Multilevel Modeling of Pipeline Energy Systems for Solving their Analysis and Design Problems

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***Abstract* — The complexity and scale of pipeline energy systems (PES) necessitate the use of multilevel (in terms of structure, problems, and methods) modeling for their analysis, calculation, and optimization, which are based on the theory of hydraulic circuits (THC). This theory was originally proposed at the Melentiev Energy Systems Institute, SB RAS, and since then has been undergoing further development. The use of methodological approaches to multilevel modeling described in this paper allows switching from large systems to hierarchically connected systems of lower dimensionality, that is from complex problems to simpler ones. The use of these approaches for PES analysis and development is illustrated with specific examples. The paper provides the findings of our studies on the municipal heat supply system.**

***Index Terms* — pipeline systems, analysis, design, multilevel modeling, decomposition, hierarchy, model, optimization, software package.**

I. INTRODUCTION

Modern pipeline energy systems (heat supply, water supply, oil supply, gas supply, etc.) are engineering structures that are unique with respect to their scale and complexity and that are of increasing importance for the energy, economy, industry, public utilities sector, and other spheres of life of the country and society. Solving the problems of their design, reconstruction, operation, and dispatching efficiently is impossible without relying on the appropriate methodological backbone. The theoretical basis for solving problems of design and control over operation of pipeline systems of various types and serving various purposes is the theory of hydraulic circuits (THC) originally proposed at the Melentiev Energy Systems Institute, SB RAS, and successfully undergoing further development there. This theory is the basis for modeling, calculation, evaluation, and optimization of pipeline and hydraulic systems of various types [1]. Within the framework of the THC, the problem of optimal PES design is defined so as to cover a wide range of problems and consists in finding the optimal direction for changing the structure and parameters of systems, identification and elimination of «bottlenecks», replacement of outdated technologies and equipment with new energy-efficient solutions, meeting the requirements of reliability of heat supply and controllability of systems while satisfying the physical and technical conditions of their operation and complying with constraints on operating parameters [2]. The specific feature of solving the problem of optimal PES design is that it involves the development of its own algorithm made up of subproblems (structure optimization, parameter optimization, analysis of reliability of the system, hydraulic analysis, etc.) that vary on the case by case basis as applied to the set of considered PESs, given their specific features. As a rule, it is a complex iterative computational process during which subproblems for various PESs can be solved in different orders and by employing different methods depending on the predefined goal. One of the possible algorithms for solving the problem is presented in Figure 1.

The above problems are solved for the PESs of the real-life size and complexity which is due to their multi-ring structure, availability of multiple control elements (pumping and throttle stations, regulators), and a large number of pipelines. As a result, the calculation of such PESs proves unfeasible within a reasonable amount of time. The means of overcoming the above mentioned difficulties is the application of approaches based on decomposition into simpler subproblems of PES calculation schemes or the problems that are to be solved. Decomposition is a part

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of the multilevel modeling methodology, which assumes transition from an initial complex problem to a hierarchically connected set of problems of lower dimensionality and complexity when solving problems of high dimensionality. This methodology has been successfully applied at the Melentiev Energy Systems Institute, SB RAS, to solving problems of analysis and design of PESs [3-7]. Abroad, methods based on decomposition of PES calculation models and other energy systems have been widely adopted [8-10]. High dimensionality of PESs and other energy facilities, as well as high complexity of the problems being solved, are successfully overcome by making use of approaches based on aggregation [11-13] and hierarchical modeling [14-16].

II. FUNDAMENTAL PRINCIPLES OF MULTI-LEVEL PES MODELING

Mathematical and computer modeling of PES begins with the construction of its model, which describes the configuration of the PES, the composition of its equipment, and the characteristics of the latter, the state of elements and their properties (specifications, hydraulic parameters, and boundary conditions). PESs of different types share structural and topological properties and physical laws that govern the transported medium flow [1], which allows formulating the following general statements characteristic of the methodology of their computer and mathematical modeling:

1. All PESs can be modeled as a graph whose vertices correspond to the nodes (sources, connecting nodes, consumers) while the arcs correspond to the branches (pipelines, active branches with pumping stations, pressure or flow regulators).
2. The problems of mathematical modeling of the PES share their conceptual and mathematical statements, while the methods, algorithms, and dedicated software used to solve them can be universal in their nature (that is, they do not depend on the type of the PES).
3. A computer model of the PES of a certain type can be represented as the total of a graph describing the configuration of this system and a set of graphical and mathematical models describing the properties of its elements.
4. Modern PSs of different types, as a rule, are constructed as per the hierarchical principle that allows constructing hierarchical mathematical models of these systems and to solve problems by applying multilevel modeling.

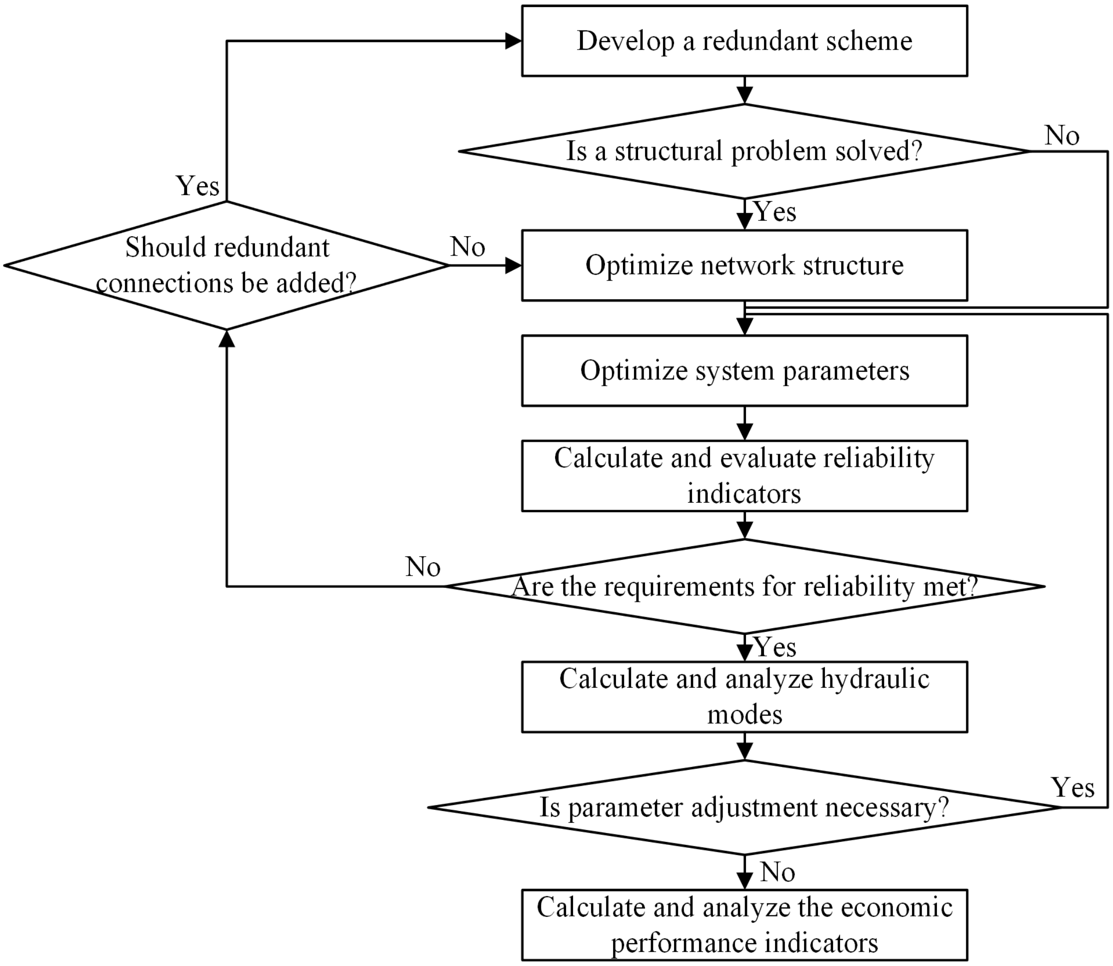

Figure 1. Algorithm for solving the PES design problems

In the case of multilevel modeling the unified model of the PES is considered as a set of hierarchically connected subsystems according to the following aspects related to the features inherent in their construction and operation:

1. Performed energy functions:
    - generation,
    - transport,
    - storage,
- consumption.
2. Sectioning of PSs according to territorial and geographical criteria.
3. The structure of the transport subsystem in the PES:
    - main networks,
    - distribution networks,
    - internal consumer networks.
4. Delimiting individual subsystems within a unified system, such as pumping and compressor stations in the network, source pumping equipment systems, supply and return main lines of heat networks, individual branches of pipelines, individual consumer systems, the distribution system of the heat transfer medium, etc.
5. Structural and topological architecture of the transport subsystem in the PES:
    - ring subnetworks,
    - tree-shaped branches.

III. Key methodological points of multilevel modeling as illustrated by the case of heat supply systems

A hierarchical model of heat supply systems (HSS) when solving the problems of control over their optimal development and operation with application of multilevel modeling allows treating the following levels individually (Figure 2):

1. HSSs in general;
2. supply and return main lines;
3. ring and tree-shaped parts (dead-end branches) of the supply and return main lines;
4. individual HSS elements (heat sources, consumers, sections, pumping stations, etc.).

The flow distribution model for each level of the HSS hierarchical model, as well as for the system as a whole, is described by the following equations:

$$Ax = G, A \epsilon R^{m \times n}, G \epsilon R^{m},$$

$$A^{T}P + H = f(s,x)$$

where A - incidence matrix of the calculation scheme; G – vector of nodal outflows and inflows of the transported medium; f – n-dimensional vector-function with elements $f_i(s_i(d_i), x_i) = s_i(d_i)x_i\left|x_i\right|^{\beta-1},\ i \in I,$ capturing the law of pressure drop at network branches, $s_i(d_i)$ - pipeline hydraulic resistance.

The flow distribution in the tree-shaped part of the network is unambiguously determined by the tree-shaped structure and nodal outflows (inflows) at the consumers' end.

To solve system of equations (1)-(2), algorithms based on efficient mathematical methods have been developed [17-18]. Application of methods of multilevel modeling together with these algorithms allows solving problems of real-life dimensionality when studying PSs.

Finding optimal parameters of elements of the HSS is a problem challenging enough to be impossible to solve without hierarchical modeling. The computational procedure for solving this problem is considered to be impossible without applying multilevel modeling and includes the following main stages [19, 20].

1. Multilevel decomposition of the HSS calculation scheme and construction of its hierarchical model.
2. Determination of the optimal parameters of the return main line using an algorithm based on the method of final ratios.
3. Defining constraints on pressure at the consumers' end at the nodes of the supply main line taking into account the obtained pressure values at the nodes of the

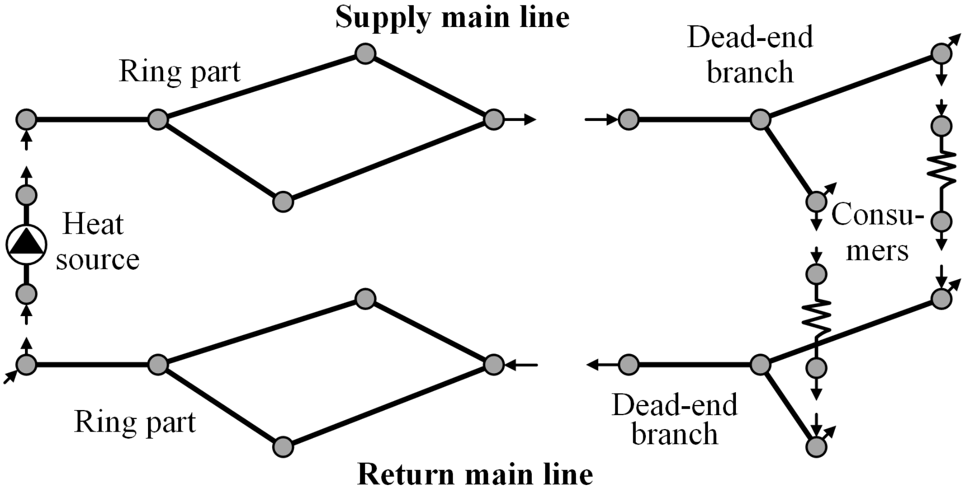

Figure 2. Levels of a hierarchical model of the heat supply system.

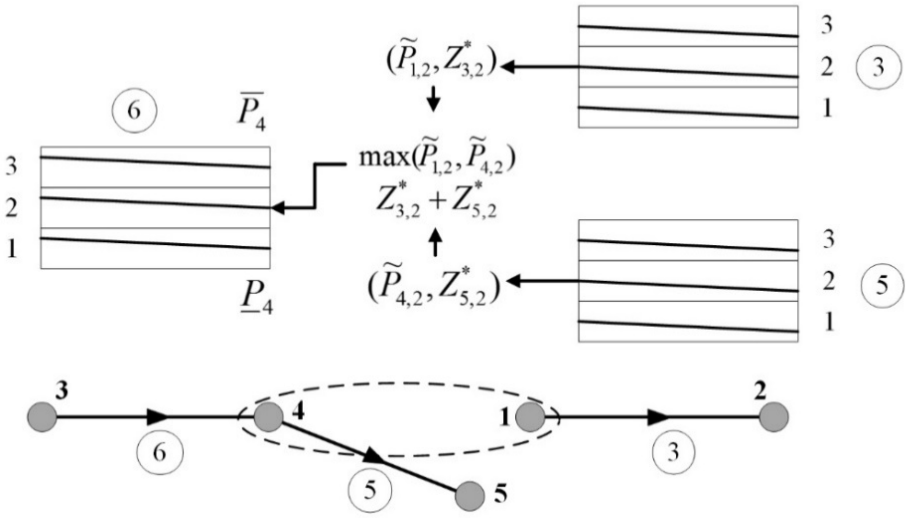

Figure 3. Model for "linking" results between hierarchical levels.

return main line to ensure the necessary heads at the consumers' end.

4. Determination of the optimal parameters of the supply main pipe using an algorithm based on the method of final ratios.
5. Calculation of total costs and capital expenditures for the HSS as per the parameters obtained during optimization.

To solve the problem of determining optimal parameters of supply and return main lines an algorithm is developed as based on the application of the method of final ratios and with the emphasis on calculation that takes into account hierarchical construction of a model of the HSS. This algorithm consists of the following steps:

1. Defining set J_L of nodes of the scheme, which have incident areas belonging to both ring and dead-end branches of the network.
2. Calculating initial flow distribution in the ring part of the network and at dead-end branches.
3. Performing the «forward pass» of the DP method for determination of suboptimal variants of parameters of all dead-end branches.
4. Transferring pressure and cost values of suboptimal variants obtained at the level of dead-end branches to the level of ring networks for all nodes $j \in J_L$.
5. Performing the «forward pass» of the DP method for determination of suboptimal variants of parametres of the ring part of the HSS, in doing so pressure and cost values of the ring part and dead-end branches are «linked» at nodes $j \in J_L$.
6. Selecting the variant corresponding to the solution with the lowest cost at the source with the highest performance.
7. Performing the «backward pass» of the DP method to restore the parameters and cost components of the ring and dead-end parts of the network.
8. Calculating flow distribution in the ring part of the network and at dead-end branches.
9. If the criteria of ending the computational process are not met, the transition to step 5 is performed.

Suboptimal solutions obtained at the nodes connecting dead-end branches to the ring part of the network, are «reconciled» with the results for the ring part during the computational process as per the final ratios method. In doing so, the following principle is used. If the node is the initial node both for the sections of the ring part and for the

Table 1 - Parameters of heat network sections before and after the reconstruction.

Section number as per the scheme	L_i	Before the reconstruction				After the reconstruction			
		h_i	x_i	v_i	d_i	h_i	x_i	v_i	d_i
	m	mm/m	t/h	m/s	mm	mm/m	t/h	m/s	mm
63	12.0	61.9	1461.8	2.0	517	6.1	1473.6	1.4	616
496	10.0	8.4	85.0	2.4	359	1.6	85.0	1.8	414
557	11.0	5.4	48.1	1.4	359	4.8	48.1	1.4	414
561	10.0	12.1	126.6	1.4	359	3.4	126.6	0.7	414
476	10.5	13.7	68.0	2.3	69	7.9	68.0	1.5	100

sections of dead-end branches, then a «linking» of pressure values and summing up of cost values take place in the cells of this node. Let $J^{(i)}$ denote a set of nodes where it is required to «link» the pressure values at node j at step i of the computational process. «Linking» the pressure values is done as per expression

$$P_{jz} = \max_{k\in J^{(i)}} \tilde{P}_{kz}, \quad z = 1,\dots,\mu.$$

Let $I^{(i)}$ denote a set of all sections coming from node j, the costs of which should be taken into account at step i of the computational process. The costs are summed up as per expression

$$Z^{*}_{iz} = \sum_{r\in I^{(i)}} Z^{*}_{rz}, \quad z = 1,\dots,\mu.$$

Figure 3 presents a fragment of the hierarchical model of a heat network. After calculating section 5, one has to determine the parameters of section 6. Prior to its calculation, pressure and cost values are «linked» between the levels of the hierarchical model of the heat network.

The main feature of the proposed algorithm is that for dead-end branches the «forward pass» of the DP is performed only once, and parameter determination is performed only for the ring part of the network during the iterative process of the method of final ratios . To this end the solutions of the ring part and the dead-end branches are «linked» according to the principles indicated above.

The proposed algorithms implemented in the SOSNA software package are used to solve real-life problems of optimal HSS reconstruction. The calculations of the HSS of the Tsentralny and Admiralteysky districts of St. Petersburg, the city of Bratsk, and the urban locality of Magistralny. The aggregated scheme of the Bratsk HSS is shown in Figure 4. District heating of this system is provided by four heat sources: GDB (Galachinskaya District Boiler House).2, GDB (Galachinskaya District Boiler House).1, IHPP (Irkutsk Heat Power Plant)-6-2, and IHPP (Irkutsk Heat Power Plant)-6-1. The calculation scheme of the heat network contains 632 sections and 613 nodes.

As a result of performing the calculations, we have identified optimal flow distribution in the system; sections of the network with insufficient throughput capacity where an increase in diameters of pipelines is required; required operating pressure values of pumping stations; rational available heads at the consumers' end, etc. Table 1 shows the parameters of the sections recommended for re-laying (pipeline length values (L_i), specific pressure drop values (h_i), heat transfer medium consumption values (x_i), heat transfer medium velocity values (v_i), pipeline diameters (d_i) before and after reconstruction.

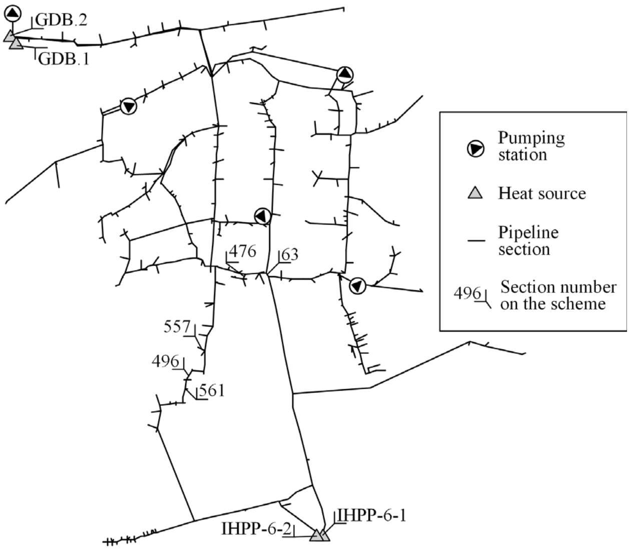

Figure 4. Heat supply scheme of Bratsk.

The algorithms implemented as part of the SOSNA software package that take into account multilevel decomposition of the model of the heat network provided a solution to the problem in 4 seconds. Applying parallel computations in combination with multilevel decomposition of the network model allowed obtaining the solution in 1.5 seconds. The SOSNA software package, which had been earlier used at the Melentiev Energy Systems Institute SB RAS for determination of optimal HSS parameters and which does not make u1se of multilevel decomposition of the model arrived at the solution of the problem in 166 seconds.

The performed comparative analysis of the results of calculations obtained with the aid of the SOSNA software package of the previous and new versions are given in Table

Table 2. Costs and capital expenditures in the heat network of Bratsk

Main pipe	Discounted costs, mln rubles / year	Capital expenditures, mln rubles
SOSNA software package		
Return	424.24	34.9
Supply	396.11	34.9
Total	820.35	69.8
	SOSNA software package (new version)	
Return	424.24	34.9
Supply	396.11	34.9
Total	820.35	69.8

2. It presents the values of the discounted costs of the HSS and the capital expenditures required for the reconstruction of the heat network. The values of the objective function of discounted total costs of the system for the software package of the previous and new versions prove consistent with each other, thus decomposition of the calculation scheme does not lead to compromising the quality of the obtained result.

IV. Conclusion

The existing PESs of the energy industry are engineering facilities that are complex in structure and composition. Solving the problems of their development involves building hierarchical mathematical models, which makes it possible to solve these problems by applying multilevel modeling. The paper lists the aspects according to which hierarchical representation of a unified PES model is carried out. Application of multilevel modeling allows switching from an initial complex problem to a hierarchically connected set of subproblems, each of which has lower dimensionality and complexity compared to the initial problem.

The study provides an example of multilevel modeling of HSS in solving the problem of determining its optimal parameters. The performed calculations attest to the effectiveness of the multilevel modeling for solving practical problems of design of the PES of real-life dimensionality and complexity.

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