Influence of hydraulic characteristics on transient behavior of ultra-high head pump turbine

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Abstract. Pump turbines with ultra-high head or low specific speed have typically pronounced “S” characteristics in generation mode, which usually leads to a very challenging situation regarding the transient behavior, especially when it is not adequately considered in the power plant layout. Though some countermeasures, e.g. asynchronous guide vane closing or fast MIV closing, can be taken in the late stage to mitigate the problem, nowadays the customers are more in favour of a solution on root, i.e. improving the “S” characteristics by optimizing the hydraulic design of pump turbine during design stage. Recently Dongfang has successfully developed several pump turbines with a head range from 580m up to 750m. An important consideration during the development is to find out a compromise between hydraulic performance and transient behavior. This paper presents how the hydraulic design influences the “S” characteristics and subsequently the transient behavior, based on the investigations performed and improvements obtained through these pumped-storage projects.

1. Background and motivation
Due to the well-known technical and economic advantages, the pumped storage power plant has been the most common form of utility-scale energy storage type worldwide. Moreover, it is also the ideal solution to compensate the volatility of the renewable energy and maintain the grid stability when integrating the renewable energy into the grid. Pushing by the high demand of the renewable energy to achieve the goal of CO2 emission reduction, the market of pumped storage in China has been booming up during the past years and for the next decade it is expected to keep growing in both scale and speed.

As one of the main suppliers of hydraulic units worldwide, Dongfang has made some remarkable progress recently in the pump turbine technology, especially in ultra-high head range. Several ultra-high head PSP projects in China, covering a head range of 580~750m and capacity level of 300~350MW, were awarded to Dongfang after competition tests in an independent lab. Some parameters of these projects are listed in Table 1.

Development of high head or low specific pump turbine is technically quite challenging in various aspects. Besides the hydraulics and safety, as described in some other publications [1-3], the transients turn to be another issue. It has been found in several recent cases that the transient behavior of PSP is not only determined by the plant layout as usually believed, but the so called “S” characteristics in turbine mode also shows a considerable influence. Therefore it is essential to use the proper 4-quadrant curves instead of one from another similar head machine during the layout of power plant to minimize...
the risk of inadequate estimation [4-6]. Situation could be more challenging in case of low specific machine since its “S”-shape is much more pronounced, as shown in Figure 1, and the induced strong pressure oscillation during load rejections could be dangers. As the “S” characteristics is directly determined by the hydraulic design, it is very important to assess the transient behavior during the design phase.

Table 1. Main parameters of Dongfang’s recent ultra-high head PSP references

| Project     | Gross head range (m) | Rated output (MW) | Rotational speed (r/min) | Units by Dongfang / Installation |
|-------------|-----------------------|-------------------|--------------------------|----------------------------------|
| Jixi        | 581–643               | 300               | 500                      | 6/6                              |
| Dunhua      | 656–701               | 350               | 500                      | 2/4                              |
| Changlongshan | 697–756             | 350               | 500                      | 4/6                              |

Figure 1. “S” characteristics of pump turbines with high (left) and low specific speed (right)

Various study regarding the influence of 4-quadrant characteristics on the transient behavior of pump turbine were published by others. X Yang made statistical analysis on 4-quadrant characteristics of different specific speed pump turbines with focus on the instability in the “S”-zone by using the spatial surface description method based on neural network [7]. J DYang et al. derived a criterion for the stability of pump turbine at runaway condition and stated that the key factor leading to the oscillation phenomenon at runaway condition is the slope of the characteristic curve at runaway point [8]. H Rong et al. developed a method to determine the “S”-characteristics of the pump turbine and made some qualitative evaluation on how the “S”-characteristics influence the operation stability [9].

The most common way to assess the transient behavior is to make transient simulation using some self-developed tools or commercial software like SIMSEN which is now widely used by many manufactures including Dongfang. However, to make simulation for every intermediate hydraulic model is quite time consuming. During hydraulic design a more efficient way is required for the designer to get quick feedback regarding the transient behavior of their designs.

Some intensive work has been carried out in Dongfang recently to improve the transients for some ultra-high head PSP projects by tuning the hydraulics. Based on the experience and output, a characteristic parameter has been defined to represent the influence of hydraulics on the transients. And thus a quantitative assessment of transient behavior can be efficiently done by comparing this single
parameter among different hydraulic models. Some details of the method and a validation case will be presented in this paper.

2. “S” Characteristics and transient behavior
As been published in many literatures [10, 11], the highly complicated flow patterns in the pump turbine near the turbine brake and reverse pump regions form the so-called “S”-shaped constant guide vane opening (GVO) curves in the 4-quadrant space, as illustrated by Figure 2. This “S” characteristics may induce some stability problems during the operation of pump turbine unit. The research reveals that the “S” characteristics at large GVO near rated angle has a significant influence on the behavior of the high head unit in transient operations, e.g. load rejection et al. However the “S” characteristics at small GVO near minimum head limit is more relevant to the turbine synchronization behavior. In this paper we focus more on the large GVO “S” characteristics.

In order to assess the influence of “S” characteristics on the transient behavior during hydraulic design phase, a quantitative parameter is desired which can represent their correlation and make the assessment easy and efficient. Based on the transient simulation and analysis on a large number of 4-quadrant curves of actual pump turbine projects, a simple assessment method is proposed using the so-called transient characteristic angle (TCA) as the indicator.

The study shows that the transient behavior is mainly influenced by two factors of the “S” characteristics. One is the discharge factor $Q_{11}$ at runaway point for a given GVO, representing the discharge capacity of the runner during transient operation. The other is maximum variation of speed factor $n_{11}$ near the turbine brake region, representing the pressure variation during transient operation. According to the positive and negative correlations of the two factors with transient behavior, a characteristic factor can be artificially defined using such an angle as expressed by Equation (1).

\[
\alpha = \arctan \frac{Q'_{11,M0}}{\Delta n_{11}} \quad (1)
\]

where:
- All variables are extracted from the rated constant GVO curve, as illustrated in Figure 3.
- $Q_{11,M0}$ indicates the discharge factor at runaway point (M=0) with the unit of l/s. It’s more practical to use $Q'_{11,M0}$ which is 1% of $Q_{11,M0}$ so that its magnitude is comparable with the denominator.
- $\Delta n_{11}$ indicates the speed factor variation between the maximum $n_{11}$ and $n_{11}$ at zero discharge (Q=0), as described in Equation (2).

\[
\Delta n_{11} = n_{11,\text{max}} - n_{11,Q0} \quad (2)
\]
According to the definition and actual 4-quadrant curves the TCA is an angle between 0 and 90 degree. Using this TCA factor the “S” characteristics of a pump turbine and the corresponding transient behavior can be easily assessed. Numbers of validation cases shows that for a certain project or pump turbines with similar specific speed, a bigger TCA value normally indicates a better transient behavior.

The study shows that the influence of the “S” characteristics on the transient behavior can be summarized as the following.

- A higher $Q_{11,M0}$ indicates better discharge capacity of the runner during transient operation, which normally leads to a better transient performance, e.g. less pressure variation in both spiral case and draft tube.
- A bigger $\Delta n_{11}$ indicates faster flow rate change during transient operation, which normally leads to stronger pressure variation induced by water hammer. Consequently the transient performance will be worse and vice versa.
- Based on the transient simulations and statistics of TCA, a target value can be set for the optimization of “S” characteristics by tuning the hydraulic designs in order to achieve satisfying transient behavior.

3. Optimization aiming at transients improvement in a case of ultra-high head pump turbine

Changlongshan PSP located in Zhejiang Province in China is featured with an ultra-high head whose main parameters are listed in Table 1. The pump turbine development was recently finalized in Dongfang. The choice of lower rotational speed, i.e. 500 r/min instead of 600 r/min, leads to an unfavorable specific speed about $n_q = 26$. Though the hydraulics for such low specific speed pump turbine is rather challenging, the transient behavior becomes a big issue since the layout of the power plant is in some aspect aggressive and has been fixed already.

Therefore during the hydraulic optimization we must always make quick assessment of the overall transient behavior using the 4-quadrant curves from model test. The TCA as a characteristic factor is quite practical in such case. Figure 4 shows the TCA values of some references with similar specific speed and 15 models we developed for this project (CLS). One case based on the layout for the 600 r/min option using a base model is also included.

From the hydraulic point of view CLS-3 is the most preferable model which shows excellent hydraulic performance, but the transient behavior by simulation using SIMSEN is not satisfying. In several transient load cases the specification for pressure rise in spiral case inlet and pressure drop in draft tube inlet cannot be fulfilled. Its TCA value is nearly the lowest one which is quite in line with the TCA theory.

Aiming to improve the transients, we went for a higher TCA value by modifying the hydraulic profiles and CLS-8 is a typical release in this direction. This model shows much better transient behavior.
and the specifications for almost all load cases can be fulfilled. And the TCA value of this model is reasonably the highest among all cases. However the sacrifices in hydraulic performance are too much to be accepted. Therefore the compromise between hydraulics and transients has to be further optimized.

![Figure 4](image.png)

**Figure 4.** TCA statistics of reference cases and CLS models

After several rounds of optimization the model CLS-12 was finally achieved showing rather good compromise between hydraulics and transients. The comparisons among these 3 models in terms of transient behavior and hydraulic performance are summarized in **Table 2** and **Table 3** successively.

For the comparison of transients two load cases are selected, i.e. full power rejection of single unit operated at rated head and maximum head with guide vane closing reject. In such case the influence of guide vane closing law and interaction with other units can be excluded so that the influence of TCA is more visible. It can be clearly observed that with higher the TCA value the transient behavior improves significantly. The results of other transient load cases are also quite in line with this tendency. Additionally it can be predicted that the transients would be not an issue at all if 600 r/min has been the choice of rotational speed.

**Table 2.** Comparison of TCA and transient simulation results for some load cases

| Model | TCA (deg) | Load case 1: single unit rejects 100% power at rated head with guide vane closing rejected | Load case 2: single unit rejects 100% power at max. head with guide vane closing rejected |
|-------|-----------|----------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|
|       |           | Maximum Pres. at SC inlet (m.WC) | Minimum Pres. at DT inlet (m.WC) | Maximum overspeed rate (%) | Maximum Pres. at SC inlet (m.WC) | Minimum Pres. at DT inlet (m.WC) | Maximum overspeed rate (%) |
| CLS-3 | 24        | 1049.2 | 43.9 | 38.2 | 1082.9 | 7.6 | 38.3 |
| CLS-8 | 42        | 954.9  | 70.0 | 36.8 | 971.5  | 58.6 | 37.0 |
| CLS-12| 32        | 972.8  | 62.3 | 37.4 | 996.4  | 52.5 | 38.0 |
According to the definition of TCA the hydraulic optimizations have a clear target to reduce $\Delta \eta_{11}$ by means of tuning the constant GVO curve more vertical and/or increase $Q_{11, M0}$ by means of rising up the runaway curve. We can quickly calculate the TCA of each model as soon as we get the rated GVO curve only in the 1st quadrat. This makes the transients assessment very efficient. However it is not easy to figure out which parameters in the hydraulic profile determines the shape of the GVO curve and runaway curve. It takes us quite some effort in trial, test and analysis before we can find the proper and systematic way to tune the design towards the favourite direction and minimize the side effect meantime.

The improvement of TCA is illustrated in Figure 5 by the comparison of “S” characteristics at rated GVO. The comparison of some main parameters regarding hydraulic performance of these 3 models is shown in Table 3 and Figure 6 and Figure 7.

Table 3. Change of the hydraulic parameters with improvement of TCA

| Model   | Pump Mode | Turbine Mode |
|---------|-----------|--------------|
|         | weighted efficiency | average discharge | Max. input power P (MW) | weighted efficiency | Max. amplitude of pressure pulsation in vaneless space $\Delta H/H$ (%) |
|         | $\Delta \eta_{P, wgt}$ ($\%$) | $Q_{ave}$ (m$^3$/s) | $\Delta \eta_{P, wgt}$ ($\%$) | $0$–$50\%$ Pr | $50$–$70\%$ Pr | $70$–$100\%$ Pr |
| CLS-8   | +0.09     | +2.8         | +30.9                   | -0.02       | +1.8         | +2.7         | +2.4         |
| CLS-12  | -0.13     | -0.8         | +2.4                    | -0.15       | -0.3         | +0.1         | -0.2         |
| 600r/min (layout) | +0.92 | -0.1 | -9.9 | +0.95 | -1.1 | -1.2 | -1.3 |
Figure 6. Comparison of prototype H-Q and efficiency in pump mode

Figure 7. Comparison of pressure pulsation amplitude in vaneless space and prototype efficiency in turbine mode at rated head

4. Summary and prospect
Recently intensive optimization work was carried out in some ultra-high head PSP projects aiming to improve the overall transient behaviour. The influence of hydraulic characteristics on the transient behavior was studied and the main output can be summarized as the following.

- The hydraulic characteristics show significant influence on the transient behavior. Therefore it is essential to use the proper 4-quadrant curves for the early estimation during the power plant layout.
- A characteristic factor, i.e. TCA, is constructed to quantify the influence. It is very practical to use TCA to make quick transients assessment and to guide hydraulic optimization.
In an ultra-high head PSP project the hydraulic design was optimized aiming to improve the transient behavior. A good compromise between hydraulics and transients was achieved and the effectiveness of TCA was confirmed.

More samples in different head range need to be counted in the statistics to further enhance the engineering practicality of the TCA method.

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