Performance Analysis for Francis Hydraulic Turbine based on Normalized Operating Condition and its Application

Youping Li[*a], Hanli Weng[b], Jian Cheng[a], FeiXiang Chen[c]

[a] Technology and Research Center of China Yangtze Power Co., Ltd, Yichang 443002,
[b] College of Electrical Engineering & New Energy of China Three Gorges University, Yichang, 443002,
[c] Yalong River Hydro-power Development Company, LTD., Chengdu, 610051.
upinglee@qq.com

The operating condition is normalized based on unit parameters and runner velocity triangle for hydraulic turbine in this paper. The hydraulic turbine performance is analyzed by using the normalized operating condition parameter and the actual data obtained from the stability and performance test for prototype turbine under different water heads for a certain hydropower plant. On this base, an instructional suggestion about the recommend output and guide vane opening under the entire operating water heads is proposed for the hydroelectric unit operation. According to theoretical analysis and actual data, the regularity of hydraulic turbine during operating can be revealed and summarized more directly and easily by means of adopting the normalized operating condition parameter. This researching conclusion could provide a new solution to analyze the hydraulic turbine performance and guide the operating of hydroelectric units safely, steadily and efficiently.

1. Introduction

The stability and energy characteristics are two important index of hydraulic turbine and can be used to reflect the performance of hydraulic turbine. The stability parameters include vibration, displacement, pressure fluctuation and etc. (WANG (1986)). The energy characteristics include such as the efficiency (η) and output

(P) of hydraulic turbine (YAN el al (2012)). Above-mentioned performance parameters of hydraulic turbine vary greatly with different operating conditions (Ha and Kim (2009), XIE and XU (2009), D el al (2012)). In order to make clear the characteristics of the unit and guide the operation, model and prototype tests are usually performed at different water heads and outputs to draw the hill charts (LI and HUANG (2011), and get the safe and stable operating condition area (LI et al (2007), QIAO et al (2014)).

By summarizing a large amount of document about hydraulic stability of turbine in the world, PAN et al (2002) analyzed the factors, such as draft tube vortex, blade vortex, Karman vortex, that cause hydraulic instability of turbine, and the author gave the proposals that it is necessary to optimize the operating and avoid being operated at strong vibration operating zone to reduce the vibration during operation for hydraulic turbine. When discussing the relationship between the pressure pulsation in the turbine draft tube and the operating condition of Francis hydraulic turbine, the relationships between the pressure pulsation and the circumferential component in the outlet as well as the unit parameters were analyzed, WU et al. (1998) pointed out that it is important to select appropriate unit parameters when designing Francis runner with better stability. LAI (2004) analyzed the hydraulic instability of operation caused by the vortex core and channel vortices, and researched the relationship between vortex and flow behavior at runner exit, based on the analysis and by means of the calculation of flow behavior, the author suggested a method to predict the zones of the unstable operation and the draft tube pressure pulsation when a Francis turbine operates at partial load.

Generally, unit discharge (Q_{11}) and unit speed (n_{11}) are adopted to describe the hill chart for model turbines, as for protypes the water head (H) and output (P) or discharge (Q) are used (IEC60193-1999, H (2010), Shi et al. (2012)). After the design and installation for hydraulic turbine, the operating condition is closely related to the flow pattern in passageway actually. The operating condition of hydraulic turbine described by two parameters can hardly indicate the flow pattern simply and clearly. As a consequence, the hydraulic turbine performance is

difficult to be directly analyzed, and the influence of the flow pattern on the hydraulic turbine performance cannot be disclosed exactly by two operating condition parameters.

On the basis of above analyses, a parameter representing the flow pattern should be taken into account to discover the influence of flow pattern on the performance for hydraulic turbine during operating, which is defined as the normalized operating condition parameter for hydraulic turbine in this paper. Furthermore, the practical application of this parameter is discussed.

2. Normalized operating condition parameter for hydraulic turbine

For the researches on similarity law of hydraulic turbine and the performance of model turbine, there are two important parameters: unit discharge (Q_{11}) and unit speed (n_{11}), which are respectively defined as follows (LIU (1997))

$$(1)$$

$$Q_{11} = \frac{Q}{D_2^2 \sqrt{H}}$$

$$(2)$$

$$n_{11} = \frac{nD_2}{\sqrt{H}}$$

Where Q is discharge, D_2 is diameter of runner, n is the rotational speed and H is net water head of hydraulic turbine.

Defining a new parameter c as the normalized operating condition parameter for hydraulic turbine, which is expressed by:

$$(3)$$

$$c = \frac{Q_{11}}{n_{11}}$$

In virtue of (1)-(3), equation (4) comes into existence:

$$(4)$$

$$c = \frac{Q_{11}}{n_{11}} = (\frac{Q}{D_2^2 \sqrt{H}}) / (\frac{nD_2}{\sqrt{H}}) = (\frac{Q}{D_2^2}) / (nD_2)$$

Figure.1 is used to analyze the runner outlet velocity triangle of hydraulic turbine. In this figure, V_2 is the absolute velocity of flow at the runner outlet; U_2 is the convicted velocity of the flow to the runner, which is equal to the rotating velocity of the runner; W_2 is the flow velocity relative to the runner; V_{u2} is the velocity component of V_2 in the runner rotating direction; V_{m2} is the velocity component of V_2 in the axial direction; α_2 is the angle between V_2 and the runner rotating direction; $V_2^{'}$ is the axial velocity of the normal discharge point of turbine; $W_2^{'}$ is the flow velocity relative to the runner of the normal discharge point of turbine; β_2 is the angle between V_2 and rotating direction, which equals to the angle of blade outlet β_{b2}.

According to Fig. 1, Q can be given by:

$$(5)$$

$$Q = V_{m2} \times \frac{\pi D_2^2}{4} \times F_e = \frac{\pi F_e \sin \alpha_2}{4} \times V_2 D_2^2 = k_1 \sin \alpha_2 \times V_2 D_2^2$$

where, $k_1 = \frac{\pi F_e}{4}$ and F_e is the effective coefficient of flow passage area at the runner outlet, which is relevant to the type and structure of hydraulic turbine.

U_2 is related to the rotating speed and discharge diameter of runner, and given by:

$$(6)$$

$$U_2 = \frac{\pi D_2 n}{60} = \frac{\pi}{60} \times n D_2$$

According to formula (6), for a certain actual operated hydraulic turbine, as the rotating speed and discharge diameter of runner have been decided, U_2 is same under all operating conditions. By virtue of the normal discharge point of turbine, U_2 can be expressed by:

$$(7)$$

$$U_2 = V_2^{'} \times ctg \beta_2 = V_2^{'} \times ctg \beta_{b2}$$

With respect to equations (4)-(7), equation (8) comes into existence:

$$c = \frac{k_1 \sin\alpha_2 V_2 D_2^2}{D_2^2} / (\frac{60U_2}{\pi}) = \frac{\pi k_1}{60} \times \frac{\sin\alpha_2 V_2}{U_2} = \frac{k_1\pi}{60ctg\beta_{b2}} \times \frac{\sin\alpha_2 V_2}{V_2'} = k\frac{V_2}{V_2'}\sin\alpha_2 = k\frac{V_{m2}}{V_2'} \qquad (8)$$

Where, $k = \frac{k_1\pi}{60ctg\beta_{b2}} = \frac{\pi^2 F_e tg\beta_{b2}}{240}$.
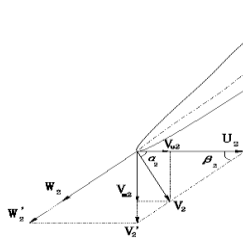

Figure 1: Runner Outlet Speed Triangle of hydraulic turbine

It can be seen from equation (8), the normalized operating condition parameter for hydraulic turbine c reflects the ratio between the axial velocities of the flow for a certain operaing condition and the normal discharge point of turbine at the runner outlet. Meanwhile, it also reflects the angle between the absolute velocity of flow and rotating direction of the runner under the certain operating condition. Therefore, it can be adopted to represent the flow pattern of hydraulic turbine for the certain operaing condition.

3. Performance analysis based on bormalized operating condition parameter for hydraulic turbine and its application

Based on the actual data obtained from performance test for hydroelectric unit at different water heads and loads with the rising of the reservoir upstream level in a hydraulic power station, the applications of the the normalized operating condition parameter c in the hydraulic turbine performance analysis and guiding the actual operation for hydraulic turbine will be discussed in this section.
The parameters of the hydraulic turbine are shown in Table 1.

Table 1: Parameters of the hydraulic turbine

Discharge Diameter of Runner D_2 (mm)	9767.4
Operating water head range (m)	86.1-114.2
Rated Output (MW)	800

3.1 Performance analysis based on normalized operating condition parameter
Fig. 2-Fig. 6 respectively show the relationships of output and parameter c to performance parameters such as pressure fluctuation, efficiency of hydraulic turbine, displacement of turbine guide bearing, vertical vibration and horizontal vibration of head cover at different water heads during performance test for the prototype hydraulic turbine in the power station.
In each figure, curves in (a) express the relationships between hydraulic turbine output and performance parameters, curves in (b) express the relationships between parameter c and performance parameters. In addition, the data in the parentheses in each figure denote the upstream water levels of the reservoir。
Table 2 lists the values of parameter c corresponding to the maximum efficiency point of hydraulic turbine, inflection point of pressure fluctuation for draft tube cone 0.3D below the runner under high part load conditions, maximum displacement point of turbine guide and maximum horizontal vibration point of head cover under different water heads respectively.
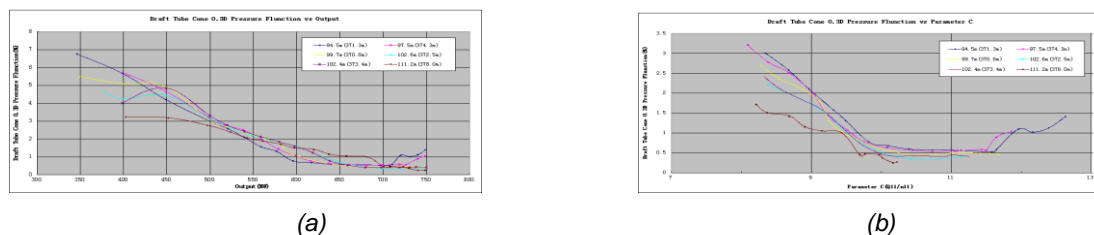

(a)   *(b)*

Figure 2: Relationships of hydraulic turbine Output and Parameter c with Pressure Fluctuation
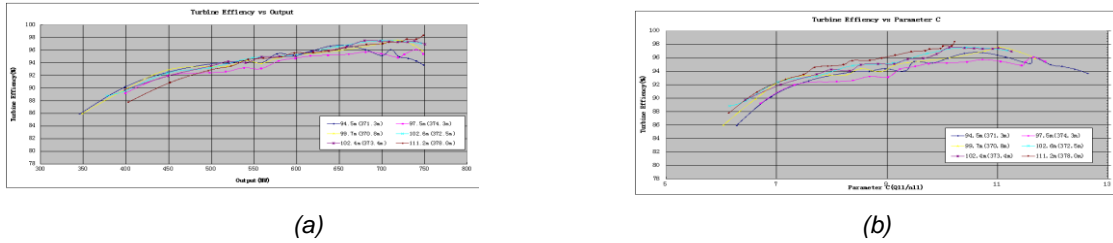
(a) *(b)*

Figure 3: Relationships of hydraulic turbine Output and Parameter c with Efficiency of hydraulic turbine
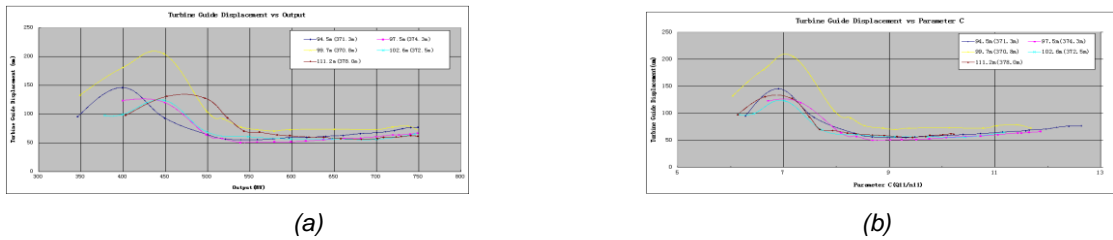

(a) *(b)*

Figure 4: Relationships of hydraulic turbine Output and Parameter c with displacement of Turbine Guide Bearing

(a) *(b)*

Figure 5: Relationships of hydraulic turbine Output and Parameter c with Vertical Vibration of Head Cover

(a) *(b)*

Figure 6: Relationships of hydraulic turbine Output and Parameter c with Horizontal Vibration of Head Cover

According to comparative analyses of hydraulic turbine performances respectively taking the output and parameter c as abscissas, it can be seen that:

(1) In the case of taking the output as abscissa, the hydraulic turbine outputs are different under different water heads at special operating conditions points such as vibration, displacement and pressure pulsation inflection point under high part load conditions, maximum vibration and displacement points, best efficacy, etc. Besides, the hydraulic turbine outputs corresponding to special operating points generally move in the direction of greater output with the rising of the water head.

(2) In the case of taking parameter c as abscissa, values of parameter c corresponding to aforementioned special operating points under different water heads nearly equal to each other (as seen in figure b).

By virtue of Table 2, it can be concluded that:

(1) Values of parameter c, which respectively correspond to best efficiency point of hydraulic turbine, upswept point under high part load conditions of pressure fluctuation for draft tube cone 0.3D below the runner. According the flow pattern in the passageway under the above conditions, upswept point under high part load conditions of pressure fluctuation corresponds to normal discharge points of turbine under different water heads. In this case, the hydraulic turbine has maximum efficiency, minimum circumferential component in the outlet and minimum pressure fluctuation.

(2) The values of parameter c corresponding to maximum displacement point of turbine guide bearing and maximum horizontal vibration point of head cover are close to each other. According the flow pattern in the passageway under the above conditions, the operating conditions deviate further from normal discharge point of

turbine, due to the increasing of circumferential component in the outlet, the pressure fluctuation, vibration and displacement will increase and the efficiency of hydraulic turbine will decrease.

In view of the above analyses, the hydraulic turbine performances under different operating conditions can be revealed more directly by means of adopting parameter c, and parameter c can represent the flow pattern of hydraulic turbine. Additionally, it is objectively proved that the flow pattern has significant effect on the performance indexes of operating hydraulic turbine.

Table 2: Values of Parameter c Corresponding to Special Operating Points under Different Water Heads

water head	the normalized operating condition parameter for hydraulic turbine			
	maximum efficiency point of hydraulic	pressure pulsation inflection point of draft tube cone	maximum displacement point of turbine guide	maximum horizontal vibration point of head cover
94.5m	10.56	10.99	6.92	6.89
97.5m	11.53	10.79	6.96	6.97
99.7m	11.02	11.10	6.94	7.07
102.4m	11.74	11.07	6.89	6.88
102.6m	11.12	10.88	6.83	6.87
111.2m	10.63	-	6.80	6.71
average value	11.10	10.97	6.89	6.90

3.2 Applications of normalized operating condition parameter for hydraulic turbine operation

Under actual operating conditions of power station, values of parameter c corresponding to the optimum operating conditions with high efficiency and low vibration, and worst operating conditions with high vibration and displacement, which are determined by means of related characteristics of hydraulic turbine and parameter c, can be acquired. Since the guide vane opening and output can be adjusted and measured quite easily, according to the above mentioned values of parameter c, the guide vane opening and output corresponding to the optimum and worst operating conditions under test water heads can be obtained. Fig. 7 illustrates the relationships of output and guide vane opening to parameter c. In the figure, the solid and dotted lines denote the values of parameter c corresponding to the optimum and worst operating conditions respectively.

Furthermore, the curves which denote the relationships of guide vane opening and hydraulic turbine output to water head under optimum and worst operating condition are established, as seen in Fig. 8. It should be noted that the actual guide vane opening under high water head cannot reach the optimum due to the limitation of generator output. In accordance with Fig. 8, the guide vane openings and outputs, which should be avoided (as shown by dotted line in Fig. 8) and recommended (as shown by solid line in Fig. 8) when the hydraulic turbine operated under all operating water heads, can be determined. In this event, the safe, stable and efficient operation of hydraulic turbine can be ensured.

Figure 7: Relationships of hydraulic turbine Output and Guide Vane Opening to Parameter C

Figure 8: Optimum Guide Vane Opening and hydraulic turbine Output under Different water heads

4. Conclusions

Operating condition of hydraulic turbine is an important factor to determine the performance of hydraulic turbine during operation. As supported with the analyses of unit parameters and runner outlet velocity triangle of hydraulic turbine, a normalized operating condition parameter for hydraulic turbine, which can represent its flow pattern, is proposed in this paper. According to theoretical analysis and actual data, hydraulic turbine characteristics can be revealed more directly by adopting the parameter. Moreover, it can provide excellent guidance for the safe, stable and efficient operation of hydraulic turbine

Actually, the water flow in the hydraulic turbine flow passageway is also affected by the flow at runner inlet. Therefore, the flow pattern through the whole passageway of hydraulic turbine can be revealed more realistically by means of combinational analyzing the velocity triangle at inlet and outlet of the runner, and establishing the relationship of the velocity triangle of the two parts. And this problem is expecting for further research.

Acknowledgements

References

Brekke H., 201O, Performance and safety of hydraulic turbines, 25th IAHR Symposium on Hydraulic Machinery and Systems, DOI: 10.1088/1755-1315/12/1/012061

Frunzăverde D., Muntean S., Mărginean G., Câmpian V., Marşavina L., Terzi R., and Şerban V., 2012, Failure analysis of a Francis turbine runner, 25th IAHR Symposium on Hydraulic Machinery and Systems, Beijing, China, DOI: 10.1088/1755-1315/12/1/012115

Ha J.H., Kim C.H., 2009, A Study on the Performance Analysis of Francis Hydraulic Turbine. Journal of the Korean Society of Marine Engineering, 33 (7): 1052-1059

IEC 60193-1999. Hydraulic turbines, storage pumps and pump-turbines-Model acceptance tests

Lai X.D., 2004, Analysis and Estimation of Hydraulic Stablity of Francis Hydro Turbine. Journal of Hydrodynamics, Ser. B, 16 (2): 194-200

Lanteri J., Migliaccio C., Ala-Laurinaho J., Vaaja M., Mallat J., and Raisanen A.V., 2009, Four-beam reflectarray antenna for Mm-waves: design and tests in far-field and near-field ranges, European Conference on Antennas and Propagation, Berlin, Germany, 2532-2535.

Li D.Z., Feng Z.X., Ding R.S., Hua H.J., Sun J.P., Zheng L.Y., 2007, Analyses on Working Stability of Hydrogenerator Units in Ertan Hydropower Station.Water Resources and Power, (4): 79-84

Li Y.P., Huang Y.F., Li J.B., 2011, Turbine Model and Model Acceptance Test for Voith Turbine of Xiluodu Hydropower Plant, Large Electric Machine and Hydraulic Turbine, (1): 46-49

Liu D.K., 1997, Hydraulic Turbine (3rd edition). Beijing: China Water Power Press (in Chinese).

Nayeri P., Yang F., and Elsherbeni A.Z., 2012, Design of single feed reflectarray with asymmetric multi-beams, IEEE Antennas and Propagation Society International Symposium, Illinois, 1 – 2, DOI: 10.1109/APS.2012.6348725.

Pan L.P., 2002, Analysis of hydraulic stability of turbine. J. Changchun Inst. Tech. (Nat.Sci.Edi), 3 (4): 41-43

Pozar D.M., Targonski S.D., and Syrigos H.D., 1997, Design of millimeter wave microstrip reflectarray, IEEE Trans. Antennas & Propag., 45 (2), 287-296, DOI: 10.1109/8.560348.

Pozar D.M., Targonski S.D., and Pokuls R., 1999, a shaped-beam microstrip patch reflectarray, IEEE Trans. Antennas & Propag., 47 (7), 1167–1173, DOI: 10.1109/8.785748.

Qiao L.L., Chen Q.J., 2014, Testing and Analysis of Operating Stability of 200WM Francis Turbine Set, Water Resources and Power, 32 (5): 148-150, 82

Qu Y., Guo C.J., Guo H., Ding J., 2014, Fast analysis for aperture efficiency and radiation patterns of reflect array antennas, International Journal of Signal Processing, Image Processing and Pattern Recognition, 7 (4), 243-254, DOI: 10.14257/ijsip. 2014.7.4.24.

Qu Y., Guo C.J., Guo H., and Ding J., 2015, Design of single-feed multi-beam reflect array using iterative Fourier techniques, International Journal of Smart Home, 9(4), 187-194, DOI: 10.14257/ijsh.2015.9.4.19.

Schulwitz L., and Mortazawi A., 2005, A compact dual-polarized multi beam phased-array architecture for millimetre-wave radar, IEEE Trans. Microw. Theory Tech., 53 (11), 3588–3594, DOI: 10.1109/TMTT. 2005.857104.

Shi F.X., Yang J.H., Wang X.H., Zhang R.H., Li C.E., 2012, The impact of inlet angle and outlet angle of guide vane on pump in reversal based hydraulic turbine performance.26th IAHR Symposium on Hydraulic Machinery and Systems, DOI: 10.1088/1755-1315/15/4/042030

Wang K., 1986, Vibration of Hydraulic Power Unit Set. Beijing: Water Resources and Electric Power Press (in Chinese).

Wu G., Wei C.X., Zhang K.W., Song L.R., 1998, The Relations between the Operating Condition and Pressure Fluctuation in Draft Tube of Francis Turbine .Journal of Huazhong University of Science and Technology, (11): 88-91. DOI: 10.13245/j.hust. 1998.11.029

Xie H.B., Xu H.Q., 2009, Operation Stability of Gezhouba Hydropower Station after its Capacity Increasing. Large Electric Machine and Hydraulic Turbine, (6): 39-43, 48

Yan Z.G., Zhou L.J., Wang Z.W., 2012, Turbine efficiency test on a large hydraulic turbine unit. SCIENCE CHIN Technological Sciences, 55 (8): 2199-2205. DOI: 10.1007/s11431-012-4914-6