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Criteria of quality and efficiency of water supply systems functioning

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Abstract. The system of main criteria of quality and efficiency characterizing the operation of water supply systems (WSS) on the time interval [0,T] is considered. The article introduces a number of new criteria for assessing the quality and efficiency of the functioning of water supply systems. In general, this system of criteria for the quality and efficiency of the functioning of WSS was effectively used both in simulation modeling and in the implementation of developments at real facilities. It is advisable to use it in the development and operation of systems for the operational control of technological processes of the functioning of WSS, in the simulation of decisions made on the operational control of the modes of operation of WSS, in the simulation of designed and reconstructed WSS, in the analysis of a specific situation on the network at a given point in time.

1 Introduction

The functioning of any system is related to the qualitative and quantitative objectives of the control of this system.

A qualitative control criterion serves to assess the extent to which the goal is achieved. This criterion can take only two values: one (in the case of achieving the goal) and zero (otherwise). Qualitative goals are strategic and placed at the highest level of the control hierarchy of the entire system. The apparent simplicity of such a control criterion is deceptive, since the functional dependence of the criterion on the controlled parameters can be very complicated.

Quantitative control goals are to reduce (or increase) the value of some criteria that reflect the modes of operation, reliability, environmental and economic efficiency of the controled object, and more.

The quality of the functioning of the pipeline system is the probability of the pipeline fulfilling its purpose - to supply consumers with the target product in the required quantities under a given pressure in accordance with the necessary requirements for a certain time.

The efficiency of the pipeline system is the cost of a resource (target product, electricity) to ensure a given quality of functioning for a certain time.

2 Criteria of quality

For the majority of pipeline systems (water, oil, gas, heat supply, etc.), the quality criterion has a general structure, since the main functional purpose of these systems is to provide consumers with the required volumes of the target product under the pressure not less than the preset. Consider the criterion for the sum of free excess pressures. Let h_j and h_j^+ be

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the current and minimum permissible pressure in the j-th node, respectively, V is the set of vertices of the network graph. Then the sum of free excess pressures at time t is calculated in accordance with expression

$$z(t) = \sum_{j \in \mathbf{V}} \left(h_j(t) - h_j^+ \right) \tag{1}$$

Under normal operating conditions the current pressure h_j must always be greater than or equal to h_j^+. Excessive excess of the current pressure over the normative leads to an increase in the consumption of electricity; increase leakage of the target product; increase the probability of pipe rupture, which in turn leads to an increase in the likelihood of damage from the accident. Evaluation of the sign of this criterion on a time interval [0, T] allows to judge the efficiency of the functioning of pipeline systems from the point of view of the latter performing their basic functional purpose.

Let's consider the work of quality and efficiency criteria on the example of real water supply systems (WSS).

For each vertex of the graph of the water supply system on a given time interval [0, T], we introduce a functional of the form [1-3]

$$Z_j = \frac{1}{T} \int_0^T \varphi(h_j(t)) dt, \tag{2}$$

where $h_j(t)$ is the random process of changing the pressure in the *j-th* node of the water supply system;

$$\varphi_j(t) = \varphi(h_j(t)) = \begin{cases} 1, \ if \ \ h_j(t) \geq h_j^+; \\ 0, \ if \ \ h_j(t) < h_j^+. \end{cases} \tag{3}$$

The functional (2) characterizes the relative time during which the water supply system fulfills its functional purpose at the *j-th* node of the system, i.e. expression (2) gives a quantitative estimate of the water supply system functioning quality for its *j-th* node. In this case - $\varphi_j(t)$ is the relative time during which the component of the criterion (1) for the *j-th* node is greater than or equal to zero

$$z_j = h_j - h_j^+ \geq 0 \ . \tag{4}$$

If the information on the value of the free pressure at the *j-th* node arrives at discrete instants of time t, t + 1, then in this case the expression (2) can approximately be replaced by the integral sum

$$Z_j = \frac{1}{T} \sum_{k=1}^{T} \varphi(h_{jk}) \Delta t_k \qquad (j \in V). \tag{5}$$

The quality of the water supply system functioning on the time interval [0, T] in the simplest case can be characterized by a functional of the form

$$Z = \frac{1}{v} \sum_{j \in V} Z_j . \tag{6}$$

The values of this criterion are in the range from 0 to 1.

3 Criteria of efficiency

Let's consider the basic quantitative criteria, allowing to estimate efficiency of functioning of water supply systems. Let us denote h_j и h_j^+ - the current and minimum permissible pressures at the *j-th* node, V is the set of vertices of the network graph, *L* is the set of pumping stations (PS) supplying water to the city water supply network, and N is the set of consumers of water. Then the criterion of total excess pressures at the time t (under the condition $h_j(t) \geq h_j^+(t)$) has the form

$$z(t) = \sum_{j \in \mathbf{V}} \left(h_j(t) - h_j^+ \right) \tag{7}$$

The most important criterion for the efficiency of the water supply systems operation is energy consumption. Let us formulate this criterion at time *t*

$$z(t) = pg \sum_{j \in L} \frac{y_j^{(a)}(t) x_j(t)}{\eta_j}, \tag{8}$$

where $y_j^{(a)}$, x_j and η_j - respectively, the loss of pressure, the flow on the *j-th* PS and its efficiency; *p* is the density of water; g is acceleration of gravity.

Integral estimation of power inputs on the time interval [0, T]

$$Z = \int_0^T z(t)dt \tag{9}$$

and with a discrete method of information retrieval

$$Z = \sum_{j=1}^{T} z_j \Delta t_j . \tag{10}$$

Maximum excess pressure at time *t*:.

$$z(t) = \max_{j \in \mathbf{N}} h_j(t) . \tag{11}$$

Total instant water consumption:

$$z(t) = \sum_{j \in L} x_j(t) . \tag{12}$$

Integral evaluation of this criterion on a time interval [0, T]:

$$Z = \int_0^T z(t)dt \tag{13}$$

and, with discreteness of incoming information, $Z = \sum_{j=1}^{T} z_j \Delta t_j$.

4 Research results

In the process of simulation modeling of technological processes of functioning of real water supply systems, the values of quality and efficiency criteria were calculated at each considered hour of the day and in general over the time interval of a day.

In the calculation results, the quality of water supply system functioning at discrete instants of time k = 0, 1, 2, ..., 23 was determined

- probability of dissatisfaction of consumers in water at the time

$$Y_0(k) = \frac{n'(k)}{n}, \tag{14}$$

where n' is the number of consumers not provided with water, i.e. for which $h_i(k) < h_i^+, i \in N' \subseteq N$; $h_i(k), h_i^+$ is the current pressure value at the time k and the minimum permissible pressure in the i-unit of water supply system, respectively;

- an indirect estimate of the water deficit in the water supply system at the time k

$$Y_1(k) = \begin{cases} \sum\limits_{i \in N} \left[h_i^+ - h_i(k) \right], \ if\ h_i(k) < h_i^+, \\ 0,\ if\ h_i(k) \geq h_i^+; \end{cases} \tag{15}$$

- the depth of water deficit in the water supply system at the time k

$$Y''_1(k) = \begin{cases} \max\limits_{i \in N} \left[h_i^+ - h_i(k) \right], if\ h_i(k) < h_i^+ \\ 0, if\ h_i(k) \geq h_i^+ \end{cases} \tag{16}$$

- the relative magnitude of the water deficit in the water supply system at the time k

$$Y_1^*(k) = \begin{cases} 1 - \sum\limits_{i \in N} \dfrac{h_i(k)}{h_i^+}, if\ h_i(k) < h_i^+, \\ 0, if\ h_i(k) \geq h_i^+ \end{cases} \tag{17}$$

The effectiveness of the operation of WSS at time k = 1, 2, ..., 23 was determined

- the sum of energy costs at the pumping stations of WSS at the time k

$$Y_2(k) = \sum_{i \in L} N_i(k) = \sum_{i \in L} \sum_{j \in Ki} N_{ij}(k), \tag{18}$$

where $L -$ set of PS; $N_i(k)$ is the value of the energy expenditure *i-th* PS at the time k; K_i is a set of aggregates *i-th* PS;

- the sum of the given energy inputs at pumping stations of the water supply system at the time k

$$Y_2^*(k) = \sum_{i \in L} \mathrm{q}_\mathrm{i}^{(\mathrm{a})}(k) h_i^{(a)}(k); \tag{19}$$

- the sum of free excess pressure in the water supply system at the time k

$$Y_2^{**}(k) = \sum_{i \in N} \left[h_i(k) - h_i^+ \right] \tag{20}$$

- the value of the maximum pressure deviation in the nodes of the water supply system at the time k from its minimum allowable value

$$Y''_2(k) = \max_{i \in N} \left[h_i(k) - h_i^+ \right] \tag{21}$$

Indicators $Y_2^{**}(k), Y''_2(k)$ must be determined in those cases when $Y_0(k), Y_1(k)$ are equal to zero.

The following indicators were used as integral criteria characterizing the quality and efficiency of the functioning of the water supply system as a whole and relative to the *i-th* consumer in the considered time interval [0, T]:

$$Y_{oi}(T)=\frac{1}{T}\sum_{k=0}^{T}\eta_{oi}(k) \qquad (22)$$

- indirect estimate of the probability of water deficit occurrence at the *i-th* node of the water supply network in the time interval [0, T];

$$Y_{1i}(T)=\frac{1}{T}\sum_{k=0}^{T}\eta_{1i}(k) \qquad (23)$$

- indirect estimate of the mean value of the water deficit in the *i-th* node of the network in the time interval [0, T];

$$Y_{1i}^{*}(T)=\frac{Y_{1i}(T)}{h_i^{+}} \qquad (24)$$

- estimate of the relative value of the water deficit in the *i-th* node of the network on the interval [0, T];

$$Y_{1i}''(T)=\max_{k=0,1,\dots,23}\left[h_i^{+}-h_i(k)\right] \qquad (25)$$

- the depth of water deficit in the *i-th* node of the network on the interval [0, T].
Here

$$\eta_{oi}(k)=\begin{cases}1, if\ h_i(k)<h_i^{+},\\ 0, if\ h_i(k)\ge h_i^{+},\end{cases} \qquad (26)$$

$$\eta_{1i}(k)=\begin{cases}h_i^{+}-h_i(k), if\ h_i(k)<h_i^{+},\\ 0, if\ h_i(k)\ge h_i^{+}, i\in N,\end{cases} \qquad (27)$$

where $h_i(k), h_i^{+}$ respectively, the current value of the pressure at the time k and the minimum allowable pressure in the *i-th* WSS node; *N* - set of network nodes with consumers.

As an indicator characterizing the quality of the water supply system functioning on the time interval [0, T], the convolution of criteria (22) of the form was used

$$Y_0(T)=\frac{1}{n}\sum_{i\in N}Y_{oi}(T) \qquad (28)$$

Expression (28) defines an indirect estimate of the average probability of occurrence of a water deficit in the water supply system over a time interval [0, T].

In addition, the convolution of the criteria (23) of the form was used

$$Y_1(T)=\sum_{i\in N}Y_{1i}(T) \qquad (29)$$

Expression (29) defines an indirect estimate of the water deficit in the water supply system on the interval [0, T].

As an indicator characterizing the efficiency of the water supply system on the interval [0, T], the expression was used:

$$Y_2(T)=\frac{1}{T}\sum_{j\in L}\ \sum_{k=1}^{T} N_j(k), \tag{30}$$

where $N_j(k)$ is the value of the expenditure of energy *j-th* PS at the time *k;*

L - the set of PS.

In addition, an indicator was used that characterizes the total cost of power at pumping stations of the water supply system on the interval [0, T].

$$Y_2'(T)=T*\sum_{j\in L} Y_2(T) \tag{31}$$

and an indicator characterizing the sum of the reduced energy inputs at pumping stations of the water supply system on the interval [0, T].

$$Y_2^*(T)=\sum_{k=0}^{T}\ \sum_{i\in L} \mathrm{q}_{\mathrm{i}}^{(\mathrm{a})}(k)h_i^{(a)}(k) \tag{32}$$

where $\mathrm{q}_{\mathrm{i}}^{(\mathrm{a})}(k), h_i^{(a)}(k)$ - respectively, the flow and pressure at the outlet *i-th* PS at the time k.

The average and total water supply by pumping stations to the network in the interval [0, T] were determined in the form

$$Y_3(T)=\frac{1}{T}\sum_{k=0}^{T}\ \sum_{j\in L} \mathrm{q}_{\mathrm{j}}^{(\mathrm{a})}(k), \tag{33}$$

$$Y_3'(T)=T*Y_3(T), \tag{34}$$

where $\mathrm{q}_{\mathrm{j}}^{(\mathrm{a})}(k)$ is the amount of water supplied by the *j-th* PS at the time *k*.

5 Conclusions

The article introduces a number of new criteria for assessing the quality and efficiency of the functioning of water supply systems.

In general, this system of criteria for the quality and efficiency of the functioning of water supply systems was effectively used both in simulation modeling and in the implementation of developments at real facilities[1-3, 6, 9-14].

It is advisable to use it in the development and operation of systems for the operational management of technological processes of the functioning of water supply systems, in the simulation of decisions made on the operational control of modes of operation of water supply systems, in the simulation of designed and reconstructed water supply systems, in the analysis of a specific situation on the network at a given point in time.

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