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ALGORITHMS FOR AUTOMATIC OF METROLOGICAL CHARACTERISTICS OF TRANSDUCERS

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Summary. *The algorithms for automatic correction of metrological characteristics of high-voltage instrument transformers in the absence of benchmark measurement signals at the source input are proposed. The investigated algorithm can be applied for automatic correction of metrological characteristics of measuring channels in the case of multiplicative distortions caused by the nonlinear dependence of the transmission coefficient on the input value*

Key words. *Systematic error, primary measuring sources, automatic correction, algorithm, iteration procedure.*

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Statement of the problem. Measurement of electric power and electricity metering is carried out in high-voltage circuits using primary measuring sources – current and voltage transformers. The errors are primarily determined by the metrological characteristics of primary measuring sources and are established by the passport data of the manufacturer. Errors of instrument transformers include systematic and random components. The systematic component of the measurement error exceeds the random one by an order of magnitude. Therefore, the main problem is to reduce the systematic error of primary measuring sources.

Actual scientific research and analysis of problems. Primary measuring sources make it possible to measure the power consumption with an error of $5 \div 10\,\%$, while the error should be within $0{,}5 \div 1\ \%$ [1]. As a result of research, it was found that it is possible to experimentally determine the metrological characteristics of instrument transformers directly at substations, under conditions of their continuous operation, without disconnecting from the high-voltage network [2, 3, 4, 5].

Based on the metrological characteristics of instrument transformers, to compensate for the systematic error correction, the tables are compiled and the results of power measurements and electricity metering are corrected. The correction is performed automatically using a computer and an appropriate algorithm [1, 2]. The use of measurement correction can reduce the errors of electric power measurements by more than five times [2, 3].

However, during commissioning work in circuits with primary transducers, the correction values are often distorted by additive, multiplicative and multiplicative-additive errors [4], and that requires a change in the correction algorithm. In this case, it is proposed to use the information about the value of the nominal conversion coefficient obtained at the high-precision installations of the manufacturer [4, 5]. The proposed algorithm for compensations of additive, multiplicative, and multiplicative-additive distortions allows to reduce the value of errors due to the use of calculated corrections obtained as a result of the convergence of the iterative compensation algorithm [4, 6, 7].

Objectives of the investigation. The main feature of the above studies is the presence of benchmark values at the input of the primary measuring source. However, practically, it is

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not always possible to have an benchmark values of the measurand of a high-voltage source. That is, in this case it is impossible to apply the traditional method of obtaining corrections. Under these conditions, it is necessary to build an algorithm of correction and selection an iterative procedure.

Presentation of material. The high-voltage transducer is described by the conversion function of the measuring value as [5, 6]:

$$y = K_n \cdot x, \tag{1}$$

where, x and y are values of the measurement parameter, respectively, at the input and output of the transducer, K_n is a nominal conversion coefficient [4].

Distortion of metrological characteristics of transducers is estimated by the deviation of K_n from the nominal value and they can be multiplicative, additive, and multiplicative and additive [4,5]. In the case of multiplicative distortions, each measured value of the signal at the output of the transducer is described by the expression:

$$\hat{y} = K_n \cdot (1+\alpha) \cdot x, \tag{2}$$

where $\hat{y}$ is the actual value of the output signal; α is the value that estimates the deviation of the transmission coefficient of the transducer from the nominal value. In this case, the relative error δ of the transducer is determined by the ratio:

$$\delta = \frac{y-\hat{y}}{y} = \frac{K_n \cdot x - K_n \cdot (1+\alpha) \cdot x}{K_n \cdot x} = -\alpha. \tag{3}$$

The essence of the automatic correction of the metrological characteristics of the transducer is that each measured value of the signal at the output of this transducer is corrected by means of corrections Π, the value of which is determined by the condition: $y_i - \Pi_i = \hat{y}_i$, which in this case, taking into account the expressions (1) and (2), gives the ratio:

$$\Pi_i = -K_n \cdot \alpha \cdot x_i. \tag{4}$$

However, in this case, it is impossible to set the appropriate measurement experiment and obtain the correction according to expression (4) because of the absence of a benchmark value of the measured value of the high-voltage source.

In this case, it is possible to determine the correction by using the following approach.

In (4), the value $K_n \cdot x_i$ corresponds to the value of the output signal y_i, the actual value of which is not known, but the measured value $\hat{y}_i$ is close to it. It can be used to determine an approximate correction by means of expression (4), the value of which can be used as a first step in an iterative procedure of correction the measured value.

We will show that by using the value $\hat{y}_i$ to determine the approximate values of the corrections and organizing the correction of the value of the measuring value in an iterative way according to a certain algorithm, we will be able to minimize the error of the measurand. Using the relation (4), we obtain:

$$\Pi_i = -K_n \alpha x_i = -\alpha y_i \approx -\alpha \hat{y}_i . \tag{5}$$

The corrected on the basis of the obtained approximate correction value of the measurand at the output of the transducer at the first step of the iterative procedure is described by the expression:

$$y_i = \hat{y}_i + \Pi_i = K_n(1+\alpha)x_i = \alpha K_n x_i (1-\alpha^2). \tag{6}$$

Only one step of correction of the measurand may not be enough, but the use of computing tools makes it possible to organize a further iterative correction procedure. However, there are two possible variants of the algorithm for implementing the iterative procedure. *The first option* is to use the first measured value $\hat{y}_i$ with its further correction at each subsequent iterative step. *The second option* is to correct by means of corrections of each integrated value:

$$\hat{y}_{out.n} = \hat{y}_{out} + \alpha \cdot \hat{y}_{out.(n-1)} ; \tag{7}$$

$$\hat{y}_{out.n} = \hat{y}_{out.(n-1)} + \alpha \cdot \hat{y}_{out.(n-1)} . \tag{8}$$

Research of options of correction algorithms.

If using *the first option of the algorithm*, we obtain the following series of corrected values for each of the n iterations:

$$1)\, y_1 = \hat{y}_1$$
$$2)\, y_2 = \hat{y}_1 - \alpha \cdot \hat{y}_1 = \hat{y}_1 \cdot (1+\alpha)$$
$$3)\, y_3 = \hat{y}_1 - \alpha \cdot \hat{y}_1(1+\alpha) = \hat{y}_1 \cdot (1-\alpha+\alpha^2)$$
$$4)\, y_n = \hat{y}_1 - \alpha \cdot \hat{y}_1 \cdot (1-\alpha+\alpha^2) = \hat{y}_1 \cdot (1-\alpha+\alpha^2-\alpha^3)$$

– –

$$n)\, y_n = \hat{y}_1 \cdot [(1-\alpha+\alpha^2-) = \hat{y}_1 \cdot (1-\alpha+\alpha^2-\alpha^3)$$

For this variant of the algorithm, according to the relation (3), the error of the n-th value of the measurand can be presented as:

$$\delta_1 = 1 - \frac{y_n}{y} = 1 - \frac{y_1 \cdot \left[1-\alpha+\alpha^2 - .... + (-1)^n \cdot \alpha^{n-1}\right]}{y} . \tag{9}$$

It is known that, $\lim\limits_{n\to\infty}\left[(1-\alpha+\alpha^2-....+(-1)^n \alpha^{n-1}\right] = \frac{1}{1+\alpha}$.

By performing the appropriate substitution in relation (9), we obtain the limit value of the error of the measured value at $n \to x$:

$$\delta_1 = 1 - \frac{K_1 x(1+\alpha)}{K_1 x} \cdot \frac{1}{1+\alpha} = 0.$$

Using the *second option* of the algorithm for organizing the iterative procedure, after each of the n iterations the value of the measurand will look like:

$$
\begin{array}{l}
1)\, y_1 = \hat{y}_1 \\
2)\, y_2 = \hat{y}_1 - \alpha \cdot \hat{y}_1 = \hat{y}_1 \cdot (1+\alpha) \\
3)\, y_3 = \hat{y}_2 - \alpha \cdot \hat{y}_2 = \hat{y}_1 \cdot (1+\alpha)^2 \\
4)\, y_4 = \hat{y}_3 - \alpha \cdot \hat{y}_3 = \hat{y}_1 \cdot (1-\alpha)^3 \\
-\,-\,-\,-\,-\,-\,-\,-\,-\,-\,-\,-\,-\,-\,-\,-\,- \\
n)\, y_n = \hat{y}_1 \cdot (1-\alpha)^{n-1}.
\end{array}
$$

In the case of applying the *second variant* of the algorithm the error of the - n value of the measurand will be as follows:

$$\delta_2 = 1 - \frac{y_n}{y} = 1 - \frac{\hat{y}_1 \cdot (1-\alpha)^{n-1}}{y}.$$

According to formula (2), we obtain for δ_2:

$$\delta_2 = 1 - \frac{K_n \cdot x \cdot (1+\alpha) \cdot (1-\alpha)}{K_n \cdot x} = 1 - (1-\alpha)^n \cdot (1+\alpha).$$

Expression $(1-\alpha)^n$ is presented як binominal series:

$$1 - \lim_{n\to\infty, \alpha<1} \left[n \cdot \alpha - \frac{n \cdot (n-1)}{1 \cdot 2} \alpha^{n-1} + \ldots - (-1)^n \alpha^n \right] = 1,$$

and the error δ_2 at $n \to \infty$ is described by the expression $\delta_2 = 1-(1+\alpha) = -\alpha$, that is, it tends to the value of the modulus of the final value $|\alpha|$.

Thus, the *second variant of the algorithm* turns out to be inoperable, when it is applied the error of the measurand despite multiple corrections does not decrease. It makes no sense to introduce the calculated correction into measurand, which is corrected after each iteration step.

The algorithm of automatic compensation of the metrological characteristics of the transducers should be built by organizing such an iterative procedure in which the first measurand is corrected at each step of the iteration.

It should be noted that the determination of the value α (it is necessary for the functioning of the compensation algorithm) is a separate task, which is not considered in this article.

In the case of additive distortions of metrological characteristics of high-voltage transducers, we have a task to investigate the possibility of using this algorithm for this case as well.

We assume that the distortion of the nominal transmission coefficient of the transducer is determined only by the influence of the additive component Δ , and the algorithm that will be investigated is presented as:

$$\hat{y}_n = \hat{y}_1 + \Pi_n, \tag{10}$$

where $\hat{y}_1$ is the first measured value of the output signal, Π_n is the value of the corrections at the n -th iteration, n is the number of iterations.

Since there is no reference value at the input, the measured value of the signal at the channel output could be determined as follows:

$$\hat{y} = K_n \cdot x + \Delta. \tag{11}$$

The error Δ is of a systematic nature and can be compensated by corrections, which can be used by the formula:

$$\Pi = -\delta_a \cdot x / K_n, \tag{12}$$

where δ_a is the value of the relative additive error, x is the value of the signal at the input of the transducer, which is set with high accuracy for the purpose of corrections.

However, according to the input condition, it is not possible to establish a benchmark signal at the input of the transducer, so it is impossible to use formula (12) to determine the corrections. However, in this case, we have parameters K_n , Δ , and the measured inaccurate value of the signal $\hat{y}$ at the channel output, that is described by formula (11). This makes it possible to determine not the experimental, but the calculated value of the corrections of the Π' type:

$$\Pi' = \frac{\delta_a}{K_n}(K_n \cdot x + \delta_a \cdot x). \tag{13}$$

The value of the corrections obtained according to expression (13) is slightly different from the value obtained by formula (12), so expression (13) must be checked for the possibility of its use in the process of automatic correction of the metrological characteristics of the transducer. Using expression (13), we describe the result of the correction in accordance with algorithm (10):

$$\Pi' = \frac{\delta_a}{K_n}(K_n \cdot x + \delta_a \cdot x), \text{ or } \hat{y}_1 = K_n \cdot x - \frac{\delta_a^2 \cdot x}{K_n}. \tag{14}$$

The second addition in the last formula is an expression for determining the absolute value of the additive error Δ_{a1} after the correction of the measured value $\hat{y}$, i.e:

$$\Delta_{a1} = \frac{\delta_a^2 x}{K_n}. \tag{15}$$

The obtained value Δ_{a1} is a value of the second order of smallness. Hence, the conclusion is that the algorithm (10), which was used for automatic correction of the metrological characteristics of the measuring channel when only multiplicative distortions are available, successfully works in the case of its application when the additive distortions are available.

We complicate the problem by assuming the availability of both multiplicative and additive distortions of the metrological characteristic of the transducer and check the possibility of applying algorithm (10) for this generalized case.

In this case the formula for determining the calculated correction, taking into account the formula (13), will look like:

$$\Pi_{\Sigma} = \alpha \cdot K_n \cdot \hat{x} - \frac{\delta_a^2 \cdot x}{K_n}, \tag{16}$$

where Π_{Σ} is the generalized correction when both multiplicative and additive distortions in the metrological characteristic of the transducer are available.

Applying the expression (10), we describe the result of the correction of the output signal using the studied algorithm as:

$$\hat{y} = K_n \cdot (1+\alpha) \cdot x + \delta_a \cdot x - \alpha\left[K_n \cdot (1-\alpha) \cdot x + \alpha \cdot x\right] - \frac{\delta_a}{K_n}\left[K_n \cdot (1+\alpha) \cdot x + \delta_a \cdot x\right].$$

After performing simple transformations, we obtain:

$$\hat{y} = K_n \cdot x - \alpha^2 \cdot K_n \cdot x - 2 \cdot \alpha \cdot \delta_a \cdot x - \frac{\delta_a^2 \cdot x}{K_n}. \tag{17}$$

In formula (14) the components $\alpha^2 \cdot K_n \cdot x$, $2 \cdot \alpha \cdot \delta_a \cdot x$, and $\delta_a^2 \cdot x / K_n$ describe the total error in the output signal caused by the influence of both multiplicative and additive distortions of the metrological characteristics of the transducer. In this total error, new components can be distinguished: additive $-\delta_a^2 \cdot x / K_n$ and multiplicative – $\alpha^2 \cdot K_n \cdot x$. Both of these components are of the second order of smallness. The third component – $2 \cdot \alpha \cdot \delta_a \cdot x$, is associated with the influence of simultaneously additive and multiplicative distortions of the metrological characteristic and it is also of the second order of smallness. As a result of the application of the studied algorithm all three components of the error are reduced to the second order of smallness and this indicates that in this generalized case the algorithm (10) works successfully. This property of the algorithm is the basis for its application for automatic correction of metrological characteristics of high-voltage transducers when both multiplicative and additive distortions are available.

We should mention another property of the studied algorithm in the case of its application for automatic compensation of the metrological characteristics of the transducer at multiplicative distortions caused by nonlinearity, when the value α is a function of the input parameter x. This function can be continuous, in the form of a jump, or be set by separate points (Fig. 1 a, b, c,). Such functions can correspond to the curves of the channel transmission coefficient shown in Fig. 1 d, e, f (straight lines K_n correspond to the nominal values of the conversion coefficient of the transducer).

The systematic error at the output of the channel, caused by the deviation of its transmission coefficient from the nominal value reduces the value K_n is to the value K with the growth of their signal The measured value of the signal at the channel output in this case is:

$$\hat{i} = K\cdot\left(1-\beta\frac{x}{x_n}\right)x, \tag{18}$$

where $\alpha(x)=\beta\cdot x/x_n$ is the nominal value of the input signal (β is the coefficient that determines the nonlinearity of the metrological characteristic of the channel).

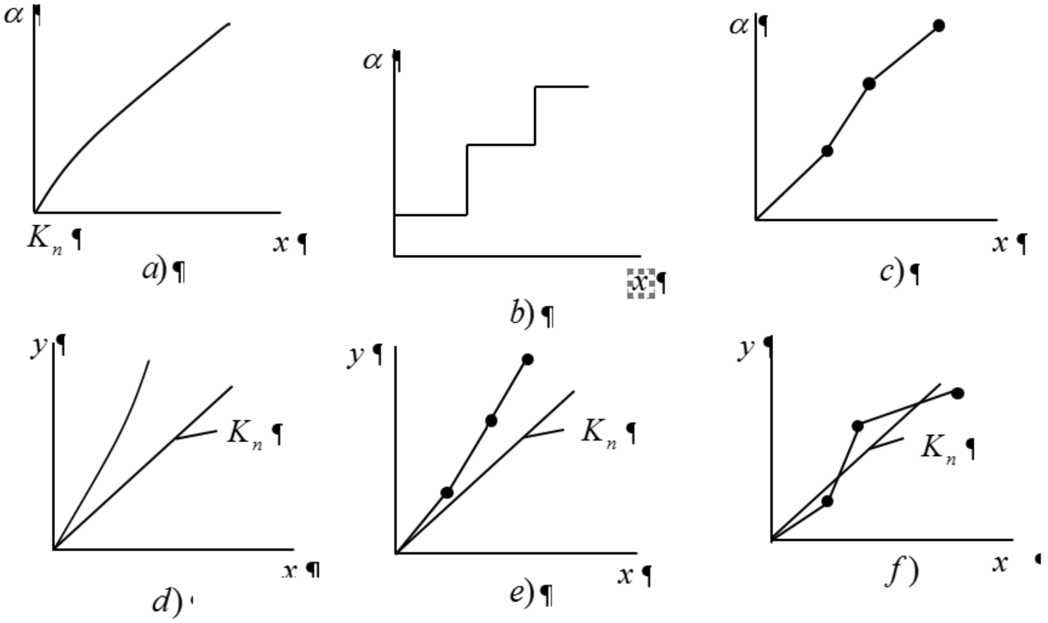

Figure 1. Multiplicative distortions of the metrological characteristics of the measured channel due to nonlinear dependence K_n on the input value

Applying the investigated algorithm in the form of (10), the formula for the corrected value of the output signal is represented by the expression:

$$\hat{i}_1 = K\cdot\hat{x}+\beta\cdot K\frac{\hat{x}}{x_n}\cdot\hat{x}\,, \tag{19}$$

where $\hat{x}=\left(1-\beta\frac{x}{x_n}\right)x.$

After simple transformations of the expression (18), the corrected value of the measurand at the output of the channel is represented as:

$$\hat{i} = K_x\left[1-2\left(\beta\frac{x}{x_n}\right)+\left(\beta\frac{x}{x_n}\right)^3\right]. \tag{20}$$

In this case, according to expression (19), the multiplicative error from nonlinearity is as follows:

$$\delta_M = -\left(\beta\frac{x}{x_n}\right)^2\left(1-\beta\frac{x}{x_n}\right) \approx -\left(\beta\frac{x}{x_n}\right)^2. \tag{21}$$

Since $\beta\frac{x}{x_n} << 1$ the value δ_M has the second order of smallness, which indicates the effectiveness of the correction procedure.

Conclusions. The algorithms for automatic correction of metrological characteristics of high-voltage instrument transformers in the absence of benchmark measurement signals at the source input are proposed.

The investigated algorithm can be applied for automatic correction of metrological characteristics of measuring channels in the case of multiplicative distortions caused by the nonlinear dependence of the transmission coefficient on the input value. In this case, for the practical implementation of the algorithm, the function must be input into the memory of the microprocessor, which provides the process for automatic correction of the metrological characteristics and use the value of this function for each correction point.

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АЛГОРИТМИ АВТОМАТИЧНОЇ КОРЕКЦІЇ МЕТРОЛОГІЧНИХ ХАРАКТЕРИСТИК ВИМІРЮВАЛЬНИХ ТРАНСФОРМАТОРІВ

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Резюме. *Проведені дослідження присвячені розв’язанню проблеми підвищення точності вимірювання електричної потужності та обліку електричної енергії у високовольтних колах. Сучасний підхід ґрунтується на зниженні систематичної складової похибки вимірювання на основі використання зразкових вхідних даних, які представлені метрологічними характеристиками трансформаторів струму та напруги. Спотворення метрологічних характеристик вимірювальних перетворювачів оцінюється відхиленням від номінального значення, які можуть бути мультиплікативними, адитивними та мультиплікативно-адитивними. Підвищення точності здійснюється за допомогою таблиць поправок, а корекція результатів вимірів виконується автоматично на ПК з побудовою відповідного алгоритму. Представлено розв’язок задачі за відсутності зразкових вимірювальних сигналів на вході джерела, що унеможливлює застосування традиційного способу отримання поправок. В цьому випадку для побудови алгоритму запропоновано використовувати наближене значення поправки та організацію ітераційної процедури, при якій перше виміряне значення коригується за допомогою поправок на кожному кроці ітерації. Досліджено та доведено успішність використання отриманого алгоритму й ефективність процедури корекції за наявності одночасно мультиплікативних та адитивних спотворень метрологічних характеристик високовольтних вимірювальних перетворювачів, так як усі отримані складові похибки зводяться до другого порядку малості. Крім цього, показано успішність застосування отриманого алгоритму у випадку його застосування для автоматичної компенсації метрологічної характеристики вимірювального перетворювача при мультиплікативних спотвореннях, зумовлених нелінійністю, коли відхилення коефіцієнта передавання вимірювального перетворювача від номінального значення є функцією від вхідного параметра .*

Ключові слова. *Систематична похибка, первинне вимірювальне джерело, автоматична корекція, алгоритм, ітераційна процедура.*

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