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Numerical simulation of hydraulic force on the impeller of reversible pump turbines in generating mode *

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Abstract: The hydraulic force on the reversible pump turbine might cause serious problems (e.g., the abnormal stops due to large vibrations of the machine), affecting the safe operations of the pumped energy storage power plants. In the present paper, the hydraulic force on the impeller of a model reversible pump turbine is quantitatively investigated through numerical simulations. It is found that both the amplitude of the force and its dominant components strongly depend on the operating conditions (e.g., the turbine mode, the runaway mode and the turbine brake mode) and the guide vane openings. For example, the axial force parallel with the shaft is prominent in the turbine mode while the force perpendicular to the shaft is the dominant near the runaway and the turbine brake modes. The physical origins of the hydraulic force are further revealed by the analysis of the fluid states inside the impeller.

Key words: Pump turbine, hydraulic force, numerical simulation, generating mode, vortex, backflow

Introduction

The pumped energy storage power plant involves an important large-scale energy storage technology, which can enhance the stability of the electric grid and relieve the fluctuations of the output power caused by the renewable energies[1,2] (e.g., the wind[3], solar and tidal[4] energies). In the pumped energy storage power plant, the reversible pump turbine (RPT) is generally adopted due to its high efficiency, flexibility and economical benefits. For recent reviews of the reversible pump turbine, readers are referred to Zhang et al.[5,6]. One of the complexities of the reversible pump turbine technologies is its frequent starts and stops, switching between different working states (e.g., the load rejection or increment, the switches between the pumping mode and the generating mode) to meet the demand of the electric grid, leading to the generations of the vortex in the turbines[5]. Zhang et al.[6] clearly defined the various kinds of the aforementioned working conditions of the reversible pump turbines.

Currently, the reversible pump turbines are being challenged by unstable flow-induced phenomenon. Zhang et al.[7] experimentally investigated the large pressure fluctuation in the prototype RPT. We found that the pressure fluctuation of the RPT could be categorized into three regions based on the load conditions and characteristics of the fluctuation. Such kind of operations could lead to serious problems for the turbine components (e.g., the mechanical fatigue of the impeller) due to the large pressure fluctuations and vibrations[8-10].

Among the forces on the reversible pump turbine systems, there are three kinds of excitation forces according to their physical origins[8]: the hydraulic forces, the mechanical forces and the electromagnetic forces. The present paper focuses on the hydraulic

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forces. As compared with the conventional hydraulic turbines (e.g., the Francis turbine[11]), the reversible pump turbine has many unique features (e.g., fewer blades and higher rotating speed), as well as different operating parameters (e.g., the high water head), leading to a much larger hydraulic forces generated within the reversible pump turbines. Hence, in most cases, there exist prominent hydraulic forces on the fluid passing components of the reversible pump turbine (especially the impeller).

The abnormal hydraulic force affects the safe operations of the pumped energy storage power plant seriously. The hydraulic force on the impeller can be decomposed into two components: the axial force (parallel with the shaft) and the force perpendicular to the shaft. The axial force could lead to the force unbalance of the turbine (e.g., the lift of the turbine), leading to the damage of the unit (e.g., the bearings and the labyrinth ring) and abnormal stops of the reversible pump turbine. And, the force perpendicular to the shaft leads to the swing of the shaft. For example, in the Tianhuangping power station of China, the frequent lifts of the rotational components of the reversible pump turbines were observed during the load increment from 200 MW to 300 MW in the generating mode, leading to the abrasive damage of the machine and hence unplanned closing down of the machine. The primary on-site study shows that the lift of the machinery is caused by the large hydraulic force on the impeller during the above transition process. In our previous experimental work[7,10], a detailed experimental study was performed based on the on-site measurements of the vibration, the pressure fluctuation and the swing of the shaft. It is desirable to shed light on the physical origins of the hydraulic force on the impeller of the reversible pump turbine.

One of the difficulties of studying the hydraulic force on the impeller of a pump turbine is the presence of a great number of influential factors on these issues (e.g., the working states, the guide vane openings and the turbine geometries). For example, in the generating mode, the pump turbine could pass three working zones: the turbine zone, the turbine brake zone and the reverse pump zone, which are separated by the runaway line and the zero-flow-rate line[6]. A recent review of the reversible pump turbine can be found in Zhang et al.[6]. Hence, it is not possible and economical to experimentally determine those forces on the whole impeller in the above working states. Instead, the numerical simulation is a good choice to fulfill this task. In the literature, a great number of simulations were carried out[12-19], relating to the reversible pump turbines, mainly focusing on two aspects: the understanding of the S-shaped performance curve and the eliminating method (e.g., the misaligned guide vanes[13] and the hydraulic design of the impeller[14,15]), and the large pressure fluctuation[16,17]. The definition of the S-shaped performance curve of the reversible pump turbine was given in Zhang et al.[6]. The existence of the S-shaped performance characteristic curve could significantly affect the safe operation of the reversible pump turbine (in terms of the rotational speed)[18,19]. The engineering background of those studies is the instability under the idle load conditions, leading to large oscillations of the rotational speed and causing difficulties to the synchronous process with the electric grid. The literature review shows that the hydraulic force on the impeller of the reversible pump turbine remains an issue to be explored.

1. Numerical methods

This section gives a detailed introduction of the numerical simulation and related setups, together with the simulated operating conditions of the model reversible pump turbine. Figure 1 shows the main components of the reversible pump turbine (e.g., the spiral casing, the stay vanes, the guide vanes, the impeller and the draft tube) marked with different colors. Figure 2 shows the details of the impeller (including the crown, the blades and the band).

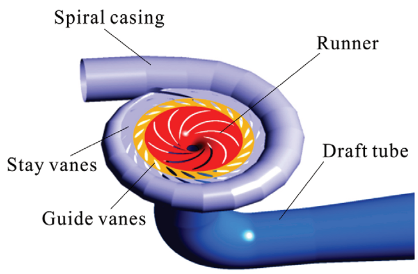

Fig.1 (Color online) The basic geometry of the investigated reversible pump turbine. The main components are marked with different colors in the figure: The stay vanes and the spiral casing (in purple color), the guide vanes (in orange color), the impeller (in red color), and the draft tube (in blue color)

The mesh convergence test is performed to ensure the validities of the present simulation. For the modelling of the rotor-stator interactions (e.g., the impeller-vanes interactions, here), the movement of the impeller is implemented through settings of the domain as a moving component.

The simulated cases are selected based on the model test of the performance curve for three guide vane openings (6°, 21° and 24°, respectively). For each guide vane opening, several typical cases are simulated in order to cover the possible operating conditions. A summary of the simulated cases is shown in Table 1 with the corresponding category of their operating conditions. In Table 1, the discharge factor (Q_{11}) is defined as