Operation of the counter-rotating type pump-turbine unit installed in the power stabilizing system

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Abstract. This serial research intends to put a unique power stabilization system with a pumped storage into practical use. The pumped storage is equipped with a counter-rotating type pump-turbine unit whose operating mode can be shifted instantaneously in response to the fluctuation of power from renewable resources. This paper verifies that the system is reasonably effective to stabilize the fluctuating power. It is necessary to quickly increase the rotational speed when the operation is shifted from the turbine to the pumping modes, because the unit cannot pump-up water from a lower reservoir at a slow rotational speed while keeping gross/geodetic head constant. The maximum hydraulic efficiency at the turbine mode is close to the efficiency of the counter-rotating type hydroelectric unit designed exclusively for the turbine mode. The system is also provided for a pilot plant to be operated in the field.

1. Introduction

For the next leap in power technologies to get a sustainable society, it is requested not only to cope with the warming global environment but also to conserve the natural ecosystem and coexist with nature. As for clean and renewable fluid resources in the world, the consumption of hydro resources is of about 2 TW at the onshore, wind resources is of about 72 TW and more than 2×10³ TW of ocean resources can be still more exploited [1], while in present, the electric power is consumed of about 1.4 TW. It is, however, too difficult to extract a constant stable power with an excellent quality from such resources whose circumstances are changed instantaneously and unexpectedly by weather systems. Nevertheless, such power stations are also required to provide the constant power with the excellent quality for the grid system in general, through electric double layer capacitors, flywheels, electric accumulators, and so on.

Pump storage systems, as green batteries, have been provided to accumulate the power from the renewable energy resources in Europe where many wind power stations are running [2]. In such systems, a traditional type pump-turbine has changed a partner from the atomic/thermal energy to the renewable energy, and not only worked to eliminate the power shortage but also stood by the blackout in the atomic power station. It may not be necessary to stabilize instantaneously the fluctuating power described above in Europe with its great grid system, but the instantaneous stabilization is required for small grids in isolated islands such as a Japan. The authors have proposed a unique power stabilization system with a pumped storage which is reasonably effective to stabilize instantaneously the fluctuating power [3]. The pumped storage is equipped with a counter-rotating type pump-turbine
unit whose operating mode can be shifted instantaneously in response to the fluctuation of power from renewable resources. In the unit, the front and the rear impellers/runners are connected to the inner and the outer armatures of a unique generator, respectively, and the impellers/runners/armatures counter-rotate at the same rotational torque. At a pumping mode, the rotating speeds of both impellers are adjusted automatically in response to the discharge, while not only the unstable characteristic but also the cavitation can be suppressed passively and effectively \[4\]. Moreover, the unit has fruitful advantages that not only the induced voltage is sufficiently high at the turbine mode without supplementary equipment such as a gearbox, but also the rotational moment rarely acts on the mounting bed because the rotational torque is counter-balanced in the impellers/runners/armatures \[5\].

In this paper, the performances of the pump-turbine unit with the impellers designed exclusively for the pump are investigated experimentally at the pumping and turbine modes, and the stabilization system is provided for the pilot plant to be operated in the field.
2. Power stabilization system with the pumped storage

The power stabilization system has been proposed [3], and is reviewed here redundantly to support discussions in the following chapters. Figure 1 shows a diagram of the power stabilization system with the counter-rotating type pump-turbine unit. The system is mainly composed of an electric accumulator with minimal capacity, a power control device, and a pump-turbine unit. As the wind may serve as a prime example for the instable and fluctuating power among the renewable energies, the wind power was appropriated as an example for the operation of the power stabilization system.

Figure 2 (a) shows the output from Intelligent Wind Power Unit in the field test [7], and the output was averaged every one minute as shown in Fig. 2(b), where the output averaged is arbitrarily 16,000 times as high as the one in Fig. 2 (a). It is assumed conveniently, here, that the wind power unit provides a constant rated power $P_G$ of 1 MW for the grid system. The output from the wind power unit is transferred directly to the electric accumulator, and the power control device detects either if the output is higher or lower than $P_G$. The power control device urges the electric accumulator not only to provide the rated power $P_G$ for the grid system but also to operate the pump-turbine unit at the pumping mode, while the wind velocity is faster than that generating $P_G$. That is, the surplus output is conserved, at once, as a potential energy. On the contrary, the power control device urges the pump-turbine unit to operate at the turbine mode converting from the potential energy to the hydroelectric output, while the wind velocity is slower than that generating $P_G$. That is, the turbine mode reforms the shortage power, and compensates the rated $P_G$ in uniting with the output from the wind power unit.
The pumping mode or the turbine mode is determined alternatively at every one minute in case of Fig. 2, where the final target of this serial work is to make the average time as short as possible.

3. Pumped storage with the counter-rotating type unit

Figure 3 shows the model counter-rotating type pump-turbine unit in the power stabilization system, which is composed of tandem impellers/runners and a peculiar generator-motor with double rotational armatures in place of the traditional mechanisms. The inner and the outer armatures in the generator-motor connect directly to the front and the rear impellers, or the rear and the front runners. The inner and the outer armatures are driven at the conditions that the rotational torque is counter-balanced and the relative rotational speed between both armatures in the AC motor is kept constant regardless of the individual rotational speed and/or the load [4][5]. As for the flow in the impellers/runners connecting...
to the armatures, the angular momentum change through the front impeller/runner must coincide with that through the rear impeller/runner. Resultantly, the flow must run in the axial direction at the rear impeller-runner outlet irrespective of the load and the discharge, while the attacking flow is in the axial direction at the inlet. Such peculiarly rotational behaviours are better suited for shifting instantaneously the operation mode, namely the flow directions without the auxiliary mechanism such as a guide vane.

At the pumping mode, the operating conditions described just above play important roles in adjusting automatically the front and the rear impeller speeds [4]. That is, the front impeller speed changes along the convex curve and the rear impeller changes along the concave curves against the discharge, in keeping the relative rotational speed constant. Such rotational behaviors suppress successfully the unstable operation at the low discharge and the cavitation at the high discharge. Besides, the unit has fruitful advantages described above at the turbine mode. The tandem runners have also proposed by Prof. Nielsen, but do not work in cooperation with the double rotational armatures [7].

Figure 4 shows the axial flow type blade profiles to investigate the performance in Chapter 4, where $R \Theta$ and $Z$ are the distances in the circumferential/tangential and the axial directions divided by the impellers/runners diameter $D = 150$ mm (the hub ratio is 0.4). The blades were designed by the three-dimensional inverse method [8], exclusively for the pumping mode which is very important for the pumped storage. The major specifications are the theoretical head $H_{ET} = 4.4$ m and the discharge $Q_D = 1.78$ m$^3$/min at the individual rotational speed $n_F = n_R = 1500$ min$^{-1}$ (subscripts $F$ and $R$ denote the front and the rear impellers). The numbers of the front and the rear blades are 5 and 4 at the pumping mode, where the numbers of the front and the rear blades are 4 and 5 at the turbine mode.

4. Complete performance

Figure 5 shows the unit discharge $Q_{11} = Q/(D^2H^{1/2})$, the positive and the negative values at the turbine/braking and the pumping modes, the unit input or the output $P_{11} = P/(D^2H^{3/2})$, $P$: the input at the pumping and the braking modes (negative value) or the output at the turbine mode (positive value), the hydraulic efficiency $\eta_1 = \rho g Q H/P$ at the pumping mode, = $P/(\rho g Q H)$ at the turbine mode, the unit rotational speeds of the front and the rear impellers/runners $N_{1F,R} = (n_{F,R} D / H^{1/2})$, and the unit relative rotational speed $N_{11} = (n_F D / H^{1/2})$, while the net/effective head is kept constant at $H = 2$ m [9]. The water is pumped up while the discharge $Q_{11}$ is negative at the positive $N_{11}$. It is necessary to make the unit relative rotational speed $N_{11}$ faster than 150 m, min$^{-1}$, for pumping up the water from the lower reservoir. The water cannot be pumped up at a slow rotational speed, because the pump head is proportional to the square of the rotational speed. Therefore, the pump-turbine is at the braking mode where $Q_{11}$ is positive, namely the turbine flow, even at the positive $N_{11}$ whose direction is at pumping mode. That is, the rotational speed must be increased rapidly when the operation is shifted from the turbine/pumping to the pumping/turbine modes.

The relative rotational speed is negative at the turbine mode in case of Fig. 5. In $Q_{11} = 0.35 \sim 0.45$ m, min$^{-1}$ (close to $N_{11} = 0$) at the turbine mode, the front runner $N_{11F}$ rotates in the same direction as the rear runner $N_{11R}$ but is faster than $N_{11R}$. Such a relative rotational speed brings a low output. The hydraulic efficiency $\eta_1$ is maximal at the moderate rotational speed, and the value is even equal to the efficiency (the dot line) of the counter-rotating type hydroelectric unit designed exclusively for turbine mode [10].

Above results suggest that this type pump-turbine unit exerts greatly effective performance for both the pumping and the turbine modes.

5. Operation at the pilot plant

The model power stabilization system was also provided for the pilot plant in the campus, as shown in Fig. 6, to be operated preliminarily in the field. The performances of the counter-rotating type impellers are expected so that the theoretical head $H_{ET} = 2.23$ m with a discharge $Q_D = 0.64$ m$^3$/min at a relative rotational speed $n_F = 3000$ min$^{-1}$. The impeller diameter is $D = 106.8$ mm with a hub ratio
0.4, the number of the front and the rear blades are 5 and 4 at the pumping mode (4 and 5 at the turbine mode), where the blade profiles are similar to Fig. 4. The pump-turbine unit is equipped with a double rotational armature type doubly fed induction generator-motor (3-phase, 2-pole, the rated output 1kW with a voltage 200V at a relative rotational speed \( n_T = 3000 \text{ min}^{-1} \)).

Figure 7 shows the performance at the pumping mode, where \( \phi \) is the discharge coefficient \( \left[ = \frac{2Q}{AD\omega} \right], \ A = \pi D^2/4, \ \omega \) the angular velocity, \( \psi \) is the head coefficient \( \left[ = \frac{8gH}{D^2\omega^2} \right] \) and INV is the input frequency which adjusts the relative rotational speed. It is confirmed that the counter-rotating type impellers suppress well the rising characteristics on the head curve \( \psi \), namely an unstable performance [4]. The system does not pump up water with enough discharge giving the maximum efficiency, due to hydraulic losses in the long penstock.

Figure 8 shows the unit discharge \( Q_{11} \), the unit output \( P_{11} \) and the hydraulic efficiency \( \eta_h \) against the unit relative rotational speed \( N_{11} \) at the turbine mode, where the valve opening [VO] gives a geometrical opening percentage of the magnetic valve installed in the penstock. The unit discharge
$Q_{11}$ increases with the decrease of $N_{11}$. The unit output $P_{11}$ and the efficiency $\eta_{h}$ increase with the increase of VO. These take the maximum values at the moderate $N_{11}$, and the maximum efficiency is $72\%$ at VO = 100 in the experiments.

The relative rotational speed $n_T$ was shifted tentatively from -890 min$^{-1}$ to 2250 min$^{-1}$ within 7 seconds, as shown in Fig. 9, where $T$ is the rotational torque. The relative rotational speed arrives $n_T = 0$ after 3 seconds from beginning of the shift and the impellers are at the braking mode till 5.5 seconds, namely within 2.5 seconds, and then starts working at the pumping mode. The rotational torque $T$ fluctuates in the early half of the shifting time (7 seconds) and the discharge $Q$ fluctuates in the later half with the aftereffect.

6. Concluding remarks

The power stabilization system with the counter-rotating type pump-turbine unit was proposed to provide a constant power with high quality for the grid system. The hydrodynamic performance of the pump-turbine unit with the impellers designed exclusively for the pumping mode was investigated experimentally, and the results proved beneficial operation at not only the pumping but also the turbine modes. The model system was also provided for the pilot plant in the field, and the operations were confirmed.

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