Numerical optimization on the "S" characteristics of model pump-turbine

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Abstract. The performance of a reversible pump turbine with S-shaped ($dQ_{11}/dn_{11}>0$) characteristics is of great harmful to the transient processes such as start-up and load rejection. When working point transition is required, then process in turbine mode must be fast, efficient and reliable. Especially during start-up, the machine must operate at a stable speed close to the no-load condition (i.e. close to the runaway characteristic) in a large operating head range while not involving a special stabilizing technique and all synchronized guide vanes are open slightly. When pump turbine operates in "S" zone, two direction flow phenomena such as turbine direction and pump direction exist in the flow passage together and the pump direction flow is responsible for "S" zone. Many vortexes are formed because the interaction between turbine and pump flow, furthermore, the vortex cause energy loss and discharge fluctuation. In order to improve the "S" characteristics of model pump-turbine and improve the safety margin of prototype pump-turbine, a criterion which can be used to justify whether pump turbine operates in the "S" zone is proposed. The criterion is the guide vane outflow angle at runaway working point. For example, there are two schemes A and B, when the guide vane outflow angle is bigger on A scheme than on B scheme, the S-shaped curve is improved. When the guide vane outflow angle is larger than runner blade installed angle at leading edge (high pressure side), the "S" zone will be removed from operation zone. How to explain this phenomenon? In fact, when the guide vane outflow angle increases, the flow discharge increase, so the main flow at turbine direction covers the main passage and the instability source such as pumping effect is suppressed, finally the S-shaped is optimal.

Keywords: pump turbine, "S" zone, guide vane outflow angle

1 Introduction

All over the world, the production of energy from renewable variable sources such as wind and solar is increasing massively. In order to integrate more and more wind and solar power in a given network, complementary power sources with high flexibility are necessary. Among them, Hydro Pumped Storage Plants (PSP) using reversible Pump-Turbine machines is an ideal complement, due to their fast response capability and their ability to store large amounts of potential energy when base load production exceeds the consumption on the grid and to release this stored energy when the power demand is higher.

Flexibility of Pumped Storage in operations is a requirement. Frequent starts and stops and fast mode changes are increasingly required, particularly from pumping mode to the generating mode. Reversible Pump-Turbine machines need to be designed for high availability, reliability and stability, especially during the start-up process in turbine mode when peak power production is required [1].

High head pump-turbine machines are more subject to the S-shaped characteristic because they are directly impacted by their own hydraulic design characteristics. Indeed, due to their low specific speed factor leading to a centrifugal design, the S-shaped phenomena in the Turbine quadrant becomes even more important and then more difficult to be mastered than for other lower head machines. Moreover, this issue will be even more difficult to master if a large head operating range is needed because the lowest head level will be shifted toward the most critical S-shaped region.

During start-up, there is no-load on the turbine shaft and the machine must be operated at stable speed close to the runaway characteristic. One necessary coupling condition is to have a rotation frequency level of the turbine in line with the grid frequency level. Just before the coupling sequence, the turbine rotation frequency must be stable without speed oscillations. If those conditions are not fulfilled, the start-up process can be slowed down or even impossible if no special stabilizing technique is used.

Reversible machines must operate efficiently in both modes – pump and turbine. This is the reason why a design compromise must be found between the Pump and the Turbine modes, including not only the continuous normal operating area but also the off-design operating range such as the start-up areas. Balancing of such hydraulic behavior is important for any kind of reversible Pump-Turbine. Because the S-shaped zone has so great damage to unite stability operation, many researchers and engineers pay more attention to S-shaped zone optimization.

Houdeline [2] gives the optimal result of significant improvement of the S-shaped characteristic of high head pump-turbine using all synchronized guide vanes based on CFD tools as well as model tests; however the optimization criterion is not given.

Yan [3] has compared with S-curve between the CFD calculation based on the commercial code ANSYS-CFX13 with the standard k-ε model and experiment result. Yan has proposed a numerical method which is effective to simulate S-curve and pressure fluctuation; the criterion of S-curve is still not given.

Gentner [4] has proposed the criterion near no load at constant wicket gate opening in dimensional and dimensionless presentation for instability is $\mathrm{d}Q_{11}/\mathrm{dn}_{11}>0$. After many times numerical simulation or test, the curve n_{11}-Q_{11} is obtained and criterion can be estimated based on $\mathrm{d}Q_{11}/\mathrm{dn}_{11}>0$. Furthermore, Gentner [4] has published two vortices structure in runner channel such as fully developed vortices and vortex structure partially developed. With fully developed vortices, fluid enters the runner only at the shroud side, while vortices block the rest of the cross section. The inflow at the hub side enters the secondary vortex and these vortices are the main contribution to the S-curve. The main driver of the primary vortex is a strong cross flow on the pressure side from hub to shroud at the leading edge. If this cross flow can be reduced or avoided, the S-shape of the characteristic can be avoided or reduced along with the associated system fluctuations. Gentner's research achievement has given hydraulic engineer a direction of optimization to improve the S-curve.

Hasmatuchi [5, 6] has compared the flow angle on runner inlet between best efficiency point and runaway point. When the pumped-turbine operates on S-curve zone, the flow angle is smaller. So Vlad's achievement has also given a direction to optimize the runner to improve the S-curve.

Hasmatuchi [7, 8] has shown the experiment result of pump-turbine operating under off-design conditions in generating mode. The main flow under off-design conditions is dominated by one stall cell rotating with the impeller at sub-synchronous speed in the vane-less space between the impeller and guide vanes. It is likely the result of flow separations developed in several consecutive impeller channels, which lead to their blockage. Obviously, this rotating hydrodynamic instability is responsible for hydraulic unbalance and strong structural vibrations.

To sum up, many researchers pay attention to the S-shaped phenomena and principle, unfortunately, a reasonable criterion whether the designing turbine could run in S-shaped zone is still not obtained by now. Guide vane flow angle at no-load working points is an effective parameter to estimate whether the S-shaped zone could exist in the range of operation zone.

Consequently, this paper focuses on the flow analysis and criterion application in the S-shaped zone. The structure of the paper is arranged as follows: Detailed specifications of the pump-turbine are introduced in section 2. Section 3 describes the CFD model, disposal of boundary condition and numerical procedures. Section 4 presents the results and discussions, such as the predicted results of discharge-speed characteristics curve, flow angle formulate and comparison. At last, conclusions are made.

Reference

1 Houdeline J B, Verzeroli J M, Kunz T and Schwery A 2008 Reversible Pump/Turbine and Generator-Motor Design -*The Last PSP Achievements Experience in Asia* (Danang, Viet Nam), 2008.

2． J-B Houdeline, J Liu, S Lavigne, etal. Start-up improvement in turbine mode for high head PSP machine. Proc., IAHR, 2012, Beijing, China, IAHRXXVI-236-117.

3. J P Yan, U Seidel and J Koutnik., Numerical simulation of hydrodynamics in a pump-turbine at off-design operating conditions in turbine mode. Proc., IAHR, 2012, Beijing, China, IAHRXXVI-052-073

4. Ch Gentner, M Sallaberger, Ch Widmer, etal. Numerical and experimental analysis of instability phenomena in pump turbines. Proc., IAHR, 2012, Beijing, China, IAHRXXVI-116-074.

5. Vlad Hasmatuchi, Mohamed Farhat, Franc¸ois Avellan, etal. Experimental Evidence of Rotating Stall in a Pump-Turbine at Off-Design Conditions in Generating Mode. Journal of Fluids Engineering, MAY 2011, Vol. 133 / 051104-1.

6. Hasmatuchi,V., Roth,S., Botero,F.,and Avellan,F., Hydrodynamics of a pump-turbine at off-design operating conditions: numerical simulation. Proceedings of the ASME-JSME-KSME joint fluids engineering conference, Japan, 2011.

7. V Hasmatuchi, S Roth, F Botero, F Avellan. High-speed flow visualization in a pump-turbine under off-design operating conditions. 25th IAHR Symposium on Hydraulic Machinery and Systems, Timisaoya, 2010, 1755-1315_12_1_012059.

8. Hasmatuchi,V.,Farhat,.and Avellan,F., Experimental investigation of a pump-turbine at off-design operating conditions, proceeding of the 3rd international meeting of the workgroup on cavitation and dynamic problem in hydraulic machinery and systems, Brno, Czech republic,2009