

# REVERSING CENTRIFUGAL PUMPS AS ALTERNATIVE TO CONVENTIONAL TURBINES FOR MICRO HYDROPOWER: A REVIEW

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## ABSTRACT

This paper presents the operation of centrifugal pumps as turbines for micro hydropower application. Block diagrams are used to present components required from intake chamber to hydropower plant and their electrical energy mechanism for micro hydropower system. A comparison of operational parameters of pump as turbine and conventional turbines is discussed. Also, the paper discusses three types of methods for selecting the centrifugal pump as turbine based on the head, flow rate, rotational speed and specific speed. Furthermore, the technique used to determine the flow rate characteristics are discussed as well as the technical guideline is tabulated to assist the application of centrifugal pump as turbine for micro hydropower scheme development.

**KEY WORDS:** block diagrams, centrifugal pump as turbine, micro hydropower

## 1. Introduction

Hydropower has been used as the affordable means of generating electricity in most of the potential off-grid areas [1,2]. Electricity is a powerful resource that has the potential to catalyse communities by changing lifestyle and provide opportunities for new range of economical activities and services [3,4]. Despite the fact that the renewable energy sources characterised as inexhaustible [5] and hydropower is the reliable source type of energy, but it needs skills and knowledge to harness the electrical energy. It required to understand the concept from the point where water from the river/stream is diverted through the penstock to a plant.

Reversing centrifugal pump as an alternative to conventional turbine has more advantages for stand-alone micro hydropower compared with conventional water turbines that include availability in large numbers with a wide range of capacity and head, low cost and easy availability of spare parts such as bearings and seals [6-11]. The means of reversing centrifugal pump to take water at the discharge part and cause to rotate in reverse direction can operate as water turbine and normally such a pump is

named a Pump as Turbine (PAT). In fact, one type of conventional turbine operates at the specific hydropower site parameters [12] and are not available to the local market, i.e only available by making order to the manufacturer that increase the cost of design the turbine based on the site characteristics and delay the scheme development [13]. Different methods developed to convert the centrifugal pump parameters to operate as turbine [14-26] and are presented in this study.

The possibility of using PAT deserves consideration for very low power plants of less than 100 kW, but there are significant reductions in the capital cost and efficiency of the plant [9]. It is often stated that capital payback period of PATs in the range of 5-500 kW is two years or less which is considerably less than that of a conventional turbine [17,27]. Furthermore, PATs can be designed at minimal annual available water to have a constant flow rate within the life of the scheme [28] and installation of more than one PAT can be possible in parallel to control demand fluctuation by switching on and off [13].

Therefore, this study increases the awareness of harness the potential micro hydropower with available resources include standard centrifugal pump available in the local market can be used as turbine, pipe and valves, manpower, skills and knowledge to improve rural electrification. Also, the study reviewed different methods used to estimate flow rate in the potential stream/river for hydropower schemes. Furthermore, the study examined the technical method of determining the low flow rate as well as the power demand forecast.

## 2. Energy Conversion in Micro Hydropower

The means of converting water energy to rotational energy involve the diversion point from the stream, conveying water through the penstock to hydropower plant as presented in block diagram in Figure 1. The diversion of water from the stream/river was conducted by using borders and maize sacks filled with clay soil to re-enforce the channel leading to the intake chamber to form a basin with sufficient depth [30].

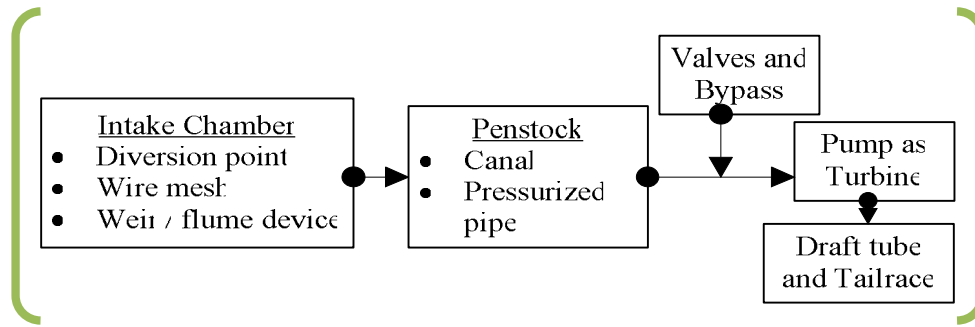


Figure 1. Block diagram of the component from intake chamber to hydropower plant

Rectangular canal and intake chamber are built with masonry techniques by using bricks, cement and sand [31]. Debris was prevented to enter at the penstock inlet by using galvanized wire mesh [30]. The penstock can be a canal or pipe with high pressurized water to convey water from the intake chamber to the hydropower plant. The use of canal followed with Polyethylene or PVC pipe covered with soil bags are easily available and light to transport to the site and suitable for micro hydropower [32,33]. The percentage of net head loss in the penstock varies from one site to another with 12.2 % [34] and 13.2 % [31]. The head loss is calculated by using Equation in [35,36].

The hydropower plant comprises of turbine and generator with the control system. In this study only standard centrifugal pump was selected to be used as the turbine for micro hydropower turbine. Standard centrifugal pumps with pressure rated of 10 bar are manufactured in a large number of sizes to cover a wide range of flow rates and heads [16]. At the same time, the conventional turbines are manufactured based on the site specifications [12]. Therefore, pumps with parts are available in the market at comparatively lower cost and shorter delivery periods when orderly from manufacturers. The selection of PAT for micro hydropower is discussed in the section 4.0.

The conversion of rotational energy to electrical energy involves the connection of generator with shaft. The application of induction generator indicated to be more suitable when connected to PAT [11]. It characterized with less expensive, simple construction with no windings,

diodes or slip rings on their rotor as well as more widely available than the synchronous generators for micro hydropower schemes [29]. Furthermore, the Residual Current Device (RCD) is connected between the consumer and Induction Generator Controller (IGC) to protect the generator windings from overheating due to excessively high currents or limit the amount of current that the consumer can draw [37]. The excess current can be directed to ballast load for instance, two 1.8 kW cooking rings have been used as a ballast load to a 2.2 kW power plant [30].

Also, IGC can be manufactured locally for Pico hydropower plant [37]. Different types of induction generators and capacitors for excitation is explained more detailed in [29] and the summary of block diagram is presented in Figure 2 to clear visualize the layout of the components. But, the induction motor/generator runs slightly above the synchronous speed when converted for use as a generator [11]. Generally, the conversion of water energy to electrical energy is presented in Figure 3 [38].

### 3. Comparison of the Operation Parameters

The common basic operational parameters of measuring the centrifugal pump performance parameters include head, flow rate, power and efficiency. The operational parameters of PAT and conventional turbines are discussed and tabulated in Table 1 to define the economical advantage.

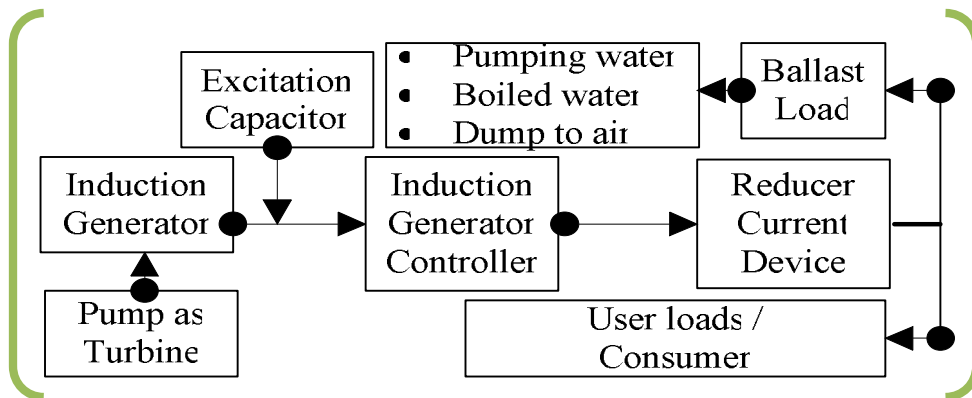


Figure 2. Block diagram for electrical energy control system

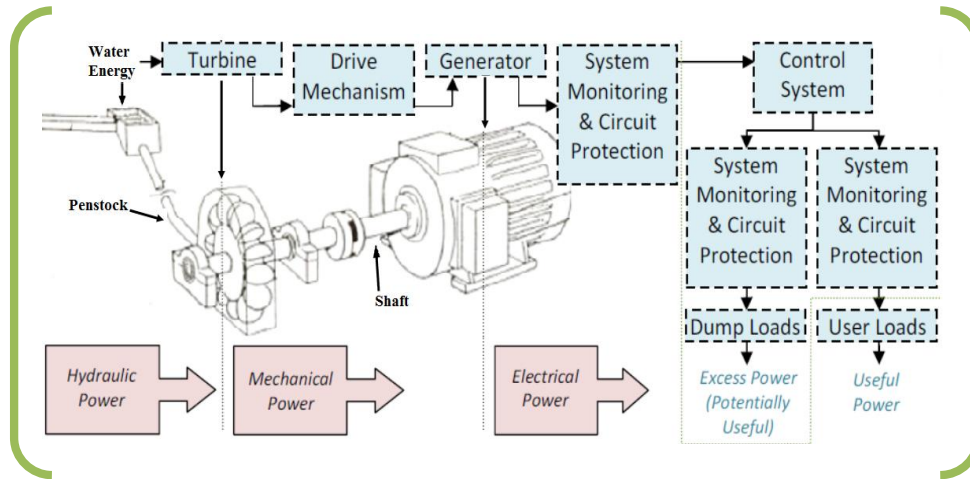


Figure 3. Micro hydropower energy conversion [38]

Table 1. Comparison of the PAT and convectional turbines

S/N	Parameters	Pump as Turbine (PAT)	Conventional Turbine
1	Costs	More advantages for < 50 % and < 50 kW [17]	High in all ranges [40]
2	Construction	Simple and sturdy [17]	Complex and suitable for specific site
3	Availability	Widespread due to application in water supply for households and irrigation, industry and sewage systems [11,39,41]	Ordered directly from the manufacturer based on the particular location and application [12]
4	Flow rate variation	Very minimal range of 80 % to 100 % [28,29]	Wide range from 20 % to 90 % [28,39]
5	Control device	Not specified, but hydraulic valves and Electronic Load Controller devices can be used [42-48]	Specified and readily available with adjustable guide vanes, nozzles or runner blades with governor
6	Efficiency	Low with steep efficiency characteristics [40,49]	High
7	Maintenance	No special equipment and skills required [17]	Special equipment and skills required [41, 50,51]
8	Spare parts	Readily available [11,17]	Ordered directly from the manufacturer

The efficiency curves of Pelton, Cross Flow, Francis and Kaplan abruptly increased to the maximum and retain their high efficiency to the highest percentage of flow rate variation from 20 % to 90 %, but the efficiency curves of the propeller turbine and PAT slightly increased to the maximum with flow rate variation only around 80 % to 100 % at the high efficiency [39]. This observation indicated PATs can be designed at minimal annual available water to have a constant flow rate within the life of the scheme [28] and installed more than one PAT in parallel during demand fluctuation by switching on and off [13].

#### 4. Methods for Selecting a PAT

The task of choosing the optimal turbine type, runner/impeller diameter, rotational speed, runner axis, elevation and number of machine units can be decided depends on the load requirement of the particular area and stream flow analysis. The load requirement of the plant can

be fixed as high as possible to reach maximum efficiency and low initial costs [12]. Both flow rate and head at the given specific site has been evaluated by stream flow analysis to determine the amount of power generated in a specific hydropower plant to reach the load requirement. The flow analysis and load requirement discussed in section 5 and only three methods which help in selection of pumps to operate as turbines were discussed such as rule of thumb, curve fitting and empirical methods. Existing of selection methods serves during the starting point of the scheme to predict performance characteristics of operating PATs [16, 52,53].

##### 4.1 Rule of the Thumb

There are possibility of pump manufacturers to produce the PAT based on the specific hydropower site parameters. The rule of thumb chart of the centrifugal pump as water turbine is presented in [17]. Furthermore, it is possible to choose a

pump with BEP of head and flow rate about 25 % lower than the required values of the turbine as presented in [15]. Generally, it is seen the most available centrifugal pump in the market can operate as water turbine in the head range 10 to 150 m and flow rate up to 0.5 m<sup>3</sup>/s.

## 4.2 Curve Fitting

According to Chapallaz et al. [17], five steps to follow based on the fitting curves for converting pumps to turbines mode based on curve fitting include; (i) To identify the potential head and flow rate of the hydropower site, (ii) To calculate the turbine specific speed ( $N_t$ ), (iii) To calculate pump specific speed ( $N_p$ );  $N_p = N_t/0.89$  (iv) To use  $N_p$  to determine the flow rate ratio, head ratio and pump efficiency, (v) To convert pump head and flow rate to design pump rotational speed. The method applied in Brazil [54] to select a suitable pump of 15 m head and flow rate of 0.21 m<sup>3</sup>/s to be used as turbine for potential site of 21.8 m head and 0.27 m<sup>3</sup>/s.

## 4.3 Empirical Methods

The empirical methods grouped into four categories include the method either based on the specific speed, efficiency, constant or both parameters. Complex empirical methods indicate to predict more accurately with more economical advantages than constant methods [13]. The empirical methods were used to estimate the head and flow rate in turbine mode based on the performance characteristics from pump manufacturers. Table 2 presents the empirical methods that are mostly used to estimate PAT in the specific site designed in [30,53,55,56] and presented frequently in the reports of [8,13,16,52,53,57,58]. Other methods include the relationship of hydraulic efficiency in pump and turbine mode.

## 5. Analysis of Stream/River Flow Characteristics

The head and flow rate parameters are the main parameters in the river/stream flow characteristics to govern the hydropower plant capacity. The head is the height interval between the upper and lower part of the specific site. It is calculated by using either survey instrument, topographical map or DEM map under ArcGIS software. The flow rate can be estimated regarding to the flow characteristics include turbulent and steady state, regular and irregular channel, low flow channel dilution and high flow in [59]. The low flow rate can be measured by using a bucket and float methods [6]; 0.6 water depth [59]; Dilution method [62, 63] and a weir method [64]. Low to average flow rate

can be measured by using a Price AA and Pygmy current meters [65]; and slope-area Manning equation [66]. Furthermore, the average to high flow rate can be measured continuously by using electromagnetic method [67, 68] and acoustic doppler current profiler method with the moving boat [69,70]. The classification of flow rate and drainage area is described in [71].

However, a Flow Duration Curve (FDC) characterizes the ability of the stream/river to provide flows of various magnitudes from the low to flood events [72-74]. The FDC is a cumulative frequency curve that indicates the percent of time of the specified flow rate was equaled or exceeded during a given period [75,76]. The FDC provides a convenient means for studying the flow characteristics of streams and compared with another of the ungauged site [77,78].

The FDC can be presented in daily, weekly or monthly during a given period arranged according to magnitude to calculate the percentage of time during which the flow rate is equaled or exceeded the specified values. The maximum flow rate can be available only 10 % of equaled or exceeded of the time per year. This can cause 90 % of the time in the year without running hydropower plant. The flow within the range of 70–99 % of the time equaled or exceeded is usually most widely used as design low flows [79] and 50 % of the time can be for medium design flow. The PAT requires the constant flow rate throughout the year and slightly change can reduce the efficiency [28].

## 6. Micro Hydropower Installation Guideline with PAT

There are two methods of estimating power demand, i.e. empirical or survey methods. The methods have been used to estimate the hydropower capacity [80]. The survey method depends on the assessing inventory of the appliances by surveying a specific area and asking users. The empirical method uses the annual growth rate of electricity for residential customers, business and light commercial as presented in [81] and multiplied by a given number of years and existing power capacity to predict the plant capacity. Therefore, the guideline will assist to make the proper capacity of the main equipments connected to the PAT for micro hydropower scheme development as presented in Table 3. However, the guideline is only serving as the supplement technical material after identifying the proper type of PAT and other specific formula for estimating different associated components to reach the power demand.

Table 2. Empirical methods

Head ratio ( $H_T/H_p$ )	Flow rate ratio ( $Q_T/Q_p$ )	Criteria	Name of Investigator
$\frac{1.38}{\left(\frac{N_T}{N_p}\right)^2} * \frac{1}{\eta_p^{1.2}}$	$\frac{1.25}{\left(\frac{N_T}{N_p}\right)^2} * \frac{1}{\eta_p^{0.8}}$	-	NMHP [14] Williams [16]
$1.1 \eta_p^{-0.8} \left[1 + (0.3 + \ln n_{sp})^2\right]^{0.3}$	$1.12 \eta_p^{-0.6} \left[1 + (0.4 + \ln n_{sp})^2\right]^{0.15}$	$\eta_T = \eta_p - 0.03$	Chapallaz et al. [17]
$\frac{1}{0.85 * \eta_p^5 + 0.385}$	$\frac{0.85 * \eta_p^5 + 0.385}{2.00 * \eta_p^{9.5} + 0.205}$	$\eta_T = \eta_p - 0.03$	Alatorre-Frenk and Troncoso – Torrez [18]
$-1.5166 + 2.369 (\eta_p \eta_t)^{-0.5}$	$-1.378 - 2.455 (\eta_p \eta_t)^{-0.25}$	Efficiency ratio = and valid for $0.1 \leq n_{sp} \leq 1.05$	Schmiedl [19]
$1.3 - \frac{6}{n_{sT} - 3}$	$1.3 - \frac{1.6}{n_{sT} - 5}$	-	Hergt [20]
$2.6 - 9.1 * \ln(5n_{sp}) + 7.96 [\ln(5n_{sp})]^{1.1}$	$1.86 - 0.551 * \ln(5n_{sp}) + 0.11 [\ln(5n_{sp})]^{2.2}$		Gopalakrishnan [21]
$\eta_p^{-1.2}$	$\eta_p^{-0.8}$	Equal efficiency	Sharma [22]
$\eta_p^{-1}$	$\eta_p^{-1}$		McClaskey and Lundqvist [23]
$\eta_t^{-1}$	$\eta_t^{-1}$	At BEP lies within $\pm 2 \% * \eta_p$	Hancock [24]
$\eta_p^{-1}$	$\eta_p^{-1}$	Equal efficiency	Childs [25]
$\eta_p^{-1}$	$\eta_p^{-0.5}$	-	Stepanoff [26]

Note. N = rotational speed,  $n_s$  = specific speed,  $\eta$  = efficiency. Subscript T= turbine mode, p = pump mode.

Table 3. Guideline to install micro hydropower with PAT

Parameter	Technical Description
Turbine	Standard centrifugal pumps are normally offered with the option of 2 or 4 poles. It is important when using a standard centrifugal pump as turbine that the impeller is not less than 90 % of the nominal diameter [11, 13]. To use one empirical method to estimate the values of head and flow rate after having the turbine head and flow rate [16] or to choose a pump with BEP of head and flow rate about 25 % lower than the required values of turbine [15].
Head	Head loss can be up to 15 % of the gross head. Standard centrifugal pump operates as the reaction turbine head range.
Flow rate	Flow rate required can be relatively large and there may not be enough water to keep the generator running during times of drought or needed to be replaced with small generator. It is advised to develop a FDC and determine the above of the 70 % of the time for the low flow to be available throughout the year.
Penstock	Rectangular canal constructed with sand, cement and aggregate can be used to shorten the distance. The distance remained to reach the plant can be connected with PVC or Polyethylene pipes to increase pressure. The material and pipes are available in the market.
Induction Generator	The electrical output of induction generator should normally be limited to 80 % of the rated power output as a motor [29]. When motor is used as generator operated at the high rotational speed compared to asynchronous generator.
Efficiency	The maximum value of efficiency varies only less than 20 % of the flow rate variation [39].
Ballast load	Total ballast load capacity should be in the range from 5 to 15 % above the design power output [82] and coils from electrical stove can be used.
Capacitors	Capacitors connected to induction generator can be calculated as in [29].
Transmission lines	Single phase transmission has the advantage up to 15 kW.
Overall comment	The type of equipment connected to micro hydropower is unlikely to be damaged when the voltage is kept within the range -25 % to + 10 %, but the frequency only up to 5 % from rated value [11]

## Conclusions and Recommendations

The energy conversion system was presented in block diagrams from the intake chamber at the upper part connected through penstock that conveys water to hydropower plant as well as the advantage of using induction generator operation for micro hydropower schemes. PAT indicated to operate with only 20 % of the flow rate variation in higher efficiency compared to conventional turbines. Furthermore, the PAT operational parameters include construction costs, availability and spare parts as well as the control devices were compared with conventional turbine. The methods used to convert centrifugal pump to operate as water turbine were presented include rule of thumb, curve fitting and empirical methods and indicated to be applied in the existing hydropower schemes.

The FDC was discussed to determine the percentage of flow rate that will be available at a given time of equaled or exceeded as well as the general guideline was tabulated to assist the selection of the main components connected to the PAT. The study recommends to estimate the flow rate that is available at the high percentage of the time and proper designing of the main components connected to the PAT for micro hydropower schemes.

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## Reference

- [1] D. Timmons, J. M. Harris and B. Roach, The Economics of Renewable Energy. Global Development And Environment Institute, Tufts University, Medford, MA, 2014.
- [2] IRENA, International Renewable Energy Agency, Renewable Energy Technologies. Cost Analysis Series. Hydropower, IRENA Innovation and Technology Centre, Germany. [http://www.irena.org/documentdownloads/publications/re\\_technologies\\_cost\\_analysis\\_hydropower.pdf](http://www.irena.org/documentdownloads/publications/re_technologies_cost_analysis_hydropower.pdf), 2012.
- [3] H. Ahlborga and M. Sjöstedt, Small-scale Hydropower in Africa: Socio-technical Designs for Renewable Energy in Tanzania Villages, *Energy Research & Social Science*, 5, 2015, 20-33.
- [4] S. Tshering and B. Tamang, Hydropower-key to Sustainable, Socio-economic Development of Bhutan, in *United Nations Symposium on Hydropower and Sustainable Development*, 2004.
- [5] M. Gejguš, C. Aschbacher and J. Sablik, Comparison of the Total Costs of Renewable and Conventional Energy Sources, *Slovak University of Technology in Bratislava*, 24(37), 2016, 99-104.
- [6] E. Baburaj, R. Sivaprakasam, C. Manikandan and K. Sudha, CFD Analysis of Pump as Turbine for Micro-Hydro Schemes, *International Journal of Innovative Research in Science, Engineering and Technology*, 2(3), 2013, 590-594.
- [7] H. Nautiyal, Varun, A. Kumar and S. Yadav, Experimental Investigation of Centrifugal Pump Working as Turbine for Small Hydropower Systems, *Energy Science and Technology*, 1(1), 2011, 79-86.
- [8] S. Derakhshan and A. Nourbakhsh, Experimental study of characteristic curves of centrifugal pumps working as turbines in different specific speeds, *Experimental Thermal and Fluid Science*, 32, 2008, 800-807.
- [9] J. Fernández, E. Blanco, J. Parrondo, M. T. Stickland and T. J. Scanlon, Performance of a Centrifugal Pump Running in Inverse Mode, in *Proceedings of the Institution of Mechanical Engineers*, 2004.
- [10] H. M. Ramos and A. Borga, Pumps Yielding Power, *Dam Engineering, Water Power and Dam Construction*, 2000, 197-217.
- [11] A. Williams, Pumps as Turbines: A User's Guide, London: Intermediate Technology Publications, 1995.
- [12] S. Sangal, A. Garg and D. Kumar, Review of Optimal Selection of Turbines for Hydroelectric, *International Journal of Emerging Technology and Advanced Engineering*, 3(3), 2013, 424-430.
- [13] C. Alatorre-Frenk, Cost Minimisation in Micro Hydro Systems Using Pumps-As-Turbines, PhD Thesis, University of Warwick, Faculty of Sciences, Department of Engineering, Coventry, United Kingdom. <http://go.warwick.ac.uk/wrap/36099>, 1994.
- [14] NMHP, Nepal Micro Hydro Power, Pump-as-Turbine Technology, ITDG, Nepal, 2005.
- [15] R. Pallabazzer and A. Sebbit, A Micro-hydro Pilot Plant for Mechanical Pumping, in *Hydropower in the New Millennium*, Bergen, Norway, Swets & Zeitlinger, 2001.
- [16] A. A. Williams, The Turbine Performance of Centrifugal Pumps: A Comparison of Prediction Methods, *Proceedings of the Institution of Mechanical Engineers, Part A. Journal of Power and Energy*, 208, 1994, 59-66.
- [17] J. M. Chapallaz, P. Eichenberger and G. Fischer, Manual on Pumps Used as Turbines, Vieweg, Braunschweig: Printed in the Federal Republic of Germany by Lengericher Handelsdruckerei, Lengerich, 1992.
- [18] C. Alatorre-Frenk and K. Troncoso-Torrez, Pequeños Hidráulicos Explotación for power generation. Diseño de One Microcentral for Tlaxiahuacan, BEng Thesis, University of Mexico, Faculty of Engineering, Mexico, 1989.
- [19] E. Schmiedl, Series Centrifugal Pumps in Turbine Operation, Pumps Meeting Karlsruhe [Section A6], 1988.
- [20] P. Hergt, A. Nicklas, H. D. Hellmann, J. Schill, D. Schmalzriedt, H. Hartmuller and H. Diederich, Status of the Boiler Feed Pump Development, in *15th Symposium of the SHMEC "Modern Technology in Hydraulic Energy Production"*, Belgrade, 1990.
- [21] S. Gopalakrishnan, Power Recovery Turbines for the Process Industry, in *3rd International Pump Symposium*, Houston, 1986.
- [22] K. R. Sharma, Small Hydro Electric Projects. Use of Centrifugal Pump as Turbines, Bangalore: Kirloskar Electric Co. Ltd, 1984.
- [23] B. M. McClaskey and J. A. Lundquist, Hydraulic Power Recovery Turbines, in *Joint Petroleum Mechanical*

- Engineering and Pressure Vessels and Piping Conference*, Mexico, 1976.
- [24] J. W. Hancock, Centrifugal Pump or Water Turbine, *Pipe Line News*, 1963, 25-32.
- [25] S. M. Childs, Convert Pumps to Turbines and Recover HP, *Hydrocarbon Processing and Petroleum Refiner*, 41(10), 1962, 173-177.
- [26] A. J. Stepanoff, Centrifugal and Axial Flow Pumps. Theory, Design and Application, 2 ed., New York: John Wiley & Sons, 1957.
- [27] S. Yang, F. Kong and B. Chen, Research on Pump Volute Design Method Using CFD, *International Journal of Rotating Machinery*, 2011, 1-7.
- [28] S. V. Jain and R. N. Patel, Investigations on Pump Running in Turbine Mode: A review of the state-of-the-art, *Renewable and Sustainable Energy Reviews*, 30, 2014, 841-868.
- [29] N. Smith, Motors as Generators for Micro-Hydropower, Southampton Row, London: Intermediate Technology Development Group, 2001.
- [30] P. Maher, Community Pico Hydro in Sub-Saharan Africa: Case Study 1. Kathamba, Kirinyaga District, Kenya, Micro Hydro Centre, The Nottingham Trent University, 2002.
- [31] M. Arriaga, Pump as Turbine - A Pico Hydro Alternative in Lao People's, *Renew Energy*, 35, 2010, 1109-1115.
- [32] A. A. Williams, Micro-hydro Applications in Rural Areas, OASYS-South Asia: Dundee Workshop, University of Nottingham, UK, 2011.
- [33] P. Maher, Community Pico Hydro in Sub-Saharan Africa: Case Study 2. Thima, Kirinyaga District, Kenya, Micro Hydro Centre, The Nottingham Trent University, 2002a.
- [34] N. Smith and G. Ranjitkar, Nepal Case Study-Part Two: Power Distribution, Safety and Costs, The Nottingham Trent University, Nottingham, UK, 2000.
- [35] C. Penche, Guide on How to Develop a Small Hydropower Plant, European Small Hydropower Association, [http://www.esha.be/fileadmin/esha\\_files/documents/publications/GUIDES/GUIDE\\_SHP/GUIDE\\_SHP\\_EN.pdf](http://www.esha.be/fileadmin/esha_files/documents/publications/GUIDES/GUIDE_SHP/GUIDE_SHP_EN.pdf), 1998.
- [36] Moody Diagram, [Online]. Available: [http://www.engineeringtoolbox.com/moody-diagram-d\\_618.html](http://www.engineeringtoolbox.com/moody-diagram-d_618.html) [Accessed 18/07/2016].
- [37] P. Smith and G. Ranjitkar, Nepal Case Study-Part One: Installation and Performance of the Pico Power Pack, The Nottingham Trent University, Nottingham, UK, 2000a.
- [38] A. Harvey, Micro-hydro Design Manual, Rugby: Intermediate Technology Publications, 2006.
- [39] J. Steller, A. Adamkowski, Z. Stankiewicz, A. Lojek, J. Rduch and M. Zarzycki, Pumps as Turbines for Hydraulic Energy Recovery and Small Hydropower, Poland, 2008.
- [40] K. H. Motwania, S. V. Jain and R. N. Patel, Cost Analysis of Pump as Turbine for Pico Hydropower Plants – a case study, *Procedia Engineering: Chemical, Civil and Mechanical Engineering Tracks of 3<sup>rd</sup> Nirma University International Conference (NUiCONE 2012)*, 51, 2013, 721-726.
- [41] R. S. Muttalli, S. Agrawal and H. Warudkar, CFD Simulation of Centrifugal Pump Impeller Using ANSYS-CFX, *International Journal of Innovative Research in Science, Engineering and Technology*, 3(8), 2014, 15553-15561.
- [42] A. Yadav and A. Appan, Electronic Load Controller as a Modern Governing Mechanism: A Review, *International Journal of Emerging Technology and Advanced Engineering*, 5(6), 2015, 218-225.
- [43] A. Carravetta, O. Fecarotta, G. Giudice and H. M. Ramos, Energy recovery in water systems by PATs: a comparisons among the different installation schemes, in *12<sup>th</sup> International Conference on Computing and Control for the Water Industry, CCWI2013*, 2014.
- [44] C. Nagpal, R. Basheer, A. Thomas, R. Daniel and I. Yusuf, Analysis and Design of Electronic Load Controllers Used in Micro Hydro Power Systems, *International Journal of Emerging Technology and Advanced Engineering*, 4(2), 2014, 26-31.
- [45] A. Carravetta, G. Giudice, O. Fecarotta and H. M. Ramos, Pump as Turbine (PAT) Design in Water Distribution Network by System Effectiveness, *Water*, 5, 2013, 1211-1225.
- [46] B. N. Roodsaria, E. P. Nowickia and P. Freereb, A New Electronic Load Controller for the Self-Excited Induction Generator to Decrease Stator Winding Stress, *Energy Procedia*, 57, 2013, 1455-1464.
- [47] A. Carravetta, G. Giudice, O. Fecarotta and H. M. Ramos, Energy Production in Water Distribution Networks: A PAT Design Strategy, *Water Resources Management*, 23, 2012, 1-15.
- [48] J. Laghari, H. Mokhlis, H. A. Bakar and H. Mohammad, Comparative Studies on Load Frequency Control for Islanded Distribution Network Connected with Mini Hydro, in *The 5<sup>th</sup> International Power Engineering and Optimization Conference 6-7 June*, Malaysia, 2011.
- [49] J. B. Patel, R. N. Mevada, D. Sardana and V. P. Rajput, Experimental and Numerical Investigation of Centrifugal Pump Performance in Reverse Mode, *International Journal of Advanced Technology in Engineering and Science*, 3(1), 2015, 1066-1072.
- [50] C. S. Kaunda, C. Z. Kimambo and T. K. Nielsen, Potential of Small-Scale Hydropower for Electricity Generation in Sub-Saharan Africa: Review Article, *International Scholarly Research Network: Renewable Energy*, 2012. 1-15.
- [51] G. A. Aggidis, E. Luchinskaya, R. Rothschild and D. C. Howard, The costs of small-scale hydro power production: Impact on the development of existing potential, *Renewable Energy*, 35, 2010, 2632-2638.
- [52] H. Nautiyal and V. A. Kumar, Reverse running pumps analytical, experimental and computational study: A review, *Renewable and Sustainable Energy Reviews*, 14, 2010, 2059-2067.
- [53] P. Singh, Optimization of Internal Hydraulics and of System Design for Pumps As Turbines with Field Implementation and Evaluation, Ph.D Dissertation, University of Karlsruhe, Karlsruhe, 2005.
- [54] Brazil, Hydropower from Pump-as-Turbines, Brazil, 2012. [http://csmres.co.uk/cs.public.upd/article-downloads/hydro\\_power-from-pumps-as-turbines.pdf](http://csmres.co.uk/cs.public.upd/article-downloads/hydro_power-from-pumps-as-turbines.pdf) [Accessed 02/04/2016].
- [55] S. Chuenchooklin, Development of Pico Hydropower Plant for Farming Village in Upstream Watershed, Thailand, in *Proceedings of Conference on Prosperity and Poverty in a Globalised World-Challenges for Agricultural Research*, Tropentag, Bonn, 2006.

- [56] A. A. Williams, N. A. Smith, C. Bird and M. Howard, Pumps as Turbines and Induction Motors as Generators for Energy Recovery in Water Supply Systems, *Journal of Chartered Institution of Water and Environmental management*, 1998, 175-178.
- [57] J. B. Bogdanovic-Jovanovic, D. R. Milenkovic, D. M. Svrkota, B. Bogdanovic and Z. T. Spasic, Pumps Used as Turbines: Power Recovery, Energy Efficiency, CFD Analysis, *Thermal Science*, 18(3), 2014, 1029-1040.
- [58] B. H. Teuteberg, Design of a Pump-As-Turbine Micro hydro System for an Abalone Farm, Final Report for Mechanical Project 878, Department of Mechanical and Mechatronic Engineering, Stellenbosch University, 2010.
- [59] R. Gravelle, Discharge Estimation: Techniques and Equipments, in *Geomorphological Techniques (Online Edition)*, London, British Society for Geomorphology, 2015.
- [60] F. F. Hooper and S. L. Kohler, Measurement of Stream Velocity and Discharge, in *Manual of Fisheries Survey Methods II: with periodic updates*, Fisheries Report 25, Ann Arbor, Michigan Department of Natural Resources, 2000.
- [61] WMO, World Meteorological Organization, Guide to Hydrological Practices: Hydrology – From Measurement to Hydrological Information, World Meteorological Organization, Geneva 2, Switzerland, 2008.
- [62] R. D. Moore, Introduction to Salt Dilution Gauging for Streamflow Measurement Part 2: Constant-rate Injection, *Streamline Watershed Management Bulletin*, 8(1), 2004, 11-15.
- [63] E. M. Shaw, *Hydrology in Practice*, 3rd edition., London: Chapman & Hall, 1994.
- [64] G. B. Adkins, *Flow Measurement Devices*, 2006.
- [65] K. G. Thibodeaux, Testing and Evaluation of Inexpensive Horizontal-axis Mechanical Current Meters, in *USCID Fourth International Conference*, 2007.
- [66] J. P. Michaud and M. Wierenga, Estimating Discharge and Stream Flows: A Guide for Sand and Gravel Operators, Ecology Publication Number. 05-10-070, 2005.
- [67] J. J. Peters, Field Measurements of Discharge and Velocity, *Discharge and Velocity Measurements*, 1988, 179-185.
- [68] M. Faraday, Experimental Researches in Electricity, *Quarterly Journal of Science and Philosophical Magazine. Philosophical Transactions*, 15, 193, 2175-177.
- [69] M. S. Chauhan, P. S. Dikshit and S. B. Dwivedi, Modeling of Discharge Distribution in Bend of Ganga River at Varanasi, *Computational Water, Energy, and Environmental Engineering*, 4, 2015, 25-37.
- [70] R. Schatzl, Comparison between Different Instruments for Discharge Measurements in Rivers, in *9<sup>th</sup> International Symposium on Ultrasonic Doppler Methods for Fluid Mechanics and Fluid Engineering*, 2014.
- [71] M. Meybeck, G. Friedrich, R. Thomas and D. Chapman, Rivers, in *Water Quality Assessments - A Guide to Use of Biota, Sediments and Water in Environmental Monitoring*, UNESCO/WHO/UNEP, 1996.
- [72] M. Yasar and N. O. Baykan, Prediction of Flow Duration Curves for Ungauged Basins with Quasi-Newton Method, *Journal of Water Resources and Protection*, 5, 2013, 97-100.
- [73] A. M. Younis and I. F. Hasan, Prediction of Flow Duration Curve for Seasonal Rivers in Iraq, *Jordan Journal of Civil Engineering*, 8(1), 2014, 29-42.
- [74] M. F. Muller, D. Dralle and S. E. Thompson, Analytical Model for Flow Duration Curves in Seasonally Dry Climates, *American Geophysical Union*, 2014, 1-18.
- [75] What is a Flow Duration Curve?, [Online]. Available: <https://www.renewablesfirst.co.uk/hydropower/hydropower-learning-centre/what-is-a-flow-duration-curve/> [Accessed 16/07/2016].
- [76] R. M. Vogel and N. M. Fennessey, Flow-Duration Curves I. New Interpretation and Confidence Intervals, *Journal of Water Resources Planning and Management*, 120( 4), 1994, 485-504.
- [77] J. K. Searcy, Flow-Duration Curves: Manual of Hydrology: Part 2. Low-Flow Techniques, Geological Survey Water-Supply paper 1542-A, 1969.
- [78] H. A. Mrope and J. Kihedu, Assessment of Hydropower Potential of Un-gauged Myombwe River Based on Hydrological Data, *International Journal of Innovative Research in Technology & Science*, 2(5), 2014, 47-54.
- [79] V. U. Smakhtin, Review Low Flow Hydrology: A Review, *Journal of Hydrology*, 240, 2001, 147-186.
- [80] H. A. Mrope and J. Kihedu, Matching the Energy Demand of Surrounding Villages with Hydropower Potential of the Un-Gauged Myombwe River, *Journal of Energy Technologies and Policy*, 5(10), 2015, 33-38.
- [81] IRA, Islamic Republic of Afghanistan, Ministry of Energy and Water, Technical Assistance Consultant's Report. Islamic Republic of Afghanistan: Power Sector Master Plan, FICHTNER GmbH & Co. KG, Germany. <http://www.adb.org/sites/default/files/project-document/76570/43497-012-afg-tacr.pdf>, 2013.
- [82] J. Portegijs, The Humming Bird Electronic Load Controller /Induction Generator Controller, 1999. Available: [http://microhydropower.net/mhp\\_group/portegijs/humbird/humb\\_main.html](http://microhydropower.net/mhp_group/portegijs/humbird/humb_main.html). [Accessed 13/04/2016].