Hierarchy of Models for the Study of National and Regional Energy Security

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***Abstract* — This paper focuses on the specific features of the hierarchical approach in the en-ergy security studies for modeling the processes of functioning and development of in-dustry-specific energy systems within a single energy sector. The experience of devel-oping and using hierarchical modeling in the study of reliability and survivability of energy systems is analyzed using the example of the unified gas supply system, oil sys-tem, oil product system, and the unified power system of Russia. In the paper, the hier-archy of models in the energy security studies is considered in terms of territory and structure.**

***Index Terms* — hierarchical modeling, energy security, energy systems, the energy sector.**

I. Introduction

The system of mathematical models used to study the national and regional energy security (EB) problems is largely based on mathematical models designed to study reliability. At the same time, reliability, being a complex index of energy system, includes such a feature of this system as survivability. The need to pay attention to survivability arises mostly when the energy system operates under the conditions other than normal, i.e. when the system components fail due to internal and external reasons, or due to a variety of external impacts. While the reliability is interpreted as a property of the energy system or the entire energy sector, the energy security is a state of being protected against the threats of a failure to meet energy needs with affordable energy resources of acceptable quality and the threats of interruptions in the energy supply (due to emergencies) in a certain world region, various groups and unions of states, individual countries, their regions, territorial and industrial entities, etc. [12]. Thus, energy security as a subject of research is not so much of a state of the energy sector itself but its (energy sector) relationship with economic, social, foreign policies, and other aspects of the existence of citizens, society and the state as a whole. This reality captures a broader meaning of the energy security concept, the research of which also includes the reliability issue of the energy sector and energy systems.

Therefore, we will consider the basic principles of the study on the energy system reliability based on hierarchical modeling, with the emphasis on the specifics of energy security research.

II. The principles of the energy system reliability study

The reliability of energy systems, following [3], is the ability of energy systems to ensure an uninterrupted supply of appropriate energy carriers of agreed quality and according to agreed delivery schedules, avoiding the situations where the danger for people and the environment exceeds a certain level. Reliability, being a complex index, includes the feature of "survivability" or the ability of energy systems to withstand large disturbances, preventing their cascade development with mass outages of consumers [4]. For complex energy systems, there is always a risk of major, cascading accidents that turn into "system-wide» failures under unfavorable circumstances, which can negatively affect fuel and energy supply to consumers. Reliability and survivability are the properties of the energy systems themselves and represent predominantly technical categories, which have an economic sense only because their decrease often entails economic damage.

The assessment of the energy sector capabilities to ensure uninterrupted fuel and energy supply under various operating conditions of the entire energy sector requires the determination of such capabilities of individual industry-

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specific systems, including those in case of large-scale disturbances. The subject of research here is the process of disturbance occurrences, the reaction of energy systems, the consequences for end energy consumers, and the method of compensation for undesirable consequences [5]. The need to study the operation of energy systems under emergencies is dictated by the general methodological principle formulated in [6]: it is quite sufficient to test simple systems under normal conditions, whereas complex systems need testing in extreme situations.

A large number of studies have been devoted to the reliability and survivability of large energy systems and the energy sector, and, especially, to the hierarchical modeling in the study of these issues, for example [7-12]. The Energy Systems Institute SB RAS (ESI) has gained extensive experience in studying various aspects of interconnected operation of the energy industries within a single energy sector, including the studies of these systems in terms of their survivability and continuous fuel and energy supply to the consumer [13-17].

III. Methodological features of the energy security studies

In the mid-1990s, the ESI (the then Siberian Energy Institute) SB RAS launched energy security research, which was a continuation of the studies on the reliability of the energy sector and energy systems. Among other things, the research determined the essence and main aspects of the energy security problem and identified "bottlenecks" in the national economy and energy sector in terms of energy security. Based on an analysis of the energy sector state and prospects for its development, the study also established and classified the energy security threats, the occurrence of which both in an individual energy system and in the entire energy sector can lead to serious failures accompanied by significant energy shortages for the consumer.

Considering the methodological aspects of the energy research in the context of energy security, one should keep in mind the following important features [1]:

- The emergencies and major accidents of extreme nature are unique in terms of the probability and conditions of their occurrence, the nature of the phenomena and processes, the nature and severity of their consequences for energy systems and consumers;
- The research requires that the energy systems be represented in sufficient detail due to a large scale of the disturbances, the possibility of development of adverse events, the need to model the response of energy facilities and consumers (given their structure and properties), since different components of energy systems and different consumers can respond differently to a large disturbance, etc.
- The need to prioritize the consumers facing the energy supply problems in case of emergency.

The aforementioned determines the use of a simulation approach as the main methodological principle of the energy research in terms of energy security and the justification of measures to increase the survivability of energy systems and to ensure energy security. Composition of the studied scenarios, among other things, is determined by the specific threats to energy security, whose materialization is considered possible in the research. The analyzed set of disturbances in specific conditions can be quite large. Since the scale of the considered disturbances is large, the occurrence of possible energy security threats will inevitably result in fuel and energy shortage for consumers, and energy consumption limitations, which are associated with economic damage to industry, agriculture, other sectors of the economy, the public utilities sector, and the energy sector itself (lower profit, increase in fines, etc.). The sizes of these shortages, energy consumption limitations, and damages are indicators, which can be used to assess the severity of the energy consequences of specific disturbances when various energy security threats materialize and to evaluate the comparative effectiveness of energy security measures.

IV. Modeling principles of the assessment of technical consequences for the energy consumer in case of large-scale energy system failures

A general scheme has been designed to assess the technical consequences of disruptions in the energy system operation within the energy sector for energy consumers. Solving the problems of survivability of each energy system requires a certain level of hierarchy and detail of the models used. The following aspects need to be detailed [4]:

1. ***The structure of energy systems***. A detailed analysis of the consequences of major accidents and the development of emergencies in the energy sector requires that the transport components of individual energy systems be presented at the level of specific energy facilities and relevant transport links, at least in the studied area and in a wide territory around it. Emergencies can occur in any place of energy systems, therefore, sufficiently detailed modeling of their structure at the national and regional levels is needed.
2. ***The operating conditions of energy systems***. Under normal operating conditions, energy facilities perform the functions assigned to them according to their production characteristics. In emergencies, when their production characteristics decrease or one or more of these facilities cease to operate, the production capabilities of the corresponding energy system or even several interconnected energy systems decrease and may be insufficient. In this case, the resulting power shortage will cause a limitation of power supply to consumers. Consideration of such situations in the research necessitates sufficiently detailed modeling of the energy system operation.
3. ***Representation of energy consumers*** Detailed representation of consumers is necessary due to

the large-scale potential disturbances leading to restrictions in the fuel and energy supply to consumers and violations of their production processes. The detailed structural representation of energy systems makes it possible to show each major consumer given its production process, and energy supply conditions. It also allows determining the resources for the consumer adaptation to energy shortages and interruptions in energy supply. In this regard, modeling the emergencies in energy systems is associated with an analysis of the energy system behavior and measures to increase the survivability only in the most typical situations defined by the characteristic points of the consumer load curves (maximum, minimum load, etc.), the equipment operating in the system and its loading [4]. Thus, at the level of energy systems under various types of emergencies, there is a "point-in-time" modeling of their operating conditions [4].

Due to the impossibility of conducting large-scale experiments on spatially extended energy systems, the most convenient way to study their survivability is to use a simulation approach when the study of the considered phenomena involves the investigation by sequentially putting forward "working hypotheses" and experimentally testing them [18]. The simulation approach is the main methodological principle of energy research in terms of providing continuous fuel and energy supply to the consumer and the rationale for measures to improve the survivability of the energy systems. A general scheme for studying the survivability of energy systems, representing the relationship between the main tasks, is shown in Fig. 1 [1].

Building a set of disturbance scenarios that reflect the most representative or characteristic combinations of external conditions for the development and functioning of energy systems is an important component of the research. The number of such characteristic situations for a complex energy system can be extremely large. This generates the need to make a reasonable choice of the most representative set of characteristic situations, which are called calculation ones. The resulting estimates and solutions must be invariant for different combinations of the conditions.

The next two tasks – identification of "bottlenecks" in the fuel and energy supply to consumers and assessment of the effectiveness of measures for specific disturbance

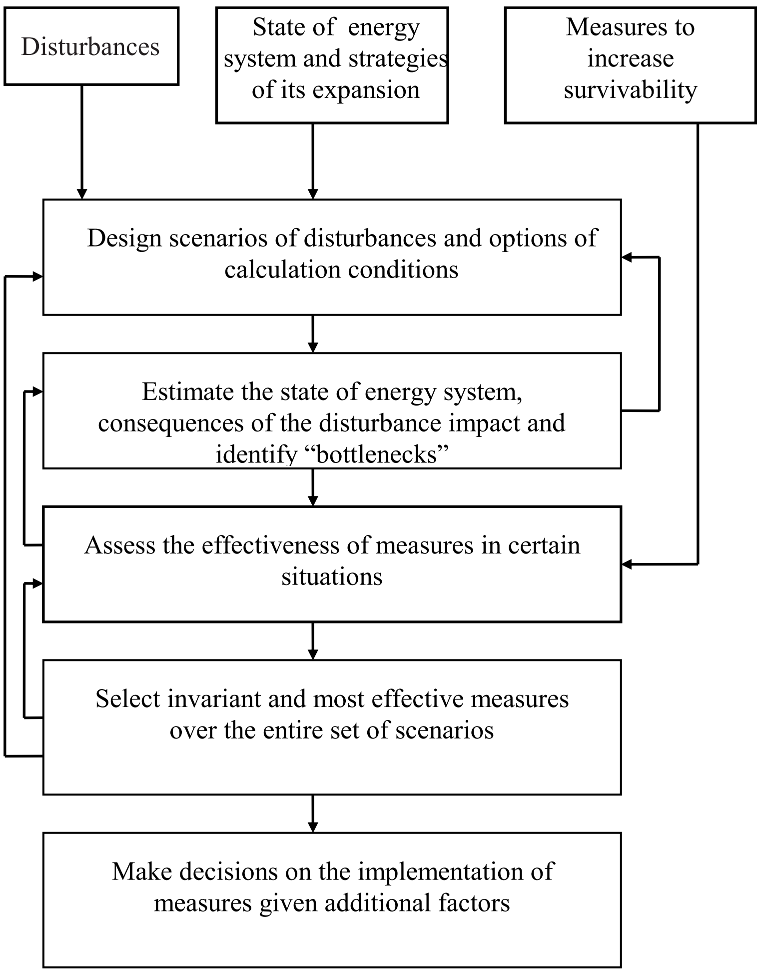

Fig. 1. The relationship between the main tasks in the research into the energy systems survivability

scenarios – have their specific features in terms of object modeling. As already mentioned, the study of the energy system survivability performs a set of subtasks at various levels of spatial and technological hierarchy where while moving from the upper levels of the hierarchy down to the lower levels, the ideas about the structure and properties of the studied system are refined and detailed. In some cases, if it is necessary to present the features of an energy system or a region, it may be appropriate to refer to industry-specific or regional models to clarify individual points.

Another task is to assess the acceptability and effectiveness of measures intended to increase the survivability of energy systems and ensure uninterrupted fuel and energy supply to consumers under specific disturbance scenarios. The models of energy systems based on linear programming methods can optimize the selection of measures when the optimizing functional and model equations are set in a certain manner. The substantiation of measures aimed at improving the survivability of energy systems and ensuring continuous fuel and energy supply to consumers is significantly complicated by the uniqueness of the considered phenomena and their consequences for the energy sector and consumers. One of the main effects of the indicated measures is the reduction in direct and indirect damage due to a decrease in energy shortage, a reduction in the risk of interrupting energy supply to essential consumers, a lower number of social consequences, etc. Damage components that can be assessed economically should be considered when analyzing the economic efficiency of the measures. The economic effectiveness of the discussed measures mainly depends on the probabilities of potential disturbances, critical and emergency conditions, and situations. Under normal operation of the energy sector, these probabilities are relatively small, and therefore, despite rather severe consequences of such situations, the measures that can prevent them and do not require large additional costs can only be acceptable.

The final stage of the studies suggests making a decision on the implementation of the measures to increase the survivability of energy systems, which is considered at the level of decision-makers. The decision making process can also employ models and expert estimates of other factors, for example, the conditions for the implementation of the measures in terms of the entire economy; environmental, social and other requirements and constraints, etc.

V. A two-level approach to the energy security study

To study the energy security problems, ESI SB RAS has proposed a two-level technology that integrates the stages of qualitative and quantitative analyses. At present, the stage of the quantitative analysis is most developed. This stage involves a study of the energy sector operation and development meeting the energy security requirements. The study is based on the linear optimization models of the energy sector and individual industries. It also relies on the technical and economic characteristics of energy facilities, reported data on the state of energy systems, and the findings of the energy development studies that provide grounds for the selection of a long-term strategy and formulation of an energy policy. Based on the adopted socio-economic development program for the national economy, which determines the demand for fuel and energy resources, the expected energy consumption levels are analyzed and assessed.

The stage of the qualitative analysis suggests the use of the above characteristics and the analysis of threats to energy security with the view to formulating the calculation conditions for the computational experiment, which is carried out in the stage of quantitative analysis. Based on the presented hierarchy of problems to be solved

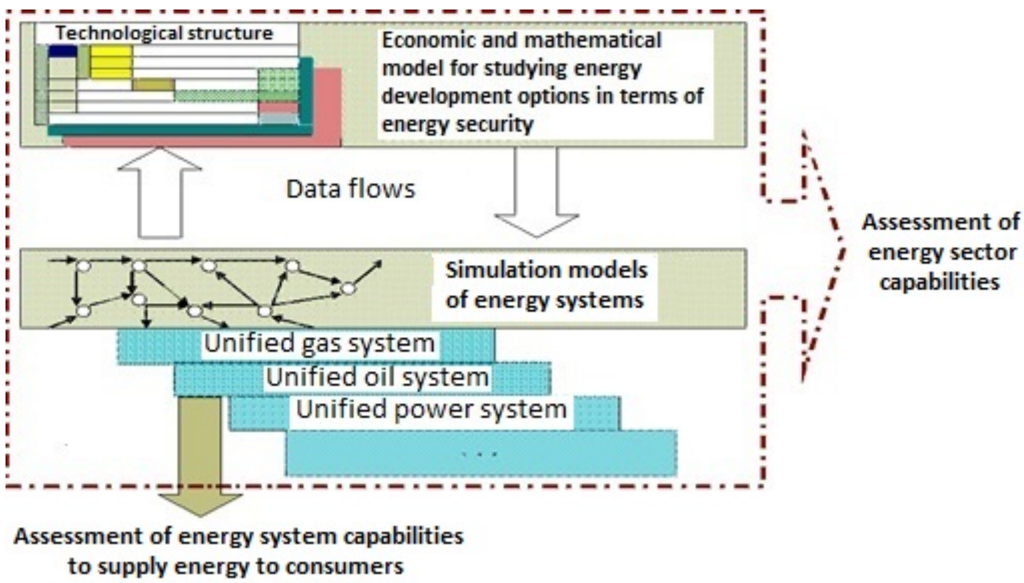

Fig. 2. The relations of linear optimization models for the study of energy security problems.

and models developed for this kind of research, a two-level system of models was proposed [19]. A methodological approach that rests on a multi-level hierarchy of energy optimization studies was used to coordinate the models of different levels of hierarchy in the considered studies. The main problems to be solved and relations between the models are presented in Fig. 2.

In this approach, the upper-level models are constructed by adequate aggregation of the lower-level models. At the same time, the lower-level models are simulation models of energy systems that are designed to analyze the development options of the energy systems, estimate their state and identify "bottlenecks" under various operating conditions. The aggregated solutions found using the upper-level models are transferred to the lower-level models and used by them as boundaries within which a detailed solution is sought.

The upper level of the hierarchy is a system of models for research aimed at assessing the state of the energy sector in case of possible disturbances and their impact on the fuel and energy supply to consumers from the energy security perspective [20]. These models are interconnected by balance and technological (structural) relationships but differ in the duration of the considered time interval, Fig. 3:

- a model for estimating the current state of the energy sector under normal and emergency operating conditions;
- a model for optimizing the territorial-production structure of the energy sector (based on the adopted energy development strategies given the possibility of emergencies).

In the models used, the territory of the country is presented in detail with the emphasis on federal districts and federal subjects of the Russian Federation. The industry-specific energy systems including backup facilities are presented with a sufficient degree of detail. The models are designed to indicate seasonal unevenness and provide yearly, quarterly, and daily consideration. They are also aimed at determining the directions and scales of the optimal energy development (given structural redundancy in the form of capacity reserves, fuel reserves, and the possibilities of interchangeability of fuel and energy resources), the optimal distribution of energy resources consumed, and the shortage of fuel and energy resources at consumers. The objective function includes not only the costs of energy development but also the fines for possible energy undersupply to consumers.

Mathematically, the problem of the optimization of fuel and energy balances in the Russian regions under possible disturbances, which is solved using the indicated models, is a classical linear programming problem. Conceptually, the approach is based on the territorial-production model of the energy sector with the blocks of electric power-, heat-, gas-, coal supply, and oil refining (fuel oil supply).

Formalized constraints of the above optimization problem are written as a system of linear equations and inequalities:

$$S_u + AX - \sum_{t=1}^{T} Y^t - \sum_{h=1}^{H} S_k^h = 0 \qquad (1)$$

$$0 \le X \le D \qquad (2)$$

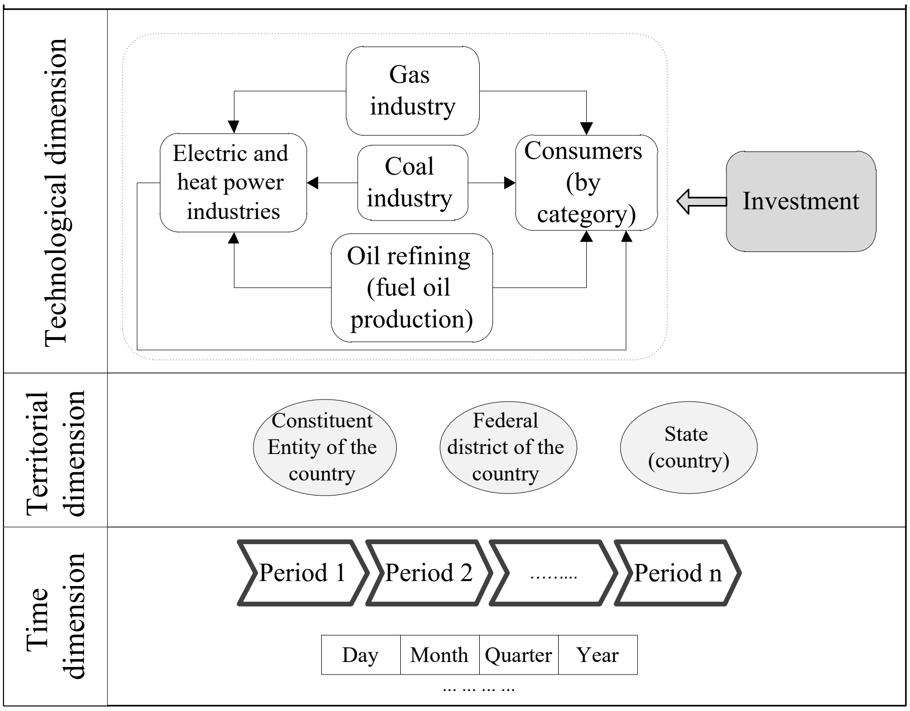

Fig. 3. The structure of the energy sector model.

$$0 \le Y^t \le R \quad (3)$$

$$0 \le S_k^h \le \overline{S^h} \quad (4)$$

$$\sum_{h=1}^{H} \overline{S}^h \le S \quad (5)$$

where t is consumer categories; h is reserve categories; X is the desired vector characterizing the intensity of the use of energy facilities (production, processing, conversion, transportation of energy resources); Y^t is the desired vector characterizing the consumption of individual fuel and energy types by certain categories of consumers (t); $S^h{}_k$ is the desired vector characterizing the volumes of fuel reserves of a considered category (h) at the end of the studied period; $S_н$ is a specified vector with its components equal to the initial levels of energy reserves; A is a matrix of input-output ratio of production (mining, processing, conversion) and transmission of certain types of fuel and energy; D is a vector determining technically feasible intensities of using individual process methods; R^t is a vector with components equal to the volumes of specified consumption of individual fuel and energy types by certain categories of consumers; $\overline{S}^h$ is a vector whose components reflect the standard volume of reserves of category h; S is a vector with components equal to the capacity of storage of a given energy resource.

The objective function has the following form:

$$(C,x)+\sum_{t=1}^{T}(r^t,g^t)+\sum_{h=1}^{H}(q^h,\overline{S}^h-S_k^h) \to \min \quad (6)$$

The first component of the objective function reflects the costs associated with the operation of the energy sector industries. Here C is the vector of unit costs for individual methods of operation of existing, reconstructed or modernized, and newly constructed energy facilities.

The second component is the damage from the shortage of each type of fuel and energy resources for each considered consumer category. Energy shortage (g^t) for the consumer of category t corresponds to the difference (R^t — Y^t). The magnitude of non-accumulation of energy reserves g^h corresponds to the difference $\overline{S}^h - S_k^h$. Vectors r^t and q^h consist of components conventionally called "specific damages". To minimize such damages, the model uses a scale of priority in satisfying the demand for certain fuel and energy types of consumers of the considered categories. The third component is similar to the second one and corresponds to the damages from the non-accumulation of reserves.

An analysis of the optimization calculation results for the considered situation enables us to determine:

- the value of shortage of certain types of fuel and energy resources for the considered categories of consumers as the value of discrepancy between the given demand and the possibility of supplying this type of energy resource;
- the values of a change in the transfer capability of energy transmission tie lines;
- rational volumes of utilization of production capacities of energy facilities and distribution of certain types of energy resources by consumer categories (the basis for choosing rational values are dual estimates, which are a system of interrelated specific economic indicators of the costs of providing additional demand for each type of fuel and energy resource).

The lower level of the hierarchy is represented by sectoral models [13-16], which make it possible to assess the potential capabilities of gas, oil, and oil product systems, and also the capabilities of the electric power system to satisfy consumers with appropriate energy resources under various operating conditions, including normal and emergency ones. The major principle of the models of the Unified oil and oil product system (UOS) and the Unified Gas Supply System (UGSS) of Russia is shown below in this section. The model of the electric power industry operation has its specific features and is presented below.

The study on the UOS and the UGSS survivability involves solving the linear programming problem in a network formulation and using the simulation flow models of the corresponding industries. In addition to the production and transport blocks, the models include the blocks of gas, oil and oil products consumption. The main consumers of the considered energy resources are represented by regions; large industrial hubs; and importing countries. There are 90 territorial units in total.

The model for assessing the production capabilities of the unified oil and oil product system under extreme situations is presented in detail in [13]. The UOS is understood as both the oil system and the oil product system. The two «related» systems are integrated through oil refining facilities. It is assumed that the production capabilities of system facilities depend on the availability of resources, and the loss of some quantity of any of the resources leads to a decrease in the production capabilities of the facility. Mathematically, the UOS is represented by a network that changes in time and as a result of a disturbance. The nodes of the network contain the entities involved in production, conversion, and consumption of material flows that implement material relations between the facilities. When estimating the state of a system after disturbance, the criterion for the optimality of the flow distribution is the minimum energy shortage for the consumer at the minimum costs of energy delivery to the consumer. In other words, the problem of the flow distribution in the system is solved to maximize the supply of energy to consumers, i.e. the problem is formalized as the maximum flow problem [21]. Two dummy nodes are added to the graph simulating the oil and oil product system: O is the total source, S is the total sink. In this case, additional sections are also introduced to connect node O with all sources and all consumers with node S. Mathematically the problem is written as follows:

$$\text{Max } f \quad (7)$$

subject to

$$\sum_{i\in N_j^+} x_{ij} - \sum_{i\in N_j^-} x_{ji} = \begin{cases} -f, \ j=O \\ 0, \ j \neq O,S \\ f, \ j=S \end{cases} \quad (8)$$

$$0 \leq x_{ij} \leq d_{ij}, \text{ for all } (i, j) \quad (9)$$

Here N_j^+ is a subset of arcs entering node *j*; N_j^- is a subset of arcs outgoing from node *j*; *f* is the value of the total flow throughout the network; x_{ij} is a flow in the arc (*i, j*); d_{ij} are constraints on the flow in the arc (*i, j*).

The maximum flow problem (7)-(9) generally has a non-unique solution. The next step is to solve the problem of the maximum flow at minimum cost, i.e. the cost functional is minimized:

$$\sum_{(i,j)} C_{ij} x_{ij} \rightarrow \min \quad (10)$$

where C_{ij} is the price or specific costs of energy transportation.

The models define the networks of main oil pipelines and main oil product pipelines; and the network of discrete transport of oil and oil products. The specificity of the UOS study is that it is necessary to find out the production capabilities of the system on three interrelated graphs (oil, light oil products, and fuel oil). This requires two stages of the research. Stage 1 suggests solving the problem of minimizing the total shortage in the oil system, given the oil balance at the network nodes, constraints on the transmission capacity of arcs and production capabilities of sources (fields) and consumers (refineries, export points). Stage 2 is aimed at solving a similar problem in the oil product system (sources are refineries and oil product import points; consumers are federal subjects of the Russian Federation, large industrial centers and points of export).

The comprehensive approach to solving the stated problems along the entire UOS process flow from oil production to oil product consumption, which is implemented in the model, provides a general assessment of the production capabilities of the entire system under corresponding disturbances in the industry.

The model for assessing the production capabilities of the UGSS under various kinds of disturbances [14] is considered as a combination of three subsystems: gas sources, main transmission network, and consumers. The listed facilities also include underground gas storages (UGS), which, depending on the situation, play the role of either consumers or sources. During the year when gas demand is lower than the average annual, gas from the system is injected into the UGS, while in the opposite case (mainly during heating period), gas is withdrawn from UGS to the system to compensate for the seasonal non-uniformity of its consumption. To solve this problem, as in the case of the UOS, linear programming tool is used in a network formulation. Its application makes it possible to determine the optimal volumes of natural gas resource to provide its supply to the consumer while minimizing the costs of gas production, transmission, and withdrawal from underground storage facilities. The solutions to the problem are the values of gas shortage at the consumption nodes.

The calculation results obtained using the industry-specific models serve as input data for the energy sector models whose output can be used to comprehensively assess the possibilities for the industries and energy sector to cope with the considered situation and serve as the basis for the formulation of the energy security requirements. Experimental calculations using a two-level system of models were mainly carried out to assess the consequences of the emergencies in the industry-specific energy systems and to identify directions for energy development from the perspective of energy security. An example of such research can be an analysis of the situation with the disconnection of a major intersection of gas pipelines in the north of the Urals Federal District. As calculations show, a relative gas shortage throughout the country due to this disconnection can reach 14% in the days of the accident. The consumers of the North-Western (37 % gas shortage) and Central (21% gas shortage) Federal Districts are most likely to suffer most. An analysis of the results obtained with the upper-level model (the level of the energy sector) showed that given the possibilities of replacing gas with heating oil and using the reserves in the industry-specific energy systems, gas shortages throughout the country in this situation can be reduced to 4.5% of the needs during the specified period. The fuel oil shortage will be 1.6%. In general, this emergency may cause a relative shortage of fuel and energy resources for the consumer in the amount of 3% of the total quarterly demand for them.

VI. Models of electric power system operation to determine power and electricity shortage in case of the energy security threat occurrence

The energy security factor is extremely important to make control decisions in the electric power industry. It is, however, difficult to factor it in because its general and economic assessment is problematic. The difficulty lies in the fact that the effect of the same measure intended to ensure the security of a system facility or an entire electric power system can differ for different electric power systems and even for different conditions of its use within one electric power system. This effect depends on where in the system the measure is applied, the time of its application and, most importantly, on technical and economic characteristics of the system where the measure is taken. It can be concluded that to correctly assess the effectiveness of the proposed measure while managing the expansion or operation of power system or its facilities in terms of energy security, one should consider the operation of the entire electric power system and, if possible, within the national and regional economy. A local assessment of this effect can lead to wrong conclusions about the feasibility of a particular measure.

One of the most difficult tasks, in this case, is to reliably quantify the level of energy security itself, since this requires laborious calculations using optimization methods and models, load flow calculations, etc. As already noted, one of the critical infrastructures that impacts on energy security is the electric power system. Given the specificity of the electric power system operation, which consists in simultaneous production, transmission, distribution, and consumption of electric energy and power, the occurrence of threats to energy supply has an instant effect on electricity consumers.

The spatial and temporal decomposition of the problems of the energy security research dictates the conditions for hierarchical construction of the models. The general trend in the construction of the electric power system models corresponds to the following principles: the closer the horizon of consideration of the power system operation to the present date, the more detailed presentation of the model is required; the larger the electric power system, the more aggregated its parameters should be. Modeling of electric power systems for energy security studies is performed in the following sequence:

4. Form a set of input data. The input data in the general case may include the topology of the design scheme of electric power system; values of available generation capacities; values of transfer capabilities of power lines included in the inter-zone tie lines; data on hourly load curves in the electric power system zones; characteristics of planned maintenance schedules for energy equipment of electric power systems (since disturbances in the system operation can occur at any time, it is necessary to sufficiently accurately reflect the actual operating conditions of the power system, given planned maintenance of equipment as well).
5. Build a scenario for the case of a disturbance.
6. Model operating conditions of an electric power system. In this case, each condition characterizes the operation of the electric power system for one hour.
7. Determine electricity and power shortages due to the disturbance.

The model [22] can be used to model the electric power system operating conditions for the energy security study. At the same time, it is necessary to minimize the power shortage arising in the electric power system due to the energy security threat occurrence:

$$\sum_{i=1}^{I}(\bar{y}_i - y_i) \rightarrow min, \tag{11}$$

Given the balance constraints

$$x_i - y_i + \sum_{j=1}^{J}(1 - a_{ij}z_{ji})z_{ji} - \sum_{j=1}^{J} z_{ij} = 0, i - 1, \dots, I, j = 1, \dots, J, i \neq j, \tag{12}$$

and linear inequality constraints on variables

$$0 \le y_i \le \bar{y}_i, i = 1, \dots, I, \tag{13}$$

$$0 \le x_i \le \bar{x}_i, i = 1, \dots, I, \tag{14}$$

$$z_{ij} \le \bar{z}_{ij}, z_{ji} \le \bar{z}_{ji}, i = 1, \dots, I, j = 1, \dots, J, \tag{15}$$

$$y_i \ge 0, x_i \ge 0, z_{ij} \ge 0, z_{ji} \ge 0, i = 1, \dots, I, j = 1, \dots, J, i \neq j \tag{16}$$

where: $\bar{y}_i$ is the value of load maximum at a node of electric power system, MW (depending on electric power system aggregation, a node can be represented by the buses of the

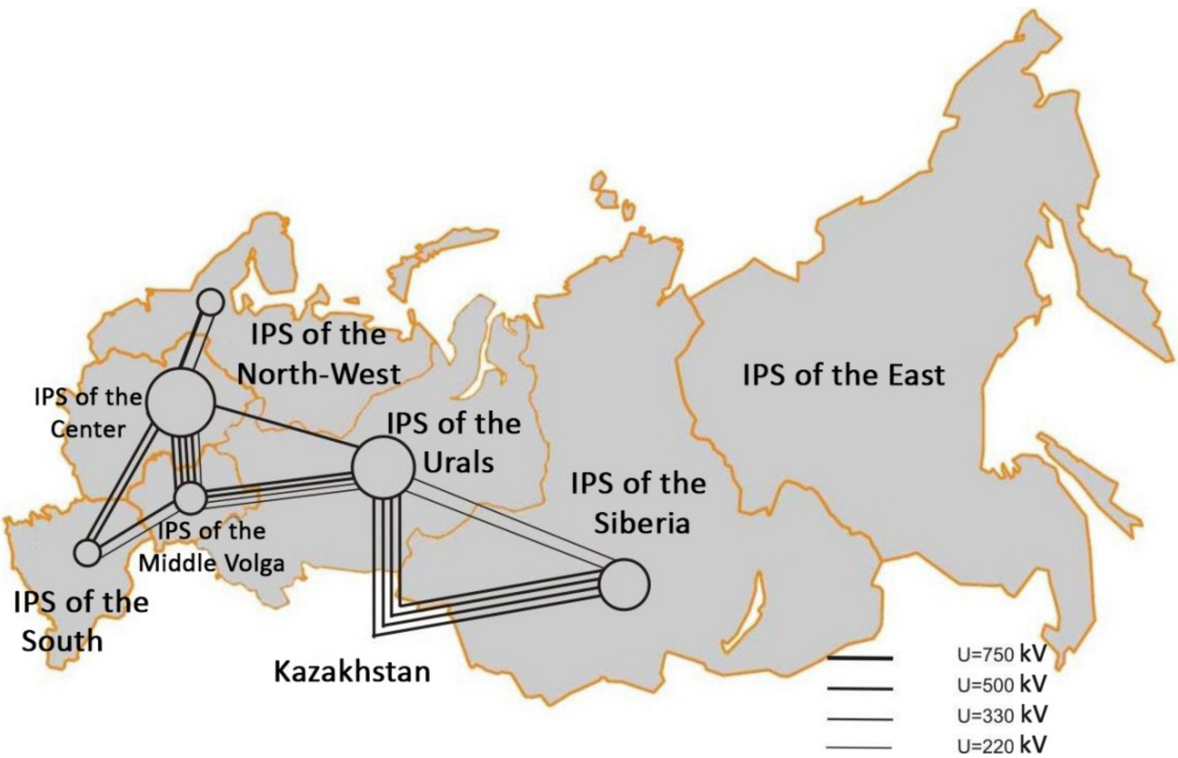

Fig. 4. Representation of Russia's unified power system for long-term energy security study.

substation and electric power plant or an area, including part of the electric power system with a set of substations and electric power plants); y_i is load covered at node i, MW; $\overline{x}_i$ is available generating capacity at node i, MW; x_i is capacity utilized at node i, MW; $\overline{z}_{ij}$ is transfer capability of tie-line between nodes i and j, MW; $\overline{z}_{ij}$ is transfer capability of tie-line between nodes j *and* i, MW; z_{ij} is power flow from node i to node j, MW; z_{ij} is power flow from node j to node i, MW; a_{ij} is coefficients of specific losses of power when transmitted from node i to node j.

In this problem, the balance is made up only for active power, but the statement of this problem with quadratic power transmission losses is a fairly accurate approximation to the balance of active and reactive powers [23].

As already noted, there can be different representations of electric power systems depending on modeling conditions. In the case of a long-term (15-20 years) modeling of an electric power system of a country (e.g. Russia) for the study of energy security, for example, to develop an energy strategy, a national power system (e.g. the unified power system of Russia) can be aggregated according to the interconnected power systems (Fig. 4).

For a horizon of the development planning reduced to short-term or medium-term periods of up to 10 years, the studies of energy security can be based on the representation of the unified power system of Russia where the zone can be represented by the constituent entity of the Russian Federation. Figure 5 shows such a model.

The electric power systems can be divided into zones according to other criteria, for example, the system operator of electric power system controls the cutsets that limit power transmission within the UES of Russia. Thus, the partition can be done according to these controlled cutsets, and then the number of zones in Russia's UES may remain the same as when the system is divided into zones along the borders of the constituent entities but the borders can shift. As to the regional aspect of the EPS modeling for the energy security study, the regional energy system model can be based on the full topology of the power system, the zones can be represented by load substations and power plants, and internal power lines can act as inter-zone tie lines. Depending on the structure of the electric power system and the specific features of its operation, the level of its stability also changes. Some disturbances in different power systems can lead to a cascading development of the emergency. In model (11) – (16), this situation is not considered. In this case, the occurrence of this threat and its consequences should be factored in by the models aimed at assessing the dynamic stability of the electric power system and the development of cascading failures.

VII. Conclusion

The system of mathematical models employed in the study into the national and regional energy security is largely based on mathematical models designed to study reliability. Moreover, the hierarchy of models in the study of energy security today is considered in terms of two main aspects:

- spatial – from regions and aggregated centers of energy consumption to federal entities at the level of districts, countries, their unions and regions of the world;
- structural – covering the whole structure of the energy economy: from industry-specific energy facilities, included in the unified production and functional complex, and the links between them to large-scale (federal and interstate) technologically connected

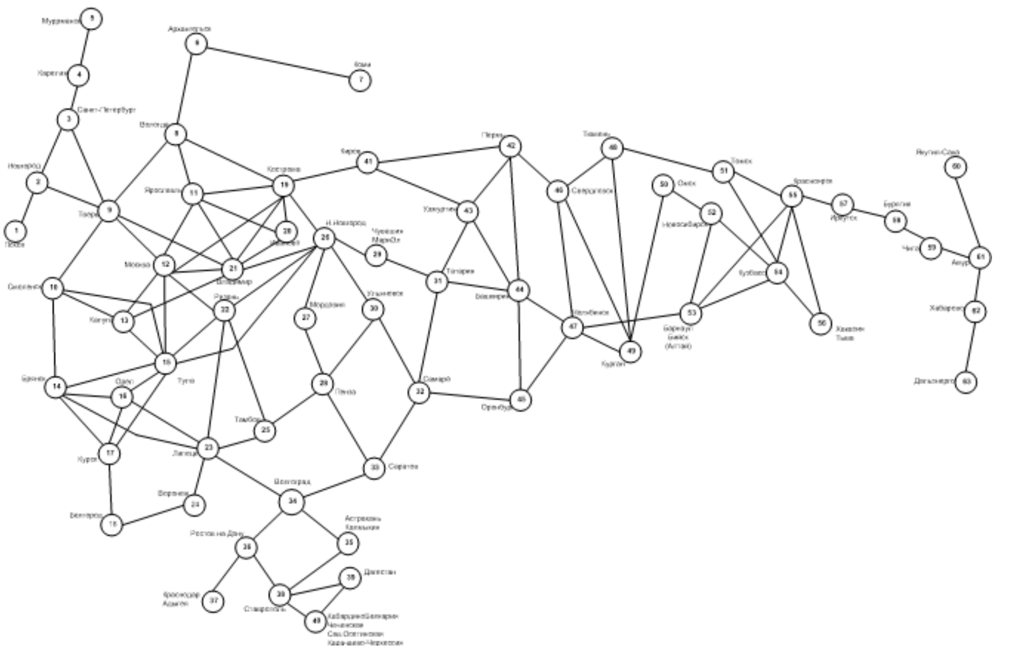

Fig. 5. Representation of Russia's unified power system for the medium- and short-term planning horizon in the energy security study.

energy systems and further to unified energy sectors of countries and regions of the world, in which industry-specific energy systems are interconnected.

This paper demonstrates the principles of hierarchical modeling on the example of the main technologically connected large-scale energy systems including a unified oil and oil product supply system; a unified gas supply system; and a unified power system of the country. The findings indicate that individual regional energy systems can also be studied in terms of the energy security of corresponding regions using the principles of hierarchical modeling, both in spatial and structural dimensions.

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