Information Technologies to Estimation the Effectiveness of Water Supply Systems Control Depending on the Degree of Model Uncertainty

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Abstract. The efficiency of implemented control depends on the degree of adequacy of used models of object. The article introduces the criteria characterizing the degree of closeness of obtained solutions when using different types of models of control object. The algorithm of estimation of quality and efficiency of water supply systems control depending on the volume and composition of operative information about the object under control is presented. Carried out researches have shown, that for maintenance of optimum values of criteria of quality and efficiency of water supply systems functioning on a control interval it is enough to have pressure measurements in all local dictating points of a network. Further increase in number of measurements does not lead to improvement of these criteria values. Researches were carried out with the use of simulation modeling method of real water supply systems functioning. Information technologies for solving the whole range of tasks necessary for getting the result are described.

Keywords: control, model, criteria, efficiency, water supply system, simulation.

1 Introduction: Problem Topicality and Research Aims

The efficiency of implemented control depends on the degree of adequacy of used object models. In order to obtain estimates of control efficiency of water supply systems (WSS) on the time interval [0, T] depending on the degree of uncertainty of the object model, i.e. on the volume and composition of operational information about its states, we will use a simulation model of real WSS functioning. Much works is devoted to mathematical modeling of WSS [1-4], theoretical bases of optimization and operative control of flow distribution in engineering networks are laid in [5-7], there are many other works on this subject [8-13]. By quality of functioning of WSS is understood [6] probability of its purpose – to supply water to consumers in necessary quantity under the set pressure according to requirements on an interval [0, T]. The efficiency of WSS functioning is understood as [6] the cost of a resource (water, electric power) for providing the preset quality of its functioning on the interval [0, T]. The purpose of these studies was to develop an algorithm for solving the task of estimating the efficiency of WSS control depending on the volume and composition of operational information about the object under control and carrying out the corresponding analysis.

2 Processes Control Simulation of Water Supply Systems

Creation of imitation models of technological processes of functioning WSS and algorithmization of processes of control of their modes allows in practice to raise quality and efficiency of functioning of these systems. At designing of the automatized control systems of technological processes of WSS the most important is a stage of working out of algorithms of operative control over modes of functioning WSS. At an estimation of their efficiency it is necessary to consider both characteristics of technological process of giving and distribution of water, and casual character of influences to which WSS is exposed. This circumstance makes it necessary to create simulation models not only of WSS and the environment in which it operates, but also the system of automatized control of functioning its modes as a whole.

The presence of such simulation models allows to generate and analyze deeper the processes of flow distribution in real WSS, to play on the models and choose the optimal structure of the control system taking into account the peculiarities of a particular WSS (dimensionality, network configuration, number of active sources), to evaluate the quality and efficiency of the implemented control. Besides, an adequate simulation model allows estimating the state of all WSS elements by actual measurements of output parameters in a number of them (the measure of proximity of these values is the main criterion of adequacy of the simulation model to the real process).

Essential feature of problems of operative control of flow distribution in WSS is absence, in a general case, analytical dependencies for output parameters of control and criteria of quality and efficiency of functioning WSS that does practically impossible search of analytical solutions. The only acceptable method of solution is imitation modeling of WSS functioning, which allows to get mathematical expectations of evaluations of quality criteria of WSS modes control efficiency under observance of imposed technological restrictions. The software implementation of the corresponding algorithms meets to the solution of individual tasks [6,15] of the operational control of WSS in the simulation model.

Simulation model of WSS is a tool for research of efficiency of algorithms at the decision of practical problems of increase of efficiency and quality of operational control of modes of functioning WSS. It is expedient to use the simulation model for training the dispatch service personnel in the pre-launch period of automatized process control systems. Also it can be used as a standard at check of adequacy of the decisions received on more simple, aggregated models WSS.

3 Conceptual Scheme of Information Technology to Support Operation Control in Water Supply Systems

The process of operational control of WSS is divided into two stages: operational planning of modes of functioning of WSS and their stabilization.

The solution to the problem of operational control of the functioning of WSS is achieved by decomposing the original problem into number of hierarchically related tasks [5-7]. Consider the structure of solving problems of operational control of the functioning of WSS (Fig.1).

Based on the operational information getting simultaneous data from sensors installed at controlled points in the network, the task of identification of the state of the flows distribution in WSS is solve. The multiple solution of this task allows to determine for each node of WSS model the vector of evaluated water consumptions, which is then use as a series to predict the water consumption of each of these nodes for the entire control interval. The solution of the task of predicting the values of nodal water consumptions for a given time interval is the input source information directly for the problem of operational planning of the operating modes of WSS. The solution of the problem of operational planning of the operating modes of WSS is determine as a result of solving of the sequence of tasks. For each discrete time instant $k = 1,2, ..., K$, the task of the optimal load distribution between pumping stations (PS) is solved. As a result of its solution, for all $k = 1,2, ..., K$, the values of water consumption and pressures at WSS outputs are determined, which ensure the pressure in the nodes is not lower than the set ones. To ensure the obtained parameters at WSS outputs, as a result of solving for all $k = 1,2, ..., K$ the task of optimization the PS operating mode for each of them are determine the optimal structure and parameters of its functioning. However, the solution obtained at the operational planning stage should be invariant with respect to the predicted level of stochastic environmental disturbances. To study its effectiveness with a known level of stochastic disturbances, the problem of analyzing the flux distribution in WSS when solving the model of control actions on the PS is solved. This task is based on a mathematical model of steady flow distribution in WSS with active elements. The described sequence of solving the operational planning problem makes it possible to obtain a solution that is invariant with respect to the predicted level of stochastic disturbances, which guarantees the necessary quality of WSS operation over the entire control interval at maximum efficiency. The pressure stabilization at the dictating points of WSS partially compensates for disturbances acting on the control object in order to prevent the regime parameters from exceeding the permissible range.

The structure of solving the complex of tasks of operational control of the functioning of real WSS is presented (Fig.1).

4 Research Results

Let's denote L - set of pump stations WSS, M - set of trunk sites WSS, N - set of knots of a network with consumers; $E = L \cup M \cup N$; $h_i, q_i, i \in E$ – pressure loss and the expense in *i*-th site WSS, $H_{inp\,i}, q_{inp\,i}, H_{out\,i}, q_{out\,i}, i \in L$ – pressure and the expense on an input and an output *i*-th PS. Let us introduce the criteria characterizing the degree of closeness of the obtained solutions when using different types of WSS model. We will evaluate the effectiveness of solving the problem of controling the

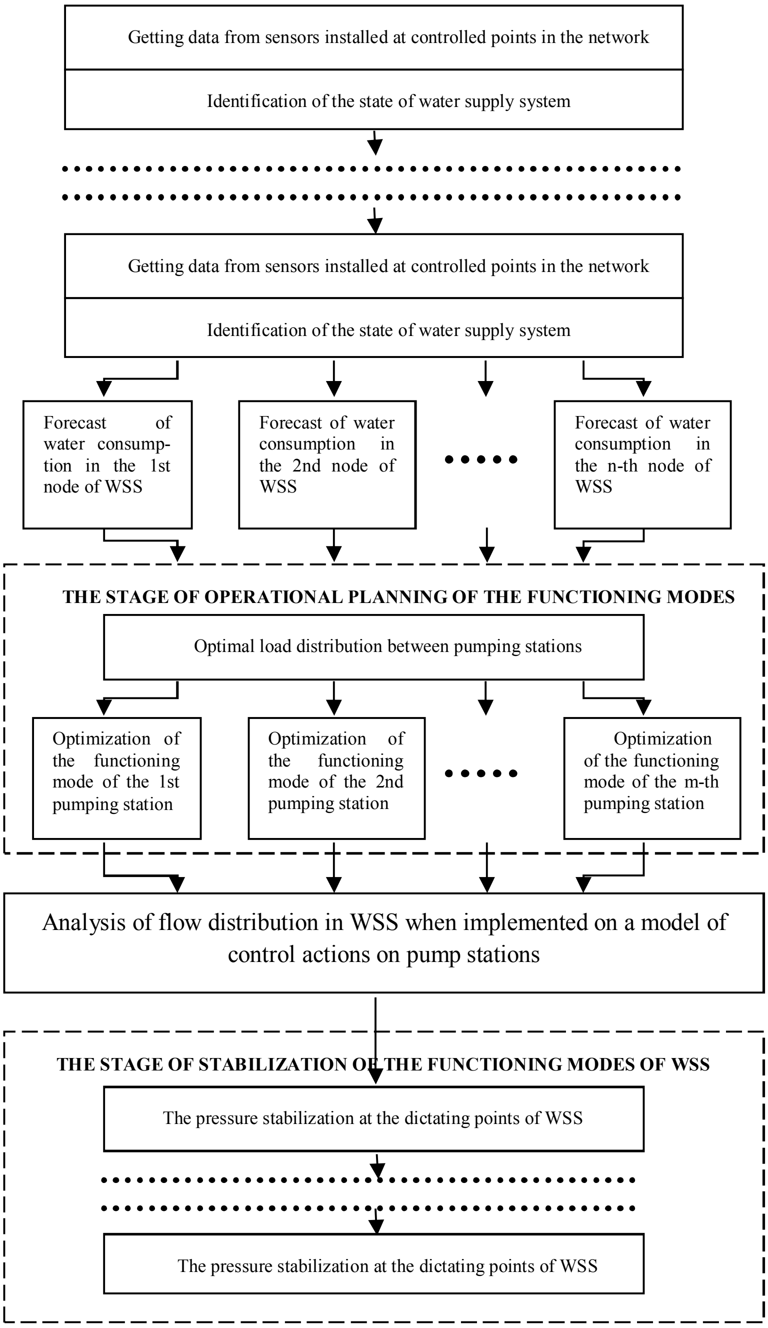

Fig.1. Conceptual scheme of information technology to support operation control in water supply system

modes of operation of WSS on the basis of an aggregated model with respect to solving this problem on the basis of a complete WSS model, which is taken as a standard. On set L of all WSS inputs we will introduce a measure characterizing the degree of closeness of the values of the variables determining their states when solving on the basis of an aggregated and complete WSS model [14, 15]:

$$P(\bar{U},\ \bar{U}^{*}) = \frac{1}{l}\sum_{i\in L}\left\{\left(\frac{H_{\mathrm{out}\,i} - H^{*}_{\mathrm{out}\,i}}{H^{*}_{\mathrm{out}\,i}}\right)^{2} + \left(\frac{q_{\mathrm{out}\,i} - q^{*}_{\mathrm{out}\,i}}{q^{*}_{\mathrm{out}\,i}}\right)^{2}\right\}. \qquad (1)$$

Since the variables $H_{out\,i}, q_{out\,i}$ are measured in different units, the use of measure (1) makes it possible to bring disparate scales to a single, dimensionless one. In addition, let us introduce a measure characterizing the maximum deviation of the variables $q_{out\,i}$, $H_{out\,i}$, $i \in L$, that determine the states of the WSS inputs from their optimal values $q^{*}_{out\,i}$, $H^{*}_{out\,i}$

$$P_{0}(\bar{H}_{\mathrm{out}\,i}, \bar{H}^{*}_{\mathrm{out}\,i}) = \max_{i\in L}\left(\frac{H_{\mathrm{out}\,i} - H^{*}_{\mathrm{out}\,i}}{H^{*}_{\mathrm{out}\,i}}\right)^{2},\ i \in L. \qquad (2)$$

$$P_{0}(\bar{q}_{\mathrm{out}\,i}, \bar{q}^{*}_{\mathrm{out}\,i}) = \max_{i\in L}\left(\frac{q_{\mathrm{out}\,i} - q^{*}_{\mathrm{out}\,i}}{q^{*}_{\mathrm{out}\,i}}\right)^{2},\ i \in L. \qquad (3)$$

Let's consider that among the set of variables, h_i, $i \in N$, characterizing the state of the outputs of the complete WSS model, the values of not all are known, but only some of them, h_i, $i \in N_0 \subseteq N$, the values of the other variables, h_i, $i \in N \setminus N_0$ are noisy. It is shown in [5] that if the observed conditions of the WSS are not met, an artificial addition of the composition of the observed variables, h_i, $i \in N \setminus N_0$ in the assumption of a uniform law of their distribution, allows us to obtain practically acceptable results. Therefore, by successively changing the number and composition of the set variables, h_i, $i \in N_0$ at the network outputs (the values $H_{out\,i}$, $q_{out\,i}$, $i \in L$ are always known in real conditions of WSS operation), and assuming that the other variables, $h_i, i \in N \setminus N_0$ are distributed according to a uniform law, it is possible by solving the problem of identification of WSS [5] to obtain estimates of values of measured and all other functionally related variables characterizing the flow distribution in the network.

The algorithm for estimating the efficiency of WSS control depending on the degree of uncertainty of the control object model is as follows:

1. Obtaining optimal estimates, further used as a benchmark, when the conditions for the observation of WSS are met.

1.1 A certain prehistory of implementation of observed variables at time moments $k = 0, -1, -2, ...$ preceding the control interval $[0, T]$, i.e. information state of the species, is considered to be given:

$$P^0 = \left\{ H_{inp\,i}(k),\ H_{out\,i}(k),\ q_{out\,i}(k),\ h_j(k) \mid i \in L, j \in N \right\}. \qquad (4)$$

For each $k = 0, -1, -2, ...$ the task of identification of the water supply network state is solved, as a result of which the estimations of nodal discharge values $\tilde{q}_j^{(H)}(k),\ j \in N$ at each of these moments become known.

1.2 On the basis of these estimations $\tilde{q}_j^{(c)}(k)$ at the moments of time $k = 0, -1, -2, ...$ for each node $j \in N$ of the network the forecast of flow rate $\hat{q}_j^{(c)}(k),\ j \in N$ for the control interval $[0, T]$ is made. Besides, on the basis of the prehistory of values, $H_{inp\,i}(k)$, $k = 0, -1, -2, ...\ \forall i \in L$ their values are predicted for the interval $[0, T]$.

1.3 For each moment $k = 0, 1, 2..., K$ the problem of optimal load distribution between PS is solved. We receive the reference values $H^*_{out\,i}(k),\ q^*_{out\,i}(k),\ i \in L$.

1.4 Determining the optimum control actions on the pumps of each PS $\forall k = 0, 1, 2..., K$ with the set values $H^*_{out\,i}(k),\ q^*_{out\,i}(k)$ as well as $H^*_{inp\,i}(k),\ i \in L$ [16]. Calculation of values of efficiency criterions $Y^*_{2i}(T),\ Y^*_2(T)$ of functioning of WSS on a control interval $[0, T]$.

2. The conditions for the observation of WSS are not fulfilled, so we supplement the composition of pressure measurements, $h_j, j \in N \setminus N_0$ in the network nodes in the assumption of the uniform law of their distribution.

2.1 In this case, the information state of WSS on the interval $[T_{-r}, 0]$ is $P = \left\{ H_{inp\,i}(k),\ H_{out\,i}(k),\ q_{out\,i}(k),\ h_j(k) \mid i \in L, j \in N_0 \subset N \right\}$. We solve the problem of identification of the network state $\forall k = 0, -1, -2, ...$ and calculate the cost estimates $\tilde{q}_j^{(c)}(k)$.

2.2 Predict the values of nodal costs $\tilde{q}_j^{(c)}(k),\ j \in N$, as well as $H_{inp\,i}(k),\ i \in L$, the interval $[0, T]$.

2.3 Optimal load distribution between PS WSS $\forall k = 0, 1, 2..., K$ at values $q_j^{(c)}(k)$, calculated at stage 2.2. We receive $\tilde{H}^*_{out\,i}(k),\ \tilde{q}^*_{out\,i}(k),\ i \in L$.

2.4 Determining the optimal structure and parameters of each PS [16] $\forall k = 0, 1, 2..., K$ at the given values $\tilde{H}^*_{out\,i}(k),\ \tilde{q}^*_{out\,i}(k)$ as well as $\hat{H}_{inp\,i}(k)$.

2.5 Analysis of the flow distribution in the WSS at implementation by the model of control actions on each PS $\forall k = 0,1,2...,K$ and values of node expenditures $q_j^{(c)}(k)$, $j \in N$, received at the stage 1.2 [14].

3. Based on the results of Step 2.5 we calculate the values of the quality criteria $Y_{0i}(T)$, $Y_{1i}(T)$, $Y_{1i}^{*}(T)$, $Y_1(T)$, $i \in N$ and efficiency $Y_{2i}(T)$, $Y_2(T)$, $i \in L$ of the WSS functioning at the interval $[0,T]$ [5]. We compare them with the optimal values of the quality and efficiency criteria of WSS functioning in the interval $[0,T]$, obtained at stage 1.4.

4. We compare the values of $H_{\text{out}\,i}(k)$, $q_{\text{out}\,i}(k)$, $i \in L$, $k = 0,1,2...,K$, obtained at stage 2.5, with the reference values of these parameters obtained at stage 1.3 in accordance with expressions (1) – (3).

5. Change the number or composition of observed variables $h_j(k)$, $j \in N_0 \subset N$ $k = 0,-1,-2,...$ and return to step 2.1.

Analyzing thus at different number and composition of observed variables $h_j(k)$ $j \in N$, $k = 0,-1,-2,...$, we will receive estimations of quality criteria and efficiency of WSS functioning on a control interval [0, T], and also estimations of criteria (1)–(3), characterizing a degree of closeness of optimum decisions received at entering of corresponding value of an error at the expense of incompleteness of composition of the operative information on operated object. If the corresponding level of stochastic environmental perturbations is set, this algorithm can be extended to the calculation of estimates of the efficiency of WSS control depending from the degree of uncertainty of the models of the control object and the environment.

5 Software for the Implementation of Modeling and Operation Control Tasks of Water Supply Systems

These studies were carried out by the author on his own, while his own developments of algorithms and information technologies was used, which are based on the scientific works of professors A.G. Evdokimov and A.D. Tevyashev [1,5-7].

Software for solving some of these tasks began to be developed in the languages of Fortran, Pascal and others. The basic is the task of hydraulic calculation, on its basis many optimization tasks are solved. Gradually, scientific developments in this direction developed, supplemented and improved, they were introduced in many large cities. Contracts with water supply enterprises, depending on the tasks required and problems to be solved, dictated what the developed software, databases, etc. should be. The development of list structures instead of the matrix form of describing the structure of a network graph was a major breakthrough in software implementation. It allowed to make hydraulic calculations of city water supply networks in seconds, and to solve many of optimization tasks listed in the article.

Currently, all software is implemented in C++, some tasks in accordance with agreements at the request of water supply enterprises are implemented in other programming languages and tools, especially using standard software package EPANET2 [17]. The developed databases were implemented with MS Access DBMS.

6 Conclusions and Future Work

The conducted researches have shown that for maintenance of optimum values of criteria of quality and efficiency of functioning of WSS on a control interval [0,T] it is enough to have pressure measurements only in all local dictating points of a network [6]. Further increase in the number of measurements does not lead to improvement of these criteria.

This conclusion is inextricably linked with the problem of optimal placement of sensors on the network. Obviously, for the preceding and subsequent control intervals not only the position of local dictating points but even the global dictating point (GDP) can change [6]. Therefore, it is reasonable to use many GDP subintervals of some long time interval as a set of control points in the network. In practice, when determining the points for optimal location of sensors on the network, it is necessary to first install the devices of temporary control of parameters in the most "suspicious" points, determined on the basis of expert estimates. After a long interval of time it is possible to place automatic control devices of parameters in the GDP of its subintervals.

In real conditions of WSS functioning, if to provide known a priori value of the minimum allowable one taking into account the value of pressure reserve in the GDP or other characteristic point of the network, the set quality of WSS functioning at the maximum efficiency can be achieved also at control on one controlled point on the basis of use of the aggregated model of object [15]. It is obvious that such aggregated models can be used to control the technological processes of the functioning of all real WSS, for which the set of characteristic points located in the zone of joint influence of all PS working on WSS is not empty.

The use and widespread adoption of information technologies of optimal control operation of WSS allows in practice to improve the quality and effectiveness of their functioning by reducing the excess pressure in the networks (and, consequently, reducing unproductive costs of water), reducing electricity costs, reducing the probability of occurrence of emergency situations in networks.

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