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Study of a Pump-as-Turbine (PaT) speed control for a Water Distribution Network (WDN) in South-Tyrol subjected to high variable water flow rates

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Abstract

The development of renewable energy technologies for producing clean energy has more and more become a priority worldwide. Research activities have not just to target the technological improvement of such systems, but they have also to consider their market deployment. In such a scenario, hydraulic machines, in particular Pumps-as-Turbines (PaTs), can play a key role in energy recovery applications. One of the main open issues of PaTs is the performance forecast in turbine mode, due to the lack of data from manufacturers, and their use in some applications with high flow rate and pressure variability, especially at part-load operating conditions like in energy recovery applications within Water Distribution Networks (WDNs). In this work, a MATLAB® Simulink model is developed for simulating a branch of the WDN located in Laives (South-Tyrol), where specific PaTs have been selected and used to substitute Pressure Reducing Valves (PRVs). A speed control by means of an inverter is performed due to the high variability of the flow rate inside the grid branch, allowing the machines to operate at their Best Efficiency Point (BEP). A preliminary analysis showed that it is possible to increase the energy production of about 23% with respect to a constant-speed machine, leading to a significant decrease of the PayBack Period (PBP).

Keywords: Small-Scale Hydropower; Energy recovery; Pump-as-Turbine; Speed control; MATLAB® Simulink

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1. Introduction

Nowadays, the production of electrical energy by the means of renewable energy resources gained more and more importance. The effects of climate changes are evident and almost all the Countries have to implement solutions to increase the share of renewable energies in their energy mix for reducing CO_2 emissions. Climate strategies and targets of the European Union are ambitious. Three targets have to be accomplished according to the 2030 climate and energy framework: i) greenhouse gas emissions reduction of, at least, 40% from the levels of 1990, ii) increase, up to 27%, of the share of renewable energies and iii) improvements by, at least, 27% in energy efficiency [1]. In developed countries as Italy, besides the development of new conventional renewable energy power plants such as wind farms, photovoltaic systems, biomass plants, it is also fundamental to deploy innovative small-scale solutions to reach the targets. In Italy, the hydropower sector is the most exploited with a share of about 42% in the electrical produced energy [2]. Large-scale hydropower is already mature and its exploitation is difficult to continue due to the lack of new sites and environmental constraints. Is such a scenario, micro-hydropower solutions for energy recovery can play a key role to exploit small hydric resources [3]. Usually, the main drawbacks of micro-hydropower projects with traditional turbines are their initial capital cost that can reach about 25% of the installation one, the maintenance costs and availability of spare parts. One solution could be the use of centrifugal pumps in reverse mode (PaTs). According to Williams [4], PaTs are available for a wide range of heads, flow rates, number and sizes; moreover, their spare parts (bearings, seals, etc.) are easily available and their installation is easy. All these features make PaTs a low cost solution compared to other technologies like Cross-flow turbines. Other authors have also investigated on the benefits of using PaTs for small-scale hydropower projects. For example, Montwani et al. [5] evidenced how, for a 3 kW capacity pico-hydro test rig, the cost of a Francis turbine can be from 6 to 8 times higher than that of a centrifugal pump. Teuteberg [6] considered a sea farm in Gansbaai in South Africa and designed a process of 97 kW micro-hydropower system using PaTs, showing the financial viability of the project. Fernández et al [7] assessed the performance of a centrifugal pump running in reverse mode: they studied the characteristic of the machine at different rotating speeds to evaluate how they can influence its efficiency and the force actuating on the impeller, concluding that the characteristic of the PaT can be obtained from the characteristic of the pump. Kusakana [8] identified PaTs as innovative technologies that can be used for the electrification of rural areas. Tao Ma et al. [9] suggested to use a PaT in standalone hybrid renewable systems with pumped storage for decreasing the initial investment costs. However, one of the biggest limitations of PaTs is the difficulty to predict their operation in turbine mode, like the efficiency at part-load conditions, due to the lack of hydraulic control studies of PaTs' performance data [10 – 11]. Other research projects recently investigated on methods to solve these problems about selecting the correct PaT and evaluating PaTs' performance in reverse mode. Rossi et al. [12] considered 32 PaTs and, by means of the non-dimensional analysis coupled with a normalization process, they elaborated a general trend to obtain the performance of a PaT operating in reverse mode. Pugliese et al. [13] performed laboratory tests on two centrifugal pumps, a horizontal single-stage and a two-stage centrifugal pump, operating as turbines, comparing the obtained results with the theoretical models that are present in literature. Barbarelli et al. [14] developed a method combining statistical and numerical models in order to select a PaT to recover energy from a pipeline. Starting from the capacity and the head of the site, this method allows to calculate the factors C_Q and C_H. C_Q is the ratio between the capacity of the pump running as a turbine at its best efficiency point (BEP) and the capacity of the same pump in direct mode at its BEP. C_H is the ratio between the head of pump operating in reverse mode at its BEP and the head of the same pump in direct mode at its BEP. C_Q and C_H catheterized the PaT that has to be installed. Derakhshan et al. [15] tested four PaTs and derived a method that is valid only for centrifugal pumps having a specific speed Ns<60: with this method, it is possible to obtain the Best Efficiency Point (BEP) of the PaT based of the specific speed that characterizes the runner. The development of mathematical models to validate the results of laboratory tests were also realized by Williams [16] and Stepanoff [17]. Recently, some authors studied the use of PaTs for energy recovery applications: for example, it is possible to use them in oil refineries instead of throttling valves [18 – 19]. Particularly interesting is the operation of PaTs with fluids other than water, like mixtures that are used in industrial applications such as oil refineries. Another application field is the energy recovery in Water Distribution Network (WDN). In this system, the energy content of water is wasted by using passive elements to control the pressure of the grid. Due to the high cost of conventional turbines and their complex design, the recovery of this energy could be economically unfeasible. PaTs are much more affordable and simple; they are present in the market with a wide range of choice and they are readily available, being a solution to this problem. Buono et al. [20] developed a 3D Computational Fluid Dynamics (CFD) model to obtain the reverse characteristic of a centrifugal pump that substituted Pressure Reducing Valves (PRV) in a WDN. They also used a test bench to obtain, experimentally, the performance curves of the PaT for validating the model. Rossi et al. [21] considered the case of the aqueduct in the city of Merano in South-Tyrol and selected a PaT to insert in one of its branch, with a constant flow rate, by applying the non-dimensional analysis to a tested hydraulic machine. Lima et al. [22] studied an innovative method using the Particle Swarm Optimization (PSW) technique to select the best PaT to insert in a WDN. The authors also outlined how the variations of water flows and heads in the network influenced the correct PaT's selection. Using this method, they selected the optimal PaT in terms of maximum energy production and chose the best location to install a higher number of PaTs. In this work, a MATLAB® Simulink model is used for simulating a branch of the WDN of Laives. In this model, two PaTs installed in series are modeled in order to exploit the average flow rate of the WDN's branch and, at the same time, assuring a pressure of 4 bar downstream. In addition, a solution for choosing the best PaT for this task, taking into account the variability of the flow rates inside the WDN of the city of Laives in South-Tyrol (Italy), is presented. However, due to the high variability of flow rates in the selected branch, the choice of using a PaT results to be complicate and its performance might be poor because the machine operates most of the time in off-design conditions, for long periods during the year. However, by means of an inverter that changes the rotating speed of the machine according to the daily flow rate trend, it is possible to regulate the rotating speed of the PaT, allowing the machine to operate closer to its BEP depending on the available flow rate. The advantages of such method, which is currently performed manually by changing the rotating speed, will be developed in the future by inserting a closed loop control able to automatically vary the rotating speed of the PaTs depending on the flow rates inside the WDN.

2. Research and methods

2.1. Case Study

In this work, a real case of the WDN located in Laives, a small city of South-Tyrol region (Italy), is considered. Laives has approximately 18,000 inhabitants: two water tanks are placed at 108 m upstream the small town for feeding the WDN. The WDN is constituted by 16 branches and the pressure inside these branches is regulated by PRVs. For obtaining an energy recovery, PaTs are proposed to replace PRVs and to grant the operating pressure of 4 bar downstream the WDN branches to allow both householders and industrial consumers to use the water. In this work, only the branch characterized by the highest water flow variability is chosen in order to highlight the advantage of the PaT's speed control, which can be extended to the other branches of the same WDN and to other water networks if both flow rate and pressure trends inside the WDN are profitable on the economic point of view for being exploited by PaTs.

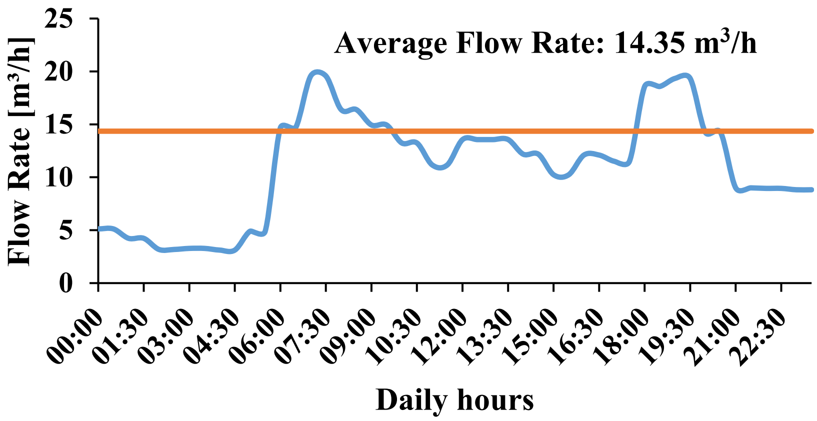

Fig. 1. Daily water flow in [m^3/h] of the selected branch of the WDN

Fig. 1 shows the hourly trend of the flow rate in the selected branch of the WDN that is recorded during a measurement campaign performed on site and the average flow rate. Being the two water tanks placed at a height of 108 m, PaTs can exploit approximately 40 m. The average flow rate used for selecting the PaT is equal to 14.35 m^3/h and it is chosen by analysing a temporal range that goes from 6:00 AM to 8:30 PM. The choice of this temporal range is due to the higher request of water from both householders and industrial consumers. If all the flow rate values are used for selecting the PaT, a lower energy recovery would be achieved: for this reason, the previous range of daily hours is considered. Finally, assuming that the daily trend of the flow rate inside the WDN branch is constant during the year [23, 24], this trend is used for performing the yearly energy analysis.

2.2. PaT's Selection

PaTs are selected considering the average flow rates and pressures inside the WDN's branch. Fig. 1 shows that the flow rate before 6:00 AM and after 8:30 PM are relatively lower than the other ones recorded during the rest of the day. In order to maximize the energy recovery, these values are not considered in the calculation of the average flow rate and pressure because they would lead to a lower size of the PaT, thus to a lower energy recovery and to lower hydraulic efficiencies available at higher flow rates. Once the two values of the average flow rate and pressure are calculated, the PaT model is chosen. In order to select the PaT, a theoretical methodology, developed by some of the authors of the present work, is used. The methodology is developed considering BEP's values related to 32 PaTs and 27 PaTs [25], operating in both modes, that are present in literature. Non-dimensional parameters are evaluated to apply a non-dimensional analysis. With the evaluation of these parameters, it was possible to correlate the specific speed, specific diameter and efficiency of PaTs in turbine mode (N_{st}, D_{st}, η_t) with the ones in pump mode (N_{sp}, D_{sp}, η_p).

$$N_{St} = 0.9051 \cdot N_{Sp} \quad (1)$$

$$D_{St} = 0.9436 \cdot D_{sp} \quad (2)$$

$$\eta_t = 0.7933 \cdot N_{Sp} + 0.605 \cdot \eta_p - 0.09246 \cdot {N_{Sp}}^2 - 0.8254 \cdot \left(N_{sp} \cdot \eta_p\right) + 0.3936 \cdot {\eta_p}^2 \quad (3)$$

Knowing the average flow rate and head of the analysed branch, the characteristics of the turbine to install in the WDN and, subsequently, N_{st} and D_{st} are identified. Knowing these values, N_{sp} and D_{sp} are evaluated, allowing to select the pump to be used as a PaT. The machine can be selected using the catalogues of the pumps' manufacturers. Finally, knowing η_p of the selected pump, it is possible to find the efficiency of the PaT in turbine mode η_t. These equations have been obtained thanks to a statistical analysis of non-dimensional data coming from experimental tests that are conducted by the authors of this work and by other scientists using various PaTs operating with pure water. The operation with fluid other than water are particularly interesting for energy recovery in specific industrial processes; however, in these applications, the accuracy of the presented correlation should be checked and corrected to take into account the different physical characteristics of the fluid.

2.3. MATLAB® Simulink Model

A MATLAB® Simulink model is prepared for simulating the selected branch of the WDN as Fig. 2 shows. All the blocks are linked through lines that constitute the analysed WDN's branch characterized by its own properties (length, section, roughness, etc.). The first block (A) is a physical signal creator that generates a signal corresponding to the considered flow rate trend reported in Fig. 1. The produced signal enters into the block that represents the hydraulic water flow source (B) that has the aim to resemble the hourly flaw rates in the WDN. This block typifies the fluid that flows inside the network. Along the water network, there are also pressure (C) and flow rate (D) sensors that monitor the respective values. The most important elements of the model are the blocks that simulate the PaTs (E). Initially, the block of the hydraulic machine is used for simulating a centrifugal pump. In order to simulate the turbine mode operation, the pump inlet is inverted with its outlet and a negative value for the rotating speed is set. The block requires also to insert some values related to the PaT's performance: for this purpose, the methodology explained in this section for evaluating the BEP values (flow rate, head and efficiency) in turbine mode and the analytical predictive method used for forecasting the performance's curves of the chosen PaT, developed by some of the authors of this work [12], are coupled for obtaining the PaTs' performance curves. Finally, the rotating speed of the PaTs is manually controlled in order to resemble an inverter that acts on PaT's rotating speed. The model allows to monitor the trend of the pressure upstream and downstream the PaT as a function of the available flow rate and to determine whether the pressure should be further reduced by means of the PRV. Moreover, a trend of the mechanical power during the operation of the machine can be recorded.

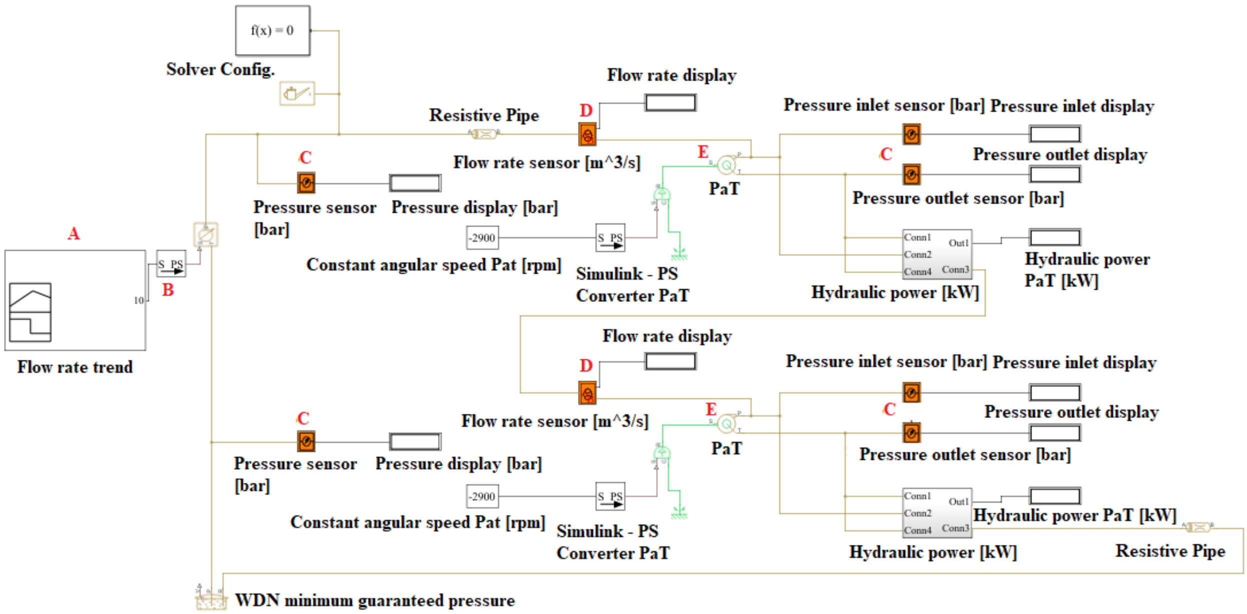

Fig. 2: MATLAB® Simulink Model

3. Results and comments

Using the methodology described in Section 2, the centrifugal pump Calpeda N 32/125 A, characterized by the operating parameters reported in Table 1 (pump and turbine mode), is selected.

Table 1. Characteristics of the PaT running in direct and in reverse mode at BEP at 2900 rpm

OPERATING MODE	PUMP	TURBINE
Flow rate [m^3/h]	13.00	14.76
Head [m]	20.0	22.8
Mechanical Efficiency [-]	0.72	0.69
Rotating speed [rpm]	2900	2900
Specific speed [-]	0.35	0.29
Impeller diameter [m]	0.121	0.121

Fig. 3 and Fig. 4 show the characteristic and the efficiency curves, respectively, of the selected PaT operating in turbine modes at four different rotating speeds: 2900, 2500, 2100 and 1500 rpm. The curves are obtained using the methodology described by Rossi et al. [12], which allows to predict the two curves knowing the values of flow rate, head and efficiency at BEP in turbine mode. Given the specific characteristics of the selected WDN branch, two PaTs in series are installed as reported in Fig. 2. This layout is chosen because it resulted to be the best balance of economic expenses and revenues. During the operation, the rotating speeds of the PaTs are varied (e.g. 2500, 2100, 1500 rpm) in order to obtain an accurate pressure control, according to the flow rate's trend and the constraints of the WDN. Future developments of the present work will be the implementation of an inverter model able to automatically vary the rotating speeds of the PaTs, guaranteeing a pressure outlet of 4 bar. The results of the simulations show that the average daily mechanical power produced by each PaT, operating from 6:00 AM to 8:30 PM, is 0.55 kW, as reported in Fig. 5. In addition, Fig. 6 shows also the trend of the mechanical efficiency achieved by each PaT. Considering the average mechanical produced power of 0.55 kW per day, a yearly energy recovery of 6430 kWh is achieved, taking into account 5835 hours/year of operation. Moreover, considering 0.22 €/kWh [26] as the average price for electrical energy, the yearly energy saving resulted to be equal to 1414 €/year. In order to highlight the advantage of a rotational speed control of the machine, a separate simulation is run at a fixed rotating speed of 2900 rpm: in order to respect the constraint of 4 bar downstream the PaTs, the flow rate cannot exceed 0.0034 m^3/s. In this case, the yearly energy recovery would be 4942 kWh, which is approximately 23% less than the case of using a variable speed technology, with an yearly energy saving of 1087 €/year.

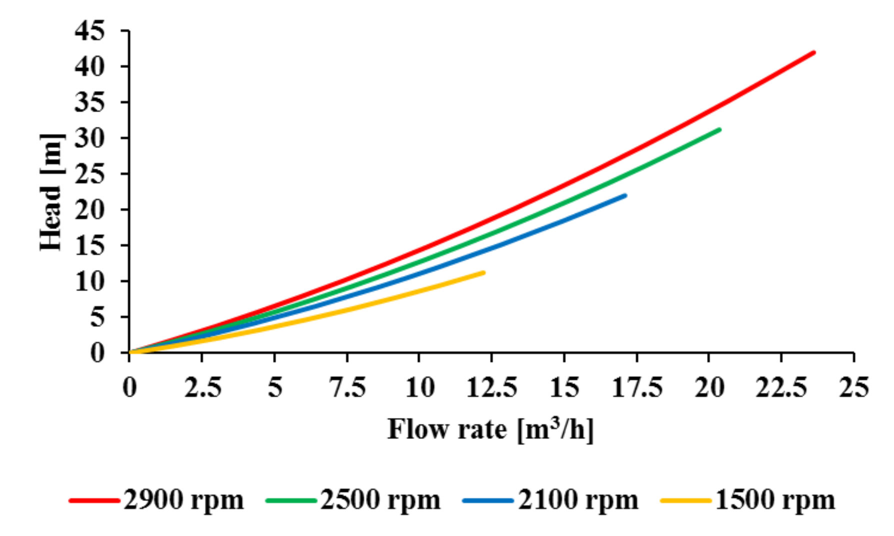

Fig. 3. Characteristic curves of the selected PaT operating at different rotating speeds

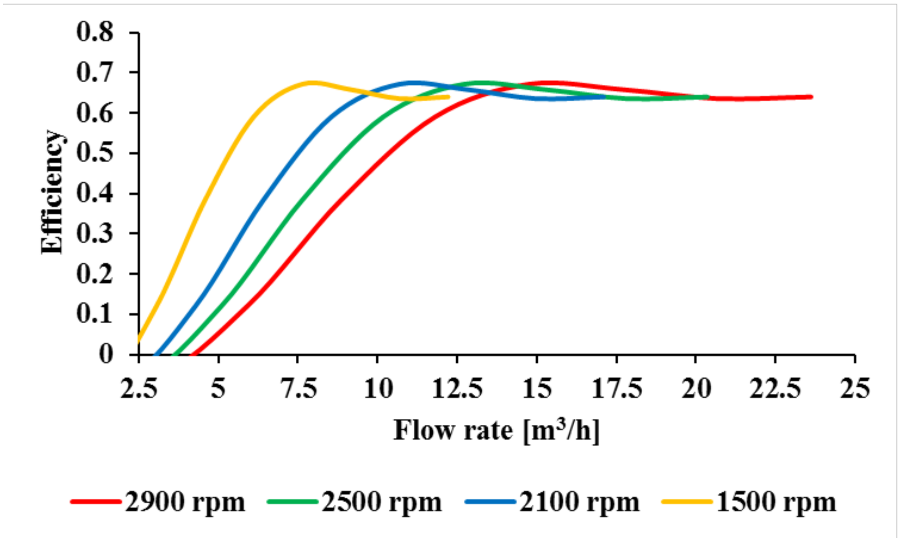

Fig. 4. Efficiency curves of the selected PaT operating at different rotating speeds

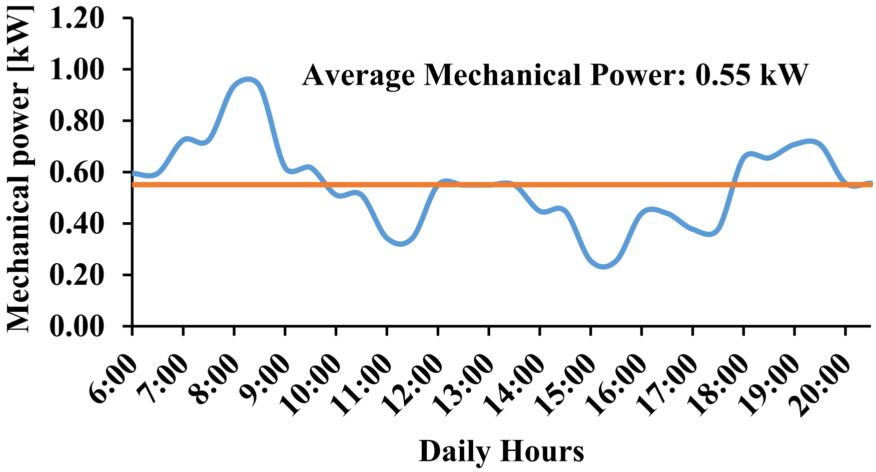

Fig. 5. Daily mechanical power produced by each PaT

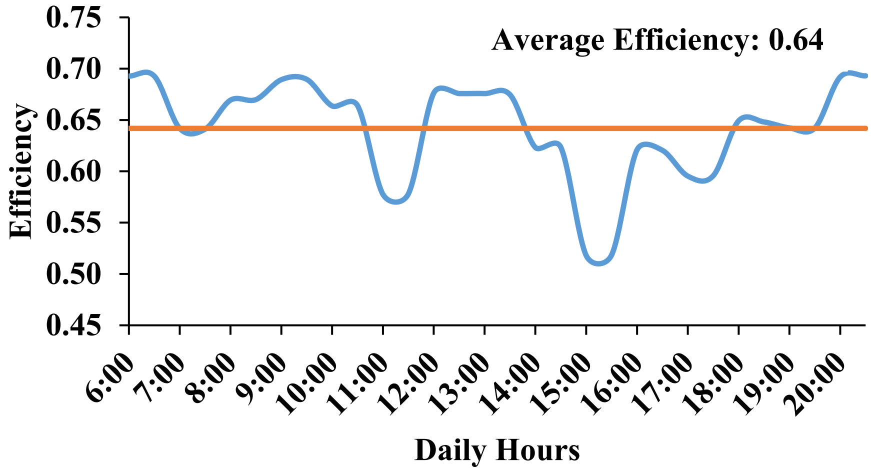

Fig. 6. Daily mechanical efficiency produced by each PaT

4. Conclusions

In this paper, the possibility to substitute PRVs with PaTs in a WDN as a solution to control pressure and recover energy has been investigated. The real case of the WDN of the city of Laives has been considered. As case study, the branch of the WDN characterized by the highest water flow variability has been selected to highlight the advantage of the PaT's speed control. This solution can be extended to the other branches of the same network or, eventually, to other networks. It is suggested to adopt this solution in other branches of the WDN or to other WDNs characterized by similar variable flow rates. Conversely, where the flow rate is almost constant, the electric energy recovery does not off-set the higher capital cost of the electric equipment for the rotational speed control. Considering the daily average flow rate and head, which characterize the selected branche, the Calpeda N 32/125 A has been selected using a method that correlates the specific speed N_{sp} and the specific diameter D_{sp} of the machine in pumping mode, with the specific speed N_{st} and the specific diameter D_{st} of the machine in turbine mode. Regarding η_t, a two variables equation that correlates both η_p and N_{sp} is used as well. In order to evaluate the performance of the PaT in the selected branch, a model based on MATLAB® Simulink is realized. The results of the simulation show the benefits due to the rotating speed variation of the machine depending on the flow rate in comparison with keeping the speed fixed at 2900 rpm. It is shown that, at a fixed speed, the yearly energy recovery would decrease by about 23%. Finally, it is demonstrated that such a solution keeps the PaTs operating close to their BEP, thus leading to a yearly energy recovery of 1414 € according to the average price of electric energy in Italy of 0.22 €/kWh.

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