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Genetic algorithms for optimal management of sprinkle irrigation systems

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Abstract The paper presents a methodology developed for the optimal management of sprinkle irrigation networks. Some typical problems are presented and solved through Genetic Algorithms (GAs), assuming that the loads (demands) at nodes are cyclic and deterministically established. In particular, an algorithm for model calibration is first introduced, aimed at the minimization of the maximum errors between measured and calculated values. Since the operation of such systems is highly water and energy demanding, two algorithms for controlling pressure and pumps are described: the first is aimed at finding the optimal location and control of a set of pressure reducing valves (PRVs) in order to maintain a desired range of pressure throughout the network, while the second is focused at finding the optimal regulation of inverters for variable speed pumps in order to minimize energetic costs. An application to a real system is finally presented.

Keywords: Optimization, Water Systems, Energy, Variable Speed Pumps.

1. Introduction

The demand of water for irrigation accounts for the largest percentage of water consumption in the world, with an average value of 70% and ranging between 30% in industrialized nations up to 90% in countries under development [1]. The most widespread method is still surface irrigation, but in these last decades the scarcity of resources has led governments and regulatory bodies to finance many projects of reconversion from surface to sprinkle systems, because of the large amount of water that can be saved (50 – 60%).

Sprinkle systems are particularly energy demanding, since energy is required for pressurizing the pipelines and sprinkler units. The energy to pump water from groundwater (or surface) sources is usually given by centrifugal pumps. Thus, two order of problems have to be faced when dealing with the management of such systems: the first is to provide an adequate level of pressure in time and space (there is actually a direct relationship between pressure and flow at active sprinklers); the second is related to optimal pump operation, in order to maintain high levels of efficiency in the irrigation season.

In recent years, genetic algorithms (GAs) have proven useful in solving optimization problems characterized by complex search spaces even with discontinuous objective functions and constraints [2].

The paper presents a methodology for the optimal operation of sprinkle irrigation systems in which sprinkler activation at nodes is cyclic and a-priori established. The procedure relies on a coupling between EPANET simulator [3] and a set of GAs developed for water systems optimization [4].

2. Basic equations

Optimal management of sprinkle irrigation systems can be achieved starting from a simulation model which represents the behavior of the network under different loading conditions. By loading condition we mean a set of sprinklers which are active at the same time and for a fixed duration, called 'turn'. A complete cycle of all turns is typically performed in one week, with each turn characterized by a duration of four hours.

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The physical constraints describing the mass and energy conservation principles for a pressurized water network are, respectively, the continuity and head-loss equations, which can be written as

$$\sum_j Q_{ij,k} - \ell_{i,k} = 0 \quad \forall \text{ node } i \tag{1}$$

$$H_{i,k} - H_{j,k} = h_{ij,k} = \begin{cases} \dfrac{10.6668\, Q_{ij,k}^{1.852} L_{ij}}{C_{ij}^{1.852} D_{ij}^{4.871}} & \text{pipe} \\ -\omega_{p,k}^2 \left[A_p - B_p \left(\dfrac{Q_{ij,k}}{\omega_{p,k}} \right)^{C_p} \right] & \text{pump} \end{cases} \quad \forall \text{ link } ij \tag{2}$$

In (1), Qij,k indicates the flow from node i to node j at turn k; ℓi,k is the flow at turn k delivered at node i (when active), which depends on pressure according to

$$\ell_{i,k} = c_i\, p_{i,k}^{\gamma} \tag{3}$$

where pi,k is the pressure at node i and ci and γ are two coefficients quantifying the relationship between flow and pressure (the coefficient ci is dependent on the type of sprinkler unit, while usually γ = 0.5). In (2), Hi,k and Hj,k are the total head at nodes i and j at turn k, while Lij, Dij and Cij are the length, diameter and Hazen-Williams friction factor for pipe connecting nodes i and j, respectively. If a pump is present in link ij, its characteristic curve is described by coefficients Ap, Bp and Cp, while ωp,k represents its relative speed setting for turn k.

3. Model calibration

Numerical simulation models are widely used for analyzing the behavior of a system under different scenarios, but their predictive ability strongly depends on the quality of calibration. Model calibration may be regarded as an optimization problem characterized by specific objective function and constraints; in particular, conservation laws (mass and energy) have to be included, resulting in a nonlinear optimization problem that has to be solved. In this paper, the objective function for model calibration is defined as [5]:

$$\min : f_1 = w_H \max_{n,k} \left| H_{n,k}^{meas} - H_{n,k}^{calc} \right| + w_Q \max_{p,k} \left| Q_{p,k}^{meas} - Q_{p,k}^{calc} \right| \tag{4}$$

where $H_{n,k}^{meas}$ and $H_{n,k}^{calc}$ represent, respectively, the measured and calculated head at turn k in node n, while $Q_{p,k}^{meas}$ and $Q_{p,k}^{calc}$ the measured and calculated flow at turn k in pipe p. w_H and w_Q are weighting factors for heads and flows.

4. Optimal pressure management

The problem of optimal pressure management in a sprinkle irrigation network is addressed through the placement and regulation of pressure reducing valves. The determination of the number of valves, together with their location and setting, is formulated as a two-criterion optimization problem, and is based on a multi-objective genetic algorithm previously developed [6].

The problem may be mathematically formulated as follows:

$$\min : f_1 = n_v \tag{5}$$

$$\min : f_2 = \sum_{k=1}^{N_T} \sum_{i=1}^{N_N} w_k\, \ell_{i,k} \tag{6}$$

subjected to:

$$H_{i,k} \geq H_{req,i} \tag{7}$$

$$n_v \leq N_v \tag{8}$$

In (5), n_v is the number of valves in a generic solution, while in (6) N_N represents the number of nodes in the network and w_k the weight associated to load condition k. In (7), $H_{req,i}$ represents the required head at node i (usually fixed), while in (8) N_v is the maximum number of valves allowed.

5. Optimal operation of variable speed pumps

The aim of the algorithm developed for inverter optimization is to determine the values of the setting of each speed controller for the time horizon of a complete irrigation turn, in order to minimize energetic consumption and with the constraint of satisfying the required pressure at every node in the system (7). The objective function can be expressed as

$$\min : f_1 = \sum_{p=1}^{N_P} \sum_{k=1}^{N_T} C_{e,k} \frac{Q_{p,k} H_{p,k}}{\eta_{p,k}} \Delta T_k \qquad (9)$$

In (9), N_P is the total number of variable speed pumps, N_T is the total number of turns (there are usually 42 turns each lasting 4 hours, to complete a week), $C_{e,k}$ is the cost of energy at turn k, $Q_{p,k}$ and $H_{p,k}$ are the flow, head and efficiency of pump p at turn k, and ΔT_k is the duration of the turns.

6. Application to a real system

The methodology has been applied to the system illustrated in Fig. 1. The network serves nearly 600 ha with a water demand ranging on a weekly basis between 450 and 560 l/s. To this end, five pumping wells are operated: three of them (Pump 1, Pump 2 and Pump3 of Fig 1) are fixed speed pumps delivering water to a booster pump (controlled by a variable speed drive), while Pump 4 and Pump San Giusto are operated with variable speed controllers. Objective of the study was to optimize the network operation in order to reduce energy costs.

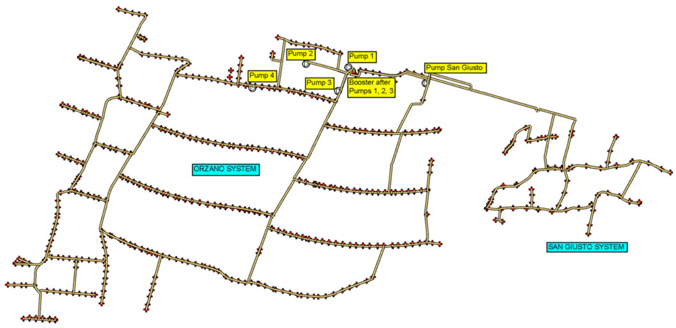

Fig.1 Layout of the system analyzed.

The model of the network has been calibrated through a series of measurement campaigns of pressure and flow in some nodes (shown in Fig. 2). Tab. 1 and 2 report the maximum error between measured and calculated values.

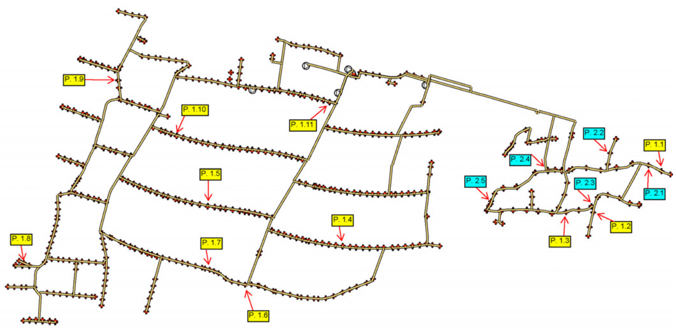

Fig.2 Localization of monitoring points for measurement campaigns.

Tab.1 Maximum differences between measured and calculated pressures.

Location	p^{meas} (bar)	p^{calc} (bar)	Location	p^{meas} (bar)	p^{calc} (bar)
P 1.1	4.8	4.6	**P 1.9**	5.5	5.6
P 1.2	4.8	4.9	**P 1.10**	5.1	5.3
P 1.3	4.7	4.8	**P 1.11**	5.3	5.5
P 1.4	5.1	4.8	**P 2.1**	3.0	2.9
P 1.5	5.2	5.1	**P 2.2**	3.0	2.9
P 1.6	4.9	5.1	**P 2.3**	3.0	3.1
P 1.7	4.6	4.9	**P 2.4**	3.8	3.6
P 1.8	5.5	5.4	**P 2.5**	4.1	3.8

Tab.2 Maximum differences between measured and calculated pressures and flows at main pumping stations.

Location	p^{meas} (bar)	p^{calc} (bar)	Q^{meas} (l/s)	Q^{calc} (l/s)
Booster after pumps 1,2,3	5.4	5.4	57	56
Pump 4	5.6	5.6	293	299
Pump San Giusto	5.0	5.5	104	100

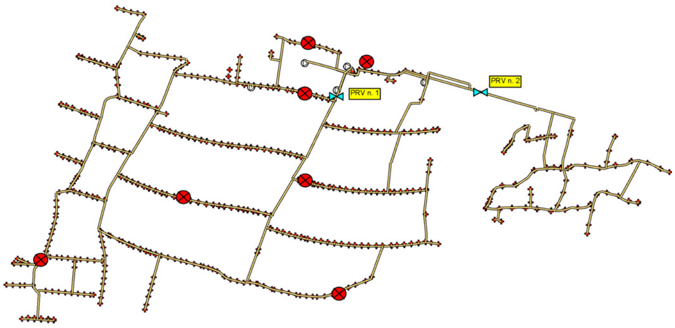

Fig.3 Optimal positioning of 7 closed valves and 2 pressure reducing valves.

Tab.3 Energetic consumption and associated cost for the system at present condition and after the proposed optimizations.

Condition	Present condition	After optimizations
Energetic consumption (kWh/week)	114253	103156
Energetic cost (€/week)	18280	16505

The application of the multi-objective pressure management algorithm resulted in an optimal location of 7 closed gate valves and 2 pressure reducing valves, as illustrated in Fig. 3. The application of the algorithm for the optimization of variable speed drive settings has lead to a 10% of savings in energetic consumption and operational cost, as reported in Tab. 3.

7. Summaries

The paper has presented a methodology for optimal management of sprinkle irrigation networks, based on a coupling between a calibrated model for system simulation and some optimization algorithms focused at the minimization of energetic consumption of pumping stations. The application of the multi-objective pressure management and of the algorithm for optimizing variable speed drive settings to a real system proved the effectiveness of the procedure.

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