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ASSESSMENT OF THE ELECTRIC POWER SYSTEM POWER LOSSES TAKING INTO ACCOUNT THE PASSIVE PARAMETERS OF TRANSFORMERS

Arakelyan V. P.
Ph.D., Associate Professor
National Polytechnic University of Armenia,
Institute of Power Engineering and Electrical Engineering,
chair of Electric Power Engineering,
Republic of Armenia, Yerevan city, Str. Teryan 105, Yerevan 0009

Abstract. ***Introductory speech on the research topic:*** *When studying the modes of electric power systems, the parameters of the mode and scheme are distinguished. Schema parameters refer to generic network parameters. Generalized parameters of the electrical network- impedances and admittances of power lines and transformers. System scheme parameters are divided into active and passive. Passive parameters are the longitudinal and transverse parameters of power lines, transformers. One of the important technical and economic indicators of the electrical system is power losses. When studying the system modes, it is necessary to take into account the influence of the longitudinal and transverse passive parameters of the transformer circuit on the losses.* ***The purpose of scientific research:***

Assessment of power losses in the electric power system, taking into account the passive parameters of transformers. Calculate the losses of active and reactive power, evaluate the change in power losses due to the longitudinal and transverse passive parameters of the transformer circuit. ***Description of scientific and practical significance of the work:*** *Scientific value of the work: A new approach to assessing power losses has been introduced, based on new formulae for calculating loss coefficients, using the Z-matrix of generalized parameters, and the influence of passive parameters of transformers. Practical significance: provides versatility for calculating, analyzing and evaluating power losses in transmission electrical networks, taking into account the passive parameters of transformers.* ***Description of the research methodology:*** *Taking into account different types of modeling of transformers of modern electric power systems, the complexity of network schemes, matrix theory, numerical methods for solving system mode equations, new formulae for calculating, estimating and structuring power losses are obtained, taking into account the passive parameters of transformers.* ***Main results, conclusions of the research work:*** *The research was carried out on a macro-model of the electric power system of Armenia. The analysis shows that the proposed formulae are applicable to transmission electrical networks. Changes in nodal powers, power loss coefficiens, power losses due to passive parameters of the system transformer scheme are estimated.*

The value of the conducted research (what contribution of this work to the relevant branch of knowledge): *The proposed approach expands the scope of transformer parameters in the calculation and analysis of power losses.* ***Practical significance of the results of work:*** *The obtained new formulae for power losses make it possible to comprehensively analyze the structure of losses, identify foci, develop organizational and technical measures to reduce them, and solve problems of voltage regulation.*

Keywords: *electric power system, transformer, passive parameter, power losses, matrix, norm.*

Introduction. In modern electric power systems, electricity production is growing at a fairly high rate. From this point of view, one of the main technical and economic indicators of the system are power losses and their calculation, structuring according to the main structural elements of the network, comprehensive analysis, evaluation, development of organizational and technical measures to reduce losses and normalization. Two winding transformers are one of the most widely used system elements. When calculating the modes of the electrical system, transformers are mainly modeled by equivalent circuits of the Γ -form and π -form. π -form equivalent circuits of transformers are widely used. The Z-matrix the generalized parameters of the electrical system is formed on the basis of the passive parameters of the π -form equivalent circuits of transformers and power lines. The representation of the passive parameters of transformers is important for solving the regime problems of the system. Currently, there are no universal formulae for estimating power losses in the system, taking into account the passive parameters of the transformer.

Literature review. When calculating the modes of electric power systems, two-winding transformers are modeled by the following equivalent circuits [1-7].

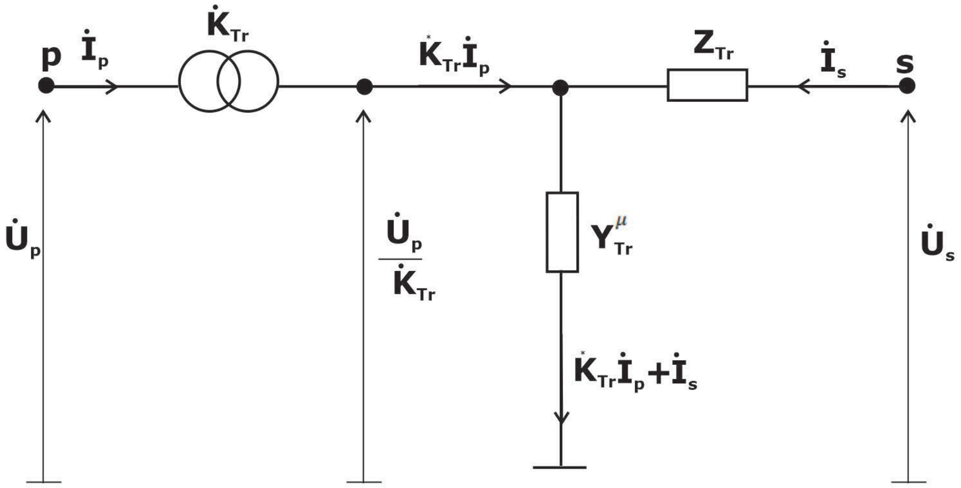

Fig. 1. Γ-equivalent circuit of a transformer

From (Fig. 1.) for the currents of the primary and secondary windings of the transformer, we obtain:

$$\dot{I}_p = Y_{pp} \cdot \dot{U}_p + Y_{ps} \cdot \dot{U}_s, \quad (1)$$

$$\dot{I}_s = Y_{sp} \cdot \dot{U}_p + Y_{ss} \cdot \dot{U}_s. \quad (2)$$

or in matrix form.

$$\begin{bmatrix} \dot{I}_p \\ \dot{I}_s \end{bmatrix} = \begin{bmatrix} Y_{pp} & Y_{ps} \\ Y_{sp} & Y_{ss} \end{bmatrix} \cdot \begin{bmatrix} \dot{U}_p \\ \dot{U}_s \end{bmatrix}. \quad (3)$$

where self and mutual admittances of the transformer are determined by the following expressions:

$$Y_{pp} = \frac{Y_{Tr} + Y^{\mu}_{Tr}}{K^2_{Tr}}, \quad (4)$$

$$Y_{ss} = Y_{Tr}, \quad (5)$$

$$Y_{ps} = -\frac{Y_{Tr}}{\overset{*}{K}_{Tr}}, \quad (6)$$

$$Y_{sp} = -\frac{Y_{Tr}}{K_{Tr}}. \quad (7)$$

where $\dot{K}_{Tr}$-complex value of the transformation ratio of the transformer.

We write the matrix equation (3) as follows:

$$\dot{I} = Y^{\Gamma} \cdot \dot{U}. \tag{8}$$

where Y^{Γ}-matrix of passive parameters (admittance matrix) of the Γ-equivalent circuit of the transformer,

$\dot{U}$- the voltage vector of the primary and secondary windings of the transformer.

$$\dot{I} = \begin{bmatrix} \dot{I_p} \\ \dot{I_s} \end{bmatrix}, \tag{9}$$

$$\dot{U} = \begin{bmatrix} \dot{U_p} \\ \dot{U_s} \end{bmatrix}, \tag{10}$$

$$Y^{\Gamma} = \begin{bmatrix} Y_{pp} & Y_{ps} \\ Y_{sp} & Y_{ss} \end{bmatrix}. \tag{11}$$

Taking into account the notation (4) - (7), expression (11) will take the following form:

$$Y^{\Gamma} = \begin{bmatrix} \frac{Y_{Tr}+Y_{Tr}^{\mu}}{K_{Tr}^{2}} & -\frac{Y_{Tr}}{\overset{*}{K}_{Tr}} \\ -\frac{Y_{Tr}}{K_{Tr}} & Y_{Tr} \end{bmatrix}. \tag{12}$$

We represent the matrix equation (8) in the form of a complex impedance, we will have:

$$\dot{U} = Z^{\Gamma} \cdot \dot{I}. \tag{13}$$

where Z^{Γ}- matrix of passive parameters (impedance matrix) of the Γ-equivalent circuit of the transformer.

$$(Y^{\Gamma})^{-1} = Z^{\Gamma}. \tag{14}$$

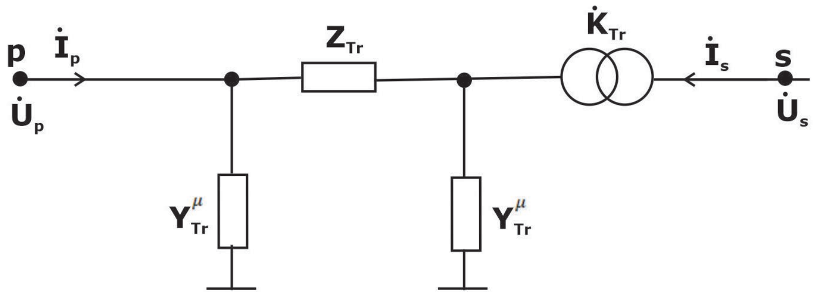

Fig. 2. π **-equivalent circuit of a transformer**

The corresponding (Fig. 2) matrix equation (8) will have the following form:

$$\dot{I} = Y^{\pi} \cdot \dot{U}. \tag{15}$$

where Y^{π}- matrix of passive parameters (admittance matrix) of the π -equivalent circuit of the transformer.

$$Y^{\pi} = \begin{bmatrix} Y_{Tr} + Y_{Tr}^{\mu} & -K_{Tr} \cdot Y_{Tr} \\ -\overset{*}{K}_{Tr} \cdot Y_{Tr} & K_{Tr}^{2} \cdot (Y_{Tr} + Y_{Tr}^{\mu}) \end{bmatrix}. \tag{16}$$

We represent the matrix equation (15) in the form of a impedance, we will have:

$$\dot{U} = Z^{\pi} \cdot \dot{I}. \tag{17}$$

where Z^{Π}- matrix of passive parameters (impedance matrix) of the π -equivalent circuit of the transformer.

$$(Y^{\pi})^{-1} = Z^{\pi}. \tag{18}$$

Calculation and estimation of losses in the form of (12) Ա (16) passive parameters of the transformer causes difficulties and difficulties in application, formation of the Y-matrix and obtaining the Z-matrix of generalized parameters of the electrical circuit of the system.

Therefore, it is necessary to improve the representation of the passive parameters of two-winding transformers for complex analysis.

Aim of the Research. To estimate power losses, it is recommended to use:

1. Г -form equivalent circuit for modeling transformers.
2. Calculated powers, due to passive parameters of transformers.
3. New formulae for calculating losses.

Main Body. Let us assume that the electric power system (EPS) consists of M + 1 nodes (see Fig. 3).

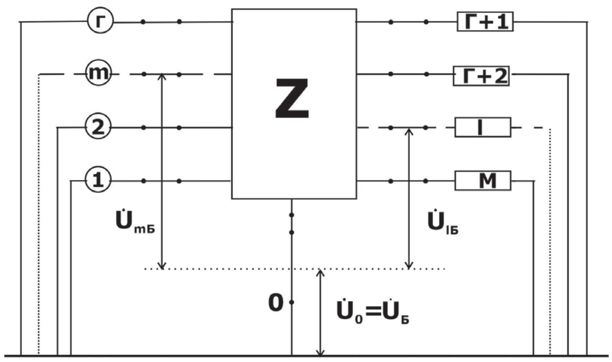

Fig. 3. Equivalent scheme of the EPS with the Z-form

It is supposed that the powers of the power plant nodes (0, 1, 2,…, Г) and load nodes (Г + 1, Г + 2,…, Г + H = M) are given. The electric power system consists of M+1 nodes. The node with index "0" is selected as the slack node. In this case, the equation of state of the electrical system in the Z-form takes the following form [8, 9, 10]:

$$\left.\begin{array}{l} \dot{U}_1 = \dot{U}_{0Б} + Z_{11} \cdot \dot{I}_1 + Z_{12} \cdot \dot{I}_2 + \cdots + Z_{1M} \cdot \dot{I}_M, \\ \dot{U}_2 = \dot{U}_{0Б} + Z_{21} \cdot \dot{I}_1 + Z_{22} \cdot \dot{I}_2 + \cdots + Z_{2M} \cdot \dot{I}_M, \\ \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots, \\ \dot{U}_M = \dot{U}_{0Б} + Z_{M1} \cdot \dot{I}_1 + Z_{M2} \cdot \dot{I}_M + \cdots + Z_{MM} \cdot \dot{I}_M. \end{array}\right\} \tag{19}$$

where $\dot{U}_{0Б}$, $\dot{U}_1$, $\dot{U}_2$, …, $\dot{U}_M$- complex voltages of nodes 0, 1, …, M of the electrical system,

$\dot{I}_1$, $\dot{I}_2$, …,$\dot{I}_M$- complex currents of nodes 1,2, …, M of the electrical system,

Z_{12},…, Z_{1M}, Z_{21},…, Z_{2M},…, Z_{M1}- mutual impedances of independent nodes of the electrical system,

Z_{11}, Z_{22},…, Z_{MM}- self-impedances of independent nodes 1, 2,…,M of the electrical system.

The nodal equation of the electrical system (19) in a compact form takes the form:

$$\dot{U} = \dot{U}_{0Б} + Z \cdot \dot{I}. \tag{20}$$

where $\dot{U}_{0Б}$ is a multidimensional slack voltage vector of the electrical system,

Z - nodal complex matrix of self and mutual impedances, due to the longitudinal and transverse passive parameters of power lines,

$\dot{U}$ - multidimensional vector of the complex voltage of independent nodes of the electrical system,

$\dot{I}$-multidimensional vector of the complex current of independent nodes of the electrical system.

The system of equations (19) is also represented in the following form:

$$\dot{U}_i = U_{0Б} + \sum_{j=1}^{M} Z_{ij} \cdot \dot{I}_j,\; i = 1,2,\dots,M. \tag{21}$$

For the loss formulae, we obtain [10].

$$\Pi_P = \sum_{i=1}^{M} \sum_{j=1}^{M} K_{ij} \cdot R_{ij}, \tag{22}$$

$$\Pi_Q = \sum_{i=1}^{M} \sum_{j=1}^{M} K_{ij} \cdot X_{ij}. \tag{23}$$

where K_{ij} is called the loss coefficient determined by the passive parameters of the power lines.

$$K_{ij} = \frac{1}{U_i \cdot U_j} \cdot \left[(P_i \cdot P_j + Q_i \cdot Q_j) \cdot \cos(\psi_{ui} - \psi_{uj}) + (P_j \cdot Q_i - P_i \cdot Q_j) \cdot \sin(\psi_{ui} - \psi_{uj}) \right]. \tag{24}$$

Let's represent the equivalent scheme of the EPS (Fig. 3.) in the form (Fig. 4.):

Taking into account the presented transformer equivalent circuit (Fig. 5.) for the calculated power of the node, we obtain:

$$\dot{S}_i^{sub} = \dot{S}_i - \Delta \dot{S}_i^{Tr} - \Delta \dot{S}_{leak\,i}^{Tr}. \tag{25}$$

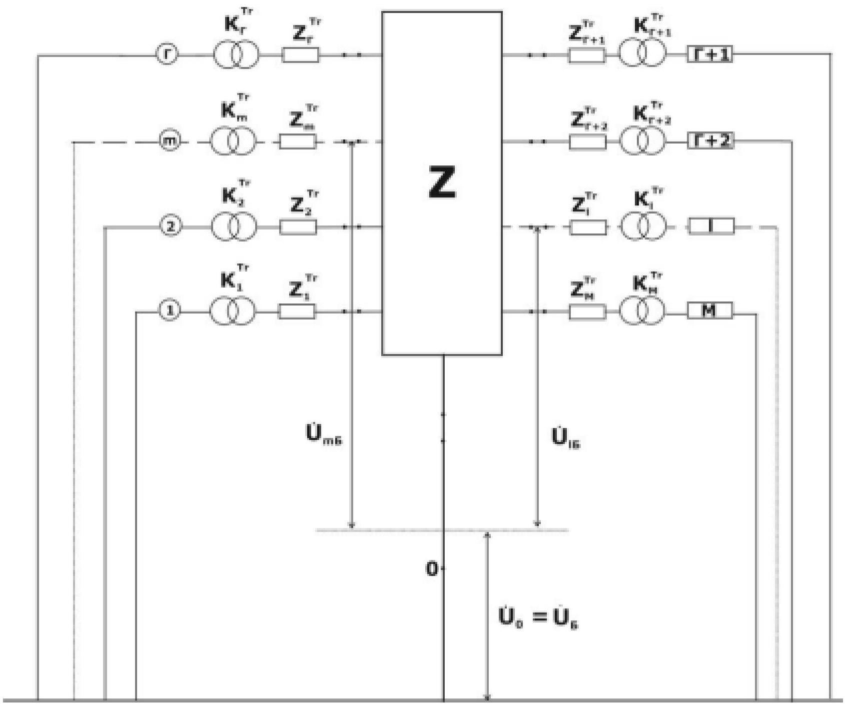

Fig.4. Equivalent scheme EPS in Z-form, taking into account the parameters of transformers

Transformers are modeled according to the Γ-equivalent circuit.

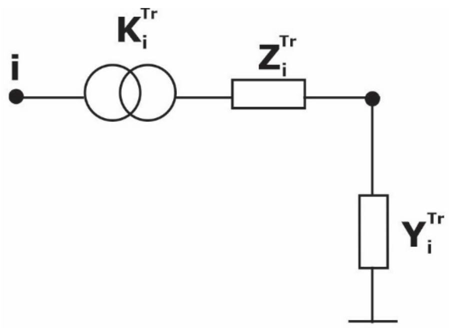

Fig.5. Γ-equivalent circuit of a step-up transformer

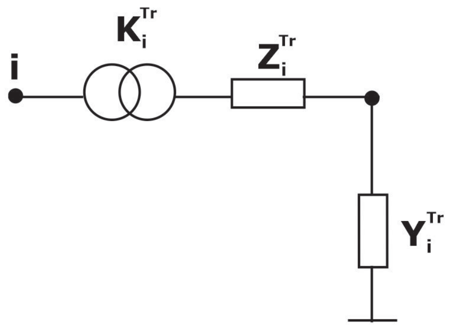

Fig.6. Γ-equivalent circuit of a step-down transformer

where $\Delta\dot{S}_i^{Tr}$-power losses of the step-down transformer are due to the impedances Z_i^{Tr}, $\Delta\dot{S}_{leak\,i}^{Tr}$- step-down transformer leakage is due to admittance Y_i^{Tr} (power loss in steel core).

Taking into account the presented transformer equivalent circuit (Fig. 6.) for the calculated power of the node, we obtain:

$$\dot{S_i^{sub}} = \dot{S}_i + \Delta\dot{S}_i^{Tr} + \Delta\dot{S}_{leak\,i}^{Tr}. \tag{26}$$

where $\Delta\dot{S}_i^{Tr}$-power losses of the step-up transformer are due to the impedances Z_i^{Tr}, $\Delta\dot{S}_{leak\,i}^{Tr}$- step-up transformer leakage is due to admittance Y_i^{Tr} (power loss in steel core).

When using transformer modeling circuits, for the presented EPS equivalent scheme (Fig. 4.) loss formulae (22) and (23) take the following form:

$$\Pi_P^{sub} = \sum_{i=1}^{M}\sum_{j=1}^{M} K_{ij}^{sub} \cdot R_{ij}, \tag{27}$$

$$\Pi_Q^{sub} = \sum_{i=1}^{M}\sum_{j=1}^{M} K_{ij}^{sub} \cdot X_{ij}. \tag{28}$$

where K_{ij}^{sub} - loss coefficient due to passive parameters of power lines and transformers.

$$K_{ij}^{sub} = \frac{1}{U_i \cdot U_j} \cdot \left[\left(P_i^{sub} \cdot P_j^{sub} + Q_i^{sub} \cdot Q_j^{sub}\right) \cdot \cos\psi_{uij} + \left(P_i^{sub} \cdot Q_i^{sub} - P_i^{sub} \cdot Q_j^{sub}\right) \cdot \sin\psi_{uij}\right]. \tag{29}$$

$$P_i^{sub} = Re\left(\dot{S_i^{sub}}\right), \tag{30}$$

$$Q_i^{sub} = Im\left(\dot{S_i^{sub}}\right). \tag{31}$$

The vectors of active and reactive power of independent nodes of the electrical system are presented as follows:

$$P = [P_1,\ P_2,\ \dots,\ P_M], \tag{32}$$

$$Q = [Q_1,\ Q_2,\ \dots,\ Q_M]. \tag{33}$$

(32) և (33) expressions for the calculated power of the electrical system nodes will look like:

$$P^{sub} = [P_1^{sub},\ P_2^{sub},\ \dots,\ P_M^{sub}], \tag{34}$$

$$Q^{sub} = [Q_1^{sub},\ Q_2^{sub},\ \dots,\ Q_M^{sub}]. \tag{35}$$

Let us estimate the change of the power in node using the Euclidean norm of vectors [11], i.e.

$$\|\Delta P\|_2 = \sqrt{\sum_{i=1}^{M}|\Delta P_i|^2}, \tag{36}$$

$$\|\Delta Q\|_2 = \sqrt{\sum_{i=1}^{M}|\Delta Q_i|^2}. \tag{37}$$

The change in loss coefficients is estimated by the Euclidean norm of the loss matrix [11], i.e.

$$\|\Delta K\|_2 = \sqrt{\sum_{i,j}^{M}|\Delta K_{ij}|^2}. \tag{38}$$

The study was carried out on the macromodel of the Armenian EPS. The simple iteration method is used to determine the power flow.The results are presented in tables. The Hrazdan Thermal Power Plant (index “0”) is represented as the slack node, the Yerevan Thermal Power Plant (index “1”), the Armenian Nuclear Power Plant (index “2”) are the generator nodes.

Table 1 Voltages

node,i	$\dot{U}_i$, kV	$\lvert\dot{U}_i\rvert$, kV	ψ_{Ui}, °
0	220+j0	220	0
1	211.8832-j6.2059	211.974	-1.6777
2	214.6686-j2.9924	214.6895	-0.7986
3	210.353–j8.3088	210.517	-2.262
4	210.4592-j7.8454	210.6054	-2.1348

Table 2 Voltages in the presence of passive parameters of transformers

node,i	$\dot{U}_i$, kV	$\lvert\dot{U}_i\rvert$, kV	ψ_{Ui}, °
0	220+j0	220	0
1	206.8961-5.7222	206.9752	-1.5842
2	208.9478-2.3068	208.9606	-0.6325
3	206.1834–j7.9452	206.3364	-2.2068
4	205.4257-j7.4004	205.559	-2.0632

Table 3 P- vectors

P	P_1	P_2	P_3	P_4
MW	240	390	867	585
P^{sub}	P_1^{sub}	P_2^{sub}	P_3^{sub}	P_4^{sub}
MW	239.1444	388.2173	873.2892	588.5188

Table 4 Q- vectors

Q	Q_1	Q_2	Q_3	Q_4
MVAr	148	241	650	439
Q^{sub}	Q_1^{sub}	Q_2^{sub}	Q_3^{sub}	Q_4^{sub}
MVAr	119.9535	182.8176	808.6308	545.8148

Table 5 K-matrix elements, A^2. Π_P =16.3366 MW, Π_Q=81.4332 MVAr

K_{ij}	1	2	3	4
1	1.7694	2.8402	-6.8121	-4.5968
2	2.8402	4.5601	-10.9187	-7.3682
3	-6.8121	-10.9187	26.495	17.8758
4	-4.5968	-7.3682	17.8758	12.0607

Table 6 K^{sub}- matrix elements, A^2. Π_P =24.3835 MW, Π_Q=120.1158 MVAr

K_{ij}^{sub}	1	2	3	4
1	1.6709	2.6522	-7.1385	-4.8349
2	2.6522	4.217	-11.1892	-7.5791
3	-7.1385	-11.1892	33.2713	22.5233
4	-4.8349	-7.5791	22.5233	15.2473

Conclusions.

1. The change in the nodal powers of the electric power system due to the passive parameters of the transformers is: $\|\Delta P\|_2$=0.52%, $\|\Delta Q\|_2$=24.2%.

2. The change in power loss coefficients due to the passive parameters of the transformers of the electric power system circuit is: $\|\Delta K\|_2$=22.29%, change in active power losses $\Delta\Pi_P$=49.25%, change in reactive power losses $\Delta\Pi_Q$=47.5%.

3. The obtained new formulae for power losses allow calculating, evaluating and structuring losses in transmission networks according to the passive parameters of the system scheme: lines, two-winding transformers.

Prospects for further research.

- Research of the calculation of power losses in system-forming electrical networks, taking into account the passive parameters of power lines and transformers.
- Research on voltage regulation in transmission networks.

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