The universal model of error of active power measuring channel

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Abstract-The types of the structures of active electric power measuring channel and features of functions of measuring transformers in their configurations are considered. The universal mathematical model of measuring channel error, which takes into account influence of channel's configuration, individual metrological performances of separate measuring devices, measuring operating conditions and the controlled electric network mode on its value, is developed. The example of application of the offered model is made.

Keywords: model, measuring channel, error.

I. Introduction

The problem of determination and reduction electric losses in networks is a very actual. In our opinion, it is very important to provide high accuracy of electric power measuring. The decision of this task must be based on an analysis and estimating errors of electric power measuring. And it is important to take into account as many as possible influencing factors. Such errors as ±(0,3–0,5)% or (1–2)% are considered as acceptable for the most measuring systems of electric power in Ukraine, which depend on power of the electrical power object (EPO)[1]. In general, over than 30 factors have an influence on the error of electric power measuring. They are exceeding of normative terms of exploitation of separate measuring tools, nonconformity the second loadings of measuring transformers to the set norms, long-term electric networks modes with parameters, which are considerably fewer than nominal, bad quality of electric power and etc [2]. For example, the error of measuring complex, which consists of measuring tools with accuracy class 0,5, can exceed 10% at adverse conditions [3].

Therefore the wide application of electronic watt-hour meters with high accuracy classes does not provide necessary accuracy of electric power measuring. At the same time the errors of electric power measuring determine difficulties in calculation of balances of electric power, they can be reason of overrate of fuel and energy resources or wrong estimation of productive and economical activity of separate enterprises and industry on the whole [4]. Therefore, it's naturally, that the problem of increasing of accuracy of electric power measuring remains in a focus of attention of subjects of Ukrainian energy market. The plenty of publications have appeared last years both in Ukraine and in Russia [5, 6]. This is a result of interest to the problem. These publications are devoted to the analysis of influence of errors of separate components of measuring channel on accuracy of electric power measuring and to possibility to correct the results of measuring. However, most of these approaches didn't take into account the influence of such factors as structure of measuring circuit, possible disagreements in the values of metrological characteristics of phases measuring transformers, unbalanced mode on measuring results. Some of these approaches consider these factors roughly [6]. As set authors, influence of the noted factors on the resultant error of measuring in a number of cases can be considerable.

In this work authors propose the universal mathematical model of error of electric power measuring channel (MC). This mathematical model takes into account all above mentioned factors which influence on the error value. The developed model is basis for the providing of high accuracy of electric power measuring.

II. Mathematical model development

The measurements of electric power in high-voltage electric networks are made by measuring complexes. These complexes consist of groups of measuring current transformers (CT) and measuring voltage transformers (VT), communication lines and measuring devices. Structure of complex is determined by the types of applied metering devices, by their number, by voltage class and by method of implementation of the electric system neutral. Functionally, in such complex it is possible to select MC, which is providing active power and energy measuring in one point of account. Such MC consists of three component parts: meter-three-phase voltage circuit, meter-three-phase current circuit and three-phase electric power meter (fig.1).

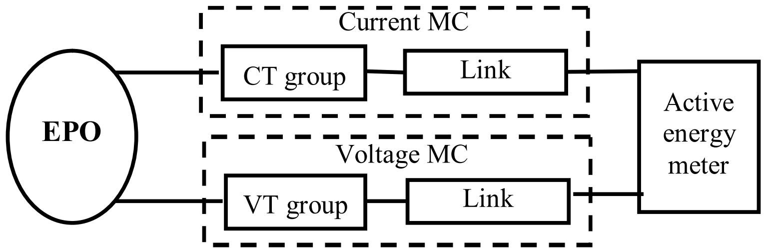

Figure 1. Electric power measuring channel

In three-phase electric networks measuring of currents are made by groups of transformers which have two or three CT. Measuring of voltages are made by groups of single-phase VTs or three-phase VT. Usually there are three-phase energy meters with two or three measuring elements in such MC. Combinations of the three-phase current and voltage meter circuits and the number of measuring elements of meter determine six possible structures of MC. There are two most widespread MC configurations in the electric systems: a) the Aron circuit which is typical for the 6-35 kV electric networks (neutral is isolated). It consists of two-element meter, of two phase CT and of two VT, which are connected on the opened triangle; b) circuit consisting of three phase CT, of three phase VT and of three-element meter. This circuit is typical for 110 kV and higher electric networks (neutral is earthed).

Studies of measuring transformers behavior in MC have showed that the conditions of phase transformers operation in the channel can differ from the conditions of single transformer operation. Their errors are different accordingly. Generally, the behavior of every measuring transformer in a three-phase circuit is depend on intensity and character of own input signal and second loading, and on intensity and character of input signals and second loadings all transformers of the group. Inequality of number of transformers in a group and measuring elements in a meter, the three-phase load unbalance, in particular, due to connecting measuring devices for current and voltage monitoring only to the phase A, define the difference of phase measuring transformers loadings. For example, in the symmetrical mode second loadings of two CT in phases A and C with connected a three-element meter, are equal on the module, but their phases differ on 60°. Thus, at the analysis of active power and energy measuring errors, measuring transformers groups is necessary to consider as the single measuring tool. Such approach complicates estimation of electric power MC errors, but it provides high precision and top quality of solving energy-savings problems.

Reference [7] offers the approach to develop the model of estimation of single measuring transformer errors. The authors apply this approach to develop the universal model of errors estimation of three-phase groups of such transformers. The input and output signals of circuit of three-phase voltage measuring transformation can be described as follows complex matrices-vectors:

$$[U_{EPO}] = \begin{bmatrix} \dot{U}_A \\ \dot{U}_B \\ \dot{U}_C \end{bmatrix}, \quad [U_M] = \begin{bmatrix} \dot{U}_1 \\ \cdots \\ \dot{U}_k \end{bmatrix},$$

where $\dot{U}_A$, $\dot{U}_B$, $\dot{U}_C$ – phase voltages of controlled EPO; $\dot{U}_1$, ... $\dot{U}_k$ – input voltages of k-element meter.

Generally, procedure of signal measuring in MC can be presented as a sequence of operations of transformation of information. There are four such operations in three-phase voltage MC. Mathematically multioperation procedure of three-phase voltage measuring can be presented in a next kind:

$$[U_M] = [M4^U]\cdot[M3^U]\cdot[M2^U]\cdot[M1^U]\cdot[U_{EPO}] = [M_c^U]\cdot[U_{EPO}], \tag{1}$$

where $[M1^U]$ – the topological matrix, which describes scheme of phase VT primary winding connections; $[M2^U]$ – the matrix, which characterizes the real scale transformation of voltages in separate VT; $[M3^U]$ – the matrix, which characterizes potential drops in the connection lines between VT and their secondary loads; $[M4^U]$ – values of elements of this topological matrix is determined the scheme of connection of VT second windings and meter measuring elements; $[M_c^U]$ – the matrix of general voltage transformation in MC.

Elements of matrixes $[M1^U]$, $[M4^U]$ are determined only the topology of circuit, while values of elements of matrixes $[M2^U]$, $[M3^U]$ depend on the operation modes of network and the VT second loading changes. In particular, the elements of matrix $[M2^U]$, which characterizes transformation of signals in the measuring transformers, are determined the amplitude and phase errors of separate transformers of group. These errors depend on input signals and secondary loads of transformers.

Measuring transformation of three-phase current in the point of account $[I_{EPO}]$ to the system of meter input currents $[I_M]$ can be presented as the sequence of three operations. It is possible to ignore influence of connection line between CTs and meter:

$$[I_M] = [M3^I]\cdot[M2^I]\cdot[M1^I]\cdot[I_{EPO}] = [M_c^I]\cdot[I_{EPO}], \quad (2)$$

where matrixes $[M1^I]$, $[M2^I]$, $[M3^I]$ are calculated like matrixes $[M1^U]$, $[M2^U]$, $[M4^U]$ (1).
Model of transformation of information in the meter can be presented as a sequence of two operations: the first is T_{kM}, which simulates the algorithm of active power calculation taking into account the number k of meter measuring elements; and the second is $T_{\delta M}$, which characterizes influence of meter metrological performances on the result of measuring.
The calculation of active power in a meter is executed on the following algorithm:

$$P_M = \mathrm{Re}\sum_{j=1}^{k} \overset{*}{I}_{Mj}\,\dot{U}_{Mj} \quad (3)$$

where $\dot{I}_{Mj}, \dot{U}_{Mj}$ – current and voltage, which are given on the j-th measuring element of meter.
In a matrix kind (3) it is possible to write as follows:

$$P_M = \mathrm{Re}\left([\overset{*}{I}_M][U_M]\right) \quad (4)$$

where $[\overset{*}{I}_M]$ – the adjoint and transposed matrix.
The meter error δ_M is a sum of a basic meter error δ_{Mb} and additional errors δ_{Mi} from l influencing factors, namely, derivation of voltage, of frequency, of ambient temperature, of magnetic-field and others:

$$\delta_M = \delta_{Mb} + \sum_{i=1}^{l}\delta_{Mi}\ .$$

Thus measuring power by a meter is given by the following equation:

$$P_{meas} = P_M(1+\delta_M) = P_M\left(1+\delta_{Mb}+\sum_{i=1}^{l}\delta_{Mi}\right). \quad (5)$$

On the basis of MC structural elements mathematical models (1–5) formalized mathematical description of multiple-operation procedure of active electric power measuring has been executed and the diagram of determination of error of channel has been built (fig.2).

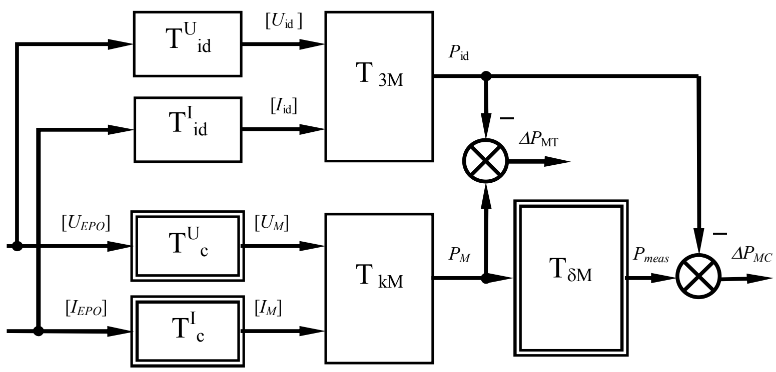

Figure 2. Flow diagram of determination of active-power measuring error

The modules T^U_c and T^I_c accordingly reflect measuring transformations of three-phase voltage (1) and of three-phase current (2). Transformation of information in the meter is presented on flow diagram with two modules: T_{kM} and $T_{\delta M}$, which are described on the top.
The branch of the ideal power measuring is represented by a channel, which consists of three CT, of three VT and of three-element energy meter. This channel measures the power most exactly. There are three modules in it. The modules T^I_{id} and T^U_{id} simulate the ideal scale transformations of phase currents and voltages of EPO in accordance with the rated transformation ratio of CT and VT; T_{3M} simulate the algorithm of calculation of active-power in a three-element meter as sums of phase powers.
Thus, total error of active power measurement by MC can be calculated using the following equation:

$$\Delta P_{MC} = P_{meas} - P_{id} = P_M(1 + \delta_M) - P_{id} = \Delta P_{MT} + \delta_M P_M. \quad (6)$$

The error component ΔP_{MT} is equal to the difference between the meter input power P_M and power P_{id}. It is determined by the metrology descriptions of CTs and VTs, by their loadings, by the number and charts of connection in groups, by the number of measuring elements of meter and by parameters of connection lines. Thus ΔP_{MT} takes into account all of the sources of errors in MC except for basic and additional errors of meter. ΔP_{MT} is calculated, taking into account (1), (2) and (4), as follows:

$$\Delta P_{MT} = \mathrm{Re}\left(\left[\overset{*}{I}_{EPO}\right]\left(\left[M_c^{IU}\right] - \left[M_{id}^{IU}\right]\right)\left[U_{EPO}\right]\right) = Re\left(\left[\overset{*}{I}_{EPO}\right]\left[M_\Delta^{IU}\right]\left[U_{EPO}\right]\right), \quad (7)$$

where $\left[M_c^{IU}\right]$ – matrix of measuring transformation of current and voltage in MC:

$$\left[M_c^{IU}\right] = \left[\overset{*}{M_c^I}\right]\left[M_c^U\right]; \quad (8)$$

$\left[M_{id}^{IU}\right]$ – matrix of ideal scale transformations of current and voltage; $\left[M_\Delta^{IU}\right]$ – matrix, which determines the error ΔP_{MT}:

$$\left[M_\Delta^{IU}\right] = \left[M_c^{IU}\right] - \left[M_{id}^{IU}\right]. \quad (9)$$

Converting (6) it is obtained:

$$P_{meas} = P_{id}\,(1+ \delta_{MT})(1+ \delta_M) = P_{id}\,(1+ \delta_{MT} + \delta_M + \delta_{MT}\,\delta_M).$$

Then total relative error of power measuring MC, at neglecting components of the second order infinitesimal, equal:

$$\delta_{MC} = \delta_{MT} + \delta_M. \quad (10)$$

III. Experimental test of the model

The model was tested with the data of experiment from the parallel account of electric power by two electronic meters ("Elvin", Ukraine) of the same accuracy class. One of them was connecting to the group of two CTs TPL-10 (accuracy class 0,5) and the group of two VTs. Second meter was connecting to the group of two CTs SL-10 (accuracy class 0,2S) and the same group of two VTs. The errors of each of these CTs had been experimentally determined at the real loading and at different values of primary currents.

The experiment was carrying out during a month on operating substation. The values of active and reactive energy were fixed by meters on 30-minute intervals. The errors of measuring of electric power δ_{MCex} were determined every day as difference of data of MC with CT of accuracy class 0,5 and data of MC with CT of accuracy class 0,2S.

The developed model was used to calculate the error of MC with CT of accuracy class 0,5 on each of the 30-minute intervals. From these data the error δ_{MC} was determined for every day. Accepted, that the networks mode is symmetrical, voltage is equal to its rated value and VT's errors can be neglected.

The results of calculation of errors for two days with the middle and minimum currents of EPO are given in Table 1.

Table 1. Comparison the experimental error δ_{MCex} and the calculated error δ_{MC}

Range of currents I_1/I_{rat}, %	Range φ, °	Experimental error δ_{MCex},%	Calculated error δ_{MC},%
7– 15	20 ÷ 34	-0,61	-0,64
0,4 –1,3	-4 ÷ -62	-3,43	-1,76

IV. The examples of application of mathematical model

Let's consider determination of error δ_{MC} of MC on fig.3.

The current errors and phase displacements of CTs in phases A and C are denoted by f_{CTA}, θ_{CTA}; f_{CTC}, θ_{CTC}. The errors of VTs, which are connected on voltages U_{AB} and U_{CB}, are denoted by f_{VTAB}, θ_{VTAB}; f_{VTCB}, θ_{VTCB}. Potential drops in the connection lines between group of VTs and their secondary loads do not take into account.

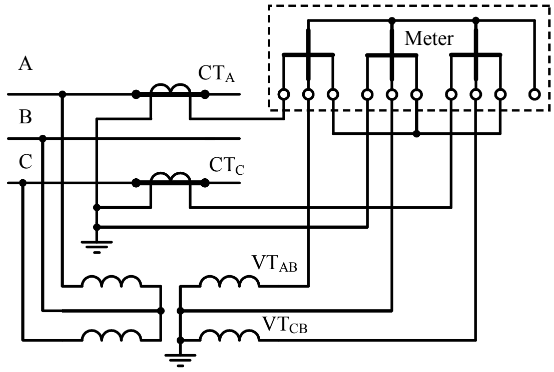

Figure 3. MC consisting of two CT, of two VT and of three-element meter

The matrixes of measuring transformation of three-phase currents and three-phase voltages in this circuit according to (1), (2) are equal:

$$\left[M_c^U\right]=\begin{bmatrix} 2/3 & -1/3 \\ -1/3 & -1/3 \\ -1/3 & 2/3 \end{bmatrix}\times\begin{bmatrix} \frac{1+f_{VTAB}}{Kn_U}e^{j\theta_{VTAB}} & 0 \\ 0 & \frac{1+f_{VTCB}}{Kn_U}e^{j\theta_{VTCB}} \end{bmatrix}\times\begin{bmatrix} 1 & -1 & 0 \\ 0 & -1 & 1 \end{bmatrix},$$

$$\left[M_c^I\right]=\begin{bmatrix} 1 & 0 \\ -1 & -1 \\ 0 & 1 \end{bmatrix}\times\begin{bmatrix} \frac{1+f_{CTA}}{Kn_I}e^{j\theta_{CTA}} & 0 \\ 0 & \frac{1+f_{CTC}}{Kn_I}e^{j\theta_{CTC}} \end{bmatrix}\times\begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix},$$

here Kn_U, Kn_I – rated transformation ratios of VTs and CTs.
The matrix $\left[M_\Delta^{IU}\right]$ for this circuit is calculated using the equations (8), (9):

$$\left[M_\Delta^{IU}\right]=\frac{1}{Kn_I Kn_U}\times$$

$$\times\begin{bmatrix} (1+f_{CTA})\cdot(1+f_{VTAB})e^{j(\theta_{VTAB}-\theta_{CTA})}-1 & -(1+f_{CTA})\cdot(1+f_{VTAB})e^{j(\theta_{VTAB}-\theta_{CTA})} & 0 \\ 0 & -1 & 0 \\ 0 & -(1+f_{CTC})\cdot(1+f_{VTCB})e^{j(\theta_{VTCB}-\theta_{CTC})} & (1+f_{CTC})\cdot(1+f_{VTCB})e^{j(\theta_{VTCB}-\theta_{CTC})}-1 \end{bmatrix}.$$

1. Let's consider that the VTs, the CTs and the meter are the ideal measurement instruments i.e. their errors equal zero. Thus, the error ΔP_{MT} depends only on configuration of MC. By performing transformation of (7), we obtain:

$$\Delta P_{MT}=Re\left(-\frac{1}{Kn_U Kn_I}\dot{U}_B\left(\overset{*}{I}_A+\overset{*}{I}_B+\overset{*}{I}_C\right)\right).$$

In the case of single phase-to-ground fault in three-phase isolated neutral system or in asymmetrical modes of grounded neutral systems there is zero-sequence current $\dot{I}_0$. Then we have the following value of error:

$$\Delta P_{MT}=-\frac{3}{Kn_U Kn_I}U_B I_0 \cos\varphi_{B,0},$$

here $\varphi_{B,0}$ – angle between vectors $\dot{U}_B$ and $\dot{I}_0$.
Such error can reach at a few percents of measuring power in networks with an isolated neutral under the long-time modes of earth-faults of one of phases on which CT is set.

2. The developed model is used to calculate the errors δ_{MC} of MC with CTs TPL-10 of accuracy class 0,5 (see section III) in balanced operating conditions at different primary currents and power factors *cos φ.* As an example fig. 4 shows the influence of the network mode (angle φ) on an error of MC.

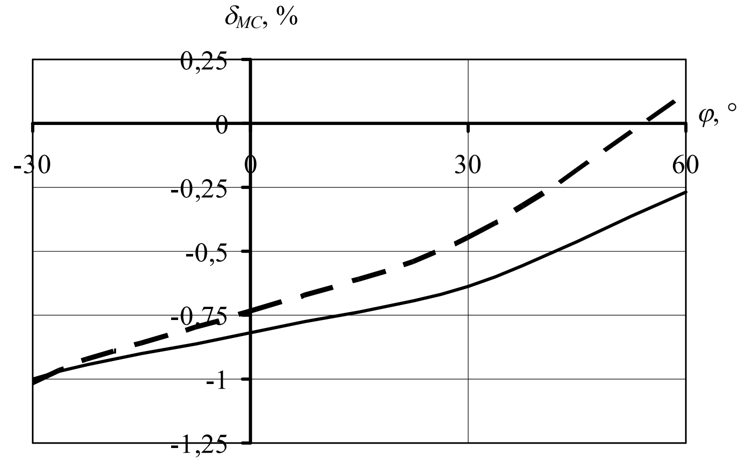

Figure 4. Dependence of the error of MC at the 10% nominal current from the angle φ

For comparison the same dependence calculated by employing other model shows of the dotted line. This model described in the Ukrainian normative document [6] doesn't take into account disagreements in the values of metrological characteristics of phases measuring transformers and recommends calculating of MC error by arithmetic average of CT errors. It explains the disagreement in a results.

V. Conclusions

The developed universal mathematical model of error of active power measuring channel on comparison with existent model allows additionally to take into account complex influence of different factors on the resultant error of measuring. These are the structure of channel, disagreements in the values of metrological characteristics of phases measuring transformers, the unbalanced mode, etc. It provides more exact analysis and evaluation of errors of electric power measuring. The model is theoretical basis for the design the measuring channels of optimum structure and high accuracy by implementation of effective methods of errors correction in the process of power measuring.

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