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FORMATION OF ELECTRIC STATIONS PRICE APPLICATIONS TAKING INTO ACCOUNT ADDRESS POWER LOSSES IN CONDITIONS OF ENERGY MARKET

The given research considers the method and algorithm for formation of price applications taking into account transit power losses in electric network of energy system, that enables to improve the method of optimal distribution of loads among stations and increase the efficiency of electric energy market functioning.

Key words: *electric station, transport of electric energy, consumer, power losses, price applications.*

Introduction

In recent decades the system of whole sale trade of electric energy operates in Ukraine, it is based on the principle of «exclusive buyer». The whole sale market of electric energy (WME), was organized, where operations of purchasing-selling of electric energy with participation of competitive energy generation companies, system operator and independent suppliers of electric energy are carried out [1, 2].

Taking into account the drawbacks of such model of the market, some countries of European Union changed over to action sale of electric energy. Nowadays it is also actual for Ukraine. In a new scheme of electric energy sale large consumers have the right to conclude direct contracts with electric stations for supply of electric energy. Regional utility companies may establish price for electric energy and sign direct contracts with individual consumers. Other consumers will obtain electric energy from balancing market.

For formation of prices for electric energy for such consumers, in modern conditions of energy market operation, it should be taken into account that their load is covered by the totality of electric stations units. At the same time each producer claims his price for supplied electric energy of the given unit. That is why, change over to the system of bilateral contracts is connected with the necessity to determine the share of each source in coverage the load of individual consumer (of energy supply company), and, on this basis, minimal price, the consumer has to pay for the received energy.

Another problem, dealing with transition to new market conditions is modern practice of distribution of the claimed load among the sources of electric energy, based on usage of price applications of electric stations units. In the calculation of the claimed price of electric energy of the individual unit cost parameters of its generation are taken into account, but expenditures, connected with its transmission over transmission lines are not taken into account. This leads to loading, first of all, of units with less specific cost, irrespective of their location relatively loads. Consequences of such approach are complications regarding the stability and maintaining of economical modes of energy systems that causes additional operating costs. Besides, system operator may have a possibility of lobbing the interests of separate energy generating companies.

Thus, it is necessary to improve the technique of price applications formation, taking into account other components of costs, namely, expenditures for transmission of electric energy by transit networks. This will lead to the change of the ratio of energy price of separate units for certain utility companies or end-consumers, that, in its turn, will influence optimal distribution of load among electric stations. Besides, taking into account in optimality criterion of the given problem of address losses component will provide preconditions for the solution of this problem together with actual problem of on-line optimization of power flows in electric systems by the minimum of electric energy losses.

It is expedient to take into account in electric energy price of the producer the transit losses of electric energy in case of energy supply in accordance with bilateral contracts. Thus, the direction of research in the given paper is the improvement of the method and algorithm of formation of price applications of electric stations on the basis of determination of transit losses of power on condition of optimal flow distribution in electric networks (EN).

Determination of power losses during electric energy transmission at economic and optimal flow distribution in electric energy system

We suggest to determine the distribution of power flows in electric energy system (EES) by the results of current distribution calculation on the basis of fixed (or modeled) mode parameters. For determination of economic current distribution in electric networks of one voltage class that provides minimum losses of electric energy for its transmission, on condition that there are no limitations on loading currents of nodes, the problem is formulated in the following manner [3]:
minimize

$$\Delta P = \dot{\mathbf{I}}_t \, \mathbf{R}_\mathrm{b} \, \hat{\mathbf{I}} \tag{1}$$

on condition

$$\left.\begin{aligned} \mathbf{M}'\mathbf{I}_a &= \mathbf{J}_a \\ \mathbf{M}'\mathbf{I}_r &= \mathbf{J}_r \end{aligned}\right\}, \tag{2}$$

where $\dot{\mathbf{I}}_t, \hat{\mathbf{I}}$, – are transposed and conjugate vectors of currents in branches (further index *t* means, that matrix or vector are transposed); $\mathbf{R}_b$ – is a diagonal matrix of active resistances of circuit branches of electric network; **M'** – is the first coupling matrix where rows, corresponding to generating nodes are struck (this is equivalent to integration of all sources of power into one calculation basis node); $\mathbf{I}_\mathrm{a}$, $\mathbf{I}_\mathrm{r}$ – are vectors of active and reactive components of currents in branches; $\mathbf{J}_\mathrm{a}$, $\mathbf{J}_\mathrm{r}$ – are vectors of active and reactive components of node currents.

Minimum losses of active power and economic currents in the branches of equivalent circuit of ES are determined by means of Lagrangian multiplier method. The solution of this problem in [4] is presented in the form:

$$\begin{bmatrix} \mathbf{I}_{ae} \\ \hline \mathbf{I}_{re} \\ \hline \mu_a \\ \hline \mu_r \end{bmatrix} = \begin{bmatrix} \mathbf{C}_R & 0 \\ \hline 0 & \mathbf{C}_R \\ \hline -2\mathbf{R} & 0 \\ \hline 0 & -2\mathbf{R} \end{bmatrix} \cdot \begin{bmatrix} \mathbf{J}_a \\ \hline \mathbf{J}_r \end{bmatrix}, \tag{3}$$

where $\mathbf{C}_R$ – is matrix of current distribution coefficients of calculated circuit of the network, where branches resistances are presented only by their active components: $\mathbf{C}_R = \mathbf{R}_b^{-1}\mathbf{M}'_t\left(\mathbf{M}'\mathbf{R}_b^{-1}\mathbf{M}'_t\right)^{-1}$; $\mathbf{R}$ – is matrix of node resistances of *R*-equivalent circuit: $\mathbf{R} = \left(\mathbf{M}'\mathbf{R}_b^{-1}\mathbf{M}'_t\right)^{-1}$; μ_a, μ_r – active and reactive components of Lagrangian multipliers.

Proceeding from (3), minimal losses of electric energy, possible in EES at preset loads in nodes irrespective of its circuit and passive parameters will be when flow distribution in EES corresponds to economic current distribution. The latter can be calculated by *R*-equivalent circuit, the example of this circuit is shown in Fig. 1, a. All sources of electric energy, powers of which are being optimized, are presented by balancing nodes.

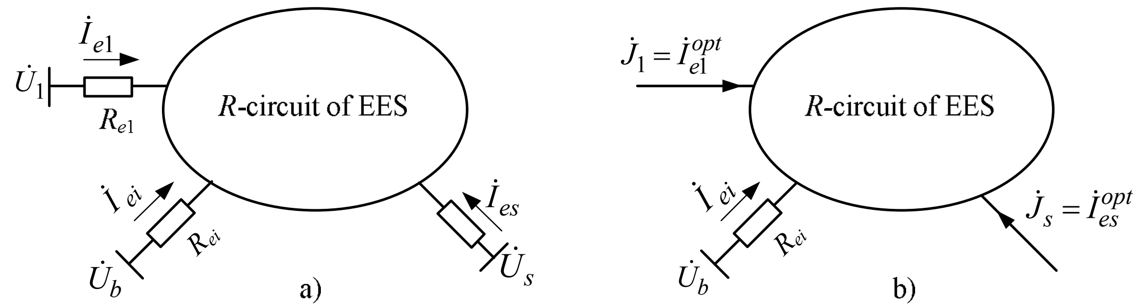

Fig. 1. Equivalent circuit for determination economic (a) and optimal (b) flow distribution in EES with presentation of electric energy sources by their economic resistances

For electric networks with transformer couplings, as it is shown in [5], optimal current distribution can be calculated by the formula:

$$\dot{\mathbf{I}}_e = \dot{\mathbf{C}}_e \dot{\mathbf{J}}, \tag{4}$$

where $\dot{\mathbf{C}}_e$ – is current distribution matrix with balanced transformation ratios, where branches resistances are presented only by their active components $\dot{\mathbf{C}}_e = \mathbf{R}_b^{-1} \dot{\mathbf{M}}_{kt}^{bl} \left(\widehat{\mathbf{M}}_k^{bl} \mathbf{R}_b^{-1} \dot{\mathbf{M}}_{kt}^{bl} \right)^{-1}$; $\dot{\mathbf{J}}$ – is vector-column of loading currents, each element of which is by known powers of load $\dot{S}_i$ and voltages in nodes $\dot{U}_i$: $\dot{\mathbf{J}} = \frac{1}{\sqrt{3}} \widehat{\mathbf{U}}_d^{-1} \widehat{\mathbf{S}}$; $\dot{\mathbf{M}}_k^{bl}$ – is the first coupling matrix of equivalent circuit of EES branches in its nodes, determined on condition of balanced transformation ratios.

Thus, if current distribution in electric networks coincides with current distribution, calculated by R-equivalent circuit with balanced transformation ratios, then it corresponds to minimum losses of active power in EES, including their component, stipulated by mutual and transit power flows [5].

Technical limitations are imposed on powers of generation nodes in practical tasks, metering of which, specifies transition from economic to conventionally optimal mode. In case of violation of certain limitation, active generation in the node is registered at maximum value, and the loaded source is withdrawn from the list of optimized ones. The obtained unbalance of power is distributed among other generating nodes of R-equivalent circuit. In optimal mode total losses of active power increase as compared with economic mode, but they are hardly possible, taking into account the limitations by the power of generation. Having calculated optimal powers of the sources except basic node in generating currents, we obtain equivalent circuit (see Fig. 1, b), that enables to create optimal current distribution in electric network, maximally approximate to economic:

$$\dot{\mathbf{I}}^{opt} = \dot{\mathbf{C}}^{opt} \dot{\mathbf{J}}^{opt}, \tag{5}$$

where $\dot{\mathbf{C}}^{opt}$ – is matrix of current distribution, that unlike matrix $\mathbf{C}_e$ contains rows and columns, corresponding to generating nodes, except basic: $\dot{\mathbf{C}}^{opt} = \mathbf{R}_b^{-1} \dot{\mathbf{M}}_{kt}^{opt} \left(\widehat{\mathbf{M}}_k^{opt} \mathbf{R}_b^{-1} \dot{\mathbf{M}}_{kt}^{opt} \right)^{-1}$; $\dot{\mathbf{J}}^{opt}$ – is vector-column, obtained from units $\dot{\mathbf{J}}$ and $\dot{\mathbf{J}}_s$: $\dot{\mathbf{J}}^{opt} = \left[\frac{\dot{\mathbf{J}}}{\dot{\mathbf{J}}_s} \right]$; $\dot{\mathbf{J}}_s$ – is vector of optimal loading currents of electric energy sources; $\dot{\mathbf{M}}_k^{opt}$ – is the first coupling matrix, analog to $\dot{\mathbf{M}}_k^{bl}$, where rows, corresponding to nodes of energy sources connection with optimized parameters are not struck.

To obtain the expression for determination of power losses in electric networks, that correspond to optimal current distribution, losses in i^{th} branch of equivalent circuit of electric network can be presented as:

$$\Delta \dot{S}_{bi} = \sqrt{3} (\dot{\mathbf{U}}_t \dot{\mathbf{M}}_{\Sigma k}^{\langle i \rangle}) \widehat{I}_i, \tag{6}$$

where $\dot{\mathbf{U}}_t\dot{\mathbf{M}}_{\Sigma k}^{\langle i\rangle}$ – is voltage drop in i^{th} branch; $\dot{\mathbf{M}}_{\Sigma k}^{\langle i\rangle}$ – is i^{th} column of coupling matrix of equivalent circuit branches in its nodes (including basic) $\dot{\mathbf{M}}_{\Sigma k}$ taking into account complex transformation ratios; $\widehat{I}_i$ – is complex conjugate value of the current in i^{th} branch of the equivalent circuit.

Having substituted (5) into (6) we obtain the expression for determination of power losses in i^{th} branch on condition of optimal current distribution, that corresponds to minimum losses as a result of mutual and transit transfers in networks:

$$\Delta\dot{S}_{bi}^{opt} = \sqrt{3}(\dot{\mathbf{U}}_t\dot{\mathbf{M}}_{\Sigma k}^{\langle i\rangle})\widehat{\mathbf{C}}_i^{opt}\widehat{\mathbf{J}}^{opt}. \qquad (7)$$

Let us introduce the designation

$$\delta\dot{\mathbf{U}}_{bi} = \sqrt{3}(\dot{\mathbf{U}}_t\dot{\mathbf{M}}_{\Sigma k}^{\langle i\rangle})\widehat{\mathbf{C}}_i^{opt}, \qquad (8)$$

the expression (7) will be written as

$$\Delta\dot{S}_{bi}^{opt} = \delta\dot{\mathbf{U}}_{bi}\widehat{\mathbf{J}}^{opt}. \qquad (9)$$

Taking into account (9), vector of power losses in the branches of ES equivalent circuit on condition of optimal current distribution

$$\Delta\dot{\mathbf{S}}_b^{opt} = \delta\dot{\mathbf{U}}_b\widehat{\mathbf{J}}^{opt}. \qquad (10)$$

Matrix $\delta\dot{\mathbf{U}}_b$ consists of n vectors-rows $\delta\dot{\mathbf{U}}_{bi}$, where j^{th} element has physical sense of complex voltage drop in i^{th} branch, stipulated by the flow of optimal share of separate current from j^{th} load node or generation.

Using (10), we can determine total losses of power in electric networks as a result of load currents flow at optimal mode, and also allocate optimal portion of transit losses in ES as a result of separate traction of electric energy on condition of energy supply in accordance with bilateral agreements. The possibility to determine optimal transit losses allows to take them into account in price application of the unit, correspondingly adjusting the power rate of certain source for each consumer. Such adjustment of the price enables to create competitive environment for generating companies, because the consumer can choose the producers, taking into account minimal losses for transmission and, correspondingly, with less cost of electric energy.

Algorithm of allocation from total losses, of the component, stipulated by the flow of load currents of k^{th} consumer from s^{th} source of energy, is illustrated in Fig. 2.

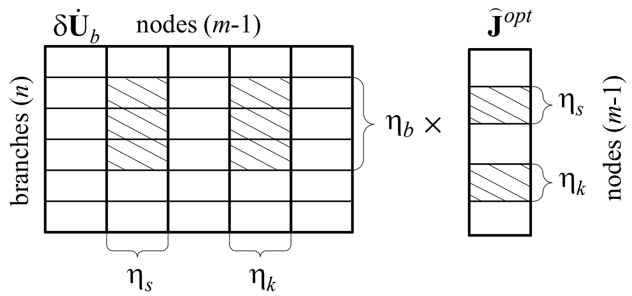

Fig. 2. Example of parameters allocation for determination of power losses in the branches η_b of transit network, stipulated by load current flow from s-th source to k-th consumer

The dimensionality of matrix $\delta\dot{\mathbf{U}}_b$ is $n\times(m-1)$. Its rows correspond to branches, and columns – to nodes of equivalent circuit of electric network without account of basic node (BN). Vector $\dot{\mathbf{J}}^{opt}$ – is vector column of loading currents in the nodes without the allowance for basic node. For evaluation of transit losses it is necessary to allocate from matrices $\delta\dot{\mathbf{U}}_b$ and $\dot{\mathbf{J}}^{opt}$ elements, corresponding to the preset list of branches of transit-network η_b, and nodes η_s (generation of s^{th}

source) and η_k (load of k^{th} consumer), between which the transaction of electric energy is performed.

In the problem of definition of transit component of power losses in the network ℓ as a result of source s energy transmission to consumer *k* three cases are possible:

1) If generation of s^{th} source completely covers load of k^{th} consumer, then the expression (10) will have the form:

$$\Delta\dot{S}^{opt}_{\ell(s,k)} = \sum_{i\in\eta_{в}} \delta\dot{\mathbf{U}}_{b(i,s)} \widehat{\mathbf{J}}^{opt}_{(s,k)} + \sum_{i\in\eta_b} \delta\dot{\mathbf{U}}_{b(i,k)} \widehat{\mathbf{J}}^{opt}_{k}\,, \tag{11}$$

where $\delta\dot{\mathbf{U}}_{b(i,s)}$, $\delta\dot{\mathbf{U}}_{b(i,k)}$ – are fragments of voltage drop matrix $\delta\dot{\mathbf{U}}_b$, corresponding to i^{th} branch of transit-network and columns from the lists, correspondingly, η_s (generation nodes) and η_k (load nodes); $\widehat{\mathbf{J}}^{opt}_k$ – is the fragment of the vector of complex conjugate currents in nodes from the list η_k on condition of optimal current distribution in ES; $\widehat{\mathbf{J}}^{opt}_{(s,k)}$ – is the fragment of the vector of complex conjugate currents in nodes from the list η_s, normalized to complex conjugate total load current of k^{th} consumer.

2) If generation of s^{th} source partially covers the load of k^{th} consumer, then the expression (10) will have the form:

$$\Delta\dot{S}^{opt}_{\ell(s,k)} = \sum_{i\in\eta_b} \delta\dot{\mathbf{U}}_{b(i,s)} \widehat{\mathbf{J}}^{opt}_{s} + \sum_{i\in\eta_b} \delta\dot{\mathbf{U}}_{b(i,k)} \widehat{\mathbf{J}}^{opt}_{(k,s)}\,, \tag{12}$$

where $\widehat{J}^{opt}_s$ – is the fragment of the vector of complex conjugate currents in nodes from the list η_s on condition of optimal current distribution in the network; $\widehat{\mathbf{J}}^{opt}_{(k,s)}$ – is the fragment of the vector of complex conjugate currents in the nodes from the list η_k, normalized to complex-conjugate total generation current of s^{th} source of electric energy;

3) If partial generation of s^{th} source partially covers load of k^{th} consumer, then the expression (10) will have the form:

$$\Delta\dot{S}^{opt}_{\ell(s,k)} = \sum_{i\in\eta_b} \delta\dot{\mathbf{U}}_{b(i,s)} \widehat{\mathbf{J}}^{opt}_{(s,ч)} + \sum_{i\in\eta_b} \delta\dot{\mathbf{U}}_{b(i,k)} \widehat{\mathbf{J}}^{opt}_{(k,ч)}\,, \tag{13}$$

where $\widehat{\mathbf{J}}^{opt}_{(s,ч)}$, $\widehat{\mathbf{J}}^{opt}_{(k,ч)}$– are fragments of the vector of complex conjugate currents in the nodes from the lists, correspondingly, η_s and η_k, normalized to complex-conjugate total partial generation current on condition of optimal current distribution in ES.

Hence, direct definition of transit component of losses in the network ℓ in the process of electric energy transmission from s^{th} source of energy to k^{th} consumer is determined by the expressions (11) – (13), depending on the conditions of energy supply.

The obtained values of transit losses can be taken into account in price applications of the producers for each consumer.

Correction of price applications taking into account bilateral contracts for energy supply

When contracts for energy supply between producer and consumer (energy supply company) are signed, expenditures for electric energy transmission must be taken into account in the price of the producer in order to provide transparency and competition. However, to match the interests of energy generating, transport and energy supply companies transmission costs, included in the price of the producer must meet the requirements of optimal mode of electric network.

While energy supply of k^{th} consumer from s^{th} source during period *T*, which is characterized by conventionally constant mode of EES, total costs are

$$B_{\Sigma s,k} = \left(P_k \cdot \beta_s + \sum_{\ell \in \mathbf{N}} \left[\Delta P_{\ell(s,k)}^{opt} \cdot c_\ell^{opt} \right] \right) \cdot T, \tag{14}$$

where P_k – is power of load, covered by the source, according to the conditions of the contract; β_s – is average disbursing price of 1 кW·h of electric energy of the source, *s*; $\Delta P_{\ell(s,k)}^{opt}$ – is real part of the transit component of power losses in electric network ℓ, stipulated by the flow of current load of k^{th} consumer from the source *s*, that is determined by (11) – (13); c_ℓ^{opt} – is average cost of transmission of 1 кW·h of electric energy by the network ℓ, taking into account the introduction of measures aimed at optimization of its modes; **N** – is a set of electric networks, used for power transit.

To specify the price of electric energy of electric stations units with an allowance of costs component for its transmission, the expression can be used

$$P_{ES\_s} = \frac{B_{\Sigma s,k}}{P_k \cdot T},$$

or, taking into account (14):

$$P_{ES\_s} = \beta_s + \frac{\sum_{\ell \in \mathbf{N}} \left[\Delta P_{\ell(s,k)}^{opt} \cdot c_\ell^{opt} \right]}{P_k}. \tag{15}$$

Assuming, that for all transactors the price of energy transmission by the networks is determined by uniform bulk tariff of energy market P_{wm}, the expression (15) has the form:

$$P_{ES\_s} = \beta_s + \frac{\sum_{\ell \in \mathbf{N}} \Delta P_{\ell(s,k)}^{opt}}{P_k} \cdot P_{wm}. \tag{16}$$

The producer can conclude a contract for energy supply with several consumers, for which the energy transmission costs will be different. Proceeding from this fact, the price for individual source must be corrected taking into account transit losses of energy transmission to possible consumers.

The example of price application correction for separate unit with allowance for costs for electric energy transmission to three various consumers is shown in Fig. 3. It is seen from the figure, that the account of costs for electric energy transmission to consumers 1 and 2 increases the claimed price of electric energy of the unit (Fig. 3, a, Fig. 3, b).

However, in case of energy transmission to consumer 3 (Fig. 3, c), the increase of generation power of the unit leads to local off-loading of transit electric network, decreasing transmission expenses (as compared with alternative variants of consumer supply 3). Proceeding from this, after revision, the price in the third and the fourth points (Fig. 3, c) decreases, since generation of the given source decreases total transit losses, and the second component of the expression (16) becomes negative. Thus, in price application of the unit for the given consumer, the price of electric energy will decrease, this will increase its possibilities of obtaining quotas for electric energy supply.

Thus, the realization of the suggested method of correction of electric stations price applications will contribute to complex increase of efficiency of coverage of energy system total load at the expense of optimization of operating units list as well as stimulating transport companies to introduction of measures aimed at optimization of electric networks modes.

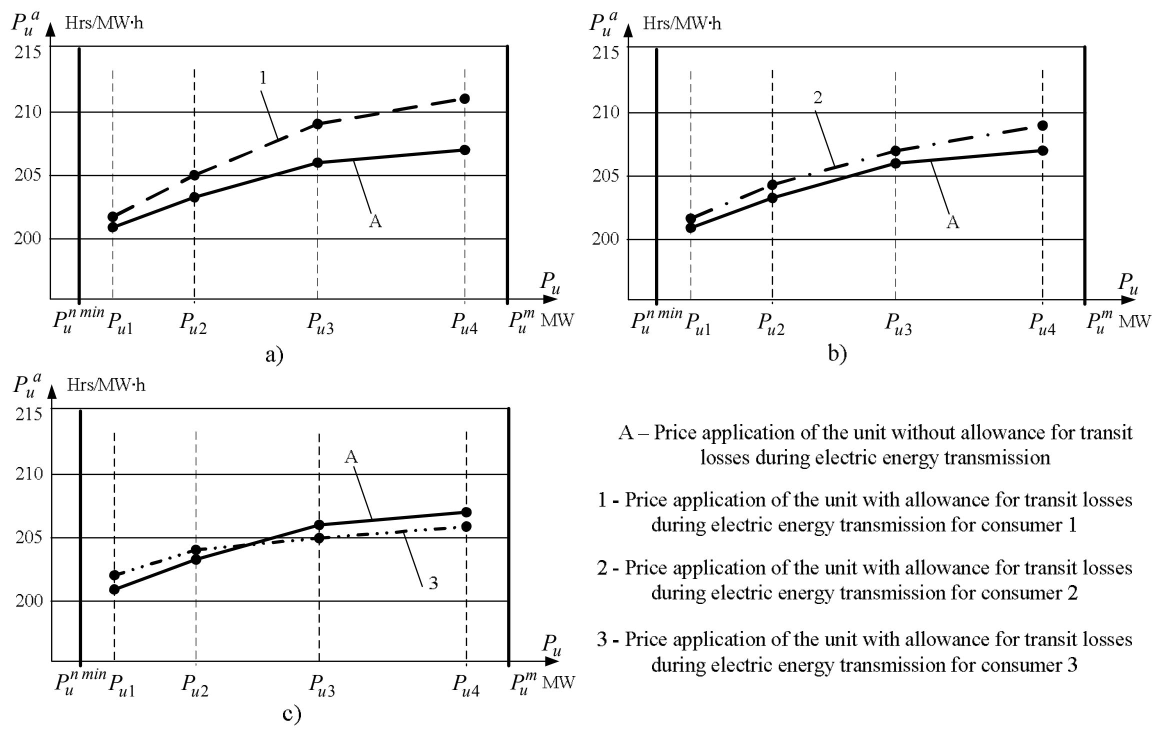

Fig. 3. Example of price applications correction of electric station unit with allowance for costs for electric energy transmission

Conclusions

In the process of optimal decision- making it is necessary to take into account the impact of individual transactors on electric system operation modes and mutual and transit losses of electric energy in electric networks. Mathematic model has been developed, algorithm for determination of power losses in electric network on condition of optimal flow distribution in electric energy system is proposed, this enables to allocate minimal transit losses in the network and take them into account in the price for electric energy in conditions of energy supply according to bilateral contracts.

Method of determination of transit power losses in electric network in new economic conditions allows to allocate the share of transit power losses in conditions of address energy supply. Account of minimal possible value of transit losses in price applications of electric energy sources allows to create competitive environment for generation companies. Using of modified price applications simplifies the solution of the problem of load distribution optimization and provides validity and transparency of decision-making and coordination of separate transactors operation on energy market.

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