Modeling and Simulation of Mechanical and Electrical Transient of Variable-Speed Pumped Storage Units

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Abstract. In order to study the operation characteristics of large capacity variable-speed pumped storage units connected to the system, the electromechanical transient model is established. Firstly, based on the basic equations of the doubly-fed machine, the generator model represented by an equivalent voltage source is built. Secondly, on the premise of coupling term cancellation, the frequency conversion controller, frequency converter and generator connection module are normalized. Then, the generator model and variable frequency controller model are integrated to form the electromechanical transient model of the unit, which is not only the fitting of external characteristics but also retains the dynamic process of the motor flux linkage and the dynamic characteristics of the controller's inner loop. Finally, the electromechanical transient model is simulated on the RTDS platform. The simulation results show that the model is correct and effective, which is of great significance to the study of transient problems of large-capacity doubly-fed units connected to the grid.

1. Introduction
The variable-speed pumped storage unit is an efficient and advanced peak-regulation and frequency-regulation power supply with the advantages of good regulation performance and high operating efficiency. Therefore, it has been widely developed in Japan, Europe and other countries in recent years. Domestic research on variable-speed pumped storage units is in its infancy and rarely involves unit modeling. Considering that the modeling of variable-speed pumped storage units and doubly-fed wind turbines have certain similarities [1], their modeling experience can be used for reference.

Transient modeling and simulation include two types: electromagnetic transient modeling and electromechanical transient modeling. In terms of electromagnetic transient modeling, references [2~4] established a detailed model of each part of the doubly-fed wind turbine, considering the switching process of electronic devices. The model was specific, accurate and suitable for studying the electromagnetic relationship and control strategy within the unit. However, there were problems such as complex models and poor integral convergence when it was used to study the interaction between units and power grids. Therefore, a simplified electromechanical transient model needs to be established. In terms of electromechanical transient modeling, the generator/inverter was equivalent to a controlled current source model in references [5~6]. Although the dynamic characteristics of the inner loop of the
controller are simulated with a small inertial link, the inertial link is only selected according to the simulation convention, which can’t truly reflect the PI parameters of the inner loop, and ignored the dynamic process of the motor flux linkage. Therefore, the equivalent model is suitable for fitting the external characteristics of small capacity units, while it is not conducive to the transient stability analysis of large capacity units. In reference [7], an electromechanical transient model considering the stator transient process was established, which greatly increased the calculation work load because of the increase of order in the system model and the high-frequency component considered in the expression containing stator transient.

At present, the mainstream domestic simulation software adopts the electromechanical transient model in which the doubly-fed motor is equivalent to a controllable current source to simulate the external characteristics of the unit. This model can neither reflect the dynamic characteristics of the unit nor calculate the internal electric current of the rotor. From the perspective of actual engineering, this paper establishes a doubly-fed machine model that considers the dynamic process of the rotor flux linkage and is represented by an equivalent voltage source. Based on the vector control strategy, under the premise that the coupling item of the controller and the coupling item of the motor are offset, the normalization of the frequency conversion controller, the frequency converter and the motor connection module is studied. Using the second-order best principle, the inner loop of the controller is adjusted to the first-order inertia link, retaining the dynamic characteristics of the inner loop. On this basis, an electromechanical transient model of the variable-speed pumped storage unit is constructed. Based on the above content, the electromechanical transient model of Fengning 300MW variable-speed pumped storage unit is built on RTDS. The simulation curve basically coincided with the electromagnetic transient model response curve, which verified the correctness of the electromechanical transient model established in this paper.

2. Electromechanical transient model of variable-speed pumped storage unit

2.1. Electromechanical transient model of doubly fed machine

In the electromechanical transient simulation, it is unnecessary to consider the transient process of doubly fed machine stator winding [8]. Thus, when the stator side adopts the generator convention and the rotor side adopts the motor convention, the equations of the doubly fed machine in the dq rotating coordinate system is as follows:

\[
\begin{align*}
    u_{sd} &= -R_i i_{sd} - \psi_{sq} \\
    u_{sq} &= -R_i i_{sq} + \psi_{sd}
\end{align*}
\]

\[
\begin{align*}
    u_{rd} &= R_{sr} i_{rd} - \omega_s \psi_{rq} + \frac{p\psi_{rd}}{\omega_{base}} \\
    u_{rq} &= R_{sr} i_{rq} + \omega_s \psi_{rd} + \frac{p\psi_{rq}}{\omega_{base}}
\end{align*}
\]

\[
\begin{align*}
    \psi_{sd} &= -L_{sr} i_{sd} + L_{mr} i_{rd} \\
    \psi_{sq} &= -L_{sr} i_{sq} + L_{mr} i_{rq}
\end{align*}
\]

\[
\begin{align*}
    \psi_{rd} &= L_{mr} i_{rd} - L_{sr} i_{sd} \\
    \psi_{rq} &= L_{mr} i_{rq} - L_{sr} i_{sq}
\end{align*}
\]

Where \( u_{sd} \), \( u_{aq} \), \( u_{rd} \), \( u_{rq} \) are stator and rotor voltage; \( \psi_{sd} \), \( \psi_{aq} \), \( \psi_{rd} \), \( \psi_{rq} \) are stator and rotor flux chains; \( \omega_s = \omega_r - \omega_t \) stands for slip angular velocity; \( L_{sr} \), \( L_{mr} \) are self-inductance of stator and rotor and \( L_{sr} \) is mutual inductance between stator and rotor.
In steady-state operation, the power equation of the stator side of the doubly fed machine can be expressed as:

\[
\begin{align*}
P_s &= u_{sd}i_{sd} + u_{sq}i_{sq} \\
Q_s &= u_{sq}i_{sd} - u_{sd}i_{sq}
\end{align*}
\] (5)

Where \( P_s \) and \( Q_s \) are the active and reactive power of stator winding respectively.

The rotor motion equation of doubly fed machine is:

\[
T_J \frac{d\omega_m}{dt} = T_e - T_m
\] (6)

Where \( T_J \) is moment of inertia of the unit and \( \omega_m \) is the mechanical angular velocity.

The above equations are differential equations with the flux linkage of the machine as the state variable, which is not conducive to the intuitive analysis of the electromechanical transient characteristics of the machine and the system. In electromechanical transient simulation, the rotor current should be eliminated and the relationship between stator current and voltage should be represented by transient potential. Therefore, according to formula (2), the rotor current is specified by the following equation:

\[
\begin{align*}
i_{rd} &= \frac{\psi_{rd} + L_m i_{rd}}{L_{rr}} \\
i_{rq} &= \frac{\psi_{rq} + L_m i_{rq}}{L_{rr}}
\end{align*}
\] (7)

By substituting formula (7) into formula (3), the rotor current in the stator flux chain can be eliminated, and the equation can be simplified as follows:

\[
\begin{align*}
\psi_{sd} &= \frac{L_m}{L_{rr}}\psi_{rd} - \left( L_{ss} - \frac{L_m^2}{L_{rr}} \right) i_{sd} \\
\psi_{sq} &= \frac{L_m}{L_{rr}}\psi_{rq} - \left( L_{qs} - \frac{L_m^2}{L_{rr}} \right) i_{sq}
\end{align*}
\] (8)

By introducing formula (8) into formula (1), the interface equation between doubly fed machine and system can be written as:

\[
\begin{align*}
u_{sd} &= v_{d}^{'d} + X_{s}' i_{sq} - R_s i_{rd} \\
u_{sq} &= v_{q}^{'d} - X_{s}' i_{sd} - R_s i_{rq}
\end{align*}
\] (9)

Where \( v_{d}^{'d} = \frac{L_m}{L_{rr}}\psi_{rd} \) is the defined d-axis transient potential; \( v_{q}^{'d} = \frac{L_m}{L_{rr}}\psi_{rd} \) is the defined q-axis transient potential and \( X_{s}' = \left( L_{sd} - \frac{L_m^2}{L_{rr}} \right) \) is the defined transient reactance.

### 2.2. Control strategy of frequency converter

Considering that the rapid charging and discharging process of dc vessels can be ignored, this paper will model the inverter as a whole without distinguishing the network side and the rotor side. The vector control strategy of stator flux-oriented d axis is adopted, and the stator windings are ignored. According to formulas (1) and (3), the following equation can be described:
According to formula (10), the relationship between stator and rotor current can be obtained as follows:

\[
\begin{align*}
    i_{sd} &= -R_s i_{sd} - \psi_{sq} = -\psi_{sq} = -(L_{ss} i_{sq} + L_{m} i_{rq}) = 0 \\
    i_{sq} &= -R_s i_{sq} + \psi_{sd} = \psi_{sd} = -L_{ss} i_{sd} + L_{m} i_{rd} = \psi_s
\end{align*}
\]

(10)

By substituting equation (11) into equation (4) and simplifying it and then substituting equation (2), the excitation voltage equation of the generator is given by:

\[
\begin{align*}
    u_{rd} &= R_s i_{rd} - \omega_s \sigma i_{rq} - \omega_s L_{m} \frac{\psi_{sq}}{L_{ss}} + \frac{\sigma}{\omega_{base}} \frac{d[i_{rd}]}{dt} \\
    u_{rq} &= R_s i_{rq} + \omega_s \sigma i_{rd} + \omega_s L_{m} \frac{\psi_{sd}}{L_{ss}} + \frac{\sigma}{\omega_{base}} \frac{d[i_{rq}]}{dt}
\end{align*}
\]

(12)

Where \( \sigma = L_{ss} (1 - \frac{L_m^2}{L_{rs} L_{ss}}) \).

In order to realize fast and no difference regulation, this paper adopted PI control for both the inner and outer loops of the double closed loop and used the feedforward compensation link to realize decoupling control. The control equation of the current inner loop of the frequency converter is obtained as follows:

\[
\begin{align*}
    u_{rd} &= \left( K_{rd-p} + \frac{K_{rd-i}}{s} \right) (i_{rd} - i_{rd}) - \omega_s \sigma i_{rq} - \omega_s L_{m} \frac{\psi_{sq}}{L_{ss}} \\
    u_{rq} &= \left( K_{rq-p} + \frac{K_{rq-i}}{s} \right) (i_{rq} - i_{rq}) + \omega_s \sigma i_{rd} + \omega_s L_{m} \frac{\psi_{sd}}{L_{ss}}
\end{align*}
\]

(13)

Based on the above principle and equation derivation, the control block diagram of the frequency converter is shown in Figure 1.

![Control block diagram of frequency converter.](image)

2.3. Normalization of generator and inverter control

Combined with the above analysis, we can get the connection relationship of inverter controller, inverter and doubly fed machine, as shown in Figure 2.
As the electromechanical transient process is slow and the dynamic process of the inverter is very fast, the modulation process of the inverter can be ignored, and then can suppose the modulation voltage output by the inverter controller is the generator excitation voltage. Based on this assumption, the coupling term in the variable frequency controller completely cancels out the coupling term of the doubly-fed motor, and a normalized simplified model can be obtained, that is, the control block diagram of the controller current inner loop, as shown in Figure 3. At the same time, based on the second-order optimal condition and stagger principle, the \((1 + \tau s)\) term of the current inner loop PI regulator can be used to eliminate the \((1 + s \sigma / (\omega_{\text{base}} R_s))\) term of the motor parameters, so that the current inner loop can be set as the first order inertial link. This not only simplifies the model, but also retains the dynamic characteristics of the inner loop. The closed-loop equivalent circuit diagram is obtained, as shown in Figure 3.

Figure 3. Current inner loop control block diagram and closed loop equivalent circuit.

### 2.4. Electromechanical transient model of variable-speed pumped storage unit

Based on the above contents, the electromechanical transient model of variable speed pumped storage unit is obtained, as shown in Figure 4. Compared with the electromechanical transient model of doubly fed wind power, this model retains the dynamic characteristics of the inner current loop through the tuning of PI parameters and motor parameters. At the same time, the generator is no longer equivalent to the current source, but the rotor current is transformed into the rotor flux through the action of the motor, and then injected into the stator voltage equation in the form of transient potential. In addition, the motor is equivalent to voltage source. Not only the dynamic of rotor flux linkage is considered, but also the internal electrical quantities such as rotor current can be observed.

According to Figure 4, the equivalent circuit diagram of the system equivalent current source can be drawn from the overlapping points of the controller's current inner ring, as shown in Figure 5. It can be seen from Figure 5 that under the excitation control, the rotor loop presents current source characteristics, but the electric potential in the generator presents voltage source characteristics due to the consideration of the first-order inertial link set by the controller's inner ring.
3. Simulation results and analysis

In order to verify the consistency of the dynamic response between the electromechanical transient model established in this paper and the electromagnetic transient model, a single-machine infinite bus system is used on the RTDS platform to build two simulation models. The model uses Fengning 300MW variable-speed pumped storage unit parameters, specifically: rated capacity is 336MVA, rated power is 300MW, stator voltage is 15.75kV and turns ratio is 2.439.

As the reactive power is constant and the active power changes, the step response characteristics of the unit is investigated. When the load is rated that $P_{cmd}$ is 0.9 p.u. and $Q_{cmd}$ is 0.436 p.u., the active power reference value drops to 0.8p.u. in 0.15s as well as the simulation curve is shown in Figure 6. Among them, the blue is the electromechanical transient response curve, and the red is the electromagnetic transient curve. It can be seen from the simulation curve that the initial value of the response waveform of the electromechanical transient state and the electromagnetic transient state has a slight static deviation, nevertheless the overall agreement is basically the same. In the case of an active power step, the q-axis component of the rotor current is mainly affected, and the two show a positive correlation. The d-axis component of the rotor current and reactive power have a dynamic response, but the steady-state value is basically unchanged. Considering the modulation effect of the inverter in the electromagnetic transient model, the waveform oscillates slightly and the power step point is slightly different from the electromechanical transient, which does not affect the overall analysis. Thus, it verifies the correctness of the electromechanical transient model proposed in this paper.

In order to verify that the electromechanical transient model can realize the decoupling control of active power and reactive power, this article carried out a control experiment of the previous working condition. This paper chose the same initial working condition that $P_{cmd}$ is 0.9 p.u. and $Q_{cmd}$ is 0.436 p.u., and dropped the reactive power reference value to 0.4 p.u. in 0.15s. The simulation curve is shown in Figure 7.
Figure 6. Comparison of electromechanical transient and electromagnetic transient response curves under active power step.

Figure 7. Comparison of electromechanical transient and electromagnetic transient response curves under reactive power steps.
It can be seen from Figure 7 that when the reactive power changes, it mainly affects the d-axis component of the rotor current, and there is also a positive proportional relationship between the two, while the steady-state value of the q-axis component of the rotor current and the active power are almost unaffected. According to Figures 6-7, the dynamic response process of electromechanical transient and electromagnetic transient under different working conditions are basically the same and the model is correct and effective. The active power depends on the rotor q-axis current as well as the reactive power depends on the rotor d-axis current. There is no coupling relationship between the rotor d-axis and q-axis current so that it realizes the decoupling control of active and reactive power.

4. Conclusion
In this paper, the electromechanical transient model of variable-speed pumped storage units is established. Considering the dynamic response of the rotor flux linkage of the motor, the interface equation between the motor and the system is expressed in the form of an equivalent voltage source. By using the second-order optimal principle, the control inner loop of the inverter is set into a first-order inertial link, which keeps the dynamic characteristics of the inner loop and can observe the internal electrical quantities such as rotor current. Based on the RTDS simulation platform, the electromagnetic transient and electromechanical transient simulation models of variable-speed pumped storage units are built. The correctness of the electromechanical transient model proposed in this paper is proved by step test and it can measure internal variables such as rotor current and realize decoupling control of active power and reactive power. It is suitable for transient stability research of large capacity variable-speed pumped storage units connected to the power grid.

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