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Generalized Technology of Hierarchical Modeling of Complex Energy Systems

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***Abstract* — This study aims at investigating the technology of hierarchical modeling of large energy systems when substantiating their development and control over their operation. To build the hierarchy of models of an energy system, we rely on the property of heterogeneity of the structure of complex systems. As a proof of concept of the technology, we present a two-level hierarchy of models employed for solving the problem of substantiating the development of the Unified Energy System of Russia.**

***Index Terms* — Large energy systems, hierarchical technology, expansion, operation.**

I. INTRODUCTION

Modern large organizational and engineering systems, that include energy systems have a complex heterogeneous structure, are known to be multi-dimensional, develop and operate under uncertainty of external conditions alongside the multi-criteria nature of the process of decision-making due to the presence of various preferences that often proof contradictory.

The structural heterogeneity is a fundamental feature of large systems. To a large extent, it determines the nature of the system's behavior and requirements for its development. The structural heterogeneity manifests itself through the presence of bottlenecks in the system (that is, limited throughput capacity between its nodes), as a result of which a large system represents a set of highly coherent subsystems (in terms of strong links between the elements of the subsystem) and loose couplings of the subsystems. One has to identify the structural heterogeneity of large systems, quantify its characteristics, take into account these characteristics in the process of modeling, analysis, and substantiation of the development of large systems and control over their operation.

Uncertainty of external conditions as applied to the operation of a large system, and, even more so, to its development predetermines the multivariate nature of possible decisions on development and control over operation of the system. Multicriteriality, especially when there are different, oftentimes contradictory, preferences held by the subjects of relations, significantly complicates the process of choosing the most preferable solutions from the set of available alternatives.

Due to the complexity and multi-dimensionality of large systems, the heterogeneity of their structure, the multivariate and multicriteria nature of the rational choice, the availability of different preferences held by the subjects of relations when making decisions, the initial statement of the problem of substantiation of the development and/or control over operation of a large system in the form of a general operations research problem proves insoluble for all practical purposes. In order to overcome this fundamental difficulty, in what follows we will investigate the hierarchical technology as a hierarchy of interrelated mathematical models (models of the object) and criteria-preference relations used for making the rational choice in favor of some solutions (models of operations), as well as various features inherent in the application of this hierarchical technology. To be more definite in our investigation of the hierarchical technology, we will stipulate the latter as applied to the problems of substantiation of the development of large energy systems with the electric power industry and electric power systems serving as our guiding examples. The reason for this being the unparalleled complexity of the problem that is instrumental in manifesting, to the largest extent possible, the diversity and inconsistency of external conditions, if compared to the problem of control over the operation of such systems [1, 2].

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II. HIERARCHICAL TECHNOLOGY

The problem of substantiation of the development of a large energy system consists, firstly, in the choice of the most preferable, in terms of a set of criteria, of its variants out of a set of given alternatives and, secondly, in the identification of the most preferable parameters of elements (objects) of the system for the chosen variant. Building a set of alternatives (variants) that represent as a whole a given area of uncertainty of external conditions of development of the system, is a challenging problem of its own that does not easily lend itself to formalization and hence is not considered here. Each variant of the system has a corresponding well-defined set of parameters of elements that is the most rational (preferable) from the point of view of the set of the pre-defined criteria.

Let $X = \{X_1, X_2, ...\}$ be a set of alternatives available for making a choice (variants of the system); $x_i=\{x_{i1},x_{i2},\dots\}$ — a set of parameters for variant i of the system; $PR = \{PR_1, PR_2, ...\}$ a set of preference relations for making a choice. Then the problem of rational choice in a rather general form can be formulated as

$$X_o = opt(X,\ \Phi);\ x_o=opt(x,\ X_o,\ PR), \tag{1}$$

where *opt* means the above preference, rationality or, in a narrower sense, optimality of choice under a set of given criteria.

Let's introduce $m + 1$ levels of the hierarchical description of the problem and define a set of preference relations at each level, as well as their interrelation between the levels, as follows:

$$PR^m \to PR^{m-1} = V_{m-1}\left(PR^m\right) \to \ldots \to PR^0 = V_0\left(PR^1\right) \tag{2}$$

The arrows in (2) indicate a change in the set of preference relations from being those of the upper level of description to those of the lower one, their modification, and possible detailing according to the composition and content of subproblems at each level of the hierarchy, preferability of criteria, the composition of key parameters (those subject to optimization), etc. The generalized functional relations at each level of the hierarchy in (2) reflect the continuity of the composition of the criteria in refining the choice at the next lower level with respect to the upper level.

It should be pointed out that in many cases when solving real-life problems the functional relations introduced in (2) are not formalized, and are understood intuitively, as it will be seen from what follows.

It is necessary to introduce a related set of descriptions of the structure and states of the system, its parameters, in other words - the hierarchy of models of the system in the following form:

$$x^0 \to x^1 = opt\, f_1\left(x^0, PR^1\right) \to \ldots \to x^m = opt\, f_m\left(x^{m-1}, PR^m\right) \tag{3}$$

To follow the arrows in (3) means to have the sequential step-by-step aggregation of the description (model) of the system, which can be carried out at each level, in general, in the most rational (optimal) way in a certain sense. Here, it is assumed that the structure and parameters of the model of the system at the lower (zero) level of the hierarchy are known. Expression (3) also reflects the fact that, in addition to aggregation at each step of the model of the system, the model of the operation, represented by the set of preferences (criteria) assumed at each step in accordance with (2), in general, gets modified.

Let us clarify the above statement that the aggregation of the model of the system at each level of the hierarchy can (should be) carried out in the most rational way. It is logically sound to relate this rationality to heterogeneity of the system structure and to aggregate highly coherent subsystems, leaving as is loose couplings of subsystems. This is well-justified, since loose coupling (sections) in almost all cases are usually the "culprits" of emergency situations as a result of overloading of these links during changes in flow distribution in the system, violations of system stability, and unfolding of emergency processes, etc. In fact, one of the key problems of the system development is to strengthen the considered loose sections in its structure, so it is expedient to leave loose couplings and sections intact during aggregation.

In fact, transformations (2) and (3) serve as preliminary in the overall process of hierarchical modeling and studies of large systems. Subsequent actions represent a sequence of subproblems for choosing solutions, which can be formalized as follows:

$$\begin{gathered}
x_o^m = opt(f_m'(x^m, PR^m);\ F_m(X, PR^m)) \\
\downarrow \\
x_o^{m-1} = opt\big(f_{m-1}'(x_o^m, PR^{m-1});\ F_{m-1}(X^m, PR^{m-1})\big), \\
\downarrow \\
\vdots \\
\downarrow \\
x_o^0 = opt(f_0', (x_o^1, PR^0);\ F_0(X^1, PR^0)
\end{gathered} \tag{4}$$

Here F stands for the transformation of a set of alternatives when solving, while moving successively from the top level of hierarchy to the bottom one, the subproblems of the overall hierarchical problem of a choice of solutions. In the process of "moving" the top-down way in (4), some alternatives will be ruled out as inefficient, that being said additional alternatives can emerge so as to make it appropriate to include them in the list of alternatives to be considered. In general, this transformation of the set of alternatives can be written down as follows:

$$X^m = X \to X^{m-1} = F_{m-1}(X^m) \to \ldots \to X^o = F_o(X^1). \tag{5}$$

In the case of sequential solving of subproblems of choice in accordance with (4), to transform the solution obtained at level $m - i$, the next lower level $m - i - 1$ will require the operation of disaggregation of the model of the system. The sequence of such disaggregation operations in general can be written down as follows:

$$\begin{gathered}
x^m \to x^{m-1} = opt\big(f_{m-1}'(x^m, PR^{m-1})\big) \to \\
\to \cdots \to x^0 = opt\big(f_0'(x^1, PR^0)\big).
\end{gathered} \tag{6}$$

Here the *opt* operation has the same meaning as in (3). The "prime" superscript in the functional relation marks the disaggregation operation of the model as an inverse of aggregation. Subscript o in ratios (4) marks the optimality of the set of system parameters obtained at the next level of the hierarchy as per the set of criteria considered at this level.

It should be noted that in the process of solving the hierarchy of subproblems of choice in accordance with (4) it may be necessary to adjust the composition of the set of preference relations at some level of the hierarchy, which can certainly be done.

The solution of the initial problem (1) in the presented hierarchical statement will be X_o^0 and x_o^0 that, in general, are different from X_0 and x_0 in accordance with (1). Here, superscript 0 indicates the lowest level of the hierarchical problem, while the lower index *o* marks the optimality of the obtained solution. It should be noted that the choice of X_o^0 and x_o^0 is more justified, because, in general, the integral hierarchical representation of the initial problem appears to be richer in the sense of detailing of the description of the model of the system and the model of the operation, than when solving the problem directly in the form of (1).

III. CASE STUDY OF APPLYING THE HIERARCHICAL TECHNOLOGY

The task of substantiation of the long-term development of the Unified Energy System (UES) of Russia, consisting in the choice of the structure of generating equipment from a number of types of units, the location of newly added units and power plants, the structure and parameters of the main power grid, taking into account the requirements of reliability of power supply to consumers, the acceptability of normal, post-emergency, and repair modes of the UES, ensuring the stability of the system in case of disturbances.

Taking into account the uncertainty of the external conditions of the UES development, let us assume that we have formulated two alternative variants of the system, i.e. $X = \{X_1, X_2\}$. We will consider two levels of the description of the problem, to this end at the upper level we will solve the subproblem of choosing the structure of generating capacity units and their location, while at the lower level it will be the subproblem of choosing the structure and parameters of the main power grid of the UES. Taking this into account, at the top level, when establishing preference relations we will assume as criteria capital expenditures for newly added generation equipment and the volume of emissions into the environment due to the operation of this equipment in the form of ash, nitrogen and sulfur oxides, etc. At the lower level, we will consider as criteria the capital expenditures for newly added power lines, the levels of reliability of power supply to consumers and the stability of the UES. Let us set the acceptability requirements for the operating modes when formulating the description (model) of the UES at the lower level.

Thus, we have the following sets of preference relations at the assumed two levels of the problem description:

$$PR^1 = \{PR^1_{cg}, PR^1_e\};\ PR^0 = \{PR^0_{cn}, PR^0_r, PR^0_s\} \tag{7}$$

where the indices $"cg"$ and $"cn"$ correspond to capital expenditures for generation capacity and the grid; while $"e"$, $"r"$, $"s"$ corresponds to criteria of environmental impact, reliability, and sustainability. The interrelation between the sets of criteria at the two considered levels of the problem description is provided through capital expenditures, since $PR_c = PR_{cg} + PR_{cn}$ and it is usually necessary to find the minimum of PR_c, while the ratio between its components can be adjusted in the transition from the top-level subproblem to the entire set of the lower level subproblems by refining the requirements for generation, taking into account the introduction of additional power lines, the need to ensure reliability and stability.

The UES models at the two levels of the problem description under consideration are as follows. At the lower level, in order to assess the acceptability of operating modes and to analyze the stability of the system, we will consider a detailed description of steady-state modes and transients in the UES in the generally accepted form, i.e. with the presentation of real or aggregated power lines, transformers, power plants and load nodes with their parameters used for such a description on the basis of the system of equations of nodal voltages. In order to analyze the reliability of electric power supply to consumers, as well as to solve the top-level subproblem, we will form an aggregate description of the UES in the form of a set of large nodes representing integrated energy systems or some other composition of subsystems, that have inherent couplings that do not limit power exchanges and therefore are not taken into account, while the aggregated nodes (subsystems) are linked to each other by some aggregated links with limited throughput capacity.

A provisional illustration of the described two-level modeling of the UES of Russia is presented in Fig. 1. Here, the conventional level of representation of the model reflects the "administrative division" principle of establishing aggregated nodes (the nodes correspond to integrated energy systems), while the refined level takes into account the availability of loose coupling within such integrated energy systems.

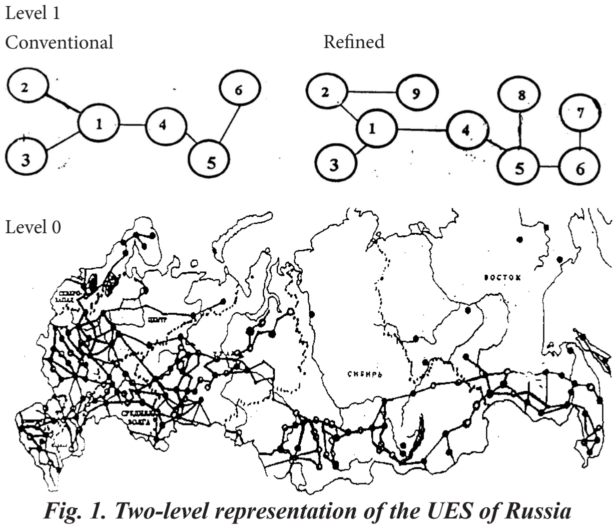

Fig. 1. Two-level representation of the UES of Russia

Thus, the upper level uses an aggregated model of the UES, while the lower level uses an extended set of models that includes the same aggregated model as well as more detailed models.

It is easy then to write down a sequence of subproblems of type (4) formally following the proposed hierarchical choice procedure, but with respect to their content the composition of these subproblems, taking into account the above clarifications, is quite clear and we will not overload the presentation with further technicalities.

As a result of the solution of a hierarchical sequence of subproblems, one of the two alternative variants of the UES will be adopted and the parameters that are optimal in terms of the assumed criteria will be determined. The special aspects of multi-criteria choice are omitted from this presentation.

References

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