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Investigation on pump as turbine (PAT) technical aspects for micro hydropower schemes: A state-of-the-art review

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ABSTRACT

Energy is unarguably the key factor for today's economic and social development within nations. Electricity as one of many energy forms is a critical input to developing countries in the struggle to the national self-satisfaction in all domains. Rural electricity supply involved institutions have recently recommended the pump as turbine (PAT)-based micro hydropower plant (MHP) schemes for remote off-grid electrification, mostly from their economic advantages. However, from different published research findings, PAT-based MHP is not only simple and economically feasible, but has presented bottlenecks in the move to its full understanding. Moreover, compared to other clean energy technologies, PAT technology has not found much literature in academic published researches, thus contributing to its limited understanding within the community. Therefore, the PAT literature availability is one way to level up its understanding, which can be helpful to academic and professional communities. In the present study, a state-of-the-art review on the two most challenging PAT aspects, namely PAT performance prediction and PAT flow stability aspects are presented. In the presented literature, the selected energy sources history leading to the actual MHP global adoption was first briefly explained, followed by an intensive literature on PAT operations, where details about PAT selection and performance prediction were provided. Finally, the PAT flow stability aspects where pump-turbine S-shape and Saddle-type characteristics constitute the main focus, were discussed. It is worth an attention to mention that the words “pump-turbine”, “Pump as turbine”, and “reversible pump turbine”; are equally used throughout the whole literature. It is within the authors wish that this paper can scale up the reader's PAT technology understanding, thus serving awareness in the same.

1. Introduction

Energy is unarguably the key factor for today's economic and social development within nations. The provision of reliable, secure and affordable energy services is central to addressing many of today's global development challenges [1]. Electricity as one of many energy forms is a critical input to developing countries in the struggle to the national self-satisfaction in all domains. Being a secondary source of energy, electricity can be obtained through the conversion of primary sources of energy, such as fossil fuels, nuclear energy or green energy [2]. From the early age, mankind require electrical energy to fulfil their needs such as lighting their houses, running industrial processes, heating and cooling for comfort, communication and numerous others [3]. However, both the demographic growth and the socio-economic development that took place during the last century have led to a continuous increase in electricity demand. These two events caused an augmentation of the yearly total world electricity generation in the period 1973–2008, which increased from 6’116 TW h/year to 20’181 TW h/year [4].

Despite this demonstrable increase in world electrical energy production, there is still shortage of electricity supply and other forms of modern energy in most of the developing countries [5]. According to the International Energy Agency, 1.4 billion people worldwide have no access to electricity [6], Sub-Sahara African region being the worst hit, yet the region is endowed with several resources from which modern forms of energy can be generated, for example hydropower [7].

Fossil fuels have been the main electrical energy sources for the past years (67%). However, owing to their fast rate depletion and the environmental pollutions they produced, many utilities have switched their generation sources to renewable energy sources [8]. Moreover, the increase in oil prices and subsequent worldwide energy crisis in 1973 prompted many countries to search and develop renewable

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sources of energy [9,10].

Many researchers and field players have shown their worries about the extensive use of conventional energy resources at the time. For instance, Akella [11] has demonstrated the undeniable contribution of conventional energy sources such as oil, coal and natural gases, to the economic development, but also showcased their serious environmental impacts. The use of renewable energy was also discussed. Thereafter, the results confirmed that after the installation of renewable energy system in remote areas, the total emission reduction in different years had been exponentially increasing [10].

Nevertheless, as far as electricity is concerned, hydropower is the most important renewable contribution to the primary energy supply mix. It represents more than 92% of all worldwide renewable energy generated, and it continues to stand as the most important renewable energy source [12].

Hydropower is a renewable energy source based on the natural water cycle, and actually the most mature, reliable and cost-effective renewable power generation technology available [13]. It contributes to around 16% of the World electricity supply generated from about 20,053 TW h of installed capacity [14]. In many countries it is the main source of power generation e.g. Norway – 99%, Brazil – 86%, Switzerland – 76% and Sweden – 50% [8]. Hydropower is the most flexible source of power generation available and is capable of responding to demand fluctuations in minutes, delivering base-load power and, when a reservoir is present, storing electricity over weeks, months, seasons or even years [6,13].

While large hydropower plants feed the national grid, typical off-grid micro hydropower plant (MHP) is the most popular solution for electrification among rural communities, supplying the power in the range of 5–100 kW, usually using a run-of-the-river to divert some of the water from the river before dropping into a pressurized penstock [15]. Note that there is no worldwide consensus classifying hydropower into specific categories [5,16,17]. However, in accordance with individual countries' administrative purposes [5,18], hydropower plants have been classified in terms of head or installed capacity, with different upper and lower limits for each category. Table 1 shows one of used classifications as found in the literature.

The main components that comprise typical MHP schemes are electromechanical equipment, civil structures, and energy distribution systems [19], the turbine being one of the critical technological components of the MHP project [5]. Small and micro hydropower installations have, historically, been cheap to run but expensive to build. This is now changing, with smaller, lighter and more efficient higher-speed turbine equipment [20].

Among the different elements of the plant, the turbine is at the earth of the energy production; it's the same for the electric generators. For these crucial elements which are directly connected to the positive column of the financial balance of the plant, it's very important to search the highest efficiency without weighed down the budget [23]. So the game has to be played on both legs but sometimes including case-sensitive priorities. The mostly met problem in micro turbines is their higher price compared to full scale ones with respect to the whole project budget, owing to their expensive manufacturing price. For instance, it's very difficult, time-consuming, and costly to develop such site-specific turbines in accordance with the local ecology [18].

Table 1
Hydropower scheme classification.

Hydro scheme	Capacity (Haidar et al. [21])	Capacity (Williams [22])
Large	More than 100 MW	More than 100 MW
Small	Up to 25 MW	1–10 MW
Mini	Below 1 MW	100 kW to 1 MW
Micro	6–100 kW	5–100 kW
Pico	Up to 5 kW	Up to 5 kW

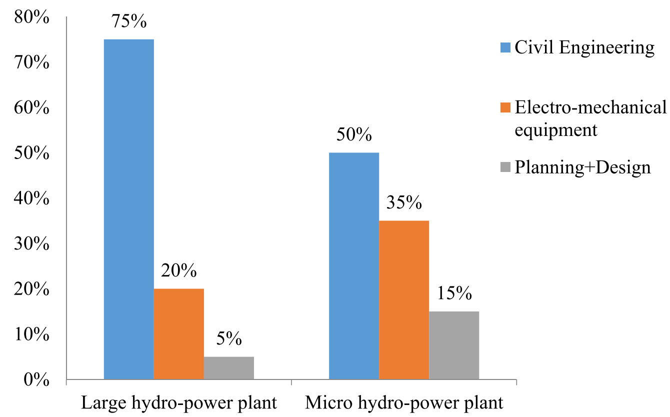

Fig. 1. Cost distribution for large and micro hydropower plants.

The cost of electro-mechanical components in large hydro-power plants is around 20% but in MHPs it is relatively high and varies from 35% to 40% of the total project cost which may rise even up to 60% or 70% of the total project cost in some typical cases [24] (See Fig. 1). Other details about large and small scale HP plants have been presented through [25]. Therefore, a better solution to this issue would be finding cheaper electro-mechanical equipment but considering three fundamental conditions, viz. simplicity, efficiency, and reliability.

One way to reduce the equipment cost has been the use of a standard pump unit as an alternative to a conventional turbine [26–29]. Pumps are mass-produced, and as a result, have different advantages for MHP compared to purpose-made turbines, viz. availability in large number of standard sizes for a wide range of heads and flows [26–28], short delivery time [28–32], long life span [29–33] and easy installation and availability of spare parts such as seals and bearings [26–28]. Islam et al. [34] discussed the possibility of setting up a micro hydro scheme in hilly areas of Bangladesh ranging from 300 to 500 m which was actually a viable proof for setting up pump turbine systems in Bangladesh.

However, the first pump turbine had been set at a remote farm in the Yorkshire Dales of the North England in 1930. This scheme has been working for a five year testing time, after which its reliability was confirmed before being transferred to other countries [26]. From then on, pump turbine has become a hot topic amongst researchers and field engineers, where indeed, it has been used at so many sites, mainly for electricity provision in remote hilly regions away from central grid reach (Table 2). Different researchers; Williams [26], Orchard and Sander [35], Ramos and Borga [36], Derakhshan and Ahmad [37], and Arriaga [38] among others, have provided information about the applications and advantages of a pump working as a turbine, mainly basing their arguments on its two most important features: "cost-effectiveness" and "simplicity".

Adding on the third one, "smallness", which is also true in a way; PAT's simple structural design would reflect its easily understandable operations. However, owing to the philosophy behind the pump's

Table 2
PAT installations.

Location	Capacity of plant	Year of installation
Sainyabuli Province, Laos [38]	2 kW	2008
Thima Kenya [39]	2.2 kW	2001
Mae Wei village, Thailand [40]	3 kW	2008
West Java, Indonesia [41]	4.5 kW	1992
Kinko village, Tanzania [42]	10 kW	2006
Fazenda Boa Esperanca, Brazil [43]	45 kW	2007
Ambotia Micro-hydro project, India [44]	50 kW	2004
British Columbia, Canada [45]	200 kW	–
Vysni Lhoty, Czech Republic [46]	332 kW	2008