Set-up of a pump as turbine use in micro-pumped hydro energy storage: a case of study in Froyennes Belgium

A Morabito¹, J Steimes¹, O Bontems², G Al Zohbi¹ and P Hendrick¹

¹Aero-Thermo-Mechanics Dept. (ATM), École Polytechnique, Université Libre de Bruxelles (ULB), Avenue F.D Roosevelt 50, 1050 Brussels, Belgium
²Agence Intercommunale IDETA scrl, Quai Saint Brice 35, 7500 Tournai, Belgium

corresponding author: alessandro.morabito@ulb.ac.be

Abstract. Its maturity makes pumped hydro energy storage (PHES) the most used technology in energy storage. Micro-hydro plants (<100 kW) are globally emerging due to further increases in the share of renewable electricity production such as wind and solar power. This paper presents the design of a micro-PHES developed in Froyennes, Belgium, using a pump as turbine (PaT) coupled with a variable frequency driver (VFD). The methods adopted for the selection of the most suitable pump for pumping and reverse mode are compared and discussed. Controlling and monitoring the PaT performances represent a compulsory design phase in the analysis feasibility of PaT coupled with VFD in micro PHES plant. This study aims at answering technical research aspects of µ-PHES site used with reversible pumps.

1. Introduction

Hydropower on a micro-scale is frequently used to bring electricity supply in remote or rural areas. Unlike large-scale hydropower plants, these applications are mostly developed without dams and wide reservoirs. A local river simply feeds them with a weir crossing the river and little or no water stored. However, an important drawback emerges: the energy production is dependent on spot water availability and thus on seasonally weather. Likewise, solar and wind energy have to deal with intermittency, even if the power plant is properly located and designed.

This usually leads to install fossil-fuel energy sources, not environmentally helpful, to supply base-load demand, e.g. diesel engines. A frequent mismatch between renewable energy production and consumption then might occur. This is why energy storage systems (ESSs) are strong allies [1].

Among energy storage technologies currently available on a small and micro scale, pumped hydro energy storage (PHES) is recognized as one of the most cost-effective because of its predictable energy characteristics, its long-term reliability and its reduced global environmental effects [2]. During off-peak demand, PHES pumps back water to an upper reservoir from a lower reservoir and stores potential energy exploitable by hydraulic turbines when it is needed.

The objective of this paper is to confirm the relevance of the complete chain of tools and methodologies to design a µ-PHES site in a concrete application by means modelling and integrating the impact of µ-PHES applications. The studied site is located in Negundo Innovation Center in Froyennes, Belgium. The micro PHES is connected to a mini-grid system, which counts already 5.2 kW peak of photovoltaic panels and 4.8 kW peak of wind turbines.
1.1. Micro PHES technology

Like hydropower, micro PHES plants require specific topologies, such as a geodetic head (H), defined by the different altitude of the water level between upper and lower reservoirs, and the possibility of water harnessing, defined by the exploitable flow rate (Q).

These systems are very site-specific and a peculiar analysis is needed. Unlike micro hydropower, which has been successfully implemented in remote regions, there are few references in the literature regarding the technical and economic feasibility of PHES at micro scale. Manolakos et al. [3] describe a stand-alone photovoltaic (PV) plant coupled with micro-PHES in Donoussa Island, Greece. A hybrid system with PV and cogenerative internal combustion engine (ICE) is coupled with lead-acid batteries, thermal and water storage and a PHES system [4]. Silva and Hendrick underline the technical feasibility in PHES in buildings but show that it may be not economically competitive when compared to other in micro scale storage technologies [5].

The hydraulic turbine used in generating mode (GM) is selected based on its operating range and its overall performance characteristics. According to H, Q and the rotation speed at best efficiency point (BEP) it is possible to calculate the specific speed of the turbo-machine. This is a relevant parameter to define the type and geometry of the machine with the best performance. During the pumping mode (PM) a single pump or a set of pumps are used to refill the emptied upper reservoir when it is economically profitable.

1.2. Pump as Turbine

The economics of a PHES system is strongly affected by the chosen set of turbo-machines in GM and PM. Relevant differences in capital costs and in efficiency emerge from this choice [6]. Using a centrifugal or diagonal pump as turbine (PaT) in GM is a valid trade-off between capital cost and performances. With respect to maintenance it has many advantages compared to custom-made turbines. Pumps are relatively simple machines, are easy to maintain and are readily available in most developing countries. From an economical point of view, it is often stated that PaTs, in the range of 1 to 500 kW, are profitable and allow capital payback periods of two years or less (which is considerably less than that of a conventional hydraulic turbine [7]).

2. The micro-PHES site in Froyennes

To design PHES, it is essential to define the capacity of the site and the choices of management of the plant itself. This imposes the available head, the capacity and the pumping and generating time frames.

2.1. Topology

In Froyennes (figure 1), the upper basin of 1500 m³ already exists. The lower reservoir can be loaded to maximum 625 m³: it limits the plant capacity to about 17 kWh. Due to the small size of the reservoir it may register a large variation (in percentage) of the available head during the working sessions from 10 m to 6 m.

![Figure 1. Overview in Negundo Innovation Center](image-url)
2.2. Pipeline and technical room
A 60 m underground pipe connects the lower reservoir and the upper reservoir. The performance of a pump in a pumping system is determined by pipeline characteristics and size. The pressure losses occur due to friction of the liquid particles against each other (shear forces) and pipe walls. Bernoulli’s equation is used to obtain the characteristic curve of a system. In general, the pressure losses appear along the pipeline (linear pressure drop) and in valves, bends and other piping fittings, which are called local pressure losses.

The rugosity of contact surface of the selected pipeline is approximately equal to 0.02 mm (for polyethylene) and the pipe internal diameter out of the technical room is 0.300 m. In the Froyennes site, according to the Coolebrok-Prandtl relation, the head loss due to the losses in straight pipe will be 0.48 m (value at the maximum predicted flow rate). Local pressure drops have been estimated under 0.52 m for the diffusers, curved pipe fittings and valves. Moreover a straight pipe of length \( L \geq 2D_{\text{pipe}} \) should be fitted before the impeller to avoid non-uniform condition entry. The formation of swirling eddies on the water surface at the lower limit of submerged is caused by asymmetric flow into the suction pipe. The velocity distribution in the sump depends on many factors: shape of the sump, disposition of the suction pipes, vertical or axial pump and the way water is fed into the sump [8].

The two pipe inlets are equipped with fine grid to protect the pump, located in the technical room next to the lower reservoir. Three valves are needed to maintain accessibility to the devices and thus allow maintenance. Due to the presence of large and heavy equipment units, the powerhouse stability must be completely secured. The excavation work eliminates superficial weathered layer, leaving a sound rock foundation. The minimum distance between the water level in the lower reservoir and the end of the suction pipe is also important to avoid any undesired pre-swirl cavitation phenomena.

2.3. PaT Selection
A centrifugal pump takes care of the regular refill of the upper reservoir and of the generating process. A variable frequency driver (VFD) will be installed in order to allow the machine to rotate in both direction and at different speeds while preserving high efficiency.

Usually pump manufactures do not normally provide the characteristic curves of pumps in reverse operation. Therefore, establishing a correlation enabling the passage from the pump characteristics to the turbine characteristics is the main challenge in selecting PaT. The hydraulic behaviour of a pump when rotates as a turbine changes. Many researchers have presented theoretical and empirical relations to predict PaT characteristics at the BEP from the performance of the pump but the results predicted by these methods are not reliable for all pumps with different specific speeds and capacities [9].

3. Experimental setup
In order to measure the real behaviour and validate the efficiency prediction computations in turbine mode, the pump has to be monitored. Figure 2 shows a schematic layout of the machines and sensors located in the powerhouse. Static pressure and temperature transmitters are installed at the inlet and outlet of the pump. Other sensors record the water levels in the reservoirs to avoid flooding. An ultrasonic flow-meter will be installed on the penstock among 10 diameters upstream and downstream of straight pipe run. In order to calculate the mechanical and electrical efficiency separately a torque-meter is equipped on the motor-pump coupling. These outputs signals at 4-20 mA will be connected to a Labview control for real-time measurement acquisition. The set up is designed for flexibility, meaning that the outputs of the system can be regulated/adjusted, since Labview also controls the VFD and an electro-mechanic valve. Further signals are linked to the monitoring system to detach water leaks, overheating of the instrumentation and danger of ice formation in the pump volute.

Attention has to be paid to the starting and stopping of the pump to safeguard the motor against unintentional rotation in reverse direction. Moreover, such monitoring shall be carried out to avoid water hammer, which could have dangerous consequences on the integrity of the whole pipeline.
4. Performance prediction of the turbo-machinery

From the desired working conditions in GM, the methods are applied backwards to find the best suitable pump to use in reverse mode. The predicted ratio of the PaT head and the pump head is presented by the dimensionless parameter $h$, while $q$ represents the discharge ratio [10-11]. A comparison between different methods depicts a weak reliability in the pump selection (figure 3). However, the subgroups defined by the impeller diameter lead to a better match with the experimental tests available in literature [12]. For pumps between 0.250 and 0.300 m impeller diameter, which likely suit the requirements in Froyennes site, the following equations depending on the specific speed $n$ are found [11]:

$$h = 5.196 \cdot n^{-0.323}, \quad q = 3.1276 \cdot n^{-0.219}$$

According to the site data (Section 2) and linking to manufacturers catalogue, the following pump has been chosen: ICN200-250F, a centrifugal pump manufactured by Ensival-Moret.

A VFD is installed to regulate the rotation speed in pumping and in reverse mode: in general, pumps operating in reverse mode work with higher head and discharge at the same rotational speed. In order to use the same pump in turbine mode, its rotation speed has to been reduced properly. Moreover an adjustment of the speed is required due to the variation of the available head in PM and GM. Based on the affinity laws, a hill diagram can be estimated and allow the machine to work as close as possible to high efficiency at different working conditions (figure 4). Its predicted working conditions as pump and turbine are showed in table 1. In design, the methods provide a range of possible PaT performances and the VFD will assist us for the last tuning on site.

![Figure 2. Schematic layout of the technical room: pressure values are measured before and after the pump. The ultrasonic flowmeter can be directly clipped on the pipe and it is able to capture the flow rate in both directions. Fittings and diffuser are designed to avoid air pockets and to reduce local pressure losses.](image)

**Figure 3.** Comparison of the ratio $h$ and $q$ estimated by several methods [9].

**Figure 4.** Predicted PaT efficiency curve at variable rotation speed.
Table 1. Pump and PaT coupled with VFD working condition data

|                     | Rated pump | Rated PaT                  |
|---------------------|------------|----------------------------|
| Selected speed [rpm]| 1000       | 730                        | 580                        |
| Electric power [kW] | 10.5       | 7.5                        | 3.4                        |
| Predicted efficiency [%] | 82.6 | 73.7 | 73.2 |
| Flow rate [m³/h] | 289.9       | 372.9                      | 287                        |

5. Conclusion and future work
A reliable storage capacity can provide an opportunity to exploit renewable resources in collaboration with power grids, meeting the requirements for a more sustainable future. To design reliable power grids, which include both conventional and renewable energy plants, it is essential to propose proper storage systems with adequate capacities. This paper presents such a pilot project, for µ-PHES, located in Froyennes (Belgium). The model results of the simulator will be compared with the experimental results confirming the method adopted. A methodology presenting the different components required to install and characterize such set-up are presented. It allows to record the characteristic curves for the selected pump and provides the needed. This measurement database will be helpful to determine the accuracy of theoretical model for PaT. The results will validate performance modelling of a micro configuration carrying out optimization and relevant consideration on transient state on PaT coupled with VFD. This will be useful for the community and to help in design of µ-PHES sites.

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