A Comparison of Prediction Methods for Design of Pump as Turbine for Small Hydro Plant: Implemented Plant

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Abstract. In developing countries, small and micro hydropower plants are very effective source for electricity generation with energy pay-back time (EPBT) less than other conventional electricity generation systems. Using pump as turbine (PAT) is an attractive, significant and cost-effective alternative. Pump manufacturers do not normally provide the characteristic curves of their pumps working as turbines. Therefore, choosing an appropriate Pump to work as a turbine is essential in implementing the small-hydro plants. In this paper, in order to find the best fitting method to choose a PAT, the results of a small-hydro plant implemented on the by-pass of a Pressure Reducing Valve (PRV) in Urmia city in Iran are presented. Some of the prediction methods of Best Efficiency Point of PATs are derived. Then, the results of implemented project have been compared to the prediction methods results and the deviation of from measured data were considered and discussed and the best method that predicts the specifications of PAT more accurately determined. Finally, the energy pay-back time for the plant is calculated.

1. Introduction

About 81% of the total primary energy supply in the world is obtained through fossil fuels. In 2014 about 32,381 million tons of CO₂ are emitted through the world. Iran relies mainly on fossil fuels based energy production due to high reserves of oil and natural gas in the country. Around 16.4% of the electricity generation in world is through hydro power [1]. At the moment In Iran, just about 0.34% of total primary energy supply is obtained through hydro power [2]. Conventional production with fossil fuels presents problems associated with the high cost, rapid depletion and detrimental environmental effects of these fuels. Renewable energy is probably the best solution. Due to rapid increase in energy consumption, the requirement of such alternatives for electricity generation has been increased.

It has been estimated that RE technologies can generate sufficient energy to fulfil all electricity demand in Iran by the year 2030 at a price level of 40.3–45.3 €/MWh, depending on the sectoral integration [3].

Among all renewable resources, small hydropower (SHP) is one of the most promising sources of energy generation. In developing countries, small and micro hydropower plants are very effective source for electricity generation. The energy pay-back time (EPBT) and greenhouse gas (GHG) emissions for SHP generation system are less than other conventional electricity generation system [4]. So, encouragement of small hydropower schemes can solve the problem of energy crises of the country. Different countries are following different criteria to classify hydro power plants. Although definitions vary, The United States Department of Energy (DOE) defines A Classification of hydro power plants, as follows in Table 1 [5]:
Greek Symbols

| Symbol | Description   |
|--------|---------------|
| Q      | discharge, m³/s |
| H      | head, m       |
| N_s   | specific speed, (m, m³/s) |
| D      | impeller diameter, m |
| BEP    | best efficiency point |
| g      | gravitational acceleration, m/s² |
| n      | rotational speed, rps |
| N      | rotational speed, rpm |
| PAT    | pump as turbine |
| P      | power, kW     |
| GHG    | Green House Gas |
| O&M    | Operation and Maintenance |

Subscripts

| Symbol | Description   |
|--------|---------------|
| n      | rotational speed, rps |
| t      | rotational speed, rpm |

Using centrifugal pumps in reverse is one of the efficient alternatives for recovering Electricity through small and micro hydro powers. The concept of electricity generation through reverse running centrifugal pump is not new. Around 80 years ago, the research on this field had been started [6].

In this paper, some of the prediction methods of BEP of PATs are derived. Besides, the measured data of a small-hydro site implemented on the by-pass of a Pressure Reducing Valve (PRV) in Urmia city in Iran are presented. The aim is evaluation of deviations between the prediction methods and the measured data in order to identify the more accurate methods. The results of implemented project have been compared to the prediction methods results available in the literature and the best method that predicts the specifications of PAT more accurately determined. Finally, the energy pay-back time for the implemented small-hydro plant is calculated.

2. Typical turbines

Hydropower systems generate electrical energy by converting the energy of falling water to mechanical energy with a turbine and from mechanical to electrical energy by generators coupled to turbines.

The turbine is situated after the pipeline and can be either classified as low or high head. With high head systems normally using turbines such as Pelton wheels or Turgo runners, according to Western North Carolina Renewable Energy Initiative [7]. Low head systems typically use Francis, Kaplan or crossflow turbines to turn the generator. A rough guide to turbine choice is given in Fig.1 (a).

3. Pump as turbines

Using pump as turbine (PAT) is an attractive and significant alternative [8]. In such a system a pump is operated in reverse so that is functions as a turbine. This is especially popular in areas where the availability of turbines is limited as pumps are typically easier to get hold of [9].

Pumps are relatively simple and easy to maintain. They also have a competitive maximum efficiency when compared to conventional turbines [8]. The mass production of pumps means that they are comparatively much more cost-effective than conventional turbines [10].

3.1. Advantages and limitations of PAT
Pumps are relatively simple machines and available in a wide range of duties. They are easily installed, operated, maintained and repaired. Besides they are available at lower cost and cheap from economical point of view. And the Capital payback period of PATs in the range of 5–500 kW is two years or less [8] [11].

The main disadvantage of PAT Is that the characteristics curves in turbine mode are not usually supplied with the pump [12]. Besides they are not as well documented as turbines. Manufacturers do not provide the characteristic of the pump running in reverse. Pump operates in turbine mode with higher head and discharge at the same rotational speed [13].

4. PAT field applications and overview on prediction methods

Due to inadequate experimental data for pumps working as turbines, the field applications of these machines are not yet well defined [8]. There are many different types of pumps that can be used as a turbine. Fig. 1 (b) gives the rough guide to aid the choice [14]. Many correlations based on theoretical approaches are available to predict the performance of a PAT. Several researchers have presented correlations for predicting the performance of a pump-as-turbine [20].

![Figure 1](image_url)

**Figure 1.** (a) Rough guide to turbine type operating ranges; (b) Choice of pumps for PAT [14]

In the following equations different methods of prediction pump reverse characteristics are presented. They are based on theoretical or experimental analyses. This equations calculate the head, flow rate at the BEP in reverse mode using the efficiency, head and flow rate value at the BEP in direct mode. Correlations are presented by following (Nₘ = Nₛ, ηₘ): Stepanoff: Equation (1) [15], Alatorre-Frenk: Equation (2) [19], Sharma: Equation (3) [17], Schmiedl: Equation (4) [21], Grover: Equation (5) [22], Hergt: Equation (6) [18] and Childs: Equation (7) [16].

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\frac{H_T}{H_p} = \frac{1}{\eta_p} \frac{Q_1}{Q_p} = \frac{1}{\eta_p} \frac{Q_1}{Q_p} = \frac{1}{\eta_p} \frac{N_st = N_s \eta_p}{R_T = P_p}; \quad (1) \\
\frac{H_T}{H_p} = \frac{1}{0.85 \eta_p^{3} + 0.385}; \quad Q_1 = \frac{0.85Q_p^{5} + 0.385}{2 \eta_p^{9.5} + 0.205}; \quad \eta = \eta_p - 0.03; \quad (2) \\
\frac{H_T}{H_p} = \frac{1}{1.2} \frac{Q_1}{Q_p} = \frac{1}{\eta_p} \frac{Q_1}{Q_p} = \frac{1}{\eta_p} \frac{R_T = P_p}{R_T = P_p}; \quad (3) \\
\frac{H_T}{H_p} = -1.4 + \frac{2.5}{\eta_p}; \quad Q_1 = -1.5 + \frac{2.4}{\eta_p}; \quad \eta = 1.158 - 0.265N_st; \quad (4) \\
\frac{H_T}{H_p} = 2.693 - 0.0229N_st; \quad Q_1 = 2.379 - 0.0264N_st; \quad \eta = 0.893 - 0.0466N_st; \quad (5) \\
\frac{H_T}{H_p} = 1.3 - \frac{6}{N_st - 3}; \quad Q_1 = 1.3 - \frac{1.6}{N_st - 5}; \quad (6) \\
\frac{H_T}{H_p} = \frac{1}{\eta_p} \frac{Q_1}{Q_p} = \frac{1}{\eta_p} \frac{Q_1}{Q_p} = \frac{1}{\eta_p} \frac{\eta_T = \eta_p}{\eta_T = \eta_p}; \quad (7)
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5. Field implementation Case study-Urmia Small Hydro Plant

The small-hydro site has been implemented on the by-pass line of a pressure reducing valve located on a pipeline which supply water to a water treatment plant in Urmia city, Iran Fig. 2 (a). A schematic is shown in Fig. 3. The flow rate and available head at the input of PRV were about 0.47 m$^3$/s and 85 m. Based on Fig. 1 (b), a double suction pump (TVP-300.500) with impeller diameter of 490 mm and specific speed 29.4 (m, m$^3$/s) was selected to install and operate as PAT. To measure the pressure a sensor ranging 0-25 bar was used and the flow rate was measured using an ultrasonic flowmeter at upstream of PAT. A 4-pole squirrel cage motor of 315 kW was coupled to the PAT with a synchronous speed of 1500 rpm. By means of a plc system, all the data are logged and valves are remotely controlled with electronic actuators and all the operation of the PAT can manually or automatically controlled by a homemade software program as shown in Fig. 2 (b).

Figure 2. (a) PAT installed in Small-Hydro site, Urmia; (b) Software developed for monitoring and control of system

Figure 3. Schematic layout of implemented plant

6. Results

Before installation of PAT, a performance test was carried by the manufacturer in pump mode. Based on test sheet, the following results were derived at BEP of pump. $Q_{\text{BEP}} = 1406$ m$^3$/h, $H_{\text{BEP}} = 62.55$ m, $P_{\text{BEP}} = 334$ kW and $\eta_{\text{BEP}} = 71.7\%$. The results and comparisons at the dimensionless scales are shown in Fig. 4. As compared to pump operation, the pump operates at higher head and discharge values in turbine mode. The non-dimensional parameters are expressed as follows:
7. Comparison of prediction methods

The results of implemented Small- hydro site have been compared to the results of prediction methods available in the literature as listed in Table 2. In Table 3 the deviations between the predictions of the methods and the measured data are presented.

It is easy to observe that large deviations are shown in methods of Alatorre-Frank and Grover for both head and flow rate values. The flow rate calculated using the methods of Stepanoff and Hergt are very close to field measurement. Also, the head value calculated using the methods of Stepanoff, Sharma, Schmiedl and Childs are close to those of measured by a margin of ±5%. The method of Hergt underestimates the head value 33.3% and the method of Schmiedl overestimates the flow rate value 37.5%. A prediction method is valid only if it accurately predicts both head ratio and flow rate ratio simultaneously for a given range of specific speeds. So, in this case, method of Stepanoff acceptably estimates both head and flow rate ratios for this centrifugal pump with \( N_s = 29.4 \) (m, m³/s).

8. Payback time

In table 4 payback time Analysis is presented. The total cost for plant included installation, operation and maintenance are 76000$. So Energy Production Costs is calculated 0.038 ($/kWh). With regard to Purchase tariff for Small-Hydro Installation on the pipelines in Iran year 2016 [23] equal to 1500 IRRs/kWh and calculation of the total income, the Capital payback period of this PAT is less than one year. In addition, the total GHG emission savings, with average minimum of 775 g CO₂-equiv./kWh GHG Emissions (from Specific Energy Sources like Lignite, Hard coal, Oil, Industrial and Natural gas) [24] is calculated 1560 tons per year.

![Figure 4](image-url)  
**Figure 4.** Dimensionless Head, Power and Efficiency curves in pump and turbine modes.
Table 2. Comparison between results of prediction methods and Measured Values in Field

| METHODS          | $H_t$ (m) | $Q_t$ (l/s) | $\eta_t$ (%) |
|------------------|-----------|-------------|--------------|
| Measured in Field | 90.7      | 463         | 68           |
| Stepanoff        | 87.2      | 461         | 71.7         |
| Alatorre-Frank   | 114.5     | 736         | 68.7         |
| Sharma           | 93.2      | 510         | 71.7         |
| Schmiedl         | 93.6      | 636         | 80.4         |
| Grover           | 138.2     | 712         | 64.5         |
| Hergt            | 60.6      | 469         | -            |
| Childs           | 87.2      | 545         | 71.7         |

Table 3. Prediction methods comparison with Measured Values in Field. Head, Capacity and Efficiency Percentage Errors

| METHODS          | Error-$H$ (%) | Error-$Q$ (%) | Error-$\eta$ (%) |
|------------------|---------------|---------------|------------------|
| Stepanoff        | -3.9%         | -0.3%         | 5.4%             |
| Alatorre-Frank   | 26.2%         | 59.1%         | 1.0%             |
| Sharma           | 2.8%          | 10.2%         | 5.4%             |
| Schmiedl         | 3.1%          | 37.5%         | 18.3%            |
| Grover           | 52.4%         | 53.9%         | -5.2%            |
| Hergt            | -33.3%        | 1.3%          | -                |
| Childs           | -3.9%         | 17.7%         | 5.4%             |

Table 4. Energy Payback Time Analysis

| Installation Cost ($) | O&M Costs ($/y) | Energy produced (MWh/y) | Energy Production Costs ($/kwh) | Energy purchase tariff ($/kwh) | Total Income ($/y) | Payback Time (Year) | Emission Savings (tons) |
|-----------------------|-----------------|--------------------------|-------------------------------|-------------------------------|-------------------|---------------------|--------------------------|
| 72000                 | 4000            | 2000                     | 0.038                         | 0.043                         | 86000             | ≤1 years            | 1560                     |

9. Conclusions

A centrifugal pump of specific speed 29.4 (m, m3/s) was installed in a SHP. As compared to pump operation, the pump operates at higher head and discharge values in turbine mode. The best efficiency in turbine mode was found 2.7% lower than best efficiency in pump mode. As a comparison in prediction methods in this study, method of Stepanoff acceptably estimates both head and flow rate values. Also, the payback time of this PAT is less than one year. However some uncertainties are still remains in prediction of turbine mode characteristics using pump operation data, future works and more experimental data can improve all methods.

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