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Efficiency calculation of hydro turbine in varying head condition and its effect on system design

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Abstract: *This paper deals the concept of efficiency calculation for varying head and varying discharge conditions of a micro hydropower plant. Due to increasing pollution and depletion of ozone layer from fossil fuels and other conventional energy sources, the renewable energy became an important source to avoid the above effects. In large hydro power plant, a dam is built to maintain the constant head. But, in micro hydro power plant, there exist a varying head and varying discharge condition due to absence of any storage system. The head variations at a site changes the unit speed and unit discharge of the turbine and caused to change in efficiency points on hill chart. A varying discharge only at the site is easy to handle but, when both head and discharge varies, it becomes complicated. In this case model test curve (Hills curve) of the turbine is used to calculate the efficiency. In this paper, the micro hydropower system has been designed and corresponding efficiency calculation of the turbine has been explained. It is found that efficiency of the turbine will depend on, both the system design and the head variation at the site.*

Keywords: Efficiency; Rotation; Unit speed and Unit flow

1. INTRODUCTION

A micro hydro power plant (MHPP) is a relatively low capacity plants. The installation and design of a micro hydro power plant mainly depends on hydrological condition at the sites. Since, an MHPP do not required a water storage, it is under a renewable energy sources. A MHPP may be Run off river type and Existing canal based type [1]. Also, some countries like Japan has allowed to make a MHPP on existing dam for irrigation and drinking water purposes. Since, hydrological condition at sites are varying and there is no storage, a micro hydro plant has to handle a varying discharge. To handle this varying discharge an optimal diameter of penstock pipe is selected. Since, the head loss is the function of Q2, when discharge at the site is varying, it changes the head available for the turbine [2]. So, the condition becomes the varying head and varying discharge. If head available at the site get changed, it will change the RPM of the turbine.

As per affinity law [3]

If Turbine diameter (D) = constant,

$$\frac{Q1}{Q2} = \frac{N1}{N2} \tag{1}$$

$$\frac{Hn1}{Hn2} = \left(\frac{N1}{N2}\right)^2 \tag{2}$$

$$\frac{P1}{P2} = \left(\frac{N1}{N2}\right)^3 \tag{3}$$

2. VARIATION OF HEAD AND ITS EFFECTS

Head variation at a hydropower plant sites occur due to following reasons:

a. If the hydro plant is dam based plant. The seasonal variation in the reservoir level of the dam, changes the gross head available at the site.

b. When the penstock pipe is under designed:

In this case the loss due to friction and other losses are very high. These losses increase with the variation of discharge [2]. Actually, this situation comes into account, when, an existing dam for irrigation or drinking purposes is used to develop hydro power plant. In this case, the water velocity inside the penstock is very high. Which is the cause of head loss.

Also, the discharge to the turbine depends on the demand of water at water purification sites or irrigations. So, the discharge varies frequently and losses are more. The increase in losses change the net head available at the site. After the announcement of the Japanese government to install hydropower plant at such sites, the situation in Japan is on the face.

c. In micro hydro power plant, the water is diverted from the main stream or existing canal without making any intake. Hence, the flow in the penstock is not the pressurized flow and the pressure available at the inlet of turbine is varying.

3. EFFECT OF HEAD VARIATION ON THE EFFICIENCY OF HYDRO TURBINES

The efficiency of hydro turbine is calculated from its model test result called Hill's chart. A HILL'S chart is an iso-efficiency curve line drawn between unit speed and unit flow of the turbine.

Unit Speed: $$n11 = \frac{N*D}{\sqrt{Hn}} \tag{4}$$

Unit Flow:

For cross flow turbine,

$$q11 = \frac{Q}{B*D*\sqrt{Hn}} \tag{5}$$

$$q11 = \frac{Q}{D^2\sqrt{Hn}} \quad \text{(Kaplan Turbine)}$$

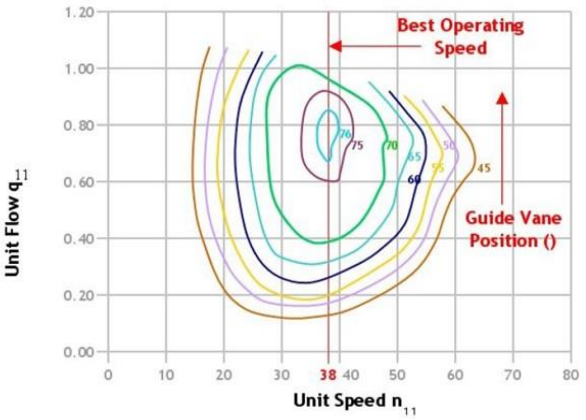

Fig. 1. Hill's chart of cross flow turbine.

In the figure the curve line in multi colors is the Iso efficiency line of the turbine. As seen in figure, the maximum efficiency is 76% and minimum is 45%. To know the efficiency of the turbine, unit flow and unit speed is needed.

Generally, at a hydropower plant site, only discharge is varying, the variation of discharge changes the unit flow ($q11 = \frac{Q}{B*D*\sqrt{Hn}}$) but unit speed is constant. The turbine developer provides efficiency curve according to this relation (Change in flow vs Efficiency). They develop the efficiency curve assuming the head at the site constant.

The change in head at the site will change both unit flow and unit speed (In some cases only unit flow). So, the efficiency point on Hills curve get changed. The efficiency curve obtained in this case is different than the one provided by turbine maker. Hence, it affects the performance of plant.

The change in head at a site will change either only unit flow or both unit flow and unit speed. It depends on the generator and connections used in plants or its system design. Hydropower systems is categorized in two parts:

3.1 Induction generator connected to grid:

In this system, the rotational speed of the generator (RPM) will always be constant until it is connected to the grid. The constant RPM of the generator force the turbine to rotate at same RPM as generator (for directly connected generator and turbine shaft). So, speed of the turbine also become constant. If, there is a change in head at the site, it will change the unit speed of the turbine.

$$n11 = \frac{N * D}{\sqrt{Hn}}$$

Here N (rpm)= constant and

for a given turbine; D= constant,

So, $n11 \propto \frac{1}{\sqrt{Hn}}$

Hence, an increase in Head will decrease the unit speed and vice versa.

Unit flow ; $q11 = \frac{Q}{B*D*\sqrt{Hn}}$

B and D are constant for a given turbine, so the change in head will change the unit flow.

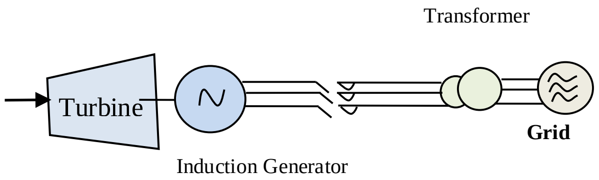

Fig. 2. System flow of Induction generator connected to Grid.

3.2 IPM generator with variable frequency controller connected to the grid

In this system the speed of generator is varying. This variation of generator speed is according to speed of turbine runner. Since, the IPM generator is connected to grid through frequency controller. The frequency controller, control the speed and provide a constant frequency to the grid. If head changes at the site, it will change the speed of the turbine according to affinity law.

$$N1/(N2) = \sqrt{Hn1}\sqrt{Hn2}$$

or $\frac{N}{\sqrt{Hn}}$ = constant

And, the speed of generator will be same as the turbine.

Since, $\frac{N}{\sqrt{Hn}}$ = constant and diameter of the turbine is constant always. The unit speed will be constant.

So,

Unit speed ; $n11 = \frac{N*D}{\sqrt{Hn}}$ = constant

Unit flow ; $q11 = \frac{Q}{B*D*\sqrt{Hn}}$ = Varying

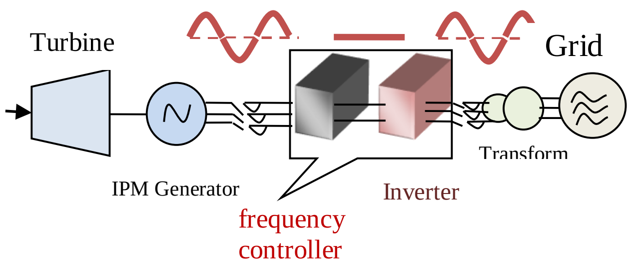

Fig. 3. System flow of IPM generator with variable frequency controller connected to the grid.

4. Efficiency calculation from Hill's Chart:

To obtained the efficiency from Hill's chart,

a. Take the value of head and discharge, at which we want to calculate the efficiency.
b. Calculate the unit speed and unit flow corresponding to given value of head and discharge.
c. Mark the point on Hill's chart corresponding to above calculated unit speed and unit flow.
d. Check the efficiency curve corresponding to that point and mention the efficiency.

Example:

To calculate the efficiency from the hills chart, let us take an example of a micro hydro turbine installed in Japan.

Qd = 0.6 m3/sec, Hn=8 m ,

Turbine type: Cross flow, Diameter (D) = 300 mm, Width (B)= 880 mm

Design speed = 358 rpm; Optimum, n11=38;

Table1. Efficiency of turbine with respect to unit speed and unit flow.

S. No.	Q	H	Unit speed	Unit flow	Turbine Efficiency (I.G System)	Turbine Efficiency (IPM System)
1	0.15	21	23.44	0.12	0	0
2	0.25	20	24.02	0.21	50	54
3	0.4	17	26.05	0.37	62	62
4	0.45	16	26.85	0.43	67	71
5	0.55	11	32.38	0.63	74	75.5
6	0.6	8	37.97	0.80	76	76

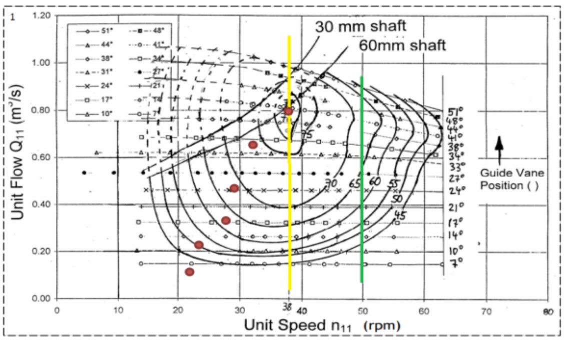

Fig. 4. Efficiency of cross flow turbine.

The yellow line on the efficiency curve shows the constant unit speed line. The red point on the Hills chart is the efficiency of turbine, when the system is consists of Induction generator (I.G.).
If the same system is consist of IPM generator with frequency controlle; the unit speed will be constant to its optim7um value to 38. And efficiency of the turbine will fall on the yellow line corresponding to each values of unit flow.
From Table.1, it is found that , turbine efficiency will be different in case of Induction generator and IPM. At low value of unit flow and unit speed, Induction generator might be (in some cases) better than IPM; but for a high values of unit flow and unit speed, IPM generator is better than Induction generator.
From Fig.6, it is found that efficiency of the turbine will be affected by head variation at the sites. The efficiency of turbine will be less for varying head site than constant head sites.

5. CONCLUSION

The paper discussed the effect of head variation on the efficiency of hydro turbine. It is concluded from the discussion that a head variation at a site will reduce the efficiency of the turbine. This reduction in efficiency will change the total energy output of the turbine. So, for exact and better calculation, a hydropower engineer should consider the head variation effect. This reduction should be consider while designing hydropower plant .

Table 2. Efficiency of turbine for constant head and speed.

S. No.	Q	H	Unit speed	Unit flow	Efficiency of Turbine
1	0.15	8	38.00	0.20	59
2	0.25	8	38.00	0.33	64
3	0.4	8	38.00	0.54	73
4	0.45	8	38.00	0.60	75
5	0.55	8	38.00	0.74	76
6	0.6	8	38.00	0.80	76

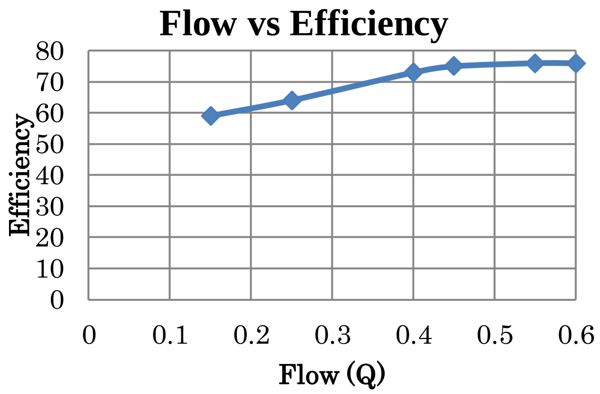

Fig. 5. Flow vs Efficiency of turbine for constant Head.

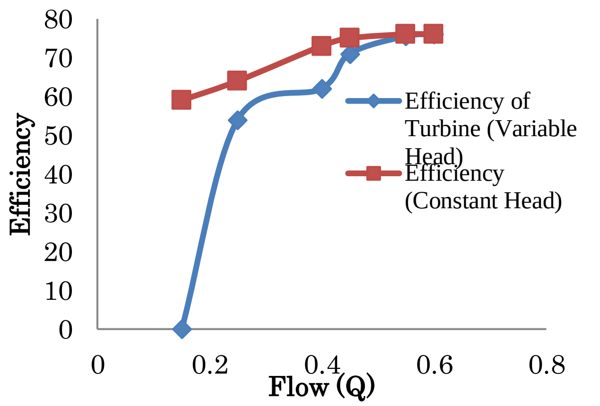

Fig. 6. Flow vs Efficiency comparison of constant Head and variable Head case.

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