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PID Controller applied in a water distribution network supplied by pumping direct

Aplicación del controlador PID en sistemas de bombeo directo

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ABSTRACT

Rapid growth in population over last few decades has resulted in changes of supply system consumption patterns. Such, require effort from companies in technical aspects; targeting need of strategies to improve operational efficiency. Management system, based on automated control, carries a strong mechanism to gauge these results. Aim of this paper is to present a comparative study of both hydraulic and electric parameters of an experimental automated network. Network behavior was analyzed under two conditions: without use of controller and with Proportional-Integral -Derivative (PID) controller. Results indicated efficiency of applied controller in different consumption scenarios. Dealing with energy efficiency, it was verified that, according to calculations related to specific energy consumption (SEC), reduction on electrical energy is notable with use of controller.

RESUMEN

En las últimas décadas, con la densidad de población, los sistemas de abastecimiento de agua han sufrido cambios en su patrón de consumo. Estos cambios requieren esfuerzos por parte de las empresas a nivel técnico, y hacer hincapié en la necesidad de estrategias orientadas a la eficiencia operativa del sistema. La gestión a través de los controles automáticos comprende un mecanismo robusto para medir estos resultados. Este trabajo presenta un estudio comparativo de los parámetros hidráulicos y eléctricos de una red experimental automatizada. El comportamiento del sistema se analizó bajo dos condiciones: sin el uso del controlador y el controlador proporcional, integral y derivativo (PID). Los resultados mostraron la eficacia del controlador utilizado para el consumo de diferentes escenarios. Con respecto a la eficiencia energética, se verificó, según el cálculo del consumo específico de energía (CE), un ahorro de energía con el uso del controlador.

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Power efficiency; supply system; PID controller.

Palabras clave:
Eficiencia energética; sistemas de abastecimiento; controlador PID.

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INTRODUCTION

The intense process of urbanization that occurred in the last decades has required major efforts in technical, organizational and financial scopes by tsanitation companies, once water distribution systems are increasingly larger and more complex, resulting in high costs of production of treated water and electrical power (Camboim, 2012).

Water supply and sewerage systems are responsible for about 3% of world energy consumption and 90% of this portion is responsibility of pumping equipment (Gomes & Carvalho, 2012). According to Ramos, Costa & Gonçalves (2012), this consumption can be diminished by at least 25% through improvements in energy efficiency of water supply system. In this way, measures that define operational strategies for hydraulic and energy efficiency are essential in current scenario.

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Service pressure control is one of basic actions for energy consumption reduction in urban water distribution systems. According to Carvalho (2012), excessive pressure on water supply network unnecessarily enhances costs and causes malfunctions in pipes and accessories, also reduces equipment lifespan.

Implementation of automated systems presents itself as a robust mechanism of operational management in real time. It enables accurate control and improvement of operating performance. Thus, use of frequency inverter coupled to automatic control systems ensures more efficient and accurate operation of water supply network.

Use of frequency inverters allows varying engine rotation speed keeping pump operation at minimum levels of power that are sufficient to fully meet demands. This ensures piezometric control of water network, energy savings, increase system reliability and extension of service life of pumping stations.

Water distribution systems work with various parameters and according to varied conditions of supply, which makes difficult to do a purely mechanical or manual monitoring. For a skillful management of these systems, it is necessary to have an efficient process for acquisition, storage and transmission of electrical and hydraulic quantities. Thus, in view of technological advancement, it has been invested in automation to achieve these goals.

Use of robust algorithms is a very effective tool in industrial automation and it could be also applied on a water supply network after make some adaptations. Programmable controllers are used in the automation phase of a system.

PID controller is the most used in feedback control systems. This is justified by its easy implementation in addition to low cost, robustness and versatility. This control technique is able to provide transient behavior and permanent regime, both satisfactory for a wide variety of procedures found in industry, which consequently promotes diversity of applications in control systems (Campestrini, 2006).

Santos-Quadros & De Almeida-Pinto (2013) discussed about control of pressures in water supply systems by using Pressure Reducing Valves (PRVs). Fluctuations in operating pressures in distribution networks were filtered by PID control system with automatic tuning. Simulations have demonstrated applicability of proposed methods since all performance indicators of system managed by PID controllers were improved comparing to water network performance with manual control.

The objective of this study was to simulate operation of a water supply network in low pressure zone and compare hydraulic and electrical parameters obtained with and without use of a controller. Control methodology adopted was PID (Proportional Integral Derivative) in its conventional form, which consists of three terms sum: a term proportional to error, a term proportional to integral of error, and a term proportional to derivative of error (De Negri, 2004).

MATERIALS AND METHODS

Automated System of Water Distribution (ASWD) is an experimental pressurized bench that simulates a water supply system located in Laboratory of Energy and Hydraulics Efficiency in Sanitation at Federal University of Paraiba – LENHS/UFPB (figure 1).

At first, scope of ASWD is to simulate a water distribution system sectored in two consumption zones (low zone and high zone) whose discharge extensions have markedly distinct topographic quotas. However, for purposes suggested in this work, an isolated analysis of the lower area is enough. It is understood by low zone the entire section (without branches) from supply reservoir (RNF) until the discharge branch RD-1 (figure 2).

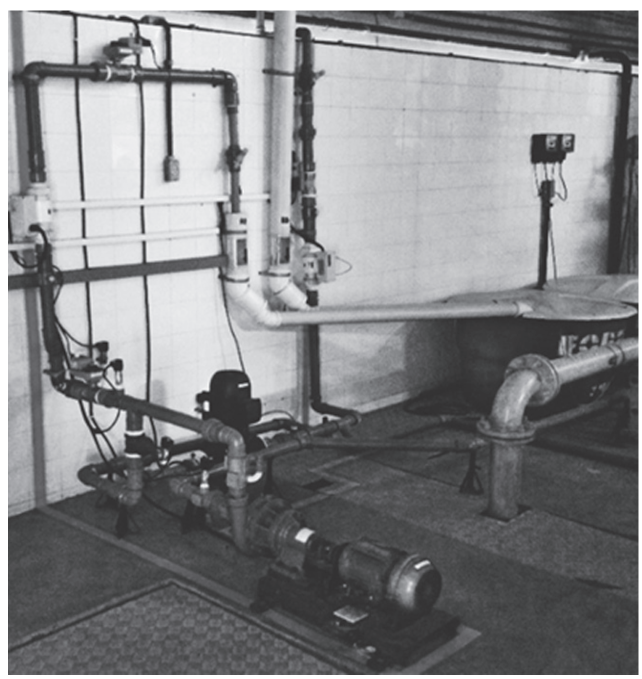

Figura 1. Automated System of Water Distribution (ASWD).
Source: Salvino, Mendonça, Monteiro, Gomes & Bezerra (2015).

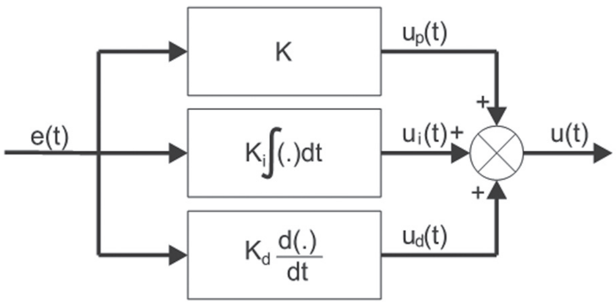

Figura 2. 3D Model of the ASWD lower zone.
Source: De Negri (2004).

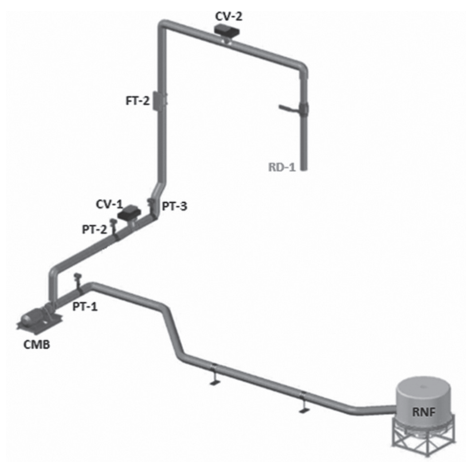

Figura 3. Schematic illustration of a PID controller.
Source: Salvino *et al*. (2015).

Pump station of this system consists of a 3 horsepower motor pump set (CMB) with three-phase induction motor (220/380V). Activation of CMB is performed through a frequency converter/inverter. It allows to maintain operating pressures at pre-established and constant levels when associated with an automatic control system, adjusting operation of pump station to frequent variations in demand that occur occasionally. This way, it will be possible to avoid overpressure and unnecessary energy costs.

Throughout water network three pressure transducers (PT-1, PT-2 and PT-3) and a transducer flow (FT-1) are arranged in order to monitor, respectively, pressure and flow of network service. In this work, dynamic pressure at point of operation of transducer PT-3 was chosen as a monitoring and control reference.

There are two proportional valves to operate on the network causing the necessary interference in hydraulic parameters. CV-2 valve is located near discharge branch and it aims to emulate flow variation demanded by changing degree of closure. For this purpose, were idealized seven consumption ranges interspersed 5º in 5º between range of 30º (maximum consumption) and 60º (minimum consumption). CV-1 valve is located at entrance of consumption zone and it has been used with a fixed degree of 20º generating a located head loss purposely. Intervention on closure degree of this valve was required to meet operational limitations of motor pump set whose maximum permissible power is 2.53 kW. This value corresponds to product of motor service factor and available engine power rating.

Reading of hydraulic parameters provided by sensors and actuators, and execution of command actions on proportional valves and frequency converter are possible because communication is established between data acquisition board from National Instruments and software LabVIEW®.

Water supply and discharge of this experimental bench are carried out by 310 L fiber glass tanks interconnected with each other.

Controller proportional, integral, and derivative (PID)

A conventional PID controller was developed in system to control rotation speed of motor pump set. This type of control was chosen because of its operational ease and low cost in addition to being one of the most utilized in industry, occupying a range between 90% and 95% (Åström & Hägglund, 1995).

PID controller is composed by three parts: Proportional, Integral, and Derivative. Sum of these terms generates output signal *u(t)*, which acts to control speed of rotation of motor pump set. Figure 3 shows a schematic illustration of PID controller.

Second Bobál, Böhm, Fessl & Macháček (2005), PID control low in time domain can be described mathematically by equation (1),

$$u(t) = Kp\left[e(t)+\frac{1}{Ki}\int_0^t e(t)\,dt + Kd\,\frac{de(t)}{dt}\right]. \qquad (1)$$

Each part is distinguished by a different function in PID controller performance. Proportional term provides a relationship between error $e(t)$ and constant of proportional gain Kp, then controller output is proportional to actual error value. It acts in transient response of system by reducing rise time, in addition to reduce permanent regime error. Term

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Integrative consists of multiplying constant of integral gain K_i and integral of error signal. $e(t)$. Use of this term eliminates error in permanent regime that is generated by action of proportional control, but can also affect transient response of system. Derivative term is responsible for reducing magnitude of overshooting caused by integrative part and also by increasing system stability, improving transient response (Haffner, 2013). Control action of Derivative part is proportional to rate of change of error signal over time and variable of derivative gain *Kd* (Åström & Wittenmark, 1995).

Where $e(t)$ represents difference between reference input and output variable of system. This error signal is input variable of controller, and output signal of controller is given by variable $u(t)$. However, to get a digital version of PID controller, it was necessary to discretize integral and derivatives components. The simplest way to discretize an integral is bringing it to a sum, reaching used form of controller on digital version for implementation in LabVIEW®, according to equation (2).

$$u(k) = K_p \left\{ e(k) + \frac{T_0}{K_i}\left[\frac{e(0)+e(k)}{2}\sum_{i=1}^{k-1} e(i)\right] + \frac{K_i}{T_0}\left[e(k)-e(k-1)\right]\right\} \quad . \tag{2}$$

It was found through tests performed with controller in ASWD experimental bench that gains that ensured the greatest synchronism of control parameters were: 0.1 for *Kp*; 0.2 for *Ki* and 0.03 for *Kd*. It was used sample time of 150 ms to collect data.

In order to test PID controller efficiency were simulated situations of variation in system demand. To emulate this scenario of operation, it was used proportional valve CV-02, whose closure angle suffered a variation of 30º to 60º. Valve angle was changed in 5 degrees every 30 s to simulate a consumption curve. Position of 30º represents the maximum consumption zone, in other words it represents situation in which pressures will be the minimum as possible, while position of 60º is related to moment of lowest consumption, in which pressures will be maximized. Valve CV-01 remained 20º opened to introduce a head loss in system. As tests were conducted extent that tests were performed, there was a collection of energy parameters through a power analyzer FLUKE®.

Tests were performed for operation of experimental network with and without using PID controller for same demand simulations. The objective was to analyze pressure at a point downstream of pump. For tests using PID controller, it was desired to control pressure on 10 mca independent of network required demand.

Analysis of electric parameters

Beyond hydraulic parameters control such as flow and pressure, it is necessary that applied control demonstrates its efficiency when subjected to analysis of electrical parameters. Frequency inverters controlled by PID must find the most efficient motor pump set operation, so that there is full compliance pressures and service demands at a low energy consumption.

It was used Fluke® case for measurement of electrical parameters. It is an energy analyzer capable of measuring the main electrical variables involved in a given system. The only parameter needed in this study is electric power of pump motor set.

Data collected during tests were used in equation (3). This equation provides Specific Energy Consumption (SEC). This parameter is widely used for evaluation of supply systems for energy efficiency, relating the energy consumed with the pumped volume (Gomes, 2009).

$$CE = \frac{Pa \times t}{V \times \frac{Hman}{100}} . \tag{3}$$

RESULTS

Figure 4 graph shows results obtained by simulating performance of system with varied consumer demand over time and without PID controller. Throughout test, motor pump set operated at a frequency of 60 Hz. Simulation begun with angle of proportional valve in position of 30º (maximum demand) and then closing angle was changed from 5º at 5º degrees every 30 s, until it reached 60º (minimum demand). Purpose of this change in valve closing angle was to simulate variation of hourly consumption occurred in a real water supply network. Sampling time used was 150 ms for data collection and the test duration was approximately 8 min and 45 s. Pink and green lines, respectively show variation of pressure and flow in simulation. In gray, it is set a reference value in which pressure should be maintained when PID controller is used.

Results shown in figure 5 were obtained by using a conventional PID controller in order to obtain system pressure control at 10 mca, while it suffers variations in demand. Graphs below show same hydraulic and electrical parameters already mentioned in test without controller.

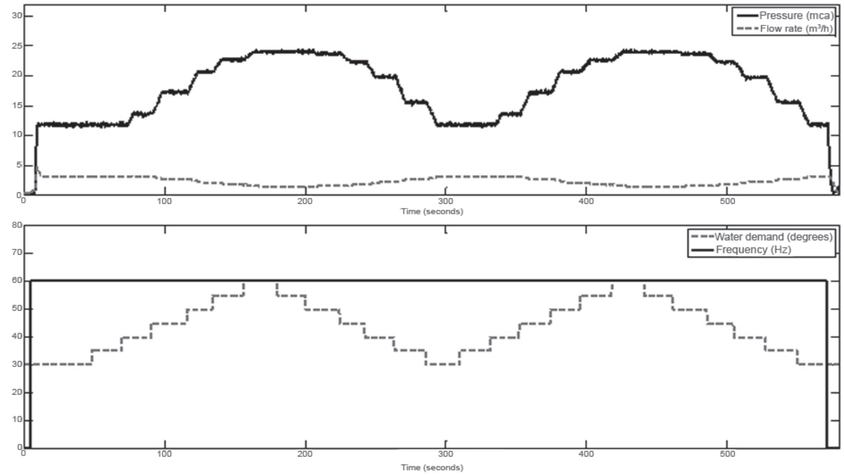

Figura 4. System operating without the action of the controller.
Source: Salvino *et al*. (2015).

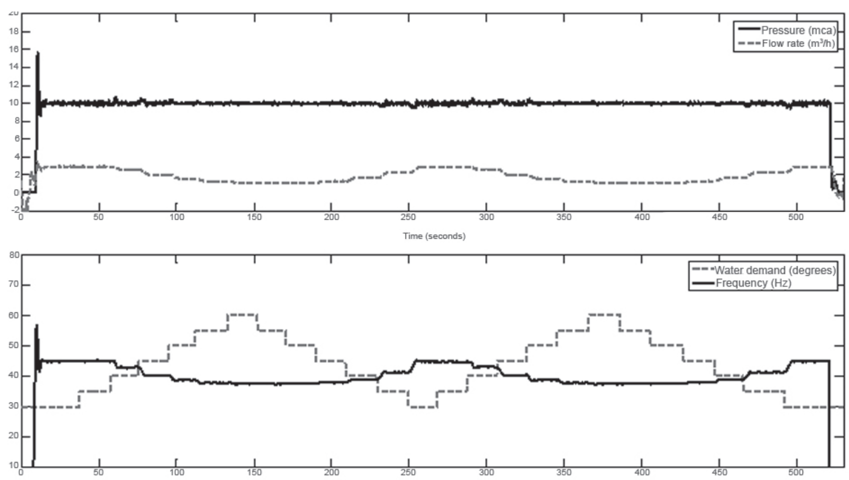

Figura 5. System operating with the action of the PID controller.
Source: Salvino *et al*. (2015).

ANALYSIS OF RESULTS

Graph illustrated in figure 4 shows that system operating without action of controller has made service pressure remained higher than reference value throughout test. In the period of minimum demand, operating pressure reached 25 mca, which represents an increase of 150% over reference value. To meet the higher demand, recorded value reached 18 mca. This occurs because absence of a control system will not allow pump set rotation speed be changed according to pressure given by reference. Regarding to electrical parameters, it can be analyzed that power consumed by pumping system in peak demand time (30º) was 2.3 kW, while at lowest demand period (60º) this value was reduced to 1 8 kW. From these values, it was possible to trace energy consumption curve. It was observed that SEC obtained ranged from 0.60 kWh/m³ at time of highest demand, and 1.21 kWh/m³ at least consumption of time.

In graph showed in figure 5, when PID controller was used to start system, initially frequency of motor pump set has met maximum demand of 45 Hz. At this stage, controller caused an overshoot and pressure reached a value close to 15 mca. In contrast, when system has reached required demand,

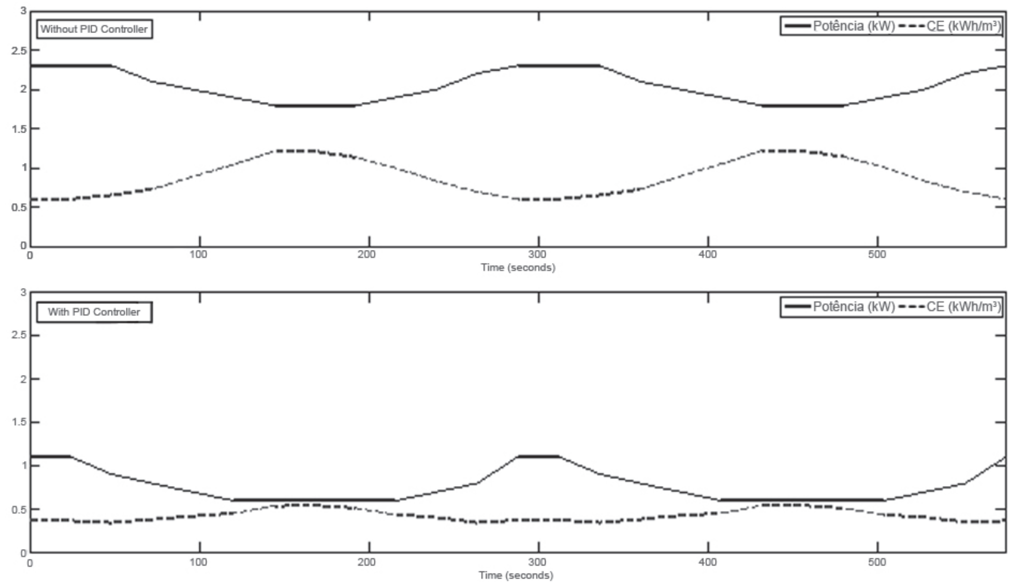

Figura 6. Power value and SEC comparison by the system with and without the PID controller.
Source: Salvino *et al*. (2015).

pressure was controlled at 10 mca. Applying controller, there was a sharp drop in electrical power used by pumping system. The moment of maximum demand, there was a consumption of 1.1 kW, while for the minimum demand amount recorded was 0.6 kW. SEC was 0.37 kWh/m³ and 0.56 kWh/m³ for the maximum and minimum demand, respectively as showed in figure 6.

Comparison of SECs values of obtained with and without use of controller shows a significant drop in electricity consumption for operating system with PID. It was also noted that in periods of maximum demand SEC reached its minimum value, while those of lower demand, values were as high as possible. This occurs because SEC reflects pumping energy cost/benefit; as in instant of maximum consumption motor pump set is operating at its maximum efficiency (best performance), lower SEC values are expected in this period.

CONCLUSIONS

Considering results obtained, it can be concluded that use of PID controller on water supply systems is serviceable and represents an effective energy efficiency action. When system analyzed was operated without use of controller, it presented a specific energy coefficient of 0.60 kW/m³ and pressure in this situation was 25 mca, in maximum demand scenario. In the same scenario, use of PID controller provided 0.37 kW/m³ of SEC and pressure was kept at 10 mca, resulting in an energy saving of 38% when compared with functioning of system without a controller. In the period of minimum demand, use of controller has secured an economy of electric energy in the order of 55.3%, in relation to same situation with system acting without a control action.

It is recommended that in future work same PID controller be used throughout experimental bench ASWD. This should be done for controller to act on actuators distributed both in the high zone, as in the lower zone of system. This methodology is indicated to compare energy efficiency of water supply systems that operate with a motor pump set and a booster water pump, simultaneously. In addition, it is recommended use of other types of controllers and to compare them with PID technique.

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