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Review of Pump as Turbine (PAT) for Micro-Hydropower

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***Abstract* — Micro-hydropower projects are the excellent alternative for electricity generation in remote areas. These projects can be installed on small streams, rivers, and channels without any recognizable effect on environment. The only problem in micro-hydro projects is the high cost of turbine, for which Pump as Turbine (PAT) is a successful solution. An objective of the present study is to review the selection criteria of PAT for various hydropower sites having different potential. Since no general model has been developed which can be used to calculate the conversion factors for PAT, so this paper focuses on the research that have been carried out in this field. The limitations of the various available models and other selection criteria have also been discussed in this paper.**

***Keywords* — Micro hydro power; Pump as Turbine; Pump in reversed mode; Review of PAT; Renewable energy**

I. INTRODUCTION

The concern on the global environment has imposed restraints on the production of electricity. The emphasis is put on the development of environmental friendly methods to promote the sustainable development. It is in these circumstances, micro-hydro power is drawing more attention. The Ministry of New Renewable Energy Sources (Govt. of India) has searched about 6000 streams in northern and north eastern India. These streams are small as compared to the requirements of large hydropower; so these can be utilized for electricity generation in between the 5 kW and 100 kW [1]. Small and micro-hydro power projects are the appropriate options for generating electricity by using such water streams. The running cost of such plants is low but initial capital cost is relatively high. So, by reducing the equipment cost in micro hydropower projects, these can become more useful and easily accessible. One of the easiest ways to reduce the equipment cost is the use of centrifugal pump in reverse mode and can be used as an alternative to conventional hydraulic turbine. Standard pump units when operated in reverse mode have a number of advantages over conventional turbines for micro-hydropower generation.

The main advantages includes availability for a wide range of heads and flows, availability in large number of standard sizes, low cost, easy availability of spare parts such as seals, bearings etc. and easy installation. According to Williams [2] the greatest advantage of using a pump as turbine for medium head sites is the practical advantage and cost advantage over other types of turbine.

The main problem of using a PAT is the difficulty of predicting accurately the turbine performance, but methods are now becoming available that overcome this difficulty. Greacen [3] also predicted that lack of PAT performance data is a significant barrier to the wider use of PAT. Other limitations include low part load efficiency and no hydraulic control.

II. CONCEPT OF PAT

Centrifugal pumps are physically and hydraulically similar to Francis turbines (without flow control device). Centrifugal pump converts the mechanical energy of impeller into pressure energy and kinetic energy of water whereas Francis turbine converts pressure energy and kinetic energy of water into mechanical energy of runner. Therefore if a centrifugal pump is operated in reverse mode, it can function as a Francis turbine. Fig.1 and Fig.2 shows the difference in working of a radial flow pump in pump mode and in turbine mode respectively.

The performance of a pump will have different best efficiency point (BEP) flow parameters when operating as a turbine. This is due to the fact that energy losses due to friction etc. must be derived from the flowing fluid in a turbine. In a pump, the energy losses are included in the mechanical energy supplied to the pump drive shaft and are not transmitted to the fluid. Therefore, for a machine operating at a particular speed, the flow and head will be less when in pumping mode than in turbine mode [4].

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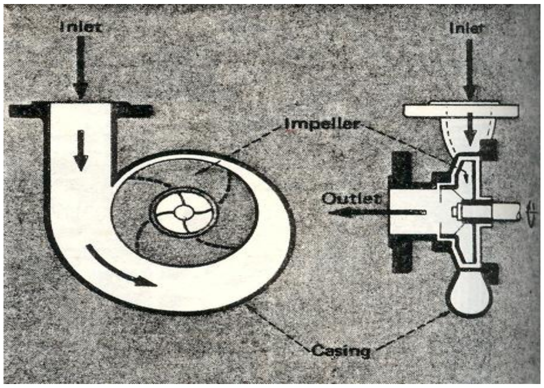

Fig.1 Radial flow pump as fluid mover [5]

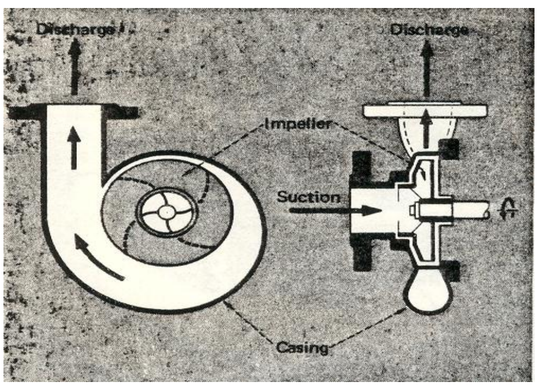

Fig.2 Radial flow pump as hydraulic turbine [5]

III. APPLICATIONS OF PAT

Although PAT is a successful solution to micro-hydropower but it can also be used as an energy recuperator in various applications such as Reverse Osmosis (RO) Systems, irrigation channels, sewage systems, water distribution systems etc.

During the reverse osmosis, sea water is subjected to high pressure and forced through a membrane which results in the retention of the salt ions. However, the main problem with this process is that the greater part of the generated pressure is lost when the brine is returned to the sea. In these systems, 70% of the pumping energy is wasted at high pressure range of 800–1000 psi [6]. Upto 80% of this energy can be recuperated by the use of running centrifugal pumps as power recovery turbines. Raja and Piazza [6] carried out the economics of Hydraulic Power Recovery Turbine (HPRT) systems with respect to the equipment cost, operating costs and payouts for the different sizes of R.O. Systems.

It was concluded that Head vs. capacity and BHP vs. capacity relationships are an essential criteria for selection and operation of HPRT's. It was found that by using of centrifugal pumps as HPRT, overall plant efficiency was increased as power consumption per unit volume of the produced water was reduced.

Mankbadi and Mikhail [7] developed a method for determining the main design parameters of the system which can be used to install the turbine-pump system across irrigation structures. The available low-head energy in irrigation channels/canals can be used to drive a turbine connected to a pump which can be used to lift water for irrigation or domestic purposes. It was concluded that off-design performance of the system can be controlled to achieve maximum pumped flow all year. Thus, turbine-pump system should be considered wherever low-head power is available.

Ramos and Borga [8] described the use of PAT as good alternative to utilize the excess available energy in natural falls, irrigation systems, water supply, sewage or rain systems which would be lost in normal conditions. Analysis of steady state conditions was done based on Suter parameters to prove that pump can be used in industrial process and production of renewable energy. It was concluded that whatever the type of the motor or alternator was adopted, PAT is an unconventional solution to energy production.

Ramos et al. [9] investigated the hydraulic system response (under steady and transient state) to analyze the results between a pressure reducing valve (PRV) and PAT (also working as PRV) in drinking pipe systems. Thus PAT can be used as PRV and can also be used to generate power using the energy stored in pressurized water. It was concluded that PAT can be better than PRV in some cases but in other cases use of both PAT and PRV was advisable.

Giugni et al. [10] investigated the method of recovery of energy from water distribution system by coupling and replacing PRV's with PAT's. An optimization was done using PIKAIA (Genetic Algorithm supported by NITSOL algorithm) as a hydraulic solver. It was concluded that PRV can be replaced or integrated with PAT to minimize losses in water distribution networks.

Teuteberg [11] designed a process of a 97 kW micro hydro system for Roman Bay Sea Farm in Gansbaai in the Western Cape Province of South Africa. The sea farm required large amount of seawater for the various growing cycles of the farm. Water was pumped in holding tanks and it was then gravity fed to the various processes of the farm.

After the water has passed through the farm it returns to the ocean by means of a single pipe. This water had still sufficient energy which was used to generate power. Experimental data from KSB pumps was used to test the accuracy of various correlations that can be used to generate turbine-mode operation curves from pump curves. A computer simulation program was programmed to help with the design process and can be used in other hydro projects to save time. A cost-benefit analysis was also given which showed that the project was financially viable. Moreover, besides increasing the efficiency of pump, it can also be used as small backup supply in case of a disruption in the grid connection.

IV. SELECTION OF PAT

A large number of theoretical and experimental studies have been done for performance prediction of PAT. But no method is reliable for the entire specific speed range and results obtained by these relations had almost ±20% deviation from experimental data [12]. Most recent attempts to predict performance of PAT have been made using Computational Fluid Dynamics (CFD). However, without verifying the CFD results by experimental data, they are not reliable.

A. Theoretical Investigations on PAT

Derakhshan and Nourbakhsh [13] reported a theoretical analysis to calculate best efficiency point of an industrial centrifugal pump running as turbine based on ‘‘area ratio”. In this method, hydraulic components of pump (in turbine mode) were estimated by using geometric and hydraulic characteristics of pump (in pump mode).

Derakhshan and Nourbakhsh [14] derived a new method to predict the BEP of a PAT based on pump’s hydraulic specifications. Using the experimental data of several centrifugal pumps (specific speed < 60), two equations were developed to estimate the complete characteristic curves of centrifugal pumps as turbines based on their best efficiency. A procedure was also presented for selecting a suitable pump to work as a turbine in a small hydro-site. The conversion factors predicted by this method were found to be in good agreement with experimental data.

Williams [15] presented a study on comparison of eight different PAT prediction methods. The test results on 35 pumps of various types and sizes were used for the comparison. It was concluded that no method could provide an accurate prediction for the all pumps. This study advocates for the testing of pump in order to be certain of its turbine characteristics before installation.

Singh and Nestmann [16] developed an optimization routine for the turbine-mode operation of radial flow centrifugal pumps to improve reliability of the basic model without changing the philosophy of the methodology used in the basic PAT. The optimization routine would essentially contain an increased database of more pump shapes (obtained from test rig.). It was found that by using the optimization routine, the errors at maximum load points were considerably reduced while errors at no-load regions were still substantial.

Singh and Nestmann [17] introduced an analytical model to study the effects of rounding of the sharp edges at the impeller periphery (or turbine inlet) on a combination of radial flow and mixed flow pumps as turbines using experimental data. Due to impeller rounding, positive impact on the overall efficiency in all operating region was found in range of 1-3%. It was concluded that the impeller rounding technique is very important for performance optimization and they recommended its application on all PAT projects. They also recommended the standardization of the rounding effects over wide range of pump shapes including axial pumps.

B. Experimental Investigations

Chapallaz et al. [18] carried out investigation on PAT conversion factors. Conversion factors graphs were developed on the basis of the specific speed of pumps. The conversion factors obtained from the graphs were found to be within acceptable limits even for the points away from best efficiency point (except for a small range).

Nepal Micro Hydro Power [19] predicted direct factors of 1.38 for the head and 1.25 for the flow rate of the any pump operating as a turbine. However, when Smit [20] did experiments on a PAT system, the experimental data showed a factor of 2 for the head and 1.65 for the flow rate. This showed that the factors can vary considerably depending on pump make and even model. Hence, factors should only be used when experimental data can be obtained from the manufacturer or data for similar pump is available.

Derakhshan and Nourbakhsh [21] presented some correlations to predict the best efficiency point of a PAT based on pump hydraulic characteristics using the experimental data. Four industrial centrifugal pumps with specific speeds from 14 to 56 (m,m^3/s) were tested experimentally. It was concluded that pumps with higher specific speeds needs lower ratios of head and discharge (for higher operating efficiency). But variations in power ratio were not proportional to variations of pump’s specific speed.

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Fernandez et al. [22] described the behavior of a centrifugal pump in turbine mode at several rotating speeds with the help of experimental investigation in a hydraulic setup. The results showed that the turbine characteristics can be predicted to some extent from the pump characteristics and the performance curves were also obtained for PAT operating at same head and speed.

Joshi et al. [23] studied a simple approach to predict PAT performance to aid in pump selection (high specific speed pump) with a case study of a micro-hydro site producing 25kW electric power from 5.5 meters of gross head. He formulated a relationship between pump and turbine specific speeds to assist in pump selection for a particular hydro site.

Suarda et al. [24] carried out an experimental analysis by using two small pumps (diffuser-pump and volute-pump) to determine performances of pumps in turbine. It was concluded that centrifugal volute-pumps as hydro turbine was a more potential alternative solution.

Nautiyal et al. [25] carried out an experimental investigation on a centrifugal pump having specific speed 18. The best efficiency in turbine mode was found 8.53% lower than best efficiency in pump mode. The experimental results of tested pump and other pumps (studied by some previous researchers) were used to develop new correlations to obtain turbine mode characteristics of pump from pump mode characteristics by using their best efficiency point and specific speed in pump mode. Values obtained from the derived correlations were compared with experimental results and results of other methods which showed very less deviation.

Singh and Nestmann [16] carried out an experimental study on three pumps with specific speeds of 18.2, 19.7 and 44.7. The prediction errors in the head of pump at the maximum load point (using the optimization routine) were considerably reduced, especially for the lower specific speed PAT. The errors for the pump with specific speed 18.2, 19.7 and 44.7 had decreased to ±2.6%, ±2.7% and ±2% bands respectively. Based on these results, it was proposed that the acceptance criteria be reduced further to ±2% in order to make the model more stringent. However, the errors in the no-load region were still substantial (in the range of ±10–20%) which was viewed as an inadequacy.

C. CFD analysis of PAT

Computational Fluid Dynamics (CFD) is an effective design tool for predicting the performance of centrifugal pumps running in turbine mode.

However, it has been found that the results from CFD and experimental analysis do not match accurately in case of PAT. It is suggested that the difference can be minimized through improvement in computational analysis by using finer mesh, numerical methods and turbulences models. CFD analysis is useful in identifying the losses in hydraulic machine components like draft tube, impeller, casing. Some of the important studies have been discussed below.

Derakhshan and Nourbakhsh [13] compared CFD and experimental results of pump working in turbine mode (specific speed of 23.5), in direct and reverse mode. CFD results supported the experimental results of pump in pump mode, but the results were not within acceptable limits in turbine mode. Similarly, the discharge, head and power values obtained by CFD were lower than the experimental values. Thus, CFD results were in good coincidence with experimental data only for pump mode.

Natanasabapathi et al. [26] investigated PAT using numerical approach. Deviation was found in the efficiency calculated from CFD at discharges away from best efficiency point (BEP). To eliminate the deviations, two rings of structured grid were introduced in between casing and runner. It was concluded that the unrealistic results can be obtained from unstructured griding across the interface between stationary and rotating frame of reference. Thus, structured griding near the interface is a solution to minimize such errors in the results.

Rawal and Kashirsagar [27] carried out numerical analysis on axial pump in turbine mode. Similarity was found between the experimental and numerical results for best efficiency point. It was concluded that numerical model was quite helpful in investigation of various parameters like internal hydraulic losses i.e. losses in the impeller, the draft tube, casing and flow pattern which could not be measured experimentally.

Rodrigues et al. [28] carried out a computational study of PAT using the concept of ‘flow zone’. The flow regime within a PAT was divided into four major flow regions i.e. volute casing, impeller, casing outlet and draft tube. Comparison was done between the experimental and numerical results of a single stage end suction centrifugal pump (NW8 Kirloskar) which was operated in turbine mode at a speed of 800 rpm. CFD predictions of the hydraulic parameters were in good agreement to the experimental results, but some deviations (within 5% to 10%) were found at certain load regions.

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Nautiyal et al. [29] carried out a study on the application of CFD and its limitations for PAT using cases of previous researchers ([14], [26], and [28]). Study reported that CFD analysis was an effective design tool for predicting the performance of centrifugal pumps in turbine mode and to identify the losses in turbo machine components like draft tube, impeller and casing, but there was a deviation in results of the experiment and CFD of turbine mode operation of pump.

Barrio et al. [30] carried out a numerical investigation on the unsteady flow in commercial centrifugal pump operating in direct and reverse mode with the help of CFD codes. Results of numerical simulation were in good agreement with the experimental results. The study revealed that in the reverse mode, the flow only matched the geometry of the impeller at nominal conditions while developing re-circulating regions of fluid at low flow rates (near the pressure side of the blades) and high flow rates (near the suction side). It also concluded that total radial load (steady and unsteady components) in turbine mode was lower than the maximum total load in pump mode for operating below turbine rated conditions and total thrust on impeller would be higher than maximum load for higher turbine flow rates.

Fecarotta et al. [31] investigated the minimum complexity of the CFD calculation mesh to perform faster and reliable simulations. The study described the CFD analysis as reliable tool to better understand the interaction between the hydro mechanical equipment and the flow behavior in spite of difficult calculation. CFD calculations were carried out to predict the turbine behavior under different flow conditions (steady and transient) and the performance curves for both modes were obtained. The analysis showed that transient calculations are good for the simulation of the real behavior of the machine as it includes interactions between the rotor, the stator and the hydrodynamic conditions.

Sedlar et al. [32] carried out CFD analysis of flow in the middle stage of the radial flow multistage pump having specific speed 23 (operating in turbine mode). Analysis showed that the hydraulic efficiency of the multistage pump in the reverse mode can be quite high, even without any expensive corrections of the manufactured parts.

D. Modifications in PAT

Saini and Ahmad [33] carried out experiments on PAT having specific speed range from 10 to 300 and developed a monogram to aid in the selection of a pump to be used as turbine for a particular site. This reduced the calculation effort involved in the selection of PAT.

Gantar [34] studied the propeller pump working in the turbine mode of operation. He found that the main problematic element was the suction bell-mouth (in reverse running of a propeller pump). He concluded that the kinetic energy at the impeller discharge in turbine mode can be utilized by replacing the bell-mouth with carefully designed concentric diffuser or with a diffuser combined with a bend. Efficiency of PAT was also increased by using the concentric diffuser.

Singh [35] discussed various possibilities of modifying the pump geometry to improve the performance of a given pump in turbine mode. The study showed that impeller rounding was the most beneficial modification.

Suarda et al. [36] modified the impeller by grinding the inlet ends of the impeller tips of centrifugal volute type pump to a bullet-nose shape. After modification, this pump was tested experimentally in turbine mode at the maximum head (13 meter) and at various capacities. The results showed that the output and efficiency of the modified centrifugal volute-pump in turbine mode was slightly better than the earlier one.

ITT Goulds' O-Head [37] (discharge head) was designed to enhance the performance of vertical turbine pumps. The O-Head aimed for smoother running with lower vibration levels. Due to its mitered radius waterway, it also offered improved efficiency due to less relative deflection at seal housing and motor support plate, a reduction of hydraulic losses, better pressure distribution in the elbow transition due to the small seal housing pipe design, and a 360^o access to the seal housing and coupling during maintenance to facilitate replacement of mechanical seal or packing. It also provided improved hydraulics (from traditional 90^o discharge designs), increased seal life due to the reduced structural deflection, shorter height and length than a conventional discharge head to reduce pump vibrations, and smaller base plate which required less foundation grouting surface.

Pandey [38] carried out experimental study to predict the performance characteristics of modified PAT. The runner vane shape was modified to reduce the shock losses at inlet and the arrangement for movable guide vane was made to improve part load efficiency. Study showed that peak efficiency was improved by 4.5% and part load efficiency had also improved.

Derakhshan et al. [14] redesigned shapes of the blades using a gradient based optimization method involving incomplete sensitivities for radial turbo machinery developed by Derakhshan et al. [13] and the optimized impeller was further modified by rounding of leading edges and hub/shroud inlet edges in turbine mode.

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After each modification, a new impeller was manufactured and tested. Experimental results showed improvement in efficiency of flow rates in part load and overload zones. An increase of -2.2%, +9.4%, +14.8%, and +2.9% in discharge, head, power and efficiency respectively was found for optimized impeller and blade behavior was improved for a wider operating range. But the head was increased slightly more than numerical optimization data. Rounding of optimized impeller improved these values to +5.5%, 11.5%, 36.1%, and 5.5% for flow rate, head, power, and efficiency respectively.

V. Conclusion

From the above study, it can be concluded that PAT is outstanding solution to the micro-hydropower particularly in isolated areas. The initial cost of the project decreases substantially which makes it more viable. The limitations of PAT can be further reduced by selecting a proper PAT for a specific site. Conversion factors for PAT can be decided on the basis of theoretical and numerical studies but its performance cannot be predicted accurately. Hence there is still a need for further research to develop a general model for calculating the conversion factors. However, the efficiency can still be increased by using the various modifications which has been suggested by researchers.

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