Planning of a water distribution network sensors location for a leakage isolation[1]

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Abstract

The paper presents a method of water distribution system sensors placement. Location of sensors depends on the purpose of monitoring of a network. In this paper, this objective has been defined as the ability to detect network failures (leakages). Therefore, the location of monitoring points should be designed so as to maximize the effectiveness of the location method. The main objective of the algorithm deployment of sensors is to find a placement that minimizes the number of components for the largest collection of leakages (faults) with the same signature. The simplest way of determining the best sensors placement is to use an exhaustive search method. However, even a slight increase in the number of possible sensors locations makes exhaustive search very inefficient. Therefore, the selection of sensors placement was performed by optimization using evolutionary genetic algorithm. The computations were performed on the example of the water supply network in Glubczyce town in Poland.

1. Monitoring of the water supply network

Water losses in the distribution network is an important issue for the water companies. It should be reduced consistently and methodically. Techniques based on locating leaks by pressure monitoring devices are more effective and less costly than search in situ [5, 6]. Hence a placement of the monitoring devices is a crucial issue to the detection and isolation of the leakages.

When designing a monitoring system one should make the choice of placement of measurement points, which is guided by two criteria: the total cost of installation of these points and the amount of information, which can be gathered with it. It is the problem of multi-criteria optimization. The first criterion is subject to minimization and the second - to maximization.

2. Problem formulation

Leakage detection is commonly based on the measurement data analysis. This problem was, however not solved in terms of local and international jural acts and norms [9, 10]. In the current Polish legal requirements, there is no specific guidance on the location of the sensors in the water supply networks. When considering the possibility of assessing the pertinence of the location of sensors for hydraulic parameters measurement, including pressure, in water networks one should pay attention to the diversity of monitoring purposes [10, 12].

It can therefore be concluded that the location of measurement points depends on the purpose of monitoring of the water supply network. In this paper, this objective has been defined as the ability

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to detect network failures (leakages). Therefore, the location of monitoring points should be designed so as to maximize the efficiency of the method used for network fault location [16].

3. Leakage detection

The applied methodology used to detect leaks is based on the classic theory of diagnosis based on a model, and implemented in the supply networks to damage detection [4, 7, 20] with a hydraulic model [2, 13, 14, 15, 17, 18, 19]. Diagnosis based on the model can be divided into two subtasks: detecting and isolation of damage [11]. Detection of damage is to observe the state of the object, and the location of damage is to identify the damaged component of the system [3, 8, 11]. Observation of the object is based on the determination of residuals $\boldsymbol{r}(k)$ determined from the measured input signal $\boldsymbol{u}(k)$ and output $\boldsymbol{y}(k)$ using the sensors installed in the monitoring system, using the following, generic, formula [8]:

$$\boldsymbol{r}(k) = \boldsymbol{\Psi}(\boldsymbol{y}(k), \boldsymbol{u}(k)) \tag{1}$$

where $\boldsymbol{\Psi}$ is a function of generating residuals, which depends on the type of the chosen strategy (the parity equation [8] or the observer [3]). At any moment of time k residuals are compared with the threshold value (zero in the ideal case or close to zero in real applications). The threshold value is determined using statistical methods and methods based on fuzzy sets [11], taking into account the presence of both measurement and model inaccuracies. If the value of the residuum is larger than the threshold, occurrence of damage is concluded. Otherwise, it is considered that the system is working properly.

Hence, the main objective of the algorithm of sensors deployment is to find a placement that allows to maximize the number of leakage signatures – distinguishable faults. This means to minimize number of sections described by the same value of residual $\boldsymbol{r}(k)$.

In the diagnostics of complex technological installations, methods of designing faults–symptoms relation that utilize expert knowledge play the most important role. Deep knowledge about the process operation helps to define this relation in a relatively simple way. Additionally, the diagnostic system designer can utilize the knowledge of process engineers or operators. The binary diagnostic matrix [11] is most often used. An example of such a matrix is presented in Fig. 1.

S/F	f_1	f_2	f_3	f_4	f_5	f_6
s_1	1	0	1	0	0	1
s_2	0	1	0	1	1	0
s_3	0	0	1	0	1	0
s_4	0	1	0	0	1	1
s_4	0	0	0	0	1	0
s_6	1	0	1	1	0	1

Figure. 1. An example of the binary diagnostic matrix.

The matrix element in the *j*-th row and the *i*-th column has the value $v_j(f_k) = 1$ if the diagnostic signal s_j detects fault f_k and the value $v_j(f_k) = 0$ otherwise. In other words, the occurrence of fault f_k brings the occurrence of the diagnostic signal $s_j = 1$, which is called a symptom. The relation R^{FS} described by the binary diagnostic matrix can be defined by attributing to each diagnostic signal the subset of faults $F(s_j)$ that are detectable by this signal:

$$F(s_j) \equiv F(s_j = 1) = \{f_k \in F: v_j(f_k) = 1\} \tag{2}$$

It can be also defined by attributing to each fault $f_k \in F$ the subset of diagnostic signals $S(f_k)$ that detect the particular fault f_k:

$$S(f_k) = \{s_j \in S: v_j(f_k) = 1\}. \quad (3)$$

where, $S(f_k)$ determines the set of k-th fault symptoms. Each matrix row corresponds to the rule of the following type (4):

$$\text{if } (s_1 = 0) \wedge \ldots \wedge (s_j = 1) \ldots \wedge (s_J = 1) \text{ then } f_k \quad (4)$$

If the signatures are identical then the faults are indistinguishable.

4. Sensor placement algorithm

Pipe network model can be represented as a graph $G = (V, E)$ [17], where E is the set of edges that represent pipes and V is a set of vertices (nodes). Vertices may reflect sources such as reservoirs or tanks and demand nodes, which are the places where the water is consumed. Each pipe connects two vertices $v_i$and $v_j$which can be written as follows (v_i, v_j).

The problem of sensors deployment, with the network representation in the form of a graph, can be formulated as an integer programming problem. Each decision variable x_j associated with a network node v_i can take a value of 1 or 0, where 1 means the sensor is installed, and 0 that is not installed in the i-th node [1].

Rows of the diagnostic matrix (Fig. 1) refer to the distribution of sensors, while columns refer to a leakage at a given node. This means that if the matrix element has a value of 1, the sensor installation on a node allows the detection of leakage associated with a given column (only in the case of a single leak).

Assumed methodology implies application of the hydraulic model of the system. First, a numerical simulation of the water supply system under standard operation is performed. For a given network load, nodal pressures are determined for all nodes, and flows in all sections of the network. Next, a set of simulations is performed for assumed network faults. This means that, in each node, in which leakage was introduced, the leakage flow is calculated using the following formula:

$$q = Cp^{\gamma} \quad (5)$$

where q – leakage flow rate, C – flow constant through the leak, for each node, this value was the same, p – pressure at the node , γ – pressure exponent (γ = 0.5).

For a given sensor deployment the number of signatures is estimated. Next, the deployments are changed so as to achieve the maximal possible number of faults signatures (distinguishable faults).

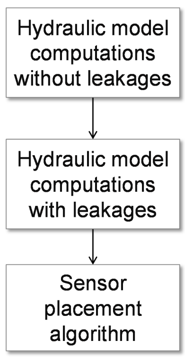


Figure 2. Sensor placement algorithm.

The main objective of the sensor placement algorithm is to minimize the number of leakages (faults), described by the same signature (the same set of symptoms). This function can be written as follows:

$$J = \min_{x_1,\dots,x_n} \max\{n_1, \dots, n_{nf}\} \tag{6}$$

where $x_1, \dots, x_n$ are decision variables which defines the specific arrangement of sensors and n_i is the number of nodes in the indistinguishable group i for a given leak f_j.

The simplest way of determining the best sensor deployment is to use an exhaustive search method. This method is simple to implement, but requires checking all the existing combinations of subsets of sensors positions to determine the subset giving the largest value of the signatures. Using this method a global solution can be obtained, but it is only effective for a set of data with a small number of network nodes. Even a slight increase in the number of possible monitoring points makes exhaustive search becomes very inefficient [21]. Therefore, in the selection of measurement points location a genetic algorithm was used.

5. Mathematical model of a water distribution system

The main task of a water supply system is to provide a sufficient amount of water at the appropriate pressure to all users of a system. Each water network consists of three main components: pumps, storage tanks and distribution network. Most systems require pumps that allow to raise the water to the desired height and to cover energy losses due to friction. The pipes can be fitted with devices to control the flow, such as return or relief valves.

Hydraulic model is described by linear and nonlinear algebraic equations, similar to the equations describing the balance of voltages and currents in electrical networks [23]. A mathematical description results from the first and second Kirchhoff's law known from electrical engineering. For the formulation of equations of a model, a structure of an investigated network has to be known. Basically, it consists of links (pipes), nodes (pipe junctions), pumps, valves and storage tanks or reservoirs. Hydraulic model calculates the water flow in each pipe, the pressure at each node, the height of water in each tank. Flows in the water supply system are calculated in accordance with the principle of conservation of mass and energy. The mass conservation law shows that the entire mass stored in the system is equal to the difference between inlet and outlet flows to the system. In the pressurized water distribution network, it is not possible to store water in pipes, although the levels in the tanks may change over time.

Assume we have a pipe network with N junction nodes and NF fixed grade nodes (tanks and reservoirs). Let the flow-headloss relation in a pipe between nodes i and j be given as:

$$H_i - H_j = h_{ij} = rQ_{ij}^n + mQ_{ij}^2 \tag{7}$$

where H is nodal head, h is headloss, r is resistance coefficient, Q is flow rate, n is flow exponent, and m is minor loss coefficient.

The value of the resistance coefficient will depend on which friction headloss formula is being used (see below). For pumps, the headloss (negative of the head gain) can be represented by a power law of the form:

$$h_{ij} = -\omega^2 \cdot \left(h_0 - r \cdot \left(\frac{Q_{ij}}{\omega}\right)^n\right) \tag{8}$$

where h_0 is the shutoff head for the pump, ω is a relative speed setting, and r and n are the pump curve coefficients. The second set of equations that must be satisfied is flow continuity in all nodes:

$$\sum_j Q_{ij} - D_i = 0 \quad \text{for} \quad i = 1, \ldots, N \tag{9}$$

where D_i is the flow demand at node i and by convention, flow into a node is positive. For a set of known heads at the fixed grade nodes, one seeks a solution for all heads H_i and flows Q_{ij} that satisfy equations (7) and (9).

6. Considered water distribution system

Glubczyce is a town in the Opole province, Poland, in the district of Głubczyce situated on the river Psina is inhabited with 23 778 people. The water supply network within Glubczyce provides water to 13 286 inhabitants (data from 2011). Water production in 2011 was estimated at 2.782 m^3/day. In the city there is one pressure zone, in which pressure varies from P_{min} = 0.2 MPa to P_{max} = 0.42 MPa.

7. Results

The presented method has been used to estimate the suboptimal location of pressure sensors deployment. The selection of sensors placement was a task of choosing the most cost-effective sensors configuration satisfying certain criteria (possibly a small group of indistinguishable nodes). This task was realized with use of numerical simulations. During the necessary computations, the simulation time was selected as 24 hours, with the time discretization step of one hour.

The series of computations was performed so as to determine position of the individual sensors. In each of the numerical experiments a different number of installed sensors was assumed (from 2 up to 12 sensors). It should be noted that the used methodology does not take into account the investment costs associated with device installation. The overall investment consist of the cost of metering equipment, which is a pressure gauge, the cost of construction of the necessary wells and necessary electronic devices (i.e. containing energy source and a data transmission unit). Moreover, in the case of pipes of different diameters, the mounting cost of a single sensor might differ. On a pipe having a large diameter it may be greater than the cost of assembling two measuring points on the small diameter pipes.

The results of the comparison of the performed computations are presented in the table (Table 1). The numerical computations have shown that in some cases a relatively large group of nodes will have the same signature (failure on any of the sections will be indistinguishable at the level of the individual group).

Figure 3 Example of a solution in which a large group of nodes (marked in red) is defined by the same signature.

Table 1. The results of the numerical computations, $J = min_{x_1,\dots,x_n} max\{n_1, \dots, n_{nf}\}$ – number of elements (nodes) with the same signature.

Number of sensors	$J = \min_{x_1,\dots,x_n} \max\{n_1, \dots, n_{nf}\}$
2	98
4	38
6	32
8	21
10	19
12	14

Applying the prescribed diagnostic system is a separate topic of fault detection, usually conducted under the assumption of single faults. After defining a set of available faults, the diagnostic signals should be reduced by these signals, which are susceptible to failure detected. Their values are in fact determined by the existence of recognized fault. The exemplary diagnostic matrix was presented in fig. 4:

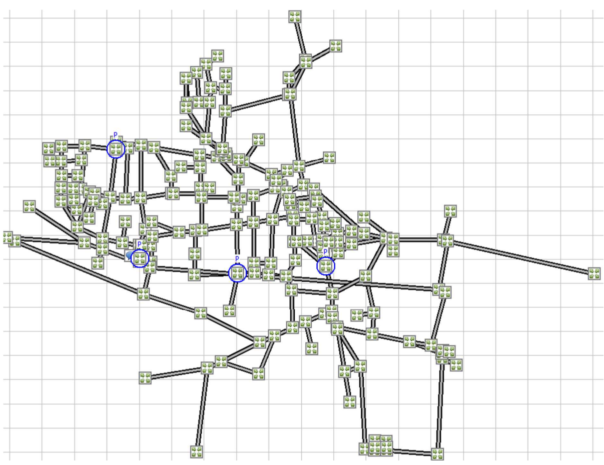
f

s

Figure 4. Example of a designated binary diagnostic matrix for 12 sensors, s - symptoms, f - failure. Black color indicates a value of 1.

As the number of sensors is increased the state of the network can be more precisely defined and the leakage can be more accurately detected. One can, however, note that the appropriate choice of a relatively small number of sensors may be equivalent, in terms of quality, of the knowledge about the network, than a large number of sensors located in less sensitive network areas. On the other hand the cost of the system and its operation is increased.

Number of sensors:2, number of signatures: 2



Number of sensors:4, number of signatures: 8

Number of sensors:6, number of signatures: 16

Number of sensors:8, number of signatures: 42

Figure 5. Examples of results of sensors location (marked as circles) for different numbers of devices.

8. Summary

The presented method for determining pressure sensor placement is designed to maximize the possibility of fault location. Normally, in the diagnosis of complex technological systems the most important factor is an expert knowledge that described the relationship between damage and symptoms [11]. Designer of a diagnostic system can additionally use the engineers', process operators' and maintenance staff's knowledge. The article presents a method for determining the diagnostic matrix using numerical computations of a hydraulic model. The results show that using the this method the suboptimal binary diagnostic matrices can be estimated.

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