2nd International Joint Conference on Water Distribution
Systems Analysis & Computing and Control in the Water Industry
Valencia (Spain), 18-22 July 2022
doi: https://doi.org/10.4995/WDSA-CCWI2022.2022.15003

DEVELOPMENT OF A TOOL FOR THE OPTIMIZATION AND REGULATION OF HYDRAULIC MICROGENERATION SYSTEMS ADAPTED TO THE DEMAND AND FLOW VARIATIONS AIMED AT THE CLEAN ENERGY RECOVERY IN WATER SUPPLY NETWORKS

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Abstract

Incorporating energy recovery systems using renewable energies in water distribution systems is being analysed and implemented to improve sustainability, ensuring the SDG-7. Pumps working as turbines are an innovative technology, and a powerful tool to reach this energy improvement. This research develops a methodology that enables the development of an analysis tool for the optimized regulation of an energy recovery system using Simulink MATLAB.

The said methodology is capable of processing variable operation systems (VOS), which considers the flow variation through time. Also, it considered the variation of the rotational speed of the machines linked directly to the efficiency aiming to maximize the recovered energy.

Finally, the methodology was applied to a real case study defining the signal parameters to the regulation equipment in terms of numbers of pumps working as turbines (PATs) in operation, rotational speed, and the degree of opening of the pressure reducing valves installed.

The tool contemplates the energy analysis, which shows the recovery of 60% of the supplied energy in the system. This daily recovered energy was above 1898 kWh, and it contributed to an increase in efficiency and sustainability.

Keywords
Hydraulic regulation, Electronic regulation, SDG, Pump working as turbine, Water distribution network, Flow variation, sustainability, variable operation system.

1 INTRODUCTION

In recent years, energy recovery systems have been proposed to lessen the use of non-renewable energies. [1]. At the same time, microgeneration systems are the most frequently demanded[2]. The addition of these new technologies leads towards new steps for further sustainable development of the society and more conscious use of the accessible resources. As a consequence of the population growth over the years, the energy cost and consumption involving the water cycle have increased, for that reason, the efficient management of the water distribution networks has been a priority [3], [4].

Numerous studies show that sustainable indexes can be improved by using microgeneration systems. Its implementation benefits decreasing pressures in the network; this decrease ensures an upturn of the leakage indexes in the supply. [5], [6]. Also, renewable energy is increased, and the optimization of the energy generation [7].

Thus, the use of reverse mode pumps, the so-called pumps working as a turbine (PAT), is a practical implementation that has been considered over recent years [8]. The application of microhydropower in combination with other renewable systems established, such as solar or wind systems, can improve the use and production of clean energy in the water cycle[9].

Various authors have carried out PATs analyse since the 1940s, including Stepanoff [10], Childs [11], Williams [12] and Pérez-Sánchez et al. [13], who defined new expressions for the estimation of the best efficient point (BEP) of a PAT and its characteristic curve from a database with over 181 different pumps. While it is true that with the use of PATs, it is possible to recover energy, regulatory strategies are needed to maximize the use of these benefits.

Hydraulic Regulation (HR) is carried out through a hydraulic circuit with elements series and in parallel and the Electrical Regulation (ER) is by means of controlling equipment such as frequency variator drives and inverters are the most common solutions in systems where PATs are used for energy production [14]. The generated power can be supplied directly to the grid or self-consumed.

Optimization tools must support the regulation improvements in the water network. The quality of service to the user needs to be a priority and water managers have to know the main constraints of the system over time such as flow, and upstream and downstream pressure to guarantee it [15].

The need arises to provide the required pressure in a variable operating regime. Variable speed operation is an approach for controlling the discharge at the pump as a turbine inlet aiming at increasing operational efficiency. For example variations in pressure and flow rate[16], [17]

This manuscript develops an optimisation modeln Simulink MATLAB[18]. This tool will represent an upgrade in the PAT management in the water system. Regarding the issue related to PATs, their selection and simulation in different scenarios, there is no software or tool previously developed for such purposes, for which emphasis is placed on the creation of a program.

The use of empirical methods to estimate the characteristic curves of the PATS is part of the innovation in order to optimize the operation in the system is part of the innovation of this tool.

2 METHODS

In this section, the methodology in which is based the tool is proposed and defined. The analysis, optimization and regulation of energy recovery is the main objective. First, it is essential to have the system constraints (Flow and upstream and downstream pressures) that will define the operational limitations.

The main field of application, but not limited to, is water distribution supplies, where the demand changes over time, hence is a variable operation system (VOS). Regulation strategies should be designed to improve the efficiency and sustainability of the supply and at the same time, never compromise the level of service for the population.

Figure 1 represents the basic layout for the hydraulic model or an energy recovery system. The model is composed of a SCADA or Flowmeter which is used to generate the input data, recording the demanded flow and pressure setpoints. It is followed by the energy recovery group, for this case, the tool and methodology only consider PATs. Two pressure-reducing valves (PRV), one is installed in parallel to the PAT group and the second one is installed in series at the outlet of the system. Last, there are control valves installed which are used for sectioning, protection of the infrastructure.

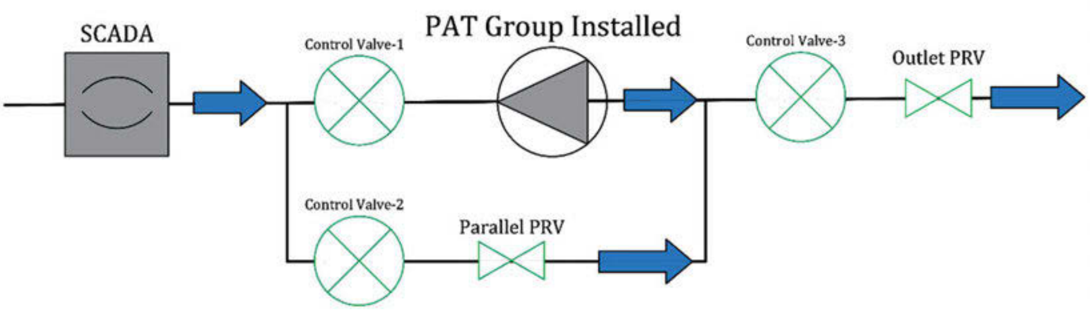

Figure 1. Hydraulic model layout.

The tool outputs the signals needed for the regulation strategies: Number of PATs working, Rotational speed and the Degree of opening of both PRV installed in the system. It is important to note that this tool have some limitations that should be addressed. PAT group should be selected beforehand, limited to simulate only 3 PAT installed in parallel, and all of the parameters should be introduced before running the simulation.

2.1 Methodology

In Figure 2, the developed methodology is shown. This is made up of three blocks: A. Model setup, B. Model simulation, and C. Model out put. Every block is composed of different sections, and those sections as well into steps that contain the different actions to be executed through the model simulation.

In the first block *(A. Model setup)* the main objective is to prepare the model prior to its simulation. All the input data should be loaded in this block for the tool to work correctly. This block has two main steps:

Step I is where all the recorded data is extracted from the database and then processed, previous being inputted into the model into a compatible format for the tool. The three main constraints that must be known are demanded flow (Qd), the upstream pressure (Pu) and downstream pressure (Pd) variation over time.

This tool can work both as an optimization tool for existing networks with energy recovery installed or as an analysis tool for proposing the implementation of energy recovery systems where the conditions allow it to. Because of that, after step I there is a decision-making block were depending on the conditions of the supply, the next step to follow will be conditioned.

If there is an existing PAT group installed, the next step is *Step II,* where all the initial configurations should be typed in the MATLAB console. Parameters are divided into six different categories according to the function they represent: 1. Parameters of the PAT group, 2. Variable-frequency drive settings, 3. Electric generator efficiency details, 4. Maximum power determination thresholds, 5. Pressure reducing valve characteristics and 6. Fluid properties.

Otherwise, if no energy recovery system is installed, *Step II.I* should be completed first. Parting from the input data, the selection process for the PAT system is made following the methodology proposed by Camilo Rosado et al. [19]. After the PAT group is selected, advance to Step II.

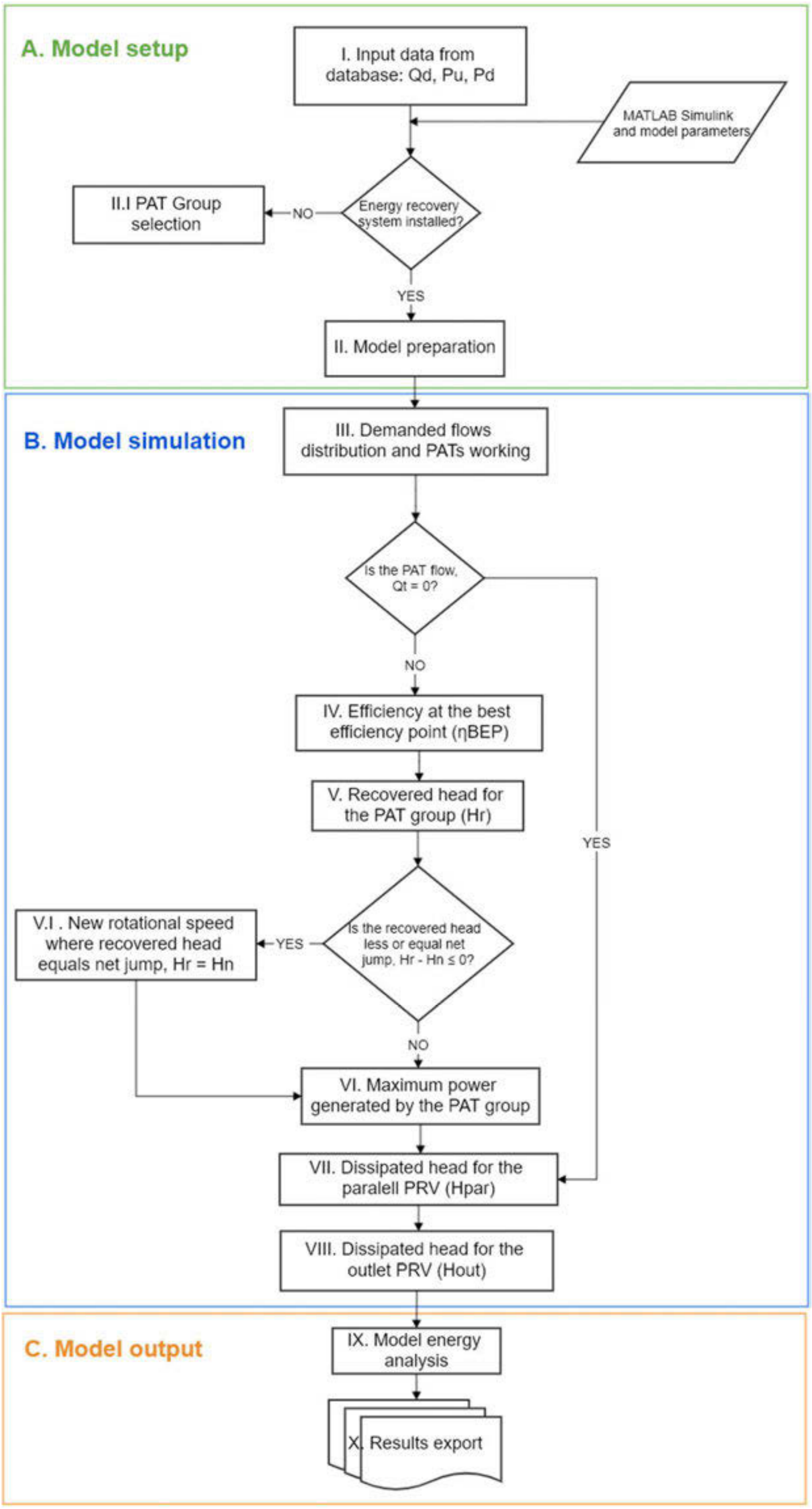

Figure 2. Proposed methodology for the analysis of the regulation in an energy recovery system.

The next block *(B. Model simulation)* comprehends the hydraulic model code, in which calculations for the PAT system and pressure reducing valves are carried out. It covers the central part of the methodology and is from *Step III* thru *Step VIII.*

The main goal is to optimize the recovered energy in order to increase the generated power with the given input data while fulfilling the population demand corresponding to flow and pressure.

Step III is where the flow distribution for the PATs and PRVs at any given moment is done. The outputs of this step comprehends the number of machines working (nf), as well as the flow turbinated for each one (Qt). Note that this tool layout is restricted to a maximum of three parallel PATs installed, for any instance, the flow will be the same for all the PATs in operation at that moment. In order to determine how many PATs should work based on the flow, the strategies proposed by [20] were used.

On the other hand, after this step another decision-making block is set, where based on the turbinated flow, methodology can go into one of two paths. If the flow rate is zero, advances to *Step VII.*

Step IV involves a iterative proccess where the goal is to appoximate to the maximum efficiency capable given the conditions at that time. Operating at the best efficient point (BEP) will be the ideal scenario, if not possible the closest is selected. To estimate the BEP, dimensionless curves are used, based on the research made by Plua et al. [21], represented in the equations:

$$h = -0.31070\left(\alpha\frac{Qt}{Q_{BEPt}}\right) + 0.1958\left(\frac{Qt}{Q_{BEPt}}\right)^2 - 0.0118\left(\frac{Qt}{Q_{BEPt}}\right) - 0.06429\alpha^2 + 1.8489\alpha - 0.2241 \tag{1}$$

$$e = 0.8271\left(\alpha\frac{Q_t}{Q_{BEPt}}\right) - 0.3187\left(\frac{Qt}{Q_{BEPt}}\right)^2 - 0.1758\left(\frac{Qt}{Q_{BEPt}}\right) - 1.035\alpha^2 + 1.1815\alpha - 0.5019 \tag{2}$$

Next, in *Step V,* the recovered head for the PATs is determined based on the rotational speed and variable-frequency drive setpoint from the previous step. Before advancing to step VI, the difference between the net jump available (Hn) and the recovered head (Hr) has to be verified to match the criteria of $Hn - Hr \leq 0$. After meeting this condition, advances to Step VII.

On the contrary, if the recovered head is larger than the available jump, a new rotational speed is determined to comply with the established criteria. With a new recovered head value, proceeds to Step VI.

Step VI is the last step involving PAT calculations. The goal is to maximize the generated power by varying the α value into a limited bracket where the tool searches for the best fitting value within the range. After completing this step, a new α value is set for the PAT, and therefore, new recovered head and efficiency values and the calculations that rely to this are obtained.

Step VII and *Step VIII* are similar steps, the dissipated head and degree of opening by both the parallel and outlet PRV is calculated, respectively. This to ensure the regulation strategies in which downstream pressure setpoint is met.

The last block is *(C. Model output),* is where all the energy analysis and results are carried out. *Step IX* is where all the results are organized, classified, and then processed. And in *Step X*, the results are exported in the format of graphs and tables; this part also generates the regulation strategies table that will guarantee an increase in the recovered energy.

3 RESULTS

3.1 Case study description

This case study was implemented in a study point of the high-pressure water distribution network of the Valencia Metropolitan System (VMS) (Spain). At this point, a PRV is installed to maintain the pressure requirements downstream. The installation of energy recovery systems was contemplated, increasing sustainability and efficiency indexes.

Figure 3 represents the layout of this scenario, where point A from the water distribution network and defined as the upstream pressure point (Pu). The net available hydraulic jump is represented (Hn) and the symbol for the energy recovery system to be installed. Demanded flow is Qd, and the population demand point is when the downstream pressure (Pd) is met.

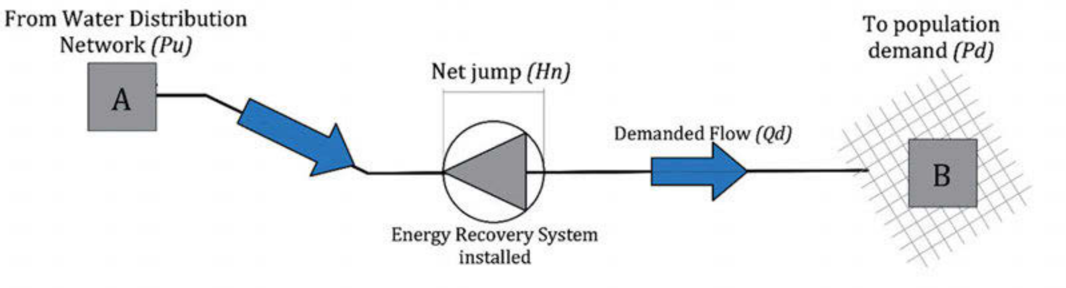

Figure 3. The layout of the case study scenario.

The data is a temporal series with records of the demanded flow and upstream and downstream pressures. The data is processed for an entire day with a 10 minute time interval for each reading. Table 1 shows a fragment of the input data structure in which all the primary constraints are defined at any given time. Also, statistics calculations were performed for analyzing the data prior to selecting the PAT group and running the simulation.

Table 1. Input Data fragment and statistics calculations

Time (Δt = 10min)	Qd (L /s)	Pu (m w.c.)	Pd (m w.c.)
2:50:00	403.76	77.94	39.74
3:00:00	385.22	78.64	38.60
3:10:00	291.79	80.89	34.38
3:20:00	183.57	83.09	31.02
3:30:00	80.94	83.98	29.21
3:40:00	56.57	83.99	29.00
Maximum Value	406.16	84.90	39.74
Minimum Value	49.79	75.58	25.08
Mean Value	302.67	79.38	32.84
Standard Deviation	149.68	3.24	4.11

The PAT group selected consists of three pumps of Bombas IDEAL, model CPH 80-210 (215 mm), with a nominal rotational speed of 2900 rpm at 50 Hz. The second part of the proposed energy recovery system is the selection of the PRV. For the valve installed in parallel, the model selected is a BELGICAST Hydroblock DN250, and for the valve connected in series is a BELGICAST Hydroblock DN350. This is complemented with five control valves for management and maintenance tasks. In Figure 4, the previously described proposed regulation layout is shown with all of its components.

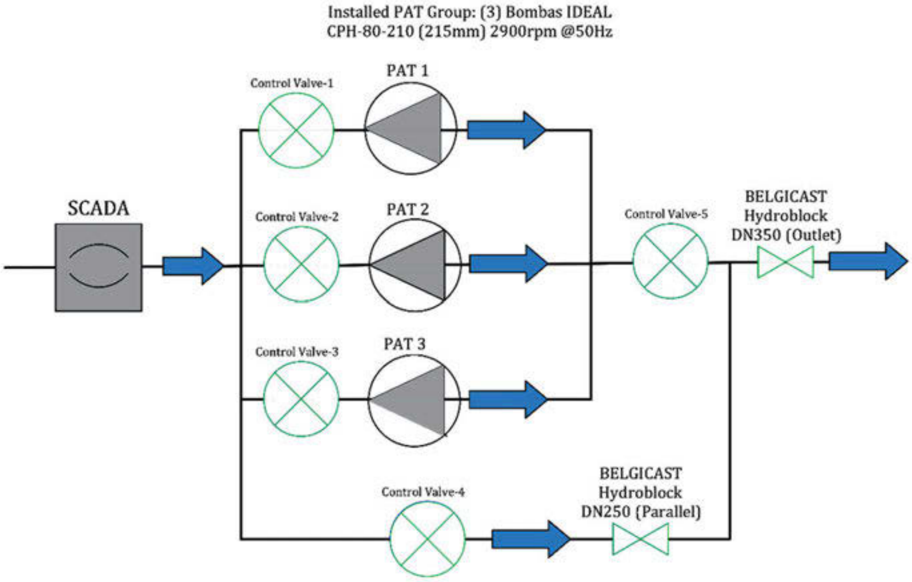

Figure 4. Proposed regulation layout

In Figure 5a is represented a turbinated flow by one PAT during the simulation. All PATs are the same model and are connected in parallel. Therefore, the PAT flow will be the same for all the working machines at that given time. The PAT operation interval was between 49 and 150 L/ s, and a mean value of 114 L/ s. On the other hand, Figure 5b shows the evolution of the number of PATs working at each time. At every moment during the simulation, at least one PAT was operating, and in the majority of the instances, three machines were used.

Figure 5c represents the temporal evolution of the heads and pressures during the simulation. Where is shown the upstream pressure (Pu), downstream pressure (Pd) and the net hydraulic jump (Hn), which is obtained by the difference between upstream pressure and downstream pressure. The recovered head for the PATs (Hr) was within the range of 28 and 54 m w.c. and a mean value of 40 m w.c. The difference between the upstream pressure and the recovered head is labelled as (Pu-Hr); the recovered head was never superior to the available net jump in any instance.

Similarly, Figure 5d shows the evolution of the dissipated heads for both pressures reducing valves. (Hpar) is for the installed in parallel and (Hout) represents the valve installed in series. During the lower demand period, the outlet PRV had a max dissipated head at 29 m w.c. The parallel valve did not work during those times because the demanded flow was above the minimum working flow for the PAT.

Figure 5e shows the graph for the accumulated and dissipated energies during the simulation. The total available accumulated energy was 3113 kWh, and the total recovered energy for the PAT group was 1898 kWh, representing 60% of the available energy and 90% of the total recoverable energy.

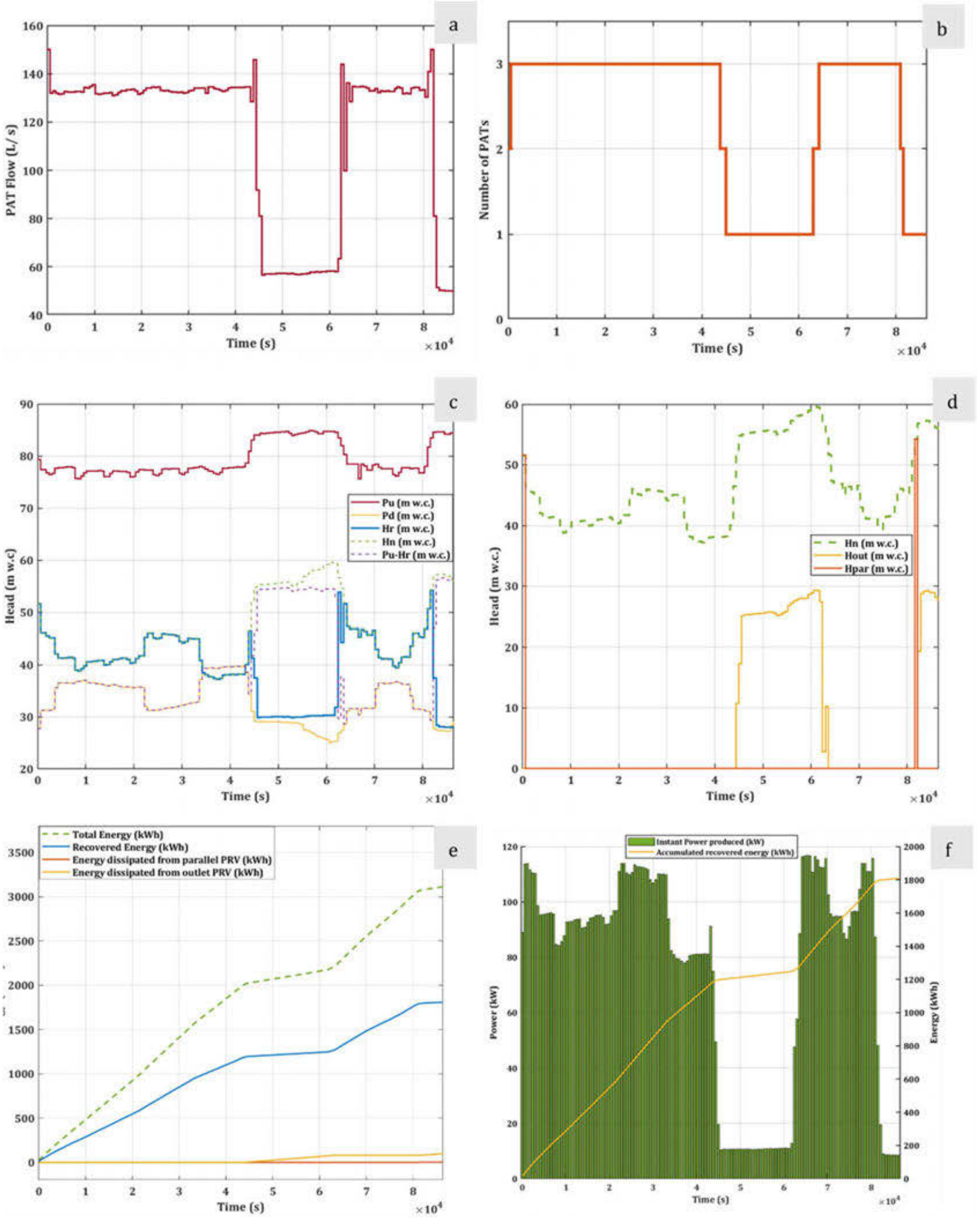

Figure 5. (a) Flow over time, (b) Number of PATs working, (c) Heads and pressures over time, (d) Dissipated heads by PRV; (e) Accumulated and dissipated energies over time; (f) Instant power produced and accumulated recovered energy.

Figure 5f shows the representation of the instant power produced for the PAT (in kW) during the simulation and the evolution of the accumulated recovered energy (kWh). Instant power oscillated between 10 and 114 kW, and average instant power of 50kW. The low demand period is where instant power is the least.

The second section of the model results is the regulation strategies, in which both hydraulic and electronic regulation for the case study are defined in Table 2. This table is composed of five columns: 1. Time, expressed in seconds parting from 0 to 86400 in this case study, 2. Number of PAT working, 3. PAT α value, 4. Degree of opening for the parallel valve and 5. Degree of opening for the outlet valve. These setpoints ensured the maximum recovered energy at any moment during the simulation.

Table 2. Regulation strategies from 43200s to 45600s

Time (s)	Number of PAT working	PAT α value (%)	Parallel PRV Degree of opening (%)	Outlet PRV Degree of opening (%)
43200	3	0.918	0	100
43800	2	0.959	0	100
44400	2	1.001	0	28
45000	1	1.045	0	13
45600	1	0.920	0	8

The variable-frequency drive values were between 0.816 and 1.045 for the minimum and maximum values, respectively, and the average value of 0.948; this supports the PAT selection wherein most of the time during the simulation PATs worked near their nominal rotational speed.

The pressure reducing valve operation was modified to optimize the water supply. For the installed in parallel, this was closed most of the time, except for one instance. On the other hand, the outlet valve was fully open most of the time and with the lowest degree of opening of 70% during the lower demand period. With the valves, the regulation strategies are completed.

4 CONCLUSIONS

Due to the lack of tools for simulation and optimization for energy recovery systems and the need to constantly seek improvements to increase the sustainability and efficiency indexes in water supply networks, the need to create this tool arises. In this manuscript, a methodology for an optimization model developed in Simulink MATLAB is presented as well as its implementation in a case study.

The optimization strategy defined in this methodology aims to maximize the energy recovered. In the same way, the parameters that dictate the behavior of the system based on the number of PAT working, rotation speed and degree of opening of the PRV are obtained.

The tool developed, operating with the methodology outlined in this work, serves both to analyze an existing installation and seek improvement solutions and in cases where it is necessary to evaluate the proposal of an energy recovery system. The innovation of this study is the incorporation of empirical methods, where characteristic curves can be approximated.

However, the limitations of the model must be taken into account: 1. If there is no energy recovery system, it must be selected first, 2. The largest number of PATs allowed is 3, and they must be installed in parallel 3. All parameters must be entered prior to running the simulation.

This optimization tool implemented in a network point of the high-pressure water distribution network of the Valencia Metropolitan System (Spain), and as a result, improving the recovered energy. Moreover, it can be used in any water distribution system as long as the variables required for the correct model simulation are available.

This is a field of research of great interest for sustainable development since it shows that it is possible to increase the energy recovered in a water distribution network and, at the same time, improve its hydraulic and energy efficiency by regulating the water resources in a more concious way.

Table 3. Abbreviations

Parameter	Definition	Units
Qd	Demanded flow.	L/ s
Pu	Upstream pressure.	m w.c.
Pd	Downstream pressure.	m w.c.
Q_{BEPt}	Flow at the best efficiency point (BEP) of the machine in turbine mode.	L/ s
H_{BEPt}	Recovered head at the best efficiency point (BEP) of the machine in turbine mode.	m w.c.
η_{BEPt}	Efficiency at the best efficiency point (BEP) of the machines in turbine mode.	%
ns_t	Specific number in turbine mode.	m, kW
Q_{BEPp}	Flow at the best efficiency point (BEP) of the machine in pump mode.	L/ s
H_{BEPp}	Head at the best efficiency point (BEP) of the machine in pump mode.	m w.c.
η_{BEP}	Efficiency at the best efficiency point (BEP) of the machines in pump mode.	%
Q_{mint}	Minimum operating flow for the PAT.	L/ s
Q_{maxt}	Maximum operating flow for the PAT.	L/ s
N_o	Nominal rotational speed of the PAT.	rpm
n	Rotational speed of the PAT at a given moment.	rpm
α	Frequency inverter value setpoint for the rotational speed.	%
α_{min}	Minimum frequency inverter value setpoint.	%
α_{max}	Maximum frequency inverter value setpoint.	%
lb	Lower bound of the range for determining the maximum power.	%
ub	Upper bound of the range for determining the maximum power.	%
Diam	Pressure-reducing valve (PRV) diameter.	mm
Kvo	Flow coefficient for the valve while fully open.	$m^3/h/\sqrt{Pa}$
g	Gravity acceleration.	in m/s^2

Qt	Flow rate turbinated by the PAT.	L/ s
h	Ratio between recovered head and recovered head at the BEP in turbine mode.	Dimensionless
e	Ratio between efficiency and the efficiency at the BEP in turbine mode.	Dimensionless
Hr	Head recovered by the PAT	m w.c.
ηt	Efficiency of the PAT	%
Hn	Net available head. Difference between upstream and downstream pressures.	m w.c.
Hpar	Dissipated head for the parallel PRV	m w.c.
Hout	Dissipated head for the outlet PRV	m w.c.
MP	Mechanical power generated by the PAT.	kW
EP	Electrical power generated by the generator.	kW
η_{elec}	Efficiency of the electrical generator.	%

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