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Selection of Pumps as Turbines Substituting Pressure Reducing Valves

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Abstract

Technical standards define operational limits for hydraulic parameters such as velocity or pressure. On this way, pressure control is a fundamental component for safe operation at water supply systems, mainly to reduce leakage, risk of disruptions and maintenance costs. The system topology and topography can define some high pressure zones and in this case the use of Pressure Reducing Valves - PRV - to maintain standards pressures on the sector is common. However, all the energy available on the fluid is dissipated trough headloss. A turbine could be used instead of the PRV to produce electrical energy and to control pressure. In general, the power available in these sites is under 100 kW, so the use of Pumps as Turbines - PAT - is recommended to reduce the investment. Due of the dynamic operation trough a day, the PAT will operate under different conditions of flow and head. This variation will affect its efficiency and head loss, which difficult the selection trough conventional methods. Therefore, this paper proposes a method for PAT selection to operate instead a PRV. The method is based in the maximization of the energy produced, constrained to the pressure limits on each node of the network. To solve this problem, the optimization technique PSO is used and the available curves in literature, on the Suter plane, are used to simulate the PAT. The method is applied on a network and the results are compared with the PRV operation.

Keywords: Pumps as Turbines; Optimization; PSO

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1. Introduction

Rational use of natural resources is increasingly important, not only for economical issues, but mainly for environmental reasons. The good operation of a water supply system is crucial for the sustainable development of a city, since they are large consumers of their water and energy resources. Climatic, social and political factors influence the consumption, and consequently the operation of a water supply system. In this context, the concept of Smart Networks arises, ensuring high quality service to inhabitants [1]. Field measurements creating a database and mathematical modeling allow decisions to be made quickly, supplying the consumer through an optimized operation, in line with the economic and environmental aspects mentioned.

Pressure control is one of the most important issues for optimized operation of networks. It is an important task to reduce the leakage volume and avoid the disruption of pipelines. The topography and topology of the system define high and low pressure zones. Technical standards establish the maximum and minimum values accepted for operation. In Brazil, ABNT through NBR12218 [2] sets the pressure in a supply network between 10 m (dynamic pressure) and 50 m (static pressure). In the low pressure areas, boosters with frequency inverters can be installed to maintain proper pressure on the network. For high-pressure zones, it is common use Pressure Reducing Valves - PRV, to maintain a sufficient pressure in the entrance sector, keeping the critical node with the desired minimum pressure.

However, from the energy view point, PRV dissipate pressure energy adding a localized head loss to the system. This energy loss opposes modern principles of rational use of resources. From this new paradigm, energy pressure could be used to actuate a turbine coupled to a generator, producing electricity and keeping the pressure reduction commitment in the sector. Due to the low power found at these sites, the use of conventional turbines is not feasible. An alternative is to use Pumps as Turbines - PAT, which have low cost and good efficiency. [3] show a similar behavior between PAT and PRV, indicating the viability in using this solution. However, [4-5], carried out simulations in extensive period and observed that during periods of low consumption, PAT is not able to insert a sufficient head loss to reduce pressure to acceptable standards. [6] find similar response of a PAT and PRV in a system in Iran, where the demand change throughout the day is not very significant. [7] propose as alternatives to improve the pressure control use variable speed PAT or add a PRV in parallel, while [8] suggest the use of multiples PAT in parallel in order to operate in different arrangements, according to the variations of daily consumption.

Despite the obvious advantages of using PAT, the selection of the machine for this purpose is complex. Traditional methods such as those proposed by [9-12] are valid only for the pump best efficiency point (BEP). Without its characteristic curve (head x flow) it is not possible evaluate the benefits in a network, since there is a wide range of available head according to the consumption. Furthermore, the PAT operation must seek not only energy production, but also the pressure control.

In this context, this paper proposes a method for PAT selection operating in water supply networks. The method is based on maximizing the benefit represented by the produced energy and the leakage volume reduced. As operating constraint, the method requires that the PAT should be able to keep the pressure on each node of the network within the established limits. The Best Efficiency Point - BEP - of the machine is set through an optimization process based on particle swarm (PSO). From these values, the specific speed of the machine is obtained selecting the nearest curve. For this, a set of complete characteristic curves of pumps available in the literature [13] and represented in Suter plan is used. In the final stage, the network is simulated with the selected machine to calculate the energy produced and the nodes pressures. The method was applied to a fictitious network, available in [14], and the results were compared with the PRV operation.

2. Pumps as Turbines Modeling

The characterization of hydraulic machines is made through curves relating head, flow, torque and speed. The alternation of the signs of these parameters define eight distinct operation areas, which can be represented by Suter plan [15]. Figure 1 shows an example of the 14 curves available in the work of [13]. The red part of the curves shows the operating zone as turbine. For each of the available curves, this operation area was identified, and considering speed as the nominal, new curves relating the dimensionless coefficients of flow, q, and head, h, were obtained, as shown in Figure 2. This new representation allowed the adjustment of a power curve (Eq. 1). Therefore, just with the machine BEP, its characteristic curve in turbine mode can be obtained, using the available dimensionless curve with nearest specific rotation.

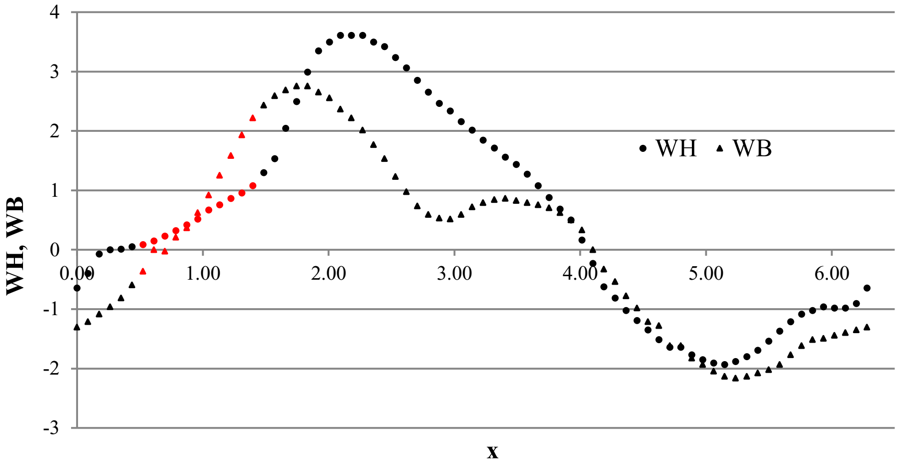

Fig. 1. Head and torque curves in Suter plan.

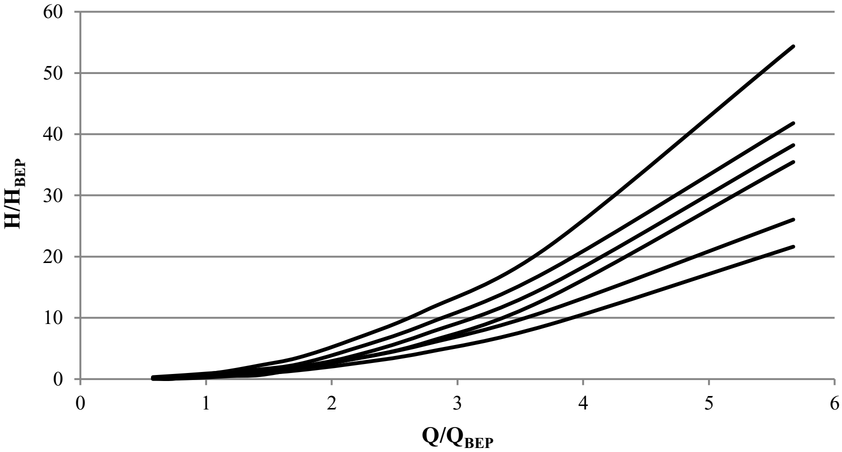

Fig. 2. Dimensionless curves in turbine mode.

$$h = a \cdot q^b \quad (1)$$

where:

a, b [dimensionless] - curve adjustment coefficients;

h [dimensionless] - head coefficient;

q [dimensionless] - flow coefficient;

3. PAT Selection Procedure

PAT selection is based on maximizing the benefit, defined by the energy produced and leakage volume reduced. Thus, considering the energy and water tariffs, the objective function is written as follows:

$$FO = \sum_{i=0}^{23}\left[t_e \cdot \frac{\gamma \cdot Q_i \cdot H_i \cdot \eta_i}{1000} + \sum_{j=1}^{n} t_a \cdot \left(Q_{j_1} - Q_{j_2}\right) \cdot 3600\right] \tag{2}$$

where:
FO [\$] - objective function to be maximized;
t_e [\$/kWh] - energy tariff;
γ [N/m^3] - water specific weight;
Q_i [m^3/s] - PAT flow in time i;
H_i [m] - PAT head in time i;
η_i [dimensionless] - PAT efficiency in time i;
n [dimensionless] - nodes affected by PAT operation:
t_a [\$/m^3] - water tariff;
Q_{j1} [m^3/s] - leakage flow in node j and time i before PAT installation;
Q_{j2} [m^3/s] - leakage flow in node j and time i after PAT installation.

As constraint, the pressure at each node affected by PAT operation must remain above the minimum limit pre-determined, as Eq. (3).

$$p_n \geq p_{min} \tag{3}$$

where:
p_n [mca] - pressure in node n;
p_{min} [mca] - minimum pressure established by standard.

To solve the optimization problem presented previously, it was used a meta-heuristic technique based on the behavior of groups, the Particle Swarm Optimization (PSO). This technique was chosen due its robustness and easy implementation. According to [16], the search process is based on the behavior of bird groups that initiate the food search randomly, but quickly organize and create a collective search pattern. Over time (iterations) the position vectors, X, and speed, V, of each particle are updated based on its inertia, its best position ever found, P, and the best position ever found by the swarm, G. Thus by Eqs. (4) and (5) a new solution is found at each iteration.

$$V_i^{k+1} = \omega \cdot V_i^k + c_1 \cdot rand_1 \cdot \frac{\left(P_i^k - X_i^k\right)}{\Delta t} + c_2 \cdot rand_2 \cdot \frac{\left(G^k - X_i^k\right)}{\Delta t} \tag{4}$$

$$X_i^{k+1} = X_i^k + V_i^{k+1} \cdot \Delta t \tag{5}$$

where:
V - particle speed;

X - particle position;
P - particle best position;
G - group best position;
The weighting coefficient of each component portion is given by:
ω - inertia coefficient;
c_1 - cognitive coefficient;
c_2 - social coefficient.

4. Results

To evaluate the proposed method, it was used the fictitious network shown in Figure 3, adapted from [14]. All pipes have 0.01 mm roughness and elevation of all nodes is equal to zero. The demand variations of this network is presented in Figure 4. In addition, it was considered that all nodes have a leakage contribution, calculated according to the pressure of this node (Eq. 6). Thus, it is also possible to compare the efficiency of the PAT reducing the leakage volume.

$$Q_l = K \cdot \sqrt{H_n} \tag{6}$$

where:
Q_l [l/s] - leakage flow;
K [l/s.m$^{1/2}$] - adjustment coefficient;
H_n [m] - pressure in node n.

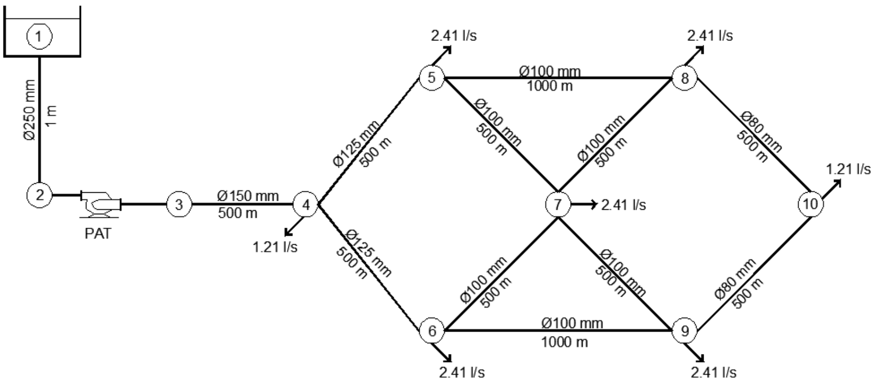

Fig. 3. Layout of water supply network [13].

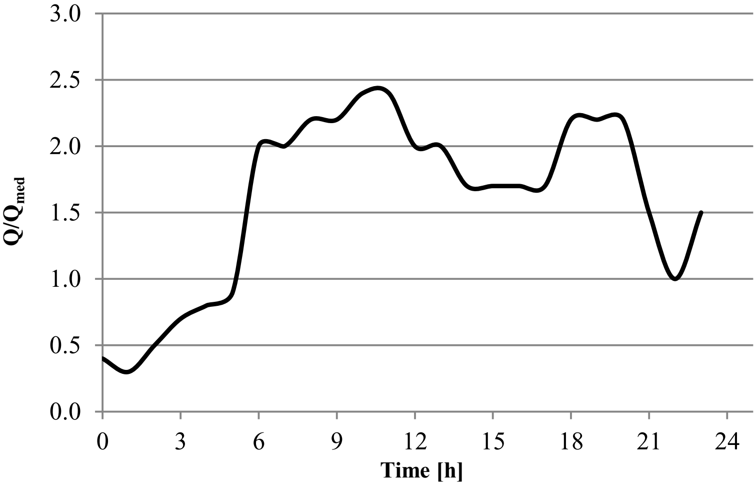

Fig. 4. Demand curve (Gomes, 2011).

As established by [2], critical node (node 10) must remain at least 10 m during the period of 24 hours. In this case, the PRV was adjusted to maintain an outlet pressure of 33 m. This configuration, there is obtained a reduction of 156. 4 m^3 volume of leaks. Subsequently, the choice of a BFT to replace the pressure reducing valve was taken. In this scenario, the operating point of the chosen machine is: Q = 29.11 l/s and H = 21.32 m. Figure 5 illustrates the behavior of the objective function, demonstrating the need for a robust technical optimization, justifying the choice of PSO. Figure 6 shows the evolution of the objective function with the number of iterations.

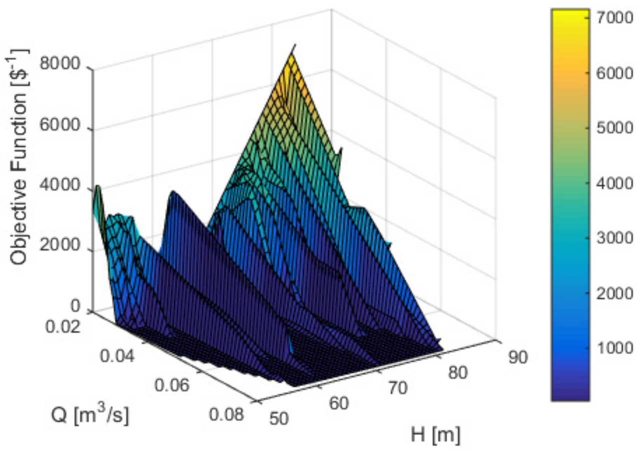

Fig. 5. Objective function of PAT selection problem.

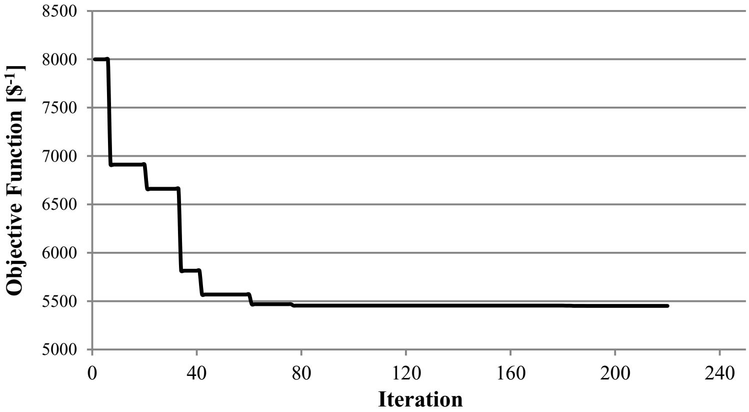

Fig. 6. Objective function evolution.

For this scenario the machine was selected to operate with best efficiency in the higher consumption period (6 to 23 h), where more energy is available. However, during periods of low consumption, there is no power generation and hence the pressure in the system remains high. Therefore, despite the 78 kWh generated, the amount of leakage was reduced by only 62.5 m^3, which corresponds to 39.94% of the volume reduced by PRV.

To improve the PAT pressure control, a second machine was selected to work in parallel and operate only in the period between 0 and 5 h. It resulted in a machine with the following operating point: Q = 9.51 l/s and H = 30.85 m. In this new scenario, there was an increase of 16.1 kWh of energy produced and 23.7 m^3 in reducing the leakage volume. Still, the PRV had better results in pressure control. However, it is necessary to evaluate the economic benefits of energy generation and reducing leaks, since a high energy tariff may lead to an attractive combination of both benefits. Figure 7 shows the pressure at the critical node for each of the situations studied.

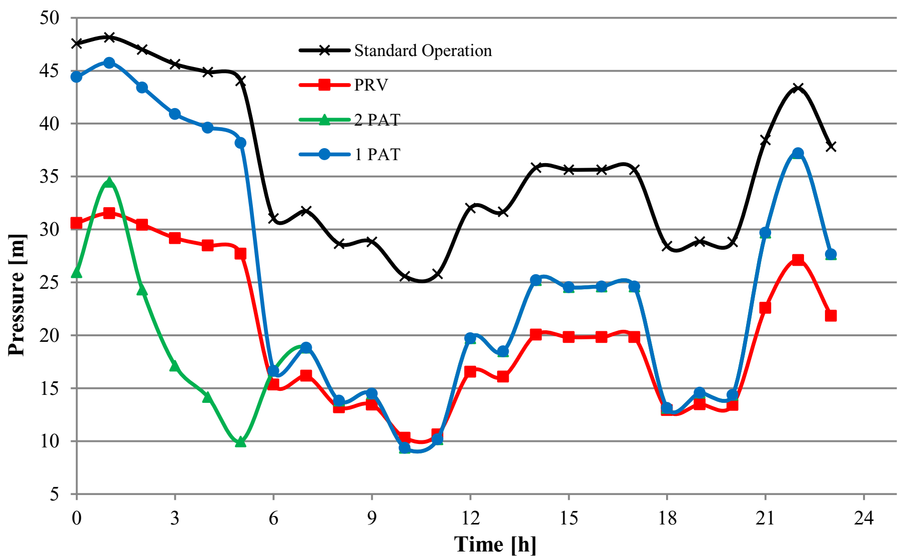

Fig. 7. Critical node pressure for different scenarios.

5. Conclusions

The presented method shows that the PAT selection occurs for the maximum flow observed in the period. In these conditions, despite the reduced pressure drop, the energy produced and the reduction in leakage volume are high. When compared to a PRV, the pressure control of a single PAT is similar only when the consumption maintains high. When flow through the PAT is low there is no energy production and the head loss produced is insignificant. Thus, it is not possible to ensure a constant outlet pressure with just one PAT. In the case studied, the use of an additional PAT for the night period improved the pressure control, almost matching PRV performance. However, the attractiveness of the investment will depend on the energy tariff, many times higher than the water production costs, which can enable the implementation of the micro hydro plant. For these reasons the presented method is fundamental to obtain the best economic solution for performing pressure control in water supply networks.

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