SMART WATER DISTRIBUTION SYSTEM

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Abstract

Paper discusses the results obtained within the elaboration of methods and algorithms for the requirements of an operative control of water distribution systems in a city agglomeration. The most often used optimization criterion is one of the electrical energy cost minimization. In the Water Distribution Network (*WDN*), energy can be accumulated in a specific time interval and can be restored in consumed water in another interval. However, the total value of energy in a given period should be equal zero because *WDN* is a closed and stable system. The value of this energy depends on the volume of the pipelines and tanks, which compose the water distribution network. The energy losses are inseparable related to the accumulation and distribution processes. So, the good understanding of spatial and quantity decomposition of energy losses is the first step towards defining optimization techniques.

Keywords - Water Distribution System, energy control, loses minimization.

1 INTRODUCTION

Water Distribution Networks (*WDN*s) are designed to deliver water from sources to consumers. The main goal of the water distribution networks is to fulfil the consumers demands denoted as σ. On the other hand, from technical point of view energy balance is a crucial for *WDN* since it is stable and autonomous system, where energy balance should be equal to zero. To achieve this it is necessary do deliver the appropriate amount of water (with the predefined pressure head and in the predefined time intervals) through pipeline system from sources (e.g. pump stations) to the consumers [3, 4, 8,13].

The stability of distribution network does not depend on its topology and technical infrastructure only. Some exterior influence like spatial and temporal variations of consumer demands are of the great importance. In the case of gas, heat or electric networks, the shifting scale of charges is a good moderator. Unfortunately, it does not apply to the water systems, because there is no possibility of water replacement as a medium.

Consumer demands are usually understood as a delivery of water volume per time unit over a given time interval. Of course, the minimal velocity head, necessary to maintain flow in consumer's node, should guarantee comfort of delivery. But realization of this demand (predefined discharge head) requires extra energy delivery to every consumer nodes, to keep the minimum level of this discharge head. So, we can state that in order to fulfill consumer's demands for water, it is adequate to deliver the energy to distribution network.

The results of our investigations in this study relate to the control of energy distribution within *WDN*. This is the first step to maintain the water distribution system in an optimal regime of work provided that the desired consumer demands σ will be fulfilled. Because of that we require good knowledge of physical rules in the network. The two Kirchhoff's laws describe these rules in a pipeline network. Energy relationships resulting from the Kirchhoff's laws are common factor of different distribution network systems. These laws accomplish more than interfacing one kind of network with another, these laws interface technical requirements with minimal energy solutions.

2 MODEL DESCRIPTION

As stated above, the energy balance in such isolated system as a water distribution network should be equal to zero in a given time interval. Coming from the source nodes, the energy is kinetic and potential when provided to the network. The total dynamic head in every sources node can be calculated accurately from the physical arrangement. The kinetic energy results from source's flow and heads value. The potential energy depends on the elevation of water resources. The potential energy component is given by nature and it is smaller in the case of well intakes, them the surface reservoirs. The kinetic energy component is related to the productivity and efficiency of pumping stations.

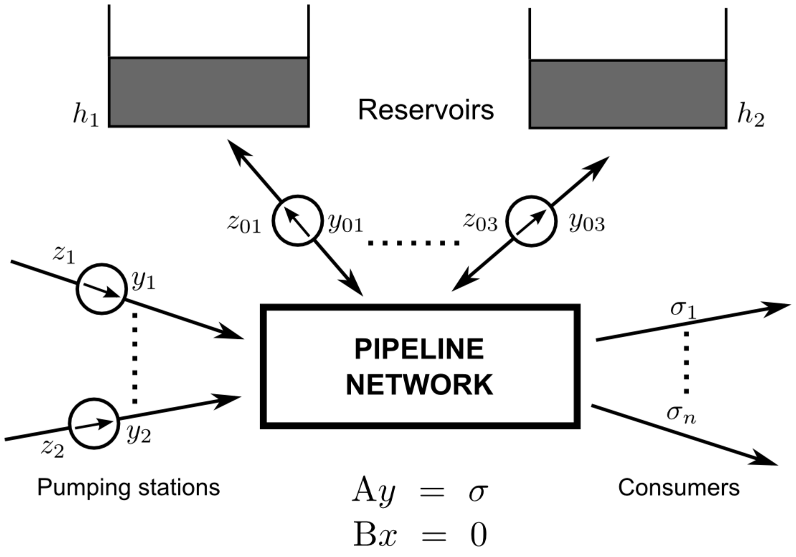

Fig.1. General structure of Water Distribution System

The following model of the kinetic energy provided to the network is used:

$$P_j\ (Q_j, H_j) = Q_j * H_j\ ;\ j = 1, \ldots, p \tag{1}$$

where H_j - is the head at j-th source node,
Q_j - is the flow at j-th source node,
p - is the total number of sources nodes.

Energy provided to the distribution network can be partitioned into three parts. One part is energy stored in the water tanks. Thanks to the algorithm described in [7] this component can be fully controlled.

Similar is not possible for other two components:

- energy provided at consumer nodes, when water is delivered,
- energy losses during water transportation process between source and consumer nodes.

The possibility of control of the two aforementioned components is discussed below.

2.1 Energy losses in a pipeline network during water transportation

Energy losses in the pipeline network during water transportation from pumping stations to consumers result from the network topology and hydraulic resistance of pipelines. The flow in each pipe i can be described as y_i, $i=1,2,\ldots,n$. The head difference x_i between two ends of a pipeline (Fig.2) is given by the following formula:

$$x_i = k_i \cdot y_i^2 \cdot \mathrm{sgn}(y_i) + d_i \qquad i = 1,\ldots,n \tag{2}$$

where d_i is the difference of elevations between two ends of the pipeline and k_i is the resistance of the pipe segment.

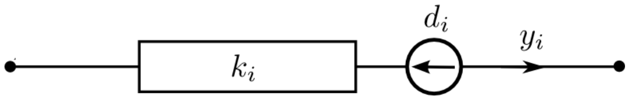

Fig.2. Elements of arc in the network.

Topological properties of a pipeline network are described by incidence matrix $\boldsymbol{A}_{[m\times n]}$ (where m denotes the number of nodes) and by loop matrix $\boldsymbol{B}_{[n\times o]}$ (where o represents the number of loops). Full description of physical rules in the pipeline network is known owing to the Kirchhoff's laws:

- The first law - material continuity at a node

$$\boldsymbol{A}\,\boldsymbol{y} = \boldsymbol{\sigma} \tag{3}$$

where $y \in R^n$ and $\boldsymbol{\sigma} \in R^m$ is a vector of consumers demands.

- The second law - loop equations

$$\boldsymbol{B}\,\boldsymbol{x} = \boldsymbol{0}; \quad \boldsymbol{0} \in R^n \tag{4}$$

The model of water distribution network consists of three aforementioned equation (2)-(4). While modelling water distribution network [1, 6] we could tackle it, putting the expression (2) into equation (4), and then solving the set of nonlinear equation (3),(4). But the simultaneous equation that appear on the *WDN* model can always be handled in an easier way, if we take into account energy minimization rules.

The function describing power loses in the pipeline network during the distribution of the water are defined as follows:

$$f(y) = \sum_{i=1}^{n} f_i(y_i) \rightarrow \min \tag{5}$$

where the friction head (loss of head on *i-th* pipe line in Fig.2)

$$f_i(y_i) = k_i \cdot y_i^3 \cdot \operatorname{sgn}(y_i) + d_i \cdot y_i \ ; \quad i = 1,\ldots,n \tag{6}$$

3 MINIMIZATION OF ENERGY LOOSES

It is known [7, 8], that goal function (5)-(6) is strictly convex and that there exists exactly one minimum that satisfies (2)–(4) constrains. The obtained analytical results [11] show that optimal solution do not depend on spatial variations of consumer demands $\boldsymbol{\sigma}$. The proper cooperation between source nodes is the crucial element of the necessary and efficient condition for the optimal solution. Having fulfilled consumers' demand, it is necessary to provide the output heads at source nodes in such way that they do not disturb working conditions of each other [10].

In connection with the above, now our main goal is to find such sources head value, that:

- consumers flow demands are fulfilled,
- constant head differences occur between each two source nodes.

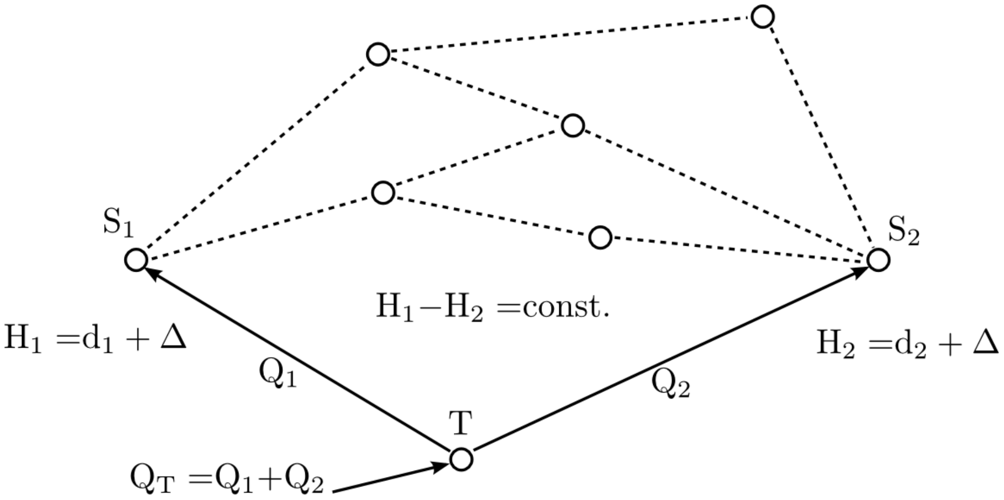

Fig.3. Modification of network model for transport costs optimization.

Taking into account the requirements mentioned above, we propose modification of the network model for simulation purposes of *WDN* (Fig.3). The set of nodes is extended by one artificial node *T*. This additional node is connected to all existing sources by the set of arcs. The corresponding Q_T flow at the node *T* is equal to the sum of receivers' demand. The heads value proportions are constant for each two source nodes and correspond to optimal sources conditions. Now the realization of this rule in operative control is easy to obtain. The optimal control of *WDN* is practically reduced to sources heads control [8, 11]. The appropriate flow value results directly from the given, modified water distribution network model (fig.3).

3.1 Energy delivered to consumers

At first glance, the fulfilment of consumers' demands in water distribution network is understood as water delivery to satisfy their needs. This requirement can be also viewed as a minimal velocity head, necessary to maintain that demand. Taking into account both of these factors, which define energy delivery problem, in further consideration the energy losses, cause by too high velocity head, occurs as a main disadvantage.

Energy losses at consumer node may be defined as a function of differences between indispensable head at consumer node and actual one. Each receiver *w* can reduce the head to the appropriate value, which can guarantee realization of demand σ_{w}.

In general, too high head value at a consumer node causes energy loss that has three main components:

- losses at consumer nodes; generated by excess head, because they are greater than necessary,

- losses at source nodes; very often, total dynamic head on the output of pumping stations or tanks are greater than necessary head resulting from the localization of sources,
- transport losses; leaks and burst, as a result of excess head during water transportation within the network.

The problem of energy losses minimization has not been considered enough yet. As mentioned above, we are quite familiar with transportation losses, but the other two aspects still need research work. The main difficulties are associated with varying in time and space consumer demands. However, the main control rule is well known: water should be delivered to consumers under such conditions, that velocity heads at each consumer's node should be minimal and expected flow must be ensured.

When the velocity head is too big, consumer reduces it, causing energy losses in the system. This attempt is not recommended in operative control due to unknown real heads as well as spatial and time distribution of consumer demands. However, for simulation purposes the distribution of both functions is assumed to be known. The goal function, describing power losses at the consumer's node during distribution of water, is defined as follows:

$$z(\sigma, H) = \sum_{w=1}^{m} \sigma_w \cdot (H_w - h_w) \to \min \tag{7}$$

where h_w - is indispensable head at consumer's node w,
σ_w - is demanded flow at consumer's node w,
H_w - is a head at the consumer's node w.

The algorithm of solving energy losses problem (7) starts when solution of problem (5) is known. At this starting point the minimal transportation energy losses are guaranted. Next, the solution of the goal function (7) under (2)-(4) constrains is constructed. There are p directions of searching determined by additional arcs connected with the new T node. The minimum at each p direction is given by one of the well known simple searching method e.g. Gauss and Seidel [5].

For the optimization purpose we adopted the modified *WDN* model, obtained from the one presented in Fig.3. Each additional arc j is parameterized with resistance k_j. In each r iteration the running value of k_j resistance is modified according to the formula:

$$\Delta k_j^r = k_j^{r-1}(z^{r-1} - z^r)/(Q_j^r)^3 \tag{8}$$

where $k^{r-1}, k^r \in R$.

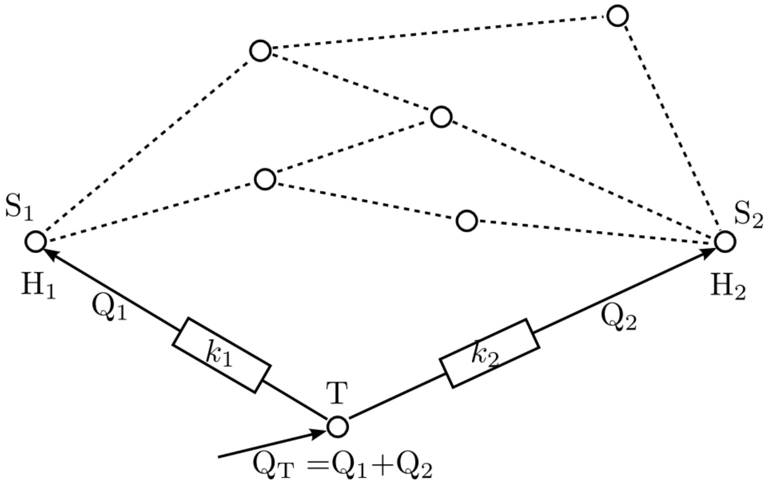

Fig.4. Adaptation of network model for minimization of losses at consumer nodes.

The procedure described above started from the solution of minimization problem (5) with (2)-(4), (6) constrains which determine minimal energy losses during water transportation. Next, it determined new acceptable consumer energy losses. It reduced, in an iterative way, source's total dynamic heads in such a way, that consumer heads are still higher than minimal. This guarantee the realization of consumer demands σ. This iterative process lead up to finding the balance between optimal solution of (5) and (7). In subsequent iterations, we minimize (7) what exacerbate (5). We do this so long, until obtained results come abreast with the arising losses from (5).

3.2 Water tanks energy balance

Network adaptatation properties relie on variable consumer demands that change in space, time and volume. The dynamic properties of *WDN* strictly depend on the tanks' presence in a network. This increases the adaptive possibilities of the system when the consumer's flow demands change in time and space. But tanks not only accumulate water but also energy. The network capacity depends also on the pipelines network capacity but due to the incompressibility of water, the main locations of energy accumulation are tanks.

The possibilities of tank's energy accumulation are significant due to two main properties:

- there are the time-varying wholesale cost of electricity (consumed generally by pumping stations);
- the consumer demands vary in time and space but the velocity heads should be at appropriate level.

Let us assume that optimal control strategy of filling the tanks is known. The filling process takes place when consumer demands are small and electrical energy prices are at low level. The head in each source (e.g. a pumping station, a tank) should be at appropriate level. The maximal head value on the tank output depends on water level, but the possibility of controlling that is constrained. If the head is too high, we could reduce it on the output of tank or consumers do it at consumer nodes. In both cases, it is necessary to use valves and some energy losses are generated.

How can these losses be minimized? If we decide to equip water distribution network with tank, its presence implies some network topology modification. The tank location and its volume cannot be random. We must take into consideration that tank works either as consumer or as source. In the first case, there is at least one condition, which should be fulfilled. Namely, the hydraulic resistance between the pumping station and tanks should be minimized. It suggests that high diameter pipeline connections between the pumping station and the tank should be used [2].

High diameter pipelines cause that during tank filling procedure the hydraulic resistance between pumping station and tank is minimized. In this way both; excess velocity head and friction head (losses of heads on pipe lines and fittings) losses are minimized too. When tank works as source, the high diameter pipeline increases energy losses in the pumping station. We try to counteract these using tank output valves. But a head reduction at tank's output valve generates also energy losses and changes water deliver

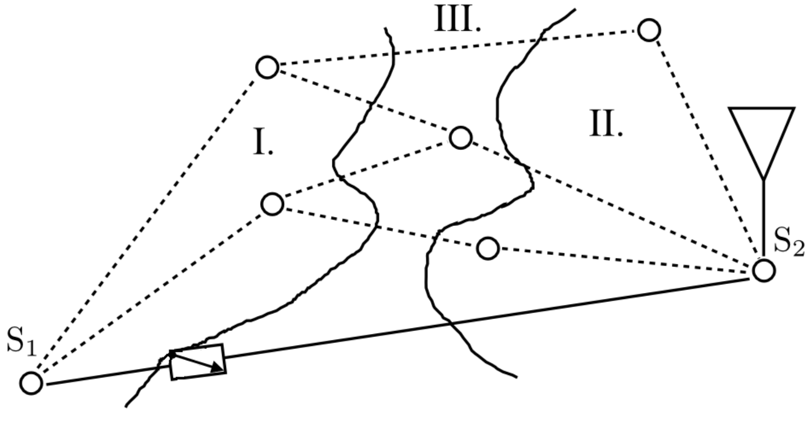

Fig.5. Water distribution network model with check valve and tank.

Our proposal is based on a specific valve system (check valves). They will be located in selected pipeline segments, not in the tanks' outputs. The proposed valves have non-linear characteristic similar to electronic diodes. This system should enable tank filling at night, as well as the reduction of the possibility of water overhead in pumping station when tank works as sources. Through simulation of the WDN, which consists of one source and one tank, three separate areas are determined (Fig.5).

The first area, marked ***I***, is always supplied from the source. To the second ***II***, water is delivered only from the tank, when it works as source of water. To the third area ***III***, water can be delivered from both elements and this depends on actual consumer's demand distribution. Generally, the proposed valve location should be within III area, on the main pipelines that connect tank and pumping station, closer to the areas ***I-III*** line border.

In this way, the minimal energy losses are guaranteed during water transportation in both directions, back and forth to water tank. During tanks filling process we have a profitable lower hydraulic resistance between pumping stations and tanks. Traditionally, when the reservoir supplies water to a network, network pressure becomes higher and this adversely affects the pumping stations. In proposed solution valves provide high hydraulic resistance when tank supplies water to a network and low hydraulic resistance during tank filling process. This reduces energy consumption rate for pumping stations.

4 CONCLUSION

Water Distribution Systems can be called *smart* for two reasons; they are widely designed and effectively managed. In our considerations we focus on minimization of energy consumption within the network. We identified two components of energy losses:

- energy losses during water transportation process between source and consumer nodes,
- energy losses at consumer nodes, when water is delivered.

Smart management is to benefit from natural behavior of the system resulting from its normall operation. *WDN* in a natural way implements the second Kirchhoff law, which guarantees minimum energy loss (5) during water transportation. This law lies at the heart of the proposed modifications (Fig.3) which guarantee minimization of transport costs.

Concerning energy losses (7) at every consumer nodes, when water is delivered, the *WDN* system itself will not guarantees minimum energy loss. Therefore, we have proposed an algorithm which allows us to find optimal solution.

Finally, if the network is equipped with tanks, we must face with two completely different situations. In this field, our proposal is the use of check valves, which completely change the structure of the network, when the situation is changing dramatically. The tank becomes to be a supplier or consumer of water.

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