Features for Optimising a Pico Hydro System for Telecommunications Base Stations in Developing Countries

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Abstract

Note: this paper considers a subset of the work discussed in “Design and Demonstration of a Pico Hydropower Generation System for Telecommunications Base Stations”. This original report has a far greater scope than can be expressed here, particularly regarding system models and the economic analysis.

As telecommunications network operators establish mobile services in emerging markets, particularly in the developing world, telecommunications infrastructure is required in increasingly remote areas. The viability of pico-hydropower (<5kW) technology as a reliable source of power for base transceiver stations is explored.

An assessment of existing low head systems in relation to design criteria indicates the most suitable option for further development is the reaction-type siphon turbine. Pico hydro systems require alternative design approaches to larger systems, and a number of different design aspects, particular to the pico-hydro siphon turbine, are analysed. This paper covers highlights from the original work, which may be of interest to others pursuing pico-hydro solutions.

Keywords

Hydropower, pico hydro, hydropower, developing countries, decentralised, energy, telecommunications

1. Introduction

The last decade has seen rapid growth in mobile phone telecommunications and it is expected that globally an additional 1 billion subscribers will be added between 1997 and 2012 (1). As network operators establish mobile services in the emerging markets, particularly in the developing world, telecommunications infrastructure is required in increasingly remote areas. Base stations, used to connect mobile phones, require a continuous power supply averaging approximately 1.5kW in order to service call traffic and generate revenue for the network operator.

When there is no access to a local electricity grid, or the grid is unsuitable, diesel generators are a common alternative or back-up to a grid connection. However, as well as being an attractive target to theft the need for constant re-fuelling becomes increasingly expensive in more remote locations (2). Technological advances have made renewable power supply an increasingly economic solution. Solar and wind power are already at the point where they are considered as the primary power source for base station sites (1). However, frequent fluctuations in solar and wind conditions can lead to the requirement for substantial investment in energy storage such as batteries.

For sites with close proximity to a river and with regular rainfall, hydropower has the potential to provide a more consistent power supply and reduce energy storage requirements. Although hydropower systems have relatively high capital costs, the life in service is long due to steady operation without high thermal or mechanical stresses. Consequently pico hydropower systems can, in certain applications, incur lower long term costs per kilowatt than diesel, wind or solar generation (Full Report, Appendix A.1 ).
2. Current Pico Hydropower Technology

Pico hydropower refers to systems with a power capacity of less than 5kW. In general, hydropower can be divided into two categories: systems operating with a large difference in elevation between an upstream headwater and downstream tailwater (“high head”); and systems operating with a low difference in elevation (“low head”). At the pico hydropower scale, high head systems are a relatively established technology with examples such as the Pelton wheel achieving efficiencies as high as 90% (4). Although there are many sites suitable for the application of low head systems, the technology is less mature, indicated by the huge variety in design and absence of a dominant technology; and an external appraisal of existing pico hydropower technology concluded that much of the claimed performance data could not be corroborated (3).

2.1 The Siphon Turbine

The siphon turbine requires installation over a dam and discharges flow through ductwork operating under siphonic action. This design is classed as a “reaction” turbine, where the runner exploits a pressure differential created by the net elevation head between the headwater and tailwater. Utilisation of a dam means the siphon turbine can provide power at much lower flow rates than other run-of-river technologies, thereby reducing the requirement for energy back-up during severe dry seasons. The siphon configuration negates a requirement for a seal between the weir structure and the ductwork; it serves to protect the electrical system from flood damage; and reduces the requirement for on-site excavation works (4).

This paper investigates potential methods to optimise the siphon turbine design, and analyses its feasibility as an alternative to current technologies. A scale model was designed and built in Bristol University’s Hydraulic Laboratories, and was used to perform experimentation on dam design, trash racks, ductwork and runner design and efficiency, and generator performance. The experimental work was supported by interdisciplinary research.

3. Specification

One of the main stakeholders of the project is an international telecommunications company who have an interest in implementing hydropower technology to power their base transceiver stations. Key criteria in designing this system included:

- Total electrical power provided by the pico hydropower system to be a constant 1.5kW.
- The system shall operate at a net elevation head of less than 2m (the same range as commercially available “ultra low head” technology”.
- It shall be possible for most of the installation to be carried out by local low-skilled labour, with civil works shall be kept to a minimum (maximum of four tonnes of poured concrete).
- The capital cost of the system should be minimised, with income generated to recover the cost of the system within three years.

4. Water Intake

In order to drive flow through the siphon turbine, a difference between inlet and outlet water levels is required. This provided by a small dam. The design of the dam depends on the local ground conditions and aims to keep the difference between inlet and outlet water levels as constant as possible over the flows that are expected in the river. These are calculated statistically from recorded river or rain data if available, otherwise the site’s plant life can provide information about past flow conditions. The difference in water levels created by the dam causes pressure on the dam, which must be resisted structurally, and also causes flow through the surrounding soil, which can remove it, undermining foundations. Foundations can also be threatened by the removal of soil due to water flowing over the dam or through the siphon. Site specific design is required due to changes in ground conditions and river flows between sites.
4.1 Estimating Expected River Flows for Dam Design using Site Biology

River flow is supplied by rainfall and stored water (groundwater, ice or snow), and varies naturally. The quantity and variation of flow affects the design of the weir: low flows may threaten power generation and therefore the viability of a site, high flows can flood the weir. Throughout these flows the weir needs to create a stable net elevation head. Flows in a river cannot be forecast generally the history of flow at a site is used to statistically predict the flow. When no flow data are available, a new approach has been suggested to use the site’s biology.

The biology of a site can yield information about the variation of flows: the presence of certain forms of life is indicative of past conditions. Plants are a good source of information because of their longevity, immobility and dependence on water. Water flow varies through different soils which can also store different amounts of water, so the river’s response to rainfall depends on the properties of the catchment. Although biologists are able to offer anecdotal evidence of which plants require variable or constant flows, little work has been done to collect this into a coherent body of information. A formal classification of the soil moisture that a plant needs to grow is the “Ellenberg Value F” which ranges from 1 (extremely dry) to 12 (submerged) [5].

Plants with high values of moisture indicate that flow varies little. For example, trees that require a near-constant water supply (high moisture) are certain kinds of “Large Broad Leaved Deciduous Trees” (6) such as some willows since their leaves have a large rate of evaporation. If these are found on site, this is a good indicator that the flow is regular.

Table 1 shows that evidence from experts and the Ellenberg Value F correlate well. Plants requiring moisture of 6 or above are good indicators of often wet conditions. Some plants such as Eucalyptus trees have adapted to survive with irregular flow conditions, other plants known as “phreatophytes” have deep roots and draw water up from a water table that may be deeper than a river. When only these kinds of plants are found on site, this indicates the river often has low flows. Lack of vegetation is an indicator of very irregular flows, although ground or environmental conditions may be preventing growth. Further work is required to consolidate the ideas proposed into a tool: ideally starting with hydrological data, the vegetation found in different catchments should be correlated with the variation of river flow.

4.2 Dam Design – Exploiting Supercritical Flow to Increase Net Head

A weir creates the difference in water levels (the “net elevation head”) required to cause flow through the siphon turbine. The net elevation head that can be achieved depends both on the characteristics of the dam and on the river flow and dictates the scaling of the siphon required to meet the power specification. It is desirable to have a stable net elevation head for the river flows expected on site, so that the ductwork and runner can be optimised to operate a fixed condition.

As the siphon turbine operates over a net elevation head (difference between up and downstream water levels), both the downstream and upstream water levels need to be considered. Water flowing over the weir when it is not flooded creates a hydraulic jump. If the jump can be designed to be downstream of the weir, this can be used to locally reduce the downstream water level.

In order to increase the net elevation head over a given weir, supercritical flow can be exploited. A weir which is not flooded has supercritical flow over the crest (7), which is followed by a hydraulic jump. Supercritical flow has increased velocity (and therefore decreased depth) and describes a condition where the inertial forces dominate the gravitational forces. When supercritical meets subcritical flow such as the normal downstream flow, a hydraulic jump occurs (8), whose characteristics vary with velocity. Designing a weir so the hydraulic is sufficiently downstream of the siphon outlet will result in a greater net elevation head that can be exploited (Full Report, Appendix A.8). A small structure at the end of the weir is used to induce the jump. If the position of the jump is not controlled and occurs over soil, it can remove it and damage the foundations of the dam (Full Report, Failure Mode: Scour, Section 6.4). Further work is required to study the

<table>
<thead>
<tr>
<th>Common Name</th>
<th>Anecdotal Evidence from Experts</th>
<th>Ellenberg F Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alder</td>
<td>Good Indicator of Wet conditions</td>
<td>[24]</td>
</tr>
<tr>
<td>Willow</td>
<td>Indicator of Wet conditions</td>
<td>[22]</td>
</tr>
<tr>
<td>Sesquile Oak</td>
<td>Often Wetter Conditions</td>
<td>6</td>
</tr>
<tr>
<td>Other Oak (e.g. English)</td>
<td>Often Dryer Conditions</td>
<td>[24]</td>
</tr>
<tr>
<td>Silver Birch</td>
<td>Found in Dry Soils</td>
<td>[21]</td>
</tr>
<tr>
<td>Downy Birch</td>
<td>Found in Wetter Soils</td>
<td>7</td>
</tr>
</tbody>
</table>

Table 1: Assessment of Tree in the UK, F values from PLANTATT Database

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local effects of the interaction between the siphon outlet and supercritical flow. Furthermore, the optimal weir profile to achieve the correct velocity of flow needs to be investigated for this application.

5. Turbine Ductwork

The siphon turbine ductwork is the conduit that transfers water power from the river to the turbine runner. Consequently, the water power available to the runner and therefore the electrical power of the whole system is dependent on ductwork efficiency.

5.1 Optimising Ductwork Size and Design

Water power available to the runner is dependent on two key factors. Firstly, flow rate through the ductwork and secondly, ductwork head losses. A greater flow rate through the system means that more power is available, but higher water velocities also increase ductwork head losses, and the efficiency of the siphon turbine ductwork in transferring net water power across the system into water power available to the runner is maximised by reducing ductwork head losses. Reducing head losses also increases the maximum power point flow rate, resulting in greater shaft speeds, therefore greater generator voltage, which reduces transmission losses.

The practical implications are that for a given power output requirement the mean ductwork area can be reduced, thereby reducing material costs and facilitating ease of installation. These results were used to design a ductwork sizing rule. Measures to reduce head losses at the inlet and draft tube were also tested and the effect of system interactions between the bend and the draft tube are explored.

5.2 Trash Screen Cleaning – Design Proposal for a Passive Control System

In order to prevent objectionably large debris from entering the ductwork of a hydropower system it is usual to install a trash screen across the approaching flow. Water flowing through a clean trash rack incurs a relatively small head loss; however, a build-up of debris can sustain major losses, to the point where flow almost ceases completely. Effective cleaning and maintenance of trash screens is a major issue for hydropower installations and can be expected to be particularly problematic for remote locations, where an autonomous screen cleaning system is required to ensure continuous power supply without regular maintenance inspections. A number of screen cleaning devices exist; a common choice for small scale, low head hydropower is the hydraulic trash rake system, which mimics the physical motion of manual raking. This system is durable and provides reliable operation; however, the requirements for civil works are large. A fixed system with a rake head 2.5m in length costs approximately £9000 (Segen Hydropower).

Aiming to improve on current methods for trash screen cleaning, a passive control screen cleaning system was designed using principals of operation unique to the siphon turbine through installing a trash screen across the horizontal inlet orifice. Sub atmospheric pressure in the siphon crest causes air to be ingested through an open air valve. Air is entrained in the flow and expelled from the system. The valve is set such that the rate of air ingestion is equal to the rate of expulsion when the trash screen is clear. As trash builds-up the drop in head across the screen increases, causing the flow rate to slow down and the rate of air entrainment to decrease. The result is that the air pressure in the crest increases and the crest height decreases. At some point, siphon action fails and the body of water below the crest and above the headwater flows backwards down the inlet purging the trash screen.

Preliminary testing on the siphon turbine model provided proof of concept; however, the screen is not completely purged with regularity. Furthermore, when half-blocked the trash rack installed across the inlet orifice incurs a significant reduction in performance compared to the screen installed across the flume cross-section.

6. Turbine Runner Design and Runner Control Systems
The turbine runner must convert as much power available in the flow as possible to mechanical shaft power. The design of the runner is dictated by the flow rates that are expected through the turbine, and its blade configuration must be designed for the expected operating conditions. Through the use of optimal blade angles, the runner should also be designed to operate at a fast design speed as possible to this will enable the generator to run more efficiently. In addition, if the runner speed is fast enough, then it can be connected directly to the generator rather than using a gearing system. As gearing systems can have very high efficiencies (up to 98%), the power output will not increase greatly, however eliminating gearing from the system will increase system reliability – a priority for a remote turbine. Given that flow rates are likely to vary, the off-design runner performance is important. Control methods may be used to maximise efficiency in varying flow conditions, but as these will increase the expense and complexity of the system, the control requirements must be balanced against the improvement in power output.

6.1 Simplified Turbine Blade Design
Commercially designed axial flow hydraulic turbines usually use aerofoil-shaped runner blades as these are designed to optimise lift and minimise drag. However, such shapes require manufacturing techniques and skills that are not easily found in developing countries. In addition, as smaller hydraulic turbines operate at lower Reynolds numbers (the ratio of inertial forces to viscous forces) than larger systems, and at low Reynolds numbers, the advantages of profiled aerofoils compared to flat sheets diminish, and their lift and drag coefficients begin to resemble those of ideal flat plates. Therefore, whilst using aerofoil profiles provides an efficiency advantage in larger systems, flat and cambered plates can be used with a very small impact on the efficiency.

Experimental results showed that, at low Reynolds numbers, cambered plates do have maximum lift coefficients equivalent to those of profiled aerofoils. However, as aerofoils can have a higher lift coefficient over a wider angle of attack, and at a greater angle of attack, they will have a slightly faster rotational speed at maximum power point, and may also perform at a higher efficiency over a range of heads.

6.2 Control Methods for the Runner
The civil works aim to supply a stable head to the turbine, but as some fluctuations are unavoidable (Section 4), the turbine will be required to operate at a range of head heights. Therefore, the turbine runner will need to operate efficiently at a range of flow velocities. Two methods were considered - variable pitch blades for a constant speed runner, and maximum power point tracking for a constant-pitch runner.

Varying the pitch of the runner blades enables the optimum angle of attack to be maintained with varying inlet water velocity, and variable pitch blade runners are used in a wide variety of hydropower turbines to optimise the blade angle depending on the inlet water velocity. Using the variable pitch blade method allows the generator to always run at a constant speed, enabling it to operate more efficiently (Full Report, Section 13). However, the moving parts required in the pitch-change mechanism will greatly increase the cost of the runner, its probability of breakage, and repairability. If the turbine used guide vanes, then the guide vane angle, rather than the blade pitch angle, could be adjusted to add the appropriate swirl angle to the inlet water. Adjustable guide vanes would also be less complex than variable pitch blades as the mechanism does not have to be solely contained in the small volume of the runner hub. However, a cheaper alternative to variable pitch blades would be to manufacture two or three constant-pitch runners, each set at a different blade angle, which would operate at the same speed but at different flow rates within the same turbine casing. These could be swapped in and out of the turbine during periods of high or low flow (or according to wet or dry seasons), to keep efficiencies high.

The maximum power point tracking optimisation method uses a variable opposing torque from the electrical generator in order to keep the runner operating at its maximum speed for a varying flow input. The maximum power point tracking method is, mechanically, a far simpler control option as the runner speed can be changed through the application of the variable generator torque. However, the change in speeds could lead to inefficiencies in the generator (Full Report, Section 13). In practice, most commercial turbines utilise an electronic power point tracking system, with larger turbines (>5kW) more likely to use pitch control mechanisms.

7. Selection of an Optimum Permanent Magnet Generator
A generator converts mechanical shaft power into electrical power, which is transmitted through cables to the base transceiver station. As indicated in several hydro system design guides, the generator of choice for off-grid pico-hydro systems is generally considered to be the induction generator (9). Their robustness has led to their industrial use as motors in every part of the world; resulting in their wide-spread availability and relatively low cost. Selection of an induction generator was carried out on the basis of its power rating and efficiency and its operating conditions are adjusted for optimum system integration after purchase through careful sizing of low-cost capacitors in the rotor circuit (9).

Recent research has challenged the use of induction generators in some pico-hydro systems, and proposed that permanent magnet generators may be a more suitable option (10). It was argued that permanent magnet generators are more efficient than induction generators when used in off-grid applications, but are generally far more expensive. At power ratings of around 1kW and below however, the research shows that either option is available at comparable prices. Furthermore, permanent magnet generators can operate at variable speeds; allowing the possibility of improving the system’s part-load efficiency. The characteristics of a permanent magnet generator are difficult to modify once specified. Unlike the simple addition of a cheap capacitor these characteristics are also likely to define its capital cost. Therefore selection of the best value generator is a complex process on which no guidance is available in the literature.
8. **Business Case**

The commercial viability of the siphon turbine is dependent on the capital costs and running costs, as well as the revenue generated by the network provider through call traffic. In order to demonstrate the trade-offs between end-to-end efficiency and system cost, a business case explored the rationale for investment in the siphon turbine over existing technologies for an example site in Scardroy, Northern Scotland (site chosen as suitable data was available). Preliminary cost quotations and a system simulation revealed a siphon turbine incorporating a 1.5m weir and a runner diameter of 0.29m could supply a required 1.5kW at a total cost over three years of £18,902 making it the most commercially viable power supply option.

9. **Conclusions, Recommendations, and Further Work**

This work demonstrated that a pico hydro system does, on an appropriate site, have the potential to generate power at a lower cost than the current alternatives. However, in practice, the “plug and play” ease of installation of diesel generators, solar panels and wind turbines, mean that pico hydropower for use in a telecommunications application (where convenience has a high priority even where there are potential economic savings per site) is still not competitive overall.

Since completion of this project, further work has begun on this area as a PhD at the University of Bristol. This PhD is focussing on the potential to extend pico hydropower in the form of off-the-shelf units, with minimal civil works to keep the cost low. The research is into using multiple low-head units to create an off-grid network, and reducing the cost by volume manufacturing this unit. If the head or flow available at the site is greater than that required by the unit, then multiple units can be used. These can then be connected to an off-grid network. Multiple sites can also be connected to the network. The main issues of focus are generating units that can work at a range of heads and flows, connecting multiple generators onto an off-grid network, controlling voltage and frequency of grid, whilst keeping the cost per kW of the system affordable.

An example business model of this application would involve a village or individual buying one or two units to start income generation activities in their rural area. Through the income generation activities, capital would be raised to buy further units, and so able to provide more power to electrifying the village and providing further income generation opportunities.
10. Acknowledgements
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