Pressure Regulation in a Water Distribution Network Using Pumps as Turbines at Variable Speed for Energy Recovery

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Abstract

Pumps that function as turbines (PATs) are considered an economical solution to control pressure in water distribution networks (WDNs) in place of pressure control valves (PCVs). Their use requires a precise operational understanding of various hydraulic conditions in a WDN. Otherwise, the efficiency of the machine is reduced by the off-design operation, making it impossible to regulate the pressure and recovering little energy. This study presents a methodology that details the pressure regulation in a municipal network by controlling the PAT speed. The WDN sectorization steps are described using EPANET 2.0 software. The selection and off-design operation of the pump are presented with several models from the literature. The machines are simulated at constant and variable speeds to replace the valves. The economic advantages are also estimated. At constant speeds, operation as a PCV occurs only in the flow close to the best efficiency point (BEP), impairing the supply in the network. At variable speeds, the PAT maintains the best efficiencies (0.62 to 0.64) and power (3.44 kW) when flows are high and speeds are low (2,400 at 11 am and 3,000 rpm at 6 pm). Thus, the pump outlet pressure and network throughput are maintained according to the values required by the PCVs. With all the pumps in operation, the system can recover 270,192.19 kWh/year. The estimated payback period is 27 months, the net present value (NPV) is US$ 64,476.18, and the internal rate of return (IRR) is 63% for the analyzed PAT.

Highlights
• A combination of two methods to predict the off-design behavior of PATs is proposed.
• A methodology for dividing WDNs into district measurement areas is proposed.
• PAT selection is detailed, and its variable speed operation is analyzed.
• A variable speed PAT regulates pressure in the WDN with valve-like performance.
• The variable speed PATs can generate 270,192 kWh/year for a network of 2,500 houses.

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1 Introduction

Studies have shown that water supply systems (WSSs) are a significant potential source for energy capture (Pasha et al. 2020) given the intense demand for renewable energy sources in recent years to meet the global demand (Soltani et al. 2020) caused by irreparable environmental changes in various sectors (Razmi et al. 2022). Technically, these systems are considered to have low energy efficiency due to the large amount of energy that is lost due to water leakage and dissipated by pressure control devices (Doghri et al. 2020). Therefore, sustainable practices are continuously sought for WSS applications to ensure a safe supply of drinking water and balance the current tensions between climate change and energy in the urbanized world (Quaranta et al. 2022), in addition to implementing some of the sustainable development goals proposed by the United Nations (UN) (United Nations Organization - UNO 2022).

Water companies are increasingly committed to reducing water and energy waste (Xu et al. 2014), making them more sensitive to these indicators due to the scarcity of energy sources and their increasingly high price (da Silveira and Mata-Lima 2021). In fact, these factors represent the two main challenges of this sector in recent years (Ferrarese and Malavasi 2020), with a focus on the energy consumed and lost in leaks in water distribution networks (WDNs). Leaks can be exacerbated by excessive pressure. Pressure control is an effective approach to reducing losses in WDNs (Mariano et al. 2021) and one of the criteria for promoting a sustainable water supply.

A common strategy in pressure management is the sectorization of WDNs (Bui et al. 2021). In this process, larger networks can be divided into smaller networks called district measurement areas (DMAs) with the help of hydraulic simulators such as EPANET, SPRING and WALTERCAD. Within the DMAs, the pressure is usually controlled by installing pressure reducing valves (PRVs) at specific locations in the network (Mehdi and Asghar 2019). Although they provide pressure control at economic or acceptable levels, valves waste much of the energy incorporated in the tubes (Dini et al. 2022). Thus, to compensate for the intensive energy consumption in WSSs, recent studies have shown that it is possible to recover wasted energy through the replacement of PRVs (Creaco et al. 2020) with pumps functioning as turbines (PATs), which are able to extract electricity from the valves (Pirard et al. 2022).

PATs are pumps that operate in inverse mode and are capable of controlling pressure while recovering energy in WDNs (Meschede 2019) instead of just consuming it. The main challenge to their wide use is the lack of knowledge about their performance in inverse mode, as manufacturers rarely provide this information (Novara and McNabola 2018). As a result, many studies have focused on predicting the performance of PATs. Many approaches use methods based on the best efficiency point (BEP) (Alatorre-Frenk 1994; Yang et al. 2012) or on a specific pump speed (Singh and Nestmann 2010; Tan and Engeda 2016). However, when installed in a WDN, a PAT must work under various conditions due to dynamic operations throughout the day (off-design) (Fontana et al. 2019), which makes it impossible to define a single operating point that describes the behavior of the machine (Polák 2019).

Recently, scientific studies on the performance of out-of-design PATs have been published, and new theoretical collaborations have been proposed. Stefanizzi et al. (2018) developed a 1-D prediction model that predicted all the characteristics of a PAT, including the prediction of more accurate off-design operating points. Rossi et al. (2019) presented a model that reconstructs the performance curves of a PAT with only a limited amount

of data related to its BEP, which represents a design restriction in many cases. Alberizzi et al. (2019) developed correlations with a MATLAB ©-Simulink model that predicted the performance of a PAT at the BEP and off-project for a WDN branch in southern Italy, with high daily flow variability.

The literature on PATs in WDNs follows methods that can be classified into three groups (Mitrovic et al. 2021): (i) those that consider a fixed operating group, with constant flow and pressure through a PAT; (ii) those that focus on selecting the optimal number and/or location of PATs within WDNs (Fecarotta and McNabola 2017); and (iii) those that consider variable PAT operating points, with a flow interval passing through the machine and a load drop linked to the PAT curve, which is the focus of the present study. Despite these studies, the use of variable-speed PATs as VRPs for pressure control and energy recovery requires further investigation.

Previous studies predicted that the greatest operational adaptability could be achieved by controlling the rotation speed of PATs (Carravetta et al. 2012). Carravetta et al. (2013) examined variable speed operation with a control strategy to increase efficiency and energy yield under variable flows in a WDN, allowing greater flow control. Jain et al. (2015) experimented with PATs to optimize geometric and operational parameters such as rotor diameter and rotational speed. The rotor tuning improved efficiency under partial load operating conditions, while the best performance of the PATs was found at speeds below the rated speed. Fecarotta et al. (2016) analyzed the reliability of the affinity law in predicting the behavior of PATs at variable velocities and used experimental data from the literature. Their results showed a significant discrepancy, and a new model was proposed to minimize the errors between the predicted and measured characteristic curves. Kramer et al. (2018) studied a PAT in the laboratory and in the field to improve the economic profitability of energy recovery installations by approximately 15 kW. The QH characteristics of the turbine at different rotation speeds were similar and therefore did not offer benefits for practical applications.

Ebrahimi et al. (2021) studied the selection of PATs to replace PRVs in three scenarios, considering constant- and variable-speed pumps. Their results showed that the change in speed produced a slightly lower amount of energy but better performance in controlling the network pressure. Tahani et al. (2020) analyzed a variable speed centrifugal pump installed in a network. The load, power and efficiency curves were improved by incorporating a speed parameter in the described PAT. Alberizzi et al. (2018) investigated a WDN with high flow rates chosen to enhance PAT velocity control. The speed variation showed excellent benefits compared to maintaining the fixed speed, which decreased energy production by approximately 23%. Delgado et al. (2019) experimentally investigated the stationary operating performance of three PATs. In this case, operational control increased the pump efficiency and energy yield. Lima et al. (2018) presented a method that simultaneously selects PATs and their operation at variable speed. Compared to constant speed and VRP operation, the variable-speed PATs showed the best results.

Despite the encouraging results of these investigations, few studies have paid attention to the pressure control of PATs operating at variable speeds in a network as the first function, generally focusing on greater energy recovery. The novelty of this study is to detail the PAT behavior as if it were the replaced valve itself, comparing the outlet pressure at the pump, at the least favorable node and throughout the WDN, previously divided into DMAs, with the control required by the valve according to the specific legislation. In addition, how the power and efficiency of the machine are modified by speed control is also evaluated.

Therefore, the objective of this study is to present a methodology that would allow the effective control of pressure in WDNs using PATs at variable speeds to replace the

pressure control valves (PCVs) strategically placed in a network previously sectored into DMAs. With the off-designation selection and prediction of PATs, from an associated model detailed in this study, it is possible to analyze the operation of the machines at variable speeds, as if the PATs were PCVs. Finally, the economic advantages of the pumps were estimated. The results showed that the division of sectors was fast and efficient due to the practicality of the software used. The associated model exhibited good prediction, and the selection of pumps occurred quickly and clearly. There was an increase in the efficiency of the machine under partial and full loads and in the power efficiency when operating at variable speeds. Thus, the pumps controlled the pressure throughout the network and consequently recovered the energy that would be wasted by the valves. The economic analysis showed that the use of PATs in WDNs is feasible.

2 Methodology

2.1 Description of the Methodology

The methodology of this study aims to facilitate the use of PATs at variable speeds to replace PCVs and analyze in detail the pressure behavior of the machines as if the PATs were the valves themselves so that they can recover the largest amount of wasted energy in the tubes. Figure 1 illustrates the methodology used in this study. Initially, the input data of a network were introduced into EPANET 2.0 software (1) to perform the sectorization process; the WDN was divided into DMAs with strategically placed valves, replaceable by PATs (2). The selection of the pump is then easily performed based on the good results of the previously validated model (3). The association of two forecasting models to define the off-design characteristic curves is then presented (4). Speed control is achieved by applying the turbomachinery affinity laws (5). To analyze the economic feasibility of using machines in WDNs, estimates of payback (RP), net present value (NPV) and internal rate of return (IRR) are made (6). The described methodology is applied in a municipal network located in the northern region of Brazil (7).

2.2 Use of PATs as Pressure Control for Energy Recovery in WDNs

2.2.1 WDN sectorization

To perform the sectorization of a WDN, the hydraulic simulator EPANET 2.0 is used. This public domain software (Rossman and others 2000) can improve a network by providing
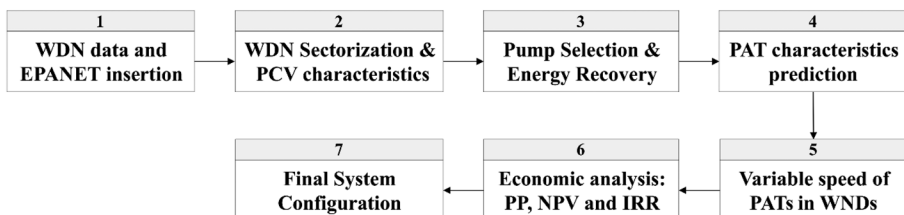

**Fig. 1** Methodology conducted for pressure control and energy recovery

good simulation effects and high operating speed (Duan et al. 2019). Initially, the following input data are entered in the program's dialog boxes: pipe, node, topography, reservoir, pump, and valve characteristics, consumption curves, reservoir volume curves, and temporal patterns. Next, EPANET solves the nonlinear energy and linear mass equations for the flow rates in the tubes and the pressures in the nodes. As a result, the program presents the current hydraulic behavior of the network (step 1), which is essential for sectorization.

Subsequently, grouping and sectorization criteria are applied to partition the network (Bui et al. 2021). The grouping aims to project the shape and dimensions of the districts based on the network topology and specific parameters recommended in the legislation, such as the maximum number of connections and the maximum length of the DMA (step 2) (ABNT 2017). The sectorization physically divides the network and defines the positioning of the meters and valves (step 3). The specification of each valve and its control are defined in this step. It is essential to confirm that the pressure follows the limits of current legislation, i.e., 10 m for the minimum dynamic pressure and 50 m for the maximum static pressure (step 4) (ABNT 2017). Otherwise, the valve output control must be modified until there is a pressure equilibrium in the DMA. Figure 2 shows the steps for the sectorization of a WDN.

2.2.2 Use of PATs to Replace PCVs

In this article, the replacement of pressure control valves (PCVs) is considered. The choice of PCVs is justified by the fact that they encounter variable pressures over time (Giustolisi et al. 2016). During operation, the process line is used as a triggering signal to open or

Fig. 2 DMA division methodology
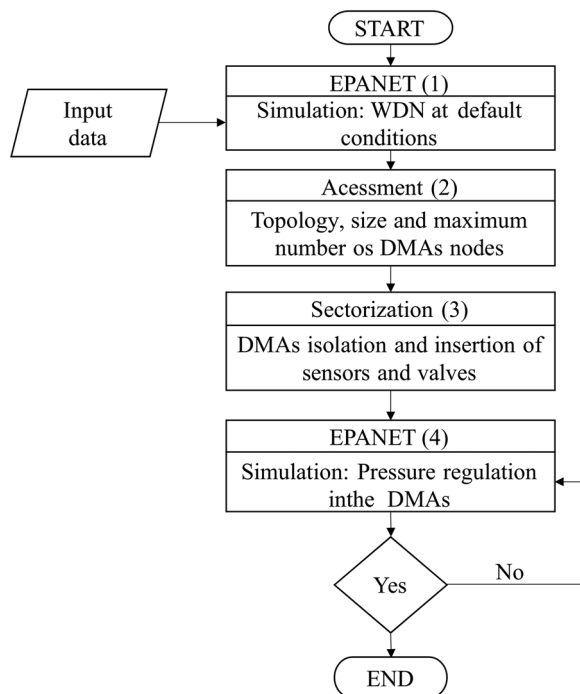
**Fig. 3** PCV installation (**a**) and PAT installation (**b**)
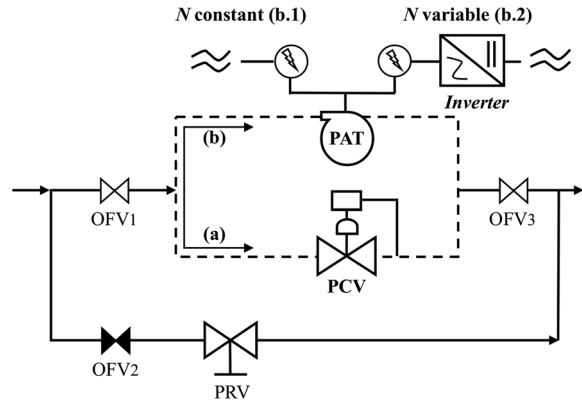
close a PCV, i.e., the operating point is regulated by the pressure immediately downstream of the valve, which is used as a signal to throttle or relieve the flow.

Figure 3 shows a PCV installation consisting of a bypass system (a) with a PRV operating in parallel. This scheme has two on–off valves (OFV_1 and OFV_2) to control the flow direction (PCV or PRV) and another (OFV_3) for emergency maintenance of the PCV. In another configuration, the PAT replaces the PCV, and the same scheme is used (b). The pump is set to run from 6:00 am to 11:00 pm. From 11:01 pm to 5:59 am, the bypass is activated and ensures PRV operation, which is used to dissipate excess pressure. When the working hours begin, OFV_1 opens, allowing for PAT flow. At the end of working hours, OFV_1 closes and OFV_2 opens, directing the flow to the PRV.

2.3 Method of Pump Selection and Energy Recovery in the WND

Figure 4 illustrates the pump selection procedures used in the WDN. The PAT selection depends on the hydraulic conditions of the PCV ($H_{PAT} = H_{PCV}; Q_{PAT} = Q_{PCV}$) (step 1). The flow rate used to select the pump is the average of the PAT operation over 18 h. An initial pump efficiency value must be assumed (η_i) (70% (Pugliese et al. 2016)) to calculate the h and q corrections in Eqs. (1) and (2) and identify the pump data at the BEP ($H_{BEP,P}$ and $Q_{BEP,P}$) (step 2). It was observed that the efficiency of the PAT should be lower than or equal to that of the pump ($\eta = \eta_p \geq \eta_{PAT}$). Using the manufacturer's catalog, the pump family is selected and used to assign the characteristic curves, including the speed (N), diameter (D) and efficiency η_{i+1} (step 3). The calculations in Eqs. (1) and (2) and the entire process described above must be repeated to identify the pump and the PAT operating point in the BEP from the value η_{i+1} identified in the manufacturer's catalog (step 4). This is necessary to avoid assuming a constant value for several machines, leading the model to present imprecise and unreliable results. In this step, it is necessary to verify if the conditions $H_{BEP,PAT} \geq H_{PCV}$ and $Q_{BEP,PAT} \geq Q_{PCV}$ are satisfied. Otherwise, another pump must be chosen from the manufacturer's catalog. The flow coefficients ($\phi_{BEP,PAT}$) and pressure ($\psi_{BEP,PAT}$) for the PAT at the BEP are determined by applying Eqs. (6) and (7), respectively (step 5). Finally, an interval is determined for ϕ_{PAT}, considering the value of $\phi_{BEP,PAT}$. Using Eqs. (3) and (4), the dimensionless pressure coefficient (ψ_{PAT}) and efficiency (η_{PAT}) of the PAT are determined from the interval of ϕ_{PAT} (step 6). The equations used in this topic will be detailed in the subsequent subtopic.

Fig. 4 Method for selecting the pump as the turbine
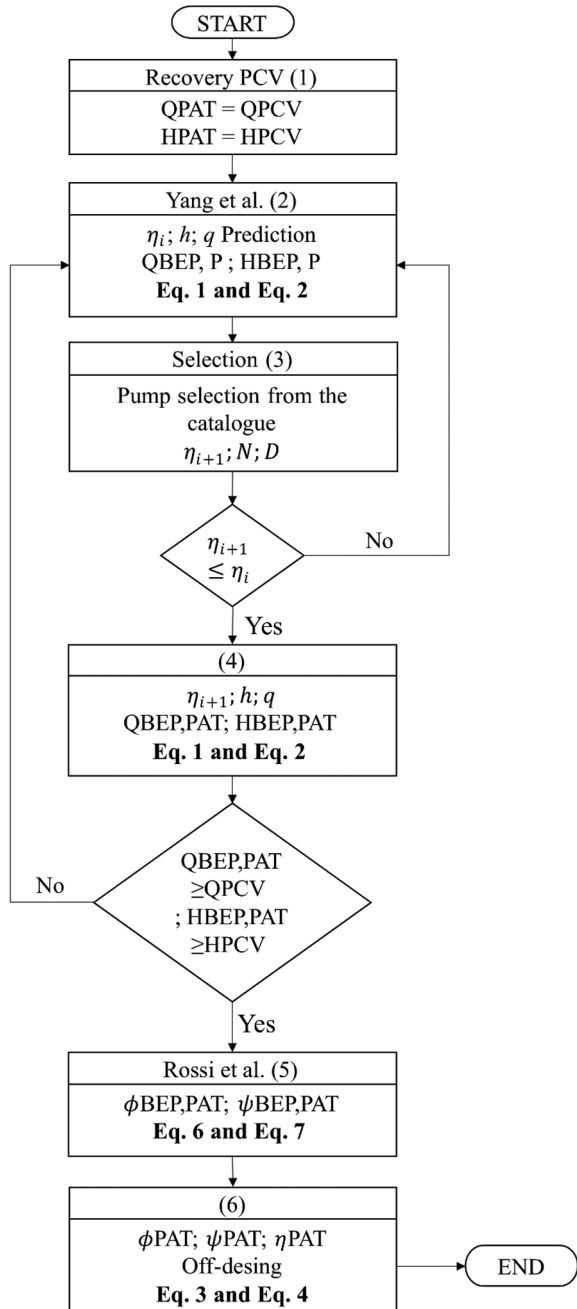
From the replacement of the PCV by the PAT (b) observed in Fig. 3, two operational scenarios are analyzed: one with a constant rotation speed for the PAT (b.1) and the other with a variable rotation speed (b.2). The objective is to analyze in which scenario the pressure in the network is better controlled, considering the variability of demand throughout

the day in the network. The speed control is performed by a dedicated inverter that modifies the frequency of the device and, consequently, its rotational speed.

2.3.1 Prediction Method for Pumps as Turbines

The combination of two methods to predict the behavior of PATs is proposed in this study. The model consists of the proposal of Yang et al. (2012) for the determination of the BEP in turbine mode and Rossi et al. (2019), whose formulation predicts the general behavior of an off-design PAT. The selection of these models was based on the best results obtained compared to other traditional studies (Stepanoff 1957; Sharma 1985) and partial load characteristic curve prediction models (Singh and Nestmann 2010; Novara and McNabola 2018). In addition, the machines used by the authors have a wide range of specific speeds and efficiencies, which provides more accurate and reliable results. These parameters are useful to define the hydraulic performance of a centrifugal pump, and considering them can help to accurately predict the performance of a PAT (Nautiyal and Varun 2010), since the emphasis of this proposed association is on better efficiency.

Equations (1) and (2) describe the calculations of the proposed model in Yang et al. (2012), and Eqs. (3)–(7) describe the model proposed in Rossi et al. (2019), where h is the head coefficient, q is the flow rate coefficient, η_p is the initial efficiency of the pump, H_{PAT} is the turbine height of the nominal pump rotation [m], H_P is the pump height at nominal rotation [m], Q_{PAT} is the flow rate of the turbine at nominal pump rotation [m^3/s], Q_P is the flow rate of the pump at nominal rotation [m^3/s], ϕ is the flow coefficient, ψ is the height coefficient, η_t is the turbine efficiency, N is the rotation [rps], D is the machine diameter [m], and g is the gravity acceleration [m/s^2].

$$h = \frac{1,2}{\eta_p^{1,1}} = \frac{H_{PAT}}{H_P} \tag{1}$$

$$q = \frac{1,2}{\eta_p^{0,55}} = \frac{Q_{PAT}}{Q_P} \tag{2}$$

$$\frac{\psi_{PAT}}{\psi_{BEP,PAT}} = 0.2394R^2 + 0.769R \tag{3}$$

$$\frac{\eta_{PAT}}{\eta_{BEP,PAT}} = -1.9788R^6 + 9.0636R^5 - 13.148R^4 \\ + 3.8527R^3 + 4.5614R^2 - 1.3769R \tag{4}$$

$$R = \frac{\phi_{PAT}}{\phi_{BEP,PAT}} \tag{5}$$

$$\phi = \frac{Q}{ND^3} \tag{6}$$

$$\psi = \frac{gH}{(ND)^2} \tag{7}$$

The model is validated with experimental results of PATs available in the literature (Derakhshan and Nourbakhsh 2008; Singh and Nestmann 2010; Nautiyal et al. 2011; Rossi et al. 2019). The experimental data were standardized due to the differences in the inverse characteristics of PATs determined differently by the authors. Therefore, the dimensionless coefficients (ψ-ϕ) and the specific velocity (N_s) were standardized by Eqs. (6), (7) and (8).

$$Ns = \frac{n(Q)^{0,5}}{(gH)^{0,75}} \tag{8}$$

2.4 Variable Speed of PATs in WNDs

The velocity variation is modified to adapt the PAT to the new operating conditions of a network imposed by consumption-dependent flows and pressure losses. The PAT curve is altered to ensure a change in the operating point and the highest efficiency instead of changing the system curve by inserting pressure losses (Morabito and Hendrick 2019). That is, at a given flow rate, the value of the BFT outlet pressure increases with increasing speed.

For this purpose, the information related to the machine selected at its BEP was considered, which is introduced in Eqs. (3) and (5) to determine the pressure (*H*) at the selected rotation speed. Then, the turbomachinery affinity laws are used to determine new speeds according to the characteristics imposed by the WDN. These laws compare the performance of a known prototype to that of a similar machine, allowing the prediction of performance curves for similar pumps (Morani et al. 2018). In particular, for the same pumps with different rotation speeds, the diameter of the machine is the same as that of the prototype ($D_1 = D_2$). Equation (9) shows the affinity laws that govern the relationships between rotational speed *N*, flow rate *Q*, head *H*, and hydraulic power *P*.

$$\frac{Q_1}{Q_2} = \frac{N_1}{N_2}; \frac{H_1}{H_2} = \left(\frac{N_1}{N_2}\right)^2; \frac{P_1}{P_2} = \left(\frac{N_1}{N_2}\right)^3 \tag{9}$$

2.5 Economic Analysis

For this analysis, the return period (RP), the net present value (NPV) and the internal rate of return (IRR) were calculated. When the discount rate is linked to the IRR, it is called the discounted period of return. The discount rate is expressed as a percentage and is considered the sum of the costs of return on capital, opportunity cost, risks and inflation (Padilha and Luiz Amarante Mesquita 2022). In the case of Brazil, the discount rate is 11.61% (Damodaran 2019).

The total cost of installing the PAT includes the sum of the capital costs (CC), operation and maintenance costs (OMC) and civil construction costs (CWC). The CC includes all the costs of essential equipment for PAT installation. The OMC consists of the

maintenance and individual operation of the device, while the CWC estimates the costs of important civil works for the adaptation of the PAT installation to the grid. The useful life of generic mechanical and electrical equipment is considered to be 15 years (Stefanizzi et al. 2020). The operating and maintenance costs are considered to be 0.5% and 2.5% per year, respectively, of the CC (Irena 2012). For CWC, 30% of the cost of capital was adopted (Fontana et al. 2012). The energy tariff was US$ 0.1468/kWh. In addition, an increase of 7.8% in the energy tariff was considered, estimated from the annual increase in tariffs in the period from 2017 to 2022 of the local electricity company.

3 Case Study

The methodology was applied to a WDN serving a neighborhood in the municipality of Tucuruí, northern Brazil. The water distribution is performed by gravity, taking advantage of the local topography (56 to 206 m). It is a mixed-type configuration, with fiber cement
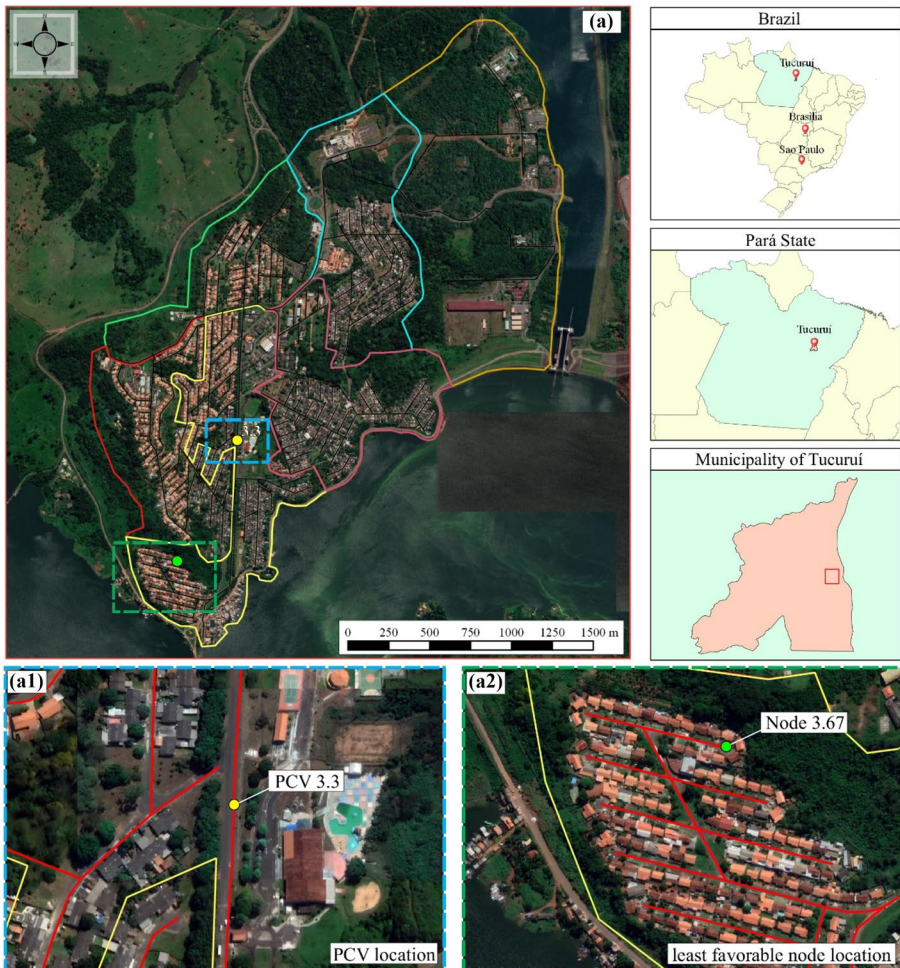
Fig. 5 Division of the WDN into DMAs (**a**), the position of PCV 3.3 (**a1**) and the least favorable node of the district (**a2**)

pipes that supply 2,500 residences, with an extension of 5,290 m². The network has serious deficiencies in pressure management, ranging from 13.09 to 156.10 m. In Brazil, the recommended pressure is 10 m for the minimum dynamic pressure and 40 m for the maximum static pressure, with a limit of up to 50 m in regions with extreme topography (ABNT 2017).

Applying the algorithm described in Fig. 2, the WDN is divided into 6 DMAs, with 14 strategically positioned PCVs controlling the pressure in the range of 10 to 50 m. Only the replacement of PCV 3.3 will be demonstrated. The PAT must maintain the operating conditions of this valve: outlet pressure of 10 m and pressure difference (ΔH) of 39.89 m, also maintaining the pressure in the least favorable node (Node 3.67) and in any other node of DMA 3 within the limits of Brazilian legislation. Figure 5 shows the WDN divided into DMAs (a), the position of PCV 3.3 (a1) and the least favorable node of the district (a2). Figure 6 shows the variation in water use in the network and PCV 3.3.

4 Results and Discussion

4.1 Validation of the PAT Prediction Model

Figure 7 shows the dimensionless ψ-ϕ (a) and η-ϕ (b) curves, representing the trends of the proposed method. The curves obtained are in acceptable agreement with the experimental data. This allows for generalizing the study and extending its application to several machines, regardless of the BEP of the pump in turbine mode, specific speed or efficiency of each machine. It is observed that the proposed association has the prior availability of the value at the BEP point, which can be considered an advantage. For example, from the BEP, Singh and Nestmann (2010) determined more precise values of the turbine operating out of design.

4.2 Characteristics of the Selected Pump

The characteristic curve of the machine in pump mode is shown in Fig. 8. The machine characteristics in pump and turbine mode in the BEP are presented in Table 1. The flow
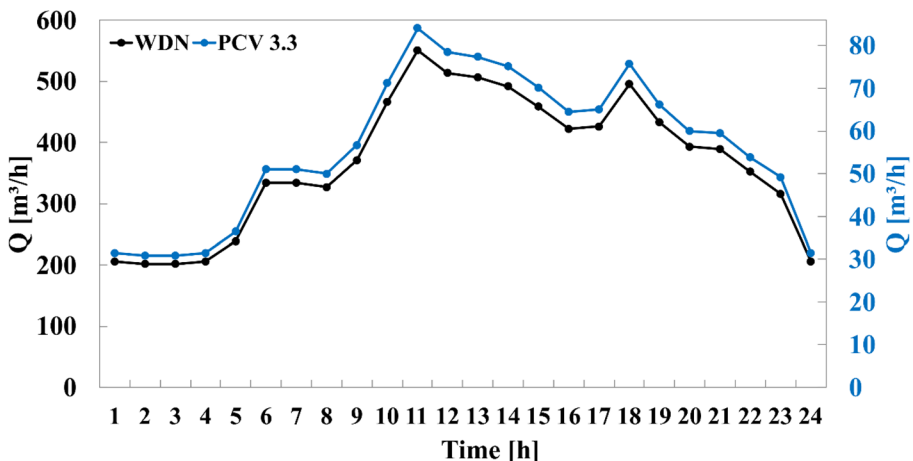

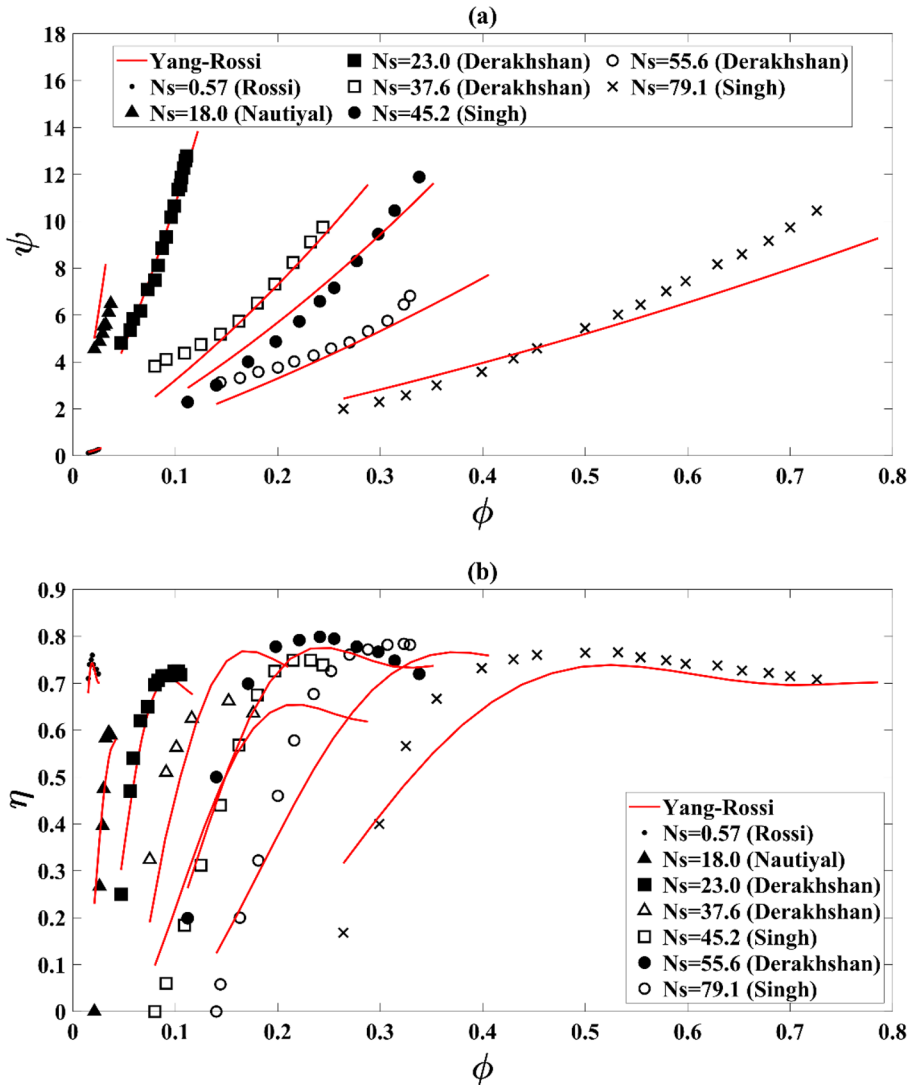**Fig. 6** Hourly variation of the network consumption pattern

Fig. 7 Method validation: ψ-ϕ (**a**) and η-ϕ (**b**) curves

and head values are higher in the turbine mode and are in agreement with the literature (Rossi and Renzi 2018). Table 2 shows the values obtained for the PAT 3.3 operating off-design. The model produces good predictions for the behavior of the PAT under design conditions and beyond.

4.3 PAT Characteristics for Constant and Variable Speeds

Figures 9 and 10 show the *HQ* (a) and *η-Q* (b) curves of the PAT operating out of design at constant and variable speeds, respectively. Figure 9 shows that only at flow rates close to the BEP

Fig. 8 Characteristics of the selected pump curve: *HQ* (**a**) and *η-Q* (**b**)
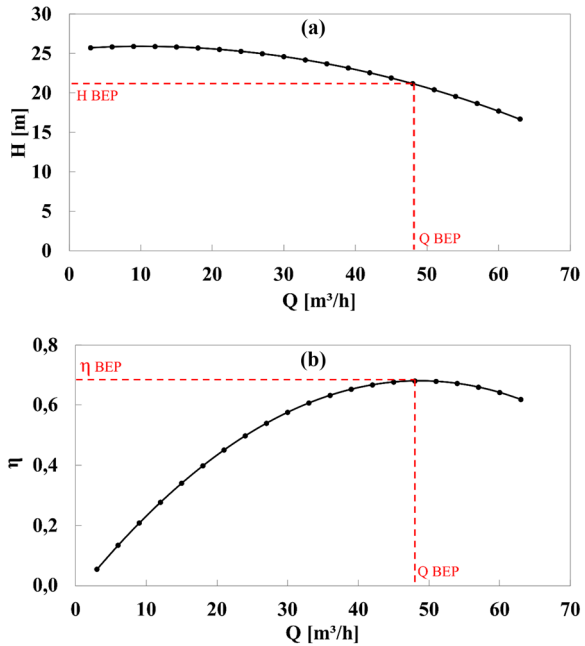
is the PAT able to approach the values of ΔH required by the PCV. On the other hand, Fig. 10 shows values close to the ΔH required by the PCV over 18 h for variable speed operation. In addition, the best PAT efficiency points occur over a wider flow range and not only at the BEP.

4.4 Network Pressure Control

At constant speed, the pump does not provide an outlet pressure of 10 m during operation. In addition, the ΔH of the PAT approaches the PCV only in two hours of operation, 10:00 am and 3:00 pm, impairing the minimum pressure required for Node 3.67. This is explained by the occurrence of flows away from the BEP at certain times of the day, resulting in pressures below the recommended levels from 11:00 am to 2:00 pm and 6:00 pm. In the remaining hours, the pressure at Node 3.67 was above 10 m. As a result, the pressures on other nodes of DMA 3 were also affected.

Table 1 Operational characteristics in the BEP of the selected INI 40–125 machine

Characteristic	Pump	Turbine
Q [m³/h]	47.66	71.86
H [m]	21.40	40.54
Efficiency [-]	0.67	0.64
Rotation speed [rpm]	3.500	
Specific rotation [rad/s]	0.75	0.57
Impeller diameter [m]	0.120	

**Table 2** Values obtained for the PAT operating off-design

φt	ψt	ηt	Qt (m³/h)	H (m)
0.182	7.378	0.626	66.04	36.85
0.186	7.577	0.632	67.50	37.85
0.190	7.777	0.637	68.95	38.85
0.194	7.980	0.640	70.40	39.86
0.198	8.183	0.640	71.86	40.54
0.202	8.389	0.640	73.30	41.90
0.206	8.596	0.640	74.75	42.93
0.210	8.804	0.639	76.20	43.98
0.214	9.014	0.639	77.66	45.03

In the period from 11:10 pm to 5:59 am, the bypass is activated, and the PRV controls the pressure accordingly. The use of the valve operating in parallel to the PAT seems to be a good solution to maintain the pressure in the network, especially in the early hours of the day, when the machines cannot adequately deal with the reduced flow.
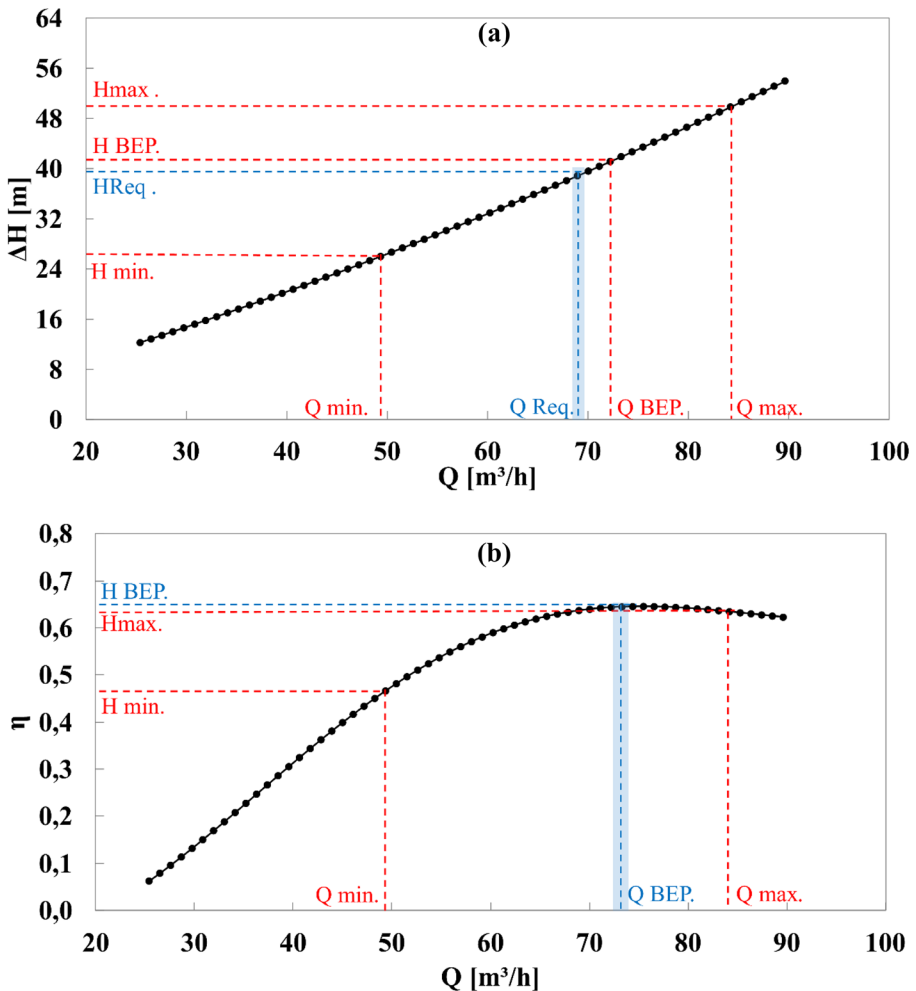

Fig. 9 Curves: *HQ* (**a**) and *η-Q* (**b**) constant speed

Fig. 10 Curves: *HQ* (**a**) and *η-Q*
(**b**) variable speed
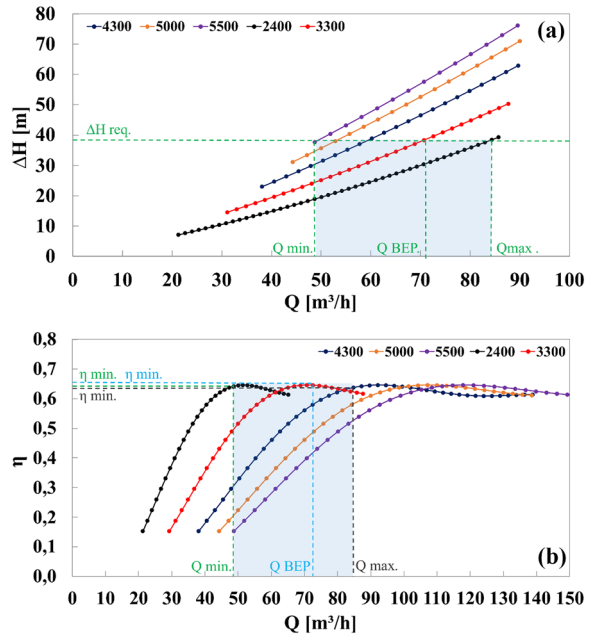
In general, the PAT was not able to adequately regulate the pressure in the network at when operating at constant speed. Certainly, with pressures greater than 50 m, the volume of losses will be high, while hours of reduced pressure can cause shortages to consumers. This suggests that the use of a PAT operating at constant speed to replace the PCVs is not an attractive solution to maintain the working pressure in a network, justifying the control of the machine speed to adapt to the variation imposed by the WDN.
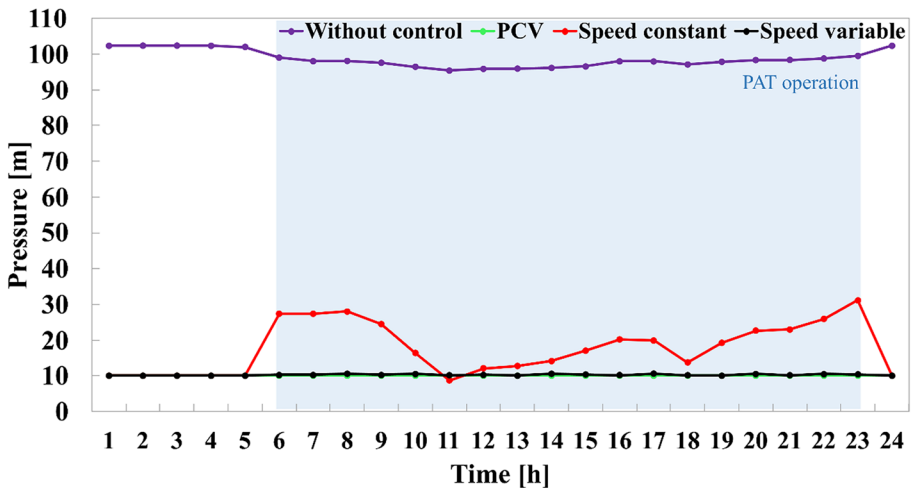
Fig. 11 Comparison of PAT output pressure at variable or constant speed, with PCV, or without control
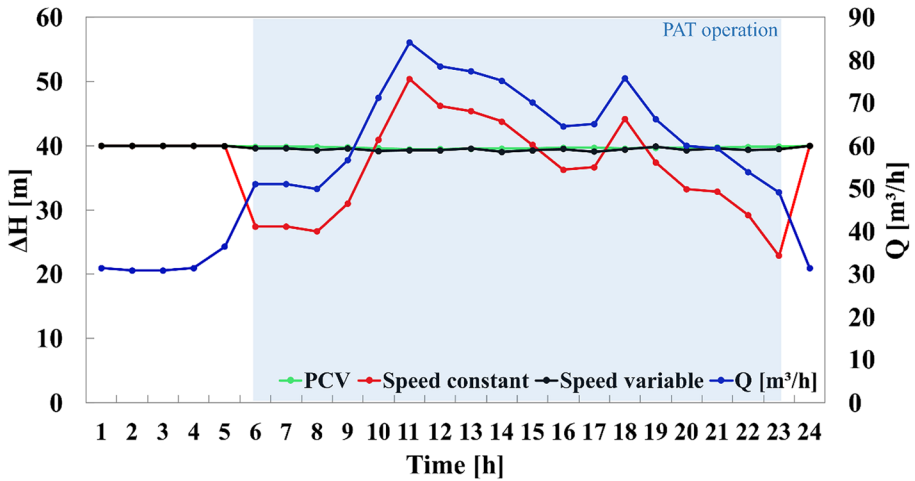
Fig. 12 Comparison of the required ΔH of the PAT at variable and constant velocities and of the PCV

On the other hand, the variable speed PAT is able to maintain the outlet pressure very close to 10 m, as indicated in Fig. 11, which compares the PAT outlet pressure at variable and constant speeds with and without control. Figure 12 shows the ΔH values required by the PAT at variable and constant speeds and with the PCV. Note that the PAT variable velocity follows the PCV. As a result, the pressure at Node 3.67 varied according to the legislation, from 11.62 to 15.05 m (Fig. 13), and the pressure at DMA 3 was properly regulated throughout the PAT operation. To illustrate, Fig. 14 compares the nodal pressures in DMA 3 at constant and variable velocities at 11:00 am and at 11:00 pm. As expected, in the period from 11:01 pm to 5:59 am, the bypass is activated, and the PRV controls the pressure according to legislation. Due to the problems faced by VRPs, such as the occurrence
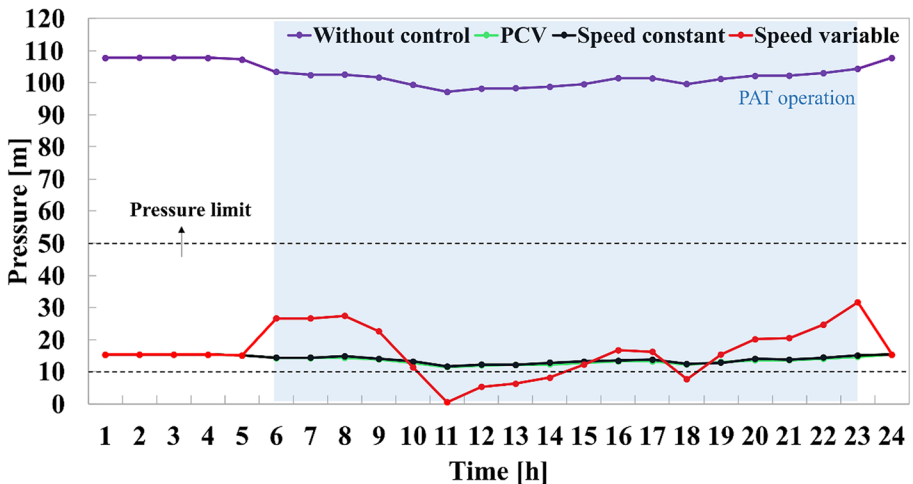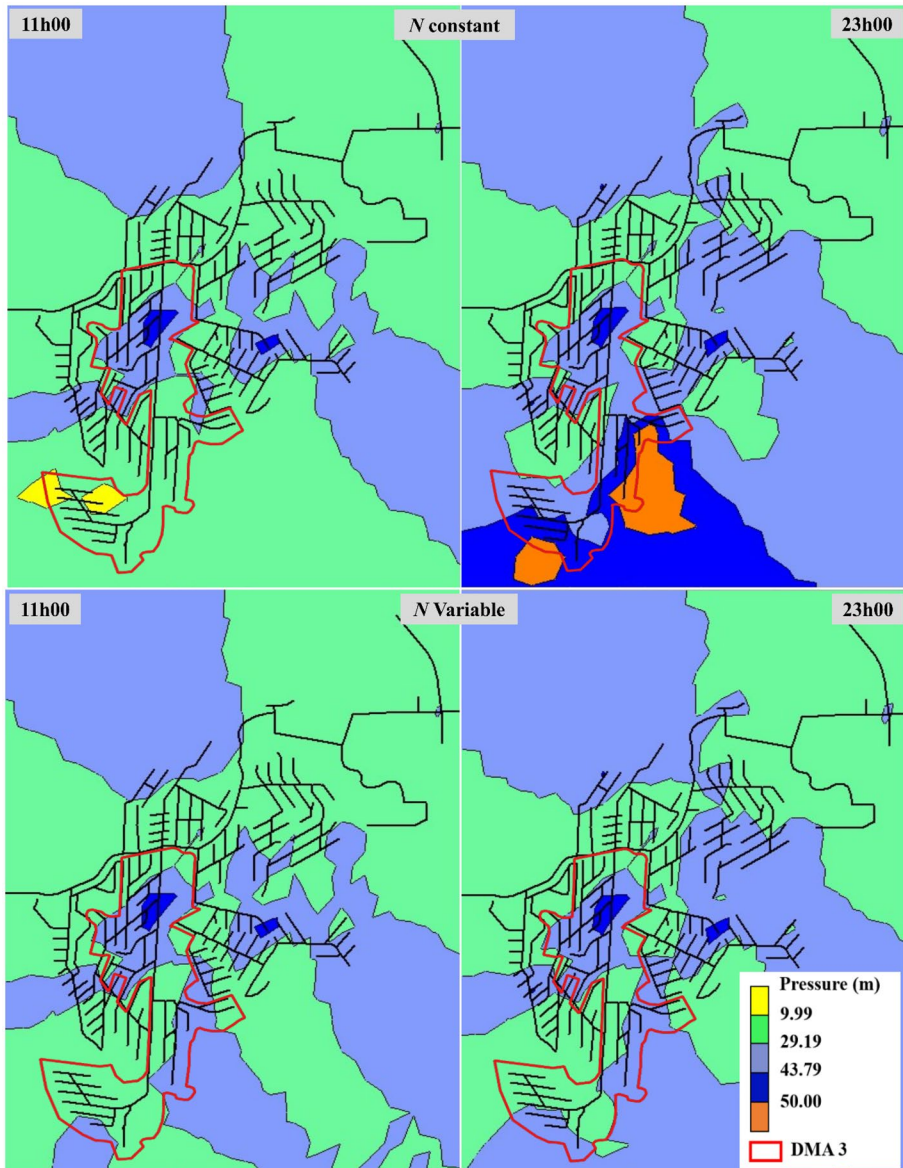

Fig. 13 Pressure at Node 3.67 at 24 h—PAT at variable or constant speed, with PCV, or without control

Fig. 14 Nodal pressures with PAT operation at constant or variable speed in DMA 3 at 11 am and 11 pm

of hydraulic transients in their operation (Abdel Meguid et al. 2011), these devices are preferred to meet the changes in user demand in an RDA because they can effectively regulate a high and variable pressure to a low and constant pressure (Covelli et al. 2016) when the BFT is not operating.

As reported, speed control is able to increase PAT efficiency and power under partial and full load operating conditions (Delgado et al. 2019). This improvement is particularly important if a PAT is used to dynamically regulate pressure or flow. In this study, to satisfy
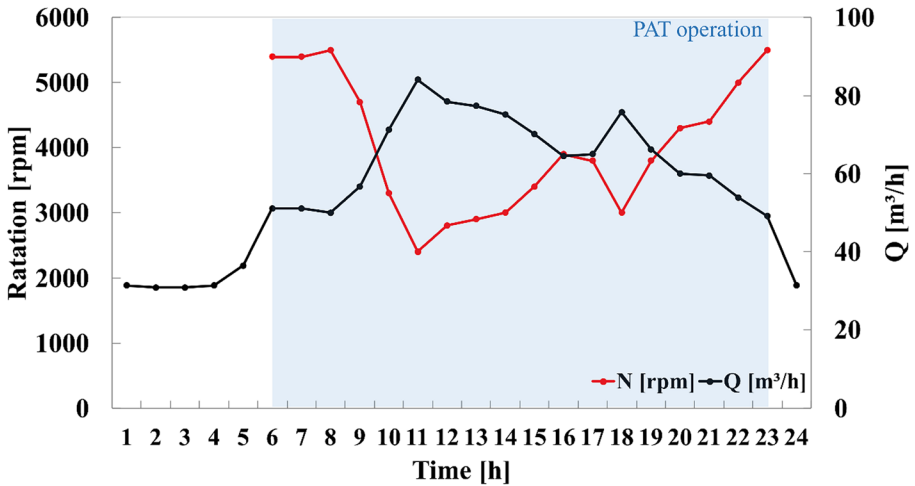
Fig. 15 Relation of the rotation speed with the flow at 18 h of operation of the PAT

this condition, as the WDN consumption increased, the rotation speed decreased, and vice versa, as reported in Fig. 15, which shows the variation in rotation speed from 2,400 to 5,500 rpm linked to consumer demand. This was confirmed in studies by Alberizzi et al. (2018, 2019), who used PATs in WDNs operating at variable speed and obtained good results in pressure control with the occurrence of higher flows. In addition, the option of reducing the downstream pressure leads to savings in potable water along the pipes. According to BRASIL SN de I sobre (2021), networks in Brazil lose 40.1% in WDNs alone due to the state of the pipes and excessive pressure. For this reason, the use of PATs at variable speeds to replace PCVs may be a viable solution to reduce persistent water losses and maintain an adequate supply.
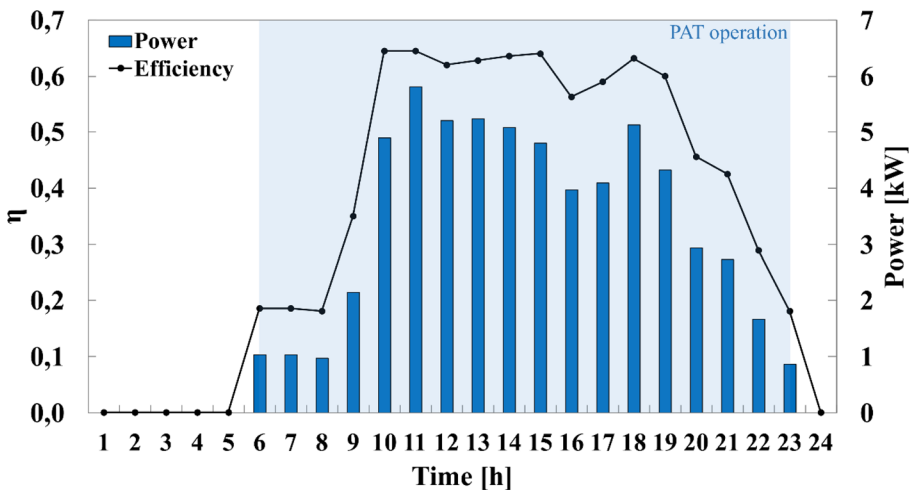

**Fig. 16** Output power and efficiency of PAT 3.3 at variable speeds

Table 3 PAT 3.3 implementation cost

Item	Cost [US$]
Cost of Capital	
PAT	1,920.16
Pressure meter	119.59
Frequency inverter	897.36
Block valve	179.85
Operation and maintenance cost	1,426.33
Cost of civil works	840.12
Total	5,383.41

4.5 Energy Recovery

Figure 16 reports the output power and efficiency achieved by PAT 3.3 at variable speeds. The average power output of the PAT is 3.44 kW. It is noted that the best power and efficiency levels occur when the grid consumption is high, from 10:00 am to 3:00 pm and to 6:00 pm. The rotation speeds are reduced at these times, at 2,400 rpm at 11 am and 3,000 rpm at 6 pm; that is, the maximum efficiency decreases with increasing rotational speed, as found in studies of Jain et al. (2015) and Lima et al. (2018). For example, at 11 am, when consumption is highest in the network, efficiency was 0.64 (maximum PAT efficiency), while at 11 pm, when consumption was practically half of 11 am, efficiency decreased significantly, reaching 0.18.

Pérez-Sánchez et al. (2018) noted that when changes in PAT rotation speed are determined using affinity laws, the errors can be significant. However, the results of this investigation reported that speed control caused the machines to regulate the pressure as if they were PCVs, favoring the recovery of 22,620.00 kWh/year by PAT 3.3. This amount would be enough to supply approximately 10 Brazilian homes for a year, with an average consumption of 200 kWh/month.
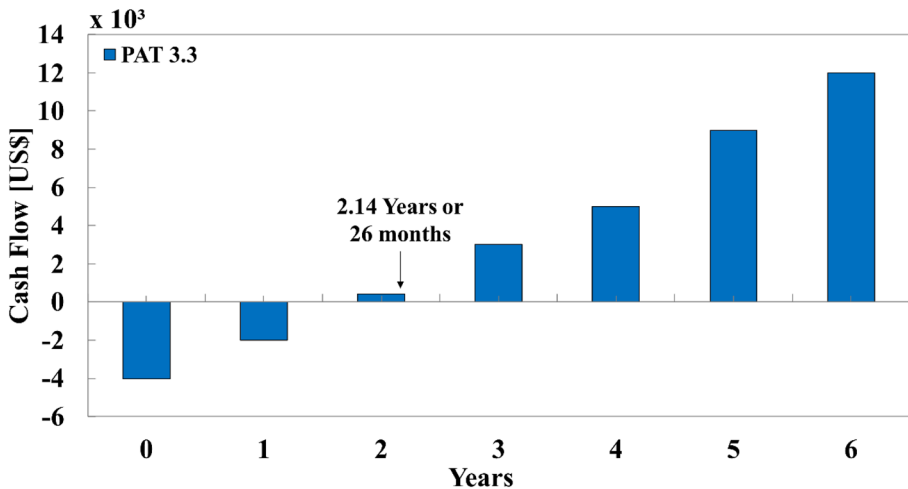
Fig. 17 PAT 3.3 system payback

By replacing the 14 PCVs, the system would generate 270,192.19 kWh/year, enough to supply 113 homes. If this energy were sold, it would generate revenue of US$ 39,664.18/year. Generation could support the security of the energy supply in the future (Kyle et al. 2021) if the company used the energy gain for self-consumption of the system. In this case, with continuous supply guaranteed by user demand, there would always be energy recovery. Therefore, adapting the WSS to production with the PAT system has the advantage of leveraging the existing components (Samora et al. 2016), such as pipes, civil structures and preexisting pumping systems.

4.6 Economic Analysis

Table 3 shows the costs obtained from Brazilian pump suppliers for PAT 3.3. The PR was calculated only for the variable speed operation, whose operational advantages were technically better. The PAT 3.3 presented a PR of 2.14 years or 26 months, with an NPV of US$ 64,476.18 and an IRR of 63%. Figure 17 shows the behavior of PR during 6 years of operation. This value is similar to previous studies (Stefanizzi et al. 2020) and was very short compared to the use of classic turbines. When PATs operate within a power range of 1–500 kW, RPs of 2 years or less are found (Carravetta et al. 2018). In this case, the operation of the PAT at variable speed would be more attractive for water supply companies.

5 Conclusions

In this article, the use of variable speed PATs to replace PCVs for pressure control and energy recovery in a water distribution network located in northern Brazil was analyzed. The WDN was divided into 6 DMAs with 14 PCVs, maintaining the pressure according to legislation. A partitioning of the network was performed with the hydraulic simulator EPANET 2.0, which proved to be an excellent tool for this task. The PCVs were replaced by PATs at constant and variable speeds. The selection of pumps was clear and easy to perform based on previous data on the valves resulting from the sectorization of the network. The validation of the association of the proposed model proved to be reliable and efficient in the construction of the PAT curves. The operation of the machine was evaluated from 6:00 am to 11:00 pm. From 11:01 pm to 5:59 am, a bypass was activated, and a parallel PRV maintained adequate pressure in the network, indicating that it was a good tool to combine with PATs in WDNs.

PAT 3.3 at constant speed maintained the pressures required by the valve only at 10:00 am and 3:00 pm, which flow close to the BEP, impairing the efficiency of the pump. As a result, the PAT did not maintain the required outlet pressure (10 m), moving away from the PCV values and causing a decrease in district pressure.

On the other hand, with a speed variation of 2,400 to 5,500 rpm, the machine adequately controlled the pressure during 18 h of operation throughout DMA 3 (10 m to 50 m). The best efficiencies were observed at lower speeds (2,400 to 3,000 rpm) and at the highest consumption in the WDN, ranging from 0.62 to 0.64 from 10:00 am to 3:00 pm and 6:00 pm. This resulted in an average PAT 3.3 power of 3.44 kW and an energy gain of 22,620 kWh/year. With the replacement of the 14 PVCs, the energy recovered would be 270,192.19 kWh/year, enough to supply 113 homes or generate revenue of USD 39,664.18/year.

The calculated PR for PAT 3.3 was 2.14 years. The reduction in water losses associated with energy generation through the PAT operating at variable speed, when evaluated

economically, shows that speed control is effective and beneficial for water supply companies. As the integration of generated energy into an electrical circuit is still a challenge, the self-consumption approach is attractive for these companies.

The methodology proposed in this study proved to be a good tool for pressure control and renewable energy recovery by PATs in WDNs. The sectorization of the network, the effective control of the pressure, the conservation of the tubes, the reduced use of chemical products and the revenues generated with the recovery of energy are some of the benefits of the studied WDN. The speed control facilitates the adaptation of the machine to the conditions imposed by the network, operating well off-design and with higher flow rates, not only at the BEP. Based on the results obtained, other variable speed operating configurations will be evaluated in future studies, with pumps operating in parallel to replace the PCVs at times of lower consumption. In addition, the reduction in the volume of leaks with the use of PATs in WDNs will be quantified.

Author Contributions DESS: Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft. **ALAM**: Data curation, Formal analysis, Methodology, Validation, Visualization, Writing – original draft, Writing - Review & Editing and Supervision. **CJCB**: Writing - Review & Editing and Supervision.

Availability of Data and Materials Datasets are available upon request

Declarations

Ethics Approval Not applicable.

Consent to Participate Not applicable.

Consent to Publish Not applicable.

Competing Interests Not applicable.

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