Modelling and Simulation of Doubly-Fed Variable-Speed Pumped Storage Unit

Zheng Tan¹, Lili Hao², Tingting Liang³, Tao Wu¹, Shanying Li¹, Hanzhi Zhang¹ and Jiali Lu²

¹State Grid Jibei Electric Power Co. Ltd. Research Institute, Beijing 100045, China
²North China Electric Power University, Hebei 071003, China
³State Grid Xinyuan Co. Ltd, Beijing 100761, China
*Corresponding author: hao_lillian @163.com

Abstract. On the basis of the mathematical model of doubly-fed variable speed pumped storage unit, the paper proposes a coordinated control strategy between the AC excitation system and governor. Based on the operation curve of pump-turbine, the optimal speed and gate opening of doubly-fed variable speed pumped storage unit are determined by active power command and real time water head. Simultaneously, the method taking into account of active power command and frequency fluctuation will make doubly-fed variable speed pumped storage unit to automatic regulate the frequency rapidly. Finally, the doubly-fed variable speed pumped storage unit is simulated by Real Time Digital Simulator (RTDS) software under the generating and pumping mode to validate and analyse the operational characteristics and performance.

1. Introduction
With the increasing concern over the depletion of fossil fuels and global warming, the development of renewable energy technologies is becoming increasingly attractive. However, wind and solar power as an unstable power makes trouble for power system operation and frequency stability[1]-[3]. Hence, there are several possible methods are developed to suppress the frequency fluctuation, including high energy batteries, compressed air, and pump storage power stations. Among these, pump storage power unit is considered as reliable energy storage system[4]. However, the synchronous machine is generally applied on the Conventional Pump Storage Unit(CPSU), which suffers some drawbacks. For example, the power output is only controlled by the turbine governor, which is not able to make contribution on frequency control in pumping mode; and CPSU cannot generate power over full range of water head [5].

Therefore, a Doubly-Fed Variable Speed Pumped Storage Unit(DFVPSU) has been developed, which employs Doubly-Fed Induction Machine(DFIM) to replace the synchronous machine to achieve wide variable operation of water head[6]-[8]. Meanwhile, a specific capacity cyclo-converter is connected in rotor circuit to achieve the energy transmission, which can make a great contribution on the ability of power control, increasing energy efficiency highly, and improving power quality of power system[9]-[11].

This paper presents a coordinated control strategy between the AC Excitation System (ACES) and the governor. The detailed model and its operational characteristics are evaluated and verified to suppress effectively the power system frequency fluctuation.
2. Modelling of DFVSPSU
A schematic diagram of DFVSPSU is shown in Fig. 1, which is constructed by DFIM, pump-turbine, and ACES respectively. The pump-turbine is connected to the DFIM rotor to achieve the energy conversion between mechanical power and electrical power. The DFIM is constructed from a wound rotor induction machine where its stator is directly connected to the grid and its rotor is fed by bi-directional voltage source converters, which are constructed by rotor side converter and stator side converter. The speed and torque can be regulated by controlling the rotor side converter.

\[
\begin{align*}
\begin{bmatrix} u_{abc} \\ u_{rabc} \end{bmatrix} &= \begin{bmatrix} -R_s & 0 \\ 0 & R_r \end{bmatrix} \begin{bmatrix} i_{abc} \\ i_{rabc} \end{bmatrix} + \begin{bmatrix} p\psi_{abc} \\ p\psi_{rabc} \end{bmatrix} \\
\psi'_{abc} &= -L_m \begin{bmatrix} -L_s & L_r \end{bmatrix} \begin{bmatrix} i_{abc} \\ i_{rabc} \end{bmatrix}
\end{align*}
\]

Where, \( u_{abc}, i_{abc} \) and \( \psi_{abc} \) are the three-phase stator voltage, current and flux linkage, respectively. \( u_{rabc}, i_{rabc} \) and \( \psi_{rabc} \) are the three-phase rotor voltage, current, and flux linkage respectively. \( R_s \) and \( R_r \) are the resistance of stator and rotor. \( L_m \) is the stator inductance, \( L_r \) is the rotor inductance, and \( L_s \) is the mutual inductance of stator and rotor.

The mathematical model of DFIM is established under the synchronization reference frame[12]. The equation of voltage and flux linkage are shown as (3) and (4).

\[
\begin{align*}
\begin{bmatrix} u_d \\ u_q \end{bmatrix} &= -R_i \begin{bmatrix} i_d \\ i_q \end{bmatrix} - \omega_i \begin{bmatrix} \psi_d \\ \psi_q \end{bmatrix} + \frac{dv_{ud}}{dt} \\
\psi_d &= -L_di_d + L_m i_{dl} \\
\psi_q &= -L_i i_q + L_m i_{ql} \\
\end{align*}
\]

\[
\begin{align*}
\begin{bmatrix} \psi_{sd} \\ \psi_{sq} \end{bmatrix} &= -L_i \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} + \frac{dv_{psd}}{dt} \\
\psi_{sd} &= -L_i i_{sd} - L_m i_{sdl} \\
\psi_{sq} &= -L_i i_{sq} - L_m i_{s ql}
\end{align*}
\]

Where, \( \omega_s \) is the synchronous frequency, and \( \omega_i \) is the rotor frequency. \( u_{sd}, u_{sq}, i_{sd}, i_{sq} \) and \( \psi_{sd}, \psi_{sq} \) are the \( d \)-axis and \( q \)-axis voltage, current and flux linkage of stator respectively. \( u_{psd}, u_{psq}, i_{psd}, i_{psq} \) and \( \psi_{psd}, \psi_{psq} \) are the same parameters for rotor. \( L_s \) is the equal stator inductance, \( L_r \) is the equal rotor inductance, and \( L_m \) is the equal mutual inductance.
2.2 Modeling of Pump-Turbine and Speed Governing System

The dynamic mathematical model of the reversible pump-turbine and its regulating system are as follows.

\[
\begin{align*}
    m_t &= \frac{\partial m_t}{\partial h} h + \frac{\partial m_t}{\partial n} n + \frac{\partial m_t}{\partial \mu} \mu \\
    q_t &= \frac{\partial q_t}{\partial h} h + \frac{\partial q_t}{\partial n} n + \frac{\partial q_t}{\partial \mu} \mu \\
    G_h(s) &= \frac{h(s)}{q_t(s)} = -T_w s
\end{align*}
\] (5)

where \( m_t \) is the input (output) torque of pump-turbine. \( q_t \) is the flow of water. \( h, n, \) and \( \mu \) are the water head, rotor speed and gate vane opening respectively. \( T_w \) is the water inertial time constant.

The block of transfer function for the pump-turbine considering water diversion system is shown in Fig. 2.

Within the range of rotational speed, the coefficients are constant approximately. The typical values are illustrated in [13]. Therefore, the transfer function is shown as below.

\[
P = \frac{1 - T_w s}{1 + 0.5 T_w s} \mu
\] (6)

2.3 Coordinated Control of Governor and AC Excitation System

The optimal operating speed of DFIM changes with the power variation, since the power is determined by governor and ACES. Mechanical power and rotational speed of the pump-turbine are adjusted by the governor through the gate opening.

On the one hand, the ACES rapidly adjusts the power according to the power given signal \( P^* \); on the other hand, based on the operational curve of pump-turbine, the optimal gate opening and the optimal speed are calculated theoretically. Then, the gate opening and optimal speed tracking are achieved by the governor. Thereby, the coordinated operation of governor and ACES makes DFVSPSU to operate at the optimal speed and rapid response. The control block diagram is shown in Fig. 3.
The DFVSPSU is adopted to participate the system frequency control to suppress the frequency fluctuation of power system. The detailed structure of frequency control is shown in Fig. 4.

![Fig. 4 The structure of frequency control](image)

### 3. Simulations and Discussions

In this section, the model of variable speed pump storage unit is built by the RTDS software in generating and pump mode to analyze the ability of frequency control and peak load control. The simulated parameters of DFVSPSU is shown in Table 1.

| Parameters                        | Value       |
|-----------------------------------|-------------|
| Rated Power (MW)                  | 300         |
| Stator Voltage (kV)               | 15.75       |
| Turns Ratio (Rotor/Stator)        | 0.41        |
| Rated Power Factor (Generate & Pump) | 0.9 & 0.98 |
| Pole Number                       | 14          |
| Water Head (m)                    | 400         |
| Thermal Rated Power (MW)          | 600         |
| Rated Voltage of Thermal (kV)     | 20          |

#### 3.1 Simulation of Frequency Control

A comparison of frequency regulation of DFVSPSU is presented in this section to analyse the effect on power system, so a power system of thermal power unit and DFVSPSU is shown in Fig. 5.

![Fig. 5 Thermal-DFIM System](image)

In generating mode, the initial value of load is 400MW, if the active power command ($P_{order}$) is 0.3pu, the load suddenly increases by 50MW in 1.0s. In pumping mode, the initial value of load is 380MW, and the $P_{order}$ is 0.3pu, the load drops 50MW in 1.0s. The simulated results are shown in Fig. 6 and 7.
According to the comparison between Fig. 6 and 7, the following conclusions can be obtained:

1) In this system, the active power of DFVSPSU could be adjusted within 0.6s throughout the link of frequency control, so the system frequency could be resumed to stability in 1 second. However, without DFVSPSU in the system, the frequency adjustment depends on the thermal power unit only when the load abruptly, it means that the responded time is quite slow. Therefore, the link of frequency control in DFVSPSU worked on the converters could obtain the fast response, while the thermal power unit gives a slower response due to the large inertia.

2) Suppressing the frequency fluctuation is performed better with DFVSPSU participation in system than that of without DFVSPSU.

3.2 Simulation of Peak Load Regulation
To analyse the characteristics of DFVSPU participating in power system peak load regulation, the operational characteristics of DFVSPU and CPSU are simulated and compared in both generating and pumping mode, which are shown in Fig. 8 and 9.
According to the comparison of Fig. 8 and 9, the characteristics of DFVSPSU and CPSU can be summarized:

1) The optimal operational speed of the DFVSPSU is adjusted rapidly with the active power changes, but the CPSU always operates at fixed speed.

2) In generating mode, when the requirement of active power increases suddenly, the speed of DFVSPSU will decrease slowly to release the rotating mass, this part of energy will convert to electrical power rapidly. Then, the angle of gate opening will change to the given value with the rotational speed of the DFVSPSU rise again till to the optimal speed. However, the operational principle is different in pumping mode, the speed will increase directly when the requirement of power abrupt changed, because the DFVSPSU is running as motor, there is no necessary to consume mechanical power for power compensation.

3) The response time of DFVSPSU is reduced 90%, compared with that of CPSU. Because the active power of CPSU is controlled by the mechanical equipment only. However, the power electronic equipment is used on DFVSPSU to achieve the faster response than that of CPSU.

4. Conclusion

In this paper, a 300MW variable speed pumped storage unit is modelled and simulated. Based on the specific structure of power system, the simulation results validate the effectiveness of proposed control technologies.

The advantage the DFVSPSU is that of rapid response, which is obviously faster than the CPSU to control the power adjustment. In generating mode, the DFVSPSU could control the rotational speed of doubly-fed induction machine to send or absorb electrical power, and thus to suppress the frequency fluctuation of power system. On the other hand, the DFVSPSU could change its rotational speed to obtain more input power in pumping mode, which is similar to generating mode. The further work will
extend to find a method to maximize the function of the DFVPSU supporting the power system stability.

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