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Modeling and control of water booster pressure systems as flexible loads for demand response

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HIGHLIGHTS

- A dynamic model of a Water Booster Pressure Systems is proposed and validated.
- It is achieved a 27% flexibility in the power consumption without stopping water flow.
- A strategy to offer spinning reserve services with a systems aggregation is presented.
- A controller for the aggregator is designed and evaluated in simulation.

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ABSTRACT

Water Booster Pressure Systems (WBPSs) are responsible for supplying water and maintaining pressure in a building pipeline. These systems are potentially useful to offer energetic services required by the System Operator (SO) through demand response, considering the spread use of these hydraulic devices in high-rise buildings. In this article, a dynamic model for a WBPS is developed in order to evaluate it as a flexible load for demand response applications. The model is built from first-principles and tuned with experimental data of air pressure, power consumption and water flow, obtaining an error of 1.11% in the energy demand between the experimental and the simulated data. It is shown that the WBPS can operate as a flexible load by changing the pressure set point. Additionally, it is achieved a flexibility of 27% in the energy power consumption without stopping the water flow in the building and it is shown that WBPS can provide Spinning Reserve Services. Finally, this work proposes an aggregator of systems, based on a Proportional-Integral Gain Scheduling controller, that can track the SO requirements with an error lower than 0.86%.

1. Introduction

Electrical power demand has been increasing throughout the world over the past few decades, as well as generation capacity. However, at certain moments generation plants cannot fulfill the power request by customers, due to contingencies in the grid or during peak hours. This leads to require a new paradigm where the demand is able to react to different contingencies [1,2]. Indeed, it is needed a transformation to load response instead of generation response in which the customers reduce their consumption, manually or automatically, for decreasing the risk of failure [3]. These actions are possible on Demand Response (DR) plans [4], managing a tradeoff between comfort and reliability. In [5], DR is defined as "Changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized".

Safety problems emerge due to the imbalance between load and generation, for example, large frequency deviations can make the system collapse. Hence, in order to avoid system instabilities, the system operator can adapt different ancillary services depending on the component that unbalances the system [6]. Ancillary services refer mainly to frequency and reserves services. Reserves are usually classified according to the timescale in which they respond. According to [7], the FERC (Federal Energy Regulatory Commission) definitions of reserves applied in North America are:

- *Regulation:* It deals with the continuous changes in load and generation that create energy imbalances and frequency fluctuations. Units must respond in few seconds.

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- *Spinning reserve:* It restores the generation and load balance in the event of a contingency, responding almost simultaneously to a contingency. Units must be fully available within 10 min.
- *Non-spinning reserve:* It also restores the generation and load balance in the event of a contingency. It is served by off-line units with rapid start-up. Units must be fully available within 10 min.
- *Replacement reserve:* In is intended to substitute the faster and more expensive reserves so as to reduce regulation costs. Units must be fully available within 30 min.

Balance problems can be handled by DR initiatives in the energy consuming sectors. In [8], winter DR achievable potential is estimated for each sector during peak periods, obtaining 130 MW for the residential, 78 MW for the commercial and 4 MW for the industrial sector in the Puget Sound region of the northwest United States. Moreover, in order to solve balance problems, these sectors take advantage of several flexible loads that can provide energy services to the grid.

Flexible loads can be clustered into two categories: adjustable and deferrable loads [9]. An adjustable load is flexible during all time service. For example, Thermostatically Controlled Loads (TCLs) are adjusted by modifying the temperature set-point fixed by the user [10]. A deferrable load has a fixed energy requirement at the end of the service. For example, a pool pump must be switched on a determined amount of time by the end of the day and can provide regulation services by turning it on and off [11]; or an Electric Vehicle (EV) state of charge should be above a certain level at the departure time [12]. EVs can be modeled as a flexible load by changing their load profile[13,14]. EVs can provide ancillary services such as regulation services [15], spinning reserve [16,17], among others. In [18], EVs flexibility quantification is developed integrating renewable energy fluctuations.

Regarding the buildings sector, there are several flexible loads that can provide regulation services, such as lighting, HVAC, computers and others electrical appliances that can increase or decrease the building consumption, see e.g. [19]. In [20], a smart building operator that is capable of modulating the aggregated energy consumption is considered with the purpose of providing regulation services. In [21], a demand side load management technique is developed in order to maximize the user satisfaction and minimize the cost through a residential building load control. In [22], a dynamic model of a variable air volume system is developed and simulated. It is investigated the response of the system to four common demand response strategies over a range of cooling loads and implementation intensities. Also, it is demonstrated the use of the model to simulate a 10-min spinning reserve provision.

TCLs have been employed to provide regulation reserve by varying the temperature set point, see e.g. [6,23]. Model predictive control (MPC) strategies are developed in [24,25], while in [26] is analyzed a distributed MPC. In [6] a priority control is proposed. In addition, in [27] commercial and residential TCLs are modeled to quantify their flexibility.

Pump systems can also be modeled as flexible loads. Buildings of considerable height present important challenges in pumping water to the upper floors [28]. Water distribution systems can provide balancing services with demand response through pump scheduling. In [29], a branch and bound algorithm is proposed in order to offer financial benefits to the system operator. It is clarified that a large amount of water distribution systems would provide a short-term operational reserve, also a power reserve of 3 MW is estimated for the UK. Whereas in [30], a commercial building pumping system with a tank on the top is used as an energy storage component to respond to the market price and provide demand response services. This approach is carried out by dynamic programming methods and a 30.9% saving in the electricity cost is achieved.

Pump systems are mathematically modeled in [31] and simulated in [32,33]. Their dynamic modeling is based on basic laws of physics and fluid mechanics. Pump systems control is based on two position controllers or variable frequency drives, [34,35]. Different techniques are used to control the input speed of the pump. For example, in [33,36] a PID controller is designed and evaluated in simulation, while in [37] a Hardware-in-the-Loop simulator is carried out, where the variable speed driver is connected via a programmable logical controller through Profibus communication.

In this article, a Water Booster Pressure System (WBPS) is modeled and controlled as a flexible load. This system is responsible of supplying water and maintaining pressure in a building pipeline. The operation of the pump and tank are directly related to the building water consumption, thereby, a control system is required to satisfy the variable water demand. When the operating pressure is decreased, it generates a reduction in power consumption and in water pressure for the users, especially on the higher floors of the building. This work aims at modifying the system operating pressure, not cutting the water supply in the building or stopping the WBPS operation, limiting the discomfort caused to the consumers.

First, WBPS dynamics are modeled by first-principles and tuned by experimental data of a 6-floor university building with a single WBPS. Then, it is shown that the WBPS can provide spinning reserve services to the grid, by evaluating its flexibility through set point changes. In order to evaluate flexibility, the effect of parameters such as minimum and maximum consumption levels, the amount of required energy, limitations in commutation frequency and turn-on time, on power consumption are evaluated. Finally, an aggregation strategy, which responds when the system operator requires a power reduction service, is proposed. Thus, the primary contributions of this paper are: (1) a model of WBPSs as flexible loads validated with experimental data; (2) the definition of the energy service that the system can provide to the grid; and (3) the design of a control architecture that leads to providing the energy service with a set of WBPSs.

The rest of the paper is organized as follows. Section 2describes the model of the system, taking into account the centrifugal pump and the pressure tank, for later being implemented in a simulation. Section 3explains the flexibility that a WBPS can have in power consumption and also defines the energy service that the system can provide. Section 4shows the proposed aggregation architecture, its aim is to respond to a request of power consumption reduction, sent by the SO. Finally, in Section 5, conclusions and future work are presented.

2. Water booster pressure system model

In order to determine the potential of a Water Booster Pressure System (WBPS) for use as flexible load, a model that can reproduce its dynamics is built. This section presents a model of a WBPS settled and validated with experimental data. It begins explaining the general operation of the system, then the model is proposed and compared with experimental data. Table 1 summarizes the nomenclature and units of the system variables.

2.1. System model

Fig. 1 shows a WBPS. The system stores energy in the tank as compressed air with the purpose of guaranteeing a minimal pressure in all the pipelines and taps of the building. The system acts supplying water from the reservoir to the tank by the centrifugal