Parameter Identification of Transformers and Transmission Lines Based on Synchronized Measurements

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Abstract - **The parameters of power transformers and transmission lines, as a rule, are determined by reference data, but during the operation, it might vary essentially from the actual data. There are noted the reasons for the parameters' modification. This paper explains the opportunity of parameter identification based on the synchronized measurements during the operation of the studied object. The methods of parameter identification can be based on one, two or more measurements. Two-winding power transformers and transmission lines can be represented in the form of quadripole, so, applying only the current and voltage synchronized measurement on both terminals it is possible to obtain parameters of the Γ-, T- and Π-forms equivalent schemes. There are presented a final and intermediate formula for transformer parameters. Also, there are obtained a similar formula for transmission lines. Besides, for transmission lines, there are obtained expressions for the method of the current balance, then for power balance. The last-mentioned methods are based on two samples of measurements and haven't been previously described in any other source. All proposed methods were verified with the models of real transformers and transmission lines. The obtained results show the high accuracy of parameter identification for the proposed methods. For power transformers, the influence of load factor upon the values of parameters was analyzed. It is worth noting that the most reliable results are obtained from measurements at the load factor β=0.55..0.85. For the model of the transmission line, there were compared the results of all proposed methods: the relative errors of calculation for all mentioned methods are less than 1%. The main contribution of this paper lies in the explanation of the novel method of quadripole (based on one measurement) for parameter identification of transformers and electric lines. That represents a good advantage over other methods with multiple measurements.**

Cuvinte cheie: *transformator, linie electrică, măsurări sincronizate, parametrii schemelor echivalente în forma in Γ, T şi Π, pierderi de mers în gol, coeficienţii cuadripolului, balanţa curenţilor, balanţa puterilor.*

Keywords: *transformer, transmission line, synchronized measurements, parameters of equivalent circuit in Γ-, T- and Π-forms, no load losses, quadripole coefficients, currents balance, powers balance.*

I. INTRODUCTION

Transformers and transmission lines (TL) being the most used elements of transmission and distribution power systems have their own specific mathematical models, that take the form of equivalent schemes. The parameters of equivalent schemes are widely used for identification of power and energy losses, fault location, diagnostics of the equipment deterioration, relay settings calculation, etc. As a rule, these parameters are determined from reference or technical data. However, it is mentioned in many sources that parameters may change their values during operation or may be set incorrectly due to a number of factors not being taken into account. For example, in [9] it is specified that probable errors in series resistance setting for electric lines are about 18-20%, series reactance error changes within ±10%, shunt conductance and shunt susceptance errors vary within the limits of ±30%.

The accurate knowledge of power transformer parameters, probably, is even more important, because there are noted some problems in this domain in the energy sector of many The Commonwealth of Independent States (CIS) countries: a significant part of the transformers has run out of life, but continues to be operated due to lack of financial resources for their replacement, in addition, there is a high level of actual electricity losses [1]. Windings and insulation are the most susceptible to numerous aggressive factors and determine the life of the transformer. But the existing methods that perform diagnostics on a working transformer (partial discharge method, infrared diagnostics) do not allow estimating the technical condition of its separate elements. In many sources [2], [7], [8] specific connections between defects in the transformer and changes in its electrical parameters are described. In the works [4], [5] and [6] it is noted that in the process of operation, the no-load losses ΔP_0 increases, and within 30-40 years of operation, this growth can reach tens of percent (Fig. 1).

No-load losses of transformers are one of the main components of the regulations governing power losses of the power grid utility. In addition, the exact definition of no-load losses is very important for network enterprises in the case when the calculation with the subscribers for the consumed electricity is carried out by metering devices installed at low voltage. In this case, the no-load losses are determined by calculation.

Thus, the problem of identification the electrical parameter of transformers and of the level of no-load losses becomes actual. By changing the resistance of the windings can be judged on the integrity of the electrical circuits and the condition of the contact connections.

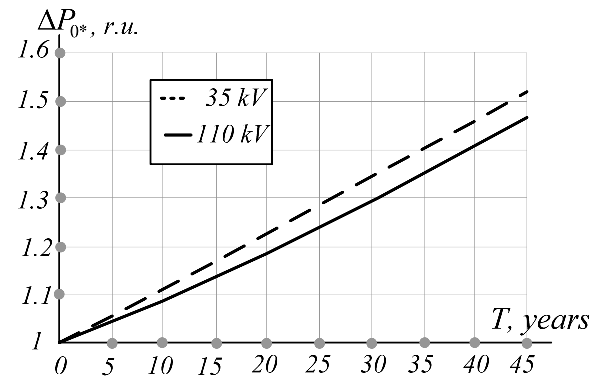

Fig. 1. Character of change of power losses in magnetic cores of power transformers 35 and 110 kV during operation [6].

The change in the series reactance of the windings indicates the presence of deformation and damage in the windings. The losses in the transformer magnetic circuit and its magnetizing power are very important diagnostic parameters, because allow estimating the condition of the transformer magnetic system.

The existing methods of diagnostics of transformer and transmission lines parameters are based on the experiments of no-load and short-circuit. However, these experiments are associated with disconnection of the studied object from the network and losses from undersupply of electricity, as well as labor and material costs.

By using modern devices for recording emergency processes and relay protection installed at both ends of TL or transformer the samples of synchronized voltage and current values measured in real time can be obtained. In turn, this makes it possible to determine the parameters of transformers during their operation. At the moment, methods based on one [9], [11], [12] or two measurement regimes [2], [7], [9], [11] are used to identify the parameters of two-winding transformers.

The main disadvantage of these methods is the need to select several regimes for measurements with similar or identical power values or the presence of non-linear equations. It is also necessary to know in advance the voltage regulation step, and the mathematical model of the transformer should be presented in a strictly defined form. In addition, in [10] it is noted that the existing methods for calculating parameters ensure the correct identification only for the longitudinal parameters of the equivalent circuits (R_t, X_t), and the transverse components (R_μ, X_μ) are determined with significant errors due to the very small value of the no-load current I_0.

This paper proposes a new approach to determining the diagnostic parameters of the transformer based on the results of a single measurement, and might be implemented for different equivalent circuits of a two-winding transformer (Fig. 2). Further in the paper this novel method will be verified for the transmission lines and compared with other methods of TL's parameters identification based on two samples of measurements: methods of currents' balance and powers' balance.

A two-winding transformer can be represented as an asymmetric quadripole (in other words two-port network) regardless of the used equivalent circuit. Then the input and output parameters will be related through the characteristic coefficients $\underline{A}$, $\underline{B}$, $\underline{C}$ and $\underline{D}$. Knowing these coefficients, it will be easy to find the impedance of the longitudinal and transverse branches of any equivalent circuit. Thus, the main task of the proposed method is to calculate the coefficients of the quadripole by the values of the input and output parameters.

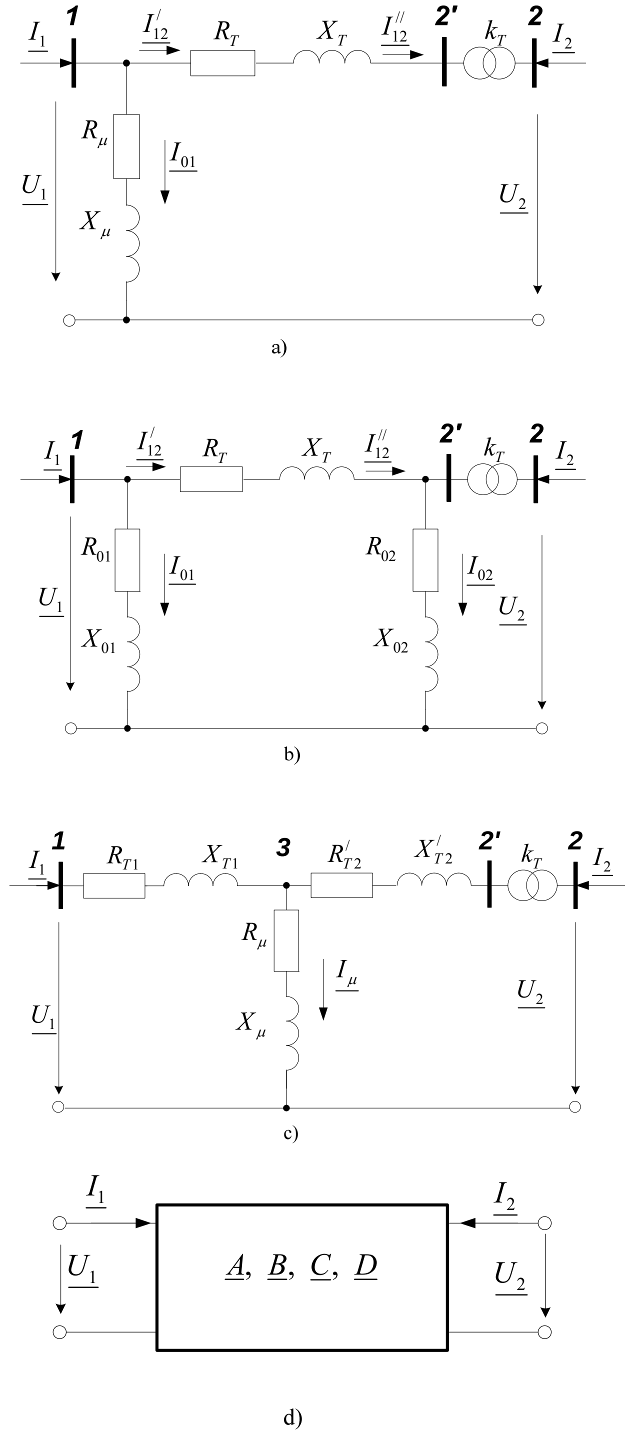

Fig. 2. Equivalent circuit of two-winding transformer: a)Γ-form; b) Π-form; c) T-form; d) as a quadripole.

II. METHOD DESCRIPTION

A. Parameter idetificitation for transformers

The essence of the method will be presented on the example of the Γ-form equivalent circuit (fig. 2 a). The measured values for this circuit are the voltages $\underline{U}_1$ and $\underline{U}_2$ and currents $\underline{I}_1$ and $\underline{I}_2$ in nodes 1 and 2.

For node 1 it is obtained:

$$\underline{I}_1 = \underline{I}_{12}^{/} + \underline{I}_{01}, \tag{1}$$

where

$$\underline{I}_{12}^{/} = \underline{I}_{12}^{/} = \frac{\underline{I}_2}{\overset{*}{\underline{k}}_t}, \tag{2}$$

$$\underline{I}_{01} = \frac{\underline{U}_1}{\underline{Z}_\mu}. \tag{3}$$

It is also known that:

$$\underline{U}_1 = \underline{U}_2 \cdot \underline{k}_t + \frac{\underline{I}_2 \cdot \underline{Z}_t}{\overset{*}{\underline{k}}_t}, \tag{4}$$

here and further $\overset{*}{\underline{k}}_t$ is a conjugate complex of the transformation ratio. Substituting expressions (2), (3) and (4) in (1), it results:

$$\underline{I}_1 = \frac{\underline{I}_2}{\overset{*}{\underline{k}}_t} + \frac{\underline{U}_1}{\underline{Z}_\mu} = \frac{\underline{I}_2}{\overset{*}{\underline{k}}_t} + \frac{\underline{U}_2 \cdot \underline{k}_t}{\underline{Z}_\mu} + \frac{\underline{I}_2}{\overset{*}{\underline{k}}_t} \cdot \frac{\underline{Z}_t}{\underline{Z}_\mu}. \tag{5}$$

If the Γ-form equivalent circuit is represented as the quadripole, then the following equations for quadripole are obtained:

$$\underline{U}_1 = \underline{U}_2 \cdot \underline{k}_t + \frac{\underline{Z}_t}{\overset{*}{\underline{k}}_t} \cdot \underline{I}_2, \tag{6'}$$

$$\underline{I}_1 = \frac{\underline{U}_2 \cdot \underline{k}_t}{\underline{Z}_\mu} + \frac{\underline{I}_2}{\overset{*}{\underline{k}}_t} \cdot \left(1 + \frac{\underline{Z}_t}{\underline{Z}_\mu}\right). \tag{6''}$$

Thus, the values of the coefficients are obtained:

$$\begin{aligned}
\underline{A} &= \underline{k}_t; \\
\underline{B} &= \frac{\underline{Z}_t}{\overset{*}{\underline{k}}_t}; \\
\underline{C} &= \frac{\underline{k}_t}{\underline{Z}_\mu} = \underline{Y}_\mu \cdot \underline{k}_t; \\
\underline{D} &= \frac{1}{\overset{*}{\underline{k}}_t} \cdot \left(1 + \frac{\underline{Z}_t}{\underline{Z}_\mu}\right).
\end{aligned} \tag{7}$$

Then the main determinant of the quadripole will be equal to:

$$\underline{A} \cdot \underline{D} - \underline{B} \cdot \underline{C} = = \underline{k}_t \cdot \frac{1}{\overset{*}{\underline{k}}_t} \cdot \left(1 + \frac{\underline{Z}_t}{\underline{Z}_\mu}\right) - \frac{\underline{Z}_t}{\overset{*}{\underline{k}}_t} \cdot \frac{\underline{k}_t}{\underline{Z}_\mu} = \frac{\underline{k}_t}{\overset{*}{\underline{k}}_t}. \tag{8}$$

For the real value (no imaginary part) of $\underline{k}_t$ this expression takes the form $\underline{A} \cdot \underline{D} - \underline{B} \cdot \underline{C} = 1$, as for passive symmetrical quadripole.

Next, the values of the coefficients of the quadripole in the case of conversion of the output parameters to the input will be found, for this reason a system of equations is written in matrix form:

$$\begin{bmatrix} \underline{U}_2 \\ \underline{I}_2 \end{bmatrix} = \begin{bmatrix} \underline{A} & \underline{B} \\ \underline{C} & \underline{D} \end{bmatrix}^{-1} \cdot \begin{bmatrix} \underline{U}_1 \\ \underline{I}_1 \end{bmatrix} = = \frac{\overset{*}{\underline{k}}_t}{\underline{k}_t} \cdot \begin{bmatrix} \underline{D} & -\underline{B} \\ -\underline{C} & \underline{A} \end{bmatrix} \cdot \begin{bmatrix} \underline{U}_1 \\ \underline{J}_1 \end{bmatrix} = \begin{bmatrix} \underline{A}' & \underline{B}' \\ \underline{C}' & \underline{D}' \end{bmatrix} \cdot \begin{bmatrix} \underline{U}_1 \\ \underline{I}_1 \end{bmatrix} \tag{9}$$

Then for the given system of equations the following coefficients are obtained:

$$\begin{aligned}
\underline{A}' &= \frac{1}{\overset{*}{\underline{k}}_t} \cdot \left(1 + \frac{\underline{Z}_t}{\underline{Z}_\mu}\right) \cdot \frac{\overset{*}{\underline{k}}_t}{\underline{k}_t} = \left(1 + \frac{\underline{Z}_t}{\underline{Z}_\mu}\right) \cdot \frac{1}{\underline{k}_t}; \\
\underline{B}' &= -\frac{\underline{Z}_t}{\overset{*}{\underline{k}}_t} \cdot \frac{\overset{*}{\underline{k}}_t}{\underline{k}_t}; \\
\underline{C}' &= -\frac{\underline{k}_t}{\underline{Z}_\mu} \cdot \frac{\overset{*}{\underline{k}}_t}{\underline{k}_t}; \\
\underline{D}' &= \underline{k}_t \cdot \frac{\overset{*}{\underline{k}}_t}{\underline{k}_t} = \overset{*}{\underline{k}}_t;
\end{aligned} \tag{10}$$

$$\underline{A}' \cdot \underline{D}' - \underline{B}' \cdot \underline{C}' = = \frac{\overset{*}{\underline{k}}_t}{\underline{k}_t} \cdot \left(1 + \frac{\underline{Z}_t}{\underline{Z}_\mu}\right) - \frac{\underline{Z}_t}{\underline{k}_t} \cdot \frac{\overset{*}{\underline{k}}_t}{\underline{Z}_\mu} = \frac{\overset{*}{\underline{k}}_t}{\underline{k}_t}.$$

Replacing the expression $\underline{a} = 1 + \frac{\underline{Z}_t}{\underline{Z}_\mu}$ the following equations are obtained:

$$\underline{U}_1 = \underline{U}_2 \cdot \underline{k}_t + \frac{\underline{Z}_t}{\overset{*}{\underline{k}}_t} \underline{I}_2 = \underline{k}_t \cdot \underline{U}_2 + \underline{B} \cdot \underline{I}_2. \tag{11}$$

$$\underline{I}_1 = \frac{\underline{U}_2 \cdot \underline{k}_t}{\underline{Z}_\mu} + \frac{\underline{I}_2}{\overset{*}{\underline{k}}_t} \left(1 + \frac{\underline{Z}_t}{\underline{Z}_\mu}\right) = \underline{C} \cdot \underline{U}_2 + \underline{a} \frac{1}{\overset{*}{\underline{k}}_t} \cdot \underline{I}_2 \tag{12}$$

$$\underline{U}_2 = \left(1+\frac{\underline{Z}_t}{\underline{Z}_\mu}\right)\cdot \underline{U}_1 \cdot \frac{1}{\underline{k}_t} - \frac{\underline{Z}_t}{\overset{*}{\underline{k}}_t}\cdot\frac{\overset{*}{\underline{k}}_t}{\underline{k}_t}\cdot \underline{I}_1 = \tag{13}$$

$$= \underline{a}\underline{U}_1\cdot\frac{1}{\underline{k}_t} - \underline{B}\frac{\overset{*}{\underline{k}}_t}{\underline{k}_t}\cdot\underline{I}_1$$

$$\underline{I}_2 = -\frac{\underline{U}_1\cdot\underline{k}_t}{\underline{Z}_\mu}\cdot\frac{\overset{*}{\underline{k}}_t}{\underline{k}_t} + \underline{I}_1\cdot\overset{*}{\underline{k}}_t = \tag{14}$$

$$= -\underline{C}\cdot\underline{U}_1\cdot\frac{\overset{*}{\underline{k}}_t}{\underline{k}_t} + \underline{I}_1\cdot\overset{*}{\underline{k}}_t$$

Using addition of expressions (11) and (13) the parameter value $\underline{a}$ is displayed:

$$\underline{a} = \frac{\underline{U}_1\cdot\underline{I}_1\cdot\overset{*}{\underline{k}}_t + \underline{U}_2\cdot\underline{I}_2\cdot\underline{k}_t - \left|\underline{k}_t\right|^2\cdot\underline{U}_2\cdot\underline{I}_1}{\underline{I}_2\cdot\underline{U}_1}. \tag{15}$$

The coefficient $\underline{B}$ is determined from the expression (11):

$$\underline{B} = \frac{\underline{U}_1 - \underline{k}_t\cdot\underline{U}_2}{\underline{I}_2}. \tag{16}$$

And from expression (14) the coefficient $\underline{C}$ is determined:

$$\underline{C} = \frac{\left(\left|\underline{k}_t\right|^2\cdot\underline{I}_1 - \underline{k}_t\cdot\underline{I}_2\right)}{\underline{U}_1\cdot\overset{*}{\underline{k}}_t}. \tag{17}$$

Resistance $\underline{Z}_\mu$ is also determined:

$$\underline{Z}_\mu = \frac{\underline{Z}_t}{\underline{a}-1}. \tag{18}$$

The table below will present the formula for determining the coefficients $\underline{a}$, $\underline{A}$, $\underline{B}$, $\underline{C}$ and $\underline{D}$ for Γ-, T- and Π-form equivalent circuits (see TABLE I).

Thus, to determine the coefficients of the quadripole, as well as the transformer impedances by this method, it is necessary to use measurements of currents and voltages in the single regime at the terminals of the primary and secondary windings of the transformer - $\underline{U}_1$, $\underline{I}_1$ and $\underline{U}_2$, $\underline{I}_2$ (otherwise set $\underline{U}_1$, $\underline{S}_1$ and $\underline{U}_2$, $\underline{S}_2$), it is also required to determine the real value of the transformation ratio. Many power transformers are equipped with a voltage regulation system (automatic or mechanical), and to obtain information about k_t remotely at the moment is not possible, thus it is proposed to obtain the value k_t by calculation. If we refer again to the expression (5)

$$\underline{I}_1 = \frac{\underline{I}_2}{\overset{*}{\underline{k}}_t} + \frac{\underline{U}_1}{\underline{Z}_\mu}. \tag{5}$$

and neglect the second term (magnetization current) due to the fact that this will not significantly affect the final result (the error of calculations will be less than 1%), the value of $\overset{*}{k}_t$ can be calculated:

$$\overset{*}{\underline{k}}_t = \frac{\underline{I}_2}{\underline{I}_1}. \tag{19}$$

Then

$$\underline{k}_t = \frac{\overset{*}{\underline{J}}_2}{\overset{*}{\underline{J}}_1}, \tag{20}$$

i.e.:

$$\left|k_t\right|^2 = \overset{*}{\underline{k}}_t\cdot\underline{k}_t = \frac{\underline{I}_2}{\underline{I}_1}\cdot\frac{\overset{*}{\underline{I}}_2}{\overset{*}{\underline{I}}_1} = \frac{\left|\underline{I}_2\right|^2}{\left|\underline{I}_1\right|^2} \tag{21}$$

Thus, the modulus of the transformation ratio is determined by a simplified formula:

$$\left|k_t\right| = \frac{\left|\underline{I}_2\right|}{\left|\underline{I}_1\right|} \tag{22}$$

The resulting value k_t is then compared with the nominal value to determine the voltage regulation tap - n. Thus, it is simple to find the real value of the transformation ratio during the measurement.

B. Parameter identification of transmission lines

Similar to a two-winding transformer the transmission line can be represented by the equivalent scheme in Γ-, T- and Π-forms. The most used model of transmission lines has the equivalent scheme in Π-form (Fig. 3).

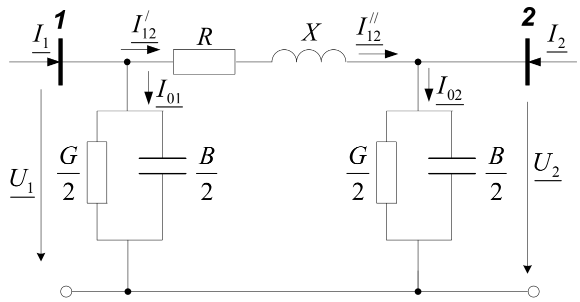

Fig. 3. Equivalent scheme of the transmission line in Π-form.

Taking into consideration that transmission line can be represented by passive quadripole it is possible to determine the coefficients $\underline{A}$, $\underline{B}$ and $\underline{C}$ ($\underline{D}$ will be equal to $\underline{A}$) for Π-form equivalent circuit.

TABLE I.

FORMULA FOR TRANSFORMER PARAMETERS PRESENTED IN DIFFERENT FORMS

Γ-form		
$\underline{a}=\dfrac{\underline{U_1}\cdot\underline{I_1}\cdot\overset{*}{\underline{k_t}}+\underline{U_2}\cdot\underline{I_2}\cdot\underline{k_t}-\left\lvert\underline{k_t}\right\rvert^2\cdot\underline{U_2}\cdot\underline{I_1}}{\underline{I_2}\cdot\underline{U_1}}$	$\underline{A}=\underline{k_t}$	$\underline{B}=\dfrac{\underline{U_1}-\underline{k_t}\cdot\underline{U_2}}{\underline{I_2}}$
$\underline{C}=\dfrac{\left(\left\lvert\underline{k_t}\right\rvert^2\cdot\underline{I_1}-\underline{k_t}\cdot\underline{I_2}\right)}{\underline{U_1}\cdot\overset{*}{\underline{k_t}}}$	$\underline{D}=\dfrac{1}{\overset{*}{\underline{k_t}}}\cdot\underline{a}$	$\underline{Z_t}=\underline{B}\cdot\overset{*}{\underline{k_t}}$ $\underline{Z_\mu}=\dfrac{\underline{a}-1}{\underline{Z_t}}$
T-form		
$\underline{a}=\dfrac{\underline{U_1}\cdot\underline{I_1}\cdot\overset{*}{\underline{k_t}}+\underline{U_2}\cdot\underline{I_2}\cdot\underline{k_t}}{\underline{I_2}\cdot\underline{U_1}+\left\lvert\underline{k_t}\right\rvert^2\cdot\underline{U_2}\cdot\underline{I_1}}$	$\underline{A}=\underline{a}\cdot\underline{k_t}$	$\underline{B}=\dfrac{\underline{U_1}^2-\underline{k_t}^2\cdot\underline{U_2}^2}{\underline{I_2}\cdot\underline{U_1}+\underline{I_1}\cdot\underline{U_2}\cdot\left\lvert\underline{k_t}\right\rvert^2}$
$\underline{C}=\dfrac{\left((\overset{*}{\underline{k_t}})^2\cdot\underline{I_1}^2-\underline{I_2}^2\right)\cdot\underline{k_t}}{\left(\underline{I_2}\cdot\underline{U_1}+\underline{I_1}\cdot\underline{U_2}\cdot\left\lvert\underline{k_t}\right\rvert^2\right)\cdot\overset{*}{\underline{k_t}}}$	$\underline{D}=\dfrac{1}{\overset{*}{\underline{k_t}}}\cdot\underline{a}$	$\underline{Z_\mu}=\dfrac{\underline{k_t}}{\underline{C}}$ $\underline{Z_t}=\dfrac{2\cdot(\underline{a}-1)}{\underline{Y_\mu}}$
Π-form		
$\underline{a}=\dfrac{\underline{U_1}\cdot\underline{I_1}\cdot\overset{*}{\underline{k_t}}+\underline{U_2}\cdot\underline{I_2}\cdot\underline{k_t}}{\underline{I_2}\cdot\underline{U_1}+\left\lvert\underline{k_t}\right\rvert^2\cdot\underline{U_2}\cdot\underline{I_1}}$	$\underline{A}=\underline{a}\cdot\underline{k_t}$	$\underline{B}=\dfrac{\underline{U_1}^2-\underline{k_t}^2\cdot\underline{U_2}^2}{\underline{I_2}\cdot\underline{U_1}+\underline{I_1}\cdot\underline{U_2}\cdot\left\lvert\underline{k_t}\right\rvert^2}$
$\underline{C}=\dfrac{\left((\overset{*}{\underline{k_t}})^2\cdot\underline{I_1}^2-\underline{I_2}^2\right)\cdot\underline{k_t}}{\left(\underline{I_2}\cdot\underline{U_1}+\underline{I_1}\cdot\underline{U_2}\cdot\left\lvert\underline{k_t}\right\rvert^2\right)\cdot\overset{*}{\underline{k_t}}}$	$\underline{D}=\dfrac{1}{\overset{*}{\underline{k_t}}}\cdot\underline{a}$	$\underline{Z_t}=\underline{B}\cdot\overset{*}{\underline{k_t}}$ $\underline{Z_0}=2\cdot\underline{Z_{01}}=2\cdot\underline{Z_{02}}=\dfrac{\underline{a}-1}{2\cdot\underline{Z_t}}$

Thus, the expressions from table I for transmission line take form:

$$\underline{A}=\frac{\underline{U_1}\cdot\underline{I_1}+\underline{U_2}\cdot\underline{I_2}}{\underline{I_2}\cdot\underline{U_1}+\underline{U_2}\cdot\underline{I_1}}. \tag{23}$$

$$\underline{B}=\frac{\underline{U_1}^2-\underline{U_2}^2}{\underline{I_2}\cdot\underline{U_1}+\underline{I_1}\cdot\underline{U_2}}. \tag{24}$$

$$\underline{C}=\frac{\underline{I_1}^2-\underline{I_2}^2}{\underline{I_2}\cdot\underline{U_1}+\underline{I_1}\cdot\underline{U_2}}. \tag{25}$$

Further the longitudinal and transversal components of transmission line are obtained. So the problem of parameter identification for transmission lines can be solved with the help of the one sample of syncronized measurement of currents and voltages. However, the authors of this paper have elaborated the two-measurement method for transmission line. This novel method is based on the either currents balance or powers balance, applied for Π-form equivalent scheme. It is worth mentioning that in this case it was decided to represent the longitudinal and transversal branches of equivalent scheme with the admittances:

$$G_{12}=\frac{R}{R^2+X^2},\ B_{12}=\frac{X}{R^2+X^2},$$
$$G_{22}=G_{12},\ B_{22}=B_{12}-\frac{b_0\cdot l}{2}. \tag{28}$$

According to the 1st Kirchhoff law for node 2 is obtained:

$$(G_{12}-jB_{12})\cdot\underline{U_1}-(G_{22}-jB_{22})\cdot\underline{U_2}=\underline{I_2}, \tag{29}$$

or by multiplying both parts by conjugate complex of $\underline{U_2}$ it is obtained expression for conjugate value of apparent power

$$(G_{12}-jB_{12})\cdot\underline{U_1}\cdot\overset{*}{\underline{U_2}}-(G_{22}-jB_{22})\cdot\left\lvert\underline{U_2}\right\rvert^2= \\ =\overset{*}{\underline{S_2}}. \tag{30}$$

Further it was decided to move from work in phasor values to work with their projections on the vector $\underline{U_2}$, therefore, values of angles between vector $\underline{U_1}$ and $\underline{U_2}$, named δ_2, and between vector $\underline{U_2}$ and $\underline{I_2}$, named φ_2 are calculated. So the values of $\underline{U_1}$ and $\underline{I_2}$ can be represented by expressions:

$$\begin{aligned} \underline{U_1} &= |U_1| \cdot \cos\delta_2 + j \cdot |U_1| \cdot \sin\delta_2, \\ \underline{I_2} &= |I_2| \cdot \cos\varphi_2 + j \cdot |I_2| \cdot \sin\varphi_2 \end{aligned} \quad (31)$$

Simplifying expression (29) and dividing it into real and imaginary parts there are obtained two different equations with 4 common unknown parameters:

$$\begin{aligned} & G_{12} \cdot |U_2| - G_{22} \cdot |U_1| \cdot \cos\delta_2 + \\ & + B_{12} \cdot |U_1| \cdot \sin\delta_2 = |I_2| \cdot \cos\varphi_2, \\ & - G_{22} \cdot |U_1| \cdot \sin\delta_2 - B_{12} \cdot |U_1| \cdot \cos\delta_2 + \\ & + B_{22} \cdot |U_2| = |I_2| \cdot \sin\varphi_2. \end{aligned} \quad (32)$$

For determining those 4 parameters it is necessary to solve the system of 4 equations rewritten for 2 measurement samples in matrix form:

$$[U] \cdot [Y] = [I],$$

$$[U] =$$

$$= \begin{bmatrix} |U_2^{(1)}| & -|U_1^{(1)}|\cos\delta_2^{(1)} & |U_1^{(1)}|\sin\delta_2^{(1)} & 0 \\ 0 & -|U_1^{(1)}|\sin\delta_2^{(1)} & |U_1^{(1)}|\cos\delta_2^{(1)} & |U_2^{(1)}| \\ |U_2^{(2)}| & -|U_1^{(2)}|\cos\delta_2^{(2)} & |U_1^{(2)}|\sin\delta_2^{(2)} & 0 \\ 0 & -|U_1^{(2)}|\sin\delta_2^{(2)} & |U_1^{(2)}|\cos\delta_2^{(2)} & |U_2^{(2)}| \end{bmatrix},$$

$$[Y] = \begin{bmatrix} G_{12} \\ G_{22} \\ B_{12} \\ B_{22} \end{bmatrix}, \quad (33)$$

$$[I] = \sqrt{3} \begin{bmatrix} |I_2^{(1)}|\cos\delta_2^{(1)} \\ |I_2^{(1)}|\sin\delta_2^{(1)} \\ |I_2^{(2)}|\cos\delta_2^{(2)} \\ |I_2^{(2)}|\sin\delta_2^{(2)} \end{bmatrix} \Rightarrow$$

$$[Y] = [U]^{-1} \cdot [I].$$

That is the essence of the method of current balances.

After simplifying expression (30) and dividing it into real and imaginary parts, it is necessary to solve the system of 4 equations rewritten for 2 measurement samples in matrix form – expressions (34).

$$[U^2] \cdot [Y] = [S],$$

$$[U^2] =$$

$$= \begin{bmatrix} |U_2^{(1)}|^2 & -|U_1^{(1)}||U_2^{(1)}|\cos\delta_2^{(1)} & |U_1^{(1)}||U_2^{(1)}|\sin\delta_2^{(1)} & 0 \\ 0 & -|U_1^{(1)}||U_2^{(1)}|\sin\delta_2^{(1)} & |U_1^{(1)}||U_2^{(1)}|\cos\delta_2^{(1)} & |U_2^{(1)}|^2 \\ |U_2^{(2)}|^2 & -|U_1^{(2)}||U_2^{(2)}|\cos\delta_2^{(2)} & |U_1^{(2)}||U_2^{(2)}|\sin\delta_2^{(2)} & 0 \\ 0 & -|U_1^{(2)}||U_2^{(2)}|\sin\delta_2^{(2)} & |U_1^{(2)}||U_2^{(2)}|\cos\delta_2^{(2)} & |U_2^{(2)}|^2 \end{bmatrix},$$

$$[Y] = \begin{bmatrix} G_{12} \\ G_{22} \\ B_{12} \\ B_{22} \end{bmatrix}, \quad (34)$$

$$[S] = \begin{bmatrix} P_2^{(1)} \\ Q_2^{(1)} \\ P_2^{(2)} \\ Q_2^{(2)} \end{bmatrix} \Rightarrow$$

$$[Y] = [U^2]^{-1} \cdot [S].$$

That is the essence of the method of power balances.

III. CASE STUDIES

In this section there are represented some case studies to demonstrate accuracy of the obtained results and the effectiveness of proposed methods. The calculations were performed with the help of software complex RastWin, which ensured the measured values of currents and voltages at both ends of studied object.

A. Parameter identification for real power transformers

The method for identification the catalog parameters of the power transformers was tested on the transformers of different voltage levels (110/35 kV, 35/10 kV, 10/0.4 kV), of different types (with oil TM or air TS coolant), chosen as the most frequently used in the Moldavian power distribution system.

Calculations of parameters on the basis of mathematical models of real transformers showed high accuracy of determination R_t, X_t and X_μ. However, due to the fact that I_0 is a small value, to ensure reliable value of R_μ is not possible. Therefore, it is proposed to calculate this parameter using the magnitude of the angle of magnetic losses (δ_0):

$$R_\mu = X_\mu \cdot tg\delta_0 \quad (35)$$

There are the results of calculations of parameters for two-winding transformers of different powers and voltage classes, represented by the model in Γ -, T- and Π-form below in the TABLE II.

TABLE II.

ERRORS OF THE IDENTIFIED PARAMETERS FOR DIFFERENT CIRCUIT FORMS

Parameter	TRDN-16000/115/10,5			
	rated, Ω	*Г-form* $\varepsilon_{\%}$	*T-form* $\varepsilon_{\%}$	*П-form* $\varepsilon_{\%}$
R_t	4.391	1.503	5.62	5.716
X_t	86.678	0.085	0.253	0.235
$R_\mu \cdot 10^4$	1.947	1.857	2.56	2.56
$X_\mu \cdot 10^5$	1.148	0.436	3.92	3.92
parameter	**TD-16000/35/10,5**			
	rated, Ω	*Г-form* $\varepsilon_{\%}$	*T-form* $\varepsilon_{\%}$	*П-form* $\varepsilon_{\%}$
R_t	0.431	0.696	4.872	4.872
X_t	6.11	0.033	0.327	0.327
$R_\mu \cdot 10^3$	2.664	0.529	2.831	2.831
$X_\mu \cdot 10^4$	1.218	0.657	2.956	2.956
parameter	**TMN-2500/35/11**			
	rated, Ω	*Г-form* $\varepsilon_{\%}$	*T-form* $\varepsilon_{\%}$	*П-form* $\varepsilon_{\%}$
R_t	4.606	10.074	5.276	5.297
X_t	31.515	0.425	0.235	0.254
$R_\mu \cdot 10^3$	3.28	6.324	4.688	4.332
$X_\mu \cdot 10^4$	3.74	5.963	4.332	4.332
parameter	**TM-1600/10/0,4**			
	rated, Ω	*Г-form* $\varepsilon_{\%}$	*T-form* $\varepsilon_{\%}$	*П-form* $\varepsilon_{\%}$
R_t	0.645	0.465	1.55	1.55
X_t	3.694	0.027	0.162	0.162
$R_\mu \cdot 10^3$	3.07	4.281	1.18	1.18
$X_\mu \cdot 10^4$	1.169	0.68	2.974	2.974
parameter	**TSZ-1600/10/0,4**			
	rated, Ω	*Г-form* $\varepsilon_{\%}$	*T-form* $\varepsilon_{\%}$	*П-form* $\varepsilon_{\%}$
R_t	0.531	1.695	4.896	4.896
X_t	3.712	0.054	0.431	0.431
$R_\mu \cdot 10^3$	0.869	2.378	0.225	0.225
$X_\mu \cdot 10^3$	5.059	1.067	1.502	1.502

Below the graphs of the dependence of the error of determining the parameters for different equivalent circuits on the load factor of the transformer β are represented. The load factor of the transformer is calculated as:

$$\beta = \frac{I_2}{I_{2r}}, \quad (36)$$

where I_{2r} is rated value of secondary current. The study was performed on the basis of mathematical model of power transformer type TRDN-16000/115/10,5.

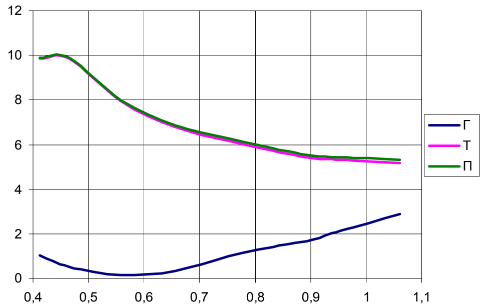

Fig. 4. Dependence $R_t = f(\beta)$

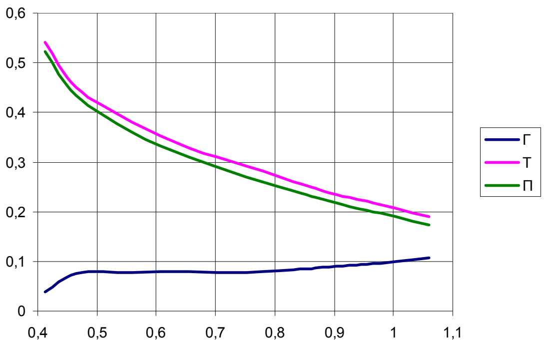

Fig. 5. Dependence $X_t = f(\beta)$

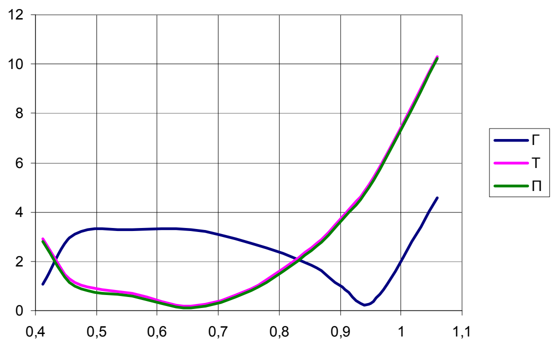

Fig. 6. Dependence $R_\mu = f(\beta)$

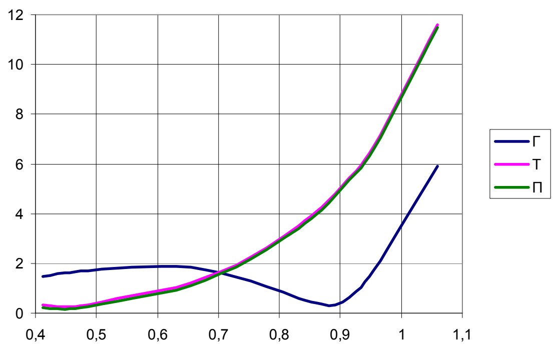

Fig. 7. Dependence $X_\mu = f(\beta)$

The fact that load factor has different effect upon the series and shunt parameters should be taking into consideration while estimating one or another parameter. When considering in the complex the most reliable results will be obtained for the load factor $\beta = 0.55\ldots0.85$.

B. Parameter identification for real transmission line

For verifying the accuracy of results obtained by the method of quadripole, method of currents balance and method of powers balance the model of transmission line 110 kV 100-km-long made AL-OL-185/24 was used. The parameters calculated from catalog data of studied line are:

$$R = 15.4\ Ohms,\ \ X = 42\ Ohms,\ \ B = 2.82 \cdot 10^{-4}\,Sm.$$

These parameters calculated in the admittance form with the help of the formula (28) are shown in the first column of the TABLE III.

There were obtained two samples of measurement for both terminals of TL during the different load factor. The method of quadripole was verified for both samples of measurements. The results are represented in table below.

TABLE III.

TRANSMISSION LINE PARAMETERS (IDENTIFIED AND REFERENCE VALUES)

Parameter/ reference value	**Obtained relative error $\varepsilon_{\%}$, %**			
	quadripole 1st sample	***Quadripole 2nd sample***	***Current balance***	***Power balance***
$G_{12} = 7.96554 \cdot 10^{-3}\,Sm$	0.511	0.511	0.764	0.764
$B_{12} = 20.99 \cdot 10^{-3}\,Sm$	0.037	0.037	0.201	0.201
$B_{22} = 20.85 \cdot 10^{-3}\,Sm$	0.037	0.036	0.201	0.201

Taking into consideration the obtained results it is worth mentioning that the proposed methods ensure high accuracy values of transmission lines parameters, the relative error of calculation in each case being less than 1%.

IV. CONCLUSIONS

The proposed method for determining the passive parameters of a two-winding transformer from synchronized measurements in the operating mode is applicable to all known equivalent circuits, regardless of the power and type of transformer. In general results with least errors were obtained for the Γ-form equivalent circuit. Upon analyzing the sensitivity of the described method it is worth noting that the most reliable results are obtained from measurements at the load factor $\beta = 0.55\ldots0.85$.

All proposed methods of transmission lines parameters identification show high accuracy results for Π-form equivalent schemes. However, the relative errors for method of quadripole are less. The method of quadripole has one more advantage in comparison with methods of current and powers balances: it requires only one sample of synchronized measurements. Besides, it is worth noting that this method can be applied without modifications for T-form equivalent schemes of transmission lines and ensures high accuracy values regardless the load factor of the line.

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REFERENCES

[1] P.A. Butyrin, T.A. Vasikovskaia,M.E. Alpatov, “Research of simplified transformer models,” (in Russian), ELEKTRO, no. 1, pp. 10-12, 2007.

[2] K.A. Andreev, “Increase the efficiency of functional diagnostics of electrical components of power transformers under load,” (in Russian), abstract of Ph.D. thesis. Tula, RF, 2013.

[3] D.V. Dzhumik, “Determination of parameters of equivalent circuits of power transmission lines, power capacitors and resistors, reactors by arrays of instantaneous values of currents and voltages in operating modes,” (in Russian), abstract of Ph.D. thesis. Tomsk, RF, 2008.

[4] A.A. Stepanova, “Improvement of models for calculation and analysis of power and energy losses in power transmission lines,” (in Russian), abstract of Ph.D. thesis. Stavropoli, RF, 2014.

[5] V.V. Korotkov, A.B. Kozlov, A.V. Korotkov, “Quantitative evaluation of the dependence of no-load losses of power transformers on the service life,” (in Russian), Increased efficiency of power systems operation, Edition VIII , Ivanovo, RF, 2007.

[6] P.Iu. Krasovskii, “Calculation of technological losses of electric power taking into account service life,” (in Russian), Electrification of transport, no. 10, RF, 2015.

[7] A. V. Pankratov, “Monitoring of parameters of single-phase transformer equivalent circuits in relation to the task of monitoring the status of their active parts,” (in Russian), abstract of Ph.D. thesis. Tomsk, RF, 2009.

[8] V.V. Kiryuha, Yu.M. Gorbenko, V.S. Yablokova, “Development of under-load transformer diagnostics algorithm”, (in Russian), scientific works of Dalirybvtuz,[Online]. Available:https://elibrary.ru/item.asp?id=26562036 [Accessed: Oct. 16, 2019].

[9] A.N. Alyunov, “Identification of parameters of electrical systems equivalent circuits by data of emergency process recorders,” (in Russian), abstract of Ph.D. thesis. Vologda, RF, 2004.

[10] G.M. Cfasman, A.G. Mordkovich, “Parameter identification of transformer equivalent schemes in monitoring and diagnostics systems,” (in Russian), RF: ELEKTRO, no.5, pp. 6-9, 2011.

[11] C. Borda, A. Olarte and H. Diaz, "PMU-based line and transformer parameter estimation," 2009 IEEE/PES Power Systems Conference and Exposition, Seattle, WA, 2009, pp. 1-8.

[12] B. Vicol, "On-line overhead transmission line and transformer parameters identification based on PMU measurements," 2014 International Conference and Exposition on Electrical and Power Engineering (EPE), Iasi, 2014, pp. 1045-1050.