Розглянуто математичні моделі й алгоритми визначення втрат електроенергії в неоднорідних електричних мережах, викликаних їх взаємовпливом. Показано спосіб зменшення цих втрат за допомогою лінійних регуляторів, встановлених в мережі нижчої напруги. Запропоновано метод визначення оптимального місця встановлення цих пристроїв

Ключові слова: взаємовплив електричних мереж, додаткові втрати електроенергії, керування потоками потужності, лінійні регулятори, крос-трансформатор

Рассмотрено математические модели и алгоритмы определения потерь электроэнергии в неоднородных электрических сетях, вызванных их взаимовлиянием. Показан способ уменьшения этих потерь с помощью линейных регуляторов, установленных в электрических сетях низшего напряжения. Предложен метод определения оптимального места установки этих устройств

Ключевые слова: взаимовлияние электрических сетей, дополнительные потери электроэнергии, управление потоками мощности, линейные регуляторы, кросс-трансформатор

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OPTIMAL CONTROL OF MUTUAL IMPACT OF ELECTRIC GRIDS FOR THE REDUCTION OF THEIR ELECTRIC ENERGY LOSSES

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1. Introduction

Modes of electrics grids, united in electric system by means of power transformers and autotransformers are interconnected and any mode variations in one grid influence the state in other grids, i. e. in electric power systems (EPS) connected for parallel operation by inter systems links, the interaction of their modes is observed. One of the reasons of mode non optimality is non-uniformity of EPS. As a result of non-uniformity of EPS electric grids modes interaction produces negative impact on power transfers between neighboring systems (mutual external transfers) on transfers between electric grids of various voltage of separate systems (mutual proper transfers) and on transit transfers of power by electric grids of the considered system analysis of literature [1–3] shows that the consequence of electric grids of EPS modes interaction is additional losses of electric energy, that reduce their economic efficiency.

Cases are known [4] when system-forming grids of the existing power pools operate in parallel with the couplings on lower voltage levels of utility companies. Parallel operation of overhead transmission lines (OL) of different voltage because of high level of non-uniformity causes problems in the process of transport and distribution of electric energy. Due to non-uniformity mutual power transfers occur among electric grids of EPS, these transfers load the grids of contiguous utility companies. Also it is known [5], grids of higher voltages are unloaded in parallely operating grids of lower voltage (Fig. 1). The consequences are additional losses of electric energy and overload of switching devices and overhead transmission lines of lower voltage.

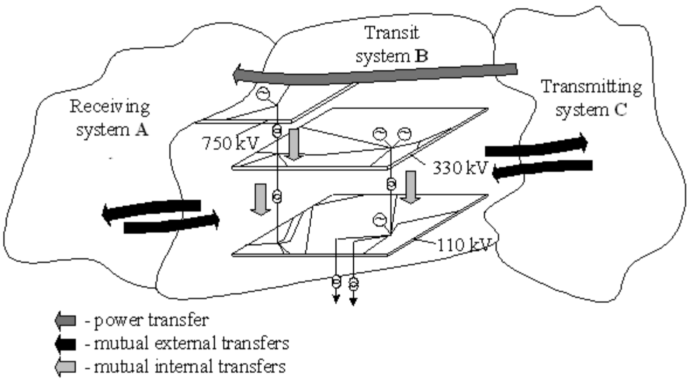

Fig. 1. Example of EPS, where transit of power is performed

The above-mentioned cases of electric grids interaction change flux distribution and lead to the increase of power losses in the process of transport and distribution of electric energy as compared with standard values.

That is why the aim of the research is improvement of EPS normal modes control by means of optimal usage of cross-transformers (CT) in low voltage (LV) electric grids.

In accordance with the aim of research the following problems are to be solved: study the degree of influence of mutual and transit power transfers on the level of active electric energy losses; develop the method, aimed at determination of optimal place of CT location and its phase shifting angle by the criterion of optimization of active power general system losses; investigate changes of additional losses of active power ΔP_{LVi}^{HV} and electric energy as a result of transfers, caused by the impact of high voltage grid (HV).

Study of the degree of mutual and transit power transfers impact on the level of electric energy losses is the problem of great importance.

Its solution enables to control and evaluate the impact of power transfers of electric grids on additional losses in distributive grids of utility companies and analyze the consequences of electric grids interaction [6]. The given paper considers the possibilities of compensation of electric energy additional losses in electric grids, caused by their interaction, introducing electromotive force (e. m. f.) in the contours by means of linear regulators of booster transformers (BT) or CT type.

2. Analysis of the literature sources

Investigation of power losses in power networks and ways to reduce them is a burning problem in many countries [7, 8]. There are a lot of ways to solve this problem [9, 10]. One of these ways is the optimal mode control of electric power systems (EPS) using the criterion of minimum active power losses [11]. It is known that in the EPS modes of implementation by means of optimal control algorithms are (auto-) transformer with tap-changing under load [11], phase-shifting controllers [5, 12], cross-regulation transformers and other equipment.

However, the use of autotransformers with tap-changs ing under load (TCL) does not always make possible to ensure the requirements for voltage levels, maximum capacity transportation on scheme branches of electrical systems (transmission lines, transformers, etc.), minimal losses of active power, reliability of power transmission. Under such circumstances, it is reasonable to use sliding phase transformers [12–14].

The use of such transformers in after-emergency operation and during EPS-equipment repairs (high-voltage power lines, transformers, power plant generators, etc.) is cost-effective when there are not enough opportunities of modern methods of EPS regimes regulation, and installation of extra TLC-transformers (which is more expensive then sliding phase transformer) is not advisable because of the fact that after-emergency and maintenance regimes are not very common.

It was therefore decided to use sliding phase transformers [15]. That is, if the electrical network has different power, then forcibly changing the angle between power vectors HV and LV in transformer power grids (in the grids with cross-transformers) it is possible to redistribute power flows between the lines of the electrical grid. This allows you to offload LV networks, which reduces system-wide loss of active power, accidents due to overloaded transmission lines; increases network reliability, etc. [11, 15].

We know that shifting transformers are installed in HV electrical networks [13, 15–17], but on the above considerations, we believe that it is also advisable to investigate the feasibility and effectiveness of shifting transformers installation in LV networks. This installation will not only relieve the LV network under EPS normal conditions and partially unload overloaded intersystem HV transmission lines when repairing or under emergency operation.

3. Problem set-up

Due to interaction of electric grids and transit power fluxes there appears problems dealing with determination of additional losses of power and electric energy. The results of these problems solution are used for the analysis and evaluation of electric grids interaction and impact of transit transfers on modes, particularly on the losses in the grids of HV and LV. In accordance with the value of these losses, measures, aimed at their optimization in HV and LV grids are developed. Depending on the form of property of HV and LV grids the agreements can be reached regarding minimization of total losses ΔP_{Σ} in them and determination of transformation ratios of transformers and coupling autotransformers:

$$\min\left\{\Delta P_{\Sigma} = \Delta P_{HV} + \Delta P_{LV}\right\}, \tag{1}$$

where ΔP_{HV}, ΔP_{LV} – power losses in HV and LV grids, correspondingly.

But taking into account the fact that in case of parallel operation of HV and LV grids, losses increase only in LV grid, then the problem (1) will consist in the necessity “to force out” the given transit power transfers from LV grid into HV grid, i.e., such problem is solved:

$$\min\left(\Delta P_{LV}\right). \tag{2}$$

The complexity of realization of problem (2) solution results is that the facilities, by means of which, they can be practically achieved (transformers, coupling autotransformers, BT) are often in HV grids and the access on the side of LV grids is limited, because HV and LV grids belong to different owners. Hence, from the side of LV grids there is one way out – install BT in their grids. In this case the problems appear determination of the most efficient place of BT installation in LV grid, its constructive peculiarities (for instance, BT that performs longitudinal regulation, transversal regulation or longitudinal-transversal regulation) and parameters (for instance, power, voltage, phase angle of phase shifting transformer, etc.); evaluation of the expediency of the BT of the proposed type usage (with regulated or non-regulated, active, reactive or complex transformation ratios).

On the first glance because leveling e.m.f. depends on loading both of HV grid and LV grid then BT must be with of tap-changing-under load. The reason of additional losses of power and electric energy is non-uniformity of the grids, i.e., negative impact of HV grid on LV grid is observed. On the other hand, taking into account that the risen of negative impact of HV grid on LV grid, i. e. emerging of additional losses of power and electric energy is non-uniformity of the grids which is the design parameter, then it is expedient to study the possibility of mounting BT with non regulating transformation ratio. In latter case by means of such BT (much more cheaper than in the first variant) constant component of additional losses, that depends only on grid non-uniformity will be compensated.

In electric grids of some countries of world, for example, BTs are efficiently used, which shift angle of secondary voltage vector of the transformer relatively the primary voltage on the constant value [18]. Such transformers are called CT [18] and the process of power fluxes correction itself in order to reduce losses from transit transfers is called cross-transformation technology. The advantage of cross-transformers is that they do not have of tap-changing under load, but accept stage switching, for instance by means of auxiliary switches. It is known that they are installed in electric grids of HV. However proceeding from the above-mentioned considerations, we think that it is expedient to study the possibility and efficiency of BT of cross-transformers type mounting in LV grids.

4. Mathematical model for allocation of total losses in LV electric grid and losses from induced transit transfers

In [19] it is shown that power losses in the branches of electric grids can be determined:

$$\Delta\dot{\mathbf{S}}_{\text{br}} = \dot{\mathbf{T}}_{\text{kCT}}\dot{\mathbf{S}} + \dot{\mathbf{V}}_{\text{nb}}, \tag{3}$$

where $\Delta\dot{\mathbf{S}}_{\text{br}} = \Delta\mathbf{P}_{\text{br}} + \Delta\mathbf{Q}_{\text{br}}$ – vector of losses of active and reactive powers in branches, $\Delta\mathbf{P}_{\text{br}} = \text{Re}(\Delta\dot{\mathbf{S}}_{\text{br}})$ – vector of active losses in branches; $\dot{\mathbf{S}} = \mathbf{P} + \text{j}\mathbf{Q}$ – vector of powers in nodes, $\mathbf{P} = \text{Re}(\dot{\mathbf{S}})$ – vector of active power in nodes; $\dot{\mathbf{T}}_{\text{kCT}}$ – matrix of the coefficients of power losses distribution in the branches of equivalent circuit, depending or the powers in its nodes, taking into account transformation ratios of transformer couplings, including branches, containing CT; $\dot{\mathbf{V}}_{\text{nb}}$ – vector-column of power losses in the branches of equivalent circuit as a result of non-balanced transformation ratios.

Each row of matrix $\dot{\mathbf{T}}_{\text{kCT}}$, that contains the coefficients of power losses distribution for ith branch of the equivalent circuit from the power in its nodes, is determined by the formula:

$$\dot{\mathbf{T}}_{\text{kCTi}} = \left(\dot{\mathbf{U}}_{\text{t}}\mathbf{M}_{\text{ki}}\right)\widehat{\mathbf{C}}_{\text{ki}}\dot{\mathbf{U}}_{\text{d}}^{-1}, \tag{4}$$

where $\dot{\mathbf{U}}_{\text{t}}$, $\dot{\mathbf{U}}_{\text{d}}$ – transposed vector and diagonal matrix of voltages in nodes, including basic; $\mathbf{M}_{\text{ki}} = \mathbf{M}_{\text{kATi}} + \mathbf{M}_{\text{kCTi}}$ – ith column of branches connections matrix in nodes $\mathbf{M}_{\text{k}}$, where for branches with transformers instead of values “-1” there are values of their transformation ratios; $\widehat{\mathbf{C}}_{\text{ki}}$ – ith row of current distribution matrix $\dot{\mathbf{C}}_{\text{k}} = \mathbf{z}_{\text{br}}^{-1}\mathbf{M}_{\text{kt}}\left(\widehat{\mathbf{M}}_{\text{k}}\mathbf{z}_{\text{br}}^{-1}\mathbf{M}_{\text{kt}}\right)^{-1}$ with the account of transformer couplings; $\mathbf{z}_{\text{br}} = \mathbf{r}_{\text{br}} + \text{j}\mathbf{x}_{\text{br}}$ – diagonal matrix of branches resistances (here and further sign ^ means that matrix or vector is conjugate, t – that they are transposed).

The value of losses in the ith branch as a result of non-balanced transformation ratios of transformer couplings is determined by the formula:

$$\dot{\mathbf{V}}_{\text{nbi}} = \left(\dot{\mathbf{U}}_{\text{t}}\mathbf{M}_{\text{ki}}\right)\widehat{\mathbf{D}}_{\text{bi}}\widehat{\mathbf{U}}_{\text{b}}, \tag{5}$$

where $\widehat{\mathbf{U}}_{\text{b}}$ – vector column of voltages in balancing nodes; $\widehat{\mathbf{D}}_{\text{bi}}$ – ith row of conductance matrix $\dot{\mathbf{D}}_{\text{b}} = \mathbf{z}_{\text{br}}^{-1}\left(\mathbf{M}_{\text{bkt}} - \mathbf{M}_{\text{kt}}\left(\widehat{\mathbf{M}}_{\text{k}}\mathbf{z}_{\text{br}}^{-1}\mathbf{M}_{\text{kt}}\right)^{-1}\mathbf{Y}_{\text{b}}\right)$, that limit currents from non-balanced transformation ratios in closed contours of electric grid (in case of open electric grid a balanced transformation ratios $\dot{\mathbf{D}}_{\text{b}}$ in transformed into zero matrix); $\mathbf{M}_{\text{bkt}}$ – sub-matrix of the unions of balancing nodes, that is allocated from the transposed connection matrix $\mathbf{M}_{\text{kt}}$; $\mathbf{Y}_{\text{b}} = \widehat{\mathbf{M}}_{\text{k}}\mathbf{z}_{\text{br}}^{-1}\mathbf{M}_{\text{bkt}}$ – fragment of matrix of nodal conductance, that corresponds to balancing nodes.

If coefficient of power losses distribution for the ith branch $\dot{\mathbf{T}}_{\text{kCTi}}$ and vector of nodes powers $\dot{\mathbf{S}}$ are grouped separately for HV and LV grids, then power losses in any ith branch of LV grid can be determined as two components – losses from own transfers, which are determined by the powers of own nodes, $\Delta\text{P}_{\text{LVi}}^{\text{LV}}$, and additional losses as a result of transfers, caused by the impact of HV grid, $\Delta\text{P}_{\text{LVi}}^{\text{HV}}$:

$$\begin{aligned}\Delta\text{P}_{\text{LVi}} &= \Delta\text{P}_{\text{LVi}}^{\text{LV}} + \Delta\text{P}_{\text{LVi}}^{\text{HV}} = \\ &= \left|\dot{\text{T}}_{\text{kCTi}}^{\text{LV}}\,\dot{\text{T}}_{\text{kCTi}}^{\text{HV}}\right|\left|\begin{matrix}\text{P}^{\text{LV}}\\ \text{P}^{\text{HV}}\end{matrix}\right| = \dot{\text{T}}_{\text{kCTi}}^{\text{LV}}\text{P}^{\text{LV}} + \dot{\text{T}}_{\text{kCTi}}^{\text{HV}}\text{P}^{\text{HV}},\end{aligned} \tag{6}$$

where $\dot{\text{T}}_{\text{kCTi}}^{\text{LV}}, \dot{\text{T}}_{\text{kCTi}}^{\text{HV}}$ – coefficients of power losses distribution for ith branch of LV grid from powers of grids LV and HV nodes correspondingly; $\text{P}^{\text{LV}}, \text{P}^{\text{HV}}$ – correspondingly vectors of node powers for HV and LV grids.

Knowing power losses, caused by the impact of HV grid in each branch of LV grid, total losses in LV grid, caused by the impact of HV grid can be determined:

$$\Delta\text{P}_{\text{LV}}^{\text{HV}} = \sum_{\text{i}\in\text{M}_{\text{LV}}}\Delta\text{P}_{\text{LVi}}^{\text{HV}},$$

or, taking into account (6):

$$\Delta\text{P}_{\text{LV}}^{\text{HV}} = \sum_{\text{i}\in\text{M}_{\text{LV}}}\dot{\text{T}}_{\text{ki}}^{\text{HV}}\text{P}^{\text{HV}}, \tag{7}$$

where M_{LV} – set of number of branches of LV grid.

It is known [20] that optimality conditions of mutual and transit transfers are similar to flaw distribution optimality conditions of the whole EPS (except the necessity to calculate optimal current distribution in equivalent r-circuit of the grid with balanced transformation ratios), that is why, to provide energy saving operation modes of electric grids by means of maximum reduction of additional power losses and to interaction of electric grids modes, we propose to use leveling e.m.f. as controlled variables [21]. That is why, e.m.f. are introduced in the contours of the circuit, using regulating effect of AT and CT, direction of which is that forced current distribution approached to economic one.

Such an approach enables to improve the known model of leveling e.m.f. [11], taking into account CT parameters and formulated conditions of optimality of mutual and transit transfers and use it for determination of optimizing impacts in the system of automatic control by power flows and voltage in EPS [22].

Hence, for determination of leveling e.m.f. it is necessary to improve the control laws of system of automatic control in LV grids, that enables to reduce additional losses as a result of mutual and transit power transfers.

Leveling e.m.f. in the contours of the circuit, that contain CT on conditions of optimal modes are determined by means of constant coefficients (similarity criteria) π_a^e and π_r^e, which do not depend on the parameters of current mode:

$$\pi_a^e = \left[\mathbf{E}_{alev}^{(b)}\right]_d^{-1} \mathbf{N}\,\mathbf{x}_{br}\mathbf{C}_r \left[\mathbf{J}_r^{(b)}\right]_d = \text{idem}, \tag{7}$$

$$\pi_r^e = \left[\mathbf{E}_{rlev}^{(b)}\right]_d^{-1} \mathbf{N}\,\mathbf{x}_{br}\mathbf{C}_r \left[\mathbf{J}_a^{(b)}\right]_d = \text{idem}, \tag{8}$$

where $\mathbf{N}$ – direct matrix of branches connections in the contours of the circuit; $\mathbf{C}_r = \mathbf{r}_{br}^{-1}\mathbf{M'}_t\left(\mathbf{M'}\mathbf{r}_{br}^{-1}\mathbf{M'}_t\right)^{-1}$ – matrix of current distribution coefficients of EPS calculation circuit (equivalent r-circuit of EPS); $\mathbf{r}_{br}$ – diagonal matrix of branches active resistance; $\mathbf{M'}$ – the first matrix of incidence grid, where row, corresponding to generation nodes (it is equivalent to combining of all supply sources in one calculating balancing node) are deleted, $\mathbf{M'}_t$ – transposed first matrix of incidence grid $\mathbf{M'}$; $\mathbf{J}_a^{(b)}$ and $\mathbf{J}_r^{(b)}$ – vectors of active and reactive components of nodal currents in the mode with minimum losses due to interaction.

They are similar to corresponding e.m.f. of the mode, taken as a basic. That is, ES leveling e.m.f. are similar for various modes.

Components of leveling e. m. f. in criterial form:

$$\begin{aligned}\mathbf{E}_{*lev.a} &= \boldsymbol{\pi}_{a1}^e + \boldsymbol{\pi}_{a2}^e\,\mathbf{J}_{*a}^b + \boldsymbol{\pi}_{a3}^e\,\mathbf{J}_{*p}^b,\\ \mathbf{E}_{*lev.r} &= \boldsymbol{\pi}_{r1}^e + \boldsymbol{\pi}_{r2}^e\,\mathbf{J}_{*r}^b + \boldsymbol{\pi}_{r3}^e\,\mathbf{J}_{*a}^b,\end{aligned} \tag{9}$$

where $\boldsymbol{\pi}^e = \begin{bmatrix}\boldsymbol{\pi}_{a1}^e & \boldsymbol{\pi}_{a2}^e & \boldsymbol{\pi}_{a3}^e\\ \boldsymbol{\pi}_{r1}^e & \boldsymbol{\pi}_{r3}^e & \boldsymbol{\pi}_{r2}^e\end{bmatrix}$ – matrix of similarly criteria in criterial model of leveling e.m.f. in the contours of EPS.

Leveling e.m.f. are determined they are similar to corresponding e.m.f. of the basic mode (for r-circuit). That is, for various modes in EPS, leveling e.m.f. are similar. For realization of optimal mode of EPS it is necessary to introduce them into independent contours of the circuit by means of adjusting transformation ratios of regulation devices [11].

Active and reactive components of AT and CT transformation ratios are determined by the following expression:

$$\begin{aligned}\mathrm{k_a} &= 1-(\mathrm{Re}(-\mathrm{N_{кзб}ZC_rJ}))_d\,\mathbf{U}_b^{-1}\,\mathbf{E}_{*lev.a},\\ \mathrm{k_r} &= 1-(\mathrm{Im}(-\mathrm{N_{кзб}ZC_rJ}))_d\,\mathbf{U}_b^{-1}\,\mathbf{E}_{*lev.r}.\end{aligned} \tag{10}$$

That is why, complex transformation ratio of AT and CT that corresponds to the chord of graph tree is found from the expression

$$\mathrm{k} = \mathrm{k_a} + \mathrm{j}\cdot\mathrm{k_r} = \mathrm{k_{AT}}\cdot e^{j\delta}. \tag{11}$$

Optimal transformation factor of AT is $\mathrm{k_{AT}}=\sqrt{\mathrm{k_a^2}+\mathrm{k_r^2}}$, then it enables to determine optimal phase shifting angle of CT: $\delta=\mathrm{arctg}\left(\dfrac{\mathrm{k_r}}{\mathrm{k_a}}\right)$.

5. Development of the algorithm for determination of optimal branch of CT installation and its optimal phase shifting angle

We propose the algorithms for determination of optimal by expected decrease of general system losses of active power branch of CT location and CT phase-shifting angle, block-diagrams of which are shown in Fig. 2 and Fig. 3.

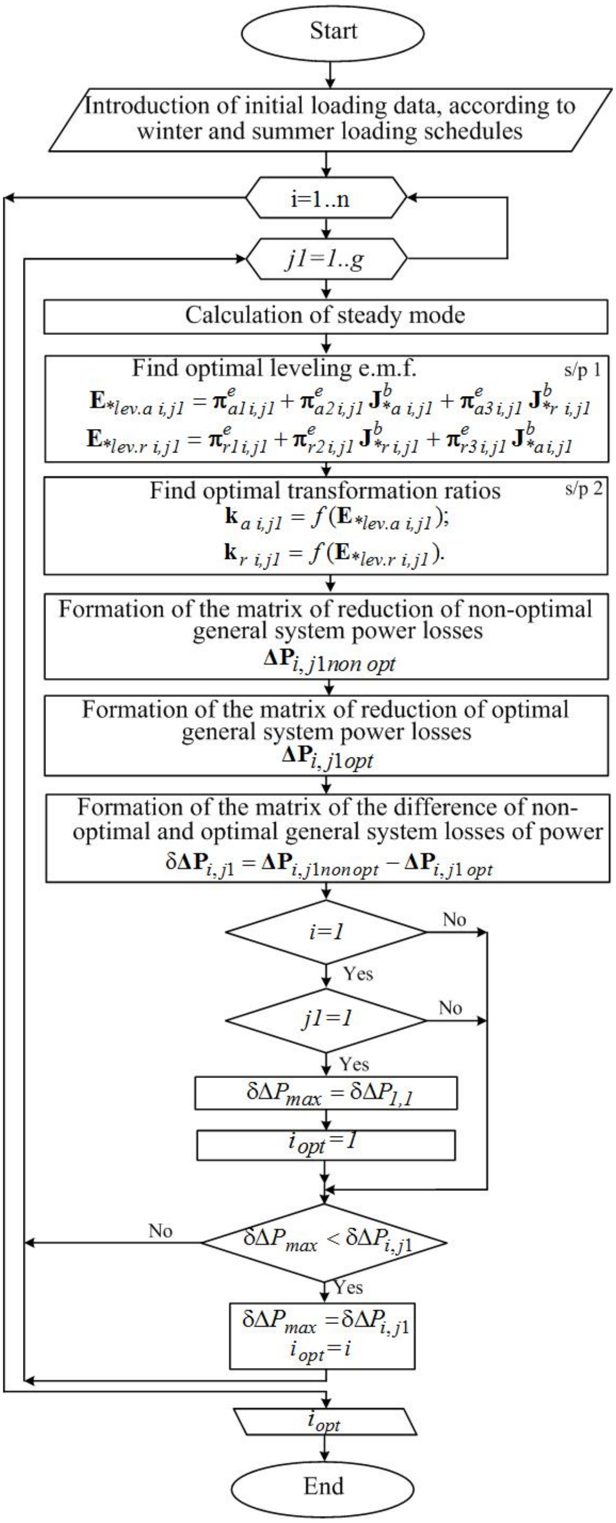

Fig. 2. Block-diagram of the algorithm intended for determination of optimal branch of CT

Algorithm of determination of the branch of optimal location of CT is shown in Fig. 2, and the algorithm of determination of CT optimal phase-shifting angle, located in this branch, is shown in Fig. 3. According to Fig. 2: *i* – conventional numbers of transformers branches (except the branch, located in the graph tree), where the possibility of CT installation is considered; $j1$ – number of the stage of daily schedule of loading (first, winter, then, summer); $\mathbf{E}_{*lev\ a}$, $\mathbf{E}_{*lev\ r}$ – relative values of active and reactive components of leveling e.m.f., that must be introduced in the contour of EPS circuit for compensation of the impact of different parameters of contour transformers and non-uniformity of branches; $\pi^{e}_{a1i,j1}$, $\pi^{e}_{a2i,j1}$, $\pi^{e}_{a3i,j1}$, $\pi^{e}_{r1i,j1}$, $\pi^{e}_{r1i,j}$, $\pi^{e}_{r1i,j}$ – similarity criteria of current mode parameters to the parameters of economic mode of uniform grid [21]; $\mathbf{k}_{a\ i,j1}$, $\mathbf{k}_{r\ i,j1}$,– longitudinal and transversal components of transformation ratios of the investigated transformers branches; $\Delta\mathbf{P}_{i,j1\ non\text{-}opt}$, $\Delta\mathbf{P}_{i,j1\ opt}$ – general system losses of active power in the branches of EPS circuit, caused by non-optimal and optimal (correspondingly) transformation ratios of the transformer of the investigated grid during EPS operation at i^{th} stage of loading schedule; $\delta\,\mathbf{P}_{i,j1\ opt}$ – reduction of general system loads of active power in the branches of EPS circuit, caused by using of tap-changing under load of power transformers and CT of investigated branch during EPS operation at $j1^{th}$ stage of loading schedule.; i_{opt} – number of the branch, where CT must be installed.

In accordance with Fig.3: k – transformation ratio of CT for chosen in the algorithm in Fig.2 optimal branch, for each stage of annual schedule of loading); $\mathbf{E}_{*lev\ ak}$, $\mathbf{E}_{*lev\ rk}$ – relative values of active and reactive components of leveling e.m.f., taking into account CT, installed in optimal transformer branch, which must be introduced in the contour transformers and branches non-uniformity; π^{e}_{a1k}, π^{e}_{a2k}, π^{e}_{a3k}, π^{e}_{r1k}, π^{e}_{r2k}, π^{e}_{r3k} – similarity criteria of current mode parameters to the parameters of economic mode of the uniform grid, taking into account CT [6]; $\mathbf{k}_{a\ k}$, $\mathbf{k}_{r\ k}$,– longitudinal and transversal components of transformation ratios of the investigated transformers branches; $\Delta\mathbf{W}_{k\ non\text{-}opt}$, $\Delta\mathbf{W}_{k\ opt}$ – general system losses of energy in the branches of EPS circuit, caused by non-optimal and optimal (correspondingly) transformation ratios of AT and CT of the investigated branch during EPS operation on $j1^{th}$ stage of loading schedule; $\delta\,\mathbf{W}_{i,j\ opt}$ – reduction of general system losses of energy in the branches of EPS circuit, caused by usage of tap-changing-under-load of power transformers and CT of investigated branch during EPS operation at $j1^{th}$ stage of loading schedule; k_{opt} – optimal value of phase-shifting angle of CT, that will be introduced or removed at various modes of EPS operation; δ – CT phase shifting angle.

To determine optimal branch and optimal transformation ratio of CT, algorithms of the Fig. 2 and Fig. 3 are used. In accordance with the given algorithm of the Fig. 2, introduction of initial data and formation of the set lists of nodes and branches is performed at the beginning of the algorithm, as this stage does not require computations. At the next stage optimal transformation ratios of AT and CT for all transformer branches are determined by turn, corresponding to each stage of daily loading schedule using the known method of optimal transformation ratios determination (subprogram 1 and 2) [11, 21].

By means of subprogram 1 (s/p 1) in Fig 2, 3 elements of similarity criteria matrices are determined. At the first step of the subprogram 1, parameters, necessary for calculation of normal mode of EPS are introduced. After calculation of the mode arrays of diagonal matrix of voltage in nodes, vector of nodal loadings are formed and vector of setting currents of basic mode is parameters of equivalent circuit of electric grid the first matrix of connections, taking into created. Account transformation ratios in obvious form is using this matrix, matrix of nodal conductance's is determined, that corresponds to balancing nodes. Matrix of current division coefficients is formed, it corresponds to economic mode on the basis of equivalent r-circuit of electric grid with balanced transformation ratios. Further, the second matrix of connections, taking into account transformation ratios is formed. At the next step of subprogram 1 the vector of contour e.m.f. is determined, it is used for determination of leveling e.m.f. for basic mode. At the final stage of subprogram 1 operation the formation of similarly criteria matrix is performed for it determination the results of the previous calculation are used.

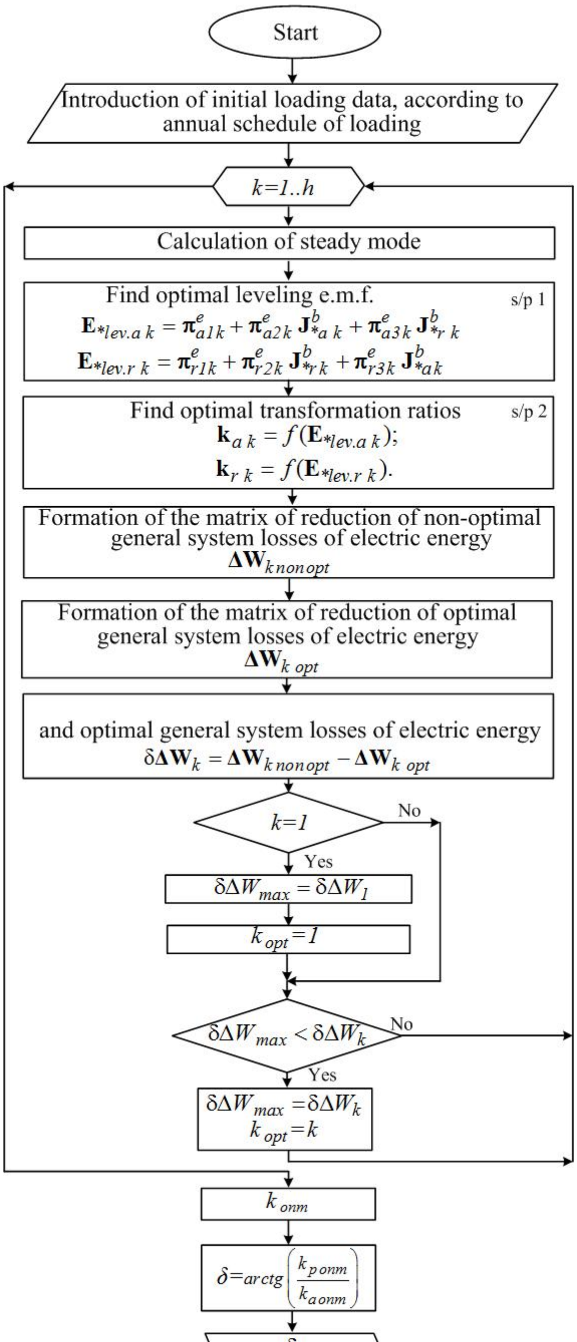

Fig. 3. Block-diagram of the algorithm, intended for determination of phase shifting angle of CT

With the help of the subprogram 2 (s/p 2) in Fig. 2 and Fig. 3 optimal transformation ratios are determined. Using the parameters of EPS current mode vectors of setting current of EPS independent nodes are determined. Further, optimal leveling e.m.f., introduced into independent contour of the circuit by means of transformation ratios of regulating devices, are calculated.

In s/p 2 (determination of optimal transformation ratios) reading of similarity criteria matrix from s/p 1 together with setting currents and leveling e.m.f. of basic mode is provided. S/p 2 ends with determination of optimal transformation ratios of AT and CT.

Further matrix of difference of non-optimal power losses and optimal power losses is formed, during the analysis of its value optimal branch for CT installation is determined.

Algorithm, shown in Fig. 3 enables to find optimal transversal component of CT transformation ratio, that is installed in the branch, determined, using algorithm initial data, described above and annual loading schedule are introduced. Optimal transformation ratios of AT and CT are found in the branch, by chosen by means of s/p 1 and s/p 2. Vector-column of the difference of electric energy losses is formed, from this vector thee value of maximum decrease of energy losses is chosen and optimal value of CT transformation ratio, at which this decrease was achieved, is deduced is. Further optimal angle of CT δ is derived.

6. Analysis of the results of computer modeling of LV grids with CT normal modes

For determination of optimal (according to the criterion of minimal general system losses of electric energy) place of CT installation and CT phase-shifting angle (δ) the study of their impact on losses is performed. Let us consider the determination of normal mode parameter on the example of IEEE 230–138 kV testing circuit (Fig. 4), taking into account daily schedule of load change (Fig. 5).

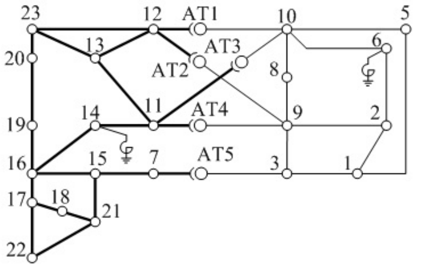

Fig. 4. IEEE 230-138 kV testing circuit on 23 nodes

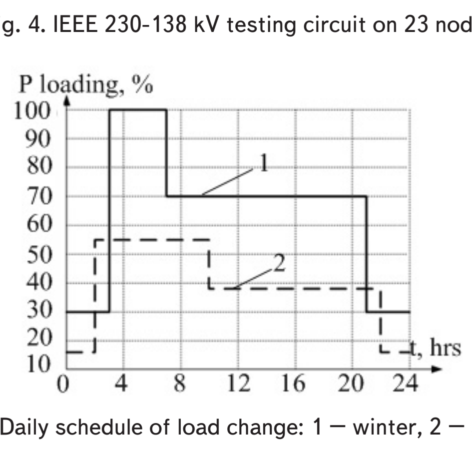

Fig. 5. Daily schedule of load change: 1 — winter, 2 — summer

As a result of optimal mode calculation at each section of the schedule of loads the value of optimal transformation ratios of AT and phase-shifting angle of CT condition of their turn wise installation in transformation branches which are chords in the system basic contours (branches 10–12, 9–12, 9–11) is obtained [2]. We will determine optimal combinations of δ and transformation ratios of AT (k_{AT}) on the example of winter daily load schedule (for summer the calculation is performed in the same manner).

The results of the calculations are shown in Fig. 6, 7 and Fig. 8. On the graph, the dependences of active power losses of electric grid on the number of transformer branches, in which calculated optimal k_{AT} and δ for 100 %, 70 % and 30 % of maximum daily loading were introduced turn wise, that corresponds to Fig. 5 in four modes (1 – non-optimal k_{AT} and it is missing; 2 – optimal k_{AT} and CT is missing; 3 – optimal k_{AT} and optimal place of CT installation and its δ; 4 – non-optimal k_{AT} and optimal place of CT installation and its δ).

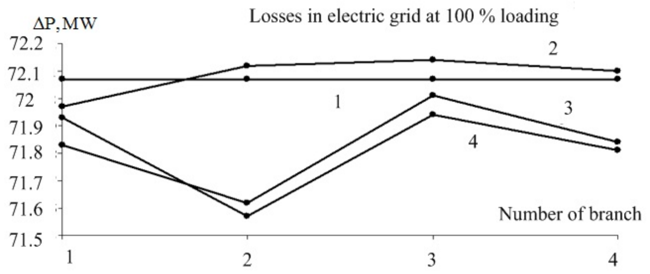

Fig. 6. Dependence of power losses due to k_{AT} and δ at 100 % loading

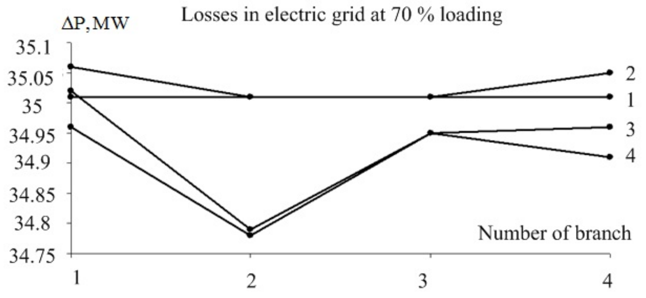

Fig. 7. Dependence of power losses due to k_{AT} and δ at 70 % loading

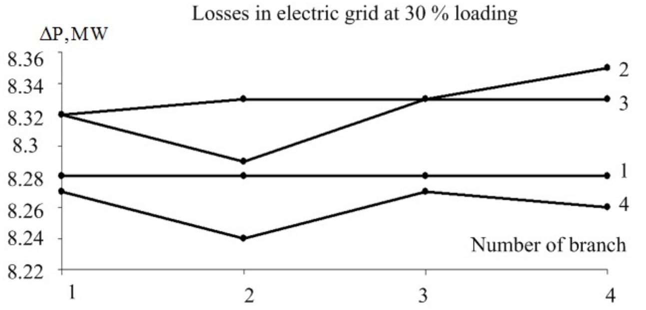

Fig. 8. Dependence of power losses due to k_{AT} and δ at 30 % loading

The results of calculations show (Fig. 6), that at 100 % loading for mode optimization (if CT is missing) it would be necessary to perform AT tap-changing- under-load switching of 12–9 branch. But as a result of CT installation, we could avoid not only regulation of tap-changing- under-load but also decrease power losses (ΔP) by 0.7 %. The result of steady mode calculation in case of AT tap-changing- under-load and δ regulation at different loads are given in Table 1. After analysis of all the results branch 11–10 turned out to be optimal but at other parameters of overhead transmission line better variants can be obtained in case of simultaneous usage of CT in several branches. Then it is necessary to carry out the research to determine the most efficient place of CT installation.

Table 1

The results of research of steady mode at regulation of tap changing under load and δ

Loading		Transformers parameters		ΔP, MW	δP, MW	δW, MW
Duration, hrs	P, % from max loading	k_{AT}, r.u.	δ, radian			
Determined transformation ratios at 30 % loading						
k_{12-9} = 0.6498; k_{11-10} = 0.6487; k_{11-9} = 0.6479; k_{12-10} = 0.6524						
Transformer branch 11–10						
Determined transformation ratios at 100 % loading						
4	100	0.6487	-	72.07	-	-
4	100	0.6436	-	72.12	-0.05	-0.2
4	100	0.6436	0.0306	71.62	0.45	1.8
4	100	0.6487	0.0306	71.57	0.5	2
Determined transformation ratios at 70 % loading						
k_{12-9} = 0.6404; k_{11-10} = 0.6442; k_{11-9} = 0.6423; k_{12-10} = 0.6448						
14	70	0.6442	-	35.01	-	-
14	70	0.6452	-	35.01	0	0
14	70	0.6452	0.0232	34.79	0.22	3.08
14	70	0.6442	0.0232	34.78	0.23	3.22
Determined transformation ratios at 30 % loading						
k_{12-9} = 0.6456; k_{11-10} = 0.6449; k_{11-9} = 0.645; k_{12-10} = 0.6479						
6	30	0.6449	-	8.28	-	-
6	30	0.6492	-	8.33	-0.05	-0.3
6	30	0.6492	0.01	8.29	-0.01	-0.06
6	30	0.6449	0.01	8.24	0.04	0.24

Table 1 contains the difference of active power losses (δP) and the difference of electric energy losses (δW) in the process of transition from the current to optimal δ that is the index of power losses and energy losses decrease in electric grid during optimal control of the mode. By means of calculation the losses of active power were determined, turn wise changing location of CT with optimal for investigated mode in each of the transformer branches. We choose the branch, where general system losses of active power are minimal. Further we find optimal δ. Let us consider the case when only one CT can be switched on depending on voltage limitations in nodes, currents in branches and for providing minimal losses of power.

In our example (Fig. 3, 4) six variants of δ are obtained for optimal branch of its location. We are to choose only one. Selection of δ is done by the criterion of minimal annual losses of electric energy. If we carry out the choice of optimal δ according to minimal values of power losses then this will lead to different choice of δ, because at each change of load schedule the branch of optimal location of CT and the value of its transformation ratio may change. Thus we select the variant of optimal δ search according the criterion of minimal annual losses of energy. We pass from the considered daily loading graphs to consideration of annual loading diagram by its duration [23]. Mode calculation is carried out taking into account operation switching (introduction or removed of CT) during the year.

For determination of optimal k_{AT} all the differences of energy losses are added and we obtain the following decreases of energy losses per year ($\Sigma\delta W$) (Table 2).

Table 2

Values of energy losses decrease per year

Optimal δ, rad	Sum of the difference of energy losses, ΣδW, MW·h
0.0306	38368.8
0.0232	**<u>81643.2</u>**
0.0100	38719.2
0.0193	28557.6
0.0130	67101.6
0.0064	29784.0

Hence, it is expedient to install CT in the branch 11–10 with δ=0.0232. As it is seen from the Table 2, in this case, the greatest decrease of annual electric energy losses is expected.

7. Conclusions

It has been shown in this study that the efficient method of EPS normal modes control improvement is optimal usage of CT in low voltage electric grids.

By means of computer modeling, it is proved that there exist such modes, at which HV grids are unloaded on LV grids, that leads to additional losses of active electric energy in LV grids and the increase of general system losses of active power.

Application of CT with optimal phase-shifting angle in the branch, determined by the suggested method of determination of optimal place of CT location, allows to decrease both the losses of active power in LV grids and general system losses.

The degree of influence of mutual and transit power transfers on the level of active electric energy losses changes, depending on AT transformation ratios, on the value of CT phase shifting angle, on circuit parameters and mode of electric grid loading.

Investigations of additional losses of active power changes stipulated by displacement of transit power transfers from HV grids into LV grids proves that sometimes: uncoordinated usage of regulating devices of the transformers in HV and LV grids leads to growth of these additional power losses; usage of transformers tap-changing under load dues not allow to decrease maximally losses of active power, greater decrease of these losses can be achieved by optimal usage of cross-transformers.

References

1. Zhelezko, Yu. S. Calculation, analysis and valuation of electric energy losses in electric grids [Text] / Yu. S. Zhelezko, A. V. Arteniev, O. V. Savchenko. – Moscow ENAC, 2003. – 280 p.
2. Talasov, A. G. Losses on electric energy transit and their distribution among participants of energy exchange [Text] / A. G. Talasov // Electric stations. – 2002. – Vol. 1. – P. 20–25.
3. Stogniy, B. V. Determination of transit losses of power in fragmented electric grids of regional utility companies [Text] / B. V. Stogniy, V. V. Pavlovskiy // Energy policy of Ukraine. – 2004. – Vol. 5. – P. 60–65.
4. Idelchik, V. I. Electric systems and grids [Text] / V. I. Idelchik. – Moscow: Energoatomizdat (Publishing house), 1989. – 592 p.
5. Olshvang, M. V. Characteristic features of cross-transformer technology of energy transport in 110-765 kV grids [Text] / M. V. Olshvang // Electro. – 2004 – Vol. 2. – P. 6–12.
6. Kylymchuk, A. V. Minimization of additional losses of electricity in electric networks caused of their interaction [Text] / A. V. Kylymchuk, P. D. Lezhniuk, O. E. Rubanenko // Visnyk VPI Vinnytsia National Technical University. – 2013. – Vol. 5. – P. 48–52.
7. Yasen, M. H. Evaluation of electric energy losses in Kirkuk distribution electric system area [Text] / M. H. Yasen, S. S. Mustafa // Energy, Power and Control (EPC-IQ), 2010 1st International Conference on, 2010. – P. 339–344.
8. Babu, P. R. Operation and control of electrical distribution system with extra voltage to minimize the losses [Text] / P. R. Babu, B. Sushma // Power, Energy and Control (ICPEC), 2013 International Conference on, 2013. – P. 165–169. doi:10.1109/ICPEC.2013.6527643
9. Musa, I. Integration of Distributed Generation for network loss minimization and voltage support using Particle Swarm Optimization [Text] / I. Musa, B. Zahawi, S. M. Gadoue, D. Giaouris // Power Electronics, Machines and Drives (PEMD 2012), 6th IET International Conference on, 2012. – P. 27–29. doi: 10.1049/cp.2012.0150
10. McDonald, L Minimisation of distribution network real power losses using a smart grid Active Network Management System [Text] / L. McDonald, R. L. Storry, A. Kane, F. McNicol // Universities Power Engineering Conference (UPEC), 2010 45th International, 2010. – P. 1–6.
11. Lezhnyuk, P. D. Electric networks and systems interaction in optimal regulation processes of their regimes [Text] / P. D. Lezhnyuk, V. V. Kulyk, O. B. Burykin. – Vinnytsya: UNIVERSUM-Vinnytsya, 2008 – 123 p.
12. Bocovich, M. Overview of series connected flexible AC transmission systems (FACTS) [Text] / M. Bocovich, K. Iyer, R. M. Terhaar, N. Mohan // North American Power Symposium (NAPS), 2013. – P. 1–6. doi: 10.1109/NAPS.2013.6666915
13. Siddiqui, A. S. Application of phase shifting transformer in Indian Network [Text] / A. S. Siddiqui, S. Khan, S. Ahsan, M. I. Khan, A. Annamalai //Green Technologies (ICGT), International Conference, 2012. – P. 186–191. doi: 10.1109/ICGT.2012.6477970
14. Kolcun, M. Transformer use for active power flow control in the electric power system [Text] / M. Kolcun, D. Hluben, L. Bena, N. Djagarov, Z. Grozdev // Environment and Electrical Engineering (EEEIC), 2010 9th International Conference on, 2010. – P. 246–249. doi: 10.1109/EEEIC.2010.5489982
15. Rimez, J. Grid implementation of a 400MVA 220/150kV –15°/+3° phase shifting transformer for power flow control in the Belgian network: specification and operational considerations [Text] / J. Rimez, R. Van Der Planken, D. Wiot, G. Claessens, E. Jottrand, J. Declercq. – Cigre 2006, 2006. – P. A2-202.
16. Constantin, C. Power flow control solutions in the Romanian power system under high wind generation conditions [Text] / C. Constantin, M. Eremia, L. Toma // PowerTech (POWERTECH), 2013 IEEE Grenoble, 2013. – P. 1–6. doi: 10.1109/PTC.2013.6652353
17. El Hraiec, A. Control of parallel EHV interconnection lines using Phase Shifting Transformers [Text] / A. El Hraiec, K. Ben-Kilani, M. Elleuch // Multi-Conference on Systems, Signals & Devices (SSD), 2014 11th International, 2014. – P. 1–7. doi: 10.1109/SSD.2014.6808829
18. Lezhniuk, P. D. Evaluation of the interaction of energy systems electric grids with transformer couplings [Text] / P. D. Lezhniuk, V.V . Kulyk, O. B. Burykin // Engineering electrodynamics: Thematic issue "Problems of modern electrical engineering" – 2006. – Vol. 7. – P. 27–30.
19. Lezhniuk, P. D. Optimal control of power flows and voltage in non-uniform electric grids: monograph [Text] / P. D. Lezhniuk, V. V. Kulyk. – Vinnytsya: UNIVERSUM – Vinnytsya, 2003. – 188 p.
20. Kuznetsov, V. G. Optimization of electric grids modes [Text] / V. G. Kuznetsov, Yu. I. Tugaiy, V. A. Bazhenov. – K.: Naukova Dumka, 1992. – 216 p.
21. Lezhniuk, P. D. Modelling and formation of the conditions of self optimization of electric energy system modes [Text] / P. D. Lezhniuk, V. V. Kulyk, K. I. Kravtsov // Technical electrodynamics: Thematic issue: Problems of moderns electrical engineering. – 2002 – Vol. 3. – P. 96–101.
22. Kylymchuk, A. V. Control automation of power flows in EPS with the use of cross-transformers and similarity of the optimal modes [Electronic resource] / A. V. Kylymchuk, P. D. Lezhniuk, Ngoma Jean-Pierre // Vinnytsia National Technical University. – 2009. – Vol. 4. – Available at: http://www.nbuv.gov.ua/e-journals/vntu/2009-4/2009-4_ru.files/ru/09pdloms_ru.pdf
23. Mustafaev, R. I. Daily allowance graphics of loading and operating parameters [Electronic resource] / R. I. Mustafaev, R. G. Mironov / Problems of energy branch. – 2003. – Vol. 3. – Available at: http://www.science.gov.az/physics/PowerEng/2003/v3article/art14.pdf