Techno-economic feasibility analysis for energy production by variable speed Francis turbines in water distribution networks

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Introduction

The pressure in water distribution networks is controlled through dissipating valves with a consequent waste of a huge amount of hydraulic energy. However, these networks are characterized by remarkable daily flow rate variations, which prevent the installation of traditional Francis turbines whose performance would be negatively affected by the consequent consistent net head variations. A possible solution to overcome this problem is to adopt variable speed hydraulic turbines, which are able, by varying their rotation rate, to work with high efficiency in a wider range of net head and flow rates as well as to limit the development of unsteady pulsating phenomena in the whole distribution network.

This paper presents a techno-economic feasibility analysis for the installation of a variable-speed Francis Turbine in a real water distribution network with the aim of recovering the hydraulic energy, which would be otherwise dissipated by the valves.

The analysis has been carried out on one site of the Tshwane water distribution network in the city of Pretoria (South Africa). A 15 kW model of the variable speed Francis Turbine has been designed for being installed in the network and then experimentally analysed to determine the working range and the performance achievable by the turbine both in fixed- and variable-speed configurations.

Then, the performance curves have been exploited in a dynamic simulation model in order to verify the influence of the turbine operation with fixed and variable speed on the network behaviour and in particular on the required water level in the downstream reservoir. Once verified the technical feasibility of the turbine installation, an economic feasibility analysis has been carried out in order to determine the profitability index of the installation of both the fixed- and the variable-speed configurations.

1. Background

In the last decades, world electrical energy consumption has significantly increased with a share that has reached 17.7% in 2010 and is predicted to double by 2025 [1]. The increasing concern about environmental aspects has favoured a corresponding rapid growth of the deployment of the renewable energy sources aimed at the progressive reduction of fossil fuel exploitation and dependence. In such a context, hydropower is undoubtedly one of the most mature technologies with an electricity production of about 3500 TWh in 2010 (16.3% of the world's electricity), greater than that of the other renewable sources combined (3.6%), but much smaller than that of the fossil fuel plants (67.2%) [2]. One of the highest percentages of undeveloped potential is located in Africa (92%), and South Africa is known to be not particularly endowed with the best hydropower conditions as it might be elsewhere in Africa and the rest of the world. However, large quantities of raw and drinking water are conveyed daily under either pressurized (pumped) or gravity conditions over large distances and high elevations and, in such an energy demanding context, this represents a potential renewable energy source to exploit.

A number of water authorities throughout the world have realized the potential of conduit hydropower and implemented generating schemes [3-5]. However, water distribution networks have to be operated under sustainable water supply regimes, which is a very important aspect in operation of any hydropower generation system, and it is important to verify not only the profitability of these installations but also the reduced influence on the network required operating conditions.

To investigate the feasibility of hydropower generation at the inlets of storage reservoirs, i.e. the bulk water distribution systems, a low budget pilot hydropower generation installation, utilizing a pump operating in reverse mode, has been built and has given preliminary positive feedbacks in terms of expected return from such an investment [6]. This paper is aimed at studying more in depth this type of installation, focusing not only on the economic but also on the technical feasibility of a hydropower generation installation in the biggest site of the water distribution network of the city of Tshwane.

2. Description of the Tshwane water distribution network: Garsfontein site

The city of Tshwane in South Africa has a large water distribution network that includes 160 reservoirs, 42 water towers, 10,677 km of pipes and more than 260 pressure reducing installations (PRV) that operate at pressures up to 250 m.

The present analysis focused on the biggest site in the Tshwane water distribution network, that is the Garsfontein site. This site, located 1,508.4 m. above the sea level, is characterized by three reservoirs having a total capacity of 60,000 kl.

Four PRVs, working in parallel, are located upstream the three reservoirs with the aim of dissipating the water hydraulic energy depending on the required operating pressure.

To properly determine the operating conditions of the Garsfontein site, static pressures at the inlet and outlet of one of the PRV and flow rate have been measured for 8 months (April - November) with a sampling period of 15 minutes. Figure 1 reports the flow duration curve obtained by the acquired measurements.

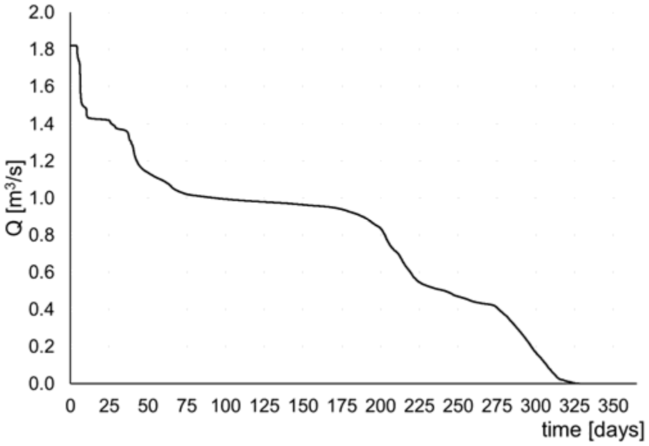

Figure 1 Flow duration curve at the Garsfontein site

Then, these data have been properly analysed by adopting the optimal sizing method proposed by Santolin et al. [7] in order to define the turbine allowing to achieve the maximum energy production. Both single- and double-machine configurations have been considered. The analysis has identified an optimal configuration with a Francis turbine whose main characteristics are reported in Table 1.

Table 1 Characteristics of the Francis turbine

Q_{des} [m^3/s]	1.29	Z [-]	6
Q_{max} [m^3/s]	1.50	D_{2e} [mm]	600
H_{des} [m]	139	D_{1e} [mm]	666
n [rpm]	1000		

3. Experimental analysis of the Francis turbine

The model turbine investigated in the present work is installed at the Turbomachinery Facility (TF), in the Department of Mechanical Engineering, University of Padova. The test rig is enabled to operate in an open loop (maximum head 15 m) configuration. The experimental measurements of the scaled down (1:2) model turbine were carried out using the open loop water circuit to get realistic conditions without significant variation of the effective head available to the turbine inlet similar to a prototype. Water from the basement was pumped to the overhead tank and flowed down to the upstream pressure tank connected to the turbine inlet pipeline. A uniform level of the water/head was maintained in the overhead tank at all operating.

The experimental measurements, calibrations, and computations were performed using the procedure and guidelines given in IEC 60041, IEC 60193, ASTM PTC 18 [8-10]. Data from the instruments were recorded using a computer with a Lab-View program developed in the laboratory.

The average pressure (Dp) was measured through four circular taps located at the turbine inlet and the draft tube outlet. A magnetic flow meter was used to measure the flow rate. Data from the pressure sensors and the flow meter were sampled at 2083 Hz and logged into the logging systems.

EC 60193 was followed for the calibration, measurements, and computations of the data. Uncertainties in the discharge and inlet pressure were ±0.05% and ±0.05%, respectively. The uncertainties in the generator input torque measurement, runner angular speed measurement were ±0.05% and ±0.5 rpm, respectively. Total uncertainty in hydraulic efficiency was ±0.2%.

A series of measurements were carried out at several operating points, ranging from a very low discharge to a high discharge (more than 14 different angles of guide vane were selected and 3 different speed values), to investigate the performance and characteristics of the Francis turbine. The steady state measurement data were used to construct a Hill diagram, for the axis of the speed factor (nED) versus the discharge factor (qED) and the efficiency lines (Figure 2).

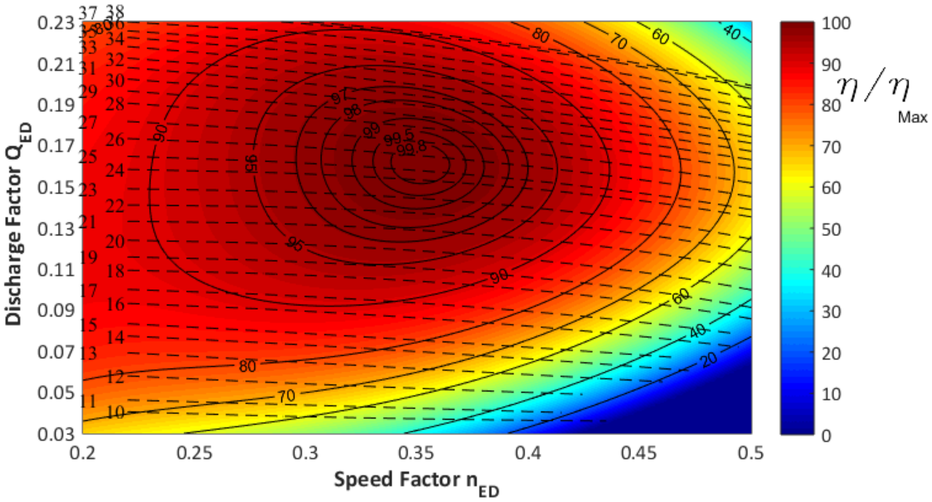

Figure 2 Hill diagram of the model Francis turbine.

4. Techno-economic feasibility analysis: fixed- vs. variable-speed Francis turbine

The technical feasibility of the installation of a hydraulic turbine in a water distribution network mainly depends on the influence of the turbine operation on the network efficiency and service quality.

To verify this influence, dynamic simulations have been carried out in order to verify the influence of the installation of the Francis turbine both in the fixed- and variable-speed configurations.

4.1 Dynamic model

A dynamic simulation model of the system depicted in Figure 3 has been developed for the above-mentioned purpose.

The simulation model considers a rigid water column approach in all system conduits. A behavioural model similar to the one described by Prescott and Ulanicki [11] has been used to model the PRV. The parameters of the behavioural model have been properly calibrated in accordance with the operating conditions of the Garsfontein site. The dynamics of the upstream reservoir has been neglected.

The PRV opening is modified in order to control the water level in the downstream reservoir by means of a proportional-integral regulator, similar to the one proposed by Prescott and Ulanicki [12]. The wicket gates opening and the rotational speed of the Francis turbine are modified in order to maximize the mechanical power.

The relation between the head at the turbine inlet, the flow through the turbine and the wicket gates opening has been modelled following the recommendations by de Mello et al. [13], including an additional term as a function of the rotational speed. The turbine mechanical power has been calculated as suggested in the reference mentioned above. The head loss between the PRV/Francis turbine outlet and the downstream reservoir has been neglected. The behaviour of the electrical machine and the frequency converter are not considered in the model.

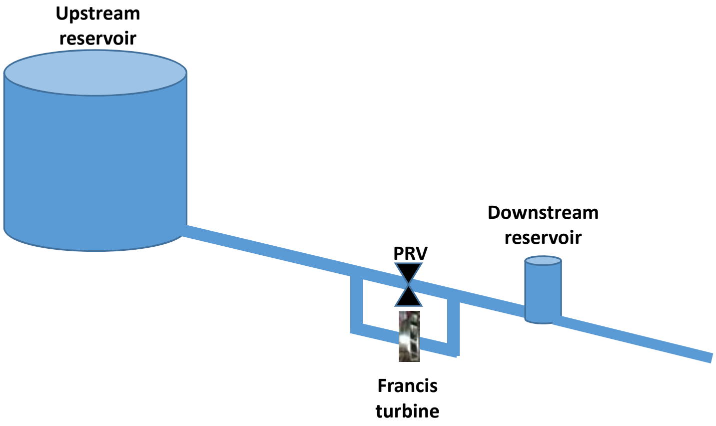

Figure 3 Scheme of the system analysed by dynamic simulations.

The water level in the upstream reservoir, flow demand profile and reference water level in the downstream reservoir are used as input variables of the simulation model. The output variables of the simulation model are: head at the PRV and turbine inlet, flow through the PRV and the turbine, wicket gates opening, rotational speed and mechanical power of the turbine, and water level in the downstream reservoir.
All simulations were carried out considering also fixed speed operation.

4.2 Influence on the water distribution network's operating conditions

In order to verify the influence of the turbine installation on the water distribution network behaviour, several simulations were carried out considering different flow demand profiles and different water levels in the upstream reservoir.
All simulations were carried out considering both variable- and fixed-speed turbine configuration.

- Test Case 1: real operating conditions
  This simulation was based on real input data in order to verify the influence of the turbine operation in real operating conditions of the network. A time period of 3,000 s, characterized by a variation of the water network flow demand (***Figure 4***) and by an upstream reservoir head of 120 m, has been chosen and simulated.

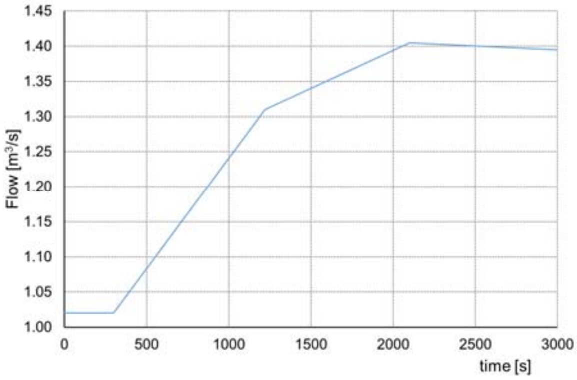

Figure 4 Water network flow demand in test case 1

- Test Case 2: hypothetical rapid variations of the water network demand
  This simulation was carried out to verify the capability of the system to react to rapid up and down variations of the water network demand in a 1000-second time horizon (***Figure 5***).

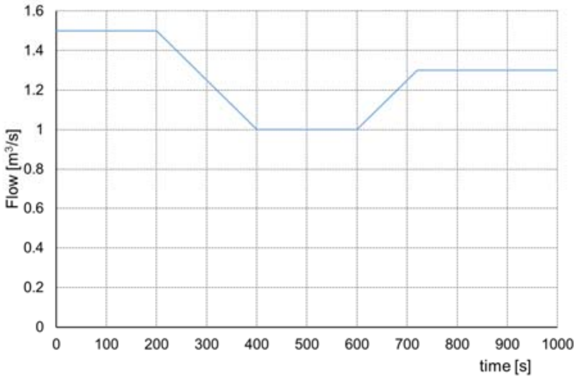

Figure 5 Water network flow demand in test case 2. Upstream reservoir level: 150 m

- Test Cases 3 and 4: hypothetical very high and very low water demand
  The influence of the turbine installation on the system behaviour in extreme operating conditions was also tested. In particular, situations with very low and very high water demands have been considered (***Figure 6***).

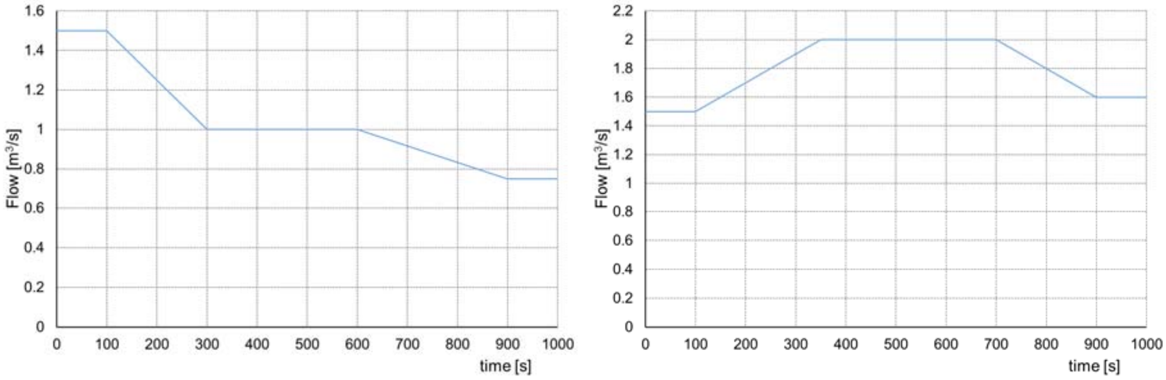

Figure 6 Water network flow demand in test case 3 (a) and 4 (b). Upstream reservoir level: a) 150 m; b) 130m.

In all the analysed cases the model manages to control the water level in the downstream reservoir and to maximize the mechanical power.

The water level oscillation in the downstream reservoir follows a weakly damped oscillatory behaviour. However, the amplitude of the oscillations is negligible in all the cases analysed (Figure 7), with a maximum oscillation amplitude of 10^{-4} in case of a significant increase of the water flow demand up to 2 m^3/s (Figure 7d). Further work is necessary to properly tune the parameters of the water level regulators in order to increase the damping of the water level oscillations.

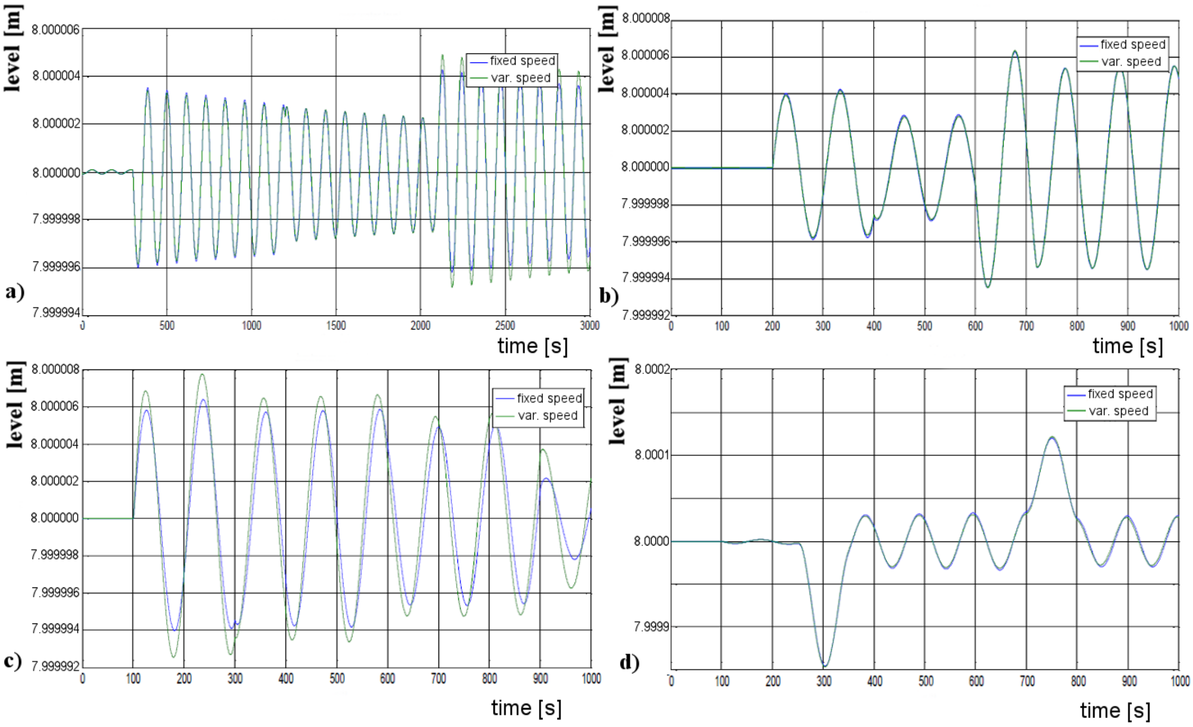

Figure 7 Water level of the downstream reservoir: a) Test case 1; b) Test case 2; c) Test case 3; d) Test case 4

This control of the water level is achieved by modifying the PRV opening and no significant differences can be highlighted between the configuration with the fixed-speed turbine and the one with the variable-speed turbine (Figure 8a).

As regards the energy production, the wicket gates opening are similarly modified in order to maximize the mechanical power (Figure 8b), but the possibility to varying the speed in the variable-speed configuration allowed the turbine to maintain higher efficiency values in comparison with the fixed-speed configuration, mainly at partial load (Figure 9).

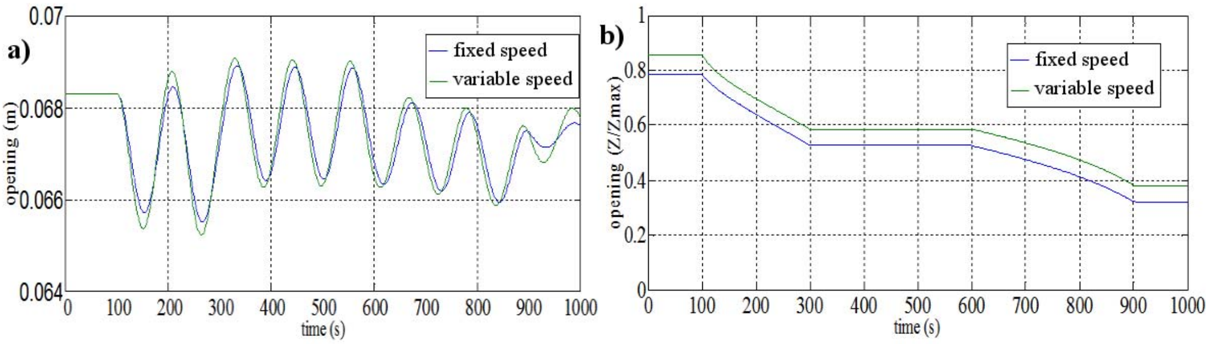

Figure 8 Opening of the wicket gates (a) and of the PRV (b) in the test case 1

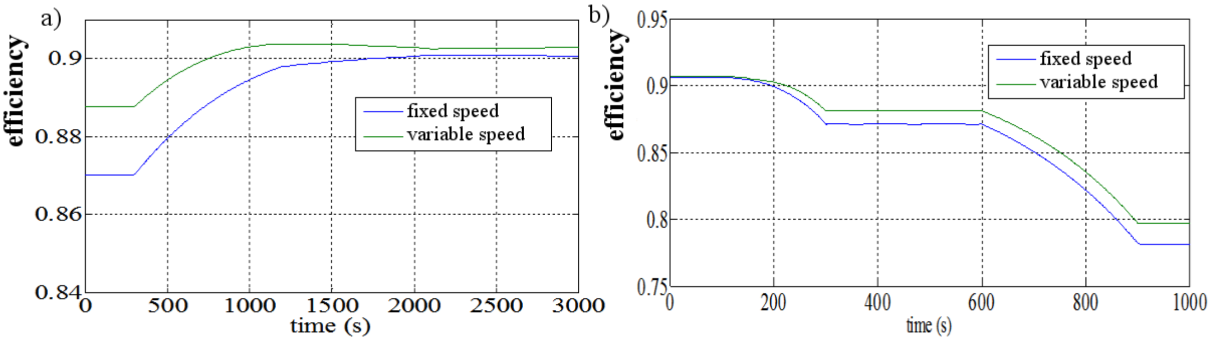

Figure 9 Turbine efficiency in the test case 1 (a) and 3 (b)

4.3 Techno-economic feasibility analysis

A longer simulation of 1-week time horizon was carried out, considering both fixed and variable speed, in order to approximately evaluate the energy production due to the operation of the turbine both with variable and fixed speed. The historical flow demand profile between 21st August 2012 and 28th August 2012 was considered as representative of the average operating conditions and used in this simulation.

The energy obtained considering variable speed was 135,149 kWh, that is 2.8% higher than the energy obtained with fixed speed (131,462 kWh).

These results were used to approximately estimate the annual energy production, which resulted to be 5,564,145 kWh/year for a fixed-speed configuration and 5,719,941 kWh for a variable-speed configuration.

Since in South Africa the price of energy production from small hydropower plants is 1.03 Rand/kWh, which is about 0.07 €/kWh, the annual revenue deriving from the turbine production would be 389,490.15 €/year for the fixed-speed configuration and 357,395.87 €/year for the variable-speed configuration.

The investment cost for a small hydropower plant equipped with a fixed-speed turbine can be estimated equal to 800,000 €, whereas that for a plant equipped with a variable-speed turbine is about 900,000 €.

The operation and maintenance costs have been estimated to be equal to 25,000 €/year for both the configurations and it has been assumed to earmark 15,000 €/year and 18,000 €/year for extraordinary maintenance of the plant equipped with the fixed-speed turbine and of the one with the variable-speed turbine respectively.

The plant life was assumed as equal to 25 years. An inflation rate by 3% and an annual increase of the energy price by 3,5% have been fixed.

To analyse the influence of the interest rate on the results, three different interest rates have been considered: 4%, 6% and 8%.

Table 2 summarizes the results of the techno-economic feasibility analysis.

Table 2 Results of the techno-economic feasibility analysis

	Fixed-speed	**Variable-speed**	**Fixed-speed**	**Variable-speed**	**Fixed-speed**	**Variable-Speed**
Interest rate	4%		6%		8%	
Net Present Value	7,183,624 €	7,266,823 €	5,528,093 €	5,562,905 €	4,313,170 €	4,330,234 €
Pay-Back Time	2.29	2.52	2.29	2.52	2.29	2.52
Profitability Index	8.98	8.07	6.90	6.18	5.39	4.81

It is clear that the plant equipped with the fixed-speed turbine is characterized by a smaller Net Present Value (NPV), but a higher Pay-Back Time (PBT) and Profitability Index (PI) in all the considered scenarios, which makes it more interesting from a techno-economic point of view. This result could be explained by the reduced variability of the operating conditions in the analysed site (see for example the flow duration curve in Figure 1) which does not allow to exploit the higher efficiency of the variable-speed turbine at part-load.

However, it must be pointed out that more variable operating conditions in the site could further increase the difference in energy production between fixed- and variable-speed, making the variable-speed configuration more profitable in terms not only of NPV but also of PBT and PI.

5. Conclusions

The paper presented a techno-economic analysis aimed at evaluating the feasibility of the installation of a turbine in water distribution networks.

The analysis has been carried out on one site of the Tshwane water distribution network in the city of Pretoria (South Africa). A 15 kW model of the variable speed Francis Turbine has been properly designed, starting from the flow rate and pressure data acquired in the site for 8 months. Then, the turbine has been experimentally analysed in the laboratory of the University of Padova in order to determine the working range and the performance achievable by the turbine both in fixed- and variable-speed configurations.

Starting from the performance curves, a dynamic simulation model has been properly built to analyse the influence of the turbine operation in parallel with the PRV operation on the network behaviour and in particular on the capability of maintaining the required water level in the downstream reservoir. The analysis has highlighted that in all the considered scenarios (real and hypothetical) the two configurations did not affect the network behaviour, since the water level oscillations in the downstream reservoir resulted to follow a weakly damped oscillatory behaviour, with negligible oscillations.

Moreover, in all cases analysed, the efficiency of the variable speed was higher than the one obtained with fixed speed, mainly at part load, and in one year of operation the energy production with the variable-speed turbine was estimated to be 2.8% higher than the one with fixed speed.

From the economic point of view, the plant equipped with the fixed-speed turbine resulted to be more interesting since characterized by a smaller Net Present Value (NPV), but higher Pay-Back Time (PBT) and Profitability Index (PI) in all the considered scenarios. However, the variable-speed turbine demonstrated its capability of maintaining higher efficiency at part load without affecting the network behaviour and in a site characterized by more variable operating conditions this configuration can be more profitable in terms not only of NPV but also of PBT and PI.

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