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Hierarchical Modeling of Electric Power System Expansion by AnyLogic Simulation Software

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***Abstract* - The paper presents a formalized interpretation of a hierarchical technology for expansion planning of large electric power system (EPS) and demonstrates the main features and characteristics of AnyLogic simulation software to study the problem of hierarchical modeling of EPS expansion.**

***Index Terms* - Electric Power System, Expansion Planning, Hierarchical Technology, AnyLogic Simulation Software.**

I. Introduction

Modern electric power systems (EPSs) are complex and territorially extended systems with an inhomogeneous structure of the electric networks. The complexity and multidimensionality of the modern EPSs, their multivariant and multicriteria character, as well as different preferences when choosing the decisions make it hardly possible to solve the problem of EPS expansion planning in the form of a general operation research problem.

A formalized hierarchic technology of solving the problem was proposed in [1] and further unfolded in [2]. The technology was based on aggregation – disaggregation of the EPS models, transformation of preference relations at choice, transformation of a set of alternatives from one hierarchy level to another. The hierarchy of the interrelated EPS models is based on the analysis of the structural heterogeneity of the system [3].

Design, development and analysis of the EPS models in an adequate simulation environment may considerably contribute to the study of the EPS controls and evolution. This environment has to support hierarchical model representation, reuse of model components, possibility to carry out a wide spectrum of experiments of the “what-if” type, a possibility to change model parameters and even model structure during experiments. Another important requirement to the simulation environment where it is possible to effectively develop and analyze EPS models is an ability to develop on the same platform models with different levels of resolution, a possibility of different modeling style and paradigms, a support of hierarchical approach to model development.

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All these requirements are met by the AnyLogic simulation platform, which is modern simulation software developed at St. Petersburg, Russia. It has been approved as a new generation simulation tool by many companies such as General Electric, Boeing Simulation Modeling Services, etc. AnyLogic is a forward-looking simulation sotware which uses object-oriented approach, Unified Modeling Language visual notation, supports agent-based modeling as well as other modeling approaches, provides rich animation of model execution and handles randomness. AnyLogic allows one to study complex system model in a random environment and to find optimal operational decisions in system control based on risk analysis. All this enables us to consider this software as a unique platform for development of hierarchical models of EPS expansion [4, 5].

The paper demonstrates the main features and characteristics of AnyLogic simulation environment and substantiates its use for the hierarchical modeling of EPS expansion. Besides, some examples of the EPS models developed in AnyLogic are present and results of studying the models are discussed.

II. Hierarchical Expansion Planning Technology

Current technology for large EPS expansion planning includes several groups of problem, which specify the structure and operating conditions of EPS stage by stage. For example, the first stage is determination of the necessary number and types of generation units, the second is selection of new transmission lines of the main grid, the third stage is the study of reliability and operating conditions of EPS variants, the last is determination of the principles and structure of the EPS control [1].

The approach deals with formalization of the hierarchical technology for large EPS expansion planning based on multi-level representation of the common expansion planning approach and description of relations between different levels.

Let $X = \{X_1, X_2, \ldots\}$ be a set of alternatives (system variant); $x \in X$, $X_i = \{x_{i1}, x_{i2}, \ldots\}$ - a set of system parameters; $Ц = \{Ц_1, Ц_2, \ldots\}$ - a set of preference relations when making choice can be formulated in quite a general form as

$$X_0 = opt(Ч, Ц);\ x_0 = opt(x, Ч, Ц) \qquad (1)$$

where opt means the preference, rationality or, in the narrower sense, optimality of choice though it can be any other kind of choice procedure.

The required level of detailed mathematical description of a system and the problem of choice in many practically important cases including problems of EPS planning turns out to be rather high and the initial problem of choice in form (1) appears to be practically unsolvable.

Introduce $m+1$ levels of problem description. To determine these levels let us first determine sets of preference relations at each level as

$$Ц^m \rightarrow Ц^{m-1} = \varphi_{m-1}\left(Ц^m\right) \rightarrow \ldots \rightarrow Ц^0 = \phi_0\left(Ц^1\right) \quad (2)$$

Introduce an interrelated aggregate of description of the system structure and state (its parameters), in other words, an aggregate of the system model:

$$\begin{aligned} & x^0 \rightarrow x^1 = opt\ f_1\left(x^0, Ц^1\right) \rightarrow \ldots \rightarrow x^m = \\ & = opt\ f_m\left(x^{m-1}, Ц^m\right) \end{aligned} \quad (3)$$

Introduce a sequential disaggregation of the system model along with (3) and on its basis:

$$\begin{aligned} & x^m \rightarrow x^{m-1} = opt\ f_{m-1}^{-1}\left(x^m, Ц^{m-1}\right) \rightarrow \ldots \rightarrow x^0 = \\ & = opt\ f_0^{-1}\left(x^1, Ц^0\right) \end{aligned} \quad (4)$$

Now solve the sequence of choice subproblems

$$\begin{aligned} & x_0^m = opt\left(x^m, Ц^m; X^m = X\right), \\ & x_0^{m-1} = opt\left(f_{m-1}^{-1}\left(x_0^m\right), Ц^{m-1}; F_{m-1}\left(X^m\right), Ц^{m-1}\right), \\ & \vdots \\ & x_0^0 = opt\left(f_0^{-1}\left(x_0^1\right), Ц^0; F_0\left(X^1\right), Ц^0\right) \end{aligned} \quad (5)$$

Transformation of alternatives can be written in the form

$$\begin{aligned} & X^m = X \rightarrow X^{m-1} = \\ & = F_{m-1}\left(X^m\right) \rightarrow \ldots \rightarrow X^0 = F_0\left(X^1\right) \end{aligned} \quad (6)$$

III. ANYLOGIC MODELING SOFTWARE

AnyLogic (AL) modeling environment (www.anylogic.com) is a new generation simulation tool, developed in St.Petersburg, Russia. It provides a unique virtual prototyping environment for large, challenging systems with discrete, continuous and hybrid behavior of local and distributed nature [4]. AL is based on the latest breakthroughs in modeling science and information technology made in the last decade such a object-oriented information handling, visual design, natural system specification using a hierarchical structure and hierarchical behavior representation and so forth.

The part of simulation model which represents logic of decision making and events (e.g. equipment failure or break of transmission line) should be based on conception of simulated system's states and discrete transitions between states. Transitions fire when events occur or when some specified conditions on system parameters are evaluated as true and cause state switches. Such sort of complex mixture of continuous and discrete parameters is typical for complex dynamic systems.

AL modeling environment employs an extended Unified Modeling Language to express visually system states and transitions to represent discrete-event behavior and equations to represent continuous behavior. Fig. 1 represents a typical state chart with hierarchical and simple states and transitions. Each state can be associated with a set of differential and algebraic equations to represent complex hybrid behavior of the specified component.

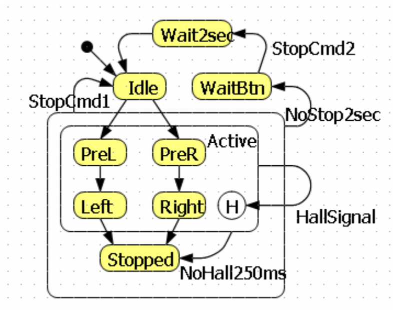

Fig.1. Representing complex behavior in AnyLogic

AL supports development models consisting of autonomous adaptive objects which one might call agents. From the computer programming view point agent-based modeling and simulation is a natural extension of object-oriented paradigm. Agents in AL are instantiations of so called "active object" which has its own structure and behavior and just represents a model component. Each agent may communicate with other agents and its environment and adapt to the environment while that is modified by external processes and other agents. While evolution individual agents change their parameters, which produces change in their actions and decisions.

Using AL the model designer can create models faster with visual, flexible, extensible and reusable active objects, standard and custom, and Java programming language. Using multiple modeling approaches and combining them one may design a more accurate model, considering all needed phenomena inside and outside the system. Besides AL has a set of analysis and optimization tools accessible directly from the modeling environment.

All this distinguishes AL as the most appropriate simulation tool for complex systems in a wide application area. AL modeling environment is a convenient means not only for simulation, it also offers a wide range of opportunities for visual representation of developed models and their parameters while execution runs.

The visual representation of AL model is mapped to Java programming language. The model is naturally open for adding Java code fragments at any level. This can be done directly in model editor. Java makes it easier to customize each model element: objects, ports, messages, timers, etc. Combined with the object-oriented modeling paradigm, this provides the unique power and flexibility in dealing with sophisticated or exotic modeling tasks.

AL offers an original technology that enables the user to rapidly create interactive animations. Animations are developed within the model editor, but they are logically separated from the model. Animations may include elementary graphical shapes as well as various types of indicators and graphs. Interactive elements such as buttons, sliders and edit boxes may be added, so the user is able to influence model behavior at runtime. There is also rich API that allows user to develop very sophisticated animations. AL animation is also 100% Java, just like the model itself, and it is displayed in the browser window in case an applet is generated from the model so executable model becomes independent of modeling tool. All inner model parameters and variables may be visualized in animation window using plots, progress bars, diagrams and text labels.

IV. Demonstration Example

Capabilities of AnyLogic Software as applied to hierarchical problem of EPS expansion planning were studied on the simplified demonstration scheme of North-Western Interconnected Electric Power System (NWIPS) as part of Unified Energy System of Russia (see Figure 2).

The equivalent scheme is represented by 6 large aggregated nodes including generation and load of aggregated areas interconnected by equivalent electric ties. The main information on aggregated nodes is given in Table I, on equivalent ties – in Table II. The equivalent ties include several real lines operating in parallel.

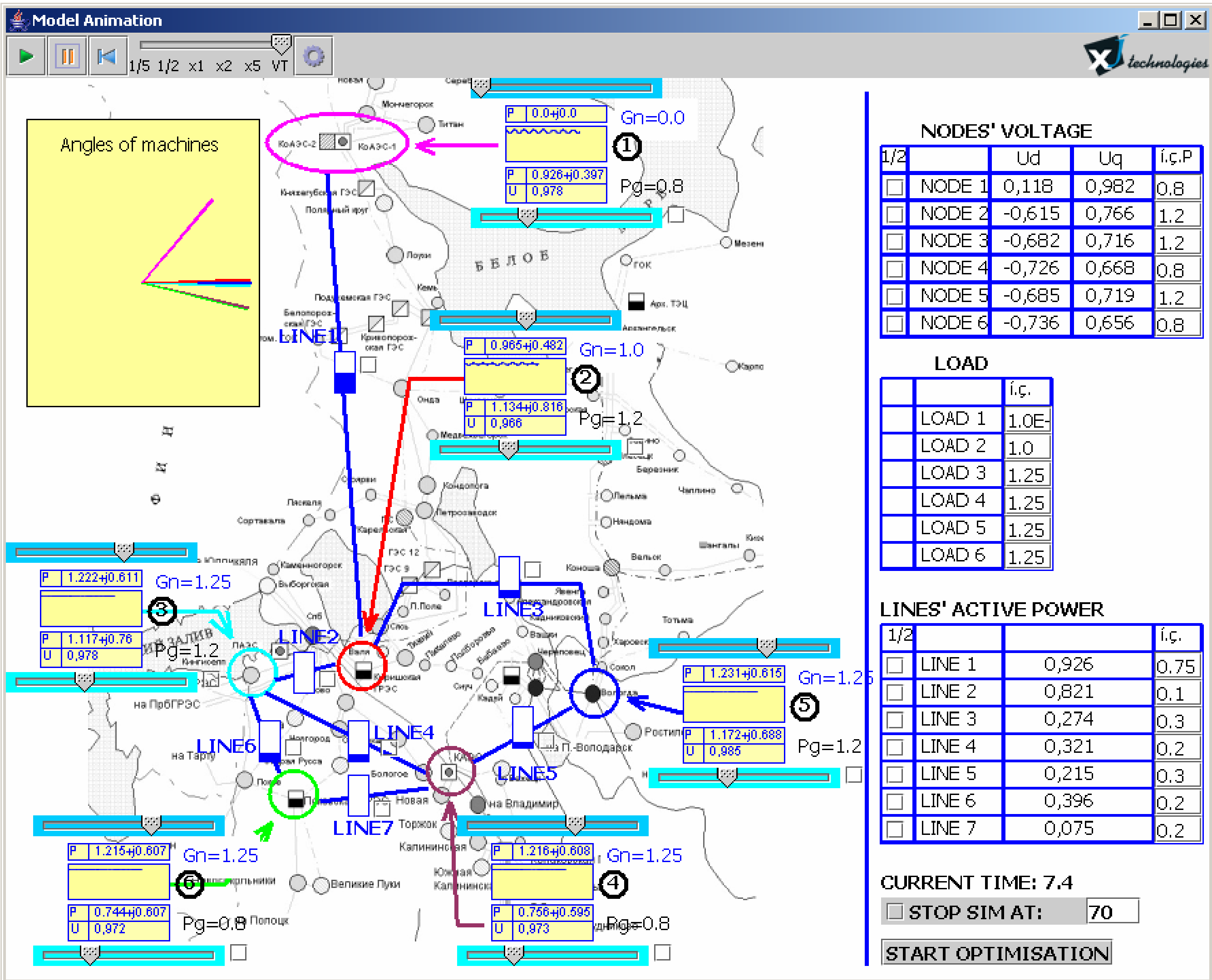

Fig.2. Representing simulation results using modeling environment AnyLogic

TABLE I
GENERATION AND LOAD IN THE NODES: INITIAL SCHEME/DESIGNED SCHEME

Node	Generation, p.u.		Load, p.u.	
	P_g	Q_g	P_l	Q_l
1	0.8/2.0	0.4/1.0	0/0.2	0/0.1
2	1.3/1.3	0.6/0.6	1.0/1.2	0.5/0.6
3	1.2/1.2	0.6/0.6	1.25/2.0	0.6/0.8
4	0.9/0.9	0.4/0.4	1.1/2.0	0.5/0.8
5	1.1/2.4	0.5/1.2	1.3/1.5	0.7/0.7
6	0.7/0.7	0.3/0.3	1.25/1.4	0.6/0.6

TABLE II. PARAMETERS OF TIE LINES: INITIAL SCHEME/DESIGNED SCHEME

Line number	Connected nodes	Imaginary impedance, p.u.
1	1-2	0.75/0.3
2	2-3	0.1/0.1
3	2-5	0.3/0.3
4	3-4	0.2/0.2
5	4-5	0.3/0.3
6	3-6	0.2/0.2
7	4-6	0.2/0.2

The system parameters given in numerator characterize its initial state. It is used to consider the problem of EPS expansion for some perspective for which the increased loads in the nodes are set (Table 1). Hierarchical consideration of the EPS expansion problem in accordance with the technology given in Chapter II includes two levels:

1) Upper level – choice and allocation of additional generation in the nodes and construction of electric ties to connect nodes thus providing power transmission from generators to consumers.
2) Lower level – check of the designed EPS performance in emergencies.

At the upper level of the problem consideration the additional generation in the EPS nodes was chosen and allocated using the tools other than AnyLogic Software.

The results are given in denominator in Table 1. Expansion of electric ties was considered as a problem of optimization by the criterion of minimum costs on additional ties. This problem was solved in a non-formalized way using AnyLogic Software interactively.

The performance of the designed EPS at the lower level of the problem consideration was checked by simulating emergency disconnection of one of the lines in each tie. The EPS transient stability at each such emergency disturbance was checked. Each equivalent generator was modeled by the Park-Gorev equations taking into account the transients in the damping loops of rotor and automatic exciting regulators similar to PSS. The loads were modeled by static voltage characteristics.

In the case of stability violation the emergency control was chosen to provide stability by disconnecting part of load on the receiving side of the tie and generation of the same magnitude on the supplying side to unload the tie. The choice of emergency control was made by solving the problem of optimal control [6].

AnyLogic Software has an advanced user interface that makes it possible to see the dynamics of the problem solution on the computer's screen. The examples of such an interface when modeling the EPS transient that was caused by the disturbance are given in Fig.2 that shows:

- Structural scheme of the EPS at issue;
- Animation of synchronous generators' rotors angles position with respect to one of the angles as a reference axe;
- Tables of EPS components state variables changing in the course of calculation;
- Diagrams of EPS components state variables changing in the course of calculation.

Figure 3 shows as an example the character of the transient of change in the generation capacity in node 1 at a sudden disconnection of generation in node 2. As is seen in Figure 3 generator in node 1 operates in an out-of-step mode with respect to the remaining part of the system. The use of emergency control stabilizes the process and prevents out-of-step conditions in the system (Fig. 4).

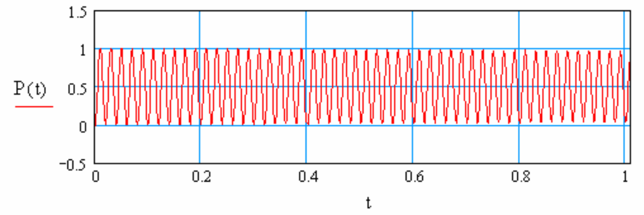

Fig. 3. Typical response to generator shedding without control action.

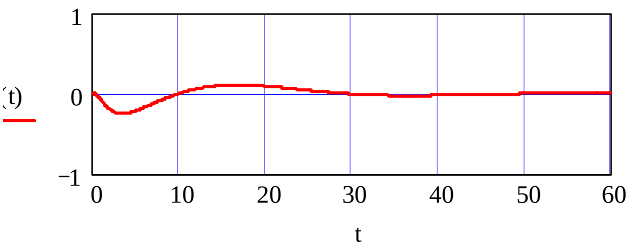

Fig. 4. Typical response to generator shedding with proposed control action system.

V. CONCLUSIONS

The demonstration example involves only very few of the AnyLogic Software capabilities. However even these are promising for using AnyLogic Sofware for solution of problems in electric power industry. Particularly attractive is the agent-based approach to modeling that is employed in AnyLogic Software. Implementation of numerous potential capabilities of AnyLogic Software is the task of further studies.

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VII. Biographies

Nikolai I. Voropai is the Director of Energy Systems Institute (Siberian Energy Institute until 1997) of the Russian Academy of Sciences, Irkutsk, Russia. He was born in Belarus in 1943. He graduated from Leningrad (St. Petersburg) Polytechnic Institute in 1966 and has been with the Siberian Energy Institute since then. N.I.Voropai received his degree of Candidate of Technical Sciences from Leningrad Polytechnic Institute in 1974, and Doctor of Technical Sciences from Siberian Energy Institute in 1990. His research interests include: modeling of power systems; operation and dynamic performance of large power interconnections; reliability, security and restoration of power systems; development of national, international and intercontinental interconnections of power systems. N.I.Voropai is a member of CIGRE, and a Senior Member of IEEE.

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Yuri G. Karpov is a Professor, Head of Distributed and Networking Department at St. Petersburg State Polytechnic University, Russia. He graduated from Leningrad Polytechnic Institute in 1965 and worked in Leningrad Polytechnic Institute since then. He received a degree of Candidate of Technical Sciences from Leningrad Polytechnic Institute in 1971, and Doctor of Technical Sciences from same Institute in 1990. The area of his scientific interests includes simulation modeling, distributed information systems, validation and verification of distributed systems. Yu.G.Karpov is a member American Mathematical Society.

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