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Low head pico hydro turbine selection using a multi-criteria analysis

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ABSTRACT

Turbine types suit specific ranges of head, flow rate and shaft speed and are usually categorised by specific speed. In the pico range, under 5 kW, the requirements are often different to that of larger scale turbines and qualitative requirements become more influential in selection. Pico hydro turbines can be applied beyond these conventional application domains, for example at reduced heads, by using non-traditional components such as low speed generators. This paper describes a method to select which turbine architecture is most appropriate for a low-head pico hydro specification using quantitative and qualitative analyses of 13 turbine system architectures found in the literature. Quantitative and qualitative selection criteria are determined from the particular requirements of the end user. The individual scores from this analysis are weighted based on the perceived relative importance of each of the criteria against the original specification and selects a turbine variant based on the total weighted score. This methodology is applied to an example of a remote site, low head and variable flow requirement, leading to the selection of a propeller turbine variant or single-jet Turgo turbine for this specification.

1. Introduction

There is a distinct link between poverty and access to modern energy [1]. With electricity, people are able to improve their productivity through the better use of their time, and so their income, which allows them to raise themselves out of poverty. Where electricity is not available many people use kerosene lamps for lighting. These lamps have health issues, pose significant safety risks, provide only a dim and inefficient light source, and can take a significant portion of the monthly income for a family [2]. In urban areas the percentage of the population with access to electricity is high, due to the low cost of connecting them to the grid. In rural locations, however, access is limited due to the high cost of extending grids to low density population centres [3]. Pico hydropower is able to provide rural electrification where grid extension is too costly and consumers have low incomes [4,5]. In a World Bank report it was shown that pico hydropower represented the cheapest opportunity for off-grid generation under 5 kW in 2005 and was projected to be at least 25% cheaper than the nearest alternative still after ten years [6].

The typical turbine solutions for these pico hydropower systems are either pumps as turbines (PAT) [7], locally made pelton wheels [8], mass manufactured propeller systems [9] or home made systems normally based on impulse turbines [10]. Selecting hydro turbines is traditionally based on the specific speed of the turbine, a pseudo non-dimensional parameter that includes head, output power and output shaft speed [11,12]. From this, the commonly used application domain for turbines is used to aid selection, as in Fig. 1, which has been compiled from [13–15]. There are alternatives such as the nomogram presented in [16], but still based on the same principle. This leads to the choice of Pelton and Turgo turbines at high heads, crossflow and radial (Francis) turbines at mid heads and propeller turbines and waterwheels at low heads. This is also reflected in the commercially available turbines for these heads. As can be seen in Fig. 1, the pico range, under 5 kW generation, appears to be sparsely covered by reported application domains. There are several commercially available pico hydro products at high, mid and low head, and these tend to follow the topology of the larger scale turbines. The low head sector of the market is dominated by propeller type turbines as shown by the three commercially available systems that are superimposed onto Fig. 1, images of which can be seen in Fig. 2. All of these turbines are propeller based in either closed flume, Fig. 2a, or open flume design, Fig. 2b and c, and are recommended to have draft tubes installed to increase the turbine efficiency.

The use of traditional 4- or 6-pole generators and direct generator–grid interfaces, as described in most literature such as [20] restricts the application domains for pico hydro turbines. For

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Nomenclature

D	Diameter of Archimedes Screw (m)
H	Head (m)
H_g	Gross Head (m)
H_{l1}	Head Loss due to Penstock (m)
H_{l2}	Head Loss due to Draft Tube (m)
H_{l3}	Head Loss due to Kinetic Energy of Outflow (m)
$Hl4$	Head Loss due to Water Entering Waterwheel (m)
H_{l5}	Head Loss due to Swirl of Water Exiting Waterwheel (m)
H_{l6}	Head Loss due to Friction of the Flow on the Water Bed for Undershot Waterwheel (m)
P	Power (W)
Q	Volume Flow Rate (m^3/s)
T	Torque (Nm)
g	Gravitational constant (m/s^2)
h_{l6}	Specific Head Loss due to Friction of the Flow on the Water Bed for Undershot Waterwheel
n	Geometrical factor for Archimedes Screw
r	Average Impact Radius (m)
Δv_w	Change in Whirl Velocity (m/s)
η	System Efficiency
ρ	Water Density (kg/m^3)
ω	Rotational Speed (rad/s)

example, the specific speed as defined in [16] for a turbine specification to produce 1 kW at between 1 and 3.5 m head with a 4- or 6-pole directly connected generator is 251–1800, suggesting a radial or axial flow reaction type turbine topology. However, introducing technologies such as low speed generators or inverter based grid interfaces generally extends a turbine's application domain, leading to other viable turbine solutions. Replacing the traditional 4- or 6-pole generator with a low speed generator operating at 200 rpm such as [21], the specific speed is now 50–240. This greatly expands the choice of turbines available to include Crossflow, Turgo and multiple-jet Pelton turbines. In addition to these selection criteria, the requirements on a pico hydro turbine tend to be different to those of a larger scale turbine; pico hydro generators require off-the-shelf solution as a unique product for each site would be too expensive for the target users. They may be located in remote locations several hours walk from

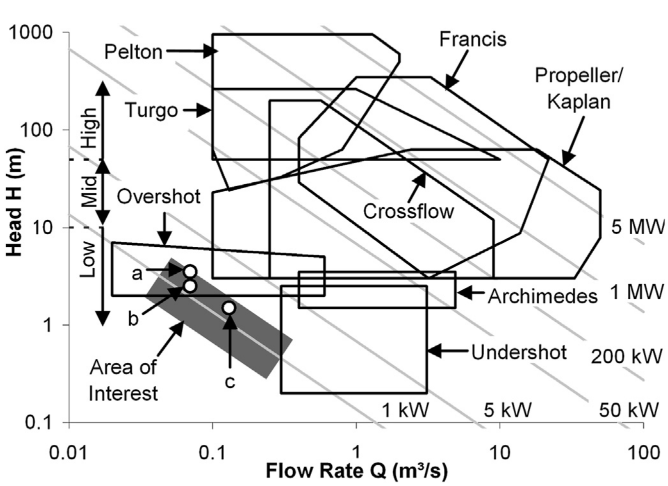

Fig. 1. Typical turbine application range chart adapted from data in [13–15] populated with three commercially available low head pico hydropower systems: a. Nepal Hydro and Electric Ltd. PT1-Mk2 [17], b. ECO-Axial ZD [18] c. Powerpal MHG-1000LH [19].

the nearest road and have no skilled labour locally to operate and maintain the system. The application domain selection method for turbines does not take these more qualitative factors into account. The methodology proposed in this paper is used to select a pico hydro turbine for a low head specification using both quantitative and qualitative criteria.

2. Turbine selection methodology

In the design of complex systems, the evaluation and selection of candidate solutions can be facilitated using a Pugh Matrix [22,23] in the early stages of a project. This approach can be subjective and still necessitates a great deal of design analysis and detailed design work in order to create an optimal solution. The traditional approach to concept design has been the subject of a great deal of adaptation and improvement recently through reviewing its application on a number of electro-mechanical machine research projects. The motivation is to demonstrate that you can get closer to the final design sooner by placing more effort on a knowledge rich and systematic approach, thereby reduce design iterations and mitigating costly design changes; helping deliver novel and efficient solutions more rapidly [24]. Specifically, concept selection may be enhanced by the inclusion of quantitative performance metrics predicted using simple physics-based models, alongside the more traditional qualitative criteria derived from the specification. These performance metrics provide a measureable and tangible way of guiding and tracking overall design performance and evolution against targets or benchmarks without committing a large proportion of development costs in prototype testing, and provide crucial decision-making information. The use of a multi-criteria selection methodology has been discussed and developed to identify the appropriate renewable energy sources for a site [25,26], however neither of these go into the more detailed selection or design of the renewable source.

A flow chart of the methodology derived for pico hydro turbine selection is shown below in Fig. 3. Each block in this chart is discussed in more detail in Sections 2.1–2.8.

2.1. Specification

Each turbine system will have a set of requirements and specification, which is developed from discussions with the project stakeholders. This will include either site conditions, such as head and flow rate, or output power requirements. There will be environmental requirements, for example the site may be in an inaccessible location, be subject to extremes in temperature or have to comply with fishery regulations. The turbine may be able to have regular maintenance checks from an onsite operator, or it may be required to be operated remotely and therefore should require minimal maintenance and have a high reliability.

2.2. Selection criteria

Using the specification and derived requirements, a set of selection criteria can then be developed. Table 1 shows some of the possible selection criteria that could be used, and divides them up into quantitative and qualitative criteria. The assignments are not definitive, as the some criteria may be either quantitative or qualitative.

2.3. Quantitative analysis

Basic fluid flow equations are used to derive simple performance characteristics about the turbine option for the quantitative analysis. The performance variables are turbine power P, overall turbine system efficiency η, flow rate Q, and gross head H_g, two of which