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Fix Speed Pump-Turbine with Incorporated Flow Control using Flapping Blade Mechanism

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Abstract

This paper proposes a new mechanism to be introduced to the Francis turbine runner which allows for flow control when it is working as a pump at the Pump Hydro Electric Storage (PHES) plant. The design will start off from an existing turbine runner. Some modification will be made to allow the blade tip to be flapped, enabling the turbine to change the water flow that it is pumping whilst maintaining an acceptable hydraulic efficiency when operating as a pump. At the same time the runner can still achieve high efficiency as a turbine. All the results are obtained from Computational Fluid Dynamic (CFD) simulation thus only hydraulic efficiency of the runner will be discussed. The flow of the pump changes from 75 Kg/s to 111 Kg/s due to the effect of the mechanism. The round trip hydraulic efficiency after the modification is between 81% - 82% which is comparable to the standard of PHES hydraulic efficiency.

Keywords: Pump Turbine, Francis Turbine, Centrifugal Pump, CFD, Flow Control

INTRODUCTION

Providing electricity to isolated and rural areas have always being a challenge especially when connecting the area with main electric grid which seems physically and financially impossible. The easiest and most popular method is by relying on fossil fuel but it is harmful to the environment and getting the fuel is a problem as well. Realising this issue, the focus on powering the rural area with renewable energy has risen significantly[1]. There have been many researches which have tried using green energy such as solar, wind and hydropower. For example Ashourian et al [2] have conducted a study on managing renewable energy on island resorts in Malaysia in order to avoid fossil fuel dependency. This paper managed to prove that it is possible to power up a village at selected resort island using both solar and wind energy with battery as a backup. It is well known fact that depending on solar and wind energy alone to power up an isolated area is impossible due to its output intermittent behaviour. Therefore to compensate this issue, a backup energy system will be required to cover when the solar and wind energy are inadequate. Besides solar and wind energy, hydropower is another option to be implemented for rural area but hydropower is only available for certain area that fulfilled some criteria so it is not available for every places.

Since fossil fuel is not an option as the backup energy system for a full green energy supply, it is common to see batteries, flywheels, and ultra-capacitors used in isolated area sites to store moderate amount of energy and distribute it when solar and wind energy is not available [3]. However, in the case of isolated area, there are some issues related to these energy storage options such as relatively short life span for which it needs to be replaced after a certain period of time [4]. Logistic and cost will also become an issue if the backup system need to be replaced frequently. Besides that, since these options will only be able to store a moderate amount of total energy, the duration of which it can replace the main energy supply will be limited, thus risking the isolated area to not having electricity when both main and backup energy supply is not available. The ideal case is the storage energy system will be able to supply energy for at least a few days.

To address this issue, Pumped Hydro Electric Storage (PHES) was proposed as a storage system for isolated area [5]. Currently, PHES is an established technology in storing electricity since 1960s when nuclear energy was started to be widely used. Although it is a proven technology for storing energy, PHES has never been used for small scale storage system. Currently the site that has adopted PHES has an output in the order of 100s of Mwatt [3]. This is mainly because of a high initial capital. Therefore at big sites, the high cost can be absorbed by its economy of scale. According to a research by Ma et al [6], even though using PHES as the storage system has a high initial capital, it is more cost effective than lead-acid batteries and conventional batteries in the long run.

Typical PHES plants consist of two reservoirs; one is lower than the other and the two reservoirs are connected by a pipe called a penstock. The turbine will be closer with the lower reservoir and is responsible to generate electricity when the water is released from upper reservoir and consume electricity to pump back the water to upper reservoir when there is excess electricity. For isolated area, normally the electricity demand is not too high as the population density is low. Therefore closed-loop or semi-open PHES types are sufficient depending on site suitability. Closed-loop PHES site means both reservoir is not part of water body and semi-open means only one reservoir is part of water body. By using these two types, the impact of the project to the river ecosystem will be minimal [7].

There are three types of machine that current PHES plants are using; the first one has a separate pump and turbine, the second has fixed speed modular machine and last one has varied speed modular machine using variable speed drive [8]. Using two separate machines are costly and will not be suitable for small and isolated areas. Although using variable speed drive has various advantages compared to fix speed modular machine, it is very costly and not many sites are adopting the technology [9]. Therefore it is not suitable to be used at small site and isolated area. As of now, there are only 8GW out of 120GW PHES site are using variable speed drive worldwide [10].

As mentioned in the previous paragraph, the PHES site types that are suitable for isolated areas are either closed-loop or semi-open. By using fix speed modular machine at this site, it means that at any time, the water flow that the machine pumps will be constant. Although it might be fine for a site that is connected to the national grid, this can be an issue for an isolated grid. For example, after a few days using the PHES to generate electricity, the upper reservoir will only be left with a small amount of water and this will not be adequate to continue supplying electricity for a few more days if the main electricity supply is not available after that. Therefore it is better if the machine can increase the water flow it can pump at that time so that the reservoir can be refilled over a shorter period of time. For the PHES application, this feature can be achieved by using variable speed drive but as mentioned earlier, it is not suitable to be used since it is very expensive.

In section 2 of this paper, the flapping blade mechanism is introduced to the turbine's runner which will enabled the machine to change the water flow that it is pumping at fixed rotating speed. In section 3, the site specification for the research is proposed because the design of the hydro turbine is site specific. Then the computational setup for the simulation is discussed. In section 4, the results from the simulation are presented and discussed. These include the mesh discretization studies and the runner performance in both turbine and pump modes. The paper is concluded in section 5.

FLAPPING MECHANISM

In concept, Francis turbine and centrifugal pump is a same machine except the direction of the water flow and the direction of the rotation are inversed. However there are some differences between the machines that make them not interchangeable. The efficiency of the machine is dependent on how good they are at extracting the energy from the water as a turbine or inserting energy to the water as a pump. The major factor that will determine the efficiency is the angle of the runner blade of the machine. Even though the runner shape of the pump and turbine are similar, the calculations to obtain the inlet and outlet angle are different. Therefore if the turbine has the correct angle with high efficiency, the same machine may have a lower efficiency when it is operating as a pump. Conventionally, PHES sites that is using a modular machine will require a very extensive design process in order to obtain acceptable efficiency for both modes [11]. By adopting flapping blade mechanism into the runner as shown in Fig. 1, the angle of the runner can be adjusted to suit which mode its' operating on.

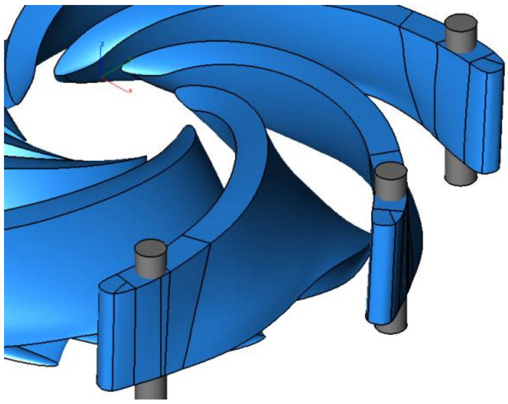

Figure 1: Overview of the runner together with flapping mechanism

Design, Meshing and Numerical Method

The runner design are site specific therefore the head, flow, power requirement, and in the case of pump-turbine, the power that the area needed when the machine generating electricity are to be determined as a first step. The site specifications are shown in Table I.

Table 1: The Parameters of the Proposed Site

Parameter	Value
Natural head	30 meter
Water Flow	90 kg/s
Pipe material	HDPE
Pipe length	150 meter
Pipe size	12 inch
Power output	25 kwatt

By using the all the information from Table I, the total dynamic head (TDH) of the site can be calculated. This represent the minimum total head output that need to be produced by the pump for that site. A simple measurement of TDH can be calculated by using (1).

$$\text{TDH} = \text{Elevation Head} + \text{Friction Head Loss} \quad (1)$$

Here, Elevation head is the total elevation between upper and lower reservoir which is 30 meter. The friction head loss is the loss from the friction due to penstock and fittings. This includes the valve and bending. In this research, only loss from the friction of the penstock was included because the fittings will only be available from detailed design of civil work of the site which is not included in this research scope. On some cases, other parameters need to be added to TDH formula such as pressure head and static suction lift. These two parameters were not included in this research. To calculate friction head loss, Hazen-Williams formula as shown at (2) was used.

$$h_f = \left(\frac{0.002083L}{d^{4.8655}}\right)\left(\frac{100Q}{C}\right)^{1.85} \quad (2)$$

where h_f is Friction head loss (feet), L is Pipe length (feet), d is Pipe inside diameter (inch), Q is Flow (gal/min), C is Hazen-Williams Friction Factor (dimensionless).

The flows that were tested are between 40 kg/s to 110 kg/s and the Hazen-Williams Friction factor for HDPE pipe is 150. Therefore the friction head losses were between 0.36 m to 0.82 m as shown at Table II.

Table II: Penstock Friction Caltulation

Flow (kg/s)	Friction head Loss (meter)	Total Dynamic Head (meter)
40	0.13	30.13
50	0.19	30.19
60	0.27	30.27
70	0.36	30.36
80	0.46	30.46
90	0.57	30.57
100	0.69	30.69
110	0.82	30.82

All the parameters are then inserted into in-house code to produce a runner design. The outer diameter of the runner is 324mm and the runner has 8 blades in total. The runner will rotates at 1500 rpm during both turbine and pump mode. The runner that is produced by the in-house code will then be modified to accommodate a small shaft at every blade and the shaft is located at pitch circle diameter (PCD) of 270 mm.

The computational domain of the mesh will consist of three regions; draft tube, runner, and vaneless area. Special attention was given to the mesh at boundary layer to ensure the turbulence model can do the calculation properly. The CFD simulation was done with ANSYS CFX using steady-state solver method. At the inlet of the pump simulation, it was assumed the total pressure will be 1 atm and the outlet of the simulation, mass flow rate was implied. For turbine simulation, the inlet of the simulation is the design head and the outlet is fixed gauge pressure.

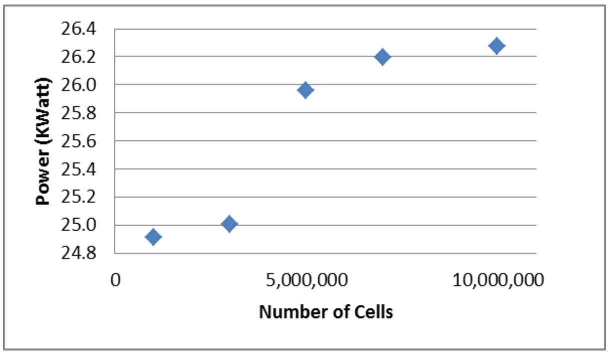

Figure 2: Mesh discretization study plot for power generated

RESULT

From mesh discretization study as shown in Fig. 2, there is an increase of power generated when the number of cell is increased from approximately 1 – 9 million. The study was made by running the simulation in turbine mode with head of 30 meter, 5 degree flow angle tangentially and 1500 rpm rotation. The result reached the asymptotic range at around 9 million cell meshes.

Since the objective of this paper focusing on the effect of the flapping blade to the runner performance in pump mode, the runner design was not further optimized. Even without further optimization, its performance can still be considered good with 94.6% hydraulic efficiency. The power generated from the turbine at BEP was 26.5 kwatt from 28 kWatt available. This amount of power is sufficient to power up the isolated area according to these research criteria.

Fig. 3 and Fig. 4 represent the performance of the runner when it was operating in pump mode. Fig. 3 represents the pattern of the pump output head against the flow. The pattern of the graph in Fig. 3 moved upwards when the angle of the flap increased. This means that the total head output of the pump improved when the angle of the flap increased. Fig. 4 represents the pump output head against the hydraulic efficiency of the pump. Whilst the total head output of the pump improved, the overall hydraulic efficiency of the pump graph does not change too much when the flapping angles were increased as shown in Fig. 4. This means that the overall performances of the pump which are the flow and the head output improves while retaining the overall efficiency performance.

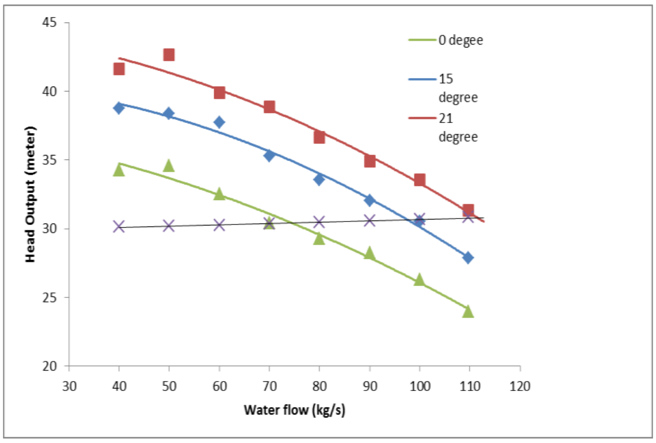

Figure 3: Pump performance graph for head output

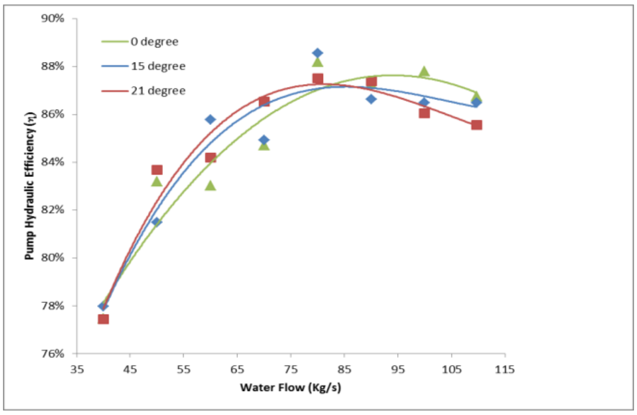

Figure 4: Pump hydraulic efficiency graph

However for a specific site, the total head output is predetermined, so the site water flow and efficiency of the pump can be measured by using the pump performance graph. In the Fig. 3, the water flow can be obtained by taking the value that is intersected between the TDH line and the graph line. By using that water flow value, the site hydraulic efficiency can be determined by referring to Fig. 4. The proposed site specific performances are shown in Table III.

Table III: Summary of the Result Based On Proposed Site

Flapping angle (degree)	TDH (Meter)	Water Flow (kg/s)	Hydraulic Efficiency	Power Consumption (kWatt)
0	30.4	75	87.0%	26
15	30.7	98	86.5%	34.5
21	30.8	111	85.6%	40

Based on Table III, when the flapping angle is increased, the water flow is also increased but the hydraulic efficiency of the pump decreased. The increase of water flow also means the power consumed by the pump is also increased. This means that while more water can be pumped to the higher reservoir by increasing the flapping angle, the hydraulic efficiency of the pump will reduced and the power needed is higher. Depending on the situations, this trade-off can be worth to take. For example, as described previously, there might be a time where it is desirable to be able to increase the water flow that is pumped in order to fill the upper reservoir as soon as possible. Besides, there is also a situation where there are abundant un-use electricity from uncontrollable source such as solar and wind power, those extra electricity can be used to pump more water by increasing the flapping angle of the pump.

Since there are two hydraulic efficiency figures for the same runner which are pump, η_p and turbine, η_t hydraulic efficiency, the two efficiencies can be combined into one value which is called round-trip η_T efficiency. The round-trip efficiency can be calculated using (3). The round-trip hydraulic efficiency for the runner is 80.98% - 82.3%. This value is acceptable because the existing PHES pump-turbine efficiencies are between 75% - 85% [12].

$$\eta_T = \eta_p \eta_t \tag{3}$$

There is no optimization work has been done to the runner design in both turbine and pump mode since it is not in the scope of the research. There is a possibility the hydraulic efficiency can be improved further if some optimization work is done to the runner design.

CONCLUSION

The design of a Francis turbine runner with flapping blade was presented. The design was tested using CFD simulations and the result shows that the design was able to increase the water flow when the flapping angle is increased. Although the hydraulic efficiency has a slight reduction when the flapping angle is increased, the round-trip efficiency shows that it is still in the range of acceptable efficiency

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