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Mathematical modeling of influence of electricity metering unit phase loads on measurement uncertainty

The uncertainty of electricity measurement in the reduced load mode of the metering unit is estimated by fuzzy function. The effect of each phase current on the function boundaries is considered by proposed mathematical model. The practical significance of the model lies in increasing the measurement accuracy of consumed electricity.

Introduction.

According to the "Energy Strategy of Ukraine until 2035", one of the main priorities of the energy sector development is the reduction of energy losses during its transmission and distribution. Synchronization of the power system of Ukraine with Continental European Power System especially emphasized the relevant of losses decrease. Non-technological losses of electricity in distribution networks can reach 20 % [1]. Such losses include, in particular, electricity that has not been metered for due to the shortcomings of the measuring equipment. The measurement of electricity consumed over a certain period of time is carried out by the commercial electricity metering unit. Such a unit for low-voltage networks includes an electricity meter and three measuring current transformers. The type of the latter is selected according to the nominal load level of the consumer. However, the level of load currents in real conditions can be several percent of the rated value for a few hours. The main reasons for the reduced load regime include downtime of technological equipment at night, due to lack of orders etc. The currents, that flow through the elements of the metering unit in the reduced load mode, are smaller than the lower limit of the current permissible range which the measurement accuracy indicators are provided according to the accuracy class. This leads to the operation of the metering unit in non-standardized mode, which significantly increases the error of electricity measurement.

Distribution system operators take certain measures to improve the accuracy of electricity metering. In particular, PJSC "Rivneoblenergo" plans to replace about 25,000 outdated electricity meters with an accuracy class of 2.5 with modern electronic and smart types of an accuracy class of at least 1.0 within 2 years. However, such measures do not allow to avoid the reduced load mode, and, accordingly, deterioration of metering accuracy. For instance, the metering unit functioning for a private industrial enterprise in the city of Rivne was evaluated with the help of PJSC "Rivneoblenergo". The unit included a digital electricity meter and measuring current transformers 200/5 of accuracy class 0.5S. It was established that the energy underestimation can exceed 80% [2]. The operation of the metering unit in the insensitivity mode was also observed, Fig. 1.

Thus, the increase of underestimating electric power in reduced load mode of the metering unit determines the relevance of mathematical modeling of measurement uncertainty.

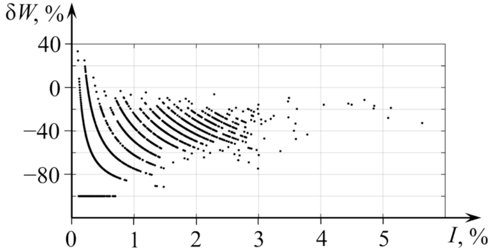

Fig. 1. Relative errors δW, %, of electricity metering versus load current I, %, for an industrial enterprise in the city of Rivne

Literature review.

Measuring current transformers are characterized by a current error that significantly increases in the reduced load mode of the metering unit. For transformers whose magnetic circuit is made of cold-rolled steel, such an error can reach −5.5% [3]. There are known a priori and a posteriori methods for estimating measurement uncertainty. A disadvantage of a priori evaluation is the overestimation of uncertainty, since all sources of measurement uncertainty are taken into account. A posteriori evaluation uses the methods of probability theory and mathematical statistics, or the methods of the possibility theory [4]. The last approach, together with the apparatus of fuzzy sets, allows estimating the uncertainty of the measurement [5]. Corrective coefficients were proposed for error of measuring current transformers compansation [6]. However, the disadvantage of this approach is low efficiency in the reduced load mode of the metering unit.

The aim of the study.

The aim is to increase the accuracy of electricity metering in the reduced load mode due to mathematical modeling of the phase currents influence of the electricity metering unit on measurement uncertainty. This will allow to obtain a tool for estimating the underaccounting of electricity, which will make it possible to increase the accuracy of financial calculations between consumers and suppliers of electricity.

Results of the study of measurement uncertainty.

We denote the electricity meter, as part of the accounting unit, PI1, and the measuring current transformers TA$_A$, TA$_B$, TA$_C$. The readings of this meter are the basis for calculations for consumed electricity. The actual value of the consumed energy is suggested to be estimated in experiments by the readings of the directly connected meter PI2. The relative deviation of the electricity, calculated according to the PI1 readings, from the actual value, based on the PI2 readings, is defined by the dependence:

$$\delta W(I_A, I_B, I_C) = \sum_{\zeta} [I_\zeta \cdot \delta W_\zeta(I_\zeta)] \cdot \left(\sum_{\zeta} I_\zeta \right)^{-1} . \tag{1}$$

To estimate the measurement uncertainty of the relative deviation $\delta W_{\zeta}(I_{\zeta})$ of the meter readings for one measuring channel depending on the current I_{ζ} value, it is proposed to find, at the confidence level λ_j^*, the boundaries of the fuzzy interval [7]:

$$\delta W_{\zeta}(I_{\zeta}) = \left[\delta W_{L\zeta}(I_{\zeta})\Big|_{\lambda_j^*};\ \ \delta W_{R\zeta}(I_{\zeta})\Big|_{\lambda_j^*} \right]. \tag{2}$$

The boundaries for $j = \overline{1,\Lambda}$ determined by (2) allow, using (1), to obtain fuzzy intervals [8]:

$$\delta W_{L(R)}(I_A, I_B, I_C)\Big|_{\lambda_j^*} = \sum_{\zeta}\left[I_{\zeta} \cdot \delta W_{L(R)\zeta}(I_{\zeta})\Big|_{\lambda_j^*} \right] \cdot \left(\sum_{\zeta} I_{\zeta} \right)^{-1}. \tag{3}$$

The set of fuzzy intervals (3) defines a fuzzy function, which, depending on the phases load of the electricity metering unit, makes it possible to estimate the measurement uncertainty, namely:

$$\delta W(I_A, I_B, I_C) = \sum_{\zeta}[I_{\zeta} \cdot \delta W_{\zeta}(I_{\zeta})] \cdot \left(\sum_{\zeta} I_{\zeta} \right)^{-1}. \tag{4}$$

Experimental studies were carried out using digital meters: PI1 type NIK2307 ART T.1600.M2.21; PI2 – NIK2307 ARP3 T.1600.M2.21. Measuring current transformers T-0.66-600/5 were used. Equipment was of 0.5S accuracy class. Approximation of the boundaries (2) of fuzzy functions $\delta W_{\zeta}(I_{\zeta})$ at confidence levels 0.8, 0.75, ..., 0.2 was carried out by the sum of exponents with a set of parameters $\{K\} = \{K^{(1)}, \ldots, K^{(5)}\}$, namely:

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

At a confidence level of 0.8 for phase B, the set of parameters for function (5) was:

$$\{L_{B1}\} = \{-1.78 \cdot 10^4;\ \ -1.00 \cdot 10^2;\ \ 2.49 \cdot 10^{-2};\ \ 9.73 \cdot 10^3;\ \ 9.87 \cdot 10^1\};$$

$$\{R_{B1}\} = \{-2.56 \cdot 10^4;\ \ -9.84 \cdot 10^{-1};\ \ 2.33 \cdot 10^{-2};\ \ -1.09 \cdot 10^4;\ \ 9.91 \cdot 10^{-1}\}.$$

The fuzzy function (4) makes it possible to estimate the uncertainty of electricity measurement by the metering unit for specific values of phase currents.

In laboratory conditions at currents I_A^*=1.02 %, I_B^*=0.18 %, I_C^*=0.22 %, the branches of the membership function μ_{abc} for (4) were approximated by polynomials:

$$\mu_{abc_L} = 1.60 \cdot 10^{-3} \cdot \delta W^3 + 4.30 \cdot 10^{-2} \cdot \delta W^2 + 3.94 \cdot 10^{-1} \cdot \delta W + 1.75. \tag{36}$$

$$\mu_{abc_R} = -2.28 \cdot 10^{-1} \cdot \delta W + 4.20 \cdot 10^{-1}. \tag{37}$$

For the experimental value of the relative deviation $\delta W_e = -5.6\%$, the actual confidence level is equal to: $\lambda_e^* = \mu_{abc_L}(\delta W_e) = 0.61$. For different levels of phase currents, 7 experiments were carried out, in each of which the actual value of the confidence level was estimated using the obtained mathematical model. The latter value was not lower than 0.54, which confirms the adequacy of the mathematical model to the experimental data.

Conclusions.

The proposed mathematical model makes it possible to estimate the uncertainty of electricity measurement in the reduced load mode of the metering unit. A characteristic feature of the model is taking into account the actual levels of phase currents. This determines the possibility of using the model as part of the metering software for correct electricity estimating during the downtime of technological equipment.

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