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Cost analysis of pump as turbine for pico hydropower plants – a case study

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Abstract

The energy scenario in rural, remote and hilly areas of India is characterized by inadequate, poor and unreliable supply of energy services. In such regions, the load density is low and extension of grid system is totally uneconomical, hence the small hydropower schemes can provide a solution for the energy problems besides solar photovoltaic, which is not available throughout the day. The main hindrance in implementing such hydropower schemes is high initial cost of conventional hydro turbines. The cost of these plants can be brought down by using centrifugal pump in turbine mode in context of various advantages associated with the pumps viz. low initial and maintenance cost, ready availability, simple construction etc. However, the efficiency of pump as turbine (PAT) is lower than that of conventional hydro turbines. For commercial justification of PAT technology, a cost analysis of 3 kW capacity pico hydropower plant was carried out by considering PAT and Francis turbine as a prime mover. The hydro turbine test rig was developed by installing PAT and its performance characteristics were plotted. The annual life cycle cost (ALCC) analysis was carried out based on initial cost of the project, capital recovery factor and annual expenses. Based on the analysis, the ALCC and the cost of electricity generated per unit were found to be very less for PAT than that of Francis turbine, which has justified the use of PAT for the case under consideration.

Keywords: Case study; cost analysis; pico hydropower; pump as turbine; renewable energy.

Nomenclature

g	acceleration due to gravity (m/s^2)
n	speed (rps)
D	runner diameter (m)
H	head (m)
L	life (years)
P	power (W)
Q	discharge (m^3/s)
Greek symbols	
Ψ	head number
ø	discharge number
π	power number
ρ	density (kg/m^3)
η	efficiency (%)

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1. Introduction

The development of any country depends upon availability of electrical energy and its per capita energy consumption, which is regarded as an index of national standard of living in the present civilization. Therefore, energy is considered as the basic input for any country for keeping the wheels of its economy moving. In rural, remote and hilly areas of India, power scenario is characterized by poor and unreliable supply of energy. Out of total 138.27 million rural households in the country; only around 56 per cent are electrified so far. There are only six states with more than 75 percent of rural households electrified; however, these states account for a meager 6 percent of the country's total rural households. There are many states with about 80 per cent unelectrified households, which constitute 43 per cent of the total rural households in the country [1].

India is fairly rich in natural sources like coal, lignite, natural gas and has immense of water power resources. The current power installed capacity in India is 2,06,456 MW; in which thermal contributes to around: 67%, hydro: 19%, nuclear: 2% and other renewable energy sources: 12% [2]. A large number of thermal power plants are running throughout the world for electricity generation on petroleum products e.g. coal, oil, gas etc., but the fast depleting nature, continuously increasing prices and global warming issues are the major complications in fulfilling the power demands from these sources. Also, delivered cost of electricity produced by thermal power plants in remote areas located in the distance range of 5-25 km is found to vary from Rs. 3.18/kWh to Rs. 231.14/kWh depending on peak electrical load and load factor [3].

World has started running out of oil and it is estimated that 80% of the world's supply will be consumed in our lifetime. Moreover, the pollution hazard arising out of fossil fuel-burning has become quite significant in recent years. Thus, it has become utmost important to look for renewable energy sources such as hydro, solar, wind and energy from ocean tides. Among all the available renewable energy sources, hydropower is considered as the most promising source of energy. India's total mean annual river flows are about 1675 X 10^9 m^3 of which the usable resources are 555 X 10^9 m^3 [4].

Large hydropower plants suffers from several problems like long gestation period, ecological changes, loss due to long transmission lines, submergence of valuable forest and underground mineral resources etc. [5]. Due to all these factors, large hydropower plants are becoming unfavourable in the current era. On the other hand, small/micro/mini/pico hydropower projects are free from these aspects. Different countries are classifying small hydropower (SHP) according to the total capacity of the plant. In India, pico-hydro is defined as hydroelectric power generation under 5 kW capacity [6]. A pico-hydro power system can provide electricity to a small, remote community for basic requirements like lighting of bulbs, radios, televisions and can also be used for many other applications. These small units were not more in use for many years, but recent increase in the demand of energy has forced to use such energy from which power can be obtained easily and in cheaper form.

The cost of electro-mechanical components in large hydro is around 20% but in micro hydro it is relatively high and varies from 35-40% of the total project cost [7]. Hence, main hindrance in implementing such hydropower schemes is high initial cost of conventional hydro turbines. The cost of these plants can be brought down by using PAT in context of various advantages associated with the pumps viz. low cost, less complexity, mass production, availability for a wide range of heads and flows, short delivery time, availability in a large number of standard sizes, ease of availability of spare parts, easy installation etc. [8-9].

The efficiency of pump in turbine mode is usually lower than that of conventional hydro turbines; however, the efficiency of such machine is not the primary selection criterion and the operation of PAT is recommended at the maximum attainable efficiency. Also, up to 100 kW capacity power plants, the use of PAT may be justifiable because, even though efficiency of PAT is lower, its use may lead to significant reduction in the capital cost of the plant, of the order of 10 to 1 or even more [10]. In this range, the investment cost for conventional hydro turbines is relatively high and the payback period can be as high as 15 years which can be reduced to 3 years using PAT [11]. Also, if PATs are used in the range of 1 to 500 kW the payback periods can be further reduced to two years or less which is considerably less than that of a conventional turbine [12-13].

For commercial justification of PAT technology, it is utmost important to carry out cost analysis of hydropower plant between PAT and conventional hydro turbine. In this paper, experimental studies carried out on 3 kW capacity pico hydro turbine test rig by installing PAT at Institute of Technology, Nirma University, Ahmedabad are presented. The ALCC analysis carried out, between PAT and Francis turbine, based on initial cost of the project, capital recovery factor and annual expenses is discussed.

2. Pump as turbine

In pumping mode, the fluid enters at suction side of pump at low pressure and gets energized by the impeller, which is rotated by some external means, and leaves the casing at high pressure. Whereas in case of PAT, the pump rotates in reverse direction, water enters in the pump at very high pressure from the casing and moves through the impeller blades and releases its pressure and kinetic energy to the impeller shaft as mechanical energy and fluid comes out from the eye of pump at low pressure.

The research on using PAT started around 1930 and the main challenge in PAT usage was the selection of a proper PAT for a small hydro-site [14]. In 1931, when Thoma and Kittredge [15] were performing the experiments on the pumps, they accidentally found that pumps can be operated very efficiently in the turbine mode also. The turbine mode operation of pump has became an important research question for many manufacturers as pumps were prone to abnormal operating conditions [13]. Knapp [16] published the performance characteristics for a few pumps based on experimental investigation. Stepanoff [17] reported the concept of various modes of pump operation in the form of four-quadrant performance curves.

In the reverse operation of pump it may be less efficient because the direction of flow is reversed and hydraulic and frictional losses increase sharply. The main difference in the pump and turbine design is that, conventional turbines having one or two flow control mechanism to increase its part load efficiency but the standard pumps are not having any flow control mechanism to increase its part load efficiency. The initial cost of the machine affects the cost of the hydropower plants only in initial phase of the project; however, the lower efficiency of the machine affects the plant on daily basis. Hence, to justify the use of PAT in pico hydropower plants, it is required to carry out the detailed cost analysis. Few researches have carried out cost analysis of micro/pico hydropower plants by considering the use of conventional hydro turbine and an equivalent PAT.

Frenk [18] carried out cost analysis of micro hydropower plant based on PAT and conventional hydro turbine. The cost of the scheme was considered as the sum of the initial investments in turbomachinery, penstock, storage reservoir and miscellaneous items. These costs were considered as a function of the size of the scheme, which indirectly depends on the rated flow, and the lifetime was assumed to be same for all the cases. The yearly operation and maintenance costs were considered as a fixed proportion of the initial investment for all the cases. It was found that, in spite of the lack of flow control devices in PATs, usually the large reduction in cost makes them more economical than conventional machines.

Chuenchooklin [19] presented the cost analysis for 1.116 kW capacity Pico hydropower plant for a farming village in Thailand, where pump was installed as turbine. The construction cost of the project was approximately US$ 4000 (45% for pipe systems, 37% for control and electricity systems and 18% for pump and turbine systems). Based on the overall electricity consumption of 8760 kWh per year and electricity charges of US 0.75 cent per kWh, the economic recovery period was estimated as 6 years. The results showed that the produced electricity was enough for the indoor electrical appliances such as electric light and some house-ware appliances. It was recommended to install PAT based pico/micro/mini hydropower plants in larger farming villages where higher head and larger flow rate are available depending on the topography characteristics.

Maher et al. [20] carried out cost comparison of different off-grid electricity generation options viz. PAT based pico hydro plant, solar home system and battery system in a rural area of Kenya. The annual life cycle cost (LCC) and cost per kWh were worked out for different options by considering the installation cost, life of the system and annual maintenance and operation costs. From the analysis, a PAT based pico hydro plant was found to be more cost effective, at less than half the installed cost per household, than an equivalent solar power system. The cost per kWh was worked out to be less than 15% of that from the cheapest solar home system, which puts it within the reach of most low-income households.

Arriaga [21] carried out the cost analysis of a 2 kW project in the Lao People's Democratic Republic for isolated communities (40–500 people). Three options were considered for the analysis viz. power generation from hydro resources using PAT and Vietnamese turbine and solar energy using PV panels. The costs were divided in energy generating equipment (EGE), civil works (CW) and energy distribution costs. From the analysis, the lowest installation cost was found in case of PAT while the PV approach was subjected to the highest investment cost. It was concluded that, the proposed PAT based hydropower project can provide a long-term reproducible system for rural communities.

3. Implementation of pico hydropower plant

The design and implementation of 3 kW capacity pico hydropower plant was done at Institute of Technology, Nirma University, Ahmedabad. The experimental test rig consisted of service pump, electromagnetic flow meter (for discharge measurement), pressure and vacuum gauges (for head measurement), PAT, draft tube, D. C. Generator and piping system. A single stage end suction centrifugal pump (head: 15 m, discharge: 1500 LPM) was selected to run in turbine mode. A resistive load bank with rheostat was used to apply the load on the PAT. The schematic diagram of the experimental setup is shown in the Fig. 1.

The performance characteristic curves of PAT were plotted at constant speed of 1500 rpm. To plot these curves, the load on the turbine was gradually increased which lead to decrease of speed. To maintain the constant speed, the discharge was increased accordingly by opening the gate valve. The experimental results are presented in the form of non-dimensional

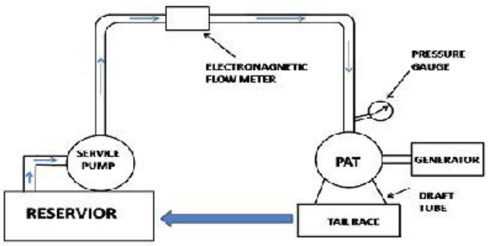

Fig. 1. Schematic diagram of experimental setup.

parameters viz. head number (Ψ), discharge number (ø), power number (π), which are defined in Eq.s (1)-(3). After performing the experiments on pump in turbine mode, overall efficiency of PAT was found to be 60% which is considered to carry out the cost analysis. The experimental graphs are shown in Fig. 2.

$$\psi = gH/n^2d^2 \tag{1}$$

$$\phi = Q/nD^3 \tag{2}$$

$$\pi = P/\rho n^3D^5 \tag{3}$$

(a) (b)

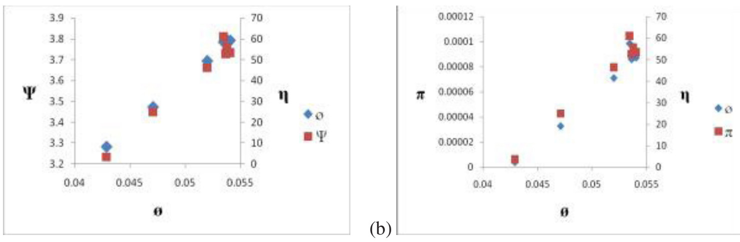

Fig. 2. (a) Head number and efficiency curves (b) power number and efficiency curves.

4. Cost analysis of 3 kW capacity pico hydropower plant – a case study

The maximum overall efficiency of PAT was found to be around 60 percent which is low in comparison with that of conventional hydro turbine (Francis turbine) which is around 70-85 percent [22]. To justify the use of PAT in pico/micro hydropower plants, annual life cycle cost analysis of 3 kW capacity pico hydropower plant was carried out as a case study by considering two options for prime mover i.e. Francis turbine and an equivalent capacity PAT.

4.1. Parameters considered in the cost analysis [23]

4.1.1. Initial cost of project

Initial cost of the project (Co) includes the cost of machine, civil work, building and miscellaneous items. In the present analysis, the costs of civil works, building and miscellaneous items were not considered assuming that these costs remain same for both the options. Hence, only initial cost of machine was considered for the analysis.

4.1.2. Capital recovery factor

The capital recovery factor (CRF) enables the determination of the annualized value equivalent to the initial investment. The CRF depends on the equipment life (L) in years and discount rate (d). It was calculated using Eq. (4).

$$CRF = \frac{d(1+d)^L}{(1+d)^L - 1} \tag{4}$$

4.1.3. Annual expenses

The annual expenses (Ac) include costs of operation, maintenance, fuel, man power and miscellaneous items for the given year. For hydropower plants, fuel cost is zero as no fuel is required. In the analysis, the costs of manpower and miscellaneous items were not considered assuming that these costs remain same for both the cases. Hence, in the analysis only operation cost (~ 5 % of initial cost) and maintenance cost (~ 10 % of initial cost) were considered as annual expenses.

4.1.4. Discount rate

The discount rate (d) represents how money is worth more at present than that in the future. The discount rate determines how any future cash flow is discounted or reduced to make it correspond to an equivalent amount today. The discount rate would always be higher than the bank interest rate as the bank interest rate represents the minimum return available by placing the money in a bank account. The CRF was calculated considering 12% annual discount rate.

4.1.5. Annual life cycle cost

It is the present value of all expenses related to a specific option during its lifetime. To compute this, present value of the annual expenditures was added to the initial investment. The annual expenditures included the energy, maintenance, labour and other costs. Generally, ALCC is used when two different options have same operation but their life is different, which is applicable in the present case. It was calculated using Eq. (5).

$$ALCC = (Co \times CRF) + Ac \tag{5}$$

4.1.6. Annual energy generated

The Annual energy generated (Ae) was worked out as the product of energy generated per hour and number of hours per year for which energy can be generated.

4.1.7. Cost of electricity generated per unit

Cost of electricity generated per unit (C) was worked out using Eq. (6).

$$C = ALCC/ Ae \tag{6}$$

4.2. ALCC analysis of pico hydropower plant

To check the economic feasibility of both the options, i.e. Francis turbine and PAT, ALCC method was used because both the options are having different life span. The equipment life (L) of PAT and Francis turbines was considered as 10 and 25 years respectively. Various data pertaining to cost, life, efficiency etc. for pump and turbine were considered in consultation with M/s Kirloskar Brothers Ltd, Pune. The details/assumptions of various parameters for Pump (running as turbine) and hydro turbine (Francis turbine) are given in Table 1. Based on these parameters, the ALCC was calculated for both the options as presented in Table 2.

Table 1. Parameter for pump (running in turbine mode) and Francis turbine

Parameter	PAT	Francis turbine
Capacity (kW)	3 kW	3 kW
Overall Efficiency (%)	60 %	80 %
Initial cost – Co (Rs)	25000/-	200000/-
Life – L (yrs)	10	25
Discount rate-d (%)	12	12
Hours of energy generation = No. of hrs/ day X No. of days/ year	24 X 200	24 X 200

Table 2. ALCC for pump (running in turbine mode) and Francis turbine

Parameter	Equation	Pump (running in turbine mode)	Francis Turbine
CRF	CRF = $d(1+d)^L / (1+d)^L - 1$	0.176984	0.1275
Annual Expenses Rs	Operation Cost @ 5% + Maintenance Cost @ 10%	2500 + 1250 = 3750 Rs	20000+10000 =30000 Rs
ALCC	ALCC= (CO * CRF) + Ac	Rs 8174.60	Rs 55000
Annual Energy Generation (KWh/Yr)	Capacity * Overall Efficiency * No of Hrs/ day * No of Days/ Yr	3*0.6*24*200 = 8640 Rs	3*0.8*24*200 = 11520 Rs
Cost of Electricity Generation	ALCC/Annual Energy Generation	Rs 0.95	Rs 4.82

5. Conclusions

Rural electrification is the first step towards the prosperity of any developing country. In view of this, a 3 kW capacity pico hydro test rig was developed by installing the PAT and maximum overall efficiency of PAT was found to be around 60 percent which is lower than that of Francis turbine, which is around 80 percent. However in pico hydro range, the cost of Francis turbine may be 6 to 8 times more than that of the centrifugal pump. For economical justification of PAT, annual life cycle cost analysis was carried out as a case study by considering both the options. Based on the analysis, the ratio of ALCC and the cost of electricity generated per unit between Francis turbine and PAT were found to be 6.8 and 5.07 respectively, which has justified the use of PAT in place of Francis turbine for the considered case under study. Considering these factors as well as various advantages associated with centrifugal pumps like ease of availability, low initial and maintenance cost, wide range of operation etc. application of PAT is recommended at the maximum efficiency point in pico/micro hydro range for power generation in rural, remote and hilly areas. The findings of the present study may be useful to the researchers working in the similar area.

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