Agricultural Water Management 163 (2016) 48–56

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Pumping station regulation in on-demand irrigation networks using strategic control nodes

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ARTICLE INFO

Article history:
Received 24 October 2014
Received in revised form 31 July 2015
Accepted 2 September 2015
Available online 15 September 2015

Keywords:
Pumps control
Pumping station efficiency
Strategic nodes
Energy savings

ABSTRACT

The development of tools focused on the management of branched irrigation networks is important for the efficient use of water and energy resources. The objective of this paper is to develop and validate a methodology and an Optimum Regulation of Pumping Stations (ORPS) tool to estimate the pressure head at all the nodes of an irrigation network based on the pressure head at a few strategic nodes of the network that are used for pumping station control. Once the pressure head at all nodes in the network is estimated, the pressure head at the pumping station can be adjusted to supply the exact pressure necessary to ensure the minimum pressure in the most restrictive of the open nodes of the network. This paper is based on the generation of demand scenarios, which aim to represent a whole range of discharges and not only the design discharge. The tool developed with this methodology has been applied in two on-demand irrigation networks with manometric regulation located in Castilla—La Mancha region (Spain). Moreover, in the analyzed irrigation networks, the use of three strategic nodes estimated the pressure of the reminder hydrants highly accurately. Thus, increasing the number of control points would not improve the accuracy of the estimates and would increase the complexity of the automation system. Using the proposed methodology, energy savings of nearly 3–5% were obtained relative to the average energy consumed for manometric regulation.

1. Introduction

In irrigable areas, energy consumption is increasing due to the modernization of activities, which are mainly focused on the pressurization of water distribution systems. Thus, efficient water and energy use are taking on greater importance in agriculture due to the widespread trends of reduced water availability and increasing energy costs, which are one of the main costs of pressurized irrigation networks (Rodríguez et al., 2007; Knox et al., 2010; Pérez Urrestarazu et al., 2010).

In irrigation networks, the pumping system for water distribution is the main energy consumer. Therefore, it is necessary to analyze the performance of pumping stations to determine the best regulation and management strategy and to enhance its energy efficiency.

Several methodologies have been developed to improve energy consumption in irrigation networks, most of which are focused on pumping stations performance. One of the main problems with the design of water distribution networks is to obtain the type of pump that best fits the water demand under specific pressure head requirements. To solve this problem, it is important to take into account the variability of the pumping station efficiency, which depends on the combination of flow discharge and pressure head required at the pumping system for each scenario when the irrigation networks is working. This consideration is especially important in on-demand irrigation networks because flow discharges and required pumping head change during the irrigation season (Lamaddalena and Sagardoy, 2000). According to Moreno et al. (2010), the design flow (high discharges) and head pressure are often the only variables considered when designing pumping stations, and the other discharge values are not usually taken into account. However, in most cases, the scenarios generated in irrigation districts lead the pumping stations to supply low or medium discharges, which can reduce the efficiency of these devices (Moreno et al., 2009; Pérez Urrestarazu and Burt, 2012). It is therefore necessary to improve the efficiency for low and medium discharges and not just for high discharges. To compute the energy efficiency at the pumping station, Moreno et al. (2007a) developed a Model for Energy Analysis of Pumping Stations (MAEEB), which

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http://dx.doi.org/10.1016/j.agwat.2015.09.001
0378-3774/

calculates the efficiency of pumping stations under different types of regulations (Planells et al., 2001).

Other methodologies to save energy in water distribution networks have been applied, such as irrigation network sectoring. Rodríguez et al. (2009) developed OPTIEN, an algorithm that simulates the potential energy savings obtained by sectoring an on-demand irrigation network. They showed that it would be possible to save more than 25% of the energy consumption in the maximum demand period if the network were operated in sectors. A further advance was achieved with WEBSO (Carrillo-Cobo et al., 2011; Navarro et al., 2012), an algorithm that includes a procedure for sectoring in pressurized irrigation networks. It was based on a topological characterization using a dimensionless coordinates system. Fernández-García et al. (2013) developed an optimization methodology aimed at minimizing energy consumption and based on operational sectoring for one irrigation network with several source nodes. None of the above-mentioned sectoring strategies considered the behavior of the pumping station when supplying a pressure head that was different from the one for which it was dimensioned. Thus, in addition to performing a sectoring strategy, it is necessary to strictly regulate the pumping station to obtain the results needed for energy savings.

Other studies based on irrigation network sectoring have considered the performance of the pumping station. Jiménez-Bello et al. (2010) developed a methodology based on genetic algorithms combined with hydraulic network modeling for irrigation network operating turns, achieving energy savings of near 36%. Fernández-García et al. (2014a) attempted to optimize the sectoring operation and pressure head, analyzing the performance of up to three frequency speed drives. Jiménez-Bello et al. (2015) developed a method to improve energy and water use by proper irrigation scheduling using a case study where water was allocated to two groups of intakes, one fed by gravity and the other by pumps.

Irrigation network sectoring management can be analyzed using methodologies based on the location of hydrants with high energy requirements, which are defined as critical control points. The use of this tool to improve energy consumption has not been previously analyzed. Rodríguez-Díaz et al. (2012) developed a tool based on critical point detection and analyzed the energy savings using this methodology in comparison to irrigation network sectoring. Other researchers have used this tool to determine the energy savings in irrigation networks with multiple water supply points (Fernández-García et al., 2014b; Gonzalez Perea et al., 2014).

The use of tools to improve on-demand irrigation network management is very important because of the high degree of flexibility of this strategy. To achieve the efficient use of energy in pumping stations in on-demand irrigation networks, the most appropriate method would be measuring the pressure at every hydrant of the network and using a pumping station control strategy that supplies the minimum pressure to each one of the open hydrants of the network. However, this strategy would be very expensive and difficult to implement in a control system.

The objective of this paper is to develop and validate a methodology and an Optimum Regulation of Pumping Stations (ORPS) tool to estimate the pressure head at all the nodes of an irrigation network based on the pressure head at a few strategic nodes of the network that are used for pumping station control. To validate this methodology, ORPS has been applied to two on-demand irrigation networks with manometric regulation located in Castilla—La Mancha region (Spain). This tool has the potential to be useful for pump control by matching the energy supply of the pumping station to the energy requirements for branched on-demand irrigation networks. With this tool, the performance of the pumping system is taken into account, depending on the pressure head and flow discharge combination for each scenario carried out.

2. Materials and methods

2.1. Proposed procedure

The proposed methodology can be divided into five sections: (1) Generation of demand scenarios, (2) Calculation of pressure at the network nodes, (3) Cluster analysis and strategic node selection, (4) Regression analysis using Artificial Neural Networks (ANN) and estimation of the pressure at all the nodes, and (5) Determination of pumping head and calculation of energy consumption.

2.1.1. Generation of demand scenarios

The first step to carry out when implementing the proposed methodology is to simulate the demand scenarios of the analyzed network. It is applied considering a period with high water demand. For this purpose, the Random Daily Demand Curve (RDDC) method, developed by Moreno et al. (2007b), is used. This method results in an appropriate simulation of on-demand irrigation networks and is used to determine the flow discharge at each pipe of the network. In this work, it is used to generate demand scenarios and to calculate the pressure at each hydrant for each scenario.

To generate the demand scenarios, each day is divided into 15-min intervals, producing 72 demand scenarios per day (considering 18 h as the daily operating time of the network (DOT)). Hence, using the RDDC method, 1000 repetitions are conducted, generating a database (72,000 scenarios) with sufficient data for performing the training, calibration, and validation steps in the Artificial Neural Network method for regression analysis, as described below.

2.1.2. Calculation of pressure at the network nodes

The irrigation network model (Moreno et al., 2008; Córcoles et al., 2010) is implemented in EPANET® software (Rossman, 2000), which has a dynamic link for the utilization of its digital library in the software developed in this paper. In each demand scenario, using EPANET® software, the pressure of the nodes of the network is calculated, which makes it possible to calculate the pressure head at the pumping station needed to supply a minimum required pressure at the most restrictive node.

2.1.3. Cluster analysis

The proposed methodology aims to establish groups of hydrants with similar patterns of pressure variation under variations in the demand of the network. To do so, a *k*-means clustering is implemented, considering the set of pressure values of each hydrant generated in the previous step. The specified criterion for forming clusters is the Euclidean distance (Alhamed et al., 2002). The *k*-means method requires knowing a priori the number of clusters in which the nodes are grouped. In this paper, the results of clustering, considering clusters 1–10, are analyzed. No more than 10 clusters are evaluated because exceeding this value would increase the cost and complexity of the automation system.

Once the clusters are formed, one node of each cluster is selected in a manner that best represents the behavior of the set of nodes in the cluster. To do this, the node with the lowest coefficient of variation of distances to the rest of the nodes in the clusters is selected. Knowing the pressure at the most representative hydrant of each cluster allows the accurate estimation of the pressure at the remaining nodes of the cluster.

2.1.4. Regression analysis using an Artificial Neural Network (ANN)

The estimation of the pressure at every node of the network based on pressure data estimated at the selected nodes requires a robust regression method. As this is a highly non-linear regression problem, an Artificial Neural Network (ANN) is considered the most adequate regression model (Bishop, 1995).