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Performance characteristics of pump-as-turbine for energy generation

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ABSTRACT

Using pump in reverse mode as hydraulic turbine is one of the best alternatives for small hydropower generation. It is also one of the best options for meeting energy needs and providing electricity in remote and rural areas. Economic growth through renewable energy and sustainable energy sectors will create more employment opportunities and improve the social conditions in the country. financial constraints are one of the major reasons why small hydro power sites are left untapped. Despite the very low operating costs of small and micro-hydro power, the initial investment costs are high, especially the cost of the turbine. The use of pumps as a turbine is a good-looking and excellent option. With the rising cost of electricity and fuel prices, small or micro hydropower is the

greatest solution for power generation to rural communities and villages. Hydraulic Energy is the oldest and largest source of renewable energy. The only problem associated with SHP generation is high cost turbines. And so, the best solution is to choose a pump to work in reverse mode as turbine popularly known (PAT).

Key words: Pump as turbine, hydropower, small hydro power, pump in reversed mode; Renewable energy

Introduction

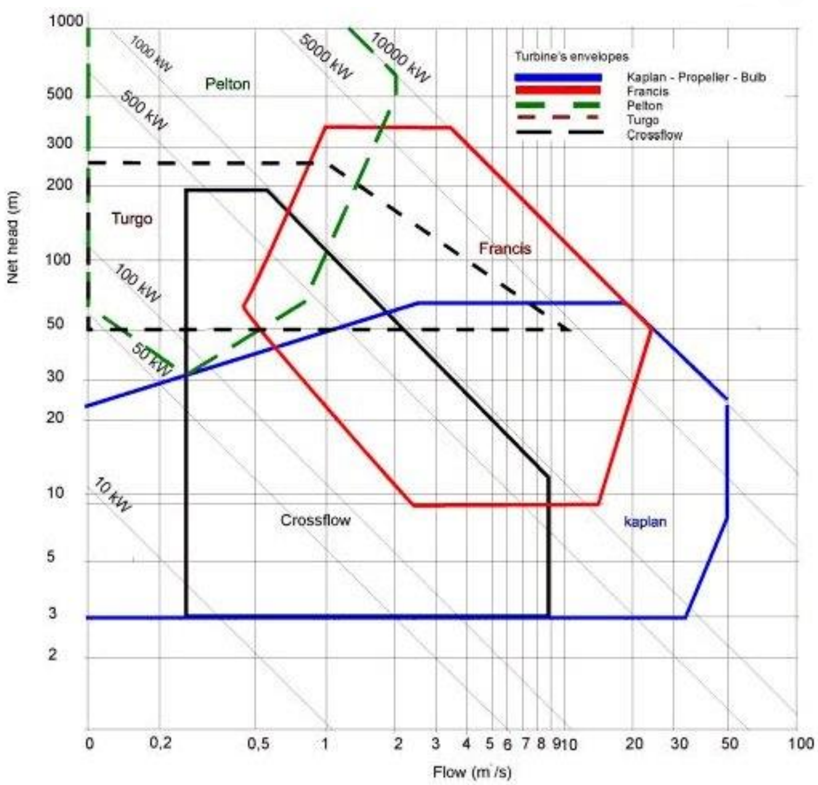
Small hydro power stations became attractive for generating electrical energy after the oil crisis of the seventies. However, cost per kW energy produced by these stations is higher than the hydroelectric power plants with large capacity. Numerous publications in recent years emphasize the importance of using Pump as turbine in order to reduce the cost of producing energy. We considered the idea of using pumps as hydraulic turbines an attractive and important alternative. Pumps are relatively simple machine, are easy to maintain and are readily available in most developing countries. From the economical point of view, it is often stated that pumps working as turbines in the range of 1 to 500 kW allow capital payback periods of two years or less which is considerably less than that of a conventional turbine. Pump manufactures do not normally provide the characteristic curves of their pumps in reverse operation. Therefore, establishing a correlation enabling the passage from the “pump” characteristics to the “turbine” characteristics is the main challenge in using a pump as a turbine. The hydraulic behavior of a pump when rotates as a turbine will be changed. In general, a pump will operate in turbine mode with higher head and discharge in the same rotational speed. Many researchers have presented some theoretical and empirical relations for predicting the PAT characteristics in the best efficiency point (BEP). A good literature review has been done by Nautiyal and Anoop Kumar [1]. But the results predicted by these methods are not reliable for all pumps with different specific speeds and capacities. Most recent attempts to predict performance of PAT, have made using CFD [2-4]. However, without verifying the CFD results by experimental data, they are not reliable. Besides, also all of these simulations included only hydraulic losses. In the present paper, a simple theoretical method to predict the BEP of PAT using theoretical analysis and empirical correlation on the basis of its pump performance is developed. The method has been compared with two other methods for some reference data. The PAT behavior is very complex and it is difficult to find just a relation to cover all pumps behavior in reverse mode. One idea is using full computational fluid dynamics to simulate PAT performance. In the next step, using commercial flow solver, all geometry of pump including inlet, impeller, chambers and volute has been simulated in modes of direct and reverse operation.

Pump as Turbine

Using a centrifugal 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 [5]. The pumped storage power plants can play an important role in stabilizing the electric power system when the electric production is excess or lacking. PAT is widely applied, which is regarded as the most cost-effective solution, even if there are also other technical arrangements such as the combinations Francis turbine/pump or Pelton turbine/pump. The reversible pump turbine can, depending on reservoir size, deliver long term energy storage, and is able to boost production (turbine) or consumption (pump) in peak power situations. The application of PAT for power generation requires the use of either a synchronous generator or induction generator (motor as generator) coupled directly to the rotating shaft of the PAT. For this reason, a nominal speed corresponding to one of the synchronous speeds of the generator (e.g. 750, 1000, 1500 or 3000 rpm) should be chosen [6].

PAT Selection

The pumps working as turbines (PATs) [7] constitute an alternative surely cheaper and manageable. Centrifugal pumps are mass-produced for a wide range of heads and flow rates so their prime cost is lower than that of the turbine and their maintenance is easier, because of the availability of spare parts, even in developing countries. The efficiency of these machines will be lower but, as they exploit otherwise wasted energy sources, this is not a critical issue. From the economic point of view, realizing a micro hydro plant using PATs having power up to 500 kW, imply payback periods less than two years [8], surely lower with respect to installations using conventional turbines. Silvio Barbarelli et al. proposed a new methodology for selecting a PAT suitable for installation in a particular site. The method involves a statistical model and a one-dimensional code whereby the statistical model allows for calculating the conversion factors CQ and CH, capable of finding the capacity and flow rate of the suitable pump for the chosen site. They concluded that by inputting these data on the composite performance chart of the manufacturer, it is possible to select the PAT [9].The authors propose a numerical model, developed during the past years [10-11], which is able to estimate the performance of the chosen pump in the reverse mode, as turbine (PAT). Firstly, the code reconstructs the geometrical parameters of the PAT, which usually are unknown, by using information provided on the manufacturer catalogue. Once deduced these data, the code calculates the losses and determines the characteristics curves of the PAT i. e. head vs. capacity and efficiency vs. capacity. The knowledge of such curves allows the operating point of the plant to be assessed. In this way, the annual yield of energy can be estimated. The case study of a pipeline whose characteristic curve is known is presented with the aim to better expose the proposed methodology. 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 tothe turbine characteristics is the main challenge in selecting PaT. The hydraulic behavior 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 [12].



The following are the advantages of PAT's as compared to other turbines: Integral pump and motor can be purchased for use as a turbine and generator set; Available for a wide range of head and flows; Available in a large number of standard sizes; Low cost; Short delivery time; Spare parts such as seals and bearings are readily available; Easy installation - uses standard pipe fittings.

PAT Characteristics

It is well known that efficiency of a centrifugal pump decreases rapidly with a drop of specific speed, and the impeller outlet diameter should be reduced considerably to increase its efficiency. With a reduced outlet diameter, it is necessary to select a larger blade discharge angle and more blades to produce the rated head. However, too many blades result in a decrease in efficiency due to the increasing blockage and skin friction in the impeller passage. Yuan [13] revealed that the splitter blade technique is one of the techniques to solve three hydraulic problems of low specific speed centrifugal pumps (lower efficiency, drooping head-flow curve and easily overloaded brake horsepower characteristics). It was observed from the studies that low or high blade numbers had increased the instability risk of head-flow curves [14], and the optimum efficiency was obtained when the blade number was between 4 and 6 [15]. M Asuaje et al. [16] studied the splitter blades effect on the performance of a centrifugal pump through both numerical simulation and experimental results. Adding splitters has negative and positive effects on the pump behavior. It increases the head rise compared to the original impeller, it has positive effect on decreasing the vibrating and radiated noise; but the efficiency is not improved since the hydraulic losses are greater.J. Zhang et al. conducted a study using the A BP artificial neural network (BPANN) model of a three-layer with 5 inputs, 20 hidden neurons and 2 outputs for predicting the efficiency and head of centrifugal pumps with splitters were built. The average relative deviation for the predicted efficiency and head were 5.97% and 4.78% respectively. And by comparing with test data, the predicted data has the similar trend, and the value of R for the predicted efficiency and head are 0.978 and 0.989 respectively, which prove that the correlation between the predicted and test value and the generalization capability are very good, and the trained network model can meet the requirement for the performance prediction of centrifugal pumps with splitters.

PAT Performance Characteristics

PATs are pumps running in reverse mode, by inverting flow direction and using the electric motor as a generator [18]. The possibility of using pumps operating in turbine mode has been widely accepted since the third decade [19,20]. Jain and Patel [21] provided a comprehensive review of the state-of-the-art of PATs, summarizing the main researches carried out. PATs generally exhibit worst performance against reaction micro-turbines but, at the same time, investment and maintenance costs are largely lower [22]. PATs also show the benefit arising from the wide set of pump models commercially available, with easier installation, maintenance activities and availability of spare parts [23]. Various researchers indicated the single-stage centrifugal pumps, operating in the range of low to medium head, as the most convenient, from both technical and economic standpoint [24-27]. On the other hand, the range of flow rates over which a single PAT unit can operate is much smaller than in a conventional turbine. From a technical viewpoint, the main issue of selecting PATs is the lack of information, as performance curves are rarely made available from manufacturers. In order to obtain this information, some authors developed experimental and theoretical models to assess PAT performances. Hancock [28] correlated discharge and head drop ratios with the efficiency in turbine mode h_t. Schmiedl [29] correlated discharge and head drop ratios to the hydraulic efficiency of the machine h_{hp}, which was calculated as follows: hhp ¼. By means of experiments on 35 pumps, Williams [30] showed that the Sharma's method [31] best fits test results with deviations from experimental data of around ± 20% [32]. Nautiyal et al. [27] correlated them with both efficiency h_p and specific speed N_{sp} in direct operation, expressed as:

N_{sp}=NQ21.H4 (4) 3 or N_{sp} NP21.H45 (5)

with N rotational speed (rps). In case of multi-stage pump, H in Eqs. (4) and (5) is the head of a single-stage. Saini and Ahmad [33] introduced a chart to calculate parameters at BEP in turbine mode as a function of the specific speed in pump mode and correction factors for head drop and discharge. Grover [34], Hergt [35] and Joshi [36] calculated head and discharge ratios at BEP as a function of specific speed in reverse mode N_{st}. Fernandez et al. [25] carried out experiments on centrifugal pumps both in direct and reverse mode, with a speed ranging between 21 and 41.5 rps. They compared the related BEP points and derived performance curves. Derakhshan and Nourbakhsh [37,38] tested 4 centrifugal pumps in turbine mode, with N_{sp} lower than 60. They introduced an innovative approach to predict the BEP of a PAT as a function of the pump characteristics. The most relevant relationships are summarized in Table 1, in terms of discharge and head ratios. Singh and Nestmann [38] introduced an optimization routine to predict performance and select radial flow centrifugal pumps in turbine mode. The relationships were validated experimentally for very low values of rotational speed. Nautiyal et al. [22] carried out an empirical investigation on centrifugal pumps, pointing out that machines operating in turbine mode were able to work at higher head and flow rates, whereas the BEP of the PAT was lower than in direct mode. They introduced a selection criterion to reduce the difference between theoretical methods and experimental results as a function of mechanical factors, pumped liquid and system characteristics.

Table 1

Models for calculating discharge and head ratios.

Model	Qtb/Qpb	Htb/Hpb
Nautiyal et al. [27]	30.303[(h_p-0.212)/ln(N_{sp})]-3.424	41.667[(h_p-0.212)/ln(N_{sp})]-5.042
Stepanoff [39]	h_p 1/2	h_p 1
Childs [40]	h_p 1	h_p 1
Sharma [31]	h_p 0.8	h_p 1.2

Alatorre - Frenk & Thomas [41]	$(0.85h^{5}_{p}$ þ $0.385)/(2h^{9.5}_{p}$ þ $0.205)$	$1/(0.85h^{5}_{p}$ þ $0.385)$
Yang et al. [42]	$1.2/h0.55_{p}$	$1.2/h1.1p$
Hancock [28]	h_{t} 1	h_{t} 1
Schmiedl [29]	1.5 þ $2.4/h^{2}_{hp}$	1.4 þ $2.5/h_{hp}$
Grover [33]	$2.379e0.0264N_{st}$	$2.693e0.0229N_{st}$
Hergt [34]	$1.3e1.6/(N_{st}-5)$	$1.3e6/(N_{st}-3)$
Derakhshan & Nourbakhsh [36]	$f(N_{sp})$	$f(N_{sp})$

Relationships predicting the BEP of the machine in reverse mode from data available in normal mode.

An inverter was also used to obtain the largest possible number of operating conditions, so as to vary in a wide range the rotational speed of the impeller. Data were presented in terms of dimensionless numbers for generalization. According to the approach proposed in Ref. [36], analytic relationships predicting PATs' performance curves were derived with respect to BEP conditions. Analysis of uncertainty was also developed to predict the reliability of the proposed formulas.

Effect of Speed on PAT Performance

The speed of a turbine varies according to the load put on it. At constant flow rate and head, if a load which is higher than design load put on a turbine, the turbine speed reduces. Also as the load put on a turbine decreases, (while keeping the head and flow rate the same), the speed of the turbine increases [44]. When it comes to PAT operating at a given site at constant flow rate, the same principle applies and plays an important role in determining the performance characteristics of a machine.

Performance Prediction of the PAT 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 [45,46]. However, the subgroups defined by the impeller diameter lead to a better match with the experimental tests available in literature [47]. 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 [46]:

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

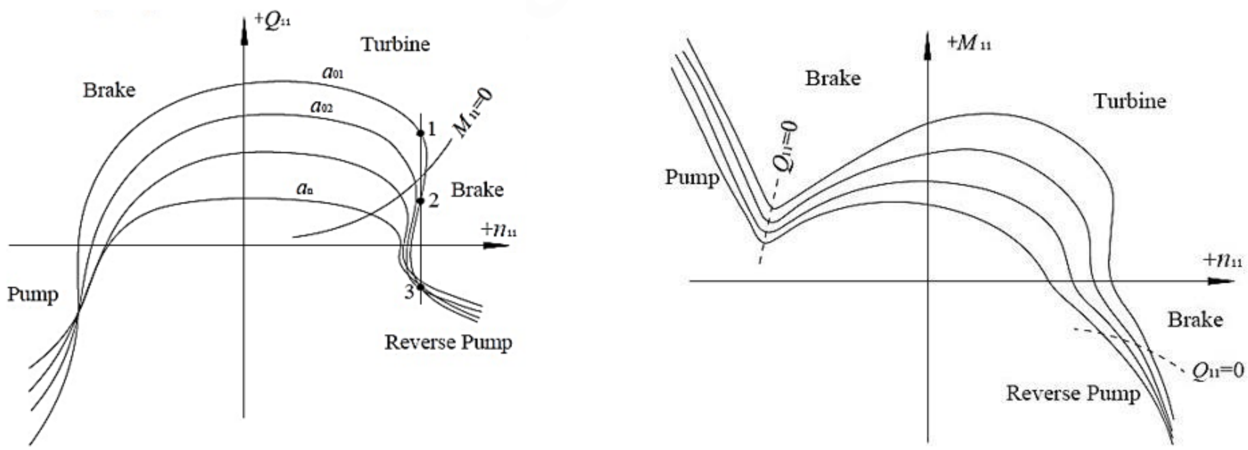


Figure 1 Four quadrant characteristics of a reversible pump turbine a) Flow-speed curve b)Torque-speed curve [48].

PUMP-Turbines stability aspects

The general system stability aspect was defined by Greitzer [48] as the ability of the system to recover its initial state after a certain perturbation, where the system can either exhibit static or dynamic stability. The criterion for stability of the pump turbine is called dynamic when the shaft is disconnected from the generator and the speed of rotation varies with the unbalanced torque; On the other hand, when the pump turbine is connected to the generator with a frequency proportional to the electric grid frequency a static stability criterion applies. In their everyday operations, pump turbines go through frequent switching between pump and turbine modes, thus sometimes working under off-design conditions. The fact that these machines can rotate and deliver the flow in two opposite directions, confer them the so called "four quadrants" operational characteristics at specific guide vane openings, allowing them to operate under five defined regimes, viz. turbine, turbine brake, pump, pump brake, and reverse pump (see Fig. 1). Each regime characteristics and working conditions were presented by Amblard et al. [49]. A pump turbine is basically a compromise between the pump and turbine but the geometry is more like the pump. Pump turbines are generally known to have steeper speed-flow characteristics than Francis turbines of same specific speeds, which under certain operating conditions, may be the source of stability problems within the machine. The pump turbine stability aspect can thus be assessed through the slope of its characteristics curves, for both pumping and turbine modes, such as head-flow and flow-speed curves. Because the pump mode of operation is known to be very sensible to decelerated flow field, which results in flow separation and related hydraulic losses as well as possible self-excited vibrations; the design of pump turbines has to be carried out with a big emphasis on the pump operating mode characteristics.

Pump-Turbine Stability Improvement

As shown in the above sections, the pump-turbine runner is the central part from which the machine efficiency and flow stability can be counted. Basically, the runner geometry can considerably influence the machine flow stability, be it saddle-type or s-shape characteristics related. Therefore, its optimization would contribute a lot to the machine stability improvement. Different studies have been carried out aiming at improving the pump-turbine stability aspects, where the most vulnerable stages, viz. start-up and load rejection, have been deeply analyzed to come up with adequate solutions to associated instabilities, where different universally applicable and case-specific technique have been presented.

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