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Optimal Sizing of Low Head Hydropower Plant- A Case Study of Hydropower Project at Head of UCC (Lower) at Bambanwala

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Abstract

Pakistan is facing serious shortfall of electricity for few decades. Small hydropower projects can alleviate the worsening situation. The sizing of a low head hydropower plant plays a vital role in establishing the feasibility of the project. The plant needs to be optimized for energy produced, efficiencies of the plant components, number of units and its financial/economic parameters. This paper presents a review on the methodologies by which low head hydropower plants are being optimized to get maximum energy output with minimal cost. The study of various researchers is being presented regarding optimal sizing and selection of small hydropower plant components. A brief summary of low head hydropower schemes in Punjab, Pakistan is also presented herein, which are presently under construction. Moreover based upon literature review and methodology adopted for the hydropower schemes in construction stage, using graphical optimization technique, optimal sizing for power site at Upper Chenab Canal Lower (UCCL) at Bambanwala is also presented. In this study a new parameter; inverse incremental energy is employed for selecting optimum flow. Two turbines (Kaplan, pit type) with combined capacity of 3.58MW are found to be optimal for the case study site.

Key Words: Optimal design; Low head hydro plant; Run-of-river; Upper Chenab Canal; Economic Internal Rate of Return

1. Introduction

The hydropower is a renewable source that significantly depends on the natural water cycle. Power generation using a hydropower scheme is the most promising power technology. The significant advantage of hydropower schemes is the flexibility in their designs that can work in various situations depending upon the hydrological conditions. The total potential of hydropower worldwide is estimated as 15,955 TWh/year [1]. Being the largest renewable energy source, hydropower is producing 16 % of the world's electricity. Presently, countries like China, Canada and United States are the largest hydropower producers [1].

Pakistan is confronting with severe shortfall of electrical power and it has been one of the most challenging problem for the past few decades. For sustainability of human life standards, energy and water are the prime factors. Pakistan has large hydropower potential either by low or by high head power projects. The total usage of energy estimated in 2006-07 was about 60 million tons of oil equivalent (mtoe). The rate of growth per capita has been escalated to 50% in the last decade. Pakistan meets its energy requirements around 41% by indigenous gas, 19% by oil, and 37% by hydro electricity. Due to large potential in Pakistan for hydropower generation, WAPDA has initiated feasibility studies and detailed designs for hydroelectric power projects with overall installed capacity of about 25,000 MW [2].

Mostly low head hydropower schemes being studied are run-of-river type with little or no storage of water and all diverted water returns to the parent stream after passing through the power scheme. The environmental impacts of the low head schemes are also minor. [3]. The Punjab Province alone has a potential of 5,895 MW on barrages and canal falls[4]. Due to enhanced interest of Government to harness this resource, it is considered necessary to review the methodology of optimization of power potential at a small hydropower project and to apply the methodology on a case study project.

The overall objective of the research is to review the optimization techniques of hydro turbines being employed all over the world. Moreover a brief review of methodology of small hydropower schemes under construction on Upper Chenab Canal, Pakistan is elaborated. Based upon above, a case study project at UCC (Lower) at Bambanwala RD 133+296 is selected to optimize energy produced using design discharge as the optimization parameter. After selection of design discharge, two scenarios (with respect to number of turbine units) are compared and best out of the two on the basis of EIRR is selected. The study will help the young engineers to carryout similar optimization for other projects.

2. Literature Review

Various researchers have put forwarded their effort to the optimal design of low head run-of-river hydropower plants.

Xiaohui Yuan et. Al. [5] designed a differential algorithm technique and chaotic law for optimization of hydro electric units for a hydropower scheme having three cascade falls in series. The objective function focused on minimization of the sum of deviation between load demand power potential throughout the whole day. It was concluded that the simulation results using differential algorithm technique shows better quality results than non linear programming and able to handle multiple variables simultaneously.

Xin-Ming Zhang et. al [6], developed a short-term self-optimization simulation model of cascaded hydropower system that balances generation and demand. The model was afterwards implemented on eight cascade in Jinsha river, China.

Ramesh et al. [7], developed a nonlinear simulation model for optimization of hydropower on series of reservoir and applied on a case study real time project at Manitoba, Canada. They concluded that impact of decision for operations at one reservoir have impact on another plant in the series.

Thomas et al [8] developed a reliability model for optimization of maintenance of hydro power components. The model simulation was based on Markov Chain solution which was applied to a case study project of Norway.

J. P. S. Catala˜o et al. [9], designed a nonlinear optimization model for power and energy for a case study project at Portuguese for run-of-the river cascade falls. It was concluded that linear programming ignore head dependency, however optimization using nonlinear technique consider head dependency and provides more realistic results.

Gingold [10], developed a model that concluded that the optimum design of a turbine is not fixed. This conclusion was based on the efficiency of the turbine which is different at various flow conditions that should be adopted from actual hill curves instead of taking a constant value of efficiency. According to Fahlbush [11], the optimal design of the turbine can only be obtained by maximization of the net energy benefit using an analytical solution of the problem.

Bleinc [12] presented computed programme designed to compute impact of hydrological parameters on power production and designed optimum sizing of the turbine. Papantonis and Andriotis [13] developed a numerical model which is based on the evolutionary algorithms approach that makes use of stochastic evolutionary algorithm for optimization of two turbines operating in parallel for specific hydraulic conditions. The numerical model was based on the two objective functions for maximization of energy and maximum exploitation of water potential together with economic. Using numerical simulation algorithm, various operation scenarios of multiple turbines to achieve maximum efficiencies of turbine units. The impact of variation in turbines sizes with efficiency was carried out. It was concluded that using multiple turbines of variable size may be more economical and enhance energy production. The study will be quite useful for similar studies in Pakistan.

More recently, Voros et al. [14] developed an empirical technique which was based on maximization of economic benefit of investment for computing physical characteristics of three commercial turbine (Pelton, Francis & Axial) and introduced a short-cut design equation for optimum flow rate and efficiency curves. This technique was applied on case study project on Kourtaliotis, Crete keeping in view its hydrogeological conditions and topology.

Montanari [15] has developed a procedure to achieve the best operation of hydraulic energy in low head sites. The method makes use of economic profitability indicators (Net Present Value, NPV), computed using plant parameters, flow rate, head, and the specific hydrologic features. The study will be useful for similar studies in Pakistan. Liu et al. [16] proposed an economic performance evaluation method for Hydropower Generating Units (HGUs). Several indicators for examining the performance of HGUs include such as ideal performance, reachable performance, etc. have been used. Kaldellis et al. [17], focused on the systematic investigation of the techno-economic viability of SHP stations. The study concludes that for enlightening the decision makers for local market sensitivity analysis should be properly conducted to ensure the feasibility of the project.

Roy et. al [18], using MATLAB fuzzy inference system developed a model for prioritization of preventive maintenance for hydropower generation in order to minimize down time and production cost. It was concluded that this novel approach is absent in engineering literatures because of its complexity.

Hosseini et al. [19] developed a model on MS Excel and MATLAB for computation of installed capacity of the turbine and its average annual energy for a case study project “Nari”(northern Iran).They optimized installed capacity and energy using model on MS Excel and then computed reliability indices based on number of units. Lopes de Almeida et al. [20] used non-linear programming, developed a SHP system numerical model for optimization. The programme not only determines the optimized installed capacity and plant characteristics but also provides risk analysis for the investor. Dursun, et al. [21] has examined that the small hydroelectric plants are more robust, environment friendly for regular development of Turkey. Shakir & Maqbool [22] also emphasized on the installation of low head hydropower generation on canal falls due to increased discharges after remodelling.

Boustani, [23] described the basic requirements for a low head hydropower projects. He envisaged that minimum two units are necessary to cater discharge during low and high flow periods. It was also suggested and concluded that the efficiency of the turbine is not constant at all flow period. However, it is changing with the change of discharge and water levels. This could only be maximized by optimizing number of units so that they operate at maximum efficiency level. The study has been utilized in the present case study at UCC Bambanwala power project.

Khan et al. (2012) have developed genetic algorithm based optimization model for optimization of rule curves for operation of reservoir for hydropower, irrigation and flood control.

Singal, et al. [25] computed economic viability of low head hydro plants on canals. They concluded that the major part of the total cost is due to electro-mechanical equipments that vary with the head. The study has been found useful in the present case study.

Mirza, Et al. [26] reviewed a survey of potential of hydro electric power generation in Pakistan. They concluded that about 350 MW potential is present on low head hydropower which is essential for the economic growth of Pakistan.

BING et. Al. [27], designed a 3-D numerical simulations for the determination of maximum efficiency of impeller of mixed flow turbines by the change of blade angle. The optimization employed various shape coefficients showed close convergence of the results. It was concluded that the maximum efficiency of mixed flow impeller is 87.2% having wide range of adjustment of blade angle and to avoid cavitations.

Bockman, et al. [28] developed a technique for the assessment of low head hydropower schemes. They envisaged that the rate of electricity prices are variable and if they are below a threshold value than its installment is unadvisable. Mardambey, [29] designed a small tool for small hydropower plants based on the hydrological parameters. He concluded that the primary governing factors are average monthly flow and corresponding water levels that will control the power optimization.

Andaroodi, [30] designed a graphical plot for the selection of turbine based on the head and discharge for initial assessment of the type of turbine to be selected. The study has been utilized for initial assessment of turbine selection. Paish, [31] developed technique for handling shortcomings in low head hydro plants. The considered plants upto 10MW and concluded that low head plants can be made viable and economical by local indigenization and putting effort for loan financing the project.

Numerous projects have been proposed on different canals of Punjab province, Pakistan, out of which three (3) projects on UCC are under construction. These include the following:

1. Marala UCC (0+000) Hydropower Project
2. Chianwali Hydropower Project
3. Deg Outfall Hydropower Project

These hydropower projects were considered as run-of-the river schemes as there is no storage on the upstream. Hydropower potential across these fall structures, has been utilized for power generation purpose. The Marala HPP lies at head of RD 0+000 (1 RD =1000 ft), Chianwali HPP at RD 128+000 and Deg Outfall HPP at RD 283+000 of the Upper Chenab Canal.32,33,34].

Graphical Optimization technique on MS Excel was adopted for determination of optimum power, energy and number of units [32,33,34]. Based on hydrological data (average monthly upstream and downstream discharges and water levels) for period from 1991-2004 (15 years) and hydraulic data (design parameters of fall structure and canal design parameters), computation of upstream discharge rating and downstream tail water rating was done. Using incremental discharges, incremental energy and power was computed for determining optimum discharge and number of units. A typical power generation curve of Marala Hydropower project is shown in Figure 1.

Economic Internal Rate of Return (EIRR) was considered as profitability indicator. Therefore, the optimal solution was envisaged to be one that produce maximum energy at lowest cost. The summary of significant parameters of these hydropower projects are given in Table 1.

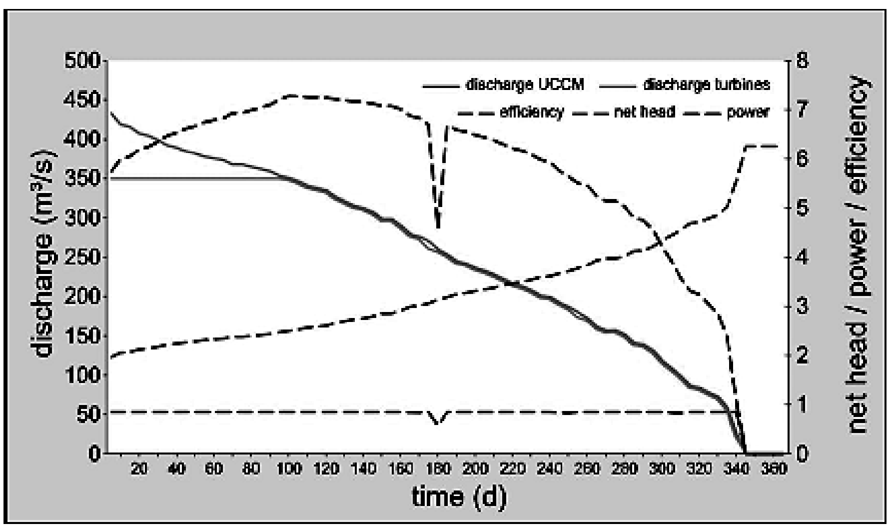

Fig. 1 Power Generation Curve [32]

Table 1: Summary of proposed HPPS on Upper Chenab Canal(UCC) in Punjab, Pakistan

Hydropower Station	Canal Design Discharge	Power House Discharge	Rated Head	No. of Units	Installed Capacity	Average Annual Energy	Runner Diameter	Total Cost	EIRR	Levelized Tarrif
	(m^3/s)	(m^3/s)	(m)		(MW)	(GWh)	(m)	(Mill. US$)	(%)	(Cent/KWh)
Marala HPP	447	350	2.56	4	7.2	48.52	3.9	18.3	14.7	3.97
Chianwali HPP	254	150	4.30	2	5.38	32.70	3.5	11.8	15.7	4.02
Deg Outfall HPP	230	150	4.02	2	5.00	29.13	3.5	11.1	14.5	4.32

Reference: ADB TA No. 4425-PAK Renewable Energy Development Project [32,33,34]

The resulting power and energy with respect to time is shown below in Figure 2.

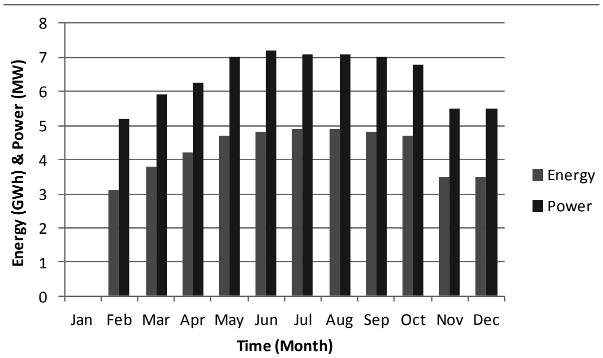

Fig. 2 Power Generation Curve [32]

Based on the literature survey made during this study, it is felt that researchers/designers have been using various methods such as analytical technique, non linear programming, shortcut design equations and graphical methods for optimization of low head hydro turbines. Therefore, there is much room available for further improvements that can be made through use of mathematical or evolutionary optimization techniques, especially in this region.

3. Design Approach & Methodology

The following pertinent steps will be carried out to arrive at an optimal design of case study hydropower project on Upper Chenab Canal at Bambanwala.

- Based on the hydrologic data of the scheme for 20 years, input rating curves will be plotted. These include discharge rating at upstream and downstream of the fall structure.
- Fluctuation in the 10-daily flows and water levels upstream and downstream will be plotted.
- Using long series of hydrologic data, flow duration curve will be plotted to establish relation between discharge and its availability in terms of percentage of time.
- Based on above, a graphical optimization model on MS Excel has been designed for power and energy computation.
- Rated discharge and head will be computed and selection of most suitable turbine will be carried out using standard chart being used by various manufacturers to categorize turbines against head and discharge.
- The power calculation has been based on single regulated and double regulated Kaplan turbines.
- The rated discharge will be optimized based on comparison of increment of energy with respect to change in discharge. A relationship between inverse incremental energy and discharge will be plotted to select the optimal discharge.
- The turbine operational limits for two possible options (2 units, 3 units) selected units of minimum and maximum discharges as well as heads available for power generation has been considered in estimation of energy generated.
- Best design discharge is selected using MS Excel spreadsheet, to optimize the installed capacity and average annual energy over a period of 20 years.
- Sizing of & operational limits for selected type of turbine (Kaplan pit type), will be carried out using US marketed software TURBNPRO (version 3.04). Based on the results of TURBNPRO the operational limits of head are again incorporated in the optimization model to refine production of energy.
- An average cost of major items has been taken from energy department for the similar type of projects in bidding stage for the year 2011. By applying inflation, the cost has been estimated for year 2014.
- Economic analysis will be carried out considering each selected rated discharge. Based on the best economic parameter most viable option will be selected having maximum EIRR.

4. Case Study of Hydro Power Plant at UCC Bambanwala

Based upon methodology adopted for power and energy estimation for above mentioned power sites, optimal sizing of Hydro power plant at head of Upper Chenab Canal Lower (UCC) at Bamanwala RD 133+296 is done which is described as follows.

The Upper Chenab Canal (UCC) off-takes from Marala barrage on the Chenab River. The construction of canal was completed in 1915. At the time of construction the design discharge of the canal was fixed at 340 m^3/s (12,000ft^3/s) which was increased to 477 m^3/s (16,850 ft^3/s) in 2006. The project location on UCC is shown in Figure 3.

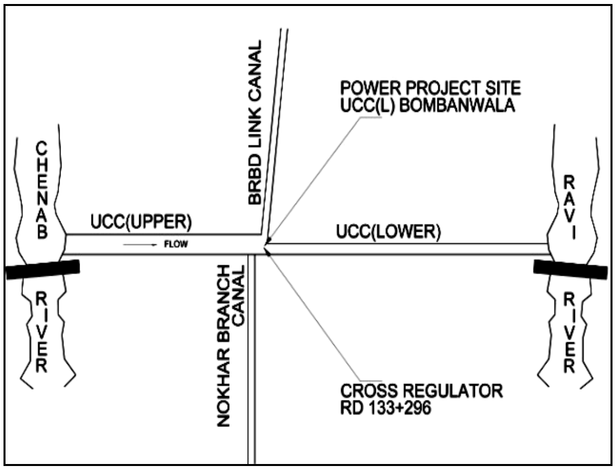

Fig. 3 Project Location on UCC

The UCC has been divided into two parts i.e. UCC Main (Upper) from RD 0+000 to RD 133+296 and UCC Main (Lower) from RD 133+296 to its confluence with the Ravi River. The Bambanwala Ravi Bedian Dipalpur (BRBD) link canal takes off from the left side of UCC cross regulator at RD 133+296 through Bambanwala regulator. Its design discharge is 206 m^3/s (7260 ft^3/s). The Nokhar branch canal regulator is on the right side of the UCC cross regulator opposite to Bambanwala regulator. The design discharge of Nokhar branch is 20.5 m^3/s (723 ft^3/s).

The design discharge of UCC Main (Upper) upstream of cross regulator is 321 m^3/s (11,325 ft^3/s), however, after diversion to the Nokhar and BRBD canals, downstream discharge reduces to only about 200 m^3/s (7,000 ft^3/s) in the UCC Main (Lower). A subsidiary weir at a distance of about 402 m (1320 ft) from the cross regulator was constructed in 2004 to control the erosion in the UCC Main (Lower) head reach.

A hydropower potential exists at the fall structure at RD 133+296. Salient features of the canal fall are given in Table 2.

Table 2 Salient Features of Fall at UCC(L) at RD 133+296

Bed level u/s of fall	234.74 m (770.16 ft)
Bed level d/s of fall	232.92 m (764.16 ft)
Height of fall	1.83 m (6.00 ft)
Design discharge d/s of fall	321 m^3/s (11,325 ft^3/s)
FSL at u/s of fall	238.70 m (783.11 ft)
FSL at d/s of fall	236.74 m (776.70 ft)
FSL at d/s of subsidiary weir	236.21 m (774.96 ft)
Difference in designed water levels	2.48 m (8.15 ft)
Crest level of fall	235.88 m (773.87 ft)
Crest level of subsidiary weir	235.42 m (772.37 ft)

The post-WAA (Water Apportionment Accord) data is considered relevant and has been analysed for use in this study. The hydrological data comprised of daily gage data and discharge data at RD 133+296 for the period 1991 to 2010. The Upper Chenab Canal is a perennial canal and water is available throughout the year for feeding the canal except during the annual closure period.

10 daily average flow and corresponding water levels has been taken for the period 1991-2010. The average 10-daily historic releases downstream of UCC RD 133+296 have been analyzed and shown in Figure 4.

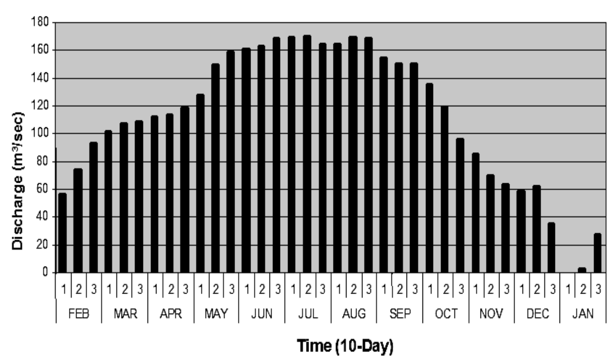

Fig. 4 10-Mean Daily Flows

The maximum discharges downstream of RD 133+296 exceeding 120 m^3/s are in the months of May to October while minimum are during Dec-Jan which is normally the canal closure period.

Flow duration curve has been prepared and shown in Figure 5. It shows the flow duration curve giving discharge against probability of exceeding.

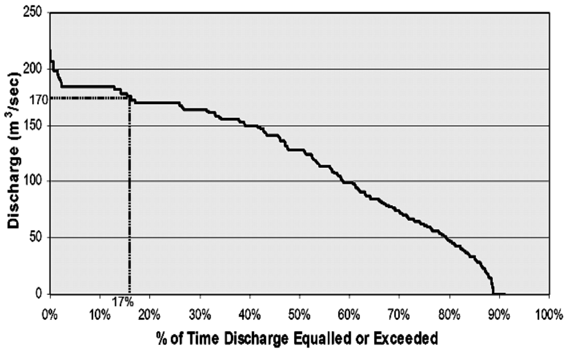

Fig. 5 Flow Duration Curve

Average 10-daily water level upstream of fall at RD 133+296 is shown in Figure 6.

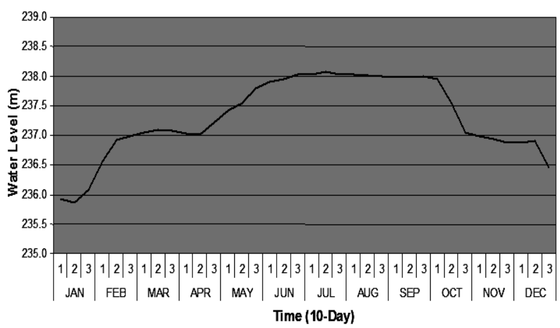

Fig. 6 10-Mean Daily Water Levels Upstream of RD 133+296

The tail water rating curve has been developed at downstream of subsidiary for a series of discharges presented in graphical form in Figure 7.

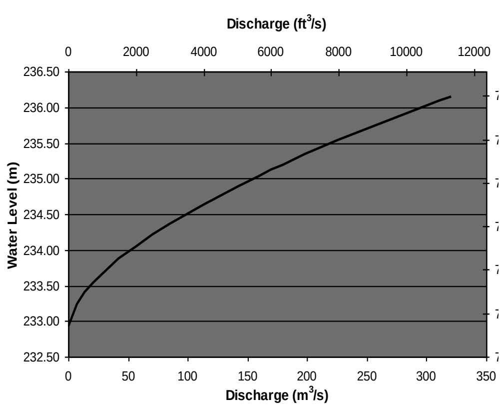

Fig. 7 Tail Water Rating Curve

The FSL of UCC upstream of fall at RD 133+296 of 238.69 m (783.11 ft) is estimated to undergo a drop of 0.50 m loss at intake weir and headrace channel while flowing towards the power house entrance. The resulting level at power house entrance will therefore be 238.20 m (781.49 ft). During normal operating conditions, tail water level will be 235.22 m (771.71 ft). The resulting net head available for power generation is therefore estimated as 2.98 m (9.78 ft).

5. Results

Graphical optimization technique has capability to optimize both linear and non-linear functions. This technique has been adopted for optimization of discharge and number of units by maximization of economic indicator i.e. Economic Internal Rate of Return (EIRR). Moreover, energy has also been optimized using design discharge as the optimization parameter in the study. The linear objective functions of power and energy which have been maximized through graphical optimization technique are shown as equation (1) and (2) respectively:

$$P = \gamma \times Q \times H \times \eta / 10^6 \quad (1)$$

Where:

P = Power (MW)

Q = Discharge (m^3/s)

H = Available gross head (m)

γ = Specific Weight of water (N/m^2)

η = Efficiency coefficient (%)

$$E = P \times T / 10^3 \ldots \quad (2)$$

Where:

E = Energy (GWh)

P = Power (MW)

T = Time (h)

5.1 Computation of Rated Discharge

Optimization studies have been carried out to size the plant. The observed 10-daily flow data for the period of 20 years along with the difference of upstream pond levels and computed tail water levels have been used for calculating the power, energy and plant factor to determine the incremental power and energy. The variation of the power, energy, inverse of incremental energy and the rated head with discharge are shown in Figure 8. The methodology presented in the UCC (RD 133+296) is quite similar to the one implements for the optimal sizing at 03 projects in construction stage enumerated in section 4, however two improvements have been made that include, computation of optimized power and discharge using 10-Daily average discharges and water levels instead of monthly basis and plotting of inverse of incremental energy that gives more clear identification of cut off point for selection of optimized discharge.

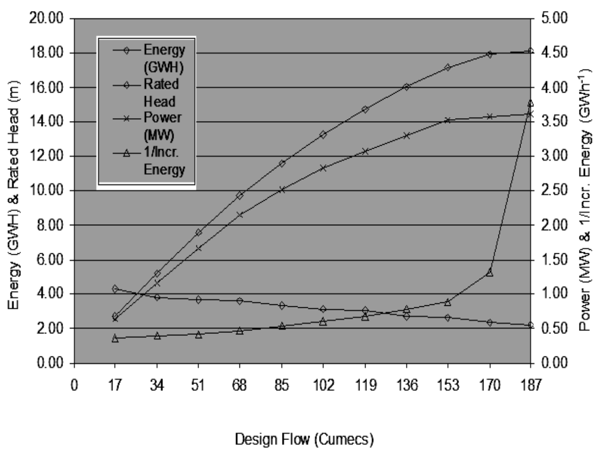

Fig. 8 Power, Average Annual Energy & Rated Head Variations with Discharge

It is clear from the Figure 8 that beyond a discharge of 170 m^3/s, there is no significant increase in energy with incremental flows. It is also clear from the plot of inverse of incremental energy that the increase in annual energy generation reduces steeply beyond discharge of 170 m^3/s. Therefore, 170 m^3/s has been selected as the design discharge.

5.2 Optimization of Number of Units

Based on the adopted design discharge of 170 m^3/s, options of two and three horizontal shaft double regulated pit turbines have been considered.

Comparison of main parameters of powerhouse for both the options is shown in Table 3. Increase in the number of units increases the project cost, due to the increase in the number of electro-mechanical equipment and the size of the powerhouse. Increasing number of units from two to three would also increase the operation and maintenance costs. In view of the foregoing, two turbine units will be considered suitable for the powerhouse

Table 3 Comparison of Number of Units

Number of units	2	3
Design Discharge, (m^3/s)	170	170
Rated Head, (m)	2.39	2.39
Discharge per turbine, (m^3/s)	85	56.66
Turbine Discharge limits, (m^3/s)	21.25 – 85	14.2–56.7
Head limits, (m)	1.4 – 3.5	1.4 – 3.5

The design discharge for each of the two turbines is 85 m^3/s which has a probability of exceedence of about 65 percent.

5.3 Selection of the Turbine Type

The available head across and discharge variations are the main factors leading to selection of type of turbines. Figure 9 shows the industry standard chart normally used for selection of type of turbines based on the head and discharge.

The rated head and the rated discharge as determined by power optimization study when plotted on Figure 9 clearly indicates that Kaplan horizontal pit type axial turbine is most suitable. The pit type horizontal unit rather than the bulb type horizontal unit has been selected for the following reasons.

- As compared to the closed bulb unit a pit installation has an open-topped bulb, permitting easy access to the generator for repairs and maintenance. The runner can be removed for maintenance without removing the generator in pit turbine unit.
- As the head and discharge range of the site are on the lower side, speed of the turbine becomes considerably low. To keep the generator size within reasonable limits, a speed increaser for the generator is required. This can only be utilised by selecting the pit turbine unit.

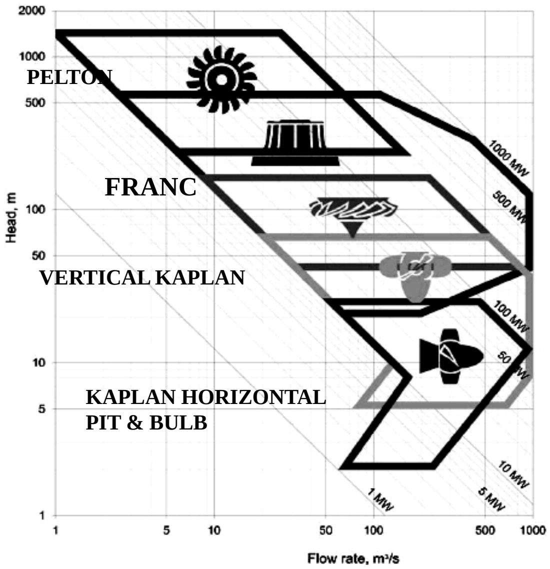

Fig. 9 Selection of Turbine Based on Discharge and Head [35]

5.4 Turbine Sizing

For plant sizing, commercial software 'TURBNPRO (Version 3.04) [36], was used to determine turbine size, speed, hill curves, setting below minimum tail water level, dimensional characteristics of turbine.

Following data were used as input to the TURBNPRO software to determine the turbine size

- Rated discharge 85 m^3/s
- Net head at rated discharge 2.39 m
- Maximum head across 5.16 m
- (pond level – bed level)
- Site elevation 229.00 m amsl
- Setting to tail water -4.0 m

The turbine solution obtained after analysis is as under:

Type of turbine	Horizontal Pit
Unit regulation capability	Kaplan
Draft Tube Type	Straight
Runner diameter	3,988 mm
Turbine operation limitation head	1.4 m – 3.5 m
Unit speed	83.3 rpm
No of blades	3
Runner hub diameter	1,608 mm
Rated turbine output	1.788 MW
Turbine efficiency	89.7 %
Installed capacity	3.58 MW

The average annual energy generated is 17.19 GWh, the installed capacity as 3.58 MW and therefore, the plant factor is 54.76 percent.

5.5 Project Cost and Economic Internal Rate of Return (EIRR)

The average bidding cost of low head hydropower projects has been taken from Punjab Power Management Unit (PPMU) for sites in construction stage, and is for computation of EIRR for Upper Chenab Canal case study. The cost of Rs.1311 Million has been taken for year 2014 comprising civil works is Rs. 669 Million and E&M costs are Rs. 445 million. This cost has been inflated based upon Pakistan Economic Survey (2013-2014) [37], by applying customer price index of 10.428% and using 1US Dollar = Rs. 98.85, which comes out to be Rs. 1725 Million. The construction period for the scheme is assumed as 32 months whereas the useful life of the project is assumed as thirty (30) years. Based upon the small hydropower station under construction stage, at UCC the foreign component is considered 38% of the total cost. The cost has been phased as 25%, 45% and 30% for the first, second and third year of construction, respectively. Based upon the evaluated cost and average annual energy of 17.19 GWh, Economic Internal Rate of Return (EIRR) is computed as 13.12%. This shows that the project is technically and economically viable.

The summary of pertinent parameters of optimized hydropower of UCC Bambanwala are tabulated in Table 4.

Table 4 Summary of Pertinent Parameters of the UCC Hydropower Scheme at Bambanwala

Canal Design Discharge		m^3/s (ft^3/s)	321 (11,325)
Power House Design Discharge		m^3/s (ft^3/s)	170 (6003)
Probability of Occurrence		(%age)	17.02
Net Head at PH Design Discharge		m (ft)	2.39 (7.84)
Installed Units Capacity		(No. x MW)	2 x 1.79 = 3.58
Turbine Configuration	Runner Dia.	m (ft)	3.988 (13.08)
	Speed	(rpm)	83.3
Average Annual Energy Generated		(GWh)	17.19
Plant Factor		(%age)	54.76
Project Cost		M. Rs	1725
EIRR		(%age)	13.12

6. Conclusions & Recommendations

1 The researchers/designers have been using different ad-hoc methodologies for achieving optimal design of hydropower schemes. However, there is much room for improvement in the conventional optimization process through use of mathematical and evolutionary optimization techniques. The present study uses a new parameter; *inverse incremental energy*, for the optimization of discharge.

2 Using graphical optimization technique to maximize energy and EIRR, it is found that 3.58 MW hydropower plant with EIRR of 13.12% on UCC at Bambanwala using Kaplan Pit type turbine with 2 units of equal size is technically and economically feasible

3 Based on current study; the Kaplan pit type turbine and graphical optimization technique are considered suitable for computing the optimal size of turbines for future similar low head hydropower schemes.

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