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Reduction of Additional Losses of Electric Energy in Parallel Operating Non-Uniform Electrical Grids Taking into Account Non-Uniformity and Sensitivity

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Abstract
The paper considers mathematical models for determination of electric energy losses in non-uniform electric grids, caused by their interaction. The method of these losses reduction by means of phase shifting transformers, mounted in the grid of lower voltage is shown. Method for determination of optimal location for these transformers mounting is suggested.

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 energy systems (EES) united for parallel operation by inter systems connections, the interaction of their modes is observed. One of the reasons of mode non optimality is non-uniformity of electric grids of EPS as constructive peculiarity of their elements, where ratio of inductive and active resistances considerably differs. Due to non-uniformity mutual power transfers occur among electric grids of EES, these transfers load the grids of contiguous utility companies. As it is known [1], grids of higher voltages are unloaded in parallel operating grids of lower voltage [2]. The consequences of this are additional losses of electric energy and overload of switching devices and overhead transmission lines of lower voltage [3, 4, 5].

The given 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. 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 of higher voltage (main) on additional losses in distributive grids of utility companies and analyze the consequences of electric grids interaction. The given paper considers the possibilities of compensation of electric energy additional losses in electric grids, caused by their interaction, introducing electromotive force in the contours by means of phase shifting transformers (PST) [6].

In world practice phase-shifting transformers are widely used. For instance, in New

England 39- bus system [7] (Great Britain) they are suggested to be installed in all intersystem communications of energy systems. In EES of Maharashtra i Utter Pradesh states [8, 9] (India) and in EES of France [10], PST are installed in overloaded or under loaded lines for redistribution electric power flows. As a result, additional losses of power decrease, reliability of the network and energy supply quality increase. But such measures are not always of positive character. While off-loading or loading of the lines general system losses of active power (GLAP) decrease, and sometimes – grow [2]. That is why, to take into consideration such drawback, the method of determination of optimal place of PST installation by accounting the coefficients of non-uniformity of EES calculation circuit branches and sensitivity of GLAP to the place of location and PST angle in EES. This enables not only to decrease additionally GLAP, off- load networks, improve the reliability of the network and decrease the relation between the cost of measures aimed at introduction of PST and electric energy, saved in the investigated time interval, substantiate economic expediency of PST usage.

2. 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 high voltage (HV) and low voltage (LV). In accordance with the value of these losses, measures, aimed at their optimization in HV and LV grids are developed. Depending of operation conditions and interaction between main and distributive grids (MEG and DEG) two variants are possible. Agreements, regarding minimization of total losses ΔP_{Σ} in HV and LV grids and determination of transformation ratios optimal values of transformers and coupling transformers can be reached.

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

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 expel" the given transit power transfers from LV grid into HV grid, i.e., such problem is solved.

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

Difficultly of the implementation of the results of this problem (2) solution is that facilities, by means of which these results can be practically achieved (transformers, coupling autotransformers) MEGs have in their fixed assets and DEG have rather limited access to them. Hence, from the position of DEG there is only one way out – install PST in their grids. In this case the following problem appear: determination of the most efficient place in LV grid where PST can be installed and its capacity.

3. Mathematical Model for Separation of Total Losses in LV Electric Grid and Losses from Given Transit Transfers

Power losses in the branches of electric grids can be determined as

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

where $\mathbf{\Delta\dot{S}}_{br} = \mathbf{\Delta P}_{br} + \mathbf{\Delta Q}_{br}$ – vector of losses of active and reactive powers in branches; $\mathbf{\dot{S}} = \mathbf{P} + j\mathbf{Q}$ – vector of powers in nodes; $\mathbf{\dot{T}}_{k}$ – 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; $\mathbf{\dot{V}}_{nb}$ – vector-column of power losses in the branches of equivalent circuit as a result of non-balanced transformation ratios.

Each row of matrix $\mathbf{\dot{T}}_{k}$, 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

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

where $\mathbf{\dot{U}}_{t}$, $\mathbf{\dot{U}}_{d}$ – transposed vector and diagonal matrix of voltages in nodes, including basic; $\mathbf{M}_{ki}$ – ith column of the matrix of branches connection in nodes $\mathbf{M}_{k}$, where for branches with the transformers instead of values "-1" values of their transformation ratios are; $\mathbf{\widehat{C}}_{ki}$ – ith row of current distribution matrix $\mathbf{\dot{C}}_{k} = \mathbf{z}_{br}^{-1}\mathbf{M}_{kt}\left(\mathbf{\widehat{M}}_{k}\mathbf{z}_{br}^{-1}\mathbf{M}_{kt}\right)^{-1}$ with the account of transformer couplings; $\mathbf{z}_{br} = \mathbf{r}_{br} + j\mathbf{x}_{br}$ – 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:

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

where $\mathbf{\widehat{U}}_{b}$ – vector column of voltages in balancing nodes; $\mathbf{\widehat{D}}_{bi}$ – ith row of conductance matrix

$\dot{\mathbf{D}}_b = \mathbf{z}_{br}^{-1}\left(\mathbf{M}_{bkt} - \mathbf{M}_{kt}\left(\widehat{\mathbf{M}}_k \mathbf{z}_{br}^{-1}\mathbf{M}_{kt}\right)^{-1}\mathbf{Y}_b\right)$, that limit currents from non-balanced transformation ratios in closed contours of electric grid (in case of open electric grid or balanced transformation ratios $\dot{\mathbf{D}}_b$ in transformed into zero matrix); $\mathbf{M}_{bkt}$ – sub-matrix of balancing nodes links, that is separated from the transposed connection matrix $\mathbf{M}_{kt}$; $\mathbf{Y}_b = \widehat{\mathbf{M}}_k \mathbf{z}_{br}^{-1}\mathbf{M}_{bkt}$ – fragment of matrix of nodal conductance, that corresponds to balancing nodes.

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

$$\begin{aligned}\Delta\dot{S}_{LVi} &= \Delta\dot{S}_{LVi}^{LV} + \Delta\dot{S}_{LVi}^{HV} = \left|\dot{T}_{ki}^{LV}\dot{T}_{ki}^{HV}\right|\begin{vmatrix}\dot{S}^{LV}\\ \dot{S}^{HV}\end{vmatrix} = ,\\ &= \dot{T}_{ki}^{LV}\dot{S}^{LV} + \dot{T}_{ki}^{HV}\dot{S}^{HV}\end{aligned} \tag{6}$$

where $\dot{T}_{ki}^{LV}, \dot{T}_{ki}^{HV}$ – coefficients of power losses distribution of LV and HV grids nodes correspondingly; $\dot{S}^{LV}, \dot{S}^{HV}$ – 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

$$\Delta\dot{S}_{LV}^{HV} = \sum_{i\in M_{LV}} \Delta\dot{S}_{LVi}^{HV},$$

or, taking into account (6)

$$\Delta\dot{S}_{LV}^{HV} = \sum_{i\in M_{LV}} \dot{T}_{ki}^{HV}\dot{S}^{HV}, \tag{7}$$

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

4. Place of PST Installation in LV Grid According to the Results of Sensitivity Analysis

In [11] it is shown, that non-uniformity of complex-closed electric grids is evaluated by the general system index

$$\boldsymbol{\gamma} = \mathbf{M}_{kt}\mathbf{x}\mathbf{r}^{-1} - \mathbf{x}_{br}\mathbf{r}_{br}^{-1}\mathbf{M}_{kt}, \tag{8}$$

where r, x – active and reactive components of nodal resistances matrix.

We will express how general system index of non-uniformity depends on the transformers transformation ratio. Matrix $\mathbf{M}_{kt}$ we will write as

$$\mathbf{M}_{kt} = \mathbf{M}_t^{+} + \mathbf{k}\mathbf{M}_t^{-}, \tag{9}$$

where $\mathbf{M}_t^{+}$ – matrix, that contains the fragment of coupling matrix, elements of which are zeros and ones with the sign "+"; $\mathbf{M}_t^{-}$ – the same matrix, but its elements are zeros and ones with the "-"; k – diagonal matrix of complex transformation ratios (if in i[th] branch the transformer is missing, then i[th] diagonal element $\dot{k}_{i,i} = 1$).

Having substituted (8) into (9) we obtain

$$\boldsymbol{\gamma} = \left(\mathbf{M}_t^{+} + \mathbf{k}\mathbf{M}_t^{-}\right)\mathbf{x}\mathbf{r}^{-1} - \mathbf{x}_{br}\mathbf{r}_{br}^{-1}\left(\mathbf{M}_t^{+} + \mathbf{k}\mathbf{M}_t^{-}\right). \tag{10}$$

After transformation (10) we will have:

$$\boldsymbol{\gamma} = \mathbf{k}\left(\mathbf{M}_t^{-}\mathbf{x}\mathbf{r}^{-1} - \mathbf{x}_{br}\mathbf{r}_{br}^{-1}\mathbf{M}_t^{-}\right) + \left(\mathbf{M}_t^{+}\mathbf{x}\mathbf{r}^{-1} - \mathbf{x}_{br}\mathbf{r}_{br}^{-1}\mathbf{M}_t^{+}\right),$$

or

$$\boldsymbol{\gamma} = \mathbf{k}\left(\mathbf{M}_t^{-}\mathbf{x}\mathbf{r}^{-1} - \mathbf{x}_{br}\mathbf{r}_{br}^{-1}\mathbf{M}_t^{-}\right) + \left(\mathbf{M}_t^{+}\mathbf{x}\mathbf{r}^{-1} - \mathbf{x}_{br}\mathbf{r}_{br}^{-1}\mathbf{M}_t^{+}\right). \tag{11}$$

As matrix k contains all transformation ratios of electric grid, including ratio of branch PST (which depends on the shift angle of PST of this branch), then it is necessary from the matrix $\boldsymbol{\gamma}$ formed according to (11), select those elements, which are the most changeable when PST shift angle is changed. For this purpose we make use of optimal solutions.

From the set of branches the selected elements γ_{ij} correspond to, it is necessary to assign the branch that has maximum γ_{ij}.

After determination of optimal place of PST installation, applying the criterion of GLAP minimum, we suggest to determine optimal value of PST shift angle [9]. However, real parameters of EES differ from the expected – calculated. That is why, synthesizing tap-changing under-load control of power transformers, switching devices of capacitor banks, tap-changing under load of PST, etc. (synthesized vector of control effects) may turn out to be not optimal. This may lead to violation of optimality conditions while normal modes control in the rate of the process of electric energy transfer.

For evaluation of the effect of the above - mentioned factors on the value of optimality criterion (minimal GLAP) we suggest to make use of mathematical apparatus of sensitivity theory.

That is, it is necessary to study the sensitivity of electric energy losses to the change of PST angles and select the branch, where the change of PST angle causes maximum decrease of general system losses of active power during time from 0 to T

$$\max\left(\frac{\partial \Delta W}{\partial \delta_i}\right)_{i=1,n} = \max\left\{\Delta P\left(\mathbf{X}(T), \mathbf{u}(T), T, \delta\right)\frac{\partial T}{\partial \delta_i} + \int_0^T \left[\frac{\partial \Delta P}{\partial \mathbf{X}} \cdot \frac{\partial \mathbf{X}}{\partial \delta_i} + \frac{\partial \Delta P}{\partial \mathbf{u}} \cdot \frac{\partial \mathbf{u}}{\partial \delta_i} + \frac{\partial \Delta P}{\partial \delta_i}\right] dt\right\}_{i=1,n}, \quad (12)$$

where ΔW – losses of electric energy in EES; ΔP – active power losses in EES; $\mathbf{X}$ – array of normal modes parameters of the investigated fragment of EES circuit; $\mathbf{u}$ – column vector of voltages in nodes; T – time fragment, when PST shift angle does not change; δ – shift angle of PST; n – numbers of PST branches.

By means of mathematical apparatus of sensitivity theory the influence of inaccuracy of PST initial angles application on the parameters of normal mode in unchangeable part of EES (in that part of the system where load schedule does not change, i.e., losses do not leave the limits of insensitivity zone), disturbing influences (short circuits on transmission lines, power surges while transmission line disconnection, etc.) can be evaluated.

5. Experimental Part

Let us consider the optimization of active power fluxes on the example of the fragment of the circuit of 110-750 kV, shown in figure 5.1. To evaluate the impact of intersystem transfer, the transit of power between nodes 599 and 945 is introduced in calculation circuit, also PST is introduced into the circuit between nodes 811 and 819.

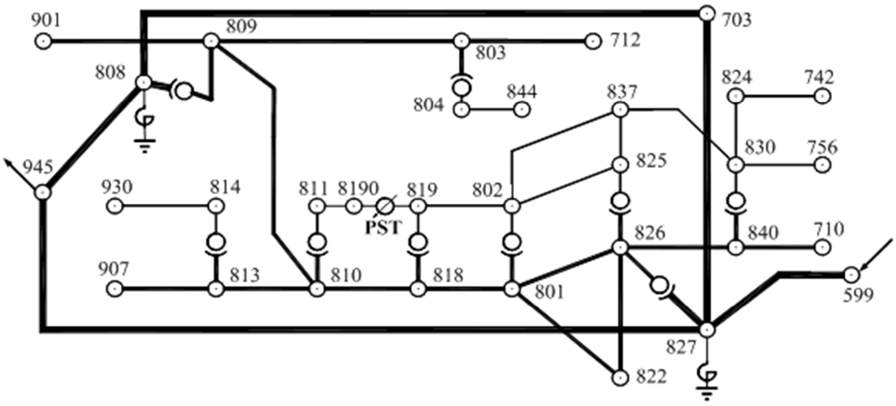

Figure 5.1. *Fragment of 110-750 kV circuit*

Using PST allows to reduce additional power losses, caused by unloading of MEG to DEG. Application of PST enables to enlarge the possibilities regarding the control of active power fluxes in EES. In this case conditions for coupling autotransformers operation at electric power stations and systems improve.

Calculation data, regarding the change of losses in EES depending on the value of power transit prior and during PST mounting in the mode of maximum loading are presented in table 5.1.

Table 5.1. *Change of losses in EES, depending on the value of power transit prior and during PST mounting in the mode of maximum loading.*

Shift angle of PST (el. degr.)	Losses of active power in the grid of 110 kV (MW)	Losses of active power in the grid of 330 kV (MW)	Losses of active power in the grid of 750 kV (MW)	General system losses of active power (MW)
Without transit of active power				
0	4.475	37.024	10.267	51.766
2	3.74	37.082	10.265	51.087
4	3.263	37.163	10.261	50.687
6	3.039	37.266	10.256	50.561
8	3.068	37.391	10.249	50.708
10	3.344	37.537	10.241	51.122
Transit 500 MW				
0	5.079	39.872	15.284	60.235
2	4.249	39.951	15.284	59.484
4	3.669	40.048	15.286	59.003
6	3.336	40.162	15.287	58.785
8	3.249	40.295	15.289	58.833
10	3.404	40.444	15.292	59.14
Transit 1000 MW				
0	5.744	43.381	31.555	80.68
2	4.805	43.461	31.565	79.831
4	4.112	43.561	31.577	79.25
6	3.661	43.68	31.591	78.932
8	3.451	43.818	31.608	78.877
10	3.479	43.975	31.626	79.08

It is seen from table 5.1, that the compensation of the impact of non-uniform electric grids using PST, optimizes power fluxes in EES, as a result, active power losses decrease. Analyzing characteristic modes of maximum and minimum loading of 110 kV grid, the most efficient is to set the angle of 6 electric degrees on PST, in this case, losses in the grid will be the least.

6. Conclusions

1. In the process of parallel operation of main and distributive electric grids of various voltage, as a result of their non-uniformity, additional power losses arise in the grids of low voltage. To reduce these losses PST can be installed. It can be mounted on the side of law voltage grid.
2. Place of PST installation in the network of lower voltage is expedient to determine by the results of compensation of negative impact of non-uniform electric networks and by maximum sensitivity of GLAP to PST angle change in this branch. For this purpose mathematical models and software, intended for determination of GLAP from transit transfers and determination of network branches with PST, that realize the greatest impact on non-uniformity of parallel operating electric networks can be used.

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Biography

Kylymchuk Anton – Engineer of Relay Protection and Automation service, Public joint-stock company “Rivneoblenergo”. Published 15 scientific papers. Main direction of scientific activity – automation of optimal control of electric power systems modes.

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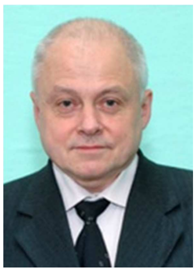

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