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CONTROL NODAL VOLTAGE LOSSES OF ELECTRIC POWER SYSTEM WITH CORRECTION TRANSFORMATION RATIOS

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Abstract. ***Introductory speech on the research topic:*** *Electrical systems are complex systems. Multifaceted connections between the elements of modern electrical systems determine the features of their management. In the course of research, the system is modeled by two interconnected components. The first component relates to modeling the electrical system modes, and the second component relates to modeling the electrical network scheme. The electrical network scheme model contains passive parameters of power lines and transformers, on the basis of which a Z-matrix of generalized parameters is formed. The influence passive parameters of two-winding transformers leads to voltage and power losses in the system. Therefore, it is necessary to take into account the possibility of changing the modules of transformation ratios when controlling the modes of the electrical system.*

The purpose of scientific research: *Control nodal voltage losses of electric power system with correction transformation ratios. Modeling of two-winding transformers with an Γ-equivalent circuit, application of an algorithm for determining transformation ratio modules, formulae for calculating voltage losses, correction formulae for transformation ratio modules.*

Description of scientific and practical significance of the work: *Scientific value of the work: A new approach to managing nodal voltage losses of an electric power system is presented, based on the Γ-equivalent circuit for modeling transformers, using a Z-matrix without passive parameters of transformers, controlling the level of nodal voltage by changing transformation ratios. Practical significance: provides universality of calculation, analysis and assessment of the influence of passive parameters of transformers on voltage and power losses in transmission electrical networks.*

Description of the research methodology: *Taking into account various types of modeling of transformers of modern electric power systems, the complexity of network schemes, matrix theory, numerical methods for solving system mode equations, an algorithm for determining transformation ratio modules, control of nodal voltage losses was carried out with correction of transformation ratio modules.*

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 algorithm for determining the transformation ratios of two-winding transformers, formulae for calculating voltage losses and formulae for correcting transformation ratios are applicable for transmission electrical networks. Nodal voltage losses in the system scheme and changes in transformation ratios caused by the passive parameters of transformers are estimated.*

The value of the conducted research (what contribution of this work to the relevant branch of knowledge): *The presented approach expands the scope of application of transformer parameters in the calculation and analysis of voltage and power losses.*

Practical significance of the results of work: *The resulting algorithm for determining transformation ratios, formulae for calculating voltage losses, and formulae for correcting transformation ratios make it possible to comprehensively analyze the level of voltage losses, control the permissible level of node voltages by changing transformation ratios and solve problems of voltage regulation.*

Keywords: *electric power system, transformation ratio, passive parameter, voltage losses, correction, matrix.*

Introduction. Modern electrical power systems have an ever-evolving, complex configuration of electrical networks. The configuration is characterized by a model of the electrical network scheme. The electrical network scheme is modeled by equivalent circuits of power lines and transformers. Typically, power lines are modeled with a π -form equivalent circuit, rarely two-winding transformers with an Γ -form equivalent circuit. The electrical network scheme model forms a Z-matrix of passive parameters. Many researches do not take into account the influence passive parameters of two-winding transformers. Passive parameters of transformers cause changes in the nodal voltages of the electrical system. Voltage and power losses in the system increase. The form of representation of passive parameters of transformers is important for solving mode problems of system. Currently, there are no researches of the modes electrical systems related to the control of the permissible level of nodal voltages.

Literature review. Calculation of steady-state modes is the basis for the control of electrical power systems. With the development of electrical networks, interest in calculating modes with the presence of transformer parameters is growing [1-7,10]. If there are transformers with complex transformation ratios in the electric power system, the matrix equation of nodal voltages takes the following form:

$$\dot{U} = \dot{U}_{0Б} + Z \cdot \dot{I}. \qquad (1)$$

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

Z - nodal complex matrix of resistances of the electrical system, taking into account the passive parameters of lines and transformers and complex transformation ratios,

$\dot{U}$ - 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.

To model transformers, π-equivalent circuits are mainly used, and in some cases, Γ-equivalent circuits.

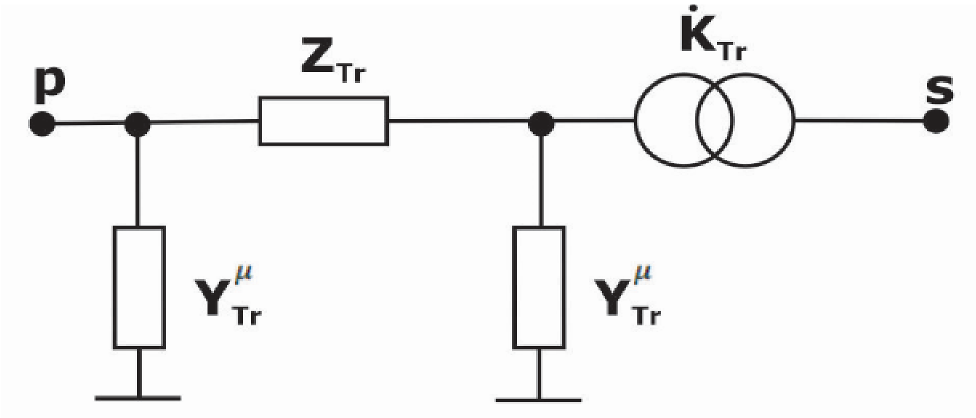

Fig. 1. π -equivalent circuit of a transformer

π-equivalent circuit of a transformer.

Z^{Π}- matrix of passive parameters (complex impedance matrix) of the П-equivalent circuit of the transformer has the following form:

$$Z^{\Pi} = \begin{bmatrix} Y_{Tr} + Y_{Tr}^{\mu} & -K_{Tr} \cdot Y_{Tr} \\ -\overset{*}{K}_{Tr} \cdot Y_{Tr} & K_{Tr}^{2} \cdot (Y_{Tr} + Y_{Tr}^{\mu}) \end{bmatrix}^{-1}. \qquad (2)$$

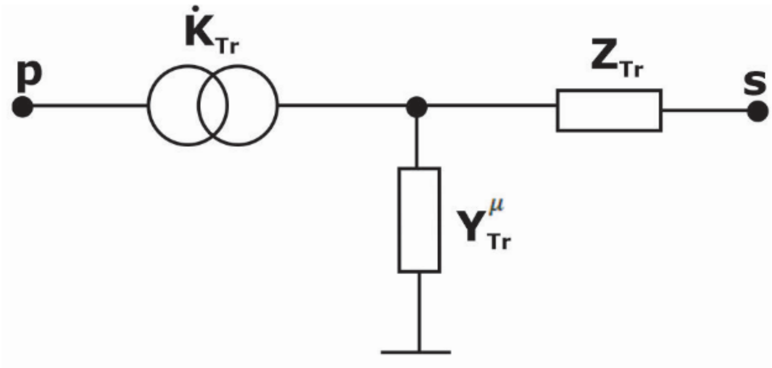

Fig. 2. Г-equivalent circuit of a transformer

Г-equivalent circuit of a transformer.

Z^{Γ}- matrix of passive parameters (complex impedance matrix) of the Г-equivalent circuit of the transformer has the following form:

$$Z^{\Gamma} = \begin{bmatrix} \frac{Y_{Tr}+Y_{Tr}^{\mu}}{K_{Tr}^{2}} & -\frac{Y_{Tr}}{\overset{*}{K}_{Tr}} \\ -\frac{Y_{Tr}}{K_{Tr}} & Y_{Tr} \end{bmatrix}^{-1}. \quad (3)$$

The Z-matrix of generalized parameters of the matrix equation (1) is formed using the Z^{Π} or Z^{Γ} matrices.

Calculation of electrical system modes using expression (1) has the following disadvantages:

1.The calculation of system modes with complex transformation ratios and its application becomes more complicated.

2. It is necessary to recalculate the Z-matrix if the transformation ratio changes.

3. Nodal voltage losses and power losses increase in the system.

To do this, it is necessary to rework the tasks of managing voltage losses of the electrical system, taking into account the passive parameters of two-winding transformers.

Aim of the Research. To control nodal voltage losses of the electric power system, it is recommended to use:

1. Г -form equivalent circuit for modeling transformers.

2. Algorithm for determining the modules of transformation ratios of electrical system transformers in nodes.

3. Formulae for nodal voltage losses of the electrical system due to the passive parameters of transformers.

4. Formulae for correcting the modules of transformation ratios of transformers due to nodal voltage losses.

Main Body. Let us present the calculation scheme of a two-winding transformer in the following form (Fig. 3).

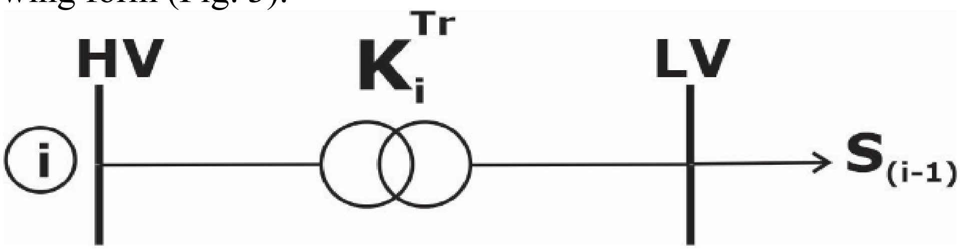

Fig.3 Calculation scheme of a two-winding transformer.

Since the supply voltage of transformers differs from its nominal voltage, control taps are installed in their windings, when they change, the transformation ratio changes within certain limits.

The transformer turns ratio is determined using the following algorithm.

1. First it is accepted:

$$U_i = U_{RTi}^{CAL} . \quad (4)$$

where

U_i- voltage module of the i-th node of the electrical system,

U_{RTi}^{CAL}- the calculated voltage value of the transformer regulating tap of the electrical system i-th node.

2. The number of initial taps of the transformer voltage regulation device is determined by the

following expression:

$$n'_{HVi} = \frac{U_{RTi}^{CAL} - U_{nomi}^{HV}}{\frac{a_i \cdot U_{nomi}^{HV}}{100}}. \quad (5)$$

where

U_{nomi}^{HV}- the high-voltage winding nominal voltage value of the i-th node transformer,

a_i- the voltage regulation degree of the i-th node transformer relative to the nominal voltage.

Let us make the following notation.

$$\Delta a_i = \frac{a_i \cdot U_{\text{номi}}^{\text{ВН}}}{100}. \quad (6)$$

Taking into account notation (6), formula (5) takes the following form:

$$n'_{HVi} = \frac{U_{RTi}^{CAL} - U_{nomi}^{HV}}{\Delta a_i}. \quad (7)$$

where

Δa_i-this is the voltage regulation step of the i-th node transformer.

The number of calculated initial control taps is rounded up.

$$n'_{HVi} \approx n_{HVi}. \quad (8)$$

3. The standard value of the transformer regulation tap voltage is determined by the following formula:

$$U_{RTi}^{ST} = U_{nomi}^{HV} \cdot (1 + n_{HVi} \cdot a_i). \quad (9)$$

Let us make the following notation.

$$w_{RTi} = 1 + n_{HVi} \cdot a_i. \quad (10)$$

where

$w_{RTi}$the relative turns number of the high-voltage winding of the i-th node transformer.

Taking into account notation (10), formula (9) will take the following form:

$$U_{RTi}^{ST} = U_{nomi}^{HV} \cdot w_{RTi}. \quad (11)$$

4.The standard value of the transformer turns ratio is determined by the following formula:

$$K_i^{Tr} = \frac{U_{RTi}^{ST}}{U_{nomi}^{LV}}. \quad (12)$$

where

U_{nomi}^{LV}- the low-voltage winding nominal voltage value of the i-th node transformer.

The transformation ratio varies within the following limits:

$$K_i^{Tr} = \begin{cases} K_{i,min}^{Tr}, & when \quad U_{RTi,min}^{ST} = K_{i,nom}^{Tr} \cdot w_{RTi}^{min}, \\ K_{i,nom}^{Tr}, & when \quad U_{RTi,}^{ST} = U_{nom,i}^{\text{ՔԼ}}, \\ K_{i,max}^{Tr}, & when \quad U_{RTi,max}^{ST} = K_{i,nom}^{Tr} \cdot w_{RTi}^{max}. \end{cases} \quad (13)$$

where

$$w_{RTi}^{min} = 1 - n_{HVi} \cdot a_i, \quad (14)$$

$$w_{RTi}^{max} = 1 + n_{HVi} \cdot a_i, \quad (15)$$

Let us assume that the electric power system (EPS) consists of M + 1 nodes (see Fig. 4).

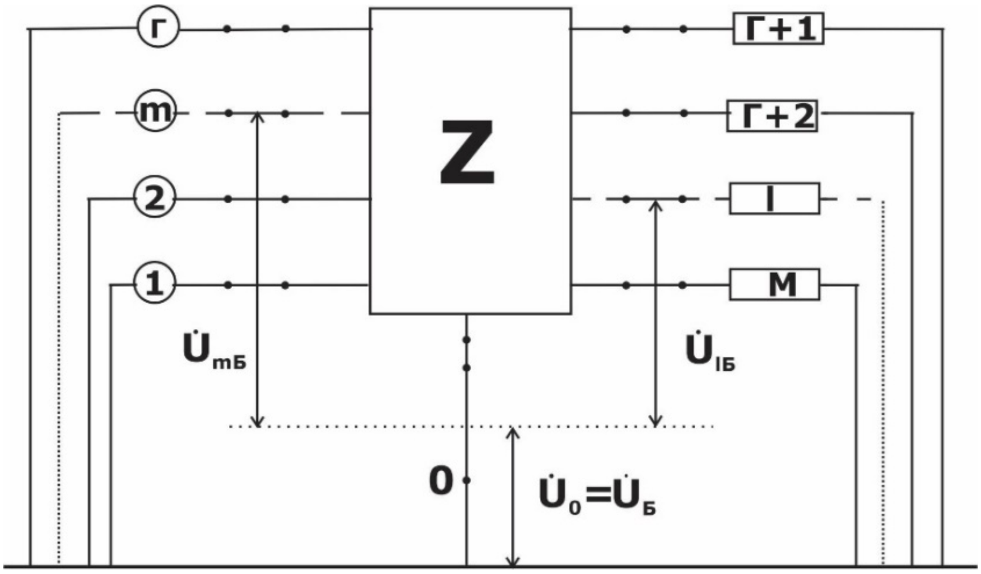

Fig. 4. Equivalent scheme of the EPS with the Z-form

The node with index "0" is selected as the slack node. In this case, the equation of steady-state of the electrical system in the Z-form takes the following form [8, 9, 10]:

$$\left. \begin{aligned} \dot{U}_1 &= \dot{U}_{0Б} + Z_{11} \cdot \dot{I}_1 + Z_{12} \cdot \dot{I}_2 + \cdots + Z_{1M} \cdot \dot{I}_M, \\ \dot{U}_2 &= \dot{U}_{0Б} + Z_{21} \cdot \dot{I}_1 + Z_{22} \cdot \dot{I}_2 + \cdots + Z_{2M} \cdot \dot{I}_M, \\ &\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots, \\ \dot{U}_M &= \dot{U}_{0Б} + Z_{M1} \cdot \dot{I}_1 + Z_{M2} \cdot \dot{I}_M + \cdots + Z_{MM} \cdot \dot{I}_M. \end{aligned} \right\} \quad (16)$$

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

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

$Z_{12}, \dots, Z_{1M}, Z_{21}, \dots, Z_{2M}, \dots, Z_{M1}$- are mutual impedances of independent nodes of the electrical system,

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

The nodal equation of the electrical system (16) in a compact form takes the form:

$$\dot{U} = \dot{U}_{0Б} + Z \cdot \dot{I}. \quad (17)$$

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.

Taking into account the passive parameters of transformers in the electric power system (Fig. 4.), the equivalent circuit of the EPS will take the following form (Fig. 5.).

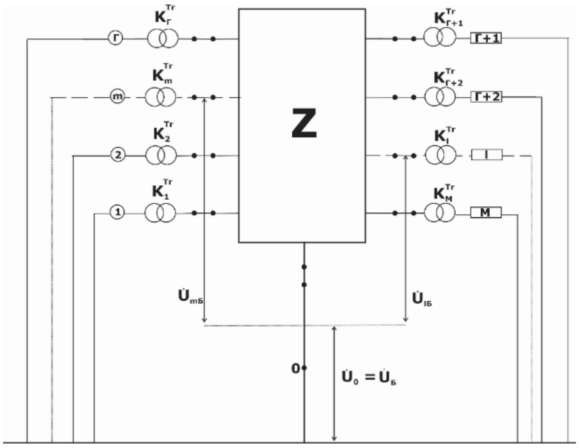

Fig. 5. EPS equivalent scheme in Z-form, taking into account the transformation ratios of transformers.

Let us write the matrix equation of the steady-state for the equivalent scheme of the electric power system presented in (Fig. 5.), we will have:

$$\dot{U}^{Tr} = \dot{U}_{0Б} + Z \cdot \dot{I}^{Tr}. \quad (18)$$

where

$\dot{U}^{Tr}$ multidimensional complex voltages vector of electrical system independent nodes, taking into account the passive parameters of transformers,

$\dot{I}^{Tr}$- multidimensional complex currents vector of electrical system independent nodes, taking into account the passive parameters of transformers.

From the difference between matrix equations (17) and (18) we obtain:

$$\dot{U} - \dot{U}^{Tr} = Z \cdot (\dot{I}\text{-}\dot{I}^{Tr}). \quad (19)$$

Using matrix equation (19), we determine the voltage losses using the following formula, we obtain:

$$\nabla \mathrm{U} = \mathrm{mod}\,\dot{\mathrm{U}} - \mathrm{mod}\,\dot{\mathrm{U}}^{\mathrm{Tr}}. \quad (20)$$

or

$$\nabla \mathrm{U} = \mathrm{U} - \mathrm{U}^{\mathrm{Tr}}. \quad (21)$$

where

$$\nabla \mathrm{U} = \begin{bmatrix} \nabla U_1 \\ \nabla U_2 \\ \dots\dots\dots \\ \nabla U_M \end{bmatrix}, \quad (22) \qquad \mathrm{U} = \begin{bmatrix} U_1 \\ U_2 \\ \dots\dots \\ U_M \end{bmatrix}, \quad (23) \qquad \mathrm{U}^{Tr} = \begin{bmatrix} U_1^{Tr} \\ U_2^{Tr} \\ \dots\dots \\ U_M^{Tr} \end{bmatrix}. \quad (24)$$

We compensate for nodal voltage losses in the electrical system caused by the presence of passive parameters of transformers by changing the transformation ratios.

Let us write matrix equation (21) in the following form:

$$U = \alpha \cdot U^{Tr}. \qquad (25)$$

where

α- change coefficient in nodal voltage of the electrical system..

$$\alpha = 1 + \nabla U / U^{Tr}. \qquad (26)$$

Using the algorithm for determining the transformation ratios of transformers, matrix equation (25) will take the following form:

$$K = \alpha \cdot K^{Tr}. \qquad (27)$$

where

K- multidimensional vector of transformers transformation ratios of the electrical system independent nodes,

K^{Tr}- multidimensional vector of transformers transformation ratios of ithe electrical system independent nodes, in the presence of passive parameters..

$$K = \begin{bmatrix} K_1 \\ K_2 \\ \dots\dots\dots \\ K_M \end{bmatrix}, \quad (28) \qquad \alpha = \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \dots\dots\dots \\ \alpha_M \end{bmatrix}, \quad (29) \qquad K^{Tr} = \begin{bmatrix} K_1^{Tr} \\ K_2^{Tr} \\ \dots\dots \\ K_M^{Tr} \end{bmatrix}. \quad (30)$$

Let us estimate the voltage losses of the nodes and the change in transformation ratios using the Euclidean norm of vectors [11], i.e.

$$\|\nabla U\|_2 = \sqrt{\textstyle\sum_{i=1}^{M} |\nabla U_i|^2}, \qquad (31)$$

$$\|\Delta K\|_2 = \sqrt{\textstyle\sum_{i,j}^{M} |\Delta K_i|^2}. \qquad (32)$$

The study was carried out on the macromodel of the Armenian EPS. The simple iteration method is used to solve the steady-state equations. 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	$\lvert\dot{U}_i\rvert$, kV	$\lvert\dot{U}_i^{Tr}\rvert$, kV	∇U, kV	α	
0	220	220	-	-	
1	211.974	206.9752	4.9988	1.0242	
2	214.6895	208.9606	5.7289	1.0274	
3	210.517	206.3364	4.1806	1.0203	
4	210.6054	205.559	5.0464	1.0245	

Table 2 - Transformers transformation ratios

node,i	K^{Tr}	K	ΔK
0	-	-	-
1	0.0761	0.0743	0.0018
2	0.0754	0.0734	0.0020
3	0.0533	0.0523	0.0011
4	0.0511	0.0499	0.0012

Conclusions:

1. Nodal voltage losses of the electric power system due to the passive parameters of transformers are: $\|\nabla U\|_2$=2.42%.

2. The change in the transformation ratios of transformers in the electrical power system scheme is: $\|\Delta K\|_2$=2.41%.

3. Nodal voltage losses of the electric power system in the presence of passive parameters of transformers are compensated by transformation ratios correction equivalent to losses.

Prospects for further research

1. Study of voltage calculations in system-forming electrical networks, taking into account the passive parameters of power lines and transformers.

2. Research on voltage regulation in transmission networks.

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