. Identification is carried out once for a specific type of accounting unit. The input values are the phase currents I_A, I_B, I_C of the load. For each of the measuring current transformers, the parameters of the static characteristic (14) are estimated, which is presented in the diagram, Fig. 1, by blocks 1, 2, 3 for phases A, B, C, respectively.

The obtained characteristics are used for estimation of the parameters of fuzzy functions (10) for each phase (blocks 4-6). The L–R boundaries approximation of such functions by the nonlinear dependence of the selected type at given significance levels, which in the general case is described by expressions (8), (9), makes it possible to obtain sets of values of the parameters of the specified nonlinear dependence, to which blocks 7-9 are corresponded.

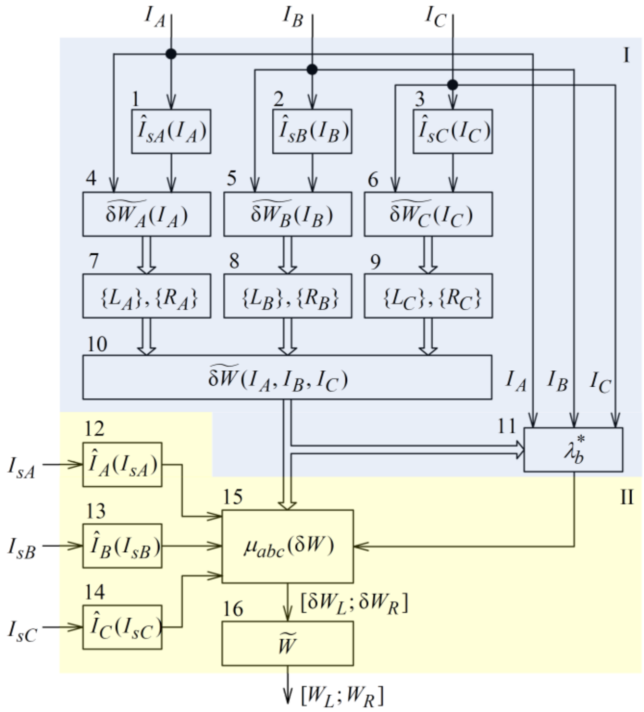

Fig. 1. **Block diagram of the mathematical model for estimating the uncertainty of electricity measurement in the reduced load mode of the accounting unit**
Source: **compiled by the authors**

At the same time, the identification of measuring channels characteristics (for example, for the phase A channel – by blocks 1, 4, 7) is carried out at the zero current of the other two channels. The independence of the measuring channels functioning makes it possible to determine the relative deviation (6) of the meter readings as part of the accounting unit from the actual value of the consumed energy. The application of such dependencies for the analytical determination of the relationship between the left and right boundaries of the fuzzy function (11), which characterizes the accuracy of accounting, with the values of phase currents, is carried out by block 10. Using the fuzzy function for the accounting unit, defined in block 10, makes it possible to estimate the confidence limit, block 11. Such evaluation is carried out according to (13) on the basis of experiments in which the accounting unit operates in the reduced load mode with asymmetric currents of three channels. As a result of characteristics identification of the accounting unit (at the output of subsystem I), an analytical expression for the fuzzy function (11) is obtained, which characterizes the uncertainty of electricity measurement (output of block 10), and the limit value of the confidence level (output of block 11).

Metrological characteristics identified in subsystem I serves as input values for subsystem II. The latter makes it possible to estimate the uncertainty of electricity measurement at specific currents during the reduced load mode. It is possible to directly measure the primary currents of the accounting unit, but this approach is characterized by disadvantages in practice. In particular, it is necessary to use additional means of current measurement designed for the flow of working and emergency currents of the consumer. In addition, for such additional means of current measurement, it is necessary to determine the static characteristics in the reduced load mode. Therefore, it seems rational to control the secondary currents of the measuring transformers included in the accounting unit. When using the ability of the digital meter of the transformer connection to measure currents and output the measured values, the implementation of the subsystem II functions can be carried out programmatically without additional hardware. This approach is also justified by the presence of static characteristics of measuring transformers, which were defined in blocks 1-3. This allows, using the inverse of (14) dependencies, to estimate the primary currents by the secondary currents, blocks 12-14.

The load currents estimated in this way are passed to block 15, which determine the membership function (12) for the fuzzy function coming from block 10. According to the obtained membership function, taking into account the limit level of confidence that comes from block 11, block 15 determines the relative deviation of the readings of the transformer connected meter from the actual value of the consumed energy, which is described by a fuzzy number δW .

At the output of block 15, the L–R boundaries of the specified fuzzy number are given at the limit confidence level:

$$\delta W = [\delta W_L;\ \delta W_R]. \tag{15}$$

The actual value of energy consumption during the reduced load mode at specified a current (the system of currents may be asymmetrical) is described by a fuzzy number, which is defined as:

$$W = \frac{W_{PI1}}{\delta W + 1}. \tag{16}$$

At the limit level of confidence, the fuzzy number W of the actual amount of electricity is characterized by the limits estimated in block 16 according to the dependence:

$$W = [W_L;\ W_R] = \left[\frac{W_{PI1}}{\delta W_R + 1};\ \frac{W_{PI1}}{\delta W_L + 1}\right], \tag{17}$$

where W_{PI1} – the amount of electricity measured by the transformer connected meter during the reduced load mode.

The boundaries of the fuzzy value (17) are the output value of subsystem II and the mathematical model. Interval [W_L; W_R] defines the boundaries in which the actual electricity consumption lies during the operation of the accounting unit in the reduced load mode at the specified limit level of confidence. For practical application, it is possible to accept the right boundary W_R of the indicated interval as the actual value of electricity consumption during the reduced load mode in the most unfavorable conditions, which opens the way to the practical application of the proposed model.

Adequacy assessment of the mathematical model

The experimental study of the characteristics of measuring current transformers in the reduced load mode was carried out for converters of type 300/5 and 600/5 of the 0.5 S accuracy class. Testing of the hypothesis regarding the possibility of using dependence (14) to describe the static characteristics of the measuring current transformer was carried out using methods of analysis of covariance. At the first stage, a one-way analysis of variance was performed to check the hypothesis H0 about the absence of a statistically significant effect of the transformation coefficient on the static characteristics of the current transformer at reduced primary current (τ_i=0). Competing hypothesis H1: $\tau_i \neq 0$. The empirical value of the F-test (F_0=0.186) is less than the critical point F_c (α; m−1; m(n−1)−1)=F_c(0.05; 5; 95)=2.310 at the significance level α=0.05. Therefore, H0: τ_i=0 cannot be rejected.

The numerical value of the assessment $\hat{\mu}=5.965 \cdot 10^{-3}$ was determined according to the dependence [39]:

$$\hat{\mu} = \overline{I}_s^* = \frac{1}{m \cdot n}\sum_{i=1}^{m}\sum_{j=1}^{n} I_{sij}^*. \tag{18}$$

To estimate the value of the parameter $\hat{\beta}$, the hypothesis H0: β=0 is tested against the hypothesis H1: β≠0. The empirical value of the F-test $F_0=4.828 \cdot 10^4$ significantly exceeds the critical point F_c(0.05; 1; 95)=3.941, which indicates acceptance of the alternative hypothesis H1: β≠0. Then the estimate of the linear regression coefficient equals to:

$$\hat{\beta} = E_{ps} / E_{pp}, \tag{19}$$

whereby

$$E_{pp} = \sum_{i=1}^{m}\sum_{j=1}^{n}\left(I_{ij}^* - \frac{1}{n}\sum_{j=1}^{n} I_{ij}^*\right)^2; \tag{20}$$

$$E_{ps} = \sum_{i=1}^{m}\sum_{j=1}^{n}\left(I_{ij}^* - \frac{1}{n}\sum_{j=1}^{n} I_{ij}^*\right)\left(I_{sij}^* - \frac{1}{n}\sum_{j=1}^{n} I_{sij}^*\right). \tag{21}$$

According to the results of the experiment, $\hat{\beta}=9.932 \cdot 10^{-1}$ was calculated. Then the statistical model for the static characteristics of the measuring current transformer of the accuracy class 0.5 S with a reduced load of the accounting unit is:

$$\hat{I}_s^*(I^*) = \hat{\mu}' + \hat{\beta} \cdot I^*, \tag{22}$$

where $\hat{\mu}' = \hat{\mu} - \hat{\beta} \cdot \overline{I}^* = -1.369 \cdot 10^{-4}$.

Checking the adequacy of such a covariance model with experimental data is carried out by testing the regression residuals at a confidence level of 0.95. According to the Kolmogorov-Smirnov test, the hypothesis about the distribution normality of the regression residuals was not rejected. The hypothesis of a zero mean of the regression residuals was not rejected according to the t-test. Using the Durbin-Watson test, it was established that the autocorrelation between the regression residuals is not statistically significant.

The experimental study of the accuracy of accounting was carried out using 600/5 current transformers of the accuracy class of 0.5 S as part of the accounting unit. To assess the deviation uncertainty of the readings of the transformer connected meter from the direct connected meter, 71 experiments were carried out on the measuring channel of phase A (Fig. 2), phase B – 66 experiments, phase C – 67 experiments.

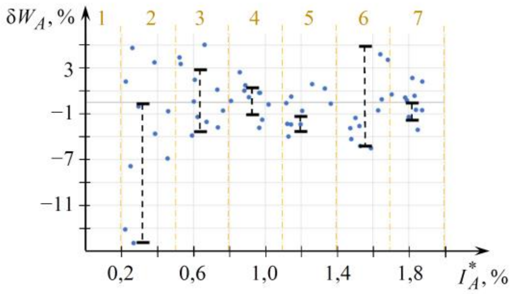

Fig. 2. **Empirical points and fuzzy intervals for δW_A characterizing the uncertainty of electricity measurement by the accounting unit in the reduced load mode at a confidence level of 0.4**
Source: **compiled by the authors**

For each confidence level, the boundaries (8), (9) of fuzzy functions (10) were approximated by the sum of two exponents:

$$F(x,\{K\}) = K^{(1)} \cdot \exp[-x / K^{(3)}] + \\ + K^{(2)} \cdot \exp[-x / K^{(4)}] + K^{(5)}, \quad (23)$$

where $\{K\}=\{K^{(1)},\ldots,K^{(5)}\}$ – a set of parameters.

For example, at a confidence level of 0.4, the fuzzy function that characterizes the uncertainty of electricity measurement by the phase A channel of a three-phase transformer connected meter in the reduced load mode is [40]:

$$\delta W_A(I_A^*) = [K_L^{(1)}; K_R^{(1)}] \times \\ \times \exp\left(\frac{-I_A^*}{[K_L^{(3)}; K_R^{(3)}]}\right) + \\ + [K_L^{(2)}; K_R^{(2)}] \times \\ \times \exp\left(\frac{-I_A^*}{[K_L^{(4)}; K_R^{(4)}]}\right) + [K_L^{(5)}; K_R^{(5)}], \quad (24)$$

where $K_L^{(1)}=-2.72\cdot10^2$; $K_R^{(1)}=-6.01\cdot10^2$; $K_L^{(2)}=2.03$; $K_R^{(2)}=9.35$; $K_L^{(3)}=9.84\cdot10^{-2}$; $K_R^{(3)}=5.64\cdot10^{-2}$; $K_L^{(4)}=2.15$; $K_R^{(4)}=1.93\cdot10^{-1}$; $K_L^{(5)}=-3.42$; $K_R^{(5)}=-7.25$.

It was established that with currents from 0.2 % to 0.8 %, the level of underaccounting in the most unfavorable conditions can be from –32 % to –8 %. As the current value increases, the largest underestimation decreases, reaching 3 % at a current of 2 %.

As an adequacy criterion of the results of mathematical modeling with the experimental data, it is proposed to consider the actual value exceeding the confidence level λ_e^* of the minimum permissible level of 0.4, which is typical for samples with a volume of up to several hundred elements [36]. 8 experiments were conducted with asymmetric currents of the measuring channels, the values of which were chosen randomly. The actual value of the confidence level in all experiments was $\lambda_e^* \geq 0{,}54$. This gives reason to accept the hypothesis about the adequacy of the mathematical modeling results to empirical data.

DISCUSSION OF THE RESULTS OF ELECTRICITY METERING ACCURACY ESTIMATION

It is proposed to evaluate the accuracy of electricity metering in the reduced load mode by the value of the relative deviation of the transformer connected meter readings from the readings of the direct connected meter. For one measuring channel, such an estimate is calculated according to dependence (5), for a three-phase accounting unit – according to (6). The correctness of using a direct connected meter to evaluate the actual energy value is determined by the operation of such a device in the current range in which the error is normalized according to the accuracy class. This approach is implemented without unnecessary complications in laboratory conditions when studying the accuracy of specific measuring equipment.

The identification of metrological characteristics of measuring channels involves the estimation of sets of dependences (8) and (9) parameters for each of the given confidence levels. Such dependencies correspond to the set of boundaries of the fuzzy function (10), which characterizes the accuracy of accounting for a specific measuring channel. This makes it possible to determine the fuzzy interval (7) of the relative deviation of meter readings on each channel according to the current value. Taking into account the obtained intervals in dependence (6) ensures consideration of the asymmetry of the phase currents during the reduced load mode.

The mathematical model, which allows estimating the uncertainty of electricity measurement, defines a fuzzy function (11), which characterizes the accuracy of measuring equipment, and a membership function (12). The latter, as it depends on the phase currents and δW, is determined for specific values of the mode parameters. A methodology for estimating the limit level of confidence (13) is proposed, which is based on the results of comparing meter readings in case of asymmetric phase currents. Such an estimation finding during preliminary tests of the accounting unit specifies the conditions for analyzing the results of field tests. Also, carrying out measurements in manufacturing conditions is simplified thanks to the preliminary identification of the metrological parameters values of the accounting unit, which is illustrated by the diagram in Fig. 1. In addition, a technique for estimating the parameters values of the universal static characteristic (14) of measuring current transformers of a given accuracy class is proposed. The use of such a characteristic allows the implementation of the proposed mathematical model exclusively at the software level of the information-measuring system, without the use of additional hardware.

The validity of the estimation of the parameters values of the universal static characteristic (22) for current transformers of the accuracy class 0.5 S is confirmed by the use of analysis of covariance methods and known tests for checking statistical hypotheses, as well as the results of the analysis of regression residuals. The adequacy of the mathematical model that estimates the accuracy of electricity measurement is confirmed by the empirical value of the confidence level (0.54) exceeding the minimum permissible value (0.4).

The disadvantages of the proposed approach include the need for preliminary identification of the metrological characteristics of a specific accounting unit. The labor intensity of such a procedure can be reduced by automating laboratory studies.

In the case of a decrease in the load level of current transformers to values at which the permissible error is not normalized for a given accuracy class (in accordance with [6]), or at which the electric energy meter of the transformer connection operates in the insensitivity mode (in accordance with the passport data of the meter), which causes underaccounting of electric energy, the energy supply company may recommend to the consumer to perform reconstruction or technical re-equipment of the electric energy accounting unit taking into account, when choosing measuring equipment, the current load level. Technical re-equipment of the accounting unit should provide for the selection of measuring current transformers in accordance with the actual power of the load operating at the consumer. Also, current transformers can be selected of a higher accuracy class. If current transformers of accuracy class 0.5 S were used before re-equipment, then it can be recommended to use devices of accuracy class 0.2 S.

If the replacement of measuring current transformers does not give a significant effect, it is possible to recommend the reconstruction of the power supply system in order to separate the accounting of electricity consumed by production machines and electricity spent on lighting the territory and auxiliary needs. In this case, the reduced load mode of the accounting unit will be eliminated, since each of the units will function in the normalized mode, which will increase the accuracy of electricity measurement.

CONCLUSIONS

Improving the metrological provision of electricity with digital and smart meters as part of distributed information-measuring systems (automated systems of commercial electricity accounting, advanced measuring infrastructure) is important for maintaining the necessary measurement accuracy. This becomes especially relevant in the reduced load mode of the accounting unit, when there is a significant underaccounting of electricity. The hypothesis about the possibility of representing the static characteristics of the measuring current transformer at a reduced load of the accounting unit by a linear statistical model has been confirmed. A mathematical model of the uncertainty of electricity measurement is substantiated, which is represented by a fuzzy function and takes into account the metrological characteristics of each of the measuring channels, the membership function for which is determined taking into account the values of the currents of the phases of the accounting unit. Adequacy of mathematical modeling results is confirmed by experimental data.

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Підвищення точності обліку електроенергії цифровими інформаційно-вимірювальними системами

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АНОТАЦІЯ

В розподільних електромережах напругою 0,38 кВ спостерігаються суттєві нетехнологічні втрати електроенергії, що призводять до фінансових збитків енергопостачальних компаній. Причиною їх виникнення є недоліки функціонування вузлів обліку під час режиму зниженого навантаження, що має місце протягом простроїв основного технологічного обладнання. Метою дослідження є підвищення точності вимірювання електроенергії вузлом комерційного обліку в режимі зниженого навантаження на основі математичного моделювання невизначеності вимірювання. Оцінювання параметрів регресії для статичної характеристики вимірювальних трансформаторів струму в режимі зниженого навантаження здійснюється з використанням методів коваріаційного аналізу та аналізу регресійних залишків. Оцінювання невипадкової невизначеності вимірювання електроенергії за одним вимірювальним каналом вузла обліку здійснювалося з використанням теорії нечітких множин. Поліноміальна апроксимація експериментальних значень функції приналежності вимірюваної величини здійснювалася з використанням методу максимальної норми. При апроксимації меж нечітких функцій використовувався метод найменших квадратів. В результаті досліджень одержано універсальну статичну характеристику вимірювального трансформатора струму визначеного класу точності при зниженому первинному струмі. Встановлено, що невизначеність вибіркових оцінок струмової похибки трансформатора струму класу точності 0,5 S змінюється від ±11,7 % до ±1,7 %. Невизначеність вимірювання електроенергії вузлом комерційного обліку в режимі зниженого навантаження запропоновано оцінювати нечіткою функцією. Розроблена математична модель враховує залежність меж нечіткого інтервалу, який характеризує результат вимірювання, від величин несиметричних струмів фаз. Зіставлення аналітично отриманої функції приналежності для відносних відхилень показів вузла обліку з емпірично одержаною величиною такого відхилення дало змогу встановити граничне значення рівня довіри, що не було менше від 0,54 при мінімально допустимому значенні 0,4 критерія адекватності. Це підтверджує адекватність результатів математичного моделювання експериментальним даним. Оцінювання невизначеності обліку електроенергії нечітким інтервалом підвищує точність вимірювання, оскільки дозволяє уточнити місячне споживання електроенергії шляхом врахування енергії, що була спожита під час режиму зниженого навантаження.

Ключові слова: Лічильник електроенергії; невизначеність вимірювання; знижене навантаження; трансформатори струму

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