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CREATION OF POWER RESERVES UNDER THE MARKET ECONOMY CONDITIONS

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The main task of the control over an electric power system (EPS) is to ensure reliable power supply at the least cost. In this case, requirements to the electric power quality, power supply reliability and cost limitations on the energy resources must be observed. The available power reserve in an EPS is the necessary condition to keep it in operation with maintenance of normal operating variables (frequency, node voltage, power flows via the transmission lines, etc.). The authors examine possibilities to create power reserves that could be offered for sale by the electric power producer. They consider a procedure of price formation for the power reserves and propose a relevant mathematical model for a united EPS, the initial data being the fuel-cost functions for individual systems, technological limitations on the active power generation and consumers' load. As the criterion of optimization the maximum profit for the producer is taken. The model is exemplified by a concentrated EPS. The computations have been performed using the MATLAB program.

1. INTRODUCTION

The market relationships and the competition between the electric power users and producers considerably raise the number of problems concerning the operation of electric power systems (EPSs). The structure of these relationships has given rise to a new class of tasks that were unknown before the introduction of the market mechanisms into the power engineering control. Thus, the following tasks have emerged: the analysis of electric power supply and demand, the determination of commercial power reserves and their optimization for an EPS, the formation of tariffs, the simulation of the market of technical services, etc. [1–10]. In particular, the need has arisen to take into account possible splitting of an EPS into financially independent subsystems, with keeping the unity – in all its aspects – of operating conditions in these subsystems. For example, such a situation has taken place in Baltic countries.

The financial interests of individual energy companies (EPSs and generating plants) often contradict with the criteria of effective operation of united electric power systems (UEPSs). Therefore, appropriate mathematical tools are needed in order to co-ordinate the differing or contradictory criteria of individual systems [2]. Under the market conditions such contradictions should be resolved if the power supply and demand balance is presented in the cost terms. The world practice shows that the organizational principles of wholesale energy markets can essentially diverge for different countries and energy companies [7, 9]. The main discrepancy stems from the formation of electric power prices (tariffs) depending on the level of a wholesale market – there could be internal tariffs of an energy company and the tariffs of united electric power systems on a regional wholesale market, which can strongly differ.

Thus, the prices of electric power flowing via the networks are determined by the wholesale market participants and **the independent territorial energy companies**. One of the strategies for the wholesale price formation is as follows.

- Energy companies with electric power surplus submit claims for selling it through the wholesale market (price, capacity).
- Deficient energy companies submit claims for buying electric energy in the wholesale market (capacity).
- The wholesale price choice starts with the minimum price offered in the claims.

Next, all the prices are looked through in ascending order, and the corresponding offered electric power capacity participating in the claimed load coverage is analyzed. The price formation is completed at the price offered by the energy company that provides the system load's coverage. Therefore, at this stage the remaining energy companies are not included in the wholesale market operation, which means losses for them since their prices have been too high to realize their surpluses. Consequently, the wholesale price is defined as the maximum price participating in the load coverage.

To propose effective solutions for EPS development and operation, a deeper technical and economic analysis of different operating conditions (OCs) is required. The optimization of these conditions should be calculated taking into account the criteria of power quality, efficiency, reliability, permissibility and technical feasibility. Of great importance is here to take into consideration the requirement of the least impact of operating power plants on the environment.

It is possible to state with confidence that for any economic system in which an EPS is functioning the task of OC optimization has priority. Under the market economy conditions the urgency of this task has risen dramatically. Its solution will allow the producer of thermal and electrical energy to raise the competitive ability in the market. It also allows the volumes and structure of the burnt fuel to be calculated for the future and the weak places in the technological processes to be revealed.

2. OPTIMIZATION OF EPS REGIMES UNDER MARKET CONDITIONS

With cancellation of the centralized control over the energy economy the following problem is brought into the foreground: how to develop the procedures for determination of optimal power flows (OPFs) taking into account the newly arisen market-oriented limitations. When exerting control over EPS functioning under competition, the system operator (SO) **is forced** to base his every decision on the calculations confirming its effectiveness and economical efficiency. The radical changes in the control principles make it necessary to revise the approaches to formulation of the OC optimization problem, which in the past successfully functioned in the vertically integrated energy companies.

As is known, in the classical formulation of the optimization problem as the main criterion for a system's operational dispatcher the optimum distribution of active load among the generating sources was assumed, which provided the least cost of equivalent fuel [10].

This was reached under the condition of equal relative increases in the fuel consumption:

$$\varepsilon_1 = \varepsilon_2 = ... = \varepsilon_n = \varepsilon_b , \qquad (1)$$

where $\varepsilon_i = \dfrac{\partial C_i}{\partial P_{gi}}$ are the characteristics of the relative increases for fuel-cost function C_i in the *i*-th node; $i = \overline{1,n}$ is the node number; *n* is the number of generating sources including a balancing node (ε_b).

For a traditional (regulated) market the mathematical problem of the OC optimization is formulated as the minimization of the total expenses for electrical energy production:

$$\min_{P_G} \sum_{i=1}^{G} C_{gi}(P_{gi}) , \qquad (2)$$

where $C_{gi}(P_{gi})$ are the total expenses of producing the P_{gi} power quantity for each individual participant in the market.

For the users, the criterion of OC optimality is determined by the least cost of the claimed generation:

$$\frac{\partial C_{g1}}{\partial P_{g1}} = \frac{\partial C_{g2}}{\partial P_{g2}} = ... = \frac{\partial C_{gG}}{\partial P_{gG}} , \qquad (3)$$

under the conditions of active load full coverage and equal short-term maximum expenses for all generating sources.

In the objective model of a competitive electric power wholesale market (EPWM) the condition of the welfare function (WFF) maximum is accepted as the optimization criterion for a market participant [6, 10–12]:

$$\left(\sum_{\ell \in L} c_\ell \cdot P_\ell - \sum_{g \in G} c_g \cdot P_g \right) \to \max \qquad (4)$$

with limitations on power flows P_{ij} from the *i*-th node to the *j*-th node via the *i*-*j*-th line or on the sum of power flows via the controlled sections (groups of lines) *S*:

$$P_{s\min} \le \sum_{(i,j) \in s} P_{ij} \le P_{s\max} , \quad s \in S , \qquad (5)$$

with the balance limitations on the active and reactive power in the nodes:

$$\left. \begin{aligned} &\sum_j P_{ij}(U_i, U_j, \delta_i, \delta_j) + \sum_{g \in G_i} P_g - \sum_{\ell \in L_i} P_\ell = 0, \; i \in N, \\ &\sum_j Q_{ij}(U_i, U_j, \delta_i, \delta_j) + \sum_{g \in G_i} Q_g - \sum_{\ell \in L_i} Q_\ell = 0, \; i \in N, \end{aligned} \right\} \qquad (6)$$

and the limitations on the range of changes for the variables to be optimized:

$$\left.\begin{array}{l} P_{g\min} \le P_g \le P_{g\max},\ \ g \in G, \\ P_{l\min} \le P_g \le P_{\ell\max},\ \ \ell \in L, \\ Q_{g\min} \le Q_g \le Q_{g\max},\ \ g \in G, \\ U_{j\min} \le U_j \le U_{j\max},\ \ j \in N \end{array}\right\}, \qquad (7)$$

where c_g, c_ℓ are the claimed prices for the active power production (sale) and consumption (purchase);

P_g, P_ℓ are the node capacities of the active power production (sale) and consumption (purchase);

P_{ij}, Q_{ij} are the active and reactive power flows via the *i-j*-th line from the *i*-th node to the *j*-th node;

Q_g, Q_ℓ are the node capacities of the reactive power production and consumption;

U_j, δ_j is the modulus and phase of voltage in the *j*-th node, respectively;

G, L are the sets of node claims for the active power production (sale) and consumption (purchase);

G_i, L_i are the sets of node claims for the active power production (sale) and consumption (purchase) in the *i*-th node;

N is the set of the electrical network nodes;

S is the set of the controlled sections.

The mathematical formulations of problems (1) and (4) are similar, though differing significantly in the specific formation of market-optimum distribution of power flows. The main differences are [10]:

- the necessity to use such methods for the solution that would combine reliability, stability and speed at obtaining the results, and that would be capable of accounting for the limitations on the types of equalities and inequalities;
- the flexibility at varying the number of additional functional limitations for the types of inequalities (e.g. power limitations in the controlled sections, the limitations for the generators on the minimum (maximum) power generation, the stop and start rate limitations for the generators, etc.);
- the inclusion, depending on the problem formulation, into the objective optimization function of essentially differing characteristics. These could be, e.g., relative increases in the fuel-cost function (FCF) based on the cost-related physical characteristics of the equipment; the tariff-price functions (TPFs) approved by the energy commissions; the price claims (PCs) of the generators and wholesale buyers sent to a competitive electric power market;
- the algorithms for accounting the limitations should be high-speed and not requiring the complete recalculation of the operation variables.

Function (4) shows that achievement of the WFF maximum to a great extent depends on the market prices for electric power. It is known [4, 6, 10] that at the formation of prices the optimum market strategy is to equalize the relative increases in prices and production costs (taking into account the network losses). The prices are therefore determined based on the mentioned increases (the so-called marginal approach – the production cost variation at minor (single) increases in the evaluated power, so such prices are often called marginal). It is evident that **the market price will differ from a marginal one, since the former additionally includes the profit component, depends on supply and demand, and is limited in compliance with social and political factors.**

3. CREATION OF POWER RESERVES

To ensure reliable supply of electric power and its high quality, independent EPSs working in parallel are forced to coordinate their operating conditions/variables [2–4, 13–15]. Attraction of resources and controls of an EPS to render help to another one is considered as technical service, which has certain limits and cost. The creation of a power reserve in a neighbouring EPS is one of such paid services. The specific character of this service lies in the fact that it is closely connected both with the current operating condition and with possible situations in the future – for example, failure of the equipment at a power plant belonging to a given EPS, increase in its users' load, etc. Under the conditions of territorial and economic disintegration the implementation of a market strategy – implying, in particular, the contractual deliveries with a penalty system for power undersupply and "local selfishness" – is possible only if the necessary reserves of generating power are available [2, 10, 13–15]. Otherwise EPSs cannot render help to each other [2–4, 10, 13–16]. Therefore, the provision of reserve is a service in which the individual market participants and an EPS as a whole are interested. The creation of the necessary capacities for a rotating power reserve is an integral part of the "one day forward" market.

The urgency of the power reserve market creation is an additional argument for revision and reformulation of the problems of EPS regime calculation as well as of the mathematical models and methods to be used for this purpose. Formulations of the problems concerning power reserves could be found in works [14–18], among which the model proposed in [15] seems to be more advanced.

To participate in a power reserve market, the *i*-th node producer has a possibility to divide its production capacities into two parts. One of them (P_{gi}) could be claimed in the form of generation and sold at price c_{gi}, whereas the second part could be left as underloaded generators (R_i) or reserve and sold at price c_{Ri}. The power reserve at the *i*-th node can be determined from the expression:

$$P_{gi} + R_i = P_{gi\max} \,. \tag{8}$$

If reserve R_i is not realized, the specific profit for the *i*-th node producer can be defined as

$$B_i = c_{gi} \cdot P_{gi} + c_{Ri} \cdot R_i - C_{gi}(P_{gi}) \,, \tag{9}$$

with the costs of starting and stopping the generating sets not taken into account.

In Eq. (9), the $C_{gi}(P_{gi})$ value is the cost of power production per time unit (or specific cost). Such cost is determined by the fuel-cost function:

$$C_{gi}(P_{gi}) = \alpha_i + \beta_i \cdot P_{gi} + \gamma_i \cdot P_{gi}^2 . \tag{10}$$

The nodal power generation must satisfy the technological limitation given in (7).

For the *i*-th node the optimum electric energy price (from the viewpoint of the maximum profit for the producer) can be defined by solving the problem of unconstrained optimization of function (9) for variable P_{gi}. Equating to zero the first derivative of B_i with respect to variable P_{gi} and taking into account function (8), we obtain the following equation:

$$\frac{\partial B_i}{\partial P_{gi}} = c_{gi} - c_{Ri} - \frac{\partial C_{gi}(P_{gi})}{\partial P_{gi}} = 0 . \tag{11}$$

From this equation we can determine power P_{gi} that could be offered by the *i*-th node producer for the power market. This power is presented as a dependence on the prices of generation (c_{gi}) and reserve (c_{Ri}) powers. For the problem under consideration this dependence is:

$$P_{gi}(c_{gi}, c_{Ri}) = \frac{c_{gi} - c_{Ri} - \beta_i}{2\gamma_i} . \tag{12}$$

Verifying the behavior of the profit function (9) extremum by taking the second derivative gives the following result:

$$\frac{\partial^2 B_i}{\partial P_{gi}^2} = -2\gamma_i \prec 0 . \tag{13}$$

The negative sign of the resultant function evidences that there is reached maximum for function (9) with the generated power P_{gi} (equal to the power offered for market).

In the case when the commercial effect (profit) is determined for an EPS as a whole, the optimum price of electric power for the node producer can be determined employing the Lagrange function:

$$L = \sum_i B_i + \sum_i \lambda_i \cdot (P_{gi} + R_i - P_{gi\max}) . \tag{14}$$

From the economic point of view, variables λ_i (Lagrange's factors) are interpreted as the shady prices of the resources defined by constraints of (8) [1, 12, 19]. By equating to zero the partial derivatives with respect to variables P_{gi}, R_i, λ_i we find the necessary conditions for the extremum of function (14) [1, 12, 19]. Solving the equations obtained gives an extreme point, which should be investigated for the maximum (minimum). This can be done using Sylvester's criterion (which is well-known in mathematics, see e.g. [19]). According to this criterion, the investigated extreme point will be the minimum if the determinants of all degrees of the Hesse matrix for function (14) are positive.

At a steady equilibrium price (EP) $c_* = c_{gi}$ in a power market, the optimum price c_{Ri} of the power reserve for the *i*-th node producer can be determined. This optimum is reached (taking into account dependences (8) and (12)) as a result of solving the unconstrained optimization problem with respect to variable c_{Ri}:

$$B_i(c_{Ri}) \to \max . \tag{15}$$

The optimum price of power reserve for the *i*-th node producer is thus determined by the expression:

$$c_{Ri} = c_* - \beta_i - 2\gamma_i \cdot P_{i\max} . \tag{16}$$

4. RESULTS OF THE STUDY

We will consider the problem of power reserve determination for a concentrated EPS with three thermal plants operating into common load. The input data are represented by fuel-cost functions for these plants (in €/h):

$$C_1 = 500 + 5.3P_{g1} + 0.004P_{g1}^2,$$

$$C_2 = 400 + 5.5P_{g2} + 0.006P_{g2}^2,$$

$$C_3 = 200 + 5.8P_{g3} + 0.009P_{g3}^2,.$$

where P_{g1}, P_{g2} and P_{g3} are in MW.

The optimization problem is to be solved with the following technological limits on the power generation (in MW):

$$200 \le P_{g1} \le 450,$$

$$150 \le P_{g2} \le 350,$$

$$100 \le P_{g3} \le 225$$

and the following limits on the power reserve (in MW):

$$25 \le R_1 \le 150,$$

$$20 \le R_2 \le 120,$$

$$10 \le R_3 \le 60.$$

In this case, the necessary power reserve for the EPS as a whole is not to be less than 110 MW, i.e.

$$\sum R_i \ge 110 .$$

To form the electric power sale price for the *i*-th node producer $i, (i = \overline{1,3})$ the above mentioned marginal approach is used. The relative increase in the fuel-cost functions for the EPS node is determined by the following expression:

$$\frac{\partial C_i}{\partial P_{gi}} = \beta_i + 2\gamma \cdot P_{gi} \,. \tag{17}$$

We will assume that the sale price of electric power for the *i*-th node producer (taking into account the expected profit) is 10% greater than the marginal price. Thus, for the *i*-th node the price of the electric power for sale can be calculated as

$$c_{gi} = 1.1(\beta_i + 2\gamma_i P_{gi}) \,. \tag{18}$$

In this case the power reserve price for the *i*-th node of EPS, taking into account function (11), will be defined as

$$c_{Ri} = 0.1(\beta_i + 2\gamma_i P_{gi}) \,. \tag{19}$$

The summary profit function B_Σ for the power plants can be formed taking into consideration expression (9). The behavior of this function for a given EPS in the optimization process with the assumed initial values of original variables P_{gi} and R_i is presented in Fig. 1. For calculation of the optimum generation and reserve power values for the three power plants the MATLAB program was used.

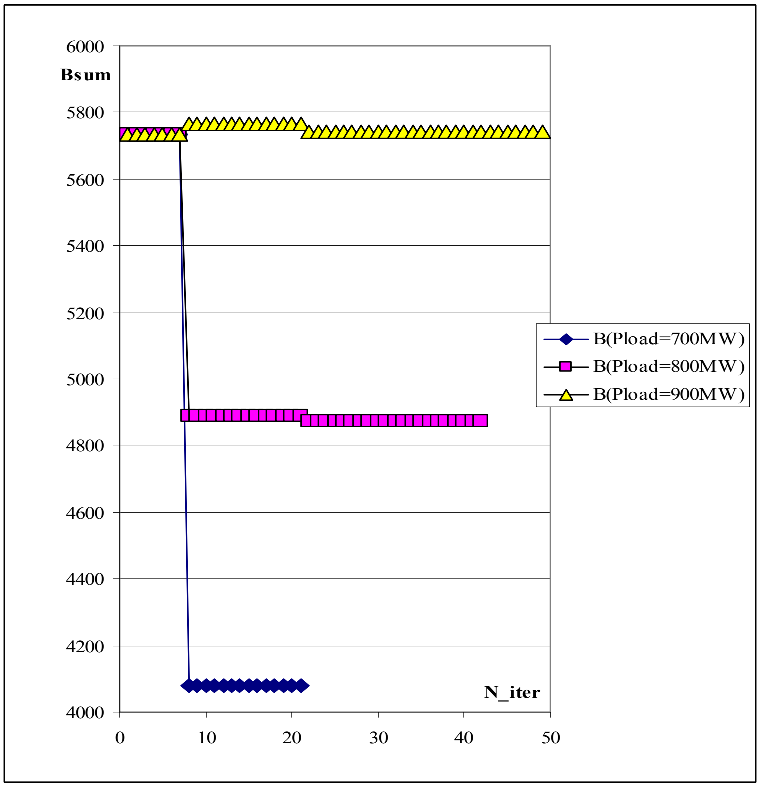

Fig. 1. The EPS profit change in the optimization process for three loads.

The EPS profit was calculated for three values of the summary load P_L : 700 MW, 800 MW and 900 MW. For each of them the following optimum variables were obtained:

$B_\Sigma(P_L = 700) = 4078$ (arbitr. units), P_1 =305 MW, P_2 = 230 MW,
P_3 =165 MW, R_1 =145 MW, R_2 =120 MW, R_3 = 60 MW;

$B_\Sigma(P_L = 800) = 4875$ (arbitr. units), P_1 = 399.5 MW, P_2 = 235.5 MW,
P_3 = 165 MW, R_1 =50.5MW, R_2 = 114.5 MW, R_3 = 60 MW;

$B_\Sigma(P_L = 900) = 5744$ (arbitr. units), P_1 = 425 MW, P_2 = 292.6MW,
P_3 = 182.4 MW, R_1 = 25 MW, R_2 = 57.4 MW, R_3 = 42.6 MW.

From the above it is seen that - with one and the same initial data - the expected profit of the EPS rises with increasing load. This is explained by the ability of power plants to raise the reserve capacities of electric power production for sale. It should be noted that, from the computational point of view, the summary EPS load reduction makes it easier to solve the problem of reserve formation. This fact is proved by a smaller number of iterations required in this case for the optimization.

5. CONCLUSIONS

1. The creation of power reserve market is one of the most important conditions for ensuring reliable supply of users with electricity as well as for EPS operation.

2. The availability of a sufficient capacity of power reserve makes it possible to extend the list of the system services under the market conditions.

3. The proposed model for evaluation of power reserve for an individual producer can be taken as a basis for creation of the necessary capacities of spinning power reserve for EPS.

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JAUDAS REZERVJU FORMĒŠANA TIRGUS EKONOMIKAS APSTĀKĻOS

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K o p s a v i l k u m s

Energosistēmas droša darbība neatkarīgi no konkurentu struktūras iespējama pie vairāku svarīgu nosacījumu ievērošanas. Svarīga vieta šajos nosacījumos ir pamatotai jaudas rezervju formēšanai un starpsistēmu savienojumu caurlaides spējām. Tirgus apstākļi būtiski ietekmē rezervju veidošanu, neatkarīgi no to veida-

lēni sasniedzami (neoperatīvi) un ātri sasniedzami (rotējoši). Cenšanās iegūt peļņu un atteikšanās no rezervēm var novest pie energosistēmas sabrukuma.

Autori darbā piedāvā lielu energoapvienību vajadzīgo rezervju jaudu apjoma formēšanas matemātisko modeli. Par modeļa izejas datiem ir atsevišķu energosistēmu patēriņu raksturlīknes, aktīvās jaudas tehnoloģiskie ierobežojumi un patērētāju slodze. Optimizācijas kritērijs ir, lai elektroenerģijas ražotājs iegūtu maksimālo peļņu. Modeļa aprobācija veikta uz koncentrētas energosistēmas shēmas piemēra. Aprēķini veikti, izmantojot Matlab programmas kompleksu.

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