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ScienceDirect

Energy Procedia 158 (2019) 117–122

Energy Procedia

www.elsevier.com/locate/procedia

10th International Conference on Applied Energy, ICAE 2018, 22-25 August 2018, Hong Kong, China

Technical and economic analysis of Pumps-as-Turbines (PaTs) used in an Italian Water Distribution Network (WDN) for electrical energy production

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Abstract

The use of renewable resources is fundamental for achieving the emissions reduction targets. Small-scale hydropower is a viable solution that has only partially been exploited so far for producing electrical energy in rural/remote zones and for recovering energy where there is availability of pressure gradients and flow rates, like in Water Distribution Networks (WDNs) or in other industrial processes. In this paper, Pumps-as-Turbines (PaTs) are studied as a potential energy recovery and pressure regulation device, considering the case study of the Egna municipality WDN, a city located in the North of Italy. An innovative analytical approach is used for selecting PaTs, depending on WDN operating data, and for forecasting the machine performance under varying operating conditions. A MATLAB® Simulink model is developed for simulating two different set-ups configurations and installation of PaTs. Finally, an economic analysis is performed by evaluating the potential energy recovery and the PayBack Periods (PBPs).

Keywords: Pump-as-Turbine; Water Distribution Network; Theoretical forecast method, MATLAB® Simulink; PayBack Period.

1. Introduction

Among the alternative energy resources, hydropower is the most used in locations where there is high availability of both water and geodetic altitudes. Nowadays, new installations of large-scale hydropower are rare as most of the available geodetic heights have been already exploited. Nowadays, the residual hydropower potential only involves small water resources or energy recovery systems in industrial and civil plants. Different typologies of turbines are available in the small-scale hydropower sector depending on the characteristics of the installation site.

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1876-6102
10.1016/j.egypro.2019.01.055

Among them, Pumps-as-Turbines (PaTs) are a viable solution to produce electrical power with a significant reduction of the plant's costs. These hydraulic machines show rather good performance in turbine mode, but their operating range is strongly reduced due to the absence of specific and controllable guide vanes. For instance, PaTs are used in Water Distribution Networks (WDNs) and in industrial plants for energy recovery purposes due to i) their price that is cheaper than conventional hydraulic turbines and ii) more availability in the market. In literature, several works tried to define a methodology able to select the most proper PaT in specific applications by supplying empirical formulations for calculating their performance in turbine mode starting with the design data in pump mode. However, there are not yet general methodologies to forecast the machine's behavior in off-design conditions. Rossi et al. [1] carried out laboratory tests of a centrifugal pump running in turbine mode using non-dimensional analysis to assess the performance data for being installed in the WDN of Merano (Italy). Further studies are involved on improving the efficiency of PaTs by revising the impeller design [2]. In this paper, a MATLAB® Simulink model that represents a branch of the WDN located in Egna (Italy) is analysed considering a new methodology for selecting PaTs and different installation layouts aiming to maximize the potential energy recovery. The paper is organized as follows: Section 2 presents the data of a WDN's branch of Egna used in the MATLAB® Simulink model together with the methodology applied for choosing PaTs considering two different installation's layouts (series or parallel) with four different pumps models. Section 3 presents the results obtained by the simulations, comparing the performance obtained by the four previous selected PaTs models and layouts. A feasibility study of the overall investment, considering the yearly energy produced by PaTs, mechanical, electric and civil costs, is also presented. Finally, Section 4 reports the conclusions of the work.

2. Research and methods

2.1. WDN operating data

The water grid of Egna (214 m a.s.l.) is fed by two different water tanks, named Villa (338 m a.s.l.) and Egna (314 m a.s.l.), installed uphill over the city. Another water tank, named Mazzon (420 m a.s.l.), has the aim to supply the previous two tanks. In this work, the branch of the grid between Mazzon and the other two tanks is analysed. An intensive measurement campaign was carried out in the selected branch by the means of a volumetric flow meter and two pressure probes located upstream and downstream the analysed branch. Data referring to a total of 164 hours of WDN's operation were collected, finding that the flow rate trend was almost constant and close to 52 m^3/h. For the evaluation of the total amount of recoverable electrical energy, it is assumed that the flow rate trend remains more or less the same during the year [3, 4] because the flow rate, coming for the water tank, is always regular and almost constant. Fig. 1 shows the hourly volumetric flow rates of the analysed part of the analysed WDN.

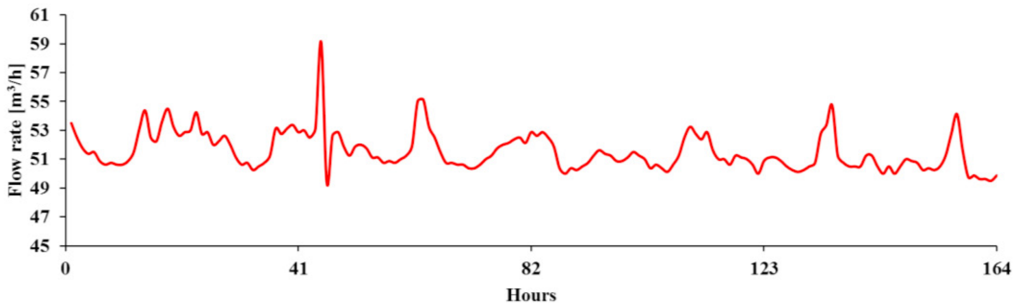
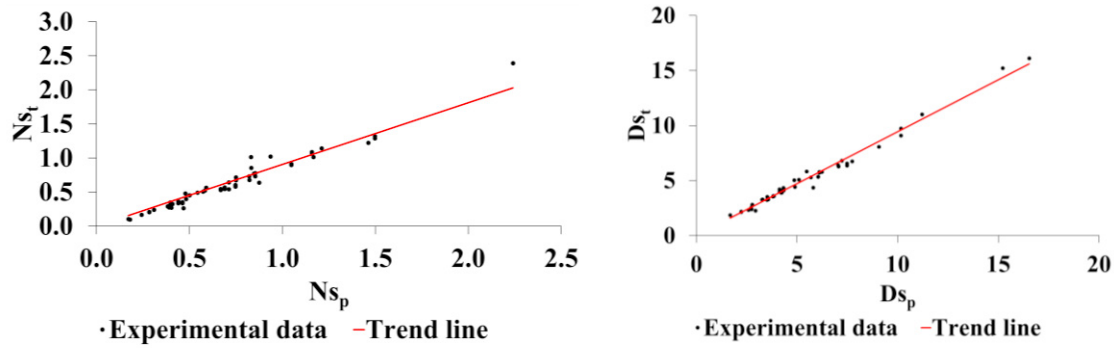


Fig. 1. Hourly volumetric flow rate of the analysed WDN in Egna

As Fig. 1 shows, the hourly volumetric flow rate is quite regular; this operating condition is particularly favorable for the introduction of PaTs because they can operate close to the optimal design point guaranteeing high efficiency and constant produced power. This specific branch was used as a test case for energy recovery by installing PaTs.

2.2. PaTs' selection

The PaT can be installed close to the lower water tank, upstream of it. The tool for selecting PaTs and for forecasting their performance regards an analytical methodology developed by some of the authors of the present work [5]. In this model, flow rates values, deriving by measurement campaigns in a real WDN's branch, are used as input conditions, while a pressure value of 1 bar is considered as PaT's pressure output since the downstream tank is at atmospheric pressure. PaTs are selected considering the average flow rate supplied by Mazzon to the other two water tanks, equal to 51.55 m^3/h. The trend of the flow rate reported in Fig. 1 is supposed to be repeated all the year, as previously stated. The available net head that can be exploited by the PaT is equal to 70 m. These two values are considered as Best Efficiency Point (BEP) values of the PaT for selecting the most proper machine to be used in this application. Due to the high values of available head, the first choice is to use a set-up of two PaTs installed in series (or a multistage PaT) for halving the available net head exploited by each single machine (35 m per each PaT) in order to use single stage machines and higher specific rotating speed, which grant a better hydraulic performance. Another set-up that consists of two PaTs installed in series in two parallel pipes of the same WDN's branch (so-called parallel set-up), where the exploited flow rate by the hydraulic machines is halved (25.57 m^3/h per PaT), is analysed in order to assess a second installation solution. The considered solutions are shown in Fig. 3. Q-H and Q-η curves of the selected PaTs are evaluated by the means of analytical formulas derived from experimental laboratory tests carried out on 32 PaTs [5] and on other 27 PaTs analysed by Stefanizzi et al. [6] in order to define both BEP values. The number of the tested machines refers to a wide range of design solutions and operating conditions that allows to define a general correlation between pump and turbine modes as well as to cover many possible ranges of flow rate and head. The main characteristic of the developed methodology consists on forecasting the performance of pumps operating in turbine mode with analytical and statistical analyses, starting from the data in pump mode. Assuming a PaT's mechanical efficiency in turbine mode equal to that in pump mode at the rated conditions [1], the BEP in reverse mode can be evaluated knowing both specific speed (N_S) and specific diameter (D_S) values in pump mode as shown in Fig. 2a and Fig. 2b, respectively. Indeed, performance data in pump mode are easily accessible from pump manufacturers' datasheets as opposed to the ones in reverse mode, allowing to select the correct PaT for each specific application as a function of the available flow rate and head.



a) b)

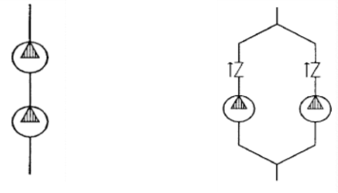
Fig. 2. Specific speed (N_S) (a) and specific diameter (D_S) (b) in both direct and reverse modes from experimental evidence

The experimental trends used for correlating the operation of PaTs in pump and in turbine modes are reported in Fig. 2a and in Fig. 2b; Eq.s. (1) and (2) that describe these trend lines have an R^2-value of 0.9488 and 0.986, respectively.

$$N_{St} = 0.9051 \cdot N_{Sp} \tag{1}$$

$$D_{St} = 0.9436 \cdot D_{Sp} \tag{2}$$

Finally, PaTs are chosen considering two different set-ups, series or parallel installation, reported in Fig. 3.



a) b)
Fig. 3. Series (a) and parallel (b) set-up

PaTs are selected considering the BEP values and the characteristic curves obtained by using analytical formulas expressed in Eq.s (1) and (2). Subsequently, the rotating speed of the machine, starting from the rated one of 2900 rpm, is decreased, according to the similarity theory, in order to properly fit the available head and flow rate for getting the highest possible hydraulic efficiency. The selected PaTs for this specific application and their BEP values are listed in Table 1, while their set-ups and operating rotating speeds are presented in Table 2.

Table 1. PaTs' performance at BEP

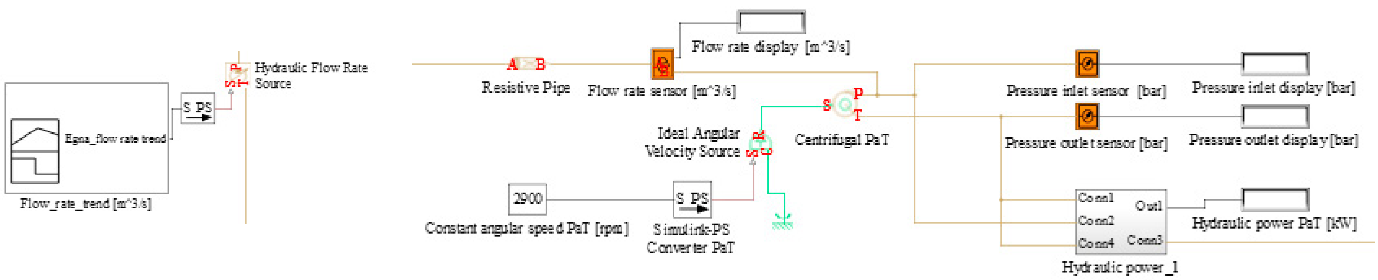
Pump model	Flow rate [m^3/h]	Head [m]	Efficiency	Power [kW]	rpm	N_S
Calpeda N50 125S-A (S-A)	54	47	0.71	4.92	2900	0.37
Calpeda N40 160A (A)	60	53	0.69	6.07	2900	0.36
Calpeda N50 125A-A (A-A)	36	57	0.53	2.97	2900	0.27
Calpeda N32 178D-A (D-A)	33	53	0.50	2.38	2900	0.27

Table 2. PaTs' set-up and their optimal rotating speeds in the analysed WDN's branch

PaTs models	
Series set-up (two PaTs)	Parallel set-up (two+two PaTs)
Calpeda N50 125S-A (S-A) – 2000 rpm	Calpeda N50 125A-A (A-A) – 2600 rpm
Calpeda N40 160A (A) – 2100 rpm	Calpeda N32 178D-A (D-A) – 2500 rpm

2.3. MATLAB® Simulink model

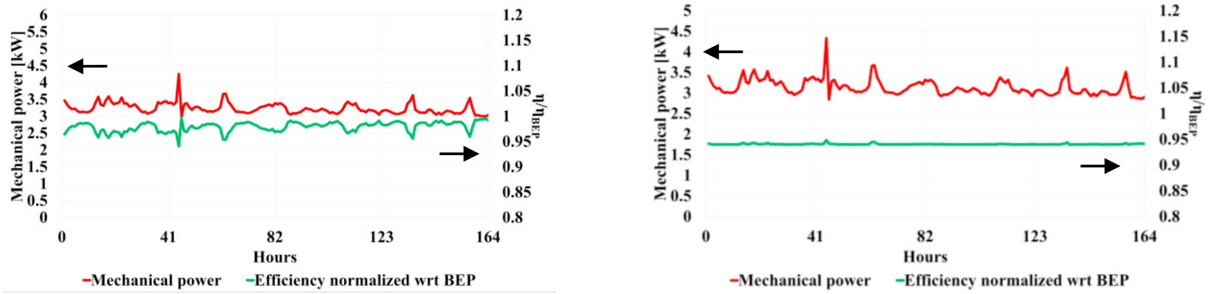
Two different layouts are studied in order to investigate the optimal set-up in terms of both energy production and economic saving. The first one refers to two PaTs that are installed in series, while the second one refers to four PaTs that are installed in series in two parallel pipes of the same WDN branch. For this purpose, a MATLAB® Simulink model has been designed taking into account the water needs of the city of Egna. The model is composed by a hydraulic flow rate source where the trend of the flow rate is defined according to the collected experimental data; moreover, the pressure losses along the pipes of the WDN's branch are considered with default friction losses coefficients. As PaTs are intended to substitute PRVs, a set of flow meters and pressure probes are inserted in the model in order to evaluate the flow rates through the PaTs and the pressure reduction. The bottom reservoir allows to set the pressure level at the end of the branch that, in this case, is equal to 1 bar. Finally, the performance data of PaTs, which are obtained with the analytical model [4], are inserted into the hydraulic machine blocks that evaluate, through the ODE solver, the effective pressure ratio and the hydraulic efficiency of the machine. Fig. 4a and Fig. 4b show the hydraulic flow rate source and the PaT's pattern, respectively.



a) b)
Fig. 4. Hydraulic flow rate source (a) and PaT's pattern (b)

3. Results and comments

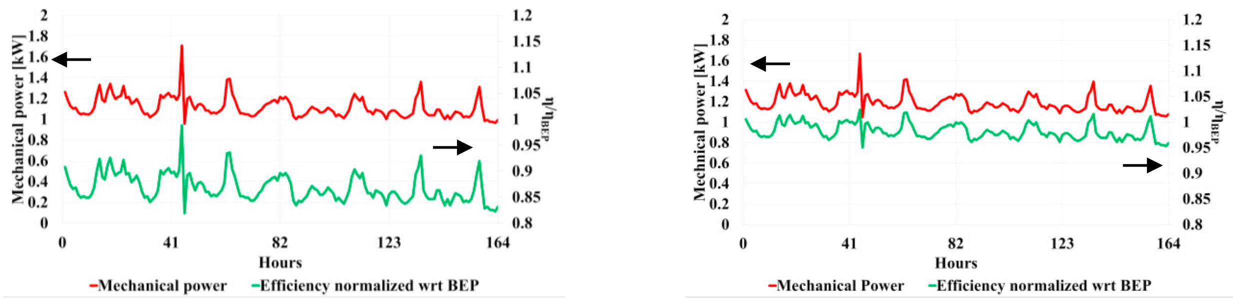
In this section, the performance's forecast of different PaTs, analysed with the MATLAB® Simulink model, and the economic analysis of their installation in the WDN of Egna are discussed. Both set-ups previously discussed were analysed. As concerns the series configuration, the performance of PaTs model A and PaTs model S-A are forecasted. Fig. 5a and Fig. 5b show the efficiency, normalized with respect to the BEP in turbine mode, as well as the mechanical power produced during the monitored time period for the two selected machines, respectively. Fig. 5a shows that, using PaTs model A, an average mechanical power of 3.23 kW and an average normalized efficiency of 98% per machine are obtained; while Figure 5b shows that an average mechanical power of PaTs model S-A of 3.13 kW is achieved together with an average normalized efficiency per machine of 94%.



a) b)

Fig. 5. Mechanical power and efficiency trends of the PaT model A (a) and the PaT model S-A (b)

Fig. 5a and Fig. 5b show that the performance of the analysed PaTs are very similar, with a slightly higher performance of PaTs model A that can achieve a higher energy recovery and, subsequently, a higher economic saving. The second analysed set-up refers to the installation of two PaTs in series installed in two different parallel branches of the WDN, constituting the so-called parallel set-up. Also in this case, a comparison between the effectiveness of different commercial pumps was performed. Fig. 6a and Fig. 6b show the efficiency, normalized with respect to the BEP in turbine mode, and the power produced as a function of the monitored time period obtained with PaTs model D-A and PaTs model A-A, respectively. Fig. 6a shows that an average mechanical power of 1.12 kW and an average normalized efficiency per machine of 87% can be achieved by using PaTs model D-A. Figure 6b shows that an average mechanical power produced by PaTs model A-A, equal to 1.18 kW, is roughly the same of that of PaTs model D-A, while the average normalized efficiency per machine is close to its BEP (98%).



a) b)

Fig. 6. Mechanical power and efficiency trends of the PaT model D-A (a) and the PaT model A-A (b)

A preliminary analysis of the investment Payback Period (PBP) is carried out in order to evaluate the economic feasibility of PaTs' installation in a real WDN. The economic analysis has been carried out taking into account that the trend of the flow rate, directly measured for 164 hours of WDN operation, repeats all year long and that the available head of 70 m remains the same. The assumption of the flow rate regularity has been already evaluated and confirmed in literature [3, 4]. By considering the previous assumption and the two different installation set-ups, the different annual energy recoveries are reported in Table 3.

Table 3. Annual energy recovery of different set-ups and PaTs' models

Set-up	Series (two PaTs)		Parallel (two+two PaTs)	
PaTs' model	A	S-A	D-A	A-A
Energy recovered [kWh]	55,814	54,156	41,041	38,554

The capital cost of the investments is evaluated considering the following items: civil works, PaTs coupled with electric motor, electric power board, piping, fittings and human labour. Subsequently, assuming a maintenance cost equal to 10% of the capital one and an electricity price for the industrial consumers of 0.22 €/kWh for the Italian market [7], net economic savings and PBPs are listed in Table 4.

Table 4. Net economic savings and PBPs of the investments

PaTs set-up	2 x A PaTs	2 x S-A PaTs	4 x D-A PaTs	4 x A-A PaTs
Capital cost [€]	20,999	21,029	41,071	42,058
Maintenance [€/year]	2100	2103	4107	4206
Economic saving [€/year]	12,450	12,080	9,155	8600
Net economic saving [€/year]	10,350	9977	5047	4394
PBP	~ 2 years	2 years and 2 months	8 years and 2 months	9 years and 6 months

Table 4 shows that there is a huge gap between the two set-ups regarding both capital costs and net economic savings that, in the case of 2 PaTs in series, are 50% higher than the parallel installation. Subsequently, PBPs of the series set-up is four times shorter than that of the parallel one. In this case, the first set-up was the optimal solution.

4. Conclusions

In this work, PaTs are intended to replace PRVs for potential energy recovery in the WDN considering the real case study of Egna (BZ). PaTs' selection is performed considering the data of the WDN by inspecting both available flow rates and heads. BEP's parameters of each PaT are evaluated through analytical relations based on specific speed (N_S) and specific diameter (D_S) obtained by using experimental tests on a set of several PaTs. A model is designed using MATLAB® Simulink to resemble the operation of the WDN branch. Due to the high available head, the first analysed set-up was the series installation of two machines, while the second was the parallel one (two plus two PaTs in parallel): in the first case, for each PaT, an average power of 3.18 kW is produced, while 1.15 kW in the second case. The average produced power in the first case led to a yearly electrical energy production of 54,985 kWh, while 39,798 kWh in the second case. Consequently, the best economic saving scenario is obtained with the series set-up, achieving a PBP between 2 years and 2 years and 2 months, while the parallel one involved a much longer PBP. In conclusion, the series set-up was the best option due to its trade-off between produced energy and investment costs. However, PaTs proved to be a good choice for performing both pressure regulation in the grid by substituting PRVs and energy recovery when the optimal lay-out is analysed and, subsequently, chosen.

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