Multi-Criteria Problems in Electric Power System Expansion Planning

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Abstract **- The paper presents different options of the power industry structure in a market environment and the nature of electric power system expansion planning problems. Mathematical methods are proposed to solve the problems of generation expansion planning. The use of a hierarchical multi-criteria game model is demonstrated for the case of "soft" regulation of the liberalized electric power industry expansion. Methods for analysis of many preference relations in electric power system expansion planning are discussed. Two illustrative case studies are presented.**

Index Terms **- Electric Power System, Market Structure, Expansion Planning Problems, Mathematical Methods**

I. Introduction

There can be different options of the electric power industry structure in a liberalized environment. These options predetermine specific features of the problems of electric power system (EPS) expansion planning. In general, these problems are solved by a rational combination of market mechanisms and state regulation, provided there are many stakeholders (power supply companies, consumers, authorities, etc.) with a great number of non-coincident criteria. And the uncertainty of future conditions for EPS expansion is responsible for a multi-variant character of possible decisions to be made and compared [1].

Complexity and multi-dimensionality of current extended EPSs, plurality of variants and criteria, and availability of different preferences in the choice of a decision make it impossible to solve the EPS expansion problem as a general synthesis problem. In the centrally planned power industry this problem was solved by the hierarchical approach that was based primarily on the expert, but a posteriori technology for problem solving. In the liberalized power industry, the problem is drastically complicated and the technology for solving it can be represented by different options depending on specific features of the industry structure [1 – 5]. Many researchers use a game-theoretical approach [4, 7 – 10], others apply additional techniques [11 – 15]. In [16], the authors present the state of the problem as a whole.

This paper is based on generalization of [1, 3 – 6, 9, 10] and is organized as follows. Chapter II shows a general approach to the problems of decision making in different cases involving many stakeholders. Chapter III explains the sense of decision making procedures in different cases of expansion problems. In Chapter IV two case studies are discussed to demonstrate certain problems of decision making. Chapter V presents the conclusions to this paper.

II. General approach

We will analyze different options of the power industry structure [2], which affects the composition and nature of the EPS expansion planning problems. These options comprise a regulated monopoly at all levels; interacting vertically integrated electric power systems at an open access to the main grid; a single electricity buyer-seller (an electric network company) at competition between generating companies; competing generating companies under a free choice of electricity supplier by selling companies or/and consumers, when the main grid renders only transportation services; selling companies competing in electricity supply to concrete consumers; and various combinations of the above considered options [3, 6].

The general problem of EPS expansion planning can be divided into three groups of problems [3]:

- the state strategies and programs for the development of the power industry and EPS (the federal, interregional and regional levels);
- strategic plans for the expansion of power companies (vertically integrated, generating, network);
- investment projects for electric power facilities (power plants, substations, transmission lines).

Decision making on EPS expansion involves different groups of stakeholders that have their own, totally different interests that are expressed by corresponding criteria. In particular [6]:

1) Electricity producers or/and sellers (vertically integrated, generating or selling companies, electric network company as a single electricity buyer-seller) and also the entities of electric power industry that render electric power

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services in the wholesale electricity market (maintenance of active and reactive power reserves, provision of system reliability, etc.) are interested in profit maximization as a result of their business.

2) Electricity consumers (selling companies of different levels, concrete consumers) are interested in minimizing tariffs for electricity bought in the wholesale or/and retail markets, and providing its quality and supply reliability.

3) The authorities (federal and regional) aim to maximize revenues of budgets of the corresponding levels, minimize the environmental impact of electric power facilities, provide national and regional energy security, etc.

4) External investors (banks, juridical and natural persons) are interested in minimizing the payback period for investment in electric power facilities, maximizing dividends, etc.

We will discuss the composition and specific features of EPS expansion planning problems in terms of technology and structure.

As for the technology, electric power system is viewed as a technically single system that consists of power plants operating in parallel and connected with each other and consumers by an electric network. EPS can be modeled in different ways depending on the problem to be solved and the level of consideration. For example, the structure and allocation of generating capacities of the Unified energy system (UES) of Russia are normally chosen on the basis of aggregated representation of large subsystems (e.g. interconnected EPSs - IPSs) and transfer capabilities of tie lines among them. If the same problem is solved for IPSs, their structure is described similarly in the form of aggregated subsystems and transfer capabilities of tie lines among them. To plan the network expansion, it is necessary to represent it in detail with generation capacities and their allocation that are determined in the previous stages. The UES level usually deals with the UHV backbone network. At the IPS level the electric network is represented in greater detail considering transmission lines, and substations of lower voltage classes. This set of problems related to the EPS expansion planning is a hierarchical sequence of problems, where decisions on system expansion are adjusted (or new decisions are made) in each stage by means of its more detailed examination in the technological and territorial aspects [6].

As for the structure, in decision making on EPS expansion, the technically single EPS is a set of structural units, i.e. companies, interacting with each other. If the expansion problems are solved depending on the structure, an EPS should be represented by vertically integrated, generating and network companies which will expand based on their technological interaction within the system. When choosing decisions on generation and transmission network expansion, the vertically integrated company, for example, has to take into consideration potential decisions of neighboring companies on their expansion. The generating company has to allow for the prospects for expansion of competing similar companies and the network company as well. The network company, in turn, should have an idea on the expansion of generating companies when analyzing trends in its expansion [2, 6].

Each generating company in this case should consider both prospects for expansion of other companies and the state energy policy (at the federal, interregional and regional levels) and mechanisms of its implementation in the form of tax, credit, tariff and other policies. Working out the strategies and programs of power industry development, the state, in turn, should implement its energy policy by taking into account the incentives, possible behavior and interaction of generating companies in their expansion [6].

III. Decision making procedures

In general, the problems of EPS expansion planning as applied to many stakeholders that are guided by many non-coincident criteria are of a multi-criteria game character. Let us examine specific features of such statements for the mentioned three groups of problems: the state strategies and programs, strategic plans of power companies, and investment projects [1, 3 – 6].

A. The state strategies and programs

The state strategies and programs for the power industry development at the federal and regional levels are devised on the basis of the multi-criteria hierarchical game statements of the problems. Such problems appear, when the state is at the upper level and the power supply companies are at the lower level. These problems are solved by the formal methods for creating the incentives for stakeholder behavior at the lower level by the appropriate mechanisms foreseen at the upper level.

Here the multi-criteria hierarchical game problems may be cooperative or non-cooperative depending on conditions [4, 6].

The electric power system development coordinated by the government is considered in [4]. A hierarchical cooperative game is formulated in the normal form between the control agent (center) A_0 and the power producers B_i, $i = \overline{1, n}$, where n is the number of power producers.

The initial conditions are presented by the tuple of three sets:

$$\{I, J, K = (K_1, \ldots, K_M)\}, \tag{1}$$

where I is the options of generation expansion, J is the scenarios of external conditions, K is the criteria of decision assessment, M is a number of stakeholders interested in generation expansion.

The rectangular $I \times J$-dimensional matrices are constructed:

$$X^k = \{x_{ij}^k\}, i = \overline{1, I},\ j = \overline{1, J}, k = \overline{1, K}, \tag{2}$$

where x_{ij}^k is a numerical estimate of the i-th expansion option by criterion k, provided the j-th external condition took place.

In fact, the center A_0 distributes regulation actions among the subdivisions $B_1,\ldots B_n$. The regulation actions can be budget subsidies, tax privileges, loans, etc. Thus, the center A_0 chooses the system of n vectors $\omega = (\omega_1 \ldots \omega_n)$ from the negative set $W = \sum_{l=1}^{n} w_l$ subject to [1, 4, 6]

$$\sum_{l=1}^{n} w_l \leq b, \tag{3}$$

where b is a constraint on the possibilities of the regulation center.

The possibilities of the company B_l are determined by the regulation action ω_l received from A_0. The company realizes the nonnegative decision vector $x_l(\omega_l) \in X$.

Let us suppose that the sets $x_l(\omega_l)$ at all ω_l contain a zero vector and increase monotonously by inclusion, i.e. $x_l'(\omega_l') \supset x_l(\omega_l)$ follows from $\omega_l' > \omega_l$, and $x_l(0) = 0$ is met (impossibility for the center to control the companies without regulation actions). Here ω_l' means a regulation action introduced at the next step after the regulation action ω_l [4, 6].

Let $x = (x_1,\ldots, x_n)$ be an expansion option for the companies $b_1,\ldots, b_n$. The payoff of the player B_l is supposed to be equal to $l_l(x_l) \geq 0, l = \overline{1, n}$. The payoff of the player A_0 is determined by the function

$$f\left(l_1(x_1),\ldots,l_l(x_l)\right) - g(\omega_1,\ldots,\omega_n) \geq 0, \tag{4}$$

where $g(\omega_1,\ldots,\omega_n)$ is a nonnegative function that characterizes the level of actions applied by the center.

The regulation center has the right of first move and may manage the possibilities of regulated companies by controlling their activities. The main purpose of the regulation center is to minimize its regulation actions. The next Chapter presents an example illustrating the proposed hierarchical approach [4].

These problems can take place at interaction of the federal and regional levels, when the state strategies and programs are devised for the power industry development. Such problems are aimed at coordinating the national and regional interests. The state priorities in the industry development are formed at the federal level and then they are transformed into concrete trends in expansion of generation capacities and electric networks in the considered region. In general, when the principles of authority sharing are adjusted and non-contradictory, the multi-criteria hierarchical game problems of a cooperative nature can be involved. The mechanisms of inducement or persuasion are applicable here, however, with somewhat different conceptual interpretation as against the previous case [1, 4].

The indicated two problems can be studied jointly as one problem that reflects interactions among three groups of stakeholders: federal and regional levels of the country and power companies. Such problems are considered, in particular, as active systems with distributed control and are also reduced to hierarchical game models [1].

In individual cases, we can use the simpler statements of the hierarchical two-level problem as a two-stage sequence of multi-criteria problems of mathematical programming. The strategy of the national power industry development is considered in the first stage; the appropriate recommendations are adjusted at the level of strategies of regional power industry development.

The general form of optimal conditions in both stages in the multi-criteria problem is the following:

$$f\left(f_1(x), f_2(x),\ldots, f_k(x)\right) \to \max. \tag{5}$$

The search of Pareto set is frequently used for the optimal solution to the problem under incomparable objectives.

Let $\langle X, \{f_i\}\rangle$ be a multi-objective optimization problem, where X is a set of alternatives, $f_i(i \in N = \{1,\ldots,n\})$ is an objective function. If there is no additional information about the problem, then the Pareto optimal alternatives are accepted as optimal alternatives, i.e. such $x^0 \in X$, from $f_i(x) \geq f_i(x^0)$ for all $i \in N$ and $x \in X$ results in $f(x) = f(x^0)$. In other words, the set of optimal alternatives is defined only by Pareto optimal axiom [1].

In general, the Pareto set does not provide a unique solution, thus the problem of multi-criteria decision making remains unsolved. The use of multi-criteria utility function is a feasible approach to solve this problem.

A similar two-stage sequence of problems can be analyzed in inter-sectoral terms, when the basic proportions in power industry development are determined in the first stage by the territorial-production model of the energy sector. Then, these proportions are adjusted on more detailed models for decision making on power industry development [1].

In the problems in question, the main attention is paid to the mechanisms of interaction between the federal and regional or the energy sector and energy industry levels of devising the state strategies and programs for the power industry development. Therefore, consideration of incentives for the behavior of power companies by one or another technique for representing uncertain factors becomes necessary. The key objective for power supply companies in this case is to work out effective economic, legal and institutional mechanisms. They are to stimulate the companies to take into account priorities of the state policy in electric power industry when making strategic plans of their expansion and making decisions on investment projects. The optimal proportions of such mechanisms can be improved by solving the hierarchical game problems between the above-mentioned stakeholders "state" and "power companies" [1, 4].

B. *Strategic plans of power companies*

Now we will analyze the next group of problems dealing with the strategic plans of power company expansion. At least three classes of such problems can be discussed here.

For the regulated monopoly without competition it may appear to be necessary to solve multi-criteria problems of mathematical programming in terms of uncertainty and different preferences [5, 6]. A rather simple way for considering uncertain factors is a scenario representation of combinations of their values. The game problems in the class of "games with nature" may be analyzed on the basis of ordinary and fuzzy payoff matrices in the other cases.

The particularity of solving the multi-criteria problems based on the utility theory under different preferences is considered in [5, 6].

Let the initial conditions be represented by a tuple of sets (1) and the solutions are considered as a set of numerical estimates of the ranks of matrices (2). In order to solve the problem of choice on the basis of multi-criteria utility function, it is necessary to determine a preference relation for the decision maker (DM). The type of the preference relation depends on the scenarios of external conditions and relative significance of each of them for DM. If the preference relation is based on the probability methodology, then according to concepts of the utility theory, recommendations for choosing an EPS expansion option are given based on the calculation of the expected utility of each option in the form

$$E_i^p = \sum_{j=1}^{J} p_j U_{ij}, \ i = 1, \ldots, I, \tag{6}$$

where p is an index indicating the probability methodology used in preference relation, U_{ij} is a generated utility function. The option with a higher numerical estimate of the expected utility is more preferable.

However, the probability methodology of the preference relation is not always acceptable. It may turn out to be more reasonable to rely on the risk methodology. The latter is especially typical of cases when some scenarios of external conditions have very low probability but their influence on decision-making should be taken into consideration. Such a situation takes place, for example, when extreme external conditions connected with large-scale events of natural, technogenic or other character are to be taken into consideration. Then, the expected utility of the EPS expansion options can be obtained from the expression

$$E_i^r = \max_i \{\min_j (U_{ij} p_j)\}, \ i = \overline{1, I}, \tag{7}$$

where r is an index indicating the risk methodology used in preference relation.

It is worth noting, that the risk methodology as a basis for the preference relation also has disadvantages because the application of (7) decreases the effect of scenarios of external conditions with a high probability on the decision choice. Both the probability and risk methodologies are limiting cases, each reflecting a real situation in formation of preference relation used by decision maker from one side only. Therefore, consideration should be given to a complex criterion on the basis of (6) and (7) [1, 5-6].

Generation of such a complex criterion involves the problem of determination of weights of its constituents. This problem can be eliminated, if the decision-making procedure is not completely formalized and the decision is chosen by decision maker on the basis of additional information characterizing dominance regions for criteria (6) and (7) to form his preferences. In this case we can 'weigh' decisions obtained by both criteria and determine when some option with maximum utility (6) ceases to be the most preferable and some option with the maximum utility (7) becomes the most preferable.

To this end, $I - 1$ equations of form [1, 5, 6]

$$\begin{aligned} & a_{i-m} E_{i\max}^p + (1 - a_{i-m}) E_i^r = \\ & a_{i-m} E_m^p + (1 - a_{i-m}) E_m^r, i \neq m, \end{aligned} \tag{8}$$

are solved, where a_{i-m} is the required parameter allowing the obtained utilities to be weighed, $a_{i-m} \in [0; 1]$; $E_{i\max}^p$ is the maximum utility of the i-th option which is calculated by relation (6); E_i^r is its associated utility value calculated by relation (7); E_m^p, E_m^r are corresponding utilities of the m-th option.

The next Chapter includes some calculation results based on the above-mentioned complex criterion [5, 6].

Since in real conditions there is no single technique to comprehensively solve the problem of choice, it is desirable for decision maker to have a set of different techniques to choose the most suitable one.

Development of a strategic plan for the network company expansion, when there are vertically integrated or purely generating companies, refers to the second class of problems. Considering, in a certain sense, a subordinate role of the network company that in the most general case implies providing competition for power producers and a free choice for power consumers, we can study the problems of the network company expansion in terms of "games with nature". In this case, the uncertainty in behavior of both power producers and consumers in the wholesale market is essential and is taken into account by the appropriate payoff matrix of the game. The conceptual meaning of uncertain factors for the network company as the single electricity buyer-seller, is determined, as before, by competition, and at the power consumption level it depends only on demand uncertainty and elasticity. In this case, however, the problem can also be examined in terms of "games with nature".

The generating companies can be coordinated especially under state regulation. Then, we considered the problem of cooperative game [7].

Finally, the third class of problems is related to the development of strategic expansion plans of competing vertically integrated or purely generating companies. Without the state regulation, the problem is reduced to a multi-criteria non-cooperative game. With the state regulation, the problem takes the form of a multi-criteria cooperative game, probably of a multi-stage character, i.e. it is reduced to a positional game [8, 9].

There are several methods to obtain the cooperative game solution. The evaluation of game solution based on the Shapley value is a generally used approach. This approach calculates the fair sharing of the common utility (money, resources, etc.) among players. The Shapley value can be determined as a weighted average of limiting contributions of a participant to every coalition in which the participant may take part.

The Shapley value φ_i can be expressed for the set of players $M = \{1, \ldots, m\}$ and the set of coalitions T_i, $i = \overline{1, M}$, where *i* is the number of players in coalition T_i, as:

$$\phi_i[v] = \sum_{\substack{T \subset M \\ i \in T}} \frac{(t-1)!(m-t)!}{m!}[v(T) - v(T/\{i\})], \qquad (9)$$

where $v(T)$ is a characteristic function of coalition *T*.

To determine this function is the key objective in such problems. Traditionally the characteristic function is considered as a cost function. In a more general case, the utility function can be used [4, 6].

The maximal constituent of Shapley value is calculated using (9) for a specified coalition, if the value of utility (6) is calculated for every possible coalition. The coalition with the maximal constituent of Shapley value corresponds to the optimal option of EPS expansion. An example of using the Shapley value to solve the problem of generating company expansion is presented in [9].

C. *Investment projects*

The problems of the third group dealing with decision making on investment projects for electric power facilities (power plants, substations, transmission lines) require a business plan for the construction of the corresponding facility. Mathematically, the problem statement depends on the investor position. If the power supply company (e.g. the network company) invests in the installation, the investment project may call for the multi-criteria assessment. For an independent investor one should allow for an incentive for behavior of the other concerned stakeholders and the problem can be associated with the game statement. It can be either cooperative or non-cooperative depending on conditions [1, 6].

IV. Case studies

This Chapter presents the calculation results based on [4] and [5]. These results are purely illustrative.

A. *Case study #1*

A hierarchical system expansion is studied for two levels. At the lower level consideration is given to two independent electric power companies, each supplies power to the consumers on the served territory. The first company (system 1) sells surplus power to the second company and foresees for this purpose an additional expansion of its generating capacities. At the upper level consideration is given to the regulation body (for example, state) that can stimulate the company expansion by regulation actions.

The objective is to choose an expansion option that will enable independent companies and the regulator to generate a suitable expansion option with more profitable expansion conditions for the donor company (company 1).

Assume general expansion conditions for both companies.

The scenarios of external conditions for the first company are:

a) Maximum power consumption without power sale at minimum fuel prices.

b) Minimum power consumption without power sale at maximum fuel prices.

c) Maximum power consumption with power sale at minimum fuel prices.

d) Minimum power consumption with power sale at maximum fuel prices.

The scenarios of external conditions for the second company are similar at the exception of the fact that the company does not sell but buys electric power.

Taking into account the illustrative character of the problem, we consider the probabilities of implementing the above scenarios of external conditions to be similar and equal to 0.25 each.

The above-mentioned expansion options include the options when company 1 sells the power generated by gas-fired power plants to company 2.

Three players are to make decisions for each company: power company, authorities and consumers. All the players had equal rights, the total of weighting coefficients for all criteria was equal to unity and each criterion participated in decision making with its weight.

The options were estimated using the following criteria:

α) investment costs (million $);

τ) current costs (million $/year);

β) budget (taxes) (million $/year);

γ) tariffs ($/kWh).

The calculation results for the accepted options of solutions for companies 1 and 2 at given external conditions in terms of the estimated criteria were analysed in [4]. Gas-fired power plants were addressed as new generating capacities to be commissioned.

Table 1 presents utilities of the options for each system and ranks of the options.

Levelling of the situation (ranking of the options, Table 1) was performed by the rising price of electricity sold. We will apply option 4 from Table 1 for further analysis of the hierarchical game, because in this option the increasing electricity demand of consumers served by company 2 is met fully [4].

Thus, in the considered problem the base (first) option (Table 2) is the option of commissioning new units with a utility of 0.5117 for company 1.

The option with introduction of regulation actions will be compared to the base one only by two criteria: capital investment and current expenditures. It is precisely these criteria that underlie a decision made by the power company. The rest of the criteria were foreseen for the other participants of decision making process: the budget for authorities and tariffs for consumers.

Table 1. Initial estimates of options.

Options	Utility and ranks (in brackets)	
	System1	System 2
1	0.5284 (2)	0.2873 (4)
2	0.5154 (3)	0.6371 (2)
3	0.5302 (1)	0.5287 (3)
4	0.5117 (4)	0.7201 (1)

Table 2. Calculation results for system 1 at specified external conditions by the criteria: capital investments and current expenditures.

Criteria	Options	External conditions (for system 1)			
		A	B	C	D
α	1	170.3	170.3	1761.5	1761.5
	2'	192.3	192.3	1783.5	1783.5
	3'	182.3	182.3	1773.5	1773.5
	4'	179.3	179.3	1770.5	1770.5
τ	1	89.9	102.5	96.1	110.8
	2'	89.9	102.4	96.1	110.7
	3'	89.9	102.4	96.1	110.7
	4'	89.9	102.4	96.1	110.7

Table 3. Newly commissioned capacities.

Options	Additional capacities (MW)	Including WPP (MW)
2',3',4'	122	10

Table 4. Comparison of utilities for expansion options.

Options	Utility
	System 1
1	0.5117
2'	0.5107
3'	0.5115
4'	0.5117

The regulator encourages company 1 to construct wind power plants (WPP). These plants have high capital investments and low current expenditures. The options corresponding to WPP commissioning will be further denoted by 2', 3', 4'.

Step 1 calculates the possibility of commissioning such plants by the company itself without regulation actions from the regulator. In this case, new option 2′ (Table 2) is generated.

Table 3 shows additional capacities including capacities of WPP to be commissioned in the case of electricity sale. As is seen from Table 2, option 2′ is characterized by a rather high level of capital investments and a small decrease in current expenditures versus the base option.

Table 4 demonstrates a decrease in the utility for option 2′.

Hence, it is unprofitable for the company to construct new plants with a high level of investments.

Thus, regulation actions of the regulator are introduced at the next step. At first they may be represented by the budget subsidies, whose value is chosen arbitrarily. With the budget subsidies of $10 million, for example, the utility of option 3′ (Table 4) remains lower than the base option 1, as before. The current expenditures are low enough and their negligible increase is not indicated in Table 2.

With the regulation actions equal to the amount of $13 million, the utilities of the base option and option 4′ coincide. The capital investments for option 4′ remain higher than the capital investments for the base option. It means that if the utilities coincide, this option can be accepted by the company.

Conditions for WPP commissioning by both companies may differ slightly in the investment per power unit (for example, it is somewhat more expensive for company 1), and the current expenditures (they are on the contrary somewhat higher for company 2, for example, due to difficulties in maintaining remote WPP, at the same time in company 1 the wind power plants are located nearby). We will not illustrate this quantitatively more complicated case, as it has nothing new compared to the previous one.

Needless to say, other regulation actions of the regulator are possible for more coordinated expansion of power companies.

B. Case Study #2

B1. Problem statement

The formation of the basic structure of one of the electric power systems in Russia is considered with regard to generating equipment types for the period of some 10 years.

In this study, the external conditions of EPS expansion are:

A) Minimum power consumption without export at a minimum fuel price.

B) Minimum power consumption without export at a maximum fuel price.

C) Maximum power consumption with export at a minimum fuel price.

D) Minimum power consumption with export at a maximum fuel price.

Without dwelling on the validity of such conditions for EPS expansion by virtue of the illustrative character of the studies, in further analysis we assume the probability of each condition to be equal to 0.25.

Three options of the EPS expansion are analysed:

1) Commissioning of new coal-fired units.
2) Commissioning of new gas-fired units.
3) Partial commissioning of coal-and gas-fired units.

The above options were estimated by six criteria:

α) investment costs (million doll.);

τ) fuel costs (million doll./year);

β) budget (taxes) (million doll./year);

η) environment (ash emissions, thousand t/year);

γ) tariffs (cent./kWh);

δ) reliability (p.u.);

The options were analysed using the software package

'Soyuz' [6]. This package is designed to choose the structure of generating capacities by equipment type, their location and formation of requirements to the transfer capabilities of ties in the multi-nodal EPS taking into account seasonal and daily non-uniformities of power consumption, specific character of operation and performance of different power plants, reliability requirements, conditions for fuel supply, etc. Reliability was calculated by simulation of failures/restorations of EPS components and evaluation of a relative magnitude of power supply to consumers. The results of the studies on the considered options of the UEPS expansion at the assumed external conditions in terms of the estimation criteria are presented in Table 5.

Table 5. Estimates of options for different external conditions.

Criteria	Options	External conditions A	B	C	D
α	1	13.5	13.5	1849.5	1849.5
	2	11.7	11.7	1602.9	1602.9
	3	12.6	12.6	1726.2	1726.2
τ	1	79.1	86.1	82.1	89.3
	2	87.2	98.9	93.4	107.1
	3	83.1	92.5	87.7	98.2
β	1	3016.0	4524.0	3317.6	4825.6
	2	3317.6	5428.8	3619.2	5730.4
	3	3166.8	4976.4	3468.4	5278.0
η	1	58.1	58.1	60.4	60.4
	2	52.5	52.5	52.5	52.5
	3	55.3	55.3	56.4	56.4
γ	1	1	1.5	1.1	1.6
	2	1.1	1.8	1.2	1.9
	3	1.05	1.65	1.15	1.75
δ	1	0.9996	0.9996	0.9974	0.9974
	2	0.9997	0.9997	0.99915	0.99915
	3	0.99965	0.99965	0.99893	0.99893

B2. Calculation and analysis of utilities

We solved the multi-criteria expansion problem using the utility theory by (6), (7). The studies were performed for two sets of criteria (in Table 6 with the corresponding weighting coefficients)**:** α - 0.2, 0.3; τ - 0.2, 0.2; β - 0.15, 0,15; η- 0.1, 0,1; γ - 0.25, 0.15; δ -0.1, 0,1.

Now let us verify the stability of decisions for each system of the expert preferences at which the rank of the options changes, i.e. let us determine at which relations of the two approaches the decisions can be considered stable. Otherwise, one can rely on the decision chosen by different methods. Note that to do this we calculated parameters a_m, $m = 1,2$, by relation (8), where m means number of the first or second method for calculation of the utilities by (6) or (7) respectively. Table 7 presents the utilities of options that are calculated by (7). Table 8 presents the values of a_m for different systems of the expert preferences.

Thus, for the first set of the expert preferences, the third expansion option is the most preferable at $a_1 \in [0;0.2499]$ and the fourth expansion option - at $a_1 \in [0.2499;1]$.

For the second set, the first option is chosen at $a_1 \in [0;0.0969]$ and the fourth option - at $a_1 \in [0.0969;1]$.

Table 6. Utilities and ranks of options.

Options	Utilities and ranks (in brackets) Set 1	Set 2
1	0.4966 (3)	0.6278 (3)
2	0.6330 (1)	0.6993 (2)
3	0.5909 (2)	0.7039 (1)

Table 7. Utilities and ranks (7).

Options	Utilities and ranks (in brackets) Set 1	Set 2
1	0.1590 (3)	0.1676 (3)
2	0.1932 (2)	0.2625 (1)
3	0.2073 (1)	0.2620 (2)

Table 8. Weighting coefficients for (8).

Systems of expert's preferences	a_1	a_2
Set 1	0.2499	0.7501
Set 2	0.0969	0.9031

V. CONCLUSIONS

In a liberalized environment, we deal with a great number of decision making problems for power system expansion planning. These problems are not simple.

The mathematical programming, game-theoretical approaches or simulation assessment can be applied to solve these problems.

The development of technologies, mathematical models and techniques for power system expansion planning is of paramount importance.

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