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Optimal Water Supply System Management by Leakage Reduction and Energy Recovery

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Abstract

In WDS characterized by significant variation in elevation, the necessity of pumping water to higher levels is conflicted by a requirement to reduce excess pressure. A multi-objective optimization methodology is presented to minimize leakage and to minimize the difference between operational pumping costs and income generated through energy recovery by strategically locating in the network Pumps operating As Turbines (PATs), which can act in an analogous fashion to conventional PRVs. The approach is demonstrated on a case study resulting in a clear economic benefit from installing PATs for energy recovery in conjunction with a combined pump-scheduling and pressure management regime.

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Keywords: Water distribution systems; Energy production; Pump As Turbine (PAT); Pressure Reducing Valve (PRV);

1. Introduction

In the management of a Water Distribution System (WDS), the pumping cost can usually be considered the predominant component of the total operating cost of the system [e.g. 1]. Several strategies have been developed for reducing pumping costs [e.g. 2, 3] including introducing variable electricity tariffs in the peak hours of the day.

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Attempts have been made to reduce costs by adopting a policy of considering a pumping schedule that should operate as far as is possible during the low cost regime [e.g. 4].

On the other hand, the aging process of the existing infrastructure leads the network inexorably towards the problem of increasing leakage which needs to be minimized - not only because this can affect the operational costs of the system but are representative of a lost volume of water resource. Given the largely pressure-dependent nature of leakage, the necessity of limiting the pressures within the network in order to reduce the volume of water lost is evident. This also requires ensuring the maintenance of acceptable levels of network performance [e.g. 5; 6; 7]. As both aspects above are of fundamental importance in the management operation, the importance of considering both as part of the same optimization formulation has been highlighted lately [e.g. 8; 1]. Furthermore, increasing energy costs has guided some approaches [e.g. 9; 10; 11; 12] towards using the pressure dissipation as a mechanism for energy production by inserting turbines or pumps operating in reverse which can act as a turbines (Pump As Turbines - PATs) [13].

On the basis of the above considerations, a novel multi-objective optimization approach which takes into consideration all of the aspects above is herein proposed. The principal aims of the optimization problem formulated are the minimization of leakages and the minimization of the difference between operational pumping costs and income generated through energy recovery.

The optimization procedure is undertaken by means of a highly-parallelized evolution algorithm [1] employing a pressure-driven analysis in order to evaluate the hydraulic constraints. Leakage quantification is done by allowing the specification of differing leakage exponents for each network node. Modelling of leakage characteristic for different pipe materials and situations is thus enabled. The same model is further able to quantify the under-delivery of water to satisfy the demand at each node.

Moreover, in order to accommodate uncertain futures, the robustness of the solutions is gauged by means of a probabilistic approach to uncertain parameters. Accordingly, the water demand is sampled from appropriate distributions [14] and integrated into the optimization process to drive it towards a more robust set of final solutions. The resulting solutions are further evaluated using Monte-Carlo simulation as a post-process. The approach is demonstrated on a real case study resulting on a clear economic benefit to installing PATs for energy recovery in conjunction with a combined pump-scheduling and leakage management regime.

2. Methodology

A multi-objective problem has been formulated by considering:

Minimize: *Leakage*
Minimize: *Annual Pumping Cost (APC) - Annual PAT Income (API)*

In particular, the leakage model considered [15] calculates leaks on a per-half pipe basis and then aggregates them into the demand nodes as per equations (1) and (2):

$$d_j^{leaks}\left(P_{j,mean}\right)=\begin{Bmatrix}\beta_j L_j P_{j,mean}^{\alpha_j} & P_{j,mean}>0\\ 0 & P_{j,mean}\le 0\end{Bmatrix} \tag{1}$$

where:

j = subscript of the j^h pipe;
$P_{k,mean}$ = model mean pressure along the j^{th} pipe in [m];
d_j^{leaks} = background leakage outflow along the j^h pipe in [m³/sec];
α_j & β_j = leakage parameters of the j^h pipe, dimensionless and [$m^{2-\alpha}$/sec];
L_j = length of the j^h pipe in [m];

$$\boldsymbol{d}_n^{leaks} = \frac{1}{2}\left|\boldsymbol{A}_{np}\right|\boldsymbol{d}_p^{leaks} = \frac{1}{2}\left|\boldsymbol{A}_{np}\right|\begin{bmatrix} d_1^{leaks} \\ \ldots \\ d_k^{leaks} \\ \ldots \\ d_{n_p}^{leaks} \end{bmatrix} \tag{2}$$

where:

$\boldsymbol{A}_{np}$ = the network incidence matrix;
$\boldsymbol{d}_n^{leaks}$ = the aggregated leakage attributed to the n^{th} node in [m³/sec]

The pumping cost, instead, has been considered by means of:

$$\text{pump cost} = \sum_{t=1}^{T}\sum_{k=1}^{N_p} P_k^t c_k^t \tag{3}$$

where: T - the number of time steps in the extended period simulation; N_p - the number of pumps in the network; P_k - the power consumption of the k^{th} pump [kWh]; c_k - energy cost tariff for the k^{th} pump [€/kWh];

The optimization is thus subject to the hydraulic equation constraints, for each time step:

$$\sum_{j=1}^{Nj,i} Q_j - Q_{DELi} = 0 \;\; (i = 1,\ldots,N_n) \tag{4}$$

$$H_{j,u} - H_{j,d} = r_j \cdot q_j^{\varepsilon} \;\; (j = 1,\ldots,N_l) \tag{5}$$

where: Q_j is the flow in the j^{th} pipe; Q_{DELi} is the delivered flow at the ith network node; $H_{j,u}$ - head at upstream node of the j^{th} pipe; $H_{j,d}$ - head at downstream node of the j^{th} pipe; r_j - coefficient of the j^{th} pipe (headloss formula, function of pipe length, diameter and roughness coefficient); ε is the flow exponent function of the headloss formula used; $N_{j,i}$ is the number of pipes connected to the i^{th} network node; N_l is the number of network links; N_n the number of network nodes.

Firstly, a solution must be hydraulically feasible – that is to say that there are no nodes in the network experiencing negative pressures and that all of the demands on the system should be met in full. The latter is achieved by specifying a minimum pressure constraint that all nodes in the network with a d emand must satisfy in order for a solution to be considered valid.

To produce a sustainable system operation, i.e. operation that is repeatable over successive days, a further constraint is implemented such that the final (i.e. end of scheduling horizon) level of any tank/reservoir in the system should be at least as high as it was at the beginning of the scheduling horizon. Additionally, the user may specify a time for each tank at which it must meet a specified level to meet any regulatory requirements.

$$P_i^t \geq P_{min} \; if \; Q_{DEL_i}^t > 0 \; i = 1,\ldots,N_n \;\; ; t = 1,\ldots,T \tag{6}$$

$$(L_{i,0} - L_{i,T}) \geq 0 \; i = 1,\ldots,N_s \tag{7}$$

where: N_s - the number of network tanks P_i – the pressure at the i^{th} network node; P_{min} - minimum pressure requirements for fully satisfy the water demand; $L_{i,0}$ – the level of the i^{th} tank at the initial time step, $L_{i,T}$ – the level of the i^{th} tank at the final time step.

The minimum pressure requirement has been set equal to 10m for all nodes with an associated demand. The extended period simulation has been considered of a single day with interval times of one hour. For each interval time the flow has been considered as a random variable and has been modelled by means of the Normal Distribution. The mean value is set at the base demand level at network nodes and the CV is set equal to 0.1, the case study considered being a large network which supplies a number of users greater than 1,000 [14]. For the purposes of pump scheduling, pump decision variables are defined as the unknown status of each pump (1 - working, 0 - not working) for each hour of the scheduling horizon (smaller time intervals can be used also, if appropriate). In addition, prior to the optimization, each pump may have its status fixed to "Always on", "Always off" or to respect the existing pump control as defined in the hydraulic model, i.e., to exclude it from the optimization process altogether. The selection of PATs can either be performed globally in which any PAT defined in the EPANET model can be installed with any of the PAT types defined or a restricted subset of the PATs can be replaced up to a user-specified quantity. In addition, the initial water levels of each of the tanks in the system can further be considered as decision variables.

The above problem has been constrained by considering all of the possible PAT allocations in the network by the allocation of different PAT curves which could be chosen as a function of the flow and pressures available at the point of installation. A wide set of PAT characteristic curves have been considered by varying the number of stages and impeller diameters in order to cover as wide a gamut of flow-pressures that might be encountered. In particular, for this case study, 33 different pumps of the KSB brand (www.ksb.com) have been modelled which can be employed as PATs in reverse mode. The rotational speed of the pump has been considered nominally 1450rpm while operating in turbine mode, rotational speed has been considered as 1500rpm.

The Best Efficiency Point (BEP) has been calculated accordingly with the formulation of Willliams [16] in which is possible to determine Q_{tb} and H_{tb} of the PAT from the BEP of the pump:

$$Q_{tb} = \frac{N_t}{N_p} \cdot \frac{Q_{pb}}{\eta_{pb}^{0.8}} \; H_{tb} = \left(\frac{N_t}{N_p}\right)^2 \cdot \frac{H_{pb}}{\eta_{pb}^{1.2}} s \tag{8}$$

where Q is the flow rate; H is the head; N is the rotational speed; η is the efficiency and with the subscripts p, t and b refers to pump, PAT, and BEP, respectively. According to the experimentation undertaken by Derakhshan and Nourbakhsh [17], the BEP of the PAT is assumed to coincide with pump BEP. The PAT power (kW) at its BEP can consequently be calculated by:

$$P_{tb} = \rho g Q_{tb} H_{tb} \eta_{tb} \tag{9}$$

where: ρ and g are the fluid density and gravitational acceleration respectively.

Because water demand varies in a water distribution network, it is also necessary to study the characteristic curves away from the BEP. The estimation of the PAT characteristic curves on the basis of the BEP has been undertaken by reference to the same experimental study described above [17], which is valid for a pump rotational speed of 1,450 rpm, a PAT Nt = 1,550 rpm and for centrifugal pumps with specific speed Ns < 60 (in metric units):

$$\frac{H_t}{H_{tb}} = 1.0283\left(\frac{Q_t}{Q_{tb}}\right)^2 - 0.5468\left(\frac{Q_t}{Q_{tb}}\right) + 0.5314 \tag{10}$$

$$\frac{P_t}{P_{tb}} = -0.3092\left(\frac{Q_t}{Q_{tb}}\right)^3 + 2.1472\left(\frac{Q_t}{Q_{tb}}\right)^2 - 0.8865\left(\frac{Q_t}{Q_{tb}}\right) + 0.0452 \tag{11}$$

The PAT power, P_t, can be calculated for each time interval in which the day has been segregated and for each PAT. The product of it for the time interval (Δt) in which the PAT is working in a day is the Energy (kWh):

$$E = \sum_{PAT=1}^{NPAT} \sum_{t=1}^{24} \rho \, g \, Q_t \, H_t \eta_t \Delta t \tag{12}$$

The PAT Annual Revenue can be thus estimated by multiplying the result of (12) by the number of the days in a year and by the energy purchase tariff . The cost of energy selling varies as a function of the total power generated. For example, according to Italian Financial law, energy price of 220 €/MWh could be considered for power generation schemes lower than 1 MW. The annual PAT income that needs to be maximized in the optimization problem is thus obtained by subtracting the PAT maintenance from the annual revenue. As a preliminary study, maintenance cost can be considered to be 15% of the total turbine installation costs, a function of the PAT installation costs and of the civil works required for its installation, which could be approximated as being 30% of the PAT installation costs [11]. The latter can be estimated on the basis of the installed power as being of the order of 545 €/kW, considering the sum of the costs of the PAT, the generator and the inverter required to connect the installation to the electrical distribution network [10]. The ratio between the total installation costs and the annual income determines the number of years before a return on investment can be expected.

3. Case Study

The case study analyzed has been the trunk mains model of the Sorrento Peninsula, Italy, managed by G.O.R.I. S.p.a.. It is located in the Campania region, between the Gulfs of Napoli and Salerno. It is supplies eight urban areas totaling around 90,000 users and an additional 70,000 seasonal users during the summer period. In particular the eight water distribution systems supplied by the system are: Vico Equense, Meta, Piano di Sorrento, S. Agnello, Sorrento, Massa Lubrense, Capri and Anacapri, as shown in Fig. 1. Two sources are responsible for supplying the entire system: the well field of Gragnano and the Fontana Grande source. The trunk mains system is located on a peninsula characterized by the Lattari mountain chain and supplies mountainside communities as well as WDS along the coastal areas. Because of the highly varying elevations of the systems, pumping stations are employed which supply the higher zones present in the network and correspondingly high pressures are established throughout the network that are reduced by means of Pressure Reducing Valves (PRVs), already present in the system. The entire system consists of two reservoirs, 68 tanks and 13 pumps. The proposed case study is of particular interest for the aims suggested in this paper, being a system in which high and low pressure zones coexist. This leads to the need to pump the water to the higher levels - and thus the necessity of minimizing pumping costs by scheduling the pump operation in accordance with the lowest-priced tariff - whilst simultaneously requiring the significant reduction of pressures in the coastal zones of the network - which is of interest for determining the trade-off between power-generation revenue and operational costs that can be obtained through the use of PATs.

The problem has been solved by considering the possibility of allocating PATs to replace the existing PRVs in the network. In order to constrain the search space, the total number of PATs to be installed has been limited to maximums of 10 and 15. As well as the 33 available PAT characteristic curves, an “install” nothing option is also available which, if selected, restores the original PRV arrangement. Furthermore, simulations have been undertaken by considering the water demand required by users firstly as deterministic and subsequently as probabilistic, allowing water demands to vary following the Normal distribution with a mean value equal to the base demand and a CV equal to 0.1. For the leakage estimation, the following parameters have been considered: α_j = 0,9; β_j= 4,00E^{-09}; simulations have been undertaken considering 24 hours of simulation with a time step of 1 hour.

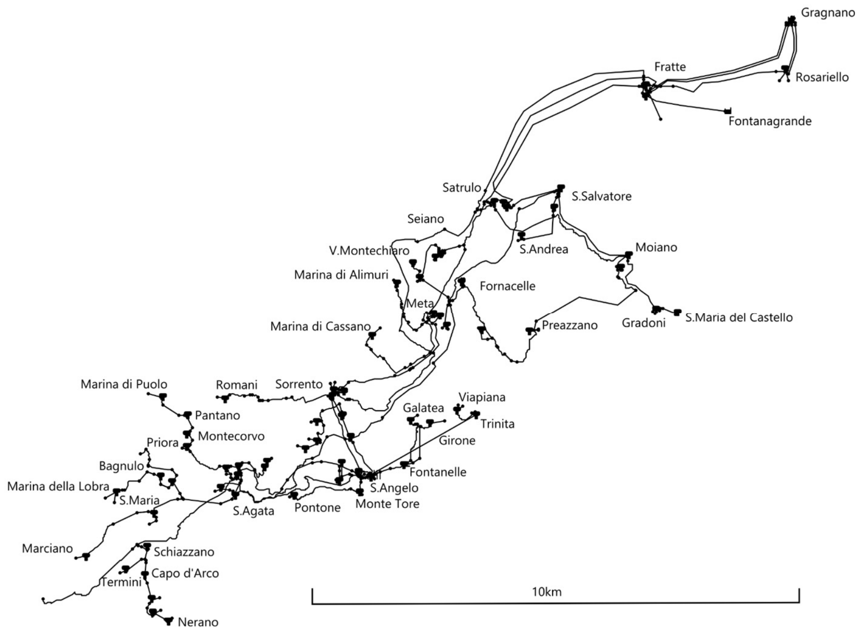

Fig. 1. Plan of the case study area

4. Results and discussion

The results obtained by applying the above approach are reflected by the following Pareto Fronts reported for the deterministic and probabilistic simulations, respectively, by considering the possibility of allocating in the system a number of installations ranging between 10 and 15 PATs. By minimizing the leakages and the difference between the pumping costs and the PAT income leads to a Pareto Front of solutions which have to take into consideration both these antithetic objectives. In fact, a trade-off exists between the necessity of reducing leakages by limiting the pressures at nodes and at the same time the need to produce energy by dissipating the higher pressures. If the number of PATs are increased in the system the benefit of turbine installation increases and already with 10 PATs the energy produced by the PATs, though not sufficient to cover the pumping costs, produces an income, as reported in Fig. 2. Stochastic simulations have, however, for the same number of installed PATs produced solutions with lower leakage values and for the same leakage rate, a greater income from the energy production (Fig. 2).

The stochastic approach, indeed, proves sensitive to even small variations in demand. This is demonstrated by the appreciably higher pumping costs associated with the stochastic solutions. These solutions maintain higher pressures within the system and maintain the tanks across the system at a higher level – resulting in more robust solutions. A commensurate increase in the income from the PAT generators is revealed as a side-effect of this higher system-wide pressure. As shown, increasing the number of PATs allocated in the system, also increasing the PAT income, although generally these solutions are also associated with greater leakage. In the case of the 15 PAT installations, it can be seen that the income from the PATs is considerably increased in respect also to a lower leakage values (Fig. 3).

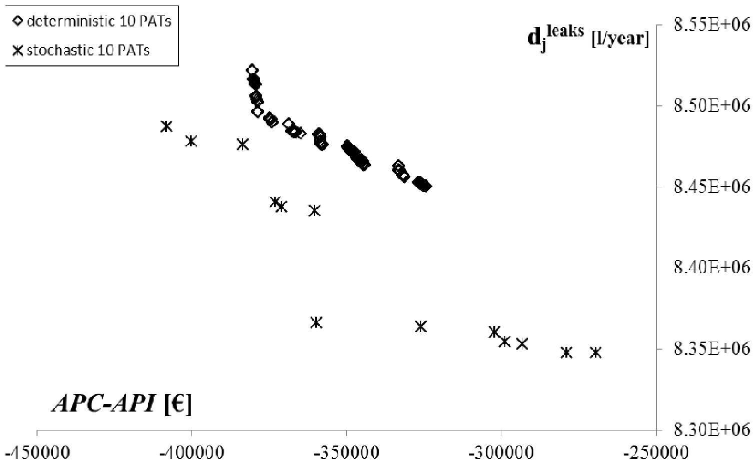

Fig. 2. Pareto Front for deterministic and stochastic simulations with 10 PATs installed

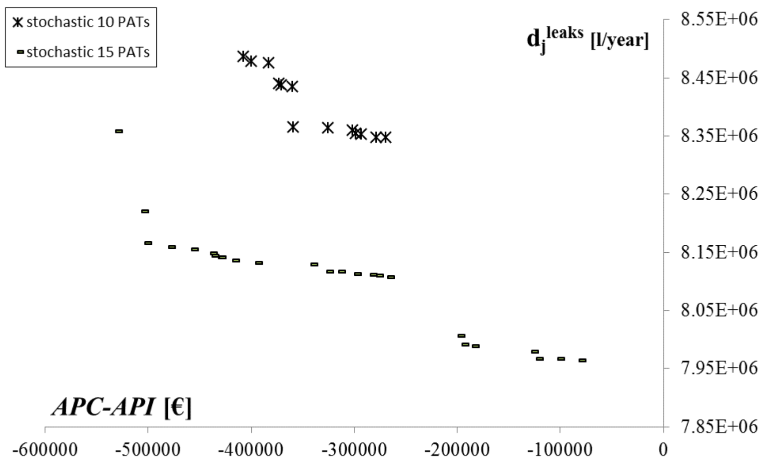

Fig. 3. Pareto Front for stochastic simulations with 10 and 15 PATs installed

Almost all of the solutions obtained present a PAT income greater with respect to the pumping costs which allows one to suggest that if the actual PRVs present in the system where replaced by PATs, the income generated could cover almost all the costs for the operation of the pumps – subject to the existence of a preferential feed-in tariff such as the one in place at the present time but at the same also the possibility to have a revenue from the energy production. This result is, naturally, partly due to the situation of the case study network and will not necessarily be applicable to other systems.

5. Conclusions

A novel methodology for the WDS pressure management has been suggested in this work, which accomplishes two objectives: the minimization of leakage and the minimization of the difference between the annual pumping costs and the annual income from PATs. The methodology assumes that PATs can be allocated along the trunk mains instead of the PRVs. The problem has been optimized by means of evolutionary algorithms employing a pressure-driven analysis. The results have been compared by considering the approach both as deterministic and probabilistic in terms of the water demanded by users. The possibility of inserting PATs along the mains for energy recovery has shown a clear economic benefit in conjunction with a pump-scheduling and pressure management regime. In the case of the case study network where a preferential feed-in tariff is in effect, PAT income has a value greater than that of the pumping costs, thus allowing a significant reduction of the operating costs. Furthermore, the solutions obtained through the stochastic optimization present higher pumping costs, with respect to the deterministic solutions, owing to the necessity of maintaining higher pressures within the system and higher tank levels across the network, and thus could be considered more robust configurations. A side effect of this higher system-wide pressure is increased income from the PAT generators for configurations in which water demand has been considered to vary probabilistically.

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