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Optimization of energy cost in water supply system

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Abstract. The decreasing amount of fossil fuels and deteriorating air quality forces the governments to introduce a rational energy management in all sectors of economy. At the beginning of the twenty-first century many water supply systems (WSSs) were oversized because of the reduction of water consumption, especially in industry. This resulted in high energy consumption in the pumping stations. Improving pumps operation will decrease energy consumption and also the water prices. The purpose of this paper is to present a method of energy optimization in WSSs. This paper presents an analysis of energy consumption in a selected water supply system. In this study pumps located in water treatment plants and pumping station cooperating with the tanks are analyzed. The study used hydraulic model of the WSS created in MOSKAN-W, which defines pumps' parameters such as flow, head, and efficiency. Using optimization options of calculation software several scenarios of energy costs were prepared.

1 Introduction

Nowadays the high demand for energy is observed, thus means of efficient electricity management become more important subject-matter than ever before. Responsible use of energy is important not only from the economical point of view but increasingly from environmental as well. According to the European Union Directive 2012/27/ EU plan, by 2020 CO_2 emissions should be reduced by 20%, share of energy produced from renewable sources increased to 20%, and the energy efficiency of all production and maintenance processes improved by 20%. European Union countries are forced to reduce energy consumption in all sectors of their economies, thereby water supply companies. Water supply systems (WSS) are required to provide population with water of satisfactory quality and sufficient quantity. For this purpose, water companies use variety of water treatment and transport processes, which are highly electricity consuming. It is estimated that means of water distribution absorb from 3% to 7% [1, 2] of electricity, worldwide. According to Copeland and Carter [3] energy consumption in WSS is distributed as follows: 67% for tap water pumping, 14% for water treatment, 11% for raw water pumping and 8% for in-plant water pumping (e.g. backwash water of filters). While Vilanova and Balestieri [1] state that

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80-90% of electricity consumption, due to water distribution, comes from running of pumping stations. These and many other researchers point the pumping stations to be a significant contributor to electricity consumption. Therefore any efficiency improvements in involved processes would be highly desirable.

There are several methods that have proven to have positive impact on reduction of energy consumption in WSS [2–4]. They can be divided into three groups: (a) implementation of control and monitoring systems SCADA (Supervisory Control And Data Acquisition), (b) installing higher efficiency pumps motors, and drives, (c) generating energy in WSS using alternative energy sources.

SCADA is used in water supply system to, through use of field devices, gather data such as: water flows and pressures, valve settings, tank storage levels, and pump operation states. SCADA's data can be used to determine the optimal parameters of pumps' working states among the others, to minimize energy consumption. For example through adjusting pump settings according to varying water demands. Dispatcher can analyze these data in a real time and control operating parameters of pumps and valves thus maintain the entire water supply system at the highest efficiency level. Trough above mentioned actions water facilities can achieve energy savings of 5% to 10% [4].

Nowadays, many WSS are oversized and rarely work at their full capacity, which often makes pumps to work at their non-optimum yield. In such situations usually throttling valves or a bypass lines are used. However, their use is not the best solution as throttling valves reduce pump efficiency by shifting their operating point away from its optimum efficiency level. Bypass lines redirect part of the flow thus they do not have much influence on pumps' operating point. An alternative to these solutions is Variable Speed Drives (VSD) which can control pump`s pressure or flow by varying the pump's rotational speed. Additionally use of VSDs allows reduction of pipe breaks (which often happen when switching pumps) thus increasing likelyhood of secondary water contamination due to breaking a bioflim. These drives can provide energy savings of 30–50% according to some sources [5], or of 10–20% according to Coelho and Andrade-Capos [3]. Yet, the most effective way to reduce electricity consumption would be to replace pumps with new ones with capacity matching water demands. The new pumps should be chosen respectively to system's capacity and operating conditions. If pumps are selected based on an actual flow and pressure a better efficiency improvements than from using VSD, alongside further cost reduction can be expected.

Using renewable energy sources in WSS is becoming more and more common. Excluding costs of implementation, these systems have many environmental and economic advantages. The renewable energy solution used in WSS can be divided into three kinds: (a) solar, (b) wind and (c) hydropower generation. For WSS the more effective and less expensive to implement solution is use of pumps as turbines (PAT). Water turbine is simple system for generating electricity, which is based on using pressure energy and speed energy of transported water. There are two kinds of turbines: (a) impulse turbine which changes the direction of water flow and (b) reaction turbines which converts water pressure and kinetic energy into energy. Many pumps available on the market can be used as turbines (in micro-hydroelectric plants with capacity of up to 100 kW) [5, 11]. However, PAT is very sensitive to changing parameters, especially head, and characterized by low efficiency, between 30% and 60%.

As it can be seen, there are many ways to reduce energy consumption in WSS. Choice of the best economic and environmental solution of energy optimization in WSS depends on reliable analysis of data and working regime of water distribution network. For this propose a hydraulic model of WSS can be used. Nowadays, modern IT techniques enable the integration of SCADA, GIS and CIS systems, resulting in dynamic models of WSS. This is a very difficult process, requiring knowledge about: all systems SCADA, GIS, CIS, the working regime of WSS, and random events (e.g. pipe failures). The software used in modeling beyond the hydraulic calculations has also optimization functions of energy consumption. All the optimization goals of WSS are in majority multi-criteria optimization tasks. There are several types of optimizations which allow to find global extreme of multi-criteria function (Integrated Objective Function-IOF), which is based on stochastic algorithms that use probability theory to define iterative method. Group of these algorithms includes, among others: genetic algorithm, clustering algorithm, evolution algorithm, and simulating annealing, accelerated random search, ant colony optimization artificial bee colony (ABC) algorithm [6–10]. In stochastic optimization algorithm the objective is to find points in which the given integrated objective function (*IOF*) reaches its global extreme. The aim of the optimization in *n*-dimensional space is to find optimum value (decision variable x^{opt}) in a feasible set X_d fulfilling relationships mentioned below:

- finding global minimum: $$\exists_{\mathbf{x}^{opt}} \forall_{\mathbf{x}\in X_d} \quad IOF(\mathbf{x}^{opt}) \leq IOF(\mathbf{x}) \tag{1}$$

- finding global maximum: $$\exists_{\mathbf{x}^{opt}} \forall_{\mathbf{x}\in X_d} \quad IOF(\mathbf{x}^{opt}) \geq IOF(\mathbf{x}) \tag{2}$$

Therefore, there is a set $X \subset R^n$, which is a compact set, and a function $IOF : X \rightarrow R$ which is a continuous function. When looking for global minimum is for feasible set there is such X that:

$$X_d = \arg\min(x) = \{IOF(x*) = \min IOF(x))\} \tag{3}$$

For this task it should be used formula:

$$\mathbf{X}_t = T_t(X_{t-1}, \mathbf{Y}_{t-1}), \text{ for } t \rightarrow \infty \tag{4}$$

where T_t is the algorithm's mechanism, and Y_t is a random variable. To solve this problem various algorithms would be used, some of which are more or less complex e.g. Pure Random Search (PRS), algorithms autonomous over time, evolutionary algorithm and algorithms not autonomous. Stochastic optimization algorithm funds its use in solving of integrated objective function for variety cases of dynamic exploitation systems, which include water systems.

2 Research object

The research object is a large WSS which supplies water to over 3 million customers. The area covered by the network is hilly with elevation differences equal to 120 m. The system is over 880 km long and it is divided into eight major divisions of networks region. Total average water production is about 330 000 cubic meter per day. Due to the closure of large factories and reduction of water consumption by productions companies, the water production of this WSS has dropped by about 40% in last 10 years. The WSS is composed of 11 water treatment plants (WTP), 15 pumping stations and 9 complexes of storage tanks with total capacity of over 374 000 cubic meters.

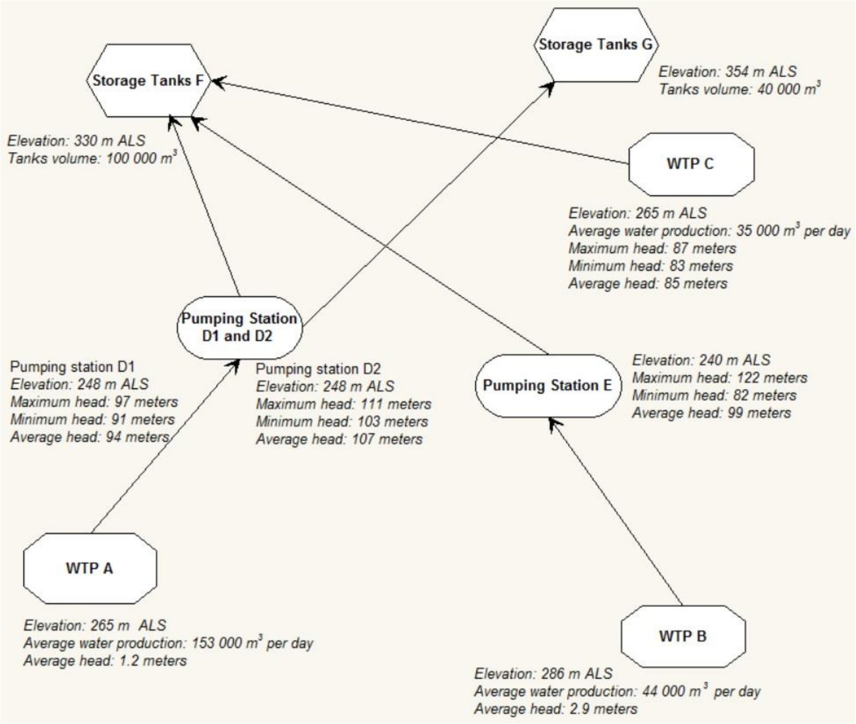

Fig. 1. Schematic diagram of a separate area of the water supply system.

This research looks in particular at the southern area of this WSS (Fig.1), including three main water treatment plants (WTP A, WTP B and WTP C) and four pumping stations (Pumping Station D1, D2 and Pumping Station E) and two reservoirs (Storage Tanks F and Storage Tanks G). Water produced by these three WTPs amounts to about 232 000 cubic meters per day, which is 70 % of total water production of this WSS. Studied WSS uses gravity and pumping to convey water to bulk buyers, delivering in this way about 56 000 cubic meter per day. Storage tanks F situated in central area of whole supply region are a strategic element of WSS, their capacity is 100 000 cubic meters. They are filled by three water treatment plants and distribute water to the northern and south-western part of the water supply area. Elevation differences between storage tanks F and WTPs are measured to be around 70 m, that’s why water has to be pumped to the tanks by pumping stations (D1,D2, E) situated in the network and WTP C. Second storage tanks are supplied only by: WTP A (pumping station D2) and WTP C (drinking water pumping station). Storage tanks F transport water to the northern part of the analyzed region.

2.1 Pumping stations

The southern area network includes the following six pumps stations (Table 1), which went through the energy consumption analysis:

a) WTP A contains eight pumps, but water is transported by gravity to pumping stations D1 and D2, this is more economical solution (elevation differences equal to 17 meters);

b) WTP B contains five pumps which are inactive for most of the time as the relatively small amounts of water demanded can be delivered by gravity due to elevation differences with pumping station E;

c) Pumping station D1 contains four pumps. During normal conditions of its operation, there is active only one pump with nominal flow 1400 m^3/h. When power plant, situated between pumping station D1 and storage tank F, connects to the network, a dispatcher switches a pump to a one with nominal flow 2400 m^3/h;
d) Pumping station D2 contains nine pumps and can work at different capacities. Usually only one small pump with nominal flow 1800 m^3/h is working, but in case of increased water demand this pump is switched to one with nominal flow 3600 m^3/h;
e) Pumping station E contains seven pumps, during normal operation there are two active pumps with nominal flow 1400 m^3/h or one pump with nominal flow 2400 m^3/h;
f) WTP C contains nine pumps, during the normal work of the pumping station of drinking water, there is one active pump with nominal capacity 1800 m^3/h, but when the water demand decreases, dispatcher can switch to pump with nominal flow 1167 m^3/h.

3 Research methodology

In this study hydraulic model of water supply system was used to perform a variety of simulations. Hydraulic model used in research is created and computed for average demand values (for period 1-31 October 2016) and checked for maximum water demand and minimum water demand. A water network graph is generated from data, collected using GIS and SCADA, and transferred to modeling software MOSKAN-W. MOSKAN-W created by ISB PAN uses calculation algorithms contained in Epanet 2.0. It also has optimization options developed on the basis of stochastic algorithms. This research uses Random Search Algorithms (RSA)[13] to calculate energy cost in pumping stations, using equation (5):

$$IOF_c = \min_{x \in S} f(\mathbf{x}) \qquad (5)$$

where **x** is a pump speed (vector of n decision variables), S is pressure in pumping stations (feasible region) and f is a function defined over S, IOF_c is energy cost. The region S is defined by fuzzy sets [14], where criteria and limitations can be approximated by the trapezoid function shown in Fig. 2.

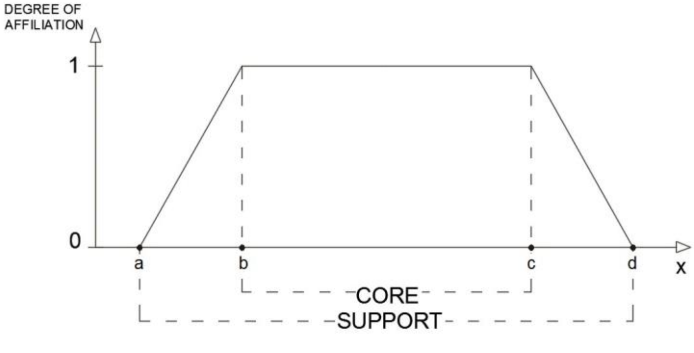

Fig. 2. Trapezoid-Shaped Membership Function.

Core is a simple non-fuzzy set, so-called an universe X and Support is a fuzzy set A. Trapezoid function is described by the following equations (6):

$$\mu_{\mathrm{A}} = \begin{cases} 0; & x \le \mathrm{a} \\ \frac{x-\mathrm{a}}{\mathrm{b}-\mathrm{a}}; & \mathrm{a} < x \le \mathrm{b} \\ 1; & \mathrm{b} < x \le \mathrm{c} \\ \frac{\mathrm{d}-x}{\mathrm{d}-\mathrm{c}}; & \mathrm{c} < x \le \mathrm{d} \\ 0; & x > \mathrm{d} \end{cases} \tag{6}$$

where x is variable, a, b, c, d are parameters of affiliation function and μ_{A} is the affiliation function, which determines to what degree element x belongs to set A. The equations (6) means that:

– if $\mu_{\mathrm{A}}=0$ – variable x does not belongs to the set A
– if $\mu_{\mathrm{A}}=1$ – variable x fully belongs to the set A
– if $0<\mu_{\mathrm{A}}<1$ – variable x partially belongs to the set A

In conducted research the following data was defined for pumping stations: minimum and maximum pressure and range of pump speed, and for the whole area: minimum and maximum energy cost. The simulation was ran for a period of 72 hours for four scenarios:
a) normal network operation when all network objects are working. Optimization for this scenario is carried out for three cases: maximum water demand, minimum water demand, and average water demand;
b) using backup pumps, in this scenario we used pumps before the modernization (in 2015 took place modernization of PS);
c) WTP B shutdown, this situation occurs when the water turbidity rapidly rises to very high values, e.g. in September 2007 water turbidity increased to 285 NTU;
d) WTP A shutdown, this situation happened once in 2003 during power failure. In scenarios "c" and "d" WTP C increased water production and opened second pump to complement water shortage in storage tanks F and G. In this scenario storage tanks delivered water to pumping station D direction by gravity.

For each object energy cost was put to calculation software (average 0.23 PLN per KW-hr) and run simulations. The results of simulations are shown in Table 1. After that, optimization calculations were started, which results are shown in Fig. 3 and 4. Value above the graph is the result of optimization, while the value below graph is an initial value for calculations, for example in scenario A, initial value for pressure of PS "D1" equals 89.86 meters and value after optimization equals 93.47 meters.

Table 1. Energy cost before optimization for each scenario.

Scenario A		Scenario C	
Daily energy cost	16 981.85 PLN	Daily energy cost	16 568.47 PLN
Annual energy cost	6 198 375.25 PLN	Annual energy cost	6 047 491.55 PLN
Scenario B		Scenario D	
Daily energy cost	18 443.76 PLN	Daily energy cost	15 265.32 PLN
Annual energy cost	6 731 972.40 PLN	Annual energy cost	5 571 841.80 PLN

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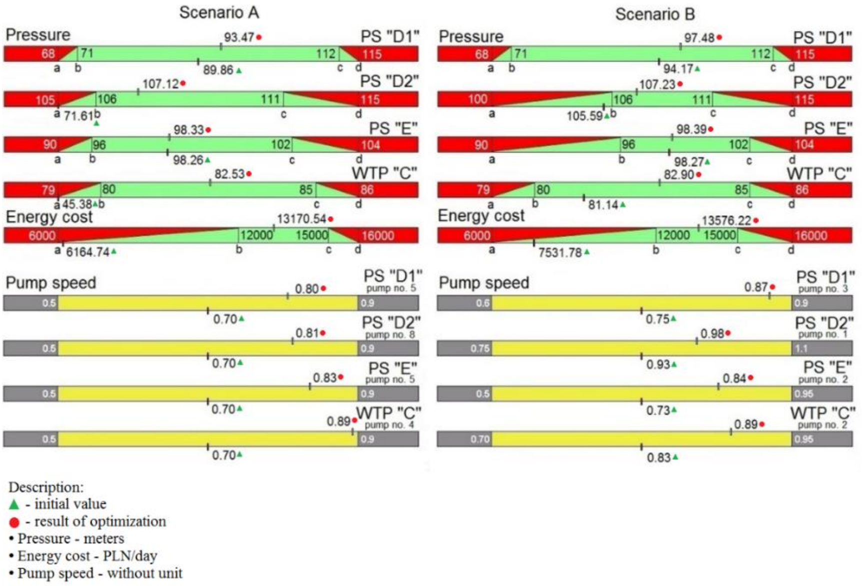

Fig. 3. Optimization results for Scenario A and B.

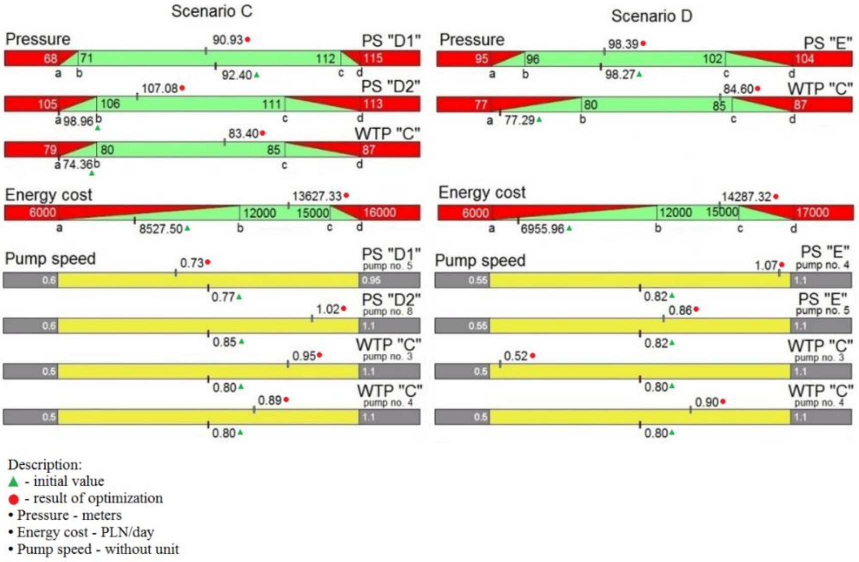

Fig. 4. Optimization results for Scenario C and D.

4 Conclusions

The paper presents optimization of energy consumption in the pumping stations using hydraulic model of WSS. Optimization options used in calculation software are based on stochastic methods with elements of fuzzy sets. The purpose of the study was to find the lowest pump speed for the desired range of pressure and energy cost. The methodology has been tested on a real water distribution network. In this study there were four scenarios conducted to find the most advantageous network operation. All simulations were run for a

given time horizon (72 hours). For each scenario, the following energy costs and costs reduction were achieved:
– scenario A: 13 170 PLN/day – 22.0% reduction
– scenario B: 13 576 PLN/day – 26.4% reduction
– scenario C: 13 627 PLN/day – 17.8% reduction
–scenario D: 14 287 PLN/day – 6.4% reduction

The study was focused on the pump speed control, which has a strong influence on the energy consumption of the pump systems and it is easy to determine with the model. The average reduction in energy cost is about 18%, the highest cost reduction (but not the lowest energy cost) was achieved in scenario B, which presents operation of old pumps, indicating that earlier pump systems had lower efficiency and were oversized. The energy cost difference between scenario A and B, before optimization, is about 8%, which shows that replacing pumps with new ones gives good results, but not the best. The similar effects can be achieved by using other elements of system improvements, such as the use of pumps as turbines to generate energy.

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