Simulation Method for Generating Mode and Pumping Mode Switching of Pumped Storage Hydropower Plant

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Abstract. The switching between generating mode and pumping mode of pumped storage power station is significant for the grid control, for example, to compensate the power fluctuation caused by the renewable energy by using the pumped storage power station. In this paper, the simulation models of various states of pumped storage power station are summarized, and the control methods of each switching stage between the generating mode and pumping mode are proposed. The method to realize each switching stage is presented, and the simulation method of each switching stage of generating mode and pumping mode is established in MATLAB/Simulink, and the switching process is realized.

1. Introduction

Power balance is the foundation of stable operation of power system, and the frequency and voltage of power system must be maintained within a certain range to maintain the balance of active power and reactive power. However, with the increase in the proportion of large-capacity rigid power supply such as nuclear power, and the large-scale development of renewable energy generation, the power balance of power system is confronted with great challenges [1, 2]. The power balance of power system can be realized through the power absorption and emission of energy storage system, which is an important way to keep the system running smoothly.

Pumped storage power station is an important way of energy storage. It has functions such as peak load shifting, frequency modulation and accident standby. Research on switching process and dynamic response of pumped storage power station is significant for the power grid to rationally use the functions of pumped storage power station.

Many studies focus on the dynamic process of pumped storage units. In Ref. [3], looping dynamic characteristics of a pump-turbine in S-shaped region during runaway was analyzed and dynamic method to simulate the critical transient parameters was proposed. In Ref. [4], dynamic response of a pumped storage hydropower plant with random power load in generating mode was analyzed. Runaway experiments were performed to verify the impact of the S-shaped characteristics on the pump-turbine runaway stability and appropriate measures were summarized to the safe and stable operation of a pumped storage station in Ref. [5]. It is worth mentioning the work presented in Ref.[6],
where the different guide-vane closing schemes for reducing the maximum transient pressures in the S-shaped region were analyzed.

The purpose of this paper is to study the simulation method for generating mode and pumping mode switching process of pumped storage hydropower plant. The remaining content of this paper is organized as follows. Section 2 summaries the model of various states of pumped storage power station. In section 3, control strategies of pumped storage power station are proposed. Switching process of pumped storage hydropower plant is analyzed in section 4. Simulation results are discussed in section 5. Finally, section 6 condenses the conclusions.

2. Model of Various States of Pumped Storage Power Station

2.1. Model of Pump Turbine

In power system researches, when the pumped storage unit operates under the generating mode, compared the operating characteristic curve of mixed flow pump-turbine characteristic curve and that of conventional turbine, it is not difficult to find that the two curves are consistent in most areas. Therefore, the nonlinear model of the turbine, the governor and the electro-hydraulic servo system of conventional turbine can be used as the model of the reversible pump-turbine in the generating mode. And the rigid water hammer model is adopted in water diversion system. The mathematical model of pump-turbine in generating mode used in this paper is shown in Fig.1 [7].

![Figure 1. Mathematical model of pump-turbine in generating mode](image)

Where, \( y \) is the guide vane opening, \( h \) is the water head; \( q \) is the water flow; \( p \) is the mechanical power; \( m_t \) is the mechanical torque; \( T_w \) is water flow inertia time constant; \( G \) is the ideal guide vane opening, which is proportional to the guide vane opening, and the coefficient \( A_t \) is related to the maximum guide vane opening \( y_{FL} \) and the no load guide vane opening \( y_{NL} \).

In pumping mode, the water head loss of unit at small guide vane opening is ignored and the model of reversible pump-turbine is similar with the model in generating mode, just the opposite water flow directions leads to different water hammer models.

2.2. Model of Doubly Fed Induction Motor

The model of doubly fed induction motor (DFIM) in the three-phase static coordinate system is able to visualize the relationship between the various electric parameters of DFIM. But the mathematical model of the DFIM in the three-phase static coordinate system is a high-order, nonlinear, and strong coupled system, which is very difficult to be analyzed and controlled. In this paper, the mathematical model of DFIM presented in Ref. [8] is adopted, in which the two-phase rotating coordinate system is obtained through PARK transformation to the mathematical model of DFIM in three-phase static coordinate system, to facilitate analysis and control.

The equations of active power, reactive power and electromagnetic torque are:

\[
\begin{align*}
    P_s &= 1.5(u_{sq}i_{sq} + u_{sd}i_{sd}) \\
    Q_s &= 1.5(u_{sq}i_{sd} - u_{sd}i_{sq}) \\
    T_e &= 1.5p_nL_m(i_{sd}i_{sq} - i_{sq}i_{sd})
\end{align*}
\]

Where, \( L_m \) is the mutual inductance; \( p_n \) is the number of poles; \( u_{sd}, u_{sq} \), \( u_{rd} \) and \( u_{rq} \) are the d,q-axis voltages of stator and rotor; \( l_{sd}, l_{sq}, l_{rd} \) and \( l_{rq} \) are the d,q-axis currents of stator and rotor.
3. Control Strategies of Pumped Storage Power Station

3.1. Model of Rotor-side Converter Control
The vector control method is adopted to realize the control of DFIM in this paper. Under the stator voltage oriented control method, the stator voltage vector is aligned with the d-axis in the synchronous rotating frame. And the following formulas can be obtained.

$$\begin{cases}
u_{sd} = U_s \\ 
u_{sq} = 0
\end{cases}$$

If the stator resistance and the dynamic process of stator flux linkage is neglected, the mathematical model of DFIM based on stator voltage orientation is shown in Fig.2.

$$\sigma = \frac{L_r^2}{(L_s L_m)}$$

3.2. Control Strategies of Pumped Storage Unit
Conventional pumped storage unit adopts the synchronous motor, and the speed is constant at the synchronous speed. The speed is controlled by the governor and guide vane opening; and the active power and the reactive power are controlled by the excitation voltage.

The variable speed pumped storage (VSPS) units can achieve the AC excitation control through the rotor side converter, so the speed, active and reactive power can be controlled independently. There are two different kinds of control methods of VSPS units.

**Figure 3.** Control strategies of pumped storage unit
The power control of VSPS units is realized on the rotor side converter of the DFIM, and the speed control of the VSPS units is realized on the governor of pump-turbine. As shown in Fig.3 (a).

When the power reference of the unit changes, the converter can respond quickly and the stator side power swiftly reach the given value. At the same time, the optimal efficiency speed is calculated according to the operating characteristics curve of the unit, and will be given to the governor, to adjust the speed of DFIM and output power of pump-turbine.

The speed control of VSPS units is realized on the rotor side converter of the VSPS, and the output of the unit is controlled by the guide vane opening. As shown in Fig.3 (b).

When the given active power signal of the unit changes, the optimal efficiency speed is calculated according to the operating characteristics curve of the unit, then it is given to the rotor side converter. By adjusting the rotor current, the speed of the unit is quickly adjusted to the most efficient speed. At the same time, the given power signal will be passed to the pump-turbine, the output power of pump-turbine can be regulated by adjusting the guide vane opening [9].

4. Simulation Method of Switching Process in VSPS Units

Compared to the conventional turbine, the operating conditions of VSPS units are more diverse and complex. During normal operation, VSPS units mainly have four kinds of stable operating conditions, which is generating mode, pumping mode, synchronous condenser operation and spinning reverse operation.

When the reversible units start up or change from a stable condition to another stable condition and normal or accidental shutdown, there will be more than 20 kinds of transition process. Such as start-up of generating mode or pumping mode, orderly shutdown of generating mode or pumping mode, load ramping or load rejection of generating mode or pumping mode, power outage, switching between generating mode and pumping mode and switching from pumping mode to synchronous condenser operation[10].

The following research mainly describes the normal operating conditions and switching process.

4.1. Generating mode simulation

4.1.1. Simulation of start-up in generating mode. Start-up of VSPS in generating mode can be divided into three stages [11]. The first stage is the self-starting stage. The stator side of DFIM is short-circuited and the rotor side is not controlled. And the guide vane opening of the pump-turbine is adjusted to the no-load guide vane opening. At this time, the electromagnetic torque $T_e$ of DFIM is zero as the d-axis rotor current is zero; in the case of no-load guide vane opening, the mechanical torque $T_m$ of DFIM is less than zero. So $T_e > T_m$, the DFIM rotates forward. When the speed of the DFIM reaches about 1.1 times of the synchronous speed, the excitation control system is put into the rotor side converter to stabilize the speed of DFIM.

The second stage is stage of preparation for grid connection. The rotor side converter exit after magnetism extinguishing, and the short-circuit switch is disconnected to prepare for grid-connected control. The third stage is no-load grid-connection stage. The rotor side converter is put into again and the synchronous grid-connection control strategy described in reference [12] is adopted to achieve the grid-connection as soon as possible.

4.1.2. Simulation of load ramping, stable operation and load rejection in generating mode. In those stages, the power priority control strategy is adopted [9]. In load ramping stage and load rejection stage, the power reference value is given in the form of a ladder or a slope in order to avoid power fluctuations.

In the stable operation stage, the reference value of the rotating speed of the unit can be adjusted according to the change of head and flow of the unit, so that the whole unit can operates in the optimal generating state; the response of the VSPS to the power dispatch of the power grid can be realized by changing the power reference value of the closed-loop control of power of the rotor side converter.
4.1.3. Simulation of orderly shutdown in generating mode. Orderly shutdown in generating mode can be divided into two stages. The first stage is grid splitting stage. After the load rejection stage, the stator side current is adjusted to zero as much as possible and then the interconnection switch is disconnected. The second stage is braking stage. There are two kinds of braking methods, which is electric braking and mechanical braking. When mechanical braking method is adopted, the DFIM will slow down to zero under the influence of its own damping. While the electric braking method is adopted, the stator side of DFIM is short-circuited, the excitation control is put into the rotor side of DFIM to reduce braking time. In pumped storage system, the operating condition is changed frequently, so the braking process should be as fast as possible. Therefore, the electric braking is adopted in this stage [13].

4.2. Pumping mode simulation

4.2.1. Simulation of start-up in pumping mode. There are many methods to start the doubly fed VSPS under the pumping mode. This paper adopts the variable frequency starting method [14]. Specific control strategy is: the stator side of the DFIM is short connected, and excitation control is put into the rotor side converter, which makes the current flows into the rotor side of DFIM is a negative phase sequence current of consistent size and frequency of 60 Hz. At this time, the input mechanical power of the DFIM is zero, that is $T_m = 0$. As the current on the rotor side is a negative-phase sequence current, the electromagnetic torque of DFIM is less than zero, that is $T_e < 0$. So $T_m > T_e$, and the DFIM rotates in reverse. Disconnect the excitation control of the rotor side when the rotating speed of DFIM is about 1.1 times of the synchronous speed, and the pumped storage unit is prepared to regulate the voltage and connect to the power grid.

The connection stage of pumping mode is similar to that of generating mode. The stator side voltage of the DFIM is adjusted by controlling the rotor side converter and the unit is connected to the grid when the stator side voltage meet the grid-connected condition.

4.2.2. Simulation of load ramping, stable operation and load rejection in pumping mode. In those stages, the speed priority control strategy is adopted [9]. In load ramping stage and load rejection stage, the power reference value is given in the form of a ladder or a slope to avoid power fluctuations.

In the stable operation stage, the speed reference value of constant speed control strategy can be adjusted according to the changing of water head and flow rate, so that the unit can operates at the optimal speed. By changing the power reference value of the pump-turbine side power control, the response of power dispatching of power grid can be realized.

4.2.3. Simulation of orderly shutdown in pumping mode. Same as the generating mode, the orderly shutdown in pumping mode can be divided into two stages. The first stage is grid splitting stage. After the load rejection stage in pumping mode, the stator side current of the DFIM should be minimized, and then turn off the interconnection switch. The second stage is braking stage, same as the generating mode, the electric braking method is adopted in this stage to reduce the braking time.

4.3. Switching between generating mode and pumping mode

The VSPS used in this paper consists of a reversible pump-turbine, a DFIM and a converter. The rotational speeds of pumped storage unit in the generating mode and the pumping mode are the opposite. So the switching between generating mode and the pumping mode needs a switching and commutation operation. In the simulation, the circuit breaker is used to realize the switching operation of the main circuit.

5. Simulation Results

The simulation of generating mode and pumping mode is established in MATLAB/Simulink, and the switching process is realized. Some parameters of DFIM are shown in table 1.
**Table 1. Parameters of DFIM**

| Parameters         | Value         | Parameters         | Value         |
|--------------------|---------------|--------------------|---------------|
| rated power        | 300MW         | stator resistance  | $Rs = 0.00103\Omega$ |
| frequency          | 50Hz          | rotor resistance   | $Rr = 0.00065\Omega$ |
| rated voltage      | 18kV          | stator inductance  | $Ls = 0.000194H$ |
| inertia $J$        | 4000000kg·m² | rotor inductance   | $Lr = 0.000267H$  |
| pole pairs $p$     | 12            | mutual inductance  | $Lr = 0.00567H$  |

Set the direction that the active power flows out of the grid as the positive power direction. And the mechanical power flows from pump-turbine to DFIM as positive direction. Assuming that the unit positive rotates under generating mode.

Fig.4 (a) and Fig.4 (b) show the speed waveform diagram and the stator side power waveform diagram during the switching process that the unit convert from generating mode to pumping mode. During $t=0s$ to $t=450s$, the rotating speed is positive and the stator side power flows from DFIM to the power grid, the VSPS operates under generating mode. During $t=450s$ to $t=850s$, the rotating speed is negative and the stator side power flows from the power grid to the DFIM, the VSPS operates under pumping mode.

The VSPS starts in generating mode during $t=0s$ to $t=90.4s$ and connect to the grid at $t=90.4s$; during $t=90.4s$ to $t=120s$, no-load operation; during $t=120s$ to $t=200s$, load ramping operation; during $t=200s$ to $t=280s$, stable operation; during $t=280s$ to $t=350s$, load rejection operation; during $t=350s$ to $t=370s$, no-load operation; Disconnect from the grid at $t=370s$ and orderly shutdown during $t=370s$ to $450s$.

The VSPS starts in pumping mode during $t=450s$ to $t=510s$ and connect to the grid at $t=510s$; during $t=510s$ to $t=530s$, no-load operation; during $t=530s$ to $t=600s$, load ramping operation; during $t=600s$ to $t=690s$, stable operation; during $t=690s$ to $t=780s$, load rejection operation; during $t=780s$ to $t=800s$, no-load operation; Disconnect from the grid at $t=800s$ and orderly shutdown during $t=800s$ to $850s$.

Fig.4(c) and Fig.4 (d) show the speed waveform diagram and the stator side power waveform diagram during the switching process that the unit convert from pumping mode to generating mode. During $t=0s$ to $t=400s$, the rotating speed is negative and the stator side power flows from the power grid to the DFIM, the VSPS operates under pumping mode. During $t=400s$ to $t=850s$, the rotating speed is positive and the stator side power flows from the DFIM to the power grid, the VSPS operates under generating mode. The switching process in generating mode and pumping mode is same as the switching process that the unit convert from generating mode to pumping mode.

In stable operation stage of generating mode, assuming that the grid will add a power step of 30MW at $t=225s$ and subtract this step at $t=255s$, Fig.4 (e) shows the comparison diagram of the power response with the instruction of the stator side. Through the comparison diagram, the conclusion that the stator side power response can follow the power instruction within a few seconds can be obtained.

In stable operation stage of pumping mode, assuming that the grid will add a power step of 50MW at $t=160s$ and subtract this step at $t=220s$, Fig.4 (f) shows the comparison diagram of the pump mechanical power with the power command signal. Through the comparison diagram, the conclusion that the pump mechanical power can follow the power command signal within a few seconds can be obtained.
Figure 4. Waveform diagram of simulation

6. Conclusion
Based on the modeling of pump-turbines and DFIM of pumped storage power stations, the control process of the switching between the generating mode and the pumping mode of the pumped storage power station is discussed in detail. And the simulation methods of the switching between the generation mode and the pumping mode are proposed. The switching process can be divided into three stages which are start-up stage, load ramping/stable operation/load rejection stage, and orderly shutdown stage. The simulation research methods of three stages in generating mode and the pumping mode are investigated respectively. The simulation models of the pumped storage unit are established in the MATLAB/Simulink. The entire switching process between generating mode and pumping mode is realized.

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