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PERFORMANCE OF OVERSIZED PUMPS CONTROLLED BY VARIABLE FREQUENCY DRIVES IN WATER SUPPLY SYSTEMS

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Abstract: Reducing water and energy consumption is an essential condition for reducing the operational costs of water supply systems (WSS). The use of pumping systems driven by variable frequency drives (VFD) is one of the most suitable alternatives to optimize the pressurization of the distribution networks and, consequently, reduce the consumption of electricity and water losses. This article aims to analyze the performance of oversized pumps, driven with variable frequency drives, from WSS. The work was carried out in two experimental setups that have oversized pumps. The methodology consisted of evaluating data collected in experimental tests using hydraulic and electric meters. Tests were realized for different operating conditions of the systems, with the variation of the rotation of the pumps, in order to obtain the pump efficiency curve according to the VFD output frequency. The results demonstrated that the use of variable frequency drives proved to be an alternative to increase the energy efficiency of the evaluated systems. It was observed that the highest efficiencies were recorded in the lowest frequency bands (30 Hz and 35 Hz), while in the values close to the nominal frequency (45 Hz to 60 Hz) there is little variation in the efficiency values.

Keywords: Water distribution systems, Pumping systems, VFD-motor-pump system, Pump efficiency, Hydraulic and energy efficiency.

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INTRODUCTION

Energy is an essential resource for various domestic and industrial activities. Global energy consumption is expected to increase 30% between 2016 and 2030. It is estimated that global energy consumption will increase from 162,500 ZW (in 2015) to 198,654 ZW in 2030 (EIA, 2016). The high demand for energy results in increased costs and high environmental impacts. Therefore, this topic must be addressed by society and researchers in order to identify opportunities that aim to reduce energy consumption.

Of the total energy consumed in the world, it is estimated that pumping systems (PS), especially centrifugal pumps, consume about 20% (Shankar *et al*., 2016). Energy is among the three main cost items of water and sewage service providers and, in many cases, r epresents the second largest expense, being lower than only personnel costs. In developing countries, energy is generally the highest cost associated with the water source (Silva *et al*., 2015). In Brazil, according to the National Energy Conservation Program for the Sanitation Sector of Eletrobras, the sanitation sector consumes between 2 and 3% of the country's electricity, 90% of which is consumed by pumping systems (Barros Filho *et al*., 2018; Bezerra *et al*., 2015).

The growing demand for water consumption in cities has made the operation of pumping systems increasingly complex (Curi *et al*., 2012). The opportunities to improve the PS energy efficiency are broadly classified into three distinct categories: component selection, sizing of the pumping system and variable speed control (DOE, 2002). In order to ensure energy efficiency of PS, a comprehensive understanding of the system requirements – e.g., minimum, average, and peak-day demand; near-term and future demand; water age; and duration of operation – are important (Cherchi *et al*., 2015). The first methods to optimize the operation of PS came with the first digital computers in the 1960s. Since then, the development of different algorithms has grown rapidly. Coulbeck and Orr (1984) used dynamic programming to optimize pump programming and selection; Zessler and Shamir (1989) optimized the operation of pumps and valves for a period of 24 hours by means of progressive optimization based on dynamic programming; Ormsbee *et al*. (1989) determined an optimal planning of the PS to minimize the operating cost, considering the variable rates of electric energy and the variation of the water demand. In recent years, several studies have been published with the objective of increasing the efficiency of pumps that operate with variable speed of rotation (Silva *et al*., 2015; Lindstedt & Karvinen, 2016; Guo *et al*., 2017; Barros Filho *et al*., 2018; Moura *et al*., 2018).

Pumping systems generally operate at fixed speeds of rotation, producing high heads during hours of low water demand, which causes unnecessary electricity consumption. In addition, these pump head generate significant pressures on the distribution networks, which contribute to the increase in water losses and make the pipes more vulnerable to ruptures. One way to solve this problem is the use of pumps with variable speeds of rotation, through the use of variable frequency drives (VFD). Variation in the speed of rotation of the PS is the most effective alternative to serve systems with variable flow rate over time. This task is essential in water supply systems (WSS) without reservoirs, where the pressure in the system is directly regulated by the pumps (Koor *et al*., 2016).

VFDs are devices that, associated with the PS, regulate the flow rate and pressure by varying the frequency of activation of the electric motor. The use of these devices is ideal for systems pressurized directly by the pumps, where there is a need for operation with flows other than the nominal design flow. Thus, such devices can be used in the WSS to promote the reduction of energy consumption and, consequently, contribute to greater energy efficiency of these systems.

The use of VFD gives the systems important hydraulic, electrical and economic advantages: reduced pressure in the pipes, reduced hydraulic and electrical transients, reduced motor inrush current, possibility of integration with automation systems, reduced consumption and, consequently, consumption reduction, electricity cost. In addition to reducing energy consumption, it is also necessary to consider reducing water losses through pressure control. In general, a 10% reduction in pressure in the pipeline network results in a reduction of approximately 12% in the volume lost by leaks (Bezerra *et al*., 2012).

When operating pressurized systems with fixed speed pumps, the PS efficiency drops significantly when the operational flow rate deviates from the

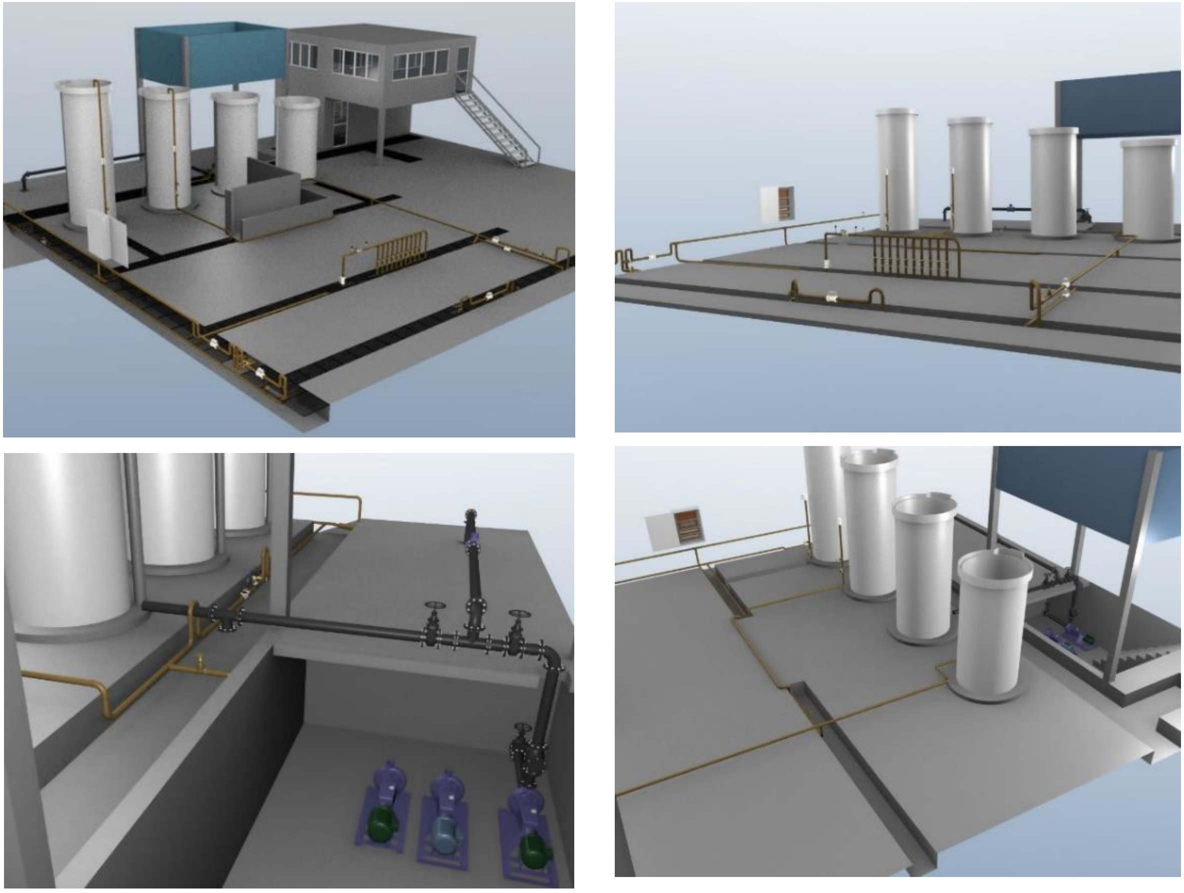

Fig. 1 Experimental setup 1 – Schematics of the PWDS.

nominal flow of the system. In view of this, oversized pumps that operate with VFD can have much higher highest efficiencies than pumps operating at a fixed rotation speed. Considering that about 75% of pumps are oversized (Koor *et al*., 2016), the use of VFD can increase the efficiency of many real systems.

The system efficiency of a VFD-motor-pump system correlates the mechanical power received by the water, the product of the flow rate and head of the pump, to the system electrical input power. In a VFD-motor-pump system, the system efficiency actually is the wire-to-water efficiency, which combines the efficiencies of the VFD, motor and pump (Rishel *et al*., 2006; DOE, 2016; Wang, 2019).

Although electric motors perform poorly when operated at lower frequencies, since Joule losses represent the largest share of losses in a motor, the efficiency of VFD-motor-pump systems may not decrease under certain operating conditions. In contrast to the efficiency models of motors, the efficiency of pumps is not impacted by VFD. Therefore, this paper aims to analyze the variation in the overall performance of oversized pumping systems, driven with VFD, in water distribution systems. The work was developed in two automated experimental setups that simulate the supply of two WSS.

MATERIALS AND METHODS

The methodology of this work comprises the analysis, through two automated experimental setups, of the energy efficiency of two water distribution systems pressurized directly by pumping systems. The experimental setups belong to the Energy Efficiency and Hydraulics in the Sanitation Laboratory of the Federal University of Paraíba (LENHS U FPB), João Pessoa, Brazil.

The first experimental setup is called the Pilot Water Distribution System (PWDS) (**Fig. 1**). It is fully instrumented and automated, which has allowed the development of research aimed at increasing the hydraulic and energy efficiency of water distribution systems (e.g., Moura *et al*., 2018). The network is 155 meters long with PVC pipes (DN 50 and DN 100) and ductile iron (DN 100). The system is equipped with water flow meters, pressure transducers, water level meters and control valves. The PWDS is pressurized by means of direct pumping, which consists of a variable frequency drives (VFD), a three-phase induction motor of 5 hp and a centrifugal pump with nominal flow of 15 L/s and head of 17 m. The communication between the sensors – pressure, water flow and water level meters – and the actuators – control valves and VFD – is done via cabling, through a programmable logic controller.

The PWDS is also composed of control panels and electrical drives, which operate according to the automation system implemented. Its function is to allow the interface between the instruments of the water distribution network and the supervisory system, in addition to serving as a control and protection panel for motors and electrical equipment. Through the human machine interface, existing on the front panel of the programmable logic controller, it is possible to read the electrical and hydraulic parameters obtained by the sensors and actuators installed in the plant. The plant has four discharges controlled and monitored outputs with flow meters and control valves. However, for the pumping system to operate oversized, the experiments were carried out with three closed discharges; the system operated with a water demand of approximately 25% of the nominal flow of the system.

From the supervision system, it is possible to send commands and obtain information from the sensors and actuators present in the water distribution network. The supervisory was developed in a LabVIEW® environment, which allows the performance of all the procedures necessary for the operation of the experiment, as well as the introduction of controllers based on several programming logics.

The second experimental setup used is called the Automated Water Distribution System (AWDS), which simulates the operation of a sectorized water distribution system, composed of two pressure zones, whose discharge branches have different elevation levels; the low zone is

1.50 m and the high zone is 6.50 m. The low zone comprises the entire stretch traveled continuously (without branches) from the distribution reservoir to the discharge 1. The high zone is represented by the stretch traveled from the reservoir to the discharge 2. The arrangements of the main elements of the AWDS are shown in **Fig. 2**.

The pumping system do AWDS consists of a VFD, a three-phase induction motor of 3 HP and a centrifugal pump. The variation in the speed of rotation of the pump, driven by an automatic control system, allows maintaining the service pressures of the networ k at constant pre-established levels. Therefore, the operation of the pumping system is adjusted to the frequent variations in the system's water demand. This way, network overpressures and unnecessary energy costs are avoided. The reading of the hydraulic parameters provided by the sensors and actuators is performed by the supervisory system, based on the communication established by means of a data acquisition device. Through this device, communication signals are transmitted for the actuation of proportional control valves and VFD.

Fig. 2 Experimental setup 2 – Automated Water Distribution System.

A conventional electromagnetic water flow meter was installed on the pipe to measure the pump water flow rate while a differential pressure transducer was installed between the discharge and suction of the pump to measure pump head. System input power was measured differently in the two experimental setups. The electrical parameters of the PWDS were obtained directly from the human-machine interface installed in the electric switchboard. In the AWDS, a conventional power meter was installed on the power supply upstream of the VFD to measure the actual system input power. With these data, it was possible to evaluate the power for different operating conditions.

In order to evaluate the effect of the rotation speed on the performance of the two pumping systems, experimental tests were carried out with the VFD output frequency varying from 30 to 60 Hz. The flow rates, pressures at the inlets and outlets of the pumps, and the system input power were measured in real time to obtain the pump characteristic curves in the different operational conditions imposed. The highest efficiency was calculated by Equations 1 and 2.

$$\eta = \frac{Ws}{W} \quad (1)$$

where η is the efficiency of VFD-motor-pump systems (%); *Ws* is motor shaft power (kW), *W* is the system input power (kW).

$$Ws = H \times Q \times 9.81 \quad (2)$$

where *H* is pump head (m), and *Q* é a flow rate (m³/s).

RESULTS AND DISCUSSIONS

The results showed that for the two pumping systems evaluated, the lower the frequency, the higher the system performance. **Fig. 3** shows the efficiency curves of the experimental tests performed on the PWDS. Based on the data obtained, it is observed that the highest efficiencies correspond to the VFD output frequencies of 30 and 35 Hz. With the system operating at the frequency of 30 Hz, the maximum value of the efficiency was 73%, while for the frequency of 35 Hz the efficiency reached 65%. From 40 Hz onwards, the maximum recorded efficiencies ranged from 58 to 55 Hz. The lowest efficiency was 35% for 50 Hz and 36% for the system operating at its nominal frequency of 60 Hz.

In order for the AWDS to work oversized, it was decided to supply water to the high and low zones separately. Therefore, the experiments were of two types: in the first, the pumping system supplies only the low zone, while in the second, the pumping system supplies water only to the high zone. The variation of the pump head as a function of flow rate and VFD output frequency is shown in **Figs. 4** and **5**, for supplying the low and high zones, respectively.

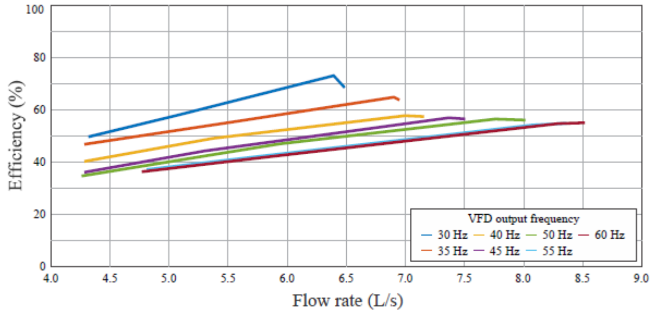

Fig. 3. PWDS results – VFD-motor-pump efficiency versus flow rate.

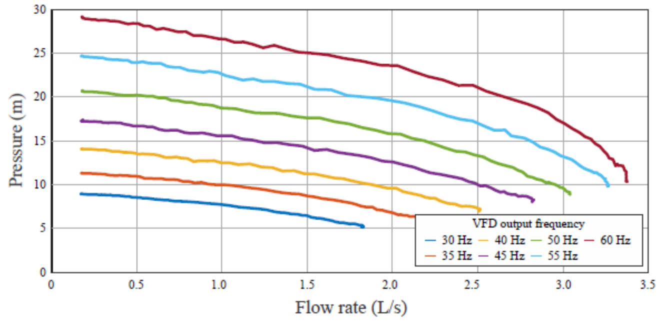

Fig. 4. AWDS results with low zone in operation – Pump head versus flow rate curves.

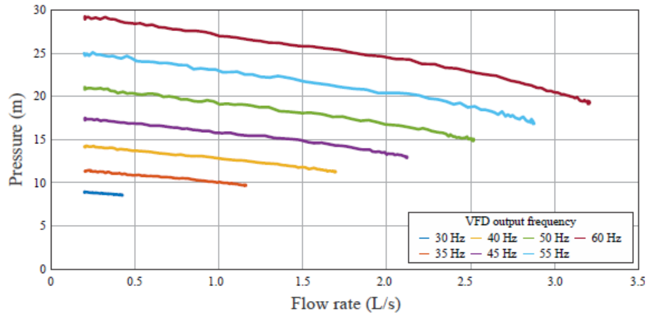

Fig. 5. AWDS results with high zone in operation – Pump head versus flow rate curves.

Assessing the performance of the pumping system based on the efficiency curves of the VFD-pump (**Figs. 6** and **7**), it is observed that the lower the frequency, the greater the efficiency of the VFD pump system. The experimental results demonstrate that for the range of 40 Hz to 60 Hz, there is little variation in the performance of the system, whose records were around 45%, for a flow range of 2.5 L/s to 3.5 L/s.

Normally, lower efficiencies are expected to be obtained for the lower frequency bands and the ideal efficiency for the motor operating at the nominal frequency, 60 Hz. However, due to the oversized of the assessed pumping systems, the lower frequencies resulted in higher efficiencies. **Figs. 8** and **9** show the behavior of the system input power in the experiments carried out on the AWDS.

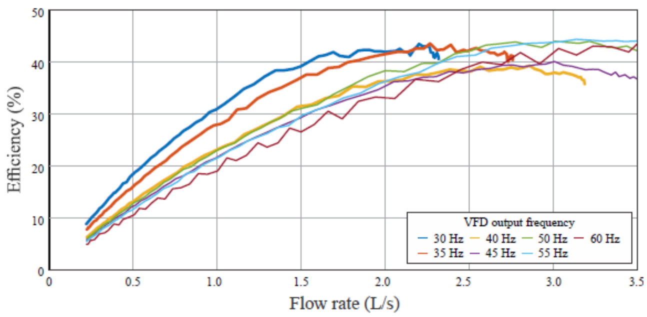

Fig. 6 AWDS results with low zone in operation – VFD-motor-pump efficiency versus flow rate curves.

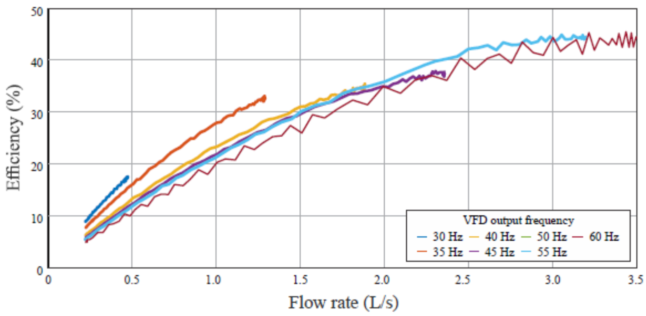

Fig. 7 AWDS results with high zone in operation – VFD-motor-pump efficiency versus flow rate curves.

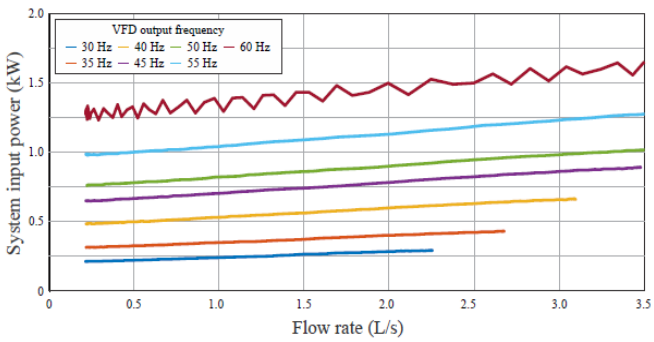

Fig. 8 AWDS results with low zone in operation – System input power versus flow rate curves.

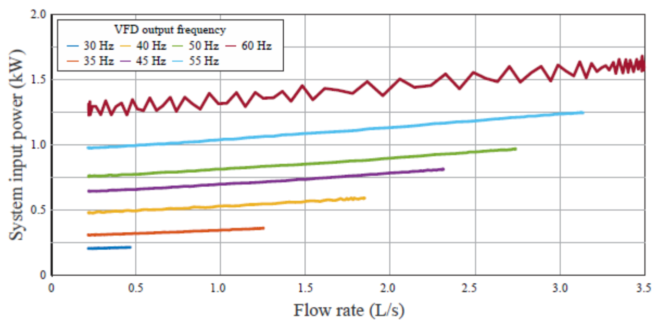

Fig. 9 AWDS results with high zone in operation – System input power versus flow rate curves.

Figs. 10 and **11** show the specific energy consumption (SEC) curves of pumping system during experiments. It is the most commonly used energy indicator to determine the pump system's energy efficiency. SEC is the ratio between the total energy the pumps consume and the volume of water entering the system. According to Gomes *et al.* (2020), this indicator is a valid energy intensity measure for the analysis of a system but does not account for unique system characteristics that have a significant effect on energy consumption, such as topography, leakage, friction losses, and demands.

Similar to the evaluation of the VFD-motor-pump efficiency, the results of the SEC measurement throughout the experiments demonstrated that the energy efficiency of the AWDS increases the lower the frequency, as the value of the SEC decreases when the frequency decreases.

CONCLUSIONS

Based on the results obtained in the two second experimental setup, operating under varying water demand conditions and with heterogeneous topologies, it was demonstrated that the overall efficiency of VFD-motor-pump system varied significantly, depending on the operating conditions and variations in the rotation speed of these systems. Experimental tests have shown that oversized pumping systems can operate at variable speeds to increase energy efficiency. The results showed that, for the two pumping systems evaluated, the lower the frequency, the higher the system performance.

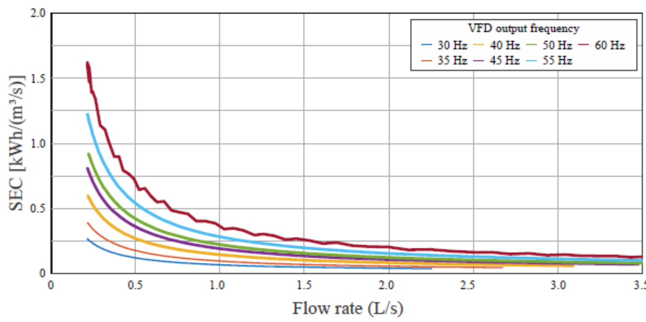

Fig. 10 AWDS results with low zone in operation – SEC versus flow rate curves.

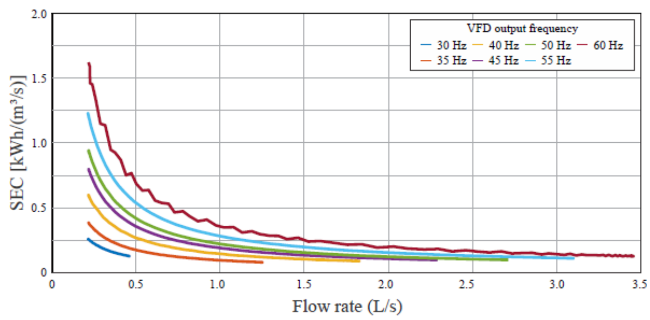

Fig. 11 AWDS results with high zone in operation – SEC versus flow rate curves.

In the PWDS, which operated with a water demand much lower than the nominal value of the system, the highest efficiencies occurred with the system operating at low frequencies.

The best efficiency of the VFD-motor-pump system, whose value was 73%, occurred with the VFD output frequency of 35 Hz, while at nominal frequency, the efficiency of the system dropped to 36%.

In AWDS, which operated with pump head varying due to the difference in elevation of water consumption points, the efficiency of the system varied significantly. For the supply of the low zone of the system, with the high zone off, the pumping system obtained its maximum efficiency (η = 44%) for a VFD output frequency of 35 Hz. In the operating condition of the high zone only, the maximum efficiency (η = 45%) was reached for the nominal frequency, as the high zone needs a greater drop to reach the required flow.

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