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ENERGY SAVINGS IN PUMPING SYSTEMS: APPLICATION OF A FUZZY SYSTEM

ECONOMIA DE ENERGIA EM SISTEMAS DE BOMBEAMENTO: APLICAÇÃO DE UM SISTEMA FUZZY

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ABSTRACT

This paper deals with the impact of variable speed drives on the power requirements and a system control performance of pumps. The investigation indicates that the adoption of Variable Speed Drives (VSD) reduces pump energy consumption in certain cases, reduces the pressure in the hydraulic networks and improves pump efficiency during most of the partial load conditions. The use of fuzzy system to provide new control functions that are outside the domain of traditional control is sought in this paper, where fuzzy control is likely to provide the greatest payoff. The development and application of a fuzzy control system for a pumping system, operating with variable rotational speed are presented to demonstrate the energy savings provided by the adoption of the PWM frequency inverter in an experimental system. The control system is responsible for maintaining the manometric height of the pump at an optimal value, eliminating any excess pressure at the critical point of the water distribution network. The results of the experiments show that the fuzzy systems are efficient and the control of the rotational speed resulted in a reduction of 35% in the consumption of electricity.

Keywords: Fuzzy system, Water distribution system, Energy efficiency, Pressure control, Variable frequency drive.

RESUMO

Este artigo apresenta a influência do uso de inversores de frequência no consumo energético de sistemas de bombeamentos e o desempenho de um sistema de controle para atuar nesses equipamentos. A pesquisa indica que a adoção de inversores reduz o consumo de energia em determinadas aplicações, reduz a pressão nas redes hidráulicas e melhora a eficiência da bomba. O desenvolvimento e aplicação de um sistema de controle *Fuzzy* para conjuntos motor-bomba operando com velocidade de rotação variável são apresentados para demonstrar a economia de energia resultado da adoção do inversor de frequência PWM em um sistema experimental. O uso deste sistema para condições de operação que estão fora do domínio do controle tradicional é procurado neste trabalho, em que o controle *Fuzzy* é susceptível de proporcionar maior retorno. O controlador é responsável pela manutenção da altura manométrica da bomba em um valor ótimo, eliminando qualquer excesso de pressão no ponto crítico da rede de distribuição de água. Os resultados das experiências mostraram que o sistema *Fuzzy* foi eficiente e o controle de velocidade de rotação resultou numa redução de 35% no consumo de eletricidade.

Palavras-chaves: Sistema *Fuzzy*, Sistema de distribuição de água, Eficiência energética, Controle de pressão, Inversor de frequência.

1 – INTRODUCTION

The first cities were founded about 3500 BC in of the basins valleys of the River Nile (Egypt), Tigris and Euphrates Rivers (Iraq). The sites chosen were near the margins of rivers or large lakes, which, in turn, became the primary source of water for the first communities. Concomitantly with the growth of cities, there was the need to develop techniques for transporting water to consumers. During the first centuries of the Christian era, the Roman Empire was responsible for the construction of numerous Water Distribution Systems (WDS).

With the emergence of electric motors in the early nineteenth century and the subsequent development of an AC distribution network and the AC motor, the water began to be driven, regardless of the aim application by motor-pump sets. Currently, few WDS operate exclusively by gravity. Thus, the electricity has become essential to make drinking water and move it across networks. Each liter of water moving in a given system requires a given power consumption. In Brazil, an average of 0.8 kW·h is necessary for producing one cubic meter of drinking water.

Pumping systems account for nearly 20% of the world's energy consumption by electric motors and 25-50% of the total electrical energy usage in industrial facilities. It is estimated that water utilities consume from 2-10% of all power use in any country, and power can consume up to 65% of a water utility's operating budget (PELLI; HITZ, 2000). In Brazil, the water and wastewater sector consumes approximately 2.5% of the total consumption of electricity, equivalent to more than 10 billion kW·h/year, of which about 90% of this energy is consumed by motor-pump sets. Throughout the useful life of the projects is common that the electricity costs for pumping systems, in most cases, exceed the investment costs.

As the energy costs are increasing, the energy efficiency of pump drives is gaining importance. Optimization of pumping systems represents a significant opportunity for utilities to save money and energy while reducing maintenance costs, increasing productivity and reducing greenhouse gas emissions. The power consumption in most WDS, around the world, could be reduced by at least 25% by implementing actions and hydraulic efficiency, which amounts to all energy used in Thailand (JAMES; CAMPBELL; GODLOVE, 2002). Several studies in Europe and the USA indicate that the industrial sector has a potential reduction of 30-50% of consumption in pumping systems (HOVSTADIUS, 2007).

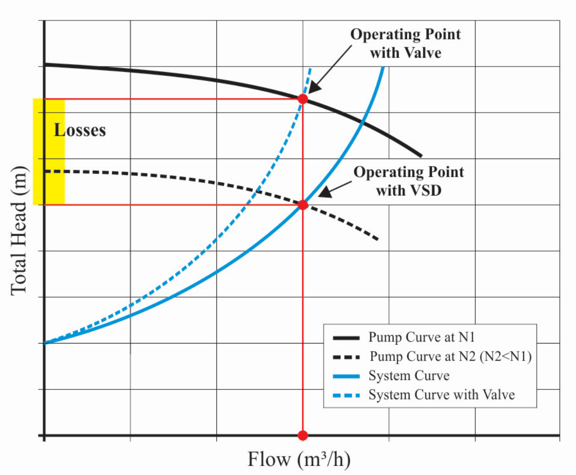
An efficient alternative to reduce energy consumption in pumping systems is the use of Variable Speed Drives (VSD). VSD can be called by different terms: AC drive, adjustable speed drives (ASD), variable frequency drive (VFD) and inverters. VSD can save 50% or more of the energy in applications that use pumps (SHEEN, 2009). The main objective of this paper is to describe the application of VSD in water supply. The application of a fuzzy system by controlling the speed of a pumping system is presented in order to demonstrate a reduction in power consumption provided by a VSD.

2 – PUMPING SYSTEM OPERATING WITH VSD

Certain pumping systems require some sort of control of flow and pressure. The flow control / pressure in the water distribution system are needed when the pump is directly in the hydraulic network, i.e., when there are no storage tanks.

The most common alternatives for controlling the flow/pressure pumping systems are: a) flow regulated by throttling, b) on/off control and c) variable speed drive. In Brazil, most pumping systems adopt the flow control through valves being operated according to operational requirements demand. This kind of control is accomplished by the addition of pressure loss by shifting the operating point of the system. It is noteworthy that with this type of control lifetime of the equipment is reduced and vibrations can occur in motor-pump assembly. Wood and Reddy (1994) define fine control of flow/pressure through valves, claiming to be the same as "driving a car with the handbrake engaged: the result is the unnecessary waste of energy". Producing 70% flow requires up to 90% of the energy used at full speed. On/off control is often used in cases where stepless control is not necessary, for instance when keeping the pressure in a tank between preset limits (SHEEN, 2009). Figure 1 show an example of operation with throttling valve and VSD (two rpms: N1 and N2), which highlights that the system operating with the valve requires a much higher manometric height. Given that smaller flows imply smaller friction losses, the yellow area in figure can be seen as energy wasted.

Figure 1 – Total head for the flow control methods of a centrifugal pump: flow regulated by throttling and variable speed drive



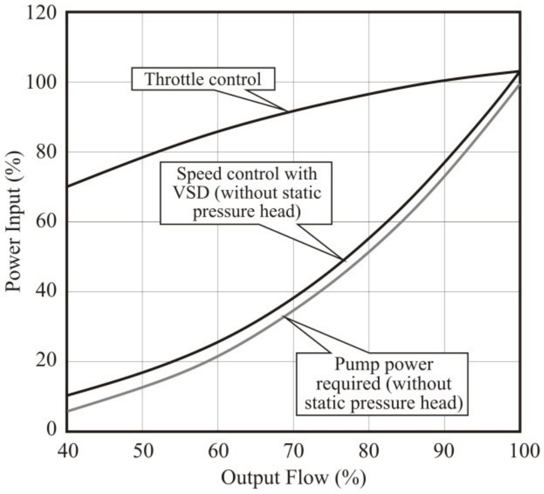
For pump stations where flow regulation is needed the best technical and economical solution is pump speed control. VSD is the most effective controller and energy saver for mechanical machines in industries (SAIDUR *et al.*, 2012). These devices improve operational flexibility of the pump drive compared with throttle control. In many cases this results in energy cost savings. Nowadays, the performance of frequency converters allows their use as an intelligent monitoring device for the pump drive (AHONEN *et al.*, 2008). Because the pump load decreases by the cube of the difference in speed, the energy usages of the motor drops off dramatically at lower speeds. Of course, this is a simplified example that does not take into effect all system losses, but it demonstrate the substantial energy savings that can be pursued and obtained through the use of VSD with centrifugal load devices (SAUER; BRADY, 2009). Though, it must be stated that not all motor applications can benefit from the VSD since, for constant-speed applications, they not only do not save energy but also lead to extra losses and capital expenses.

According to the affinity laws, the energy use of pumps varies according to the speed raised to the third power, so small changes in speed can result in huge changes in energy use. However, care must be taken in applying this concept, because they are indicated in "small" changes to speed. In general, the lower limit on speed reduction is to approximately 50% of full speed (BEZERRA; CHEUNG, 2013), and, beyond that, laws may be used for predictive purposes.

Change the rotational speed has a direct effect on the performance of the pumps. Reducing speed in the system moves the intersection point on the system curve along a line of constant efficiency. The operating point is chosen so that the pump continues to operate in its ideal region. The affinity laws are obeyed which means that there is a substantial reduction in power absorbed accompanying the reduction in flow and head.

ALMEIDA; FERREIRA; BOTH (2005) presented an approximate comparison of the performance of two different systems of flow control (Figure 2). Ferreira; Fong; Almeida (2011) concluded that the use of the VSD instead of the throttle valves to regulate the flow can produce a substantial reduction in both the environmental impact and the life-cycle cost (LCC). In variable-flow, pumping systems with VSD operating more than 2000 h/year, the estimated reduction in the greenhouse-gas emissions can reach over 35%, with a low dependency on the motor rated power, and the LCC reduction can reach over 25%, with a significant dependency on the motor rated power.

Figure 2 – Input power for different flow regulation methods of a centrifugal pump: conventional throttle-based flow regulation using a throttle valve at the pump output versus speed-based flow regulation using a VSD-fed motor (ALMEIDA; FERREIRA; BOTH, 2005)



For optimum utilization of the pump efficiency, it is recommended that the point regarding the maximum demand is situated the right of the curve of best performance. Thus, in most part of time the operating point of the system remains close to the optimal performance. In Figure 3 it is shown an example which shows that the operating point remains close to the curve of maximum output while reducing the speed of rotation of the motor-pump. In systems where the geometric gap is prevalent in manometric height, the system curve starts from the value of the static loss and, consequently, a small reduction in rotational speed of the pump provides a great variation in flow rate and pump efficiency (Figure 4). In these cases, it should be taken more attention to adopt a VSD because variations in the rotation result in significant changes in pump performance.

Figure 3 – Example of the effect of pump speed change in systems with only friction loss

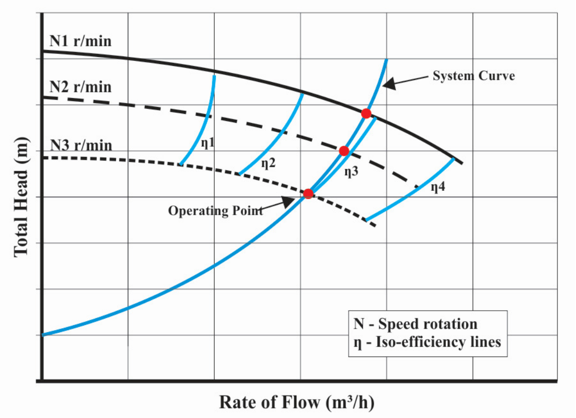
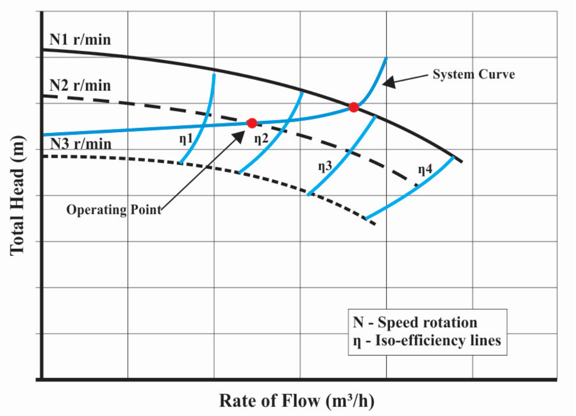


Figure 4 – Example of the effect of pump speed change in systems with high static head



For the application of frequency converters in existing engines, it should be taken care of with the real motor electrical characteristics; otherwise there is a risk of failure. Frequency converters generate voltage peaks and produce harmonics that cause heating in the motor bearings. In these cases, besides performing an operational study of the distribution network water, it is recommended a detailed study of the electromechanical motor.

The application of pumps operating with VSD in networks with direct pumping offers great potential for reducing the power consumption and improves system operation, the main advantages are:

- Enables automation of the pumping system.
- Energy saving.
- Eliminates the need for valves to start and stop the engine. This soft start extends not only the life of the motor and bearings, but also drastically reduces belt wear and tear.
- Better control in the operation of the hydraulic network.
- Minimizes the need for system stops or eliminates the jumps of production.
- Reduce pump failure caused by pump cavitation and reduce maintenance on valves.
- Reduction in the number of breaks in the pipes.
- Control of electric current of the electric motor.
- Improves the power factor.

- From a mechanical benefit standpoint, reduce thermal and mechanical stresses on motors and belts. The bearings run at reduced speeds typically last much longer than their full speed counterparts.

As drawbacks of frequency converters in WDS, there are:

- Costs of VSD are relatively expensive.
- Changing of the operating conditions of pumps, such as the income and NPSH.
- Generation of harmonic distortions and voltage limitation of the distance between the frequency converter and motor. However, there is additional equipment to overcome these problems.
- The electronic components of the converter are not tolerant to places with high humidity and corrosive.
- Chance, in some cases, of damage to the insulation of the motors.

A large-scale commercialization of frequency converters is recent; the first device was launched in the market in the late 1960's. Dewinter and Kedrosky (1989) described the expansion of the system of petroleum pumping from Cold Lake Bitumen Blend Pipeline (Canada), which changed the capacity of the lift station of the system from 130 thousand to 185 thousand barrels per day, by installing a new motor-pump set of 3,500 HP with VSD. The major concerns on choosing a VSD were initial capital cost versus energy savings, accepted industry practice, reliability and maintenance. Although the price of electricity in this period was low in Canada, the internal rate of return was less than 18%.

Generally, the researches cited in the literature discuss the use of frequency converters in real cases or evaluate the behavior of electrical parameters of induction motors operated by this equipment (DABADGAONKAR; SEN, 2011; SINGH *et al.*, 2012; IYER *et al.*, 2012). The frequency converters have some negative influence on the electrical grid and engine performance. Many researchers seek to minimize these problems. For example, the very limited research results are reported in the literature on motor starting with VSDs and the requirement of technical explanations on the topic remains strong (LIANG; ILOCHONWU, 2011). Currently, the technological level is already satisfactory, but not ideal. Burt *et al.* (2008) and Saidur *et al.* (2012) presented a detailed study on the behavior of engines operating with VSD to provide useful information for future variable speed drive applications. Liang and Ilochonwu (2011) investigated the factors that can significantly affect the motor-starting performance. An electrical submersible pump system with various lengths of downhole cables was used as a motor-starting case study.

3 – FUZZY CONTROL SYSTEMS

Traditionally, the controllers utilized for the motors are based on mathematical models in which the control system is described using one or more differential equations that define the system response to its inputs. Such systems are often implemented as PID controllers (proportional-integral-derivative controllers). In water distribution systems, a description of the mathematical model of the process is complex, may not exist, or may require a great deal of computer processing power and memory.

With the technological advances of recent decades, it can be noticed that the process control systems are more reliable. More modern and efficient controllers have been designed for complex processes. Among the intelligent systems, fuzzy control systems can be highlighted. This control system is based on Fuzzy Logic, which makes possible the inclusion of the experience of human operators in process control and industrial plants. The fuzzy systems have emerged strongly as an alternative to the automatic control of nonlinear systems with multiple inputs and output. In 1974, Mamdani applied, for the first time, a fuzzy control system of a steam engine. The researcher succeeded after numerous failed attempts with other types of controllers. The first industrial application is the control of an oven for production of cement in 1976, Denmark (HOLMBLAD; OSTERGAARD, 1982).

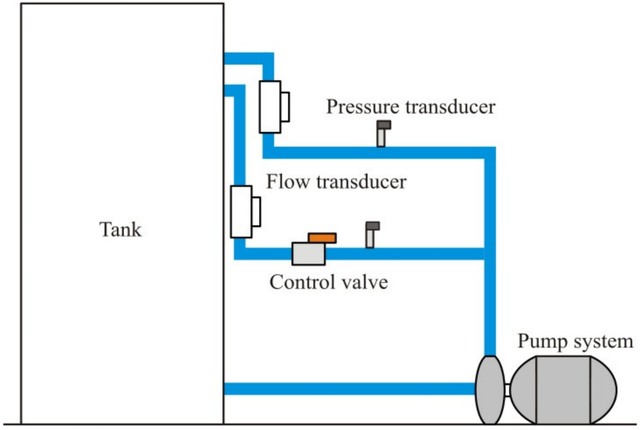
The fuzzy control systems enable the automation of various processes, ranging from housekeeping to control sophisticated industrial processes. These are widely used to control induction machines (MOHANASUNDARAM; SATHIYASEKAR; RAJASEKAR, 2012; RIGATOS, 2012; WANG *et al.*, 2012). Theories of control “conventional” apply to a wide variety of systems where the process is well defined. However, these techniques are not able to solve real problems for which mathematical modeling are impractical. In the cases it is desired the control of pressure in various parts of a water distribution system, modeling is complex, that as flows varies, the equations that define the plant change. The formulation of the control problem there will typically be discrepancies between the actual plant and the mathematical model developed for controller design. This fact strongly suggests the use of techniques for fuzzy control. In practice, it is common to apply PID control techniques, but the system cannot undergo major changes, with the risk that the control is unstable.

4 – THE CASE STUDY

In order to investigate the power consumption in a case study, it was designed and implemented an experimental system of water distribution (Figure 5) controlled by a fuzzy system. The controller automates the actions relating to the rotation speed the motor, keeping the pressure at the most critical point of the system equal to the minimum pressure required. The experimental setup consists of a reservoir, a centrifugal pump driven by an induction motor, a VSD, a control valve, two pressure transducers, two electromagnetic flowmeters and the PVC network.

The hydraulic network contains two extensions in two sectors that simulate real WDS. The control valve (CV) has the function of changing the operating conditions of the system, providing a flow variation demanded. As the CV closes, the flow decreases and consequently the upstream pressure increase. The data acquisition system consists of a portable computer and a USB data acquisition module. The module has transfer rate of 1.25 MS/s for inputs and 2.86 MS/s for outputs. The software used to control system was LabVIEW.

Figure 5 – Schematic of the experimental setup



5 – MODELING OF THE FUZZY CONTROL SYSTEM

The control system is responsible for maintaining the manometric height of the pumping system at an optimal value, eliminating any excess pressure at the critical point of the network. Mamdani model was adopted, which presents as a basic characteristic, the fact that the data sets are mapped by language. The technique adopted in the composition of various input fuzzy sets for each rule is the MAX-MIN inference method. The linguistic variables of input and output of the controller are:

- Pressure in the most unfavorable point of the system (PR). Variable defined as the pressure in the transducer with higher pressure deficit. 20 was adopted as set point for the variable PR, that is, the fuzzy controller was developed considering 20 m as minimum pressure. For reference values different from 20 m, it is necessary that the pressure measurements have their values changed for compatibility with the benchmark's default controller. This new pressure has been called the equivalent pressure and is the sum of the measured value and the difference between 20 and required pressure (reference value). The variable PR should be equal to the lower value of equivalent pressures:

$$PR = \min\{Pmes_i + 20 - Preq_i\} \quad (1)$$

Where:
$Pmes_i$ – the pressures at the measurement point i;
$Preq_i$ – the required pressure at the measurement point i.

- Frequency of actuation of the motor-pump set (FR). When a VSD is used to supply power to an induction motor, different frequencies can be applied to the motor terminal during the motor start-up and under normal operating conditions.
- Frequency delta (ΔF). Output linguistic variable of the fuzzy controller which corresponds to the increase or decrease in the value of the frequency of the supply voltage of the motor.

The linguistic variables of input and output of fuzzy system, the number and shape of pertinence functions and the universe of discourse were chosen based on recommendations of the literature, the nature of the process to be controlled, heuristics and experimental analyses. It was adopted pertinence functions with triangular and trapezoidal shapes. The choice of pertinence functions for linguistic terms plays an important role in the success of the application, but they are defined subjectively, based on experience and common sense (LEE, 1990). The fuzzy sets for the input variables are shown in Figure 6 and the fuzzy sets for the output in Figure 7.

Figure 6 – Membership functions for the input variables of the fuzzy system

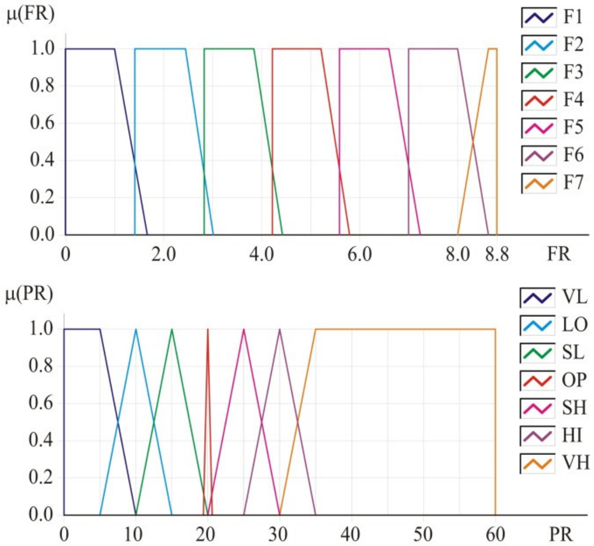
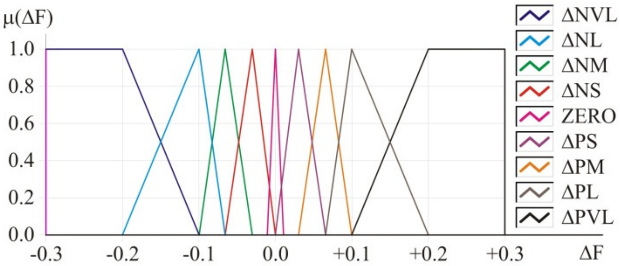


Figure 7 – Membership functions for the output variables of the fuzzy system



The output configuration of the controller is a typical set of pertinence functions for a variable of position of a servosystem, noting that near the midpoint of the equilibrium terms are denser, ensuring greater sensitivity for precise adjustment of position, while a coarsest adjustment is acceptable in more distant regions of the equilibrium point. There were nine terms of the choice to characterize qualitatively the output variable and smoothing the output signal. This smoothing is important to avoid peak currents in electric motor. The method of defuzzification is the Center of Gravity (COA). The COA method can be expressed as Equation (2).

$$du_{\mathrm{COA}} = \frac{\sum_i \mu_i(du)\ du}{\sum_i \mu_i(du)} \qquad (2)$$

Where:
$\mu(du)$ – the membership degree of du.

The aim of this procedure is to combine the individual control actions of fired rules. More than one rule could be activated or fired for a particular pair of input values. Implementing the compositional rule of inference performs this combination. With defuzzification, resultant fuzzy values of the fuzzy rules are converted into crisp values.

In Table 1 is presented the fuzzy associative matrix of the controller. The heuristic form of search of the output variable is based on the following concept:

If the pressure is less than desired, the controller increases the speed of rotation of the motor-pump if the pressure is higher than desired, the controller decreases the rotational speed of the motor-pump set.

Table 1 – Fuzzy rule base of the controller

	VL	LO	SL	OP	SH	HI	VH
F1	ΔPVL	ΔPVL	-	-	-	-	-
F2	ΔPVL	ΔPL	ΔPM	ZERO	-	-	-
F3	ΔPVL	ΔPL	ΔPM	ZERO	ΔNS	-	-
F4	ΔPVL	ΔPM	ΔPS	ZERO	ΔNS	ΔNM	ΔNM
F5	ΔPL	ΔPM	ΔPS	ZERO	ΔNS	ΔNL	ΔNL
F6	-	-	ΔPS	ZERO	ΔNM	ΔNL	ΔNVL
F7	-	-	-	ZERO	ΔNM	ΔNVL	ΔNVL

6 – RESULTS AND DISCUSSION

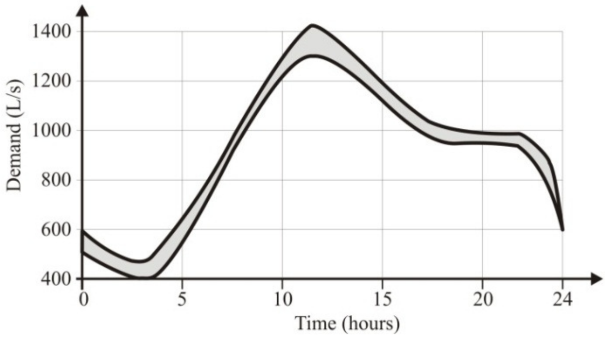
This section presents the results of experiments conducted in order to demonstrate the energy behavior of the experimental setup with VSD and validate the control system developed. They are:

- Experiment 1 – Test in open loop (no performance of the control system), with the control valve varying its opening to simulate the flow demand of a system of urban water supply.
- Experiment 2 – Test carried out with the same operating conditions of Experiment 1, but with the fuzzy controller of the frequency converter operating.

6.1 – Experiment 1

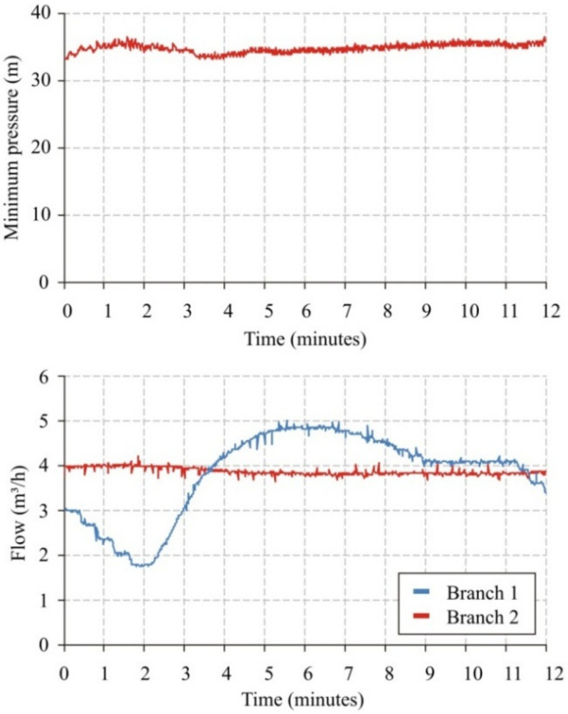
Experiment 1 was conducted with the open-loop system, i. e., without any control acting for subsequent comparison with Experiment 2. The experiment simulates the daily operation of a system of urban water supply in one of the extensions. Therefore, it was developed an algorithm in LabVIEW to simulate the demands of a real system through the remote operation of the valve CV. The opening curve of CV was based on the profile of the curve of water consumption of a hydraulic system of São Paulo, Brazil (Figure 8). The experiment time was 12 minutes (every minute equals 2 hours).

Figure 8 – Curve of residential water consumption of a hydraulic system of São Paulo, Brazil (TSUTIYA, 2008)



In Figure 9 it is shown the behavior of the flow and pressure of Experiment 1. The CV has the function of simulating the consumers soon as the flow increases, the pressure decreases, and vice versa. The average pressure at the critical point was equal to 34.94 m, which corresponds to a value of 74.7% over the ideal pressure (20 m). The average flow was 3.84 m³/h at branch 1 and 3.89 m³/h at branch 2, giving a total average flow of 7.73 m³/h.

Figure 9 – Behavior of flow in extensions and pressure at the critical point - Experiment 1



6.2 – Experiment 2

Experiment 2 was conducted with the same operating conditions of Experiment 1, but with the fuzzy controller of the frequency converter operating. This is a closed loop test with a step-like input equal to 20 for the variable PR (minimum pressure equal to 20 m). The variation of the opening angle of the CV was the same as in Experiment 1. Thus, the response of the fuzzy system to disturbances could be analyzed (changes in the system) and saving of electricity.

In Figure 10 it is shown the pressure behavior in Experiment 2. As expected, due to pressure control, there was a decrease in total average flow of 10.38%. The average pressure at the critical point was 20.20 m. The control system had an excellent response, the maximum and average errors were, respectively, 3.11% (0.62 m) and 1.02% (0.20 m).

To evaluate the efficiency of the experimental system, with and without the controller (open-loop) of the frequency converter, it was measured, online, the power consumed and calculated the specific consumption of electricity, kW·h/m³. This indicator is widely used in the water sector and is defined as the ratio of energy consumption (kW·h) of the pumping system and the pumped volume (m³), at a given time. Although the converters consume, on average, 5% of the power of the system and lead to a decrease of performance of the motor-pump set, it was found that the control of rotation provided a reduction in power consumption of 52.91 to 34.38 kW·h/day resulting in a saving of 35.02% (Figure 11). In Table 2 are shown the values of the energetic evaluation parameters for the experiments 1 and 2. The reduction of 28.13% in specific consumption of electricity expressed the improvement in energy efficiency of the system.

Figure 10 – Behavior of the flow and pressure at the critical point – Experiment 2

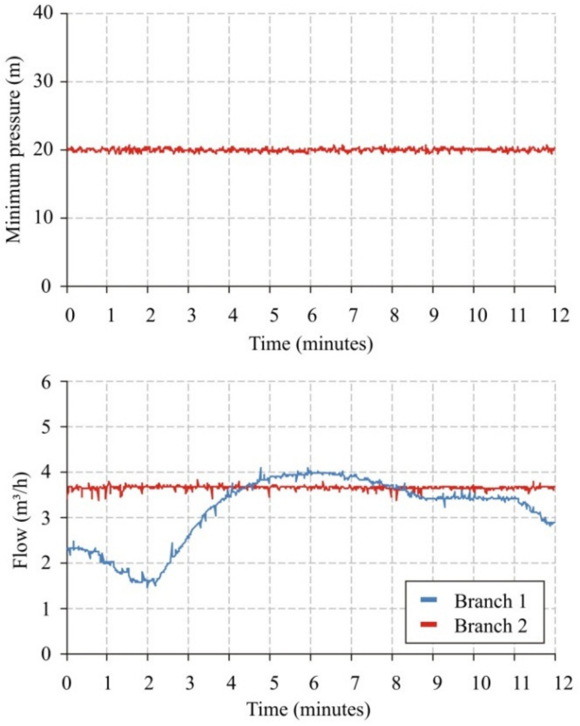


Figure 11 – Comparison of experiences 1 and 2 – power consumption and specific energy

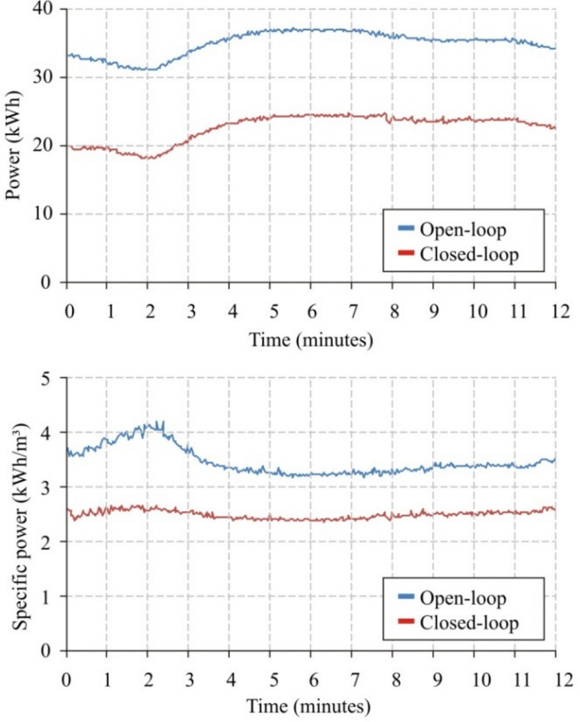


Table 2 – Consumption indicators of the experiments

	Open-loop	Closed-loop	Difference
Flow (m³/h)	7.73	6.93	10.38%
Power consump. (kW·h/day)	52.91	34.38	35.02%
Specific energy consump. (kW·h/m³)	0.288	0.207	28.13%

CONCLUSIONS

This study investigated the use of variable speed drives in water supply systems and presented a fuzzy system that was developed to control the rotational speed of an experimental setup. The VSD operated keeping the manometric height of the pumping system at a great value.

Analyzing the application of VSD in the experimental setup, it was observed that the control of the rotational speed provided a reduction in the estimated consumption of electricity of 35%, with a 28% decrease in specific consumption of electricity (kW·h/m³). The environmental benefits from energy savings also encourage the use of VSD in water supply. The increase of efficiency results in the virtual generation of clean energy and reducing emissions of greenhouse gases.

The fuzzy system developed showed itself robust, maintaining the pressure constant during variations in operating conditions. The maximum and average errors were, respectively, 3.11% (0.62 m) and 1.02% (0.20 m). Therefore, it is concluded that the Fuzzy System presents itself as an effective tool for the control of VSD.

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