Equilibrium model of Ukrainian generating capacities operation and development under market conditions

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The mathematical models of generating capacities operation and development processes which adequately reflect work of Ukrainian power system under the conditions of imperfect competition are proposed.

Keywords: **mathematical models, generation expansion planning, complementarity problem, market equilibrium.**

1. INTRODUCTION

Modern approaches to electricity-generating capacities development planning are built on the basis of mathematical models of power system.

For the power systems with vertically integrated management structure, optimization of its development only pursues a single criterion, for example, minimum of electricity production costs that is reflected in the proper single criterion optimization problems [1-4].

Introduction of market management structure of power system results in creation of power companies which independently make decisions on production and capacity development volumes. Optimization of development of such power system is carried out by solving problems with many objective functions. During the last decade the power system models, in which influence of market participants is balanced, have been developed in the EU countries and the USA [5-7].

The regime and technological specification of Ukrainian power system operation and specific standards of branch statistics do not make it possible to use foreign market models for forecasting national power system development.

Ground of plans for Ukrainian heat power stations development requires working out of original models of generating capacities operation and development processes in the imperfect competition conditions.

2. FEATURES OF UKRAINIAN POWER SYSTEM DESCRIPTION

A power system is represented by a set of nodes of electric power production-consumption, connected by internodes interfaces.

An electric network is represented by the aggregated direct current model.

The annual graph of consumption of electric power is reproduced by the load zones. Demand on electric power for detached nodes and load zones is described by linear dependences of electricity consumption volume on the price.

It is assumed that the companies-producers of electricity can demonstrate the competitive or strategic behaviour.

Generating capacities that belong to the companies are characterized by the linear cost functions.

The reliability requirements for power system operation are determined by the cold and hot reserve volumes in the system, and also limitations on generating capacities and on internodes interfaces power flows.

The electricity market is characterized by the state of imperfect competition.

In the working process producers have to attain two objectives: long-term - development of new generating capacities, and short-term - determination of operation mode of power units. These tasks are interconnected.

Taking into account long term service of power equipment, planning is made for a period longer than 20 years.

It is necessary to consider specific features of Ukrainian power system operation:

- substantial volumes of regulated production - more than 50% of electricity is produced by nuclear-, hydro-, combined heat and power plants, block-stations;
- difficulty of passing of load minimum: while choosing an equipment set for passing the maximum of electricity consumption, one_must take into account the necessity of its subsequent unloading to the level of night minimum;
- problem of providing the necessary hot reserve: total capacity of equipment in operation must exceed consumption on the specified value.

3. MODELING OF GENERATING CAPACITIES OPERATION AND DEVELOPMENT PROCESSES

For planning development of production capacities under the conditions of imperfect competition the models of real options, models of system dynamics, agent models and game models are used.

Game models make it possible to represent most precisely producers' behaviour at the market with imperfect competition and take into account the technological features of power units operation and network limitations.

Depending on the degree of market monopolization, the power system equilibrium state is described by models of perfect and imperfect competition.

Perfect competition provides the maximum_level of social welfare of market players. For description of markets with perfect competition the Bertrand model is used, in which none of producers (j) can influence the price ($p_j = p$).

The analysis of electricity market functioning shows that powerful producers, using their market power, force up electricity prices, which results in imperfect competition state. For description of markets with imperfect competition the Cournot model is usually applied. In this model producers realize that change of their production volumes (y_j) influences the price $(\partial p/\partial y_j \neq 0)$, but assume that other producers are irresponsive to the change of their production volumes $(\partial y_{-j}/\partial y_j = 0)$, where y_{-j} – is production volume of other producers.

In this research the single-stage game is applied. It is assumed that every company simultaneously forms the decision about production and capacity development volumes. Influence of their own future periods investment decisions and investment decisions of competitors on current work of the company is not thus taken into account.

3.1. Models of Ukrainian heat power plants operation and development

Power system represented by nodes $i \in I$, connected by interfaces $m \in M$, which have limitations on power flows x^l_{mt}.

Companies-producers $j \in J$ which do not collude operate in a power system.

Let $l \in L(j,i)$ – the set of types of generating equipment belonging to the company j in a node i. Generating equipment is characterized by generation costs c_{jilt} and capital investments k_{lt}. $l \in \Lambda(j,i)$ from ($L \subseteq \Lambda$) – subset of equipment, which tariffs on electric power are set for.

Costs on starting the equipment are not taken into account.

Prices on electric power are determined by the inverse functions of demand $p^{av}_{izt} = a_{izt} - b_{izt} d_{izt}$, where a_{izt} and b_{izt} – are constant coefficients. Demand on electric power in nodes $d_{izt} = s^{ar}_{izt} + s^{sum}_{izt}$ is covered by the volumes of its sales by the regulated and competitive producers $s^{sum}_{izt} = \sum_{j \in J} \left(s^{reg}_{jizt} + s^{com}_{jizt} \right)$, and also arbitrage trader s^{ar}_{izt}.

A planning period is divided into stages $t \in T$, which contains the zones of load $z \in Z$, by duration H_{zt}.

3.2. Short-term problems

The short-term problems of market players are formulated for every load zone. Below, for simplification of mathematical expressions, indexes z and t will be dropped.

We will consider the model of competitive company j. The goal of its activity is maximization of current profit π_j from production y^{com}_{jil} volumes, capacity reservation r_{jil} and sales of electricity in the nodes of the system s^{com}_{ji}. The profit of every company of that kind is following the formulation

$$\pi_j = \sum_{i \in I} \begin{pmatrix} (1-C)\dfrac{p^{av}_i - k^{reg} p^{reg}}{1-k^{reg}} \\ + C\dfrac{\begin{pmatrix} a_i - b_i\left(s^{ar}_i + s^{sum}_i\right) \\ - k^{reg} p^{reg} \end{pmatrix}}{1-k^{reg}} \end{pmatrix} s^{com}_{ji} + \sum_{i \in I}\sum_{l \in L} p^{hr} r_{jil} - \sum_{i \in I}\sum_{l \in L} c_{jil} y^{com}_{jil} - \sum_{i \in I} p^{tr}_i \sum_{l \in L}\left(s^{com}_{ji} - y^{com}_{jil}\right), \quad (1)$$

where p^{reg} – is weighted average tariff of the regulated producers; p^{tr}_i – is price of the transmission of electric power from hub to a node

i; p^{hr} – is price of hot reserve; k^{reg} – is share of deliveries by regulated producers; C – is coefficient, the value of which specifies the type of behaviour of competitive producers ($C=0$ in the case of competition behaviour according to Bertrand, and $C=1$ in case of strategic behaviour according to Cournot).

In the model of competing company j also takes into account:

- maximum load constraints

$$y_{jil}^{com} + r_{jil} \le x_{jil}, \ \forall j,i,l, \qquad (2)$$

where x_{jil} - equipment capacity;

- minimum load constraints

$$y_{jil}^{com} \ge K_{jil}^{\min} x_{jil}, \ \forall j,i,l, \qquad (3)$$

where $K_{jil}^{\min}$ – is the ratio between the minimum load and equipment capacity;

- constraint on reserve volume

$$r_{jil} \le KR_{jil} y_{jil}^{com}, \ \forall j,i,l, \qquad (4)$$

where KR_{jil} – coefficient characterizing the limiting capabilities of the equipment to keeping hot reserve;

- conditions for the passage by generating equipment daily minimum load:

$$d^{\min} \ge \sum_{j\in J}\sum_{i\in I}\sum_{l\in L}\begin{pmatrix} K1_{jil} K2_{jil} y_{jil}^{com} \\ +\left(1-K1_{jil}\right)K_{jil}^{\min} x_{jil}\end{pmatrix}, \ \forall j,i,l, \quad (5)$$

where $K1$ – factor reflecting the ability ($K1=0$) or inability ($K1=1$) to stop the equipment at night; $K2$ – coefficient characterizing the ability of equipment to unload without an overnight shut down;

- the balance of sales and production of electricity of each company

$$\sum_{i\in I} s_{ji}^{com} = \sum_{i\in I}\sum_{l\in L} y_{jil}^{com}, \ \forall j; \qquad (6)$$

- conditions for nonnegativity of variables

$$y_{jil}^{com} \ge 0, \quad \forall j,i,l; \qquad (7)$$

$$r_{jil} \ge 0, \quad \forall j,i,l; \qquad (8)$$

$$s_{ji}^{com} \ge 0, \quad \forall j,i. \qquad (9)$$

Let us consider a model of the network operator. It aims to achieve maximum profit:

$$\text{MAX} \sum_{i\in I} p_i^{tr} y_i^h, \qquad (10)$$

where y_i^h – amount of electricity, which the network operator transfers from fictive node-hub to node i.

Flow of electricity in internodes interface m is determined by

$$y_m^l = \sum_{i\in I} \gamma_{im} y_i^h, \ \forall m, \qquad (11)$$

where γ_{im} – sensitivity coefficients characterizing the dependence of power flows in the interfaces $m \in M$ from the volume of electricity inflow from nodes $i \in I$.

Flow in each interface should not exceed the limit

$$\left|y_m^l\right| \le x_m^l. \qquad (12)$$

The next case study model is behaviour of an arbitrage trader. He takes electricity in the nodes with low prices and sells at the nodes with high prices, paying the cost of transmission. The aim is to achieve maximum profit

$$\text{MAX} \sum_{i\in I}\left(p_i^{av} - p_i^{tr}\right)s_i^{ar}. \qquad (13)$$

To prevent discrimination of individual consumers it is assumed that all the electricity produced by the regulated producers is purchased by an arbitrage trader, who sells it to all nodes of grid. Meanwhile, the balance of buying and selling of electricity is secured

$$\sum_{i\in I} s_i^{ar} + \sum_{j\in J}\sum_{i\in I} s_{ji}^{reg} = 0. \qquad (14)$$

The above-mentioned individual behaviour models of the main energy market agents are closed by the terms of arrangement of their constituent variables. Arrangement of variables is carried out by:

- inverse demand function

$$p_i^{av} = a_i - b_i\left(s_i^{ar} + s_i^{sum}\right), \ \forall i; \qquad (15)$$

- power flow in the nodes

$$y_i^h = s_i^{ar} + \left(s_i^{sum} - \sum_{j\in J}\sum_{l\in L} y_{jil}^{com}\right), \forall i; \qquad (16)$$

- restriction on the total amount of hot spare capacity in the power system

$$\sum_{j\in J}\sum_{i\in I}\sum_{l\in L} r_{jil} \ge K^{hr}\sum_{i\in I} s_i^{sum}, \qquad (17)$$

where $K^{hr} < 1$ – given reserve ratio.

3.3. Long-term problems

Long-term problem of each power company is to identify the volumes of new generating capacity, which will maximize profit in the planning period. At each stage of the planning period capacity of the equipment $x_{jilt} = x_{jil0} + \sum_{\tau=1}^{t} \Delta x_{jil\tau}$ depends on the installed capacity at the beginning of the planning period x_{jil0} and the capacity increase Δx_{jilt} at subsequent stages.

Therefore, the aim of each competing company ($\forall\, j \in J$) is to achieve maximum profit

$$\pi_j = \sum_{t=1}^{T} \delta^t \left(n_t \sum_{z\in Z} \left(H_z \pi_{jzt} \right) - k_{lt} \Delta x_{jilt} \right), \qquad (18)$$

where δ – discount coefficient; n_t – number of years in stage t.

This takes into account the maximum load limit

$$y^{com}_{jiltz} + r_{jiltz} \le x_{jil0} + \sum_{\tau=1}^{t} \Delta x_{jil\tau}\,,\ \forall j,i,l,t,z\,, \qquad (19)$$

the minimum load limit

$$y^{com}_{jiltz} \ge K^{\min}_{jil} \left(x_{jil0} + \sum_{\tau=1}^{t} \Delta x_{jil\tau} \right),\ \forall j,i,l,t,z\,, \qquad (20)$$

and conditions of the daily minimum load passing

$$d^{\min}_{tz} \ge \sum_{j\in J} \sum_{i\in I} \sum_{l\in L} \left(\begin{array}{l} K1_{jil} K2_{jil} y^{com}_{jiltz} \\ + \left(1 - K1_{jil}\right) K^{\min}_{jil} \left(\begin{array}{l} x_{jil0} \\ + \sum_{\tau=1}^{t} \Delta x_{jil\tau} \end{array} \right) \end{array} \right),$$

$$\forall j,i,l,t,z. \qquad (21)$$

Equations (1-17) form a short-term equilibrium model of the of the electricity system operation.

Addition of (1-17) by equations (18-21) defines the long-term equilibrium model of capacity development.

In contrast to existing ones, proposed equilibrium models take into account the following essential features of Ukrainian power system:

- the impact of tariffs and the volume of production of regulated producers on the work of a competitive market. As a result, the generated short-term and long-run equilibrium models become nonlinear;
- the priority to produce electricity for power units, capable of stopping for the night, which makes it possible to consider the conditions for the passage of night load minimum;
- requirements for the volume of hot reserve in the energy system are taken into account by including in producers objective functions of income from hot reserve keeping $R^{hr}_j = \sum_{i\in I} \sum_{l\in L} p^{hr} r_{jil}$, and clarifying the conditions (2) and (4) for load limitations, as well as the requirements (17) for the total reserve capacity.

The formulated problems of short-term (1-17) and long-term (1-21) equilibrium are nonlinear multi-criteria optimization problems, which can not be solved by traditional methods.

Such multi-criteria optimization problems with application of Kuhn-Kurosh-Tucker (KKT) conditions are identically transformed into the problem of finding a solution of the system of equalities and inequalities. The resulting conversed problems are characterized as mixed complementarity problems, for solution of which special mathematical methods, efficient algorithms and solvers are developed [8]. PATH solver was used to develop computer models of the Ukrainian power system operation and development.

3.4. Checking the model adequacy

Model testing performed on the test data of power systems of the Benelux countries, France and Germany, confirmed the correctness of its work.

The model adequacy is proved by the coincidence of the simulation results of the equilibrium state power of Ukraine for the period of maximum load in 2006 with statistics.

4. PLANNING OF GENERATING CAPACITIES DEVELOPMENT IN THE POWER SYSTEM OF UKRAINE

The power system is represented by 8 nodes in accordance with the amount of power systems in the NEC “Ukrenergo” (Fig. 1). Burshtyn island is a separate 9-th node. The parallel operation of Ukrainian power system with UCTE is assumed starting from 2016.

Volumes of consumption of electricity, basic energy prices, prices of energy fuels are taken from [9] and [10].

In forming the characteristics of the network, considering plans for building nuclear power stations, hydro power stations - pumped storage power station, CHP and block-stations, modernization of the existing heat power station equipment, the indicators of existing development plans of energy companies are used, corrected by experts from NEC “Ukrenergo”.

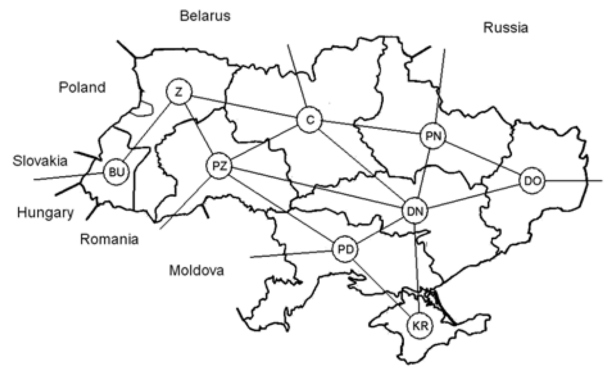

Fig. 1. Schematic network of Ukrainian power system

The calculation assumed that over the whole projection period, nuclear power, hydroelectric, PSP, CHP and block-stations sell all the electricity at regulated tariffs. Tariffs are based on actual 2006 data, followed by their step-by-step growth by 2,2%. Loads of NPS, HPS-PSPS, CHP and block-stations in the context of load zones and of nodes correspond to levels in 2006 with subsequent correction in proportion to the installed capacity of the equipment.

In the calculation the input capacity for the following new technologies is analyzed: a basic coal unit, a half-pick coal unit, combined cycle gas turbine unit. To reduce the problem size, capabilities of companies-producers on the building of new capacities in the different nodes are limited, with an allowance for its existing capacities distribution sites.

This problem has about 15 thousands of the variables.

As a result of computational experiments it was established that:

- transition from perfect competition (Bertrand model) to imperfect competition (Cournot model) leads to higher prices on average by 15,4% and a corresponding reduction in consumption by 9,3% (Fig. 2);
- under imperfect competition, manufacturers significantly reduce the building of new capacities by 43,6%, and these capacities are introduced later than under perfect competition conditions (Fig. 3).

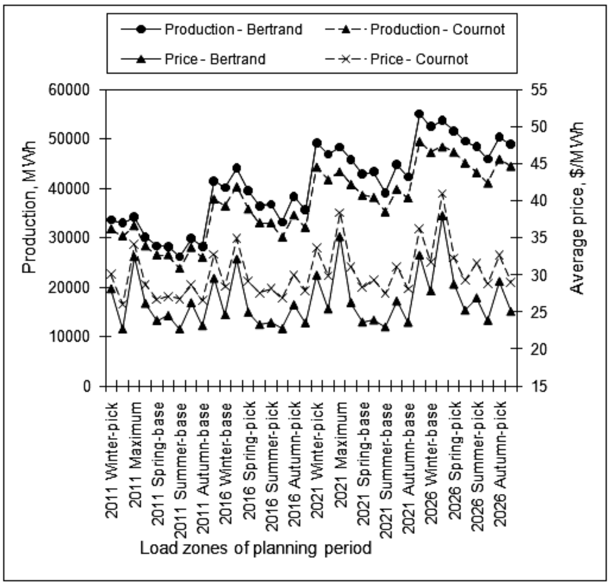

Fig. 2. The dynamics of production volumes and average prices under perfect and imperfect competition

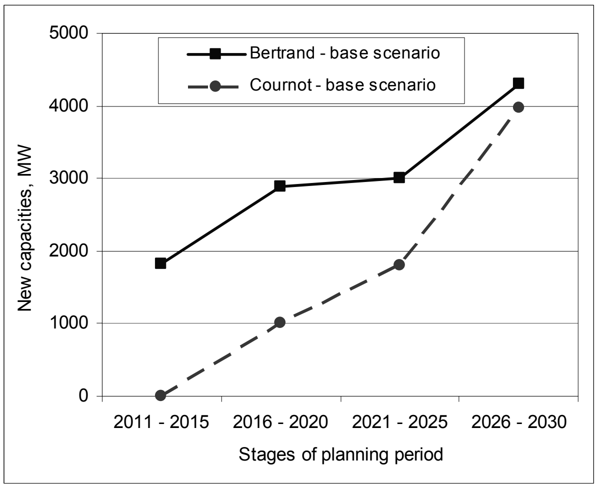

Fig. 3. Building of generating capacities in the Ukrainian power system under perfect and imperfect competition

The significance of the imperfect competition influence on the power system operation and development processes determines the need to consider this factor in models of generation capacity development and evaluation of energy market reforms.

Simulation of Ukrainian power system was conducted in a different scenario assumptions, in particular, reducing energy consumption, rising prices for energy fuels, association of power companies.

5. CONCLUSION

The study proposed equilibrium models of the Ukrainian power industry capacities operation and development in the conditions of imperfect competition. The models display adequately market mechanisms for managing the power system and its features such as the presence of significant amounts of regulated electricity production, restrictions on the use of power units to pass night time lows load, reserving generating capacity.

The results of computational experiments confirm the need for the use of equilibrium models for solving problems of planning the development of power sector of Ukraine under the market conditions.

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7. BIBLIOGRAPHIC DATA

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