Design of Francis turbine for micro hydropower applications

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Abstract. This study presents a Francis turbine designed for micro hydro application, using bovet approach of design and other general techniques, with some variations which make the manufacturing procedure relatively simpler. It also depicts the status of micro hydro in Nepal. Simplifications has been administered on runner, vane cascade and spiral casing. The study has been carried out under single flow condition, which is generally the case in micro hydropower, which divert a small portion of water from the main source, generally rivers or springs. The design procedure used for the design of each hydraulic components have been described in brief. The numerical study performed on the turbine have also been presented. Effects of simplifications administered on each component has been analysed. The small variation in efficiency due to simplifications administered has been justified for use in micro hydropower projects in view of the drop in efficiency caused due inaccuracies during manufacturing of turbine.

1. Introduction

Energy consumption is directly associated with the development of a country. During the second half of the 20th century, relationship of economics with energy production and consumption was emphasized. However, the development of huge power plants depending on fossil fuels resulted in environmental pollution. Thus, clean and renewable energy technologies gained popularity during the late 20th century[1]. Hydropower remains, by far, the most used form of Renewable energy in the world, contributing to over two-third of the renewable energy produced[2]. Ever increasing popularity of Renewable energy and the use of new technology to boost up the efficiency of hydropower will keep it on top for the days to come. Most of the developed countries have already started changing their lifestyle to minimize their carbon footprint[3]. However, developing countries like Nepal depend on traditional sources of energy like firewood, agricultural wastes and dry dung for 69% of the energy consumed[4].

Hydropower in large scale are often linked with the adverse environmental and social impacts it has; however in small scale it is considered to be one of the most environmentally benevolent source of energy as it doesn’t require huge constructions[5]. Nepal, as a developing country, has a huge opportunity to emerge as a renewable energy dependent country, by exploiting the 83,280MW of potential running through the rivers[6]. Despite having such huge potential and possibilities Nepal is still dependent on imported non-renewable sources of energy for a considerable portion of its energy needs[4]. Nepalese hydropowers are now producing
1,128.708 MW of electricity, which is just 2.8% of commercially feasible amount that can be produced [7, 6]. The report published by AEPC [7] shows that 12.45% of total population doesn’t have access to electricity, most of which belong to rural areas in the hilly and himalayan region. Even though there are numerous hydropower projects and Transmission lines under construction, a big proportion of the rural population won’t have access to the National grid compelling them to look for traditional energy sources or build remote micro hydro.

Different countries have their own policies to classify hydropower, Nepal and many other developing countries in the South Asian region classify micro-hydro as hydropower plant within the capacity range of 5 to 100 kW [8]. Even though micro-hydro has fairly matured in Nepal, the micro-hydro developers and turbine manufacturers could not develop much after the late 20th century. A study done on the prediction of turbines used in hydropower plant have predicted that 75% of hydropower will use Francis turbine [9]. Another study done on earthquake affected micro hydro pointed out that, of the 61 micro hydro studied, more than 50% micro hydro were suitable for Francis turbines. However, all those micro hydro were using Cross-Flow and Pelton turbines with very less efficiency [10]. Not being able to manufacture the compatible Francis turbines, Nepalese micro hydro developers and turbine manufacturers are installing Cross flow turbines, which are being operated at very less efficiency. This case is applicable in case of other developing countries as well, where the potential of micro hydro are not being utilized to their fullest due to lack manufacturers developing turbines with higher efficiency. Turbine Testing Laboratory (TTL) at Kathmandu University has been working relentlessly to introduce the Francis turbine technology, simplified and optimized, to the Nepalese turbine industry. The presented work describes about the status of micro-hydro in Nepal and discusses about a project being implemented at TTL, which introduces numerous simplifications in the design, such that the manufacturing of Francis turbine becomes more convenient with locally available resources, without compromising much on its efficiency.

2. Micro Hydro in Nepal

Hydropower plants with capacity of less than 100 kW are recognized as Micro Hydropower Plants in Nepal. Nepal has a very long history with Micro Hydro as it was in 1962 when the first Micro Hydro was introduced in the country by installing a 5 kW propeller turbine at Godavari Fish Farm. The turbine was manufactured by Balaju Yantra Shala (BYS) with the help of Swiss Association for Technical Assistance. Even before that, Nepal had been utilizing its hydropower through traditional water wheels called ‘Ghattas’ for mechanical power; food processing. Kathmandu Metal Industries was one of the manufacturers which introduced different designs of water wheels and supplied them to the remote areas throughout Nepal. Development and Consulting Services (DCS) was introduced as a joint venture company of then His Majesty’s government of Nepal (HMG/N) and United Mission to Nepal (UMN) very soon after the Swiss manufacturers provided the designs and drawings of turbines. When rice husking and flour milling became popular with the introduction of micro hydro in rural Nepal, Agricultural Development Bank of Nepal started financing the traditional ghattas and micro hydro since 1968. In the next two decades, ADBN invested over 83 million Nepalese Rupees to develop 685 micro hydros [11].

During the year 1974, BYS started manufacturing the Cross flow turbines which was very versatile in its operation range and relatively simple to manufacture. The design was later followed by numerous other manufacturers and they started making their own modifications in the design. Over the years, 15 different designs of Cross flow turbine were introduced. T15 is the most recent model of the cross flow turbine introduced in the Nepalese turbine manufacturing industry. Pelton Turbine was manufactured subsequently, in 1975, by Butwal Technical Institute; established in 1963 as a project of UMN with the initiations of an Norwegian Engineer, Odd Hofftun. International Agencies like SKAT, from Switzerland; ITDG, from U.K.; GATE/GTZ,
Figure 1: A typical small hydro Francis turbine with horizontal shaft[14]

from Germany and FAKT, from Germany have played vital roles in R&D, promotion, installation and monitoring & evaluation of MHP. These agencies were crucial in the introduction of different turbines currently being manufactured in Nepal. There are other private and government companies which cannot go unmentioned when it’s about the development of Micro Hydro in Nepal; Kathmandu Metal Industries Pvt. Ltd., Nepal Yantra Shala Energy Pvt. Ltd., Thapa Engineering Industries are often mentioned as the pioneers of turbine manufacturing; within Nepal and abroad[11, 12].

Seeing the opportunity to start a business, that would develop the country, young entrepreneurs of the mid 1980s started investing in the micro hydro related manufacturing companies. Those actively involved entrepreneurs started an association in December 1992 called as Nepal Micro Hydro Development Association (NMHDA). NMHDA has been helping the new entrepreneurs by providing technical trainings and collaborating with the government to develop the policies that would benefit the development of Micro Hydro in Nepal. Establishment of these agencies have facilitated the development of micro hydro in Nepal and the progress has been substantial; there are more than 3300 Micro Hydro in Nepal electrifying more than 350,000 households in the rural areas[12]. This allowed the access of electricity to almost 85% of rural population in Nepal from, just 17% in 15 years. Despite having such great contributions in the rural electrification of Nepal, the number of Micro Hydro developed has gone down by almost 66% during the year 2017/18. There are numerous possibilities and reasons for the decline of micro hydros in Nepal: promotion of other renewable sources of energy, plans of government to extend the national grid throughout the country, unreliable quality of electricity produced from micro hydro and almost no development in the technology of micro hydro turbine. The lack of initiation from the manufacturers to introduce new type of turbine in the micro-hydro range. With the development of modern technologies like smart phones and televisions, the consumers are demanding more reliable and better sources of electricity. Not being able to manufacture efficient turbines like Francis turbine has been a hurdle of Nepalese turbine manufacturers for a long time now[13]. In order to promote themselves, Nepalese turbine manufacturers should start developing more efficient turbines and gradually step into the market of small hydropower, for which there is abundant market in Nepal.

Francis turbine is a mixed flow reaction turbine with numerous components, each having a specific function in the system. Water enter into the Francis turbine through a spiral casing at high pressure. The pressurized fluid is accelerated through the guidevanes to hit the runner blade at the leading edge. The water loses its energy at the runner while driving the shaft which is coupled to generator shaft. General Electrics (GE), a key player in world hydropower development, claims that Francis turbines generate almost 60% of the total hydro electricity generated in the world. The turbine manufacturers around the world have been manufacturing
Francis turbines for a very long time. However, Nepalese turbine manufacturers have not been able to manufacture the Francis turbines even for the Micro Hydro range. In order to break the deadlock created due to the lack of initiation from the Nepalese manufacturers TTL has initiated a project to design and develop a Francis Turbine for Micro Hydropower plant in Nepal. Under the same project, a Micro Hydro, ‘Chauri Khola II Micro Hydropower Plant’ has been identified as a reference case. The existing Cross Flow turbine will be replaced by a Francis turbine designed and manufactured in Nepal. The design however, will be different from the large scale Francis Turbines that are generally available in the hydropowers.

3. Reference Case Design

Under the activities of the project ENEP-RENP-II-18-03, a micro hydro in Nepal, ‘Chauri Khola-II MHP’ has been selected as the reference case where; existing, non-functional cross flow turbine will be replaced by a Francis turbine designed specifically for the site. The design parameters used for the design for the project have been listed in Table 1. The discharge required has been diverted from a river called ‘Chauri Khola’, through a canal. The runner for reference case has been designed using a method described by Th. bovet[15] by using some modern techniques. All other components have been designed using the methods described by Hermod Brekke[14].

| S.No. | Parameters                      | Symbol | Values | Unit |
|-------|---------------------------------|--------|--------|------|
| 1     | Head                            | $H$    | 14     | $m$  |
| 2     | Discharge                       | $Q$    | 0.3    | $m^3/s$ |
| 3     | Hydraulic Efficiency            | $\eta$ | 90.0   | %    |
| 4     | Wire Power                      | $P_w$  | 37.08  | $kW$ |
| 5     | Acceleration due to gravity     | $g$    | 9.81   | $m^2/s$ |
| 6     | Rotational Speed                | $N$    | 750    | $rpm$ |
| 7     | Dimensionless Specific Speed    | $\nu_\wedge$ | 0.36 |     |

3.1. Meridional Flow Passage

The design of blade starts with development of meridional flow passage and the parameters of flow passage are functions of a non-dimensional specific speed represented by $\nu_\wedge$, which is determined by using equation 1. The '$\wedge$' symbol represents characteristics of best efficiency point. Same equation can be

$$\nu_\wedge = \frac{\omega (Q_\wedge / \pi)^{\frac{2}{3}}}{(2 \cdot E_\wedge)^{\frac{1}{3}}}$$

where:

$\omega$ = Angular speed of the runner
$E_\wedge$ = Specific hydraulic energy supplied to the turbine
$Q_\wedge$ = Volumetric flowrate through the turbine

The characteristic dimensions of the flow channel are determined by first determining the outlet radius of the blade at shroud, represented by $R_2e$, which is determined by using equation
2. Other parameters are determined by using the empirical relations provided by TH. Bovet[15]. The flow coefficient and energy coefficient for the reference case are chosen to be 0.24 and 1.51 respectively. As both hub and shroud are defined by a same family of curves, these can be defined using equation 3. As shown in Figure 2, the hub curve, represented by (i) is plotted upto one fourth of the length, while shroud curve, represented by (e) is plotted upto its total length.

\[ R_{2e} = \sqrt[3]{\frac{Q}{\pi \omega \varphi_{2e}}} \]  

(2)

where:

\[ \varphi_{2e} = \text{flow coefficient} \]

After determining the value of \( R_{2e} \), the two characteristic curves can be defined using the equation 3. In order to define the curve, its characteristic dimensions are determined, in their reduced form, using the empirical equations given in terms of the specific speed.

\[ \frac{y}{y_{max}} = \frac{16}{3\sqrt{3}} \sqrt{\frac{x}{l}} \left( 1 - \frac{x}{l} \right) \left( 1 - \frac{x}{l} \right) \]  

(3)

In order to define the leading and trailing edges of the blade, the point where these edges intersect the hub and shroud curves are determined based on the specific speed. The leading and trailing edges are considered to be parabolic curves with their vertex on shroud and passing through a specific point on the hub curve. The streamlines between two curves are interpolated. The interpolated curves within the leading and trailing edge region are taken into consideration. All the curves are saved in separate files with '.ZR' extension. These curves are imported into Ansys 18.1, Bladegen. The meridional channel imported into the Bladegen is shown in figure 3.

3.2. 3D runner design

The blade angle at the leading and trailing edges, for each streamline are calculated using the equations 4 and 5 respectively[16]. The blade angles in each streamline are distributed linearly with respect to radius normalized distance along the meridional curve. Blade angles
calculated at leading and trailing edge of each streamline are shown in Table 2. The theta angle are respectively calculated at each point in the streamline. The value of theta at the beginning of each streamline, i.e. at leading edge is 0° by default. This means that there is no lean at the inlet of the runner. In low head turbines, distances from trailing edge of guide vanes to the leading edge of the runner vary from hub to shroud. Due to this reason the blades tend to experience cavitation problems at the inlet of the runner. In order to reduce this problem lean angle is introduced at the inlet of the runner[17]. This can be done by varying the theta values at the beginning of each streamlines. Runners with lean angles can be seen in figure 4.

\[
\cot \beta_1 = \frac{\pi D_1 B_1}{Q} \left( \frac{\pi D_1^2 N}{60} - \frac{60gH_{th}}{\pi D_1^2 N} \right) \quad (4)
\]

\[
\tan \beta_2 = \frac{60 \cdot Q}{\pi D_2^2 N A_2} \quad (5)
\]

Table 2: Beta angles at inlet and outlet of each streamline

| S.No. | Streamlines       | \(\beta_1\) (Leading Edge) | \(\beta_2\) (Trailing Edge) |
|-------|-------------------|-----------------------------|----------------------------|
| 1     | Streamline 1 (Hub)| 57.34°                      | 25.65°                     |
| 2     | Streamline 2      | 53.74°                      | 23.11°                     |
| 3     | Streamline 3      | 49.78°                      | 20.17°                     |
| 4     | Streamline 4      | 45.20°                      | 16.63°                     |
| 5     | Streamline 5 (Shroud) | 36.20°                      | 13.50°                     |

3.3. Guide vanes and Stay vanes

Guide vanes are components of Francis Turbines which partially convert the pressure energy of water at its inlet to kinetic energy, thus accelerating the water on it. While the stay vanes
are components which keep the structural integrity of the spiral casing without disturbing the flow of water. In general guidevanes are moveable components which can be moved about a fixed axis. This movement is important to regulate the flow and direction of water striking the runner. The guidevane angle is regulated based on the flow available at the intake. Guidevane control mechanism is a complex system making use of high precision linkage system to move all the guide vanes synchronously. However, in case of micro hydropower projects such as the reference case being designed, the flow of water is same for most of the time throughout the year. Thus avoiding the use of moveable guide vanes. Fixing the guide vanes avoids guide vane control mechanism which reduces the cost and effort required for manufacturing a small scale turbine by a good portion. Since both guide vane and stay vane system are fixed, these two components have been combined into one single component in a fixed proportion. A separate study is going on to determine the optimal proportion in which the two vane system should be combined. For the reference case the vane cascade were combined in a 50-50 proportion by their length.

The guidevanes are designed such that the circumferential speed of the runner is matched by the rotational energy of the inflowing water [14]. Its design starts with the calculation of the outlet radius which is taken 5% more than the inlet radius of the runner. The length of guide vanes are calculated such that the number of guide vanes selected can close the flow of water completely. In other words, the length of each guide vane is 10 to 15% more than the circumference at its axis. This would not matter for the reference case as the guide vanes have been fixed. The length of guide vane affects the shape of spiral casing thus selecting the optimal length is very important. The angle at which the guide vane outlet is positioned based on the tangential and meridional velocity calculated. But the final angle at which the guidevanes are fixed are determined after obtaining satisfactory results from CFD Analysis.

\[
X_{0i} = R_{gvo} \cos \theta_i \quad (6)
\]
\[
Y_{0i} = R_{gvo} \sin \theta_i \quad (7)
\]
\[
X_{1i} = R_{gvo} \cos \theta_i + 2L_{gv} \cos(\alpha + \theta_i) \quad (8)
\]
\[
Y_{1i} = R_{gvo} \sin \theta_i + 2L_{gv} \sin(\alpha + \theta_i) \quad (9)
\]

Where:
- \( R_{gvo} \) = radius at outlet of guidevane
- \( L_{gv} \) = length of guidevane
- \( \alpha \) = guidevaneangle

Stay vanes are designed considering free vortex flow through it. The stay vanes are designed such that its shape follow the path of free vortex flow of the spiral casing. Figure shows the geometric representation of a section of stay vane. The letters shown in the figure represent respective dimensions of the entities wherever mentioned. The stay vane is designed in sections such that the angle of incidence at each section is the same as that determined at the point where guide vane starts. Equations 10 and 11 are used to determine the length and span angle of each section of the stay vane respectively. Usually, stay vanes’ length and thickness are determined iteratively by checking if they can maintain the shape of spiral casing against the internal pressure in the spiral casing. In the reference case, the length of stay vane was selected to make the ratio in which the two vanes are combined 1 : 1.

\[
dl = \sqrt{\frac{(R_{i-1} \sin \alpha_{sv})^2}{2} + (R_i^2 - R_{i-1}^2) - R_{i-1} \sin \alpha_{sv}} \quad (10)
\]
\[
d\theta = \sin^{-1} \left( \frac{d\ell \cos \alpha_{sv}}{R_i} \right) \quad (11)
\]
3.4. Spiral Casing

Spiral casing is a component of Francis turbine which distributes the water coming from the penstock throughout the circumference of the runner equally. In addition to distribution, spiral casing is also responsible for conversion of axial kinetic energy of water to circumferential kinetic energy. The spiral casing is usually designed considering free vortex flow through it. However, constant average velocity theory is also popular for low head turbines. Spiral casing of circular cross section are generally preferred in francis turbines however, for low head Francis turbines trapezoidal spiral casings are preferred due to the smaller space occupied by it. In addition to occupying smaller space, trapezoidal spiral casings require less number of joints compared to circular spiral casings, making it relatively convenient to manufacture. Moreover, trapezoidal spiral casings are found to perform on par with the circular spiral casings, thus trapezoidal spiral casing has been designed for the reference case[18].

The design of spiral casing is an iterative process in which the best combination of dimensions of cross sections are determined to satisfy the flow conditions. The Area of the section is determined by computing the available flow at each section after reducing the flow distributed in the previous section to maintain the constant circumferential velocity. The values of $R_i$, $b_i$ and $a_i$ are determined for each section such that the ratio of $b$ and $a$ remain constant in all the
section and the area formed is equal to the area computed for constant velocity[18]. Equations 12 and 13 are solved to determine the dimensions defining the trapezoidal section.

\[ A_i = a_i b_i - n_i^2 \tan \delta \]  \hspace{1cm} (12)

where:

1.75 < \frac{b_i}{a_i} < 1.85

\[ A_i = \text{Area of cross-section} \]

\[ \delta = 30^\circ \]

\[ n_i = \left( \frac{a_i}{k_n} \right)^2 \]  \hspace{1cm} (13)

3.5. Draft Tube

Draft Tube plays a very important role in recovering the unused kinetic energy in the water coming out of the runner. It makes sub-atmospheric pressure possible at the outlet of the runner which ultimately leads to better efficiency of the turbine. It is a diverging tube which increases the pressure of the water flowing through it by reducing its velocity. A simple conical type draft tube has been selected for the reference case. It is designed assuming the velocity of water at its outlet to be 2m/s. The length of draft tube can depend on the site conditions or is calculated based on the cone angle. Cone angle of 4° is recommended for effective performance of draft tube.

4. CFD Analysis

To analyze the reference case design, numerical simulation is carried out in Ansys CFX 18.1. The domain of runner created in Bladegen blade modeler are imported into Ansys Turbogrid to generate high quality hexahedral mesh. All other components are modeled in Creo Parametric then imported into Ansys 18.1 workbench for meshing. Tetrahedral mesh are generated for all other components. Mesh files of each components are imported into CFX-Pre to define settings and physical parameters for simulation. Numerous simulations are performed and modifications are made based on the results to reach the final design. The runner blade is analyzed in single passage to evaluate the performance of the blade and determine the best angle of incidence. Further simulations are performed with the domains of vane system, spiral casing and draft tube. A full domain simulation takes vigorous time and resources for execution. The parameters selected for CFD Analysis are shown in table 3.

| S.No. | Parameters       | Type                |
|-------|------------------|---------------------|
| 1     | Analysis Type    | Steady state        |
| 2     | Turbulence Model | SST                 |
| 3     | Inlet            | Mass Flow Rate      |
| 4     | Outlet           | Static Pressure     |
| 5     | Walls            | No Slip             |
| 6     | Working Fluid    | Water at 25°C       |

Figure 7: Full domain analysis
5. Results and Discussion

Performance analysis of the Francis turbine designed for a micro hydropower project has been performed, numerically. The blade designed using Bovet approach showed maximum efficiency of 95.39% on a single passage CFD Analysis. However, very low pressure regions were obtained at leading edge of the blade. The negative pressure regions were concentrated at suction side, near the shroud of the runner. This kind of phenomenon are often seen in low head francis turbines. After introduction of lean, the low pressure region was greatly reduced but didn’t vanish completely at any angle of lean. Most of the leans subjected were linear in nature. Among all the leans tried on the runner, results obtained at an lean angle of 5° was relatively better considering the pressure throughout the span of leading edge and efficiency combined. This can be observed on blade loading curves at different spans and pressure contour on the blade. Better results could be obtained with the use of lean of different natures as well as pressure balancing the blade as suggested by Hermod Brekke[14].

The guide vane and stay vane were combined in different ratios and were analyzed for the change in performance. There was no considerable difference in overall efficiency of the turbine with the small change in ratio in which the cascade were fused. However, exceptionally longer vanes, with more percentage of stay vane were relatively less efficient as suggested by other studies. The vanes were combined in the ratio of 1:1, as the results obtained were close to that obtained with the separate guide vane and stay vane. An overall efficiency of 82.47% was obtained with the distributor system and the draft tube. The loss in efficiency could be due to the losses in trapezoidal spiral casing as well as the fused vane systems which is not aerodynamic in shape.

6. Conclusion

Francis turbine with few simplifications, such that it can be manufactured without the use of sophisticated manufacturing technologies, locally, are adequate for Micro Hydro applications. Under the circumstances, in which, Micro hydro are being run by less efficient types of turbines, introducing Francis turbine will surely improve the power production. Fixing guide vanes and fusing with the stay vane doesn’t affect the efficiency greatly at the best efficiency point. As micro hydro are generally operated under one condition of flow, lack of moveable guide vane would not make much difference. The ratio in which the two vanes should be combined is to be studied further for more accurate results. Trapezoidal spiral casing can be easier to manufacture, however its effectiveness under site condition still needs to be studied. Francis turbines can be manufactured in Nepal with few simplifications and once this happens it will begin a new era for Nepalese turbine manufacturers.
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