Nonlinear simulation of speed variation of variable-speed unit under large disturbance by Simulink

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Abstract. The variable-speed pumped storage plant (VSPSP) has become an innovative technology and new orientation in recent years. Investigation of dynamic processes in operating and control of VSPSP is of great importance for safety, stability and efficiency. In this paper, a nonlinear integrated model for dynamic processes of VSPSP with doubly fed induction machines (DFIMs) is built based on Simulink. From the comparison between simulation results and on-site measurement data of a fixed-speed pumped storage plant (FSPSP), the model under load rejection is validated. Meanwhile, maximum rotational speed during transient processes is a key indicator for the safety of pumped storage units. Hence, the transient process and performance of VSPSP under load rejection are simulated and analyzed by using the model, and the speed variation of the variable-speed unit is specifically investigated. The speed rising value and relative speed rising value will decrease when the initial value increases because of the momentum conversion mechanism and the torque characteristic of pump-turbine. The result demonstrates that, if the initial speed increases in the operating range of variable-speed unit under load rejection, the maximum speed will not rise significantly, and there is a certain safety margin from the maximum allowable speed.

1. Introduction
Currently, effectively and efficiently dealing with generation intermittency of variable renewable energy in power grids is a growing study field. Variable-speed pumped storage plant (VSPSP) has the advantages [1, 2] of safety, stability and efficiency, etc. It has become the new development orientation of the global pumped-storage industry.

Many meaningful studies have been conducted on modelling and control of VSPSP [3-9]. However, to the best of the authors’ knowledge, the study on dynamic behaviour of VSPSP under large disturbance is rare. The goal of this work is to investigate the transient process and performance of VSPSP under load rejection, and the focus is on the speed variation. In this study, a nonlinear integrated model of VSPSP with doubly fed induction machines (DFIMs) is established based on MATLAB/Simulink, including the hydraulic, mechanical and electrical subsystems.

Maximum rotational speed during transient processes is a key indicator for the safety of pumped storage units. Meanwhile, continuous changing of the operating speed of variable speed unit during operation can be achieved by using DFIM. Due to thermal limitation, the speed change of DFIM normally would not exceed ±10% of the rated speed. When an emergent load rejection happens at different initial speeds within this range, the research on the speed rising rule is very important.
Therefore, this paper studies the speed rising rule of the variable speed unit under the emergent load rejection, and analyzes the corresponding reason.

This paper is structured as follows: In Section 2, the modeling method of VSPSP is briefly introduced, and a comparison between model simulation and on-site measurement data of an engineering case is presented, which can validate the model under load rejection. In Section 3, the change rule of speed variation under load rejection is specifically investigated, and the corresponding reason is analysed. In Section 4, the main works and conclusions of this paper are summarized.

2. Method and model

In this section, the model of VSPSP is developed using MATLAB/Simulink. It consists of the hydraulic, mechanical and electrical subsystems. In order to explore the change rule of speed variation under load rejection, a premise of this study is that the hydraulic-mechanical subsystem is decoupled from the electrical subsystem under the load rejection cases; hence, this work mainly focuses on the model of the hydraulic-mechanical subsystem.

In previous works for small-disturbance condition, the six coefficients \( e_y, e_{\omega}, e_h, e_{q_\omega}, e_{q_h} \) is usually used to simplify and linearize pump-turbine model [10-12]. These six coefficients are calculated from the complete curves of characteristics for pump-turbine, and they vary dramatically in different operating conditions. It is useful and convenient in the situation of small disturbances because the operating points are near the initial value. However, on the condition of large disturbances, since the operating points change drastically and in a wide range, it is not suitable to use those six constant coefficients. Hence, the model here for the hydraulic-mechanical subsystem is improved by applying look-up tables for the characteristic curves of pump-turbine. The following part of this section will briefly introduce the model (shown in Figure 1), and compare the model with a real pumped storage plant under the case of an emergent load rejection.

![Figure 1. Brief block diagram of the integrated model of variable-speed pumped storage plants.](image)

2.1 Hydraulic-mechanical subsystem (Pump-turbine and waterway)

Here, a nonlinear pump-turbine model is established, based on the characteristic curves of pump-turbine, which are shown in Figure 2 (a) and (b). It should be noticed that the characteristic curves are processed by using the logarithmic-curve-projection (LCP) method, as shown in Figure 2 (c) and (d), since the multi-valued problem in the pump-turbine characteristics [13]. The block diagram of the pump-turbine is shown in Figure 3.
Figure 2. The characteristic curves of pump-turbine: (a) Torque; (b) Discharge; (c) Torque by the LCP method; (d) Discharge by the LCP method.

Figure 3. Block diagram of the pump-turbine & waterway.

The block diagram and corresponding transfer function of the waterway system are described in Figure 4, in which the elasticity of the water column is considered.

Figure 4. The block diagram of the waterway system.

2.2 Model validation and study case.
In order to verify the model, a Chinese fixed-speed pumped storage plant (FSPSP) is chosen as the engineering case. The main purpose is to validate the model performance in simulating the hydraulic-mechanical transient process, because converter and AC exciter are completely disengaged on the condition of emergent load rejection, the dynamic behaviors of FSPSP and VSPSP are not essentially different.

The FSPSP contains two pumped storage units, and one of the units is taken as the study case. The comparison is based on the on-site measurement data and the model simulation in the transient processes of an emergent load rejection. All the parameters and characteristic curves of the pump-turbine of the model are based on this real pumped storage plant. Some of the parameters are shown in the following Table 1. The allowable maximum speed for the study case is 375 rpm, and the allowable relative speed rising value is 64%.

Table 1. Parameter settings of the pumped storage plant.

| Parameters | Value | Description               |
|------------|-------|---------------------------|
| $T_e$      | 0.44 s | Water elasticity time constant |
| $T_{wt}$   | 1.47 s | Water starting time constant of tunnel |
| $T_{wp}$   | 1.26 s | Water starting time constant of penstock |
| $T_a$      | 11.36 s | Mechanical time constant |
| $y_0$      | 0.70 p.u. | Initial guide vane opening |
| $t_c$      | 26 s   | Guide vane closing time duration |
| $n_0$      | 250 rpm | Initial rotational speed |
| $H_0$      | 210 m  | Initial water head |
| $m_{0p}$   | 0.98 pu | Initial load |

The emergent load rejection occurs at 63 s, the guide vane closed straight from 0.7 p.u. to 0 p.u. in 26 s, the load is rejected by 0.98 p.u. The comparison of measurements and simulation is shown in Figure 5. Overall, the simulation has a good agreement with the on-site measurement data. For the rotational speed variation, the simulation matches the measurements well.

If the electrical subsystem is disengaged on the condition of emergent load rejection, the dynamic behaviors of hydraulic-mechanical subsystem in FSPSP and VSPSP are not essentially different. In short, the numerical model built in this study can obtain a relatively good simulation of the dynamic behaviors for the emergent load rejection of VSPSP.

3. Speed variation under load rejection: simulation and analysis

3.1 Simulation
Continuous changing of the operating speed of variable speed unit during operation can be achieved by using a doubly-fed induction machine (DFIM). Meanwhile, the operating speed for DFIM technology cannot exceed the range of ± 10% of the rated rotational speed due to thermal limitations [16, 17]. It is meaningful to study the change rule of speed variation under load rejection, especially when the initial operating speed is different from the rated value.

In this section, a series of speed variations on the condition of load rejection under different initial rotational speeds are simulated and analysed. The initial rotational speeds are in the range of ± 10% of the rated rotational speed (250 rpm), from 230 rpm to 270 rpm. In the following simulations, the only variable is the initial rotational speed. Figure 6 describes the simulation results of the model under different initial speeds.

![Figure 6. Time-domain response under load rejection condition: (a) Rotational Speed; (b) Power.](image)

The load is rejected at 10 s, the guide vane closes in a straight line and completely closes within 20 s. Assuming the initial rotational speed difference is \(\Delta n_0\), the maximum rotational speed difference is \(\Delta n_{\text{max}}\).

An important rule for speed variation can be obtained as Equation (1):

\[
\Delta n_0 > \Delta n_{\text{max}}
\]

### Table 2. Speed variation under different initial rotational speeds

| Initial Rotational Speed (rpm) | Maximum Rotational Speed (rpm) | Speed Rising Value (rpm) | Relative Speed Rising Value (pu.) |
|-------------------------------|--------------------------------|--------------------------|----------------------------------|
| 230                           | 334.651                        | 104.651                  | 0.455                            |
| 240                           | 336.131                        | 96.131                   | 0.401                            |
| 250                           | 337.679                        | 87.679                   | 0.351                            |
| 260                           | 339.315                        | 79.315                   | 0.305                            |
| 270                           | 341.002                        | 71.002                   | 0.263                            |
Figure 7. Speeds variation under different initial rotational speeds

It means that the speed rising value would be smaller if the initial rotational speed became larger in a range of ± 10%. Detailed data are shown in Table 2 and the change rule of speed rising is described in Figure 7. It should be noticed that the difference of maximum rotational speed is smaller than the initial speed difference. The simulation values have a large safety margin from the allowable safety values (375 rpm), one reason is that a conservative guide-vane closing strategy is adopted; meanwhile, it also shows that the speed will not rise too much or even exceed the maximum allowable speed of the unit under load rejection if the initial speed increases in the operating range of variable-speed unit.

3.2 Analysis

The reason for this phenomenon can be observed in the operating point trajectory in the characteristic curves of the pump-turbine. It is shown in Figure 8 that the initial operating points are different under different initial speeds, the unit speeds $n_{1i}$ reach to maximum in the s-shaped region. To make it clearer, Figure 9 shows the relations between speed and torque for initial operating points. When the initial speed changes within ±10% of the rated speed, the larger the initial speed, the smaller the initial torque.

![Figure 8. Operating point trajectory in the characteristic curves of the pump-turbine: (a) Torque; (b) Discharge.](image-url)
For the first-order generator model, there is the following momentum equation as Equation (2).

\[ J \frac{d\omega}{dt} = T_{\text{turb}} - T_{\text{elect}} \]  

In the above equation, \( J \) is total inertia of the rotating parts (Kg\( \cdot \)m\(^2\)), \( \omega \) is rotational speed (rad/s), \( \omega = \frac{2\pi n}{60} \), \( T_{\text{turb}} \) is mechanical torque of the turbine (N\( \cdot \)m), \( T_{\text{elect}} \) is load torque (N\( \cdot \)m). After emergent load rejection, the load torque \( T_{\text{elect}} \) becomes 0. Hence, the following equation can be obtained by integration.

\[ J \Delta \omega = \int T_{\text{turb}} dt \]  

Figure 10 shows the simulation result when the initial speed is 250 rpm. From the figure, zero points of torque exactly correspond to extreme points of speed. The speed rising value is related to the integral area 1.
According to the previous analysis, it can be concluded that the torque becomes smaller as the initial speed increases. Therefore, the integral area 1 of the torque is smaller, and the speed increase value becomes smaller. This can be used to explain that the speed rising value decreases as the initial speed increases.

To compare the integral area of torque and the speed rising value more accurately, Table 3 is obtained by calculating the torque integral area 1 at different starting speeds (Figure 11).

![Figure 11. Comparison of the integral of torque at different initial speeds](image)

Table 3. Torque integral and speed variation at different initial rotational speeds

| Initial Rotational Speed (rpm) | Integral area 1 (Kg·m²/s) | Speed Rising Value by calculation (rpm) | Speed Rising Value by simulation (rpm) |
|-------------------------------|---------------------------|----------------------------------------|---------------------------------------|
| 230                           | 5.308E+07                 | 104.072                                | 104.651                               |
| 240                           | 4.880E+07                 | 95.682                                 | 96.131                                |
| 250                           | 4.463E+07                 | 87.515                                 | 87.679                                |
| 260                           | 4.052E+07                 | 79.460                                 | 79.315                                |
| 270                           | 3.626E+07                 | 71.098                                 | 71.002                                |

In Table 3, the second column is the integral area 1 of torque, the integral area decreases as the initial speed increases, so the speed rising value decreases. It can be seen from the third and fourth columns that the speeding rising values by calculating the integral area 1 of torque are closed to those by simulation, which can validate the above analysis. It should be noticed that speed rising values obtained by calculation and simulation are not exactly the same because of a slight deviation in the interpolation of the characteristic curve.

4. Conclusions

In this paper, a nonlinear integrated model for dynamic processes of VSPSP with doubly fed induction machines (DFIMs) is built based on MATLAB/Simulink, including the hydraulic, mechanical and electrical subsystems. There is no essential difference between the variable-speed unit and the conventional unit on the condition of emergent large disturbances since the electrical subsystem is decoupled from the model. Based on on-site measurement data of a Chinese FSPSP, the validation of the model under load rejection is conducted.

The transient process under load rejection is simulated and analyzed, and the speed rising rule is obtained. The speed rising rule can be explained by the momentum conversion mechanism and the torque characteristic of pump-turbine. From the torque characteristic curve, it can be seen that when the initial speed increases within the speed range of the variable-speed unit, the initial torque will decrease. Since the speed rising value is proportional to the integral of the torque, the speed rising value will
decrease. Hence, the speed rising value and relative speed rising value will decrease if the initial speed increases. The result demonstrates that, if the initial speed increases in the operating range of variable-speed unit under load rejection, the speed will not rise significantly, and there is a certain safety margin from the maximum allowable speed.

In this work, a preliminary exploration is conducted; a long-term goal is to further improve this nonlinear model, to achieve better simulation performance, and to further study dynamic behaviors of VSPSP under more complicated operating conditions.

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Appendix
Nomenclature

- $a$: coefficient in water hammer, usually be 0.5
- $s$: Laplace operator
- $D$: diameter of turbine inlet
- $f_c$: coefficient of friction
- $h$: water head
- $h_0$: initial water head
- $h_p$: per-unit value of water head
- $i_r$: the rotor current
- $J$: total inertia of the rotating parts
- $m_{11}$: unit torque
- $m_{g0}$: initial load
- $n$: rotational speed (rpm)
- $n_0$: initial rotational speed
- $n_{11}$: unit rotational speed
- $P_s$: stator active power
- $P_s^*$: set-point of stator active power
- $Q_s$: stator reactive power
- $Q_s^*$: set-point of stator reactive power
- $Q_{11}$: unit discharge
- $q$: discharge
- $V_r^*$: set-point of rotor voltage
- $V_s$: stator voltage
- $T_a$: mechanical time constant
- $T_e$: water elasticity time constant
- $T_{elec}$: load torque
- $T_s$: time constant of surge tank
- $T_{turb}$: mechanical torque of pump-turbine
- $T_{wt}$: water starting time constant of tunnel
- $T_{wp}$: water starting time constant of penstock
- $t_c$: guide vane closing time duration
- $y$: guide vane opening
- $\Delta n_0$: initial rotational speed difference
- $\Delta n_{max}$: maximum rotational speed difference
- $\omega$: rotational speed (rad/s)
- $\omega_m$: angular frequency of the rotor
- $\omega_m^*$: set-point of angular frequency of the rotor
- $\omega_i$: angular frequency of the voltages and currents of the stator windings

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